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

Fission Reactor Power Sources

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

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

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

- Power Conversion
  - Thermoelectric
  - Stirling
  - Brayton

- Heat Rejection
  - 2-Phase Loops
  - Heat Pipes
  - Pumped loops

- Reactor
  - Heat pipe cooled
  - Liquid metal cooled
  - Gas cooled

- Telecommunications
  - Klystron
  - TWT

- Electric Propulsion
  - Ion Thruster
  - Hall Thruster

- P/L Accommodation
  - Deployable Boom and Radiators
  - Non-deployed Radiators
  - Orbital Debris Shielding Approach

- Radiation Shielding
  - Reactor Neutrons and Gammas
  - Natural Environment

- Structure
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

- 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

- 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 $^{238}\text{PuO}_2$ fuel pellets.
  - Each GPHS pellet contains about 150 grams $^{238}\text{PuO}_2$ and generates 62.5 watts of heat (BOL).
SOA Radioactive Power Source
Characteristics of SOA GPHS- RTG

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

Advantages
• Long Operational Life
• High Reliability

Limitations
• Low Specific Power
• Low Efficiency (Requires more Pu)
Segmented Thermoelectrics (STE) Task Overview

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

Task manager
- Thierry Caillat, JPL

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

975K-375K segmented unicouple
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)

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

• 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
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 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
Fission Reactor Power Sources
Space Nuclear Power Sources
Reactor Power Sources

- 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

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 m²
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
STMC Technology Development
FY04 Major Accomplishments-1

HT TE Materials Development
• Identified several advanced TE materials that meet the segmented converter efficiency goal
  – N-type LaTe_x and La_{3-y}Y_{y}Te_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.