Space Power, Thermoelectrics, and Thermionics

2014 Workshop on Thermionic Energy Conversion for Space and Earth

NASA Johnson Space Center

Houston, TX

Jean-Pierre Fleurial

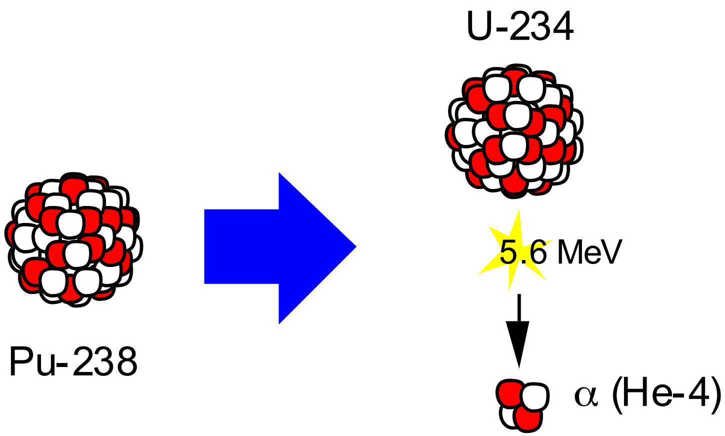
Jet Propulsion Laboratory/California Institute of Technology

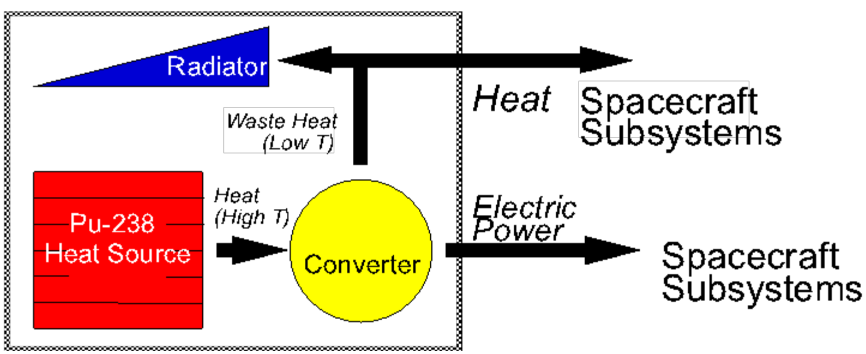
Pasadena, California, USA

October 14-15, 2014

Space Nuclear Power Systems Overview

Space Nuclear Radioisotope Power Sources





RPS Functional Diagram

- Thermal energy from a radioisotope source is converted to electrical energy

<u>Contains</u>:

- Radioisotope heat source
    - General Purpose Heat Source
- Energy converter
    - Thermoelectric
      (only flight qualified system to date)
    - Stirling
    - AMTEC
    - Thermophotovoltaics
    - LT Thermionics?
- Radiator
    - Passive
    - Active (for waste heat management)

- Suitable for applications requiring low power (< 1 kW) for long periods

JPL

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

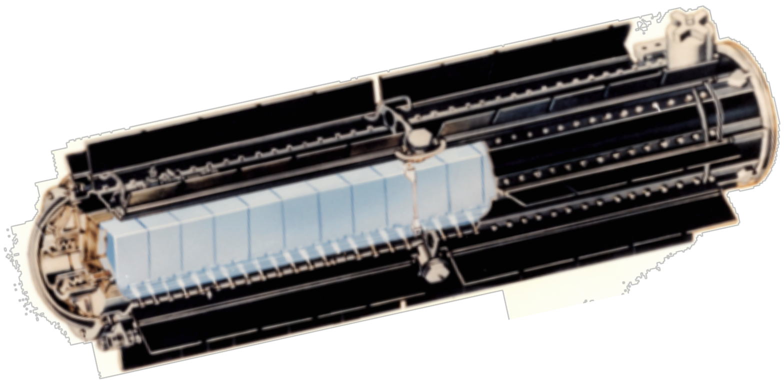
**Planned

**Total power at Beginning of Mission (W)*

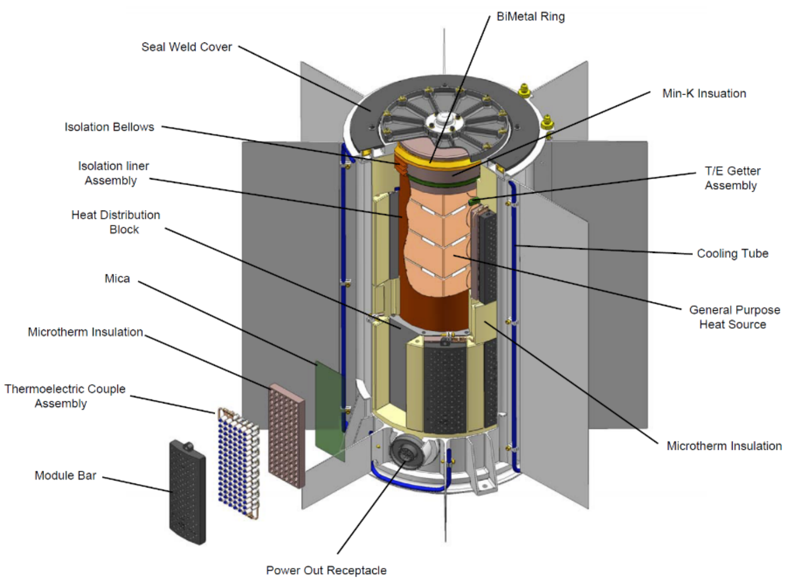
RTGs have been successfully used on a number of long-life missions

JPL

Heritage and Current RTGs



- GPHS-RTG (Cassini, New Horizons)
  - Vacuum-only operation
  - N-type and p-type Si-Ge alloys
  - Cantilevered "unicouples"
  - Heat source: ~ 4500 Wth (18 GPHS)
  - Power: ~ 295 W_e
  - Specific power: ~ 5.1 W/kg

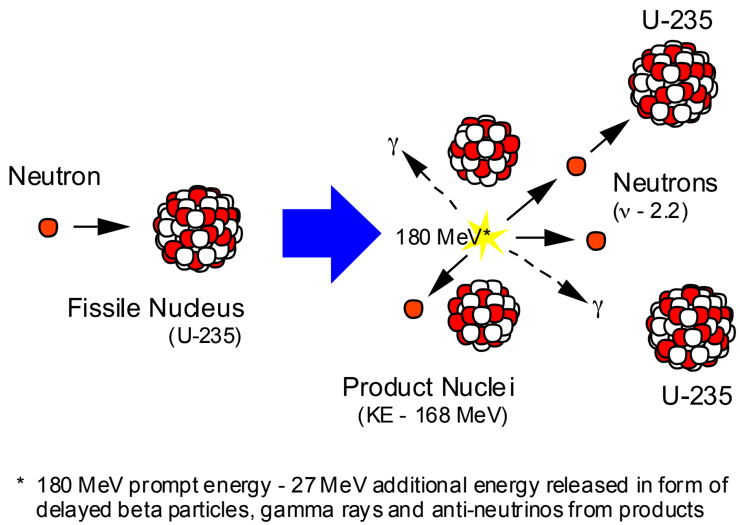


MMRTG developed by DOE, Aerojet Rocketdyne and Teledyne Energy Systems, Inc.

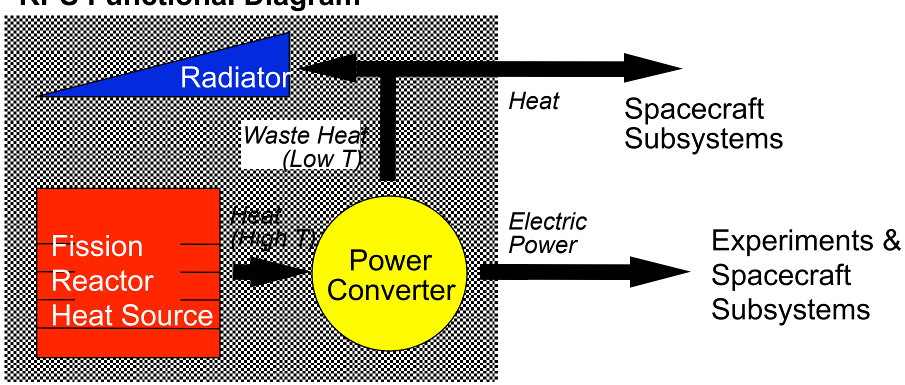
- MMRTG (Mars Science Lab, Mars 2020)
  - Developed to "Multi-Mission" specifications
  - 768 Spring-loaded couples
  - N-type PbTe and p-type TAGS/(Pb,Sn)Te
  - Heat source: ~ 2000 Wth (8 GPHS)
  - Power: ~ 122 W_e (Beginning of Life)
  - Specific power: ~ 2.8 W/kg

System-level efficiencies ~ 6.3% ; TE materials & device technologies from the 1960's

Space Nuclear Reactor Power Sources



RPS Functional Diagram



- Thermal energy from a fission reactor is converted to electrical energy

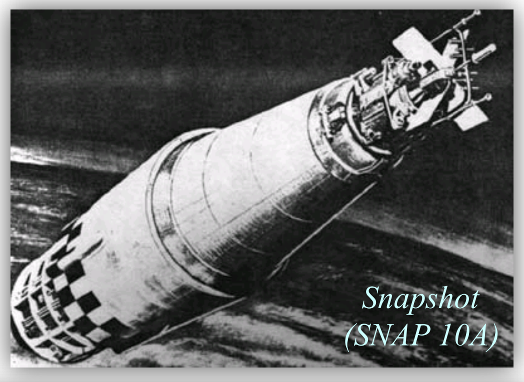
Contains :

- Heat source
- Fission reactor/shield
- Power converter
  - Thermoelectric
    (only one flown by US)
  - Thermionics (flown by USSR)
  - Brayton,
  - Stirling
  - AMTEC
- Heat transport subsystem
- Radiator subsystem
- Reactor Instrumentation and Control
- Power management and distribution

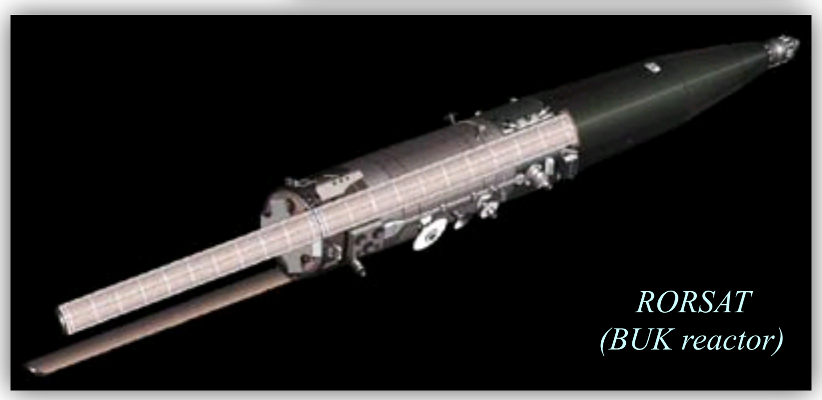
- Suitable for applications requiring high

Historical Space Reactor Power Systems

- A number of small space reactors have been developed and flown
  - Fast reactors fueled by highly enriched Uranium, reflector controlled
  - Liquid metal cooled
  - Power conversion using static energy conversion technology: either thermoelectric or thermionic
- Soviet reactors have vast bulk of flight heritage
  - 31 RORSATs launched between 1970 and 1988 (<3 kWe)
  - 2 Cosmos missions with TOPAZ reactors (~6 kWe) launched in 1987



Snapshot (SNAP 10A)



RORSAT (BUK reactor)

Reactor	Fuel Type	Coolant	Power Conversion	Thermal Power	Electrical Power	System Mass
SNAP 10A	UZrH	NaK	TE	45 kW	~500 W	427 kg
BUK	U-Mo	NaK	TE	~100 kW	~3 kW	~1250 kg*
Topaz I	UO2	NaK	Thermionic	150 kW	6 kW	~1200 kg
Topaz II	UO2	NaK	Thermionic	135 kW	5.5 kW	1061 kg

**includes boost disposal stage*

TE in Space: 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 43 nuclear power sources (42 radioisotope thermoelectric generators and one nuclear reactor) on 25 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.

A Brief History of Past Thermionic Energy Conversion Efforts at JPL

JPL Involvement with Thermionics

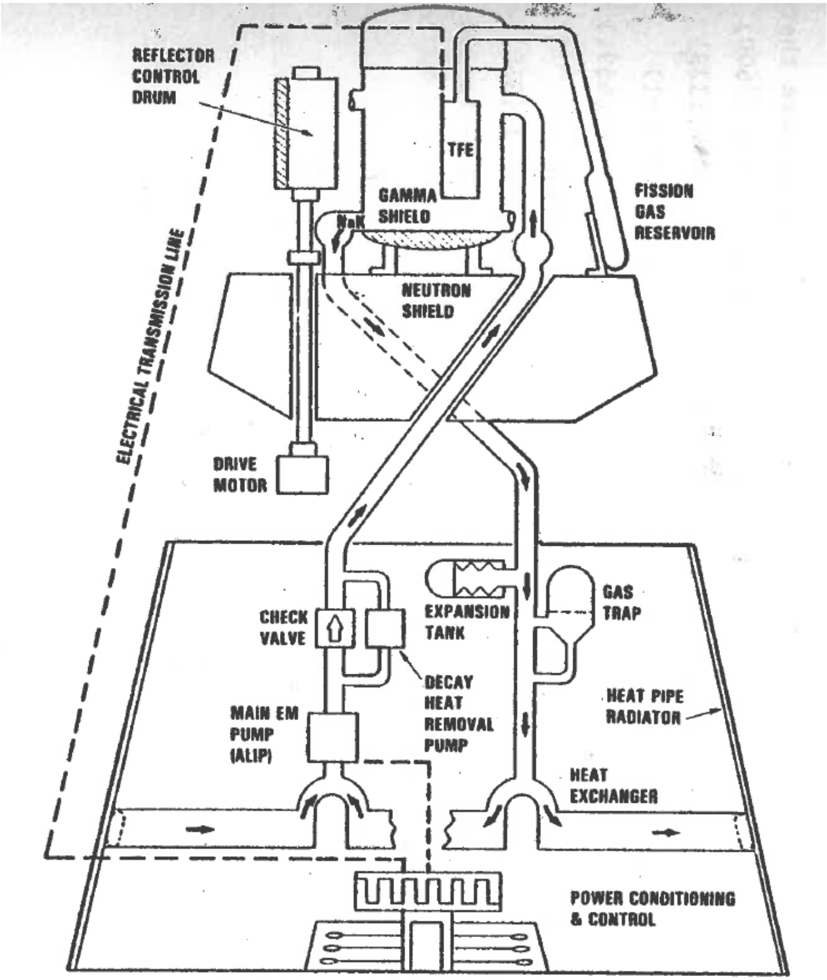
- JPL started work on thermionic Energy Conversion in 1958
  - Started work on thermoelectrics in 1961
- JPL initiated a solar thermionic converter life evaluation and generator test program in 1961
- Built and tested 4-converter generators
  - Lab test and field test using parabolic mirror
- Tested planar converters in the 1900 to 2000 K emitter temperature range
  - Life of up to 11,000 hours
  - Some converters with degradation rates as low as 5%
  - Conversion efficiencies up to 10%
  - Up to 25 W/cm^2 on the converter surface
- Program terminated in the early 1970's

JPL Involvement with Thermionic Conversion Testing

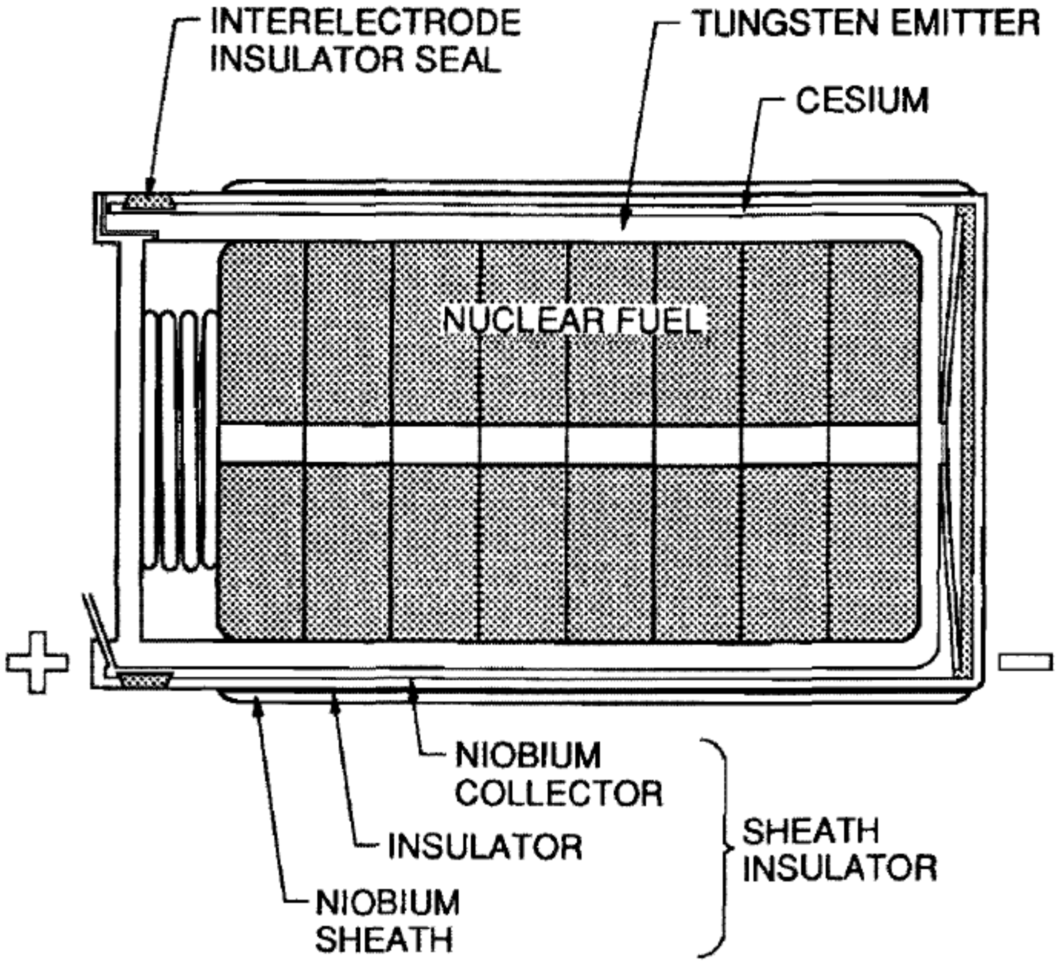
- In the 1970's JPL worked with Thermo Electron Corporation to develop and test flat plate thermionic converters
  - Converters typically had CVD <110> W emitter and a niobium collector
  - Variable separation gap from 1.25 to 40 mils
  - Emitter temperature was varied from 1600K to 2000K
  - Collector temperature was varied from 850K to 1100K
  - Cesium reservoir temperature was varied from 550K to 650K
  - Current density was measured as a function of output voltage

JPL was the program manager of SP-100

- General Atomics developed a 100 kW_e in-core thermionic design for SP-100
  - 100 kW_e net power
  - 1300 W_{th} reactor power
    - UO_2 nuclear fuel
  - 100 Vdc output voltage
  - ~ 7% System conversion efficiency
  - 7 year design lifetime
  - 1700K emitter temperature
    - W emitter
    - 20 mil initial interelectrode gap
    - Nb collector
  - Al_2O_3/Y_2O_3 insulator
  - 990K radiator temperature



Typical In-core Reactor Thermionic Converter within Fuel Element (TFE)



SP-100 Thermionic Technology Option

- JPL assessed key technical risks associated with thermionic conversion
  - Fueled emitter deformation and shorting
  - Sheath insulator swelling, cracking and debonding as a result of high neutron fluence, high temperature and high voltage
  - Graphite cesium reservoir cesium pressure stability with temperature under neutron fluence
  - Seal insulator is required to be leak tight to separate cesium from fission products for 7 years with neutron fluence

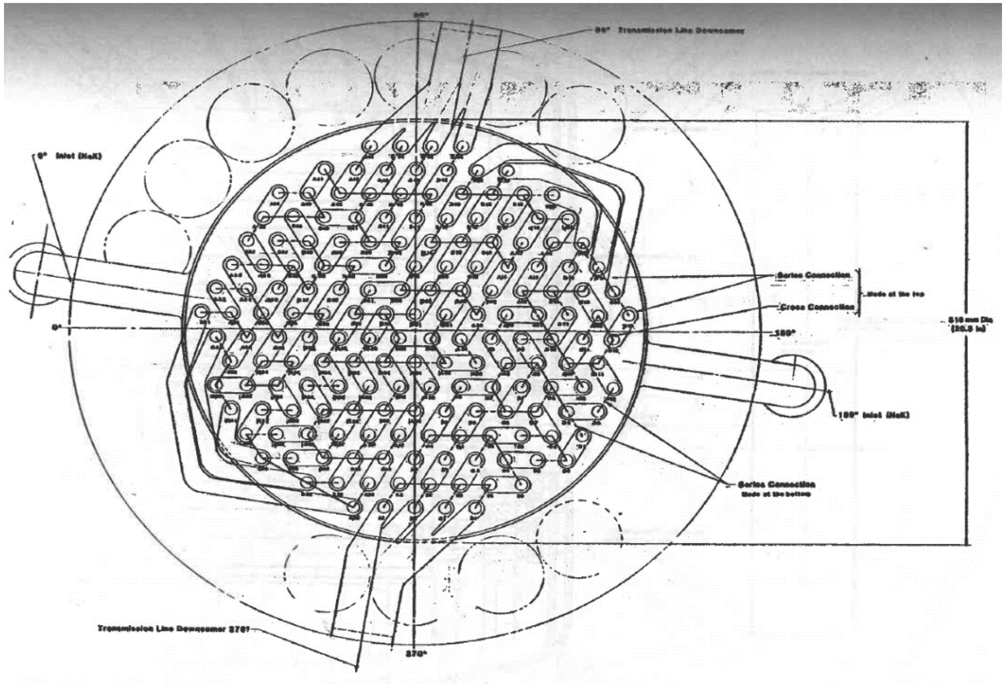
Fueled Emitter Deformation

- Emitter deforms as a result of UO_2 fuel swelling
  - This was considered to be key risk of Thermionic reactor
  - Eventually emitter will touch collector
  - Results in short circuit and loss of power
  - Fuel swelling is dependent on neutron fluence, fuel burn-up and fuel temperature
  - Extensive in-core testing of thermionic converters form 1985 through 1989
  - LANL developed the LIFE-4 code to predict emitter deformation as a function of fuel burn-up, temperature, and axial location

JPL Thermionic Reactor System Code

- JPL developed a detailed system analysis code to evaluate the reactor swelling and electrical power output
  - Used extensive thermionic performance data based developed by JPL and Thermo Electron testing of flat plate converters
    - Same emitter and collector materials used with GA design
  - Used LANL developed LIFE-4 fuel swelling data
  - Each Thermionic Fuel Element (TFE) has 6 thermionic converters connected in series
  - A total of 176 TFEs within the core arranged in five radial rings of similar power density
  - Reactor power density was estimated by LANL each of the five heights within each of the five rings and this power density was input to model
  - Model then calculated resultant emitter temperature and fuel burn-up across reactor
  - Emitter temperature and burn-up are used to estimate amount of fuel swelling

TFE Distribution Within Core and Predicted Reactor Performance



	RING 1	2	3	4	5	TOTAL
NO. OF TFE's	6	12	42	60	56	176
NO. OF CONVERTERS	36	72	252	360	336	1056

BOL AVERAGE T_E = 1767 K

INPUT REACTOR RELATIVE POWER DENSITY PROFILE

0.888	0.886	0.921	0.836	0.873
1.039	1.045	1.092	1.002	1.067
1.116	1.125	1.178	1.086	1.164
1.116	1.125	1.178	1.086	1.164
1.039	1.045	1.092	1.002	1.067
0.888	0.886	0.921	0.836	0.873

RESULTANT REACTOR TEMPERATURE PROFILE

1741.	1743.	1774.	1769.	1735.
1704.	1714.	1757.	1764.	1738.
1714.	1726.	1771.	1781.	1763.
1723.	1734.	1778.	1787.	1771.
1729.	1738.	1780.	1785.	1762.
1768.	1769.	1804.	1799.	1759.

AFTER 60,000 HOURS: AVERAGE T_E = 1726K

RESULTANT REACTOR TEMPERATURE PROFILE

1727.	1721.	1745.	1736.	1708.
1688.	1688.	1720.	1715.	1700.
1693.	1697.	1731.	1723.	1710.
1702.	1705.	1739.	1729.	1716.
1710.	1711.	1741.	1731.	1717.
1752.	1746.	1768.	1757.	1733.

Interconnection and distribution of the TFEs within the reactor core.

Reactor temperature and power profile

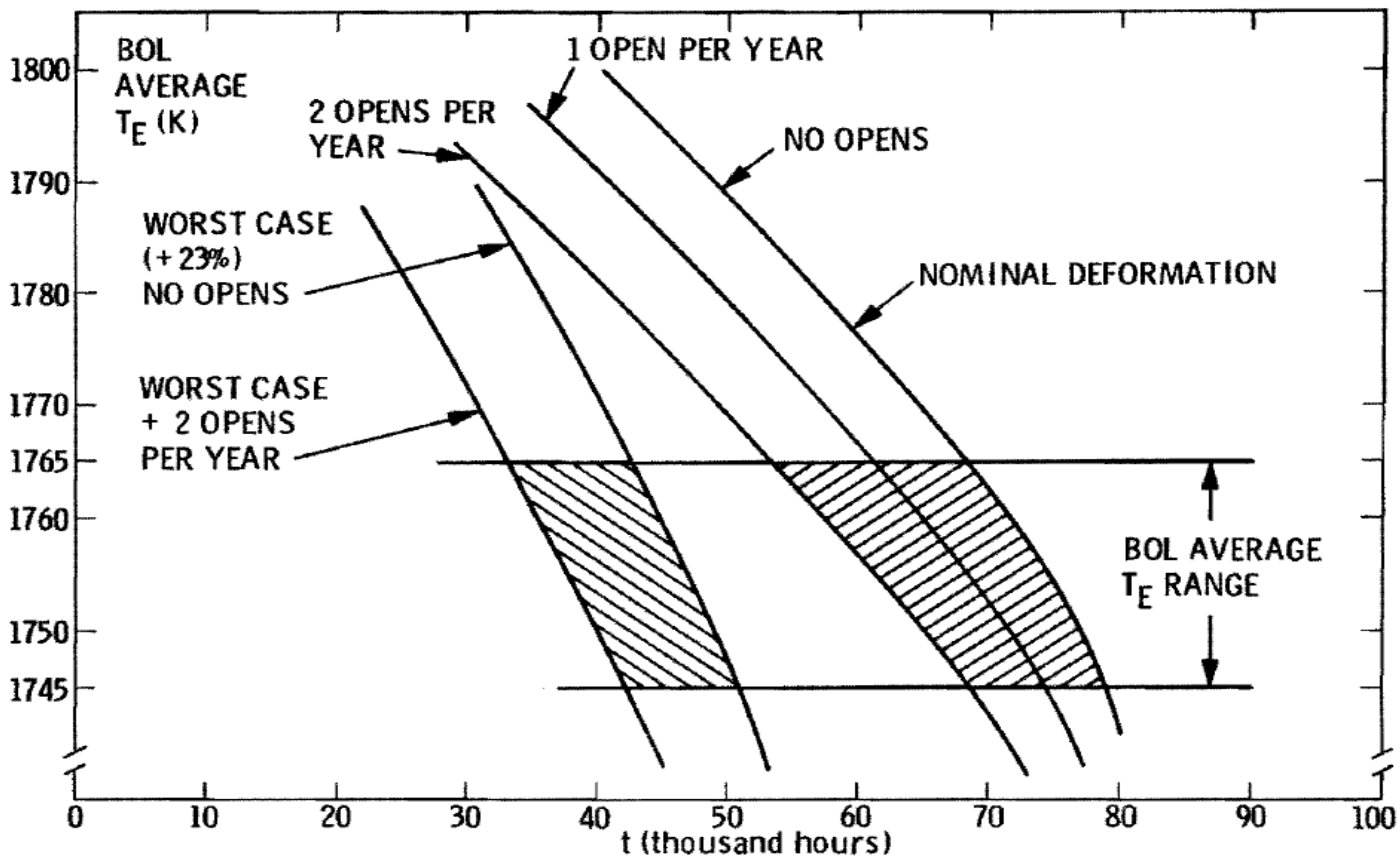
JPL SP-100 TI System Code Assumptions

- I-V performance of each of the 25 groups of thermionic converters was calculated as a function of time
- Thermionic converters are connected in a series-parallel network
  - 4 parallel strings of 264 converters in series
  - All cells in series must have same current and those in parallel will have a common voltage
  - Most converters will not be operating at the optimal point, but at the operating point determined by the series/parallel network
  - Model allows for 5 different cesium reservoir temperatures, optimized for each radial zone
    - Each TFE uses a common cesium reservoir so the cesium pressure is the same for each of the 6 converters within a single TFE
  - Model considered both short circuits from fuel swelling as well as open circuits
    - Emitter distortion will be non-uniform. Code estimates both a maximum distortion used for shorting and an average distortion used for performance calculations
  - Model also considered radiator degradation as a result of heat pipe failures from micrometeoroids and debris

JPL SP-100 TI System Code Results

- An average beginning of life emitter temperature of 1745K to 1767K is required to provide a net 100 kW of electric power to a user
  - Range of temperatures is due to uncertainties in heat transfer and mass optimization
- Operation plan was to adjust reactor power as a function of time to provide a continuous 100 kW of power output
  - Average temperature required actually decreases with time because of performance improvements associated with decreasing inter-electrode gap
- First inter-electrode shorts considered to occur when gap is less than 3 mils (0.076 mm)
  - Occurs in converters with highest temperatures, smallest fuel voids, and highest power densities
  - Evaluated both nominal and worst case emitter distortion
    - Worst case was based on the largest discrepancy (23%) between the actually measured distortion from in-core testing and the LIFE-4 model
  - Nominal initial shorting occurs at 70,000 to 80,000 hours (8 to 9 years)
  - Worst case initial shorting occurs at 40,000 to 50,000 hours (4.6 to 5.7 years)
  - The effect of one to two open circuits per year was also determined
    - In the worst case, this reduced the time to first short circuit to 32,000 to 42,000 hours

Emitter Temperature vs. Time to First Short Circuit

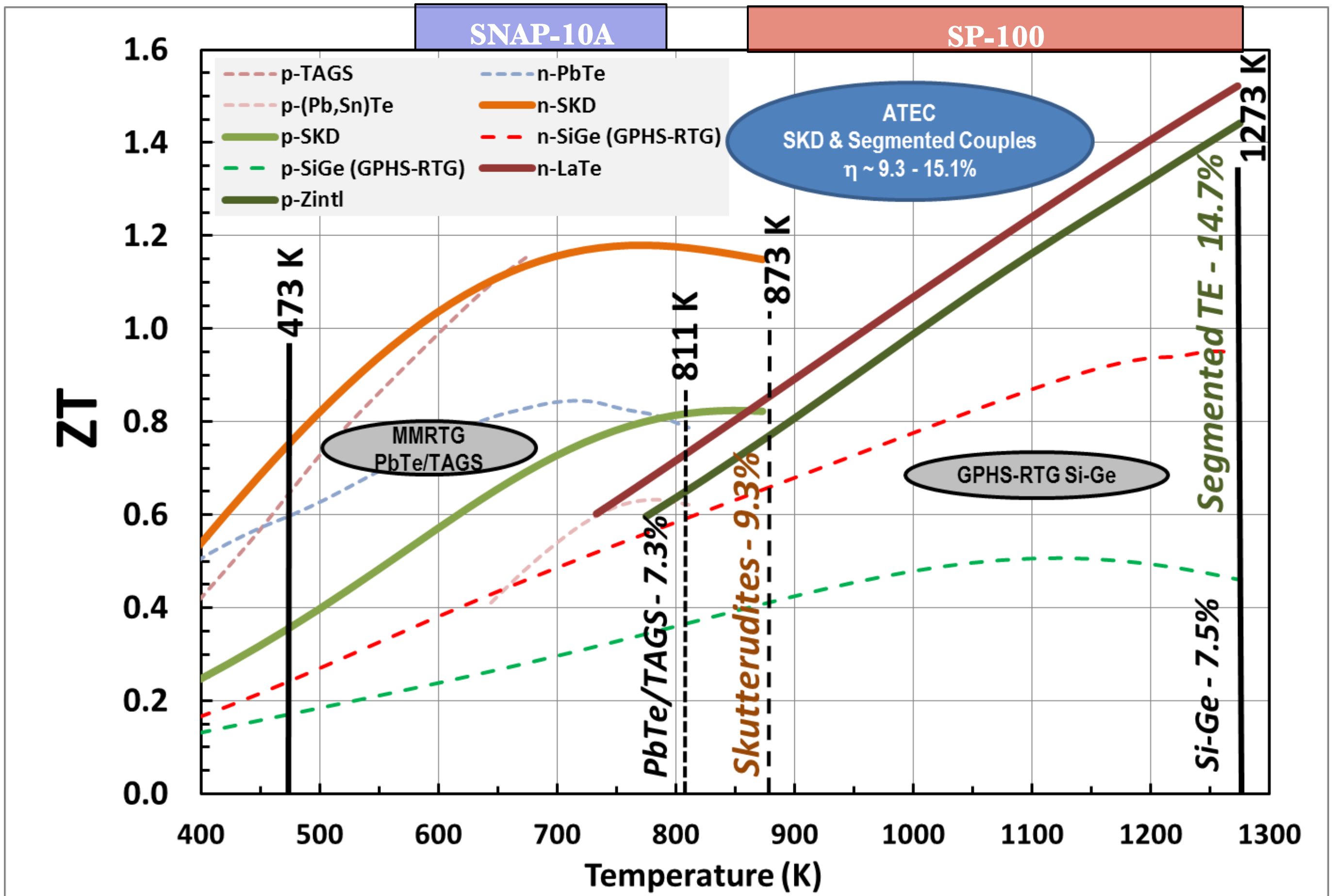


SP-100: Moved to Thermoelectrics

- JPL stopped its efforts on thermionics when thermoelectric conversion technology was selected for the SP-100 ground engineering system development (~ 1986)
- Some of the rationale was related to:
  - Experience with RTGs (life, reliability, scalability)
  - Reactor for TE-based SP-100 would also apply to dynamic conversion technologies (Brayton, Stirling)
  - High degree of integration for TI-based system (in-core converters) meant more complexity in separating reactor and power conversion technology development challenges
- Goal was for a 3000 kg, 100 kWe system
  - When program ended around 1992, SP-100 system mass estimate was at 4600 kg

The Path Forward for Space Power Systems Based on Solid-State Energy Conversion Technology (- Thermoelectrics -)

Thermoelectric Materials and Device-Level Performance:
x2 Increase over State-of-Practice Has Been Reproducibly Demonstrated



> 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%)*

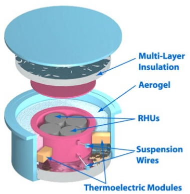
~ 9% efficiency projected for Small FPS based on 1060 K/505 K operating temperature differential *(SP-100: 4.0%)*

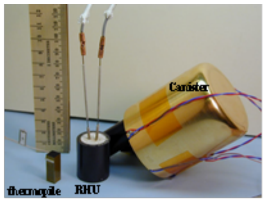
x 2 increase in ZT_{ave} over SOA Si-Ge alloys *(1275 to 475 K ΔT)* **when combined through**

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%

NASA's Advanced TE R&D – RPS Technology Advancement Project

Opportunities for TE-Based Space Power Systems

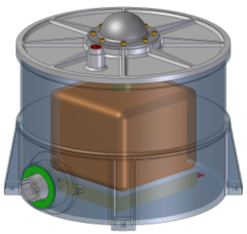


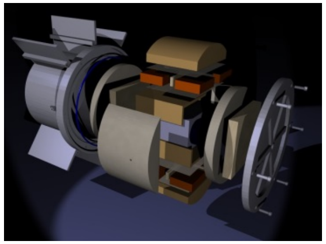


40-200 mW RTGs for low power, long life instruments and probes

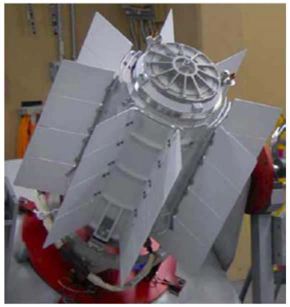
Advanced TE Technology

Small RTGs (20 to 50 W)

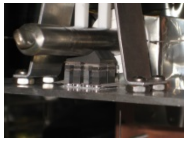


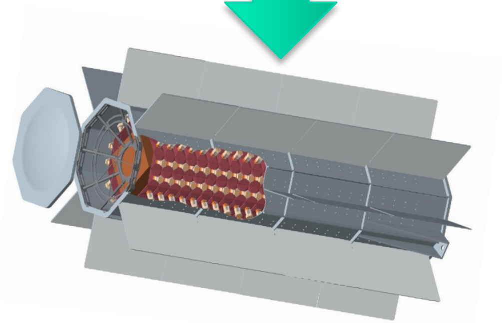


Enhanced MMRTG (160 W)



1-100 kW-class Fission Reactor Power System





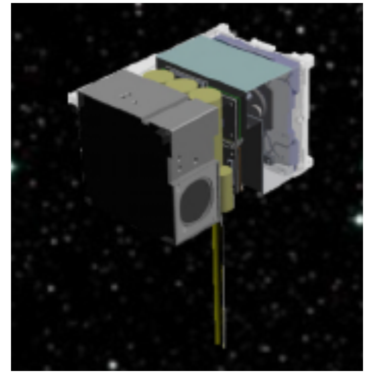
Advanced RTGs and Modular RTGs (200 to 500 W)

Advanced TE technology being developed for space nuclear power systems could also be applied to terrestrial Nuclear Power Systems, Waste Heat Recovery and auxiliary power systems

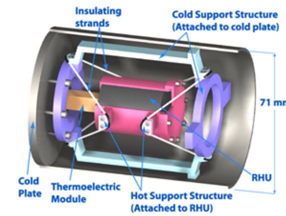
⇨ *This is also true for advanced "lower temperature" thermionics*

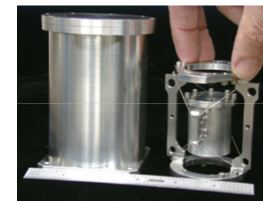
mW RPS for CubeSats and Micro Instruments

- Very small RPSs 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

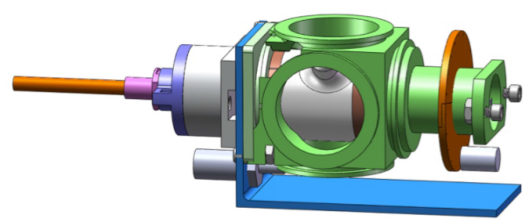


Notional S/C for MIRAGE Mission

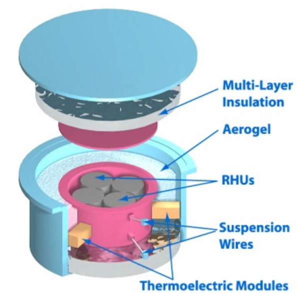




1-RHU mW-RPS Prototype



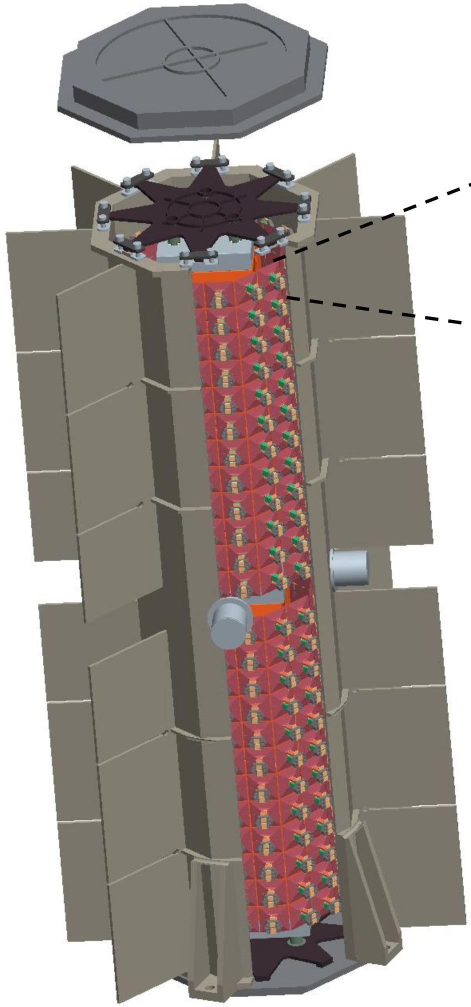
Compact Vector Helium Magnetometer

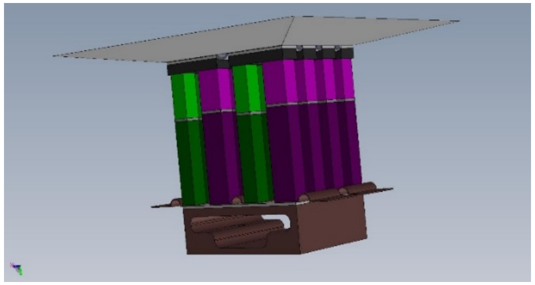


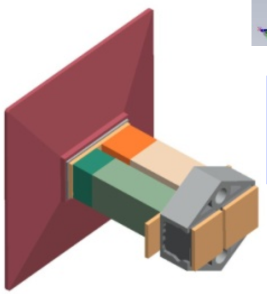
4-RHU mW-RPS concept

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.

Modular Advanced Thermoelectric Radioisotope Generator (ARTG) System Concept (up to 500 W)







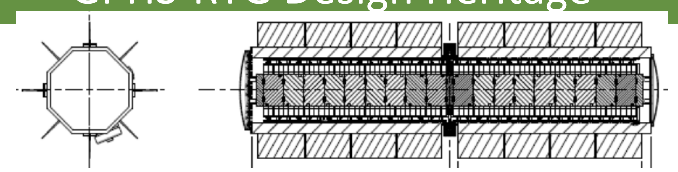
Segmented Couples and Modules

<u>Performance Predictions*</u>

- Single Point Designs from 8 to 18 GPHS
  - BOL Power: 210 to 515 W
  - BOL Specific power: 7.5 to 8.6 W/kg
- Also supports Modular ARTG Configurations from 95 W (4-GPHS) to 425 W (16-GPHS)

*From studies conducted by Aerojet Rocketdyne and Teledyne Energy Systems

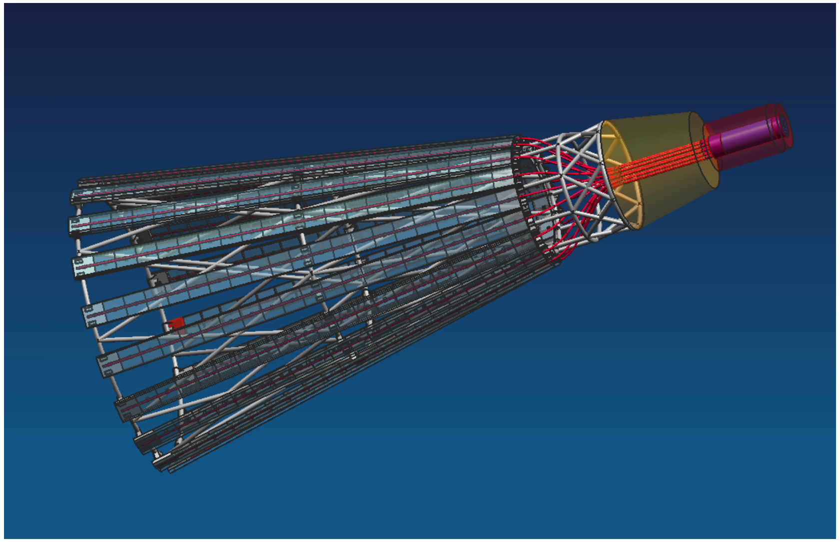
GPHS-RTG Design Heritage



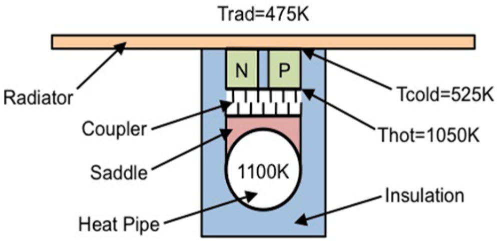
Based on ARTG conceptual design and engineering studies developed by Aerojet Rockedyne and Teledyne Energy Systems, Inc.

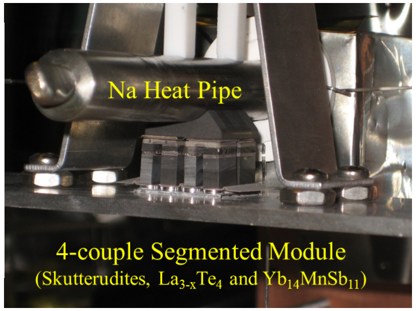
kW-Class HP-TE Small Fission Power System Concept

- **Proposed kW-Class Small FPS**
- **Reactor power : ~ 13 kW$_{th}$**
- **Mass : ~ 600 kg**
- **Power level : ~ 1150 W$_e$**
- **Voltage : ~ 40 Volts**
- **Specific power : ~ 1.7 W/kg**
- **System Efficiency ~ 8.9%**
  (x2 that of SP-100)



- **Segmented couples with their radiator fin mounted (4 couples per fin) directly onto the Na heat pipes**
  - n-Skutterudite/$La_{3-x}Te_4$
  - p-skutterudite/$Yb_{14}MnSb_{11}$
  - Av. hot junction temperature : 1050 K
  - Av. cold junction temperature: 525 K
  - Couple conversion efficiency : ~ 11%



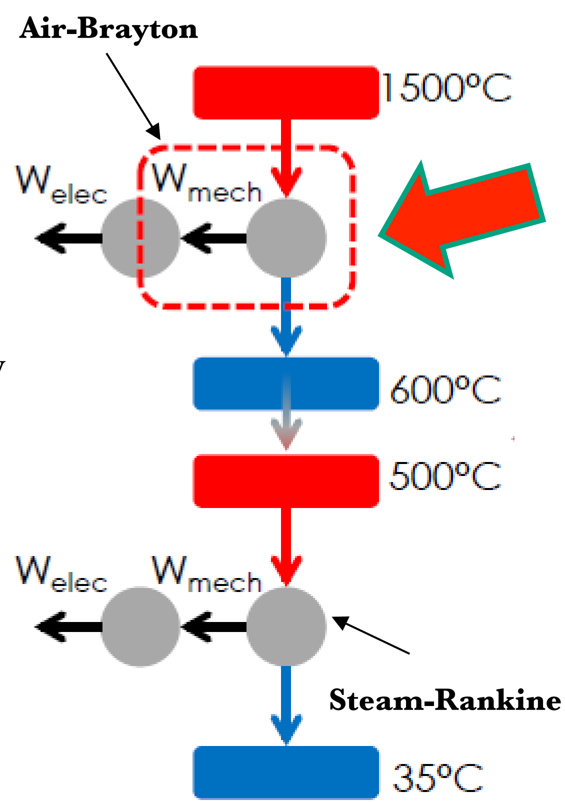


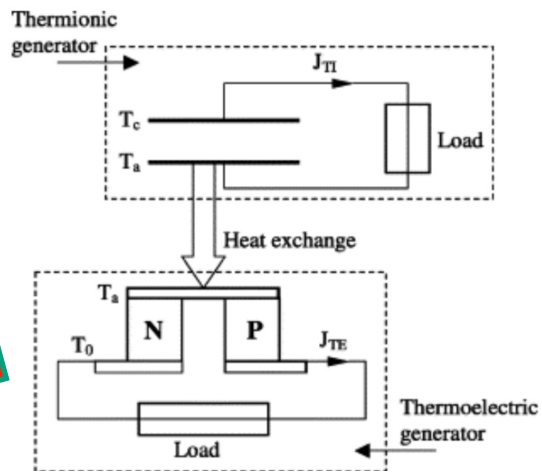
Single heat pipe with array of 21 segmented cantilevered 4-couples and radiator fins

Combining TI and TE Conversion Technologies For Terrestrial Applications

- Cascading solid-state energy conversion technologies to achieve high efficiencies is not a new idea
  - TI/TE ; TI/AMTEC
  - TI and TE have well matched characteristics
- But now more attractive:
  - New interest in high temperature topping cycles
    Much higher efficiency TE now available
  - TI best suited for taking advantage of high temperature combustion processes in power plants
  - Cascaded TI/TE approach has potential for easier integration than dynamic options with existing steam-rankine infrastructure (boilers)

Combined Cycles





TI/TE Cascade: Solid-state, no moving parts

~ 20% efficiency boost with topping cycle

Acknowlegments

- This work was performed at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration
- Part of this work has been supported by NASA's RPS Technology Advancement Project