Overview of Thermoelectric Programs at JPL

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Direct Energy Conversion Program Review and Workshop

December 13-15, 2004

Coronado Island Marriott

Coronado, CA

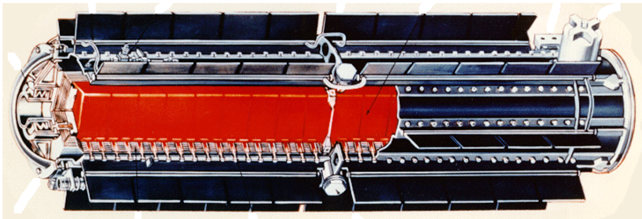
Outline

- Space Applications of Nuclear Power Systems
- Radioisotope Power Conversion Systems
- Fission Reactor Power Conversion Systems
- Summary and Conclusions

Types of Nuclear Power sources

Radioisotope Power Sources

•Suitable for applications requiring low power (hundreds of watts) for long periods



General Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS -RTG)

Fission Reactor Power Sources

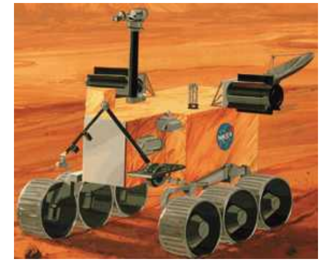
Suitable for applications requiring high Power (20-300 kW) for long periods

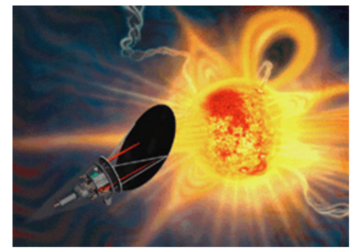
SNAP-10 A Reactor Power System

Potential Future RPS-Powered Missions

Near-term (2006 to 2015)

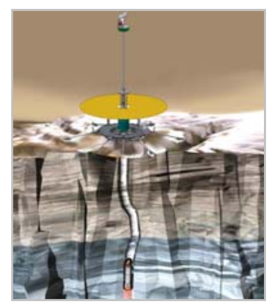
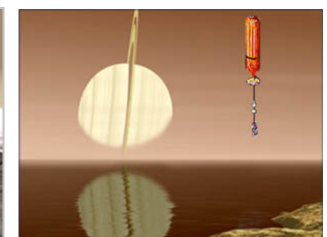
- Pluto-Kuiper Belt Explorer (launch ~2006)
- Mars Science Laboratory (launch by 2009)
- 2nd New Frontiers Mission (launch by 2010)
  - *South Pole/Aitken Basin Sample Return*
  - *Jupiter Polar Orbiter with Probes*
  - *Venus In-situ Explorer*
  - *Comet Surface Sample Return*
- Mars Astro-biology Mission
- Mars Scout Missions launches 2011 & 2015)
- Solar Probe (launch ≥2012)




Vision Missions (≥2015)

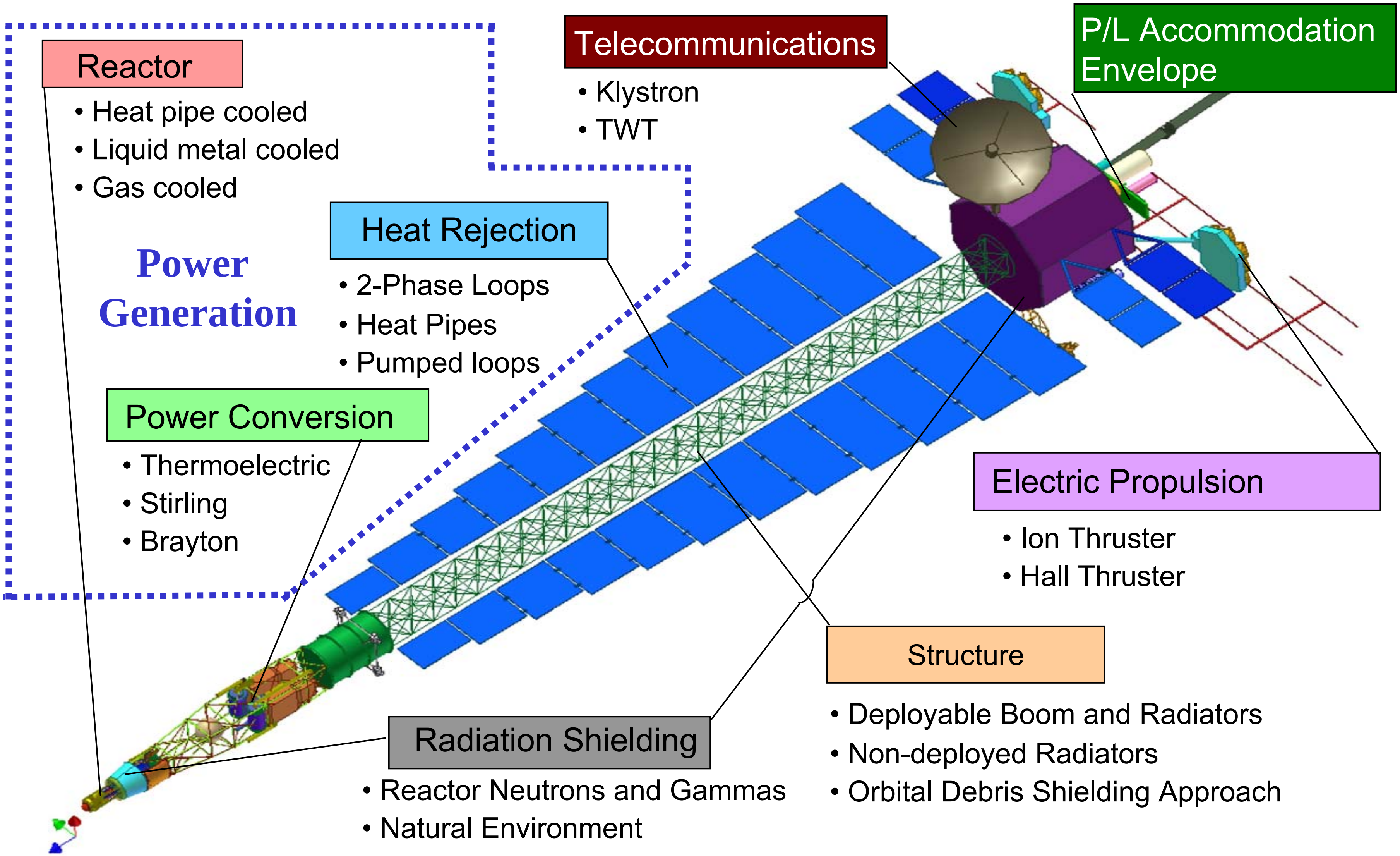
- Medium Size (New Frontiers)
  - *Trojan/Centaur Reconnaissance Flyby*
  - *Asteroid Rover/Sample Return*
  - *Io Observer*
  - *Ganymede Observer*
- Flagship Class
  - *Europa Lander*
  - *Titan Explorer*
  - *Neptune-Triton Explorer*
  - *Uranus Orbiter with Probes*
  - *Saturn Ring Observer*
  - *Venus Sample Return*
  - *Mercury Sample Return*
  - *Comet Cryogenic Sample Return*
  - *Interstellar Probe*

PROJECT PROMETHEUS

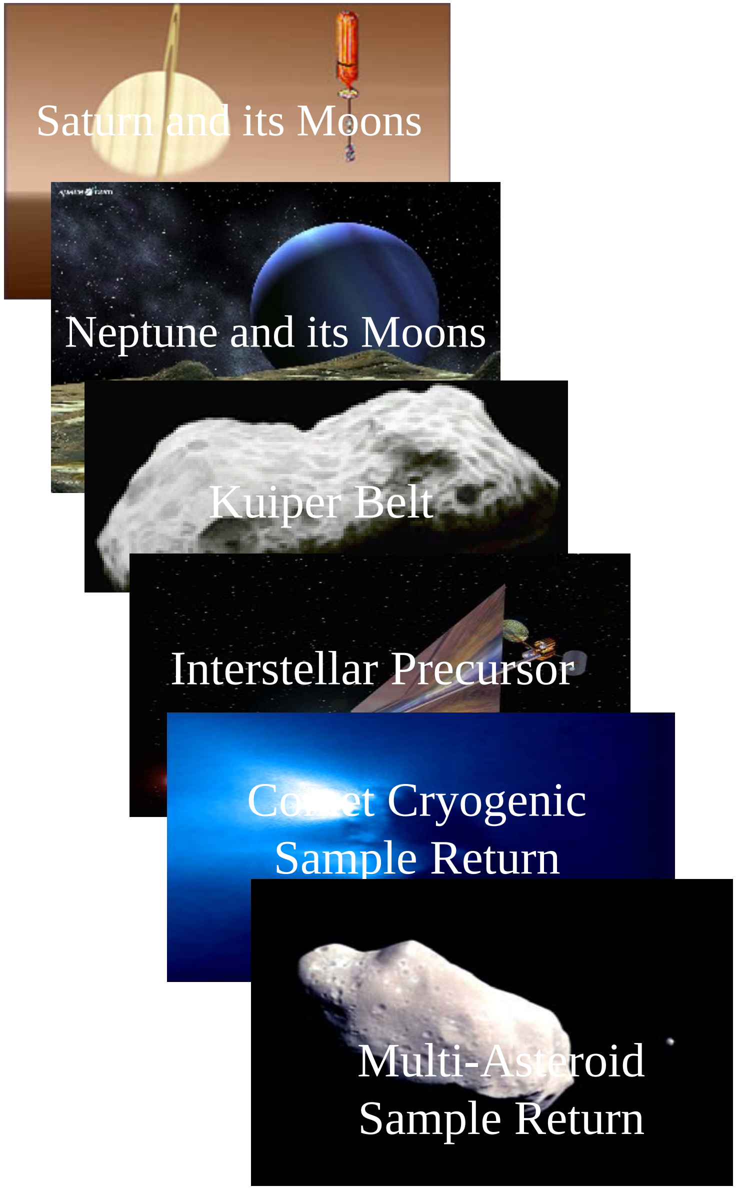
Jupiter Icy Moons Orbiter

Representative Technology Options – Conceptual Spacecraft



JIMO Follow-on Missions

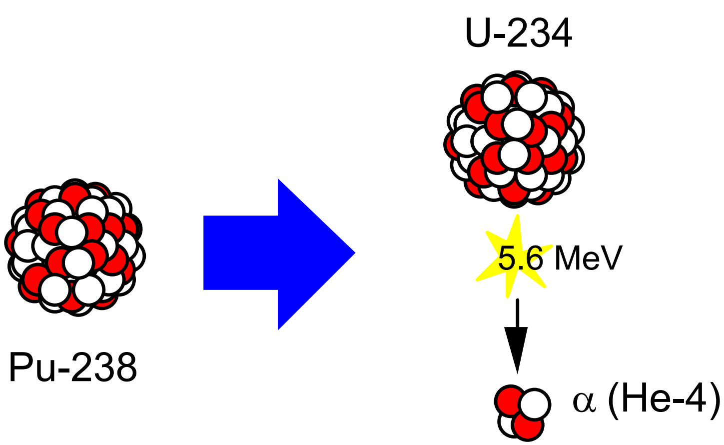
- **JIMO Follow-on Applications Initial study list:**
  - Saturn / Titan
    - Comprehensive exploration of Saturn and Titan
  - Neptune and its moons
    - Comprehensive study of the Neptunian system
  - Kuiper Belt Rendezvous
    - Rendezvous with and study multiple Kuiper Belt objects
  - Interstellar Precursor
    - 200 AU in <15 years
  - Comet Cryogenic Sample Return
    - Return a cryogenically preserved sample from a comet
  - Multi-Asteroid Sample Return
    - Study multiple asteroid types and return samples from each

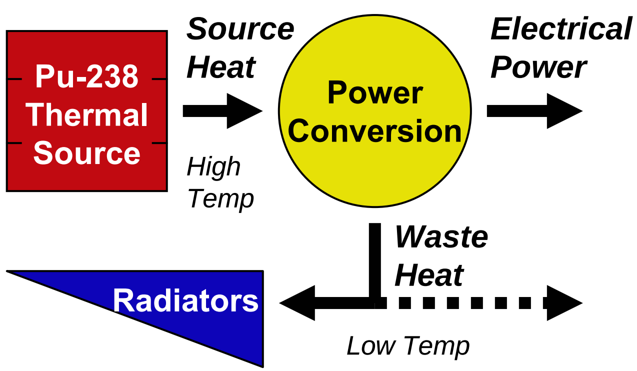


Radioisotope Power Sources

Space Nuclear Power Sources

Radioisotope Power Sources

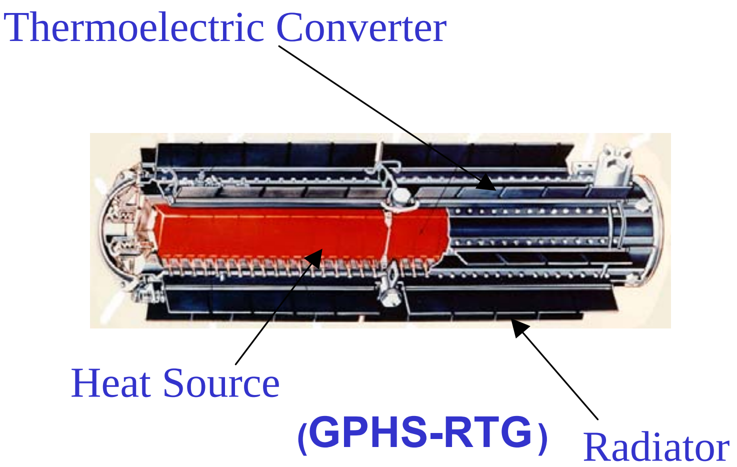




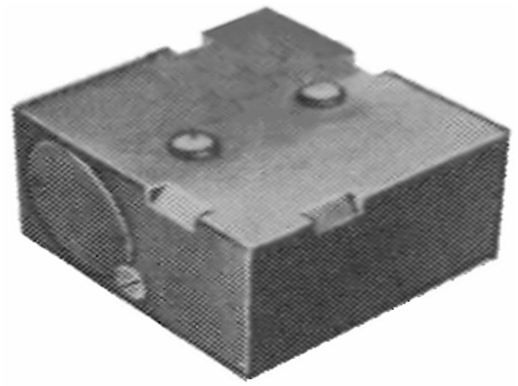
RPS Functional Diagram

- Thermal energy from a radioisotope source is converted to electrical energy
  - 87.7-year half-life
- Contain:
  - Radioisotope heat source
  - General Purpose Heat Source
  - Energy converter
    - Thermoelectric
    - Stirling
    - AMTEC
  - Radiator
    - Passive
    - Active
- Suitable for applications requiring low power (hundreds of watts) for long periods

SOA Radioactive Power Source
GPHS-RTG Description



(GPHS-RTG)

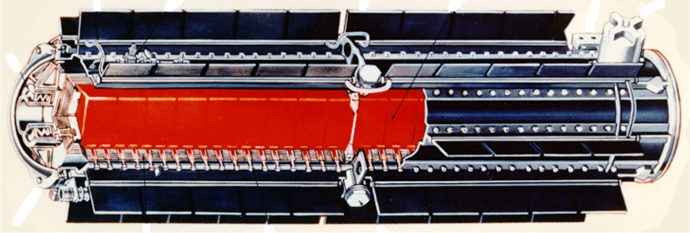


GPHS Heat Source

- Contains: Thermoelectric Converter, GPHS heat source, radiator
- Converter
  - Solid-state thermoelectric device
  - Contains 572 Si-Ge unicouples
- Heat Source
  - Contains 18 GPHS modules
- Radiator:
  - Passive and active

- Each GPHS module weighs about 1.445 kg and generates 250 watts of heat Beginning of Life (BOL).
  - Each GPHS module encapsulates four $^{238}PuO_2$ fuel pellets.
  - Each GPHS pellet contains about 150 grams $^{238}PuO_2$ and generates 62.5 watts of heat (BOL)

SOA Radioactive Power Source
Characteristics of SOA GPHS- RTG



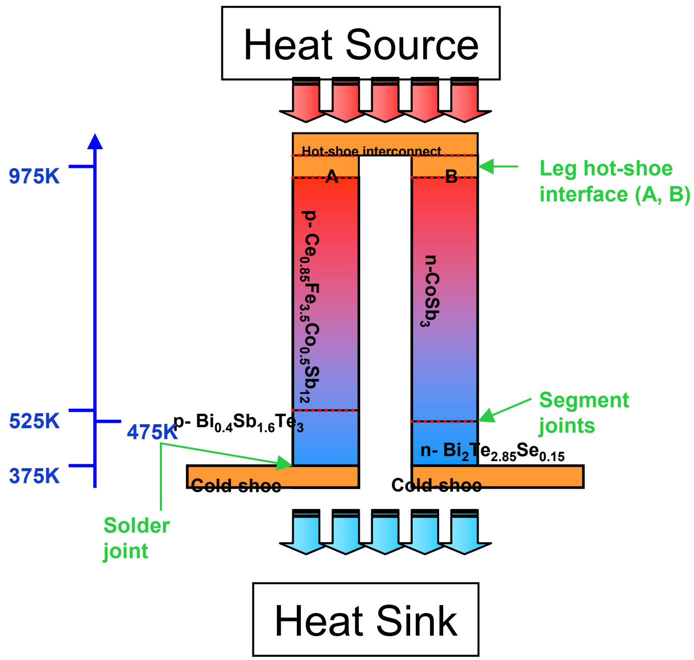
Advantages
- Long Operational Life
- High Reliability

Limitations
- Low Specific Power
- Low Efficiency (Requires more Pu)

Performance Characteristics

- Power: 285 W (BOL)
- Mass: 56 kg
- Efficiency: 6.5%
- Specific Power: 5.1 W/kg
- Life:> 20 years demonstrated
- Hot Side Temp. :1273 K
- Cold Side Temp.:573 K

Segmented Thermoelectrics (STE) Task Overview



High Performance

975K-375K segmented unicouple

Task manager

- **Thierry Caillat, JPL**

Participants

- **JPL, U. of New Mexico,**
- **CalPoly Pomona**
- **Caltech**

Overall objectives

- Develop Segmented Thermoelectric converters that can provide ~7- 11 W_e/kg specific power and ~10-12% system efficiency

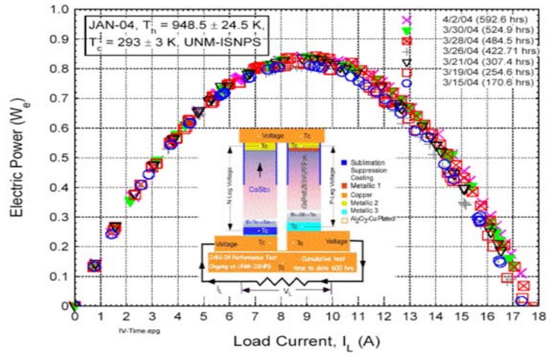
FY04-06 Specific Objectives

- Optimize unicouple fabrication techniques
- Develop sublimation control techniques/materials
- Develop unicouple thermo-mechanical model
- Demonstrate electrical performance and life
- Develop lifetime model
- Transfer technology to industry

Segmented Thermoelectrics (STE) Task
FY04 Major Accomplishments

•Fabricated Ti coated segmented TE legs and tested them in an assembled unicouple configuration. (Q2-FY04)

- Demonstrated 14 % efficiency
- Demonstrated 1000 hours continuous operation



•Developed process to fabricate segmented unicouples and fabricated first generation TE unicouples for life testing in FY06 (Q4-FY04)

Skutterudite unicouples fabricated by diffusion bonding

•Developed thin-film and aerogel encapsulation techniques to ensure long life by suppressing Sb sublimation for skutterudite materials at high operating temperatures.(Q3-FY04)

Aerogel encapsulated skutterudite coupon

•Developed second generation p-type TE material that shows improved ZT and higher temperature stability (1100K) (Q4-FY04)

RPS Systems Engineering - Task Overview

Goals/Objectives:

Provide program level mission planning and systems engineering support to near and far term RPS technologies

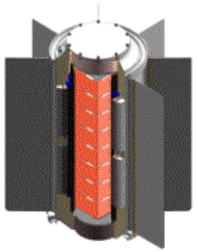
Technical Approach

- Develop RPS requirements for near term missions
- Identify new applications and conduct flight system trade studies
- Support NASA and DOE with MMRTG and SRG contracts
- Provide tech. mgmt. support to advanced RPS contracts
- Validation and verification of the performance of components and devices developed under NASA NRA programs
- Develop and maintain RPS models for design studies and lifetime prediction

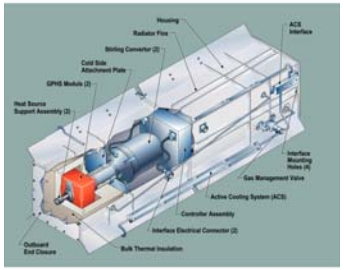
Team: JPL/NASA-GRC/DOE

Task Manager: B. Nesmith

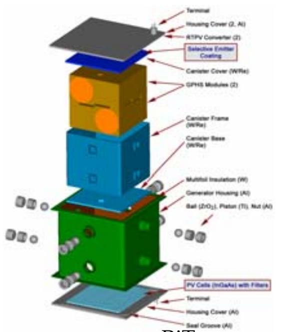
MMRTG



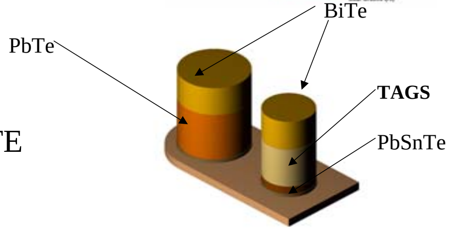
SRG



Adv. TPV



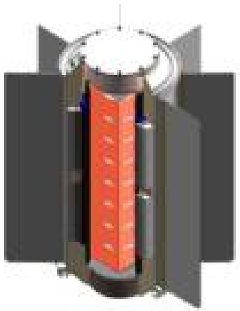
Adv. TE

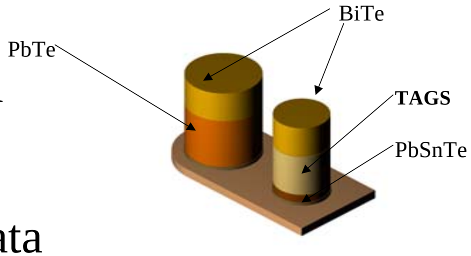


BiTe Couple

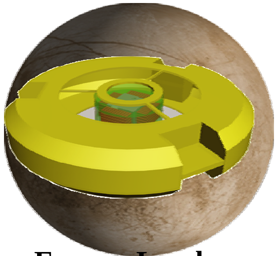
RPS Systems Engineering
FY04 Major Accomplishments

- Supported MMRTG, SRG Design Reviews and Quarterly meetings
- Upgraded model that predicts long term radioisotope thermoelectric generator performance.
  - New user friendly interface; Report published 09/2004.
  - New capabilities:MMRTG and segmented thermoelectrics.
- Completed thermoelectric property measurements of pre-production MMRTG thermoelectric materials received from Teledyne
  - Initial JPL measurements show good agreement with Teledyne data
- Prepared first draft of the Standard RPS (MMRTG/SRG) mission studies document.
  - Studies include Saturn Ring Observer (SRO), Triton Lander Mission, Manned/Unmanned Lunar Buggy mission and Titan Aerobot concept.
- Identified exploration missions that require small RPS
  - Report published in September 2004
- Supported the RPS NRA Reviews

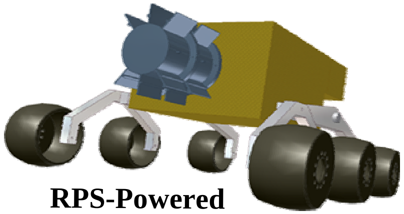




BiTe Couple



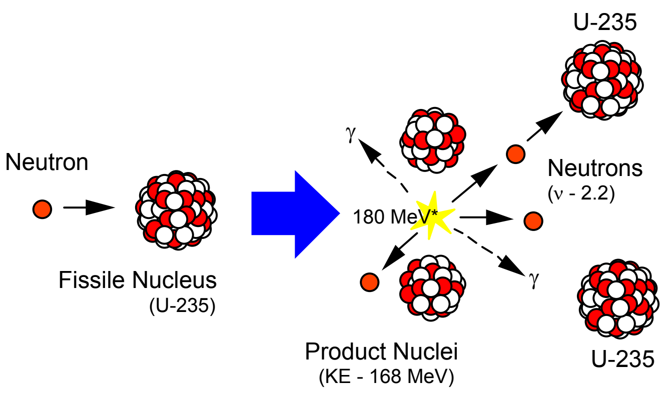
Europa Lander



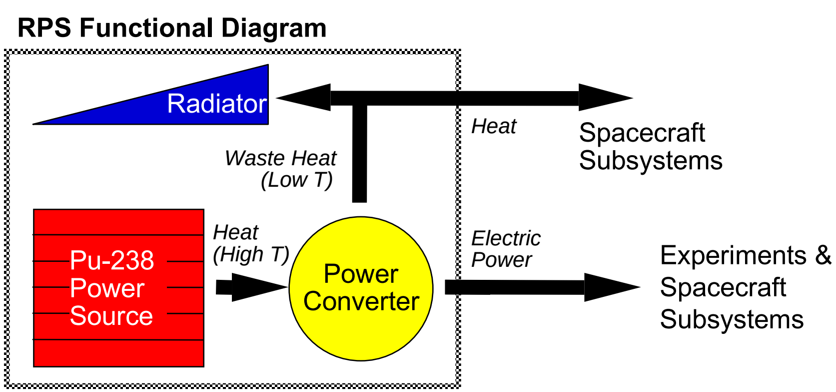
RPS-Powered Rover

Fission Reactor Power Sources

Space Nuclear Power Sources
Reactor Power Sources



* 180 MeV prompt energy - 27 MeV additional energy released in form of delayed beta particles, gamma rays and anti-neutrinos from products



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

- Contains :
  - Heat source
    - Fission reactor/shield
  - Power converter
    - Thermoelectric
    - Thermionics
    - Brayton,
    - Stirling
    - AMTEC
  - Heat transport subsystem
  - Radiator subsystem
  - Reactor Instrumentation and Control
  - Power management and distribution

- Suitable for applications requiring high Power (20-300 kW) for long periods

SP-100 System Description

Reactor: UN fuel, Li cooled, Nb1 Zr structure

Shield s/s: LiH for neutrons, depleted U for gammas, Be thermal control

Reactor I & C s/s: BeO sliding axial reflectors, in-core safety rods

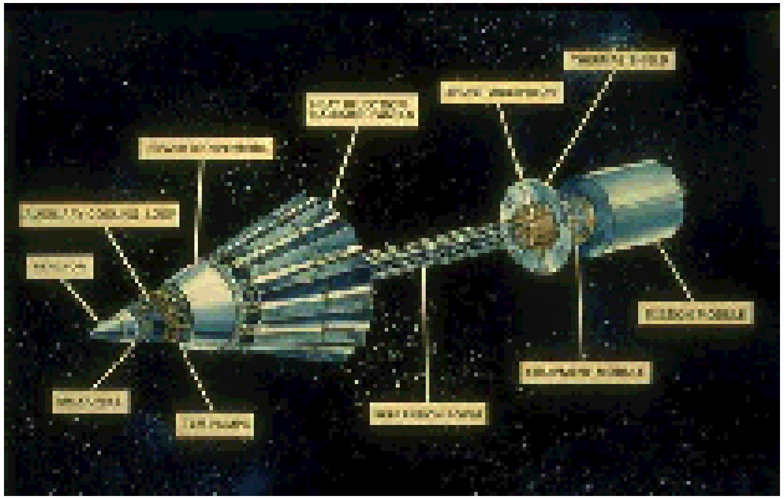
Heat Transport s/s: Nb alloy piping with Li coolant, TEM pump, He/Li separators

Power Conversion s/s: Conductively coupled Si-Ge thermoelectric multi-cells

Heat Rejection s/s: Li coolant, Ti alloy ducts, K heat pipes, C-C armor and fins

Power Conditioning and Control s/s

Mechanical & Structure s/s



System Mass: 4600 kg *(3000 kg goal)*

System Power: 100 kWe

System Life :10/7 Years

Reactor Power: 2.3 MWt

Reactor Outlet: 1375 K

Voltage: 200 VDC

Hot Shoe Temp(EOL): 1350 K

Radiator Area: 104 m^2

STMC Technology Development – Phase 2 Task Overview

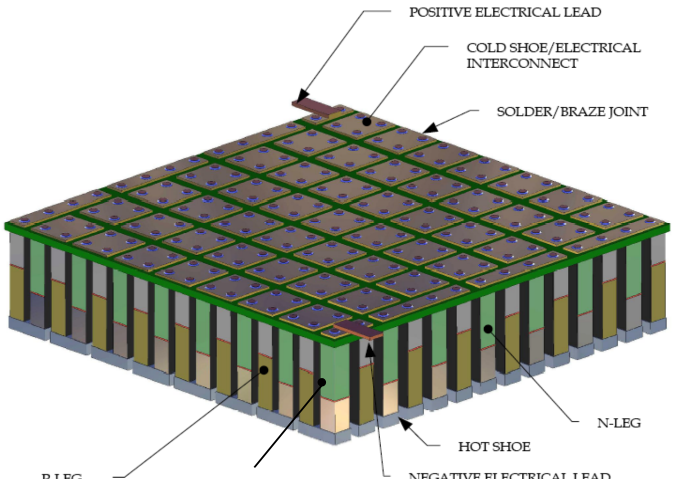
Goals/ Objectives:

- Demonstrate to ~TRL 4 the feasibility of developing a STMC technology based TE converter that operates in the 1275 to 650 K temperature range
- Demonstrate STMC thermal-to-electric conversion efficiency of ~10% using a combination of advanced thermoelectric materials
- Update Phase 1 100 kWe STMC-based PCS design showing overall system mass savings of 20-25%
- Prepare a plan to advance STMC technology to TRL 6 (Phase-2)

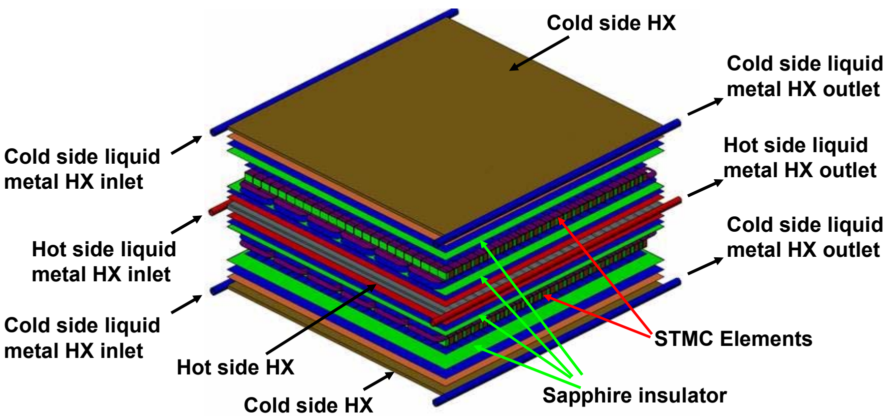
Team:

- JPL (lead)
- Boeing/Rocketdyne, Teledyne
- Caltech, Cornell, Clemson/U of Virginia, Michigan State U, Princeton, UC Davis, U of Michigan, U of New Mexico, U. So. Florida
- **Task Manager:** K. Johnson, JPL
- **Principal Investigator**: Jean-Pierre Fleurial, JPL

CY'05: Fully Functional 1275-750K STMC Module



TRL 6 Engineering Model combines a Representative Thermoelectric Converter Assembly (TCA) Panel with a Heat Rejection Subsystem



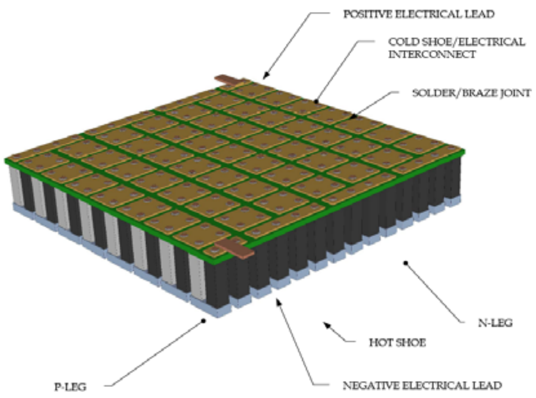
Schematic of a Conductively Coupled Thermoelectric Converter Assembly

STMC Technology Development

FY04 Major Accomplishments-1

HT TE Materials Development

CY'04: LT Skutterudite-based STMC Module Demo



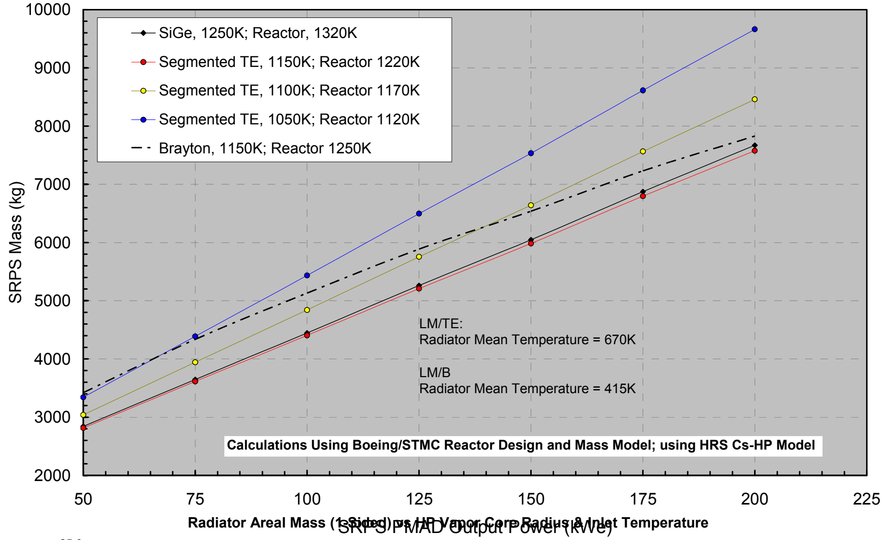
- Identified several advanced TE materials that meet the segmented converter efficiency goal
  - N-type $LaTe_x$ and $La_{3-y}Yb_yTe_4$
  - P-type Chevrel and Zintl Phases
  - High temperature n-type & p-type skutterudites
- Assessment in progress and preliminary results are very promising

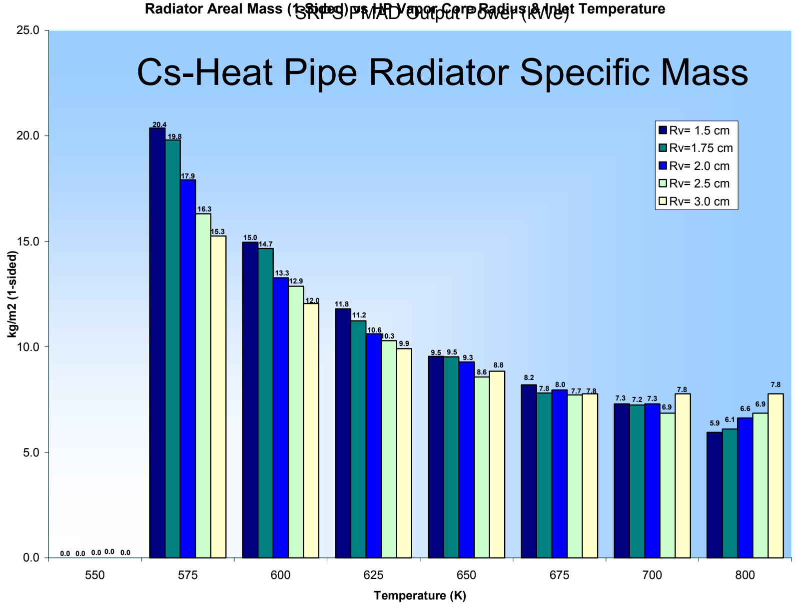
TE Multicouple Converter Development

- Cold Stage STMC design and fabrication process developed
  - Using egg-crate and aerogel technology developed by JPL
  - High voltage insulator assembly commercially fabricated.
- JPL completed fabrication of 4 large pucks (40 mm diameter) of metallized n-type and p-type skutterudites.
  - Shipped to Teledyne for dicing into legs for use in the mini-module fabrication trials

STMC Technology Development
FY04 Major Accomplishments-2

- JPL and Boeing updated the STMC SRPS model
  – Uses consistent reactor design and mass models
  – Uses new Cs heat pipe radiator mass model.
- New results show that the STMC SRPS is very attractive for Prometheus 1
  – Mass competitive with dynamic conversion
  – Offers flexibility in Reactor operating temperatures (1100 –1250K)
  – Scales well up to 200 kWe
  – Lower Reactor temperatures reduce risk and ensure extended operating life
  – Also allows for increased accelerated testing to validate performance predictions





Summary and Conclusions

- JPL is conducting in-house research and development, particularly in the area of thermoelectrics, with the support of NASA/DOE and their Laboratories/Centers, Universities and Industry to develop the thermal to electric energy conversion technologies required for future space exploration.
- These organization are working with JPL to develop the radioisotope and fission power systems required to support potential future space exploration missions.