Radioisotope Power Systems

Power System Overview for the Small RPS Centaur Flyby and the Mars Polar Hard Lander NASA COMPASS Studies

Presented by:
Robert L. Cataldo, NASA GRC

Nuclear and Emerging Technologies for Space 2014, February 24-26
Stennis Space Center, Pearlington, MS

Power to Explore

www.nasa.gov
Motivation for the Studies

- Current RPS Program Product Line: 100 We class power with ~ 30 kg
- What other size power systems should be considered for future development?
- Can smaller scale S/C and science utilize a small RPS
- Perform two mission studies with low-cost, low-mass for evaluating small GPHS RPS and RHU milliwatt RPS:
  - Low cost mission goal: equal to or less then Discovery class
  - Stricter mass and volume constraints
  - Lower power requirements
Radioisotope Power Systems Program

RPS Product Line

Power levels supplied: Historical, Current, and Potential RPS

Pu-238 (kg)

Power (Watts)

Very Small RHU based RPS
Small GPHS based RPS
ASRG
LARGEST RPS
FISSION

SNAP-3B
SNAP-19B
SNAP-9A
SNAP-19
SNAP-27
Transit RTG
GPHS RTG
MMRTG
MHW RTG
Microsat Study Assumptions

- Low cost spacecraft and mission
  - Discovery “class” cost profile
  - Multiple identical Microsats
  - Multiple targets?

- Lowest mass/size possible while maintaining high valued science

- Use of small (~60 We or less) radioisotope power to far reaches of solar system
  - Single GPHS module if possible
  - Power for science encounter
  - Reasonable power level available for timely data return
  - Battery supplies additional power during encounter and data return communication periods
RPS Powered Microsat

- Sample Mission
  - Centaur Scout ~4 microsats, launched together and then disperse to flyby different Centaurs (option to flyby in pairs)

- General Purpose Heat Source
  - Designed for launch
  - Provides 250W thermal
  - ~1.5 kg per module

- Power Options
  - Single GPHS Stirling Radioisotope Generator ~60W
  - 3 - GPHS RTG @ ~ 60W

- Microsat
  - Goal ~150 kg each microsat
  - 1-2 instruments
Specific Chiron Mission Goal

A specific, well-defined science mission is detailed here to demonstrate that there is interesting science and determine the power levels and operations concept, which are key drivers for Small RPS missions.

Characterize Chiron: structure, composition, and surface morphology.

Structure will be determined via Doppler radio science for Gravity Science (GRAV).

Composition will be determined by a hyperspectral IR spectrometer (SPEC).

Surface morphology will be determined by camera (CAM).
2060 Chiron is a minor planet in the outer Solar System. Discovered in 1977 by Charles T. Kowal (precovery images have been found as far back as 1895), it was the first-known member of a new class of objects now known as centaurs, with an orbit between Saturn and Uranus.

Although it was initially called an asteroid and classified as a minor planet, it was later found to exhibit behavior typical of a comet. Today it is classified as both, and accordingly it is also known by the cometary designation 95P/Chiron. Its rotational period is 5.917813 hours, a value determined by observing its distinct light curve.

Since the discovery of Chiron, other centaurs have been discovered, and nearly all are currently classified as minor planets but are being observed for possible cometary behavior. 60558 Echeclus has displayed a cometary coma and now also has the cometary designation 174P/Echeclus. After passing perihelion in early 2008, centaur 52872 Okyrhoe significantly brightened.

<table>
<thead>
<tr>
<th>Year</th>
<th>Radius (km)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1984</td>
<td>90</td>
<td>Lebofsky</td>
</tr>
<tr>
<td>1991</td>
<td>&lt;186</td>
<td>IRAS</td>
</tr>
<tr>
<td>1994</td>
<td>74</td>
<td>Campins</td>
</tr>
<tr>
<td>1996</td>
<td>90</td>
<td>occultation</td>
</tr>
</tbody>
</table>
The microsats execute a Jupiter gravity assist, and then after separation they can alter their trajectories to fly by different targets depending on various factors.
Microrosat and Launch Stack Configuration

Atlas 431 w/ STAR 48B kick stage
Four identical microsats each with radioisotope power system

* 3-Axis Stabilization Stage for the Star 48 BV not shown
Microsat Components

- Secondary Battery
- Power Management and Control Electronics
- IMU
- Star Tracker Electronics
- cPCI Enclosure with Power Supply
- Small SRG (RTG option)
- RCS Propellant Tank
- ACU
- Main Engine Propellant Tank
- Comm Switch
- EPC
- TWT
- Small Deep Space Transponder
- RCS Propellant Tank

Radioisotope Power Systems Program
Small Stirling Radioisotope Generator

- sSRG based on ½ ASRG with Dynamic Balancer
- 65 watts BOM (3 watts for balancer-68 watts total)
- 760 C Acceptor Temperature (BOM)
- 38 C Rejector Temperature (BOM)
- 4 K Sink
- Solid Insulation
- Dynamic Balancer sized to reduce vibration below dual opposed ASRG configuration
- 28 +/- 6 volt output
- Includes out of voltage range shunt
- Mass estimate from current ASRG
Small Radioisotope Thermoelectric Generator

- Study began with a single GPHS RTG
  - Small RTG Assumptions
    - BOL Power: 21.25 We
    - Mass: 10.32 kg
    - Dimensions: 0.64m diameter (including fins), 0.17m height
    - Efficiency: 8.5%
    - Specific Power: 2.06 W/kg
    - Hot Junction: 538 C
    - Cold Junction: 50 C
    - Thermoelectric materials: PbTe/TAGS/BiTe couples with 5V output
    - 1 GPHS Module
    - Output Degrades 2.5% per year (same as advanced eMMRTG)
    - 5 Volt output

- Final Configuration is a 3 GPHS RTG
  - BOL Power: 63.75 We
  - Mass: 20 kg
  - Dimensions: 0.64m diameter (including fins), 0.31m height
  - Output Degrades 2.5% per year (same as advanced eMMRTG)
  - Reconfigured to produce 28 volt output (same as MMRTG)
  - First estimate of 6 parallel strings (16 for MMRTG)
Small Stirling Radioisotope Generator (sSRG)

Small Radioisotope Thermoelectric Generator (sRTG)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Small SRG</th>
<th>Small RTG</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOM Power</td>
<td>65 W</td>
<td>64 W</td>
</tr>
<tr>
<td>EOM Power (12 year mission)</td>
<td>57 W</td>
<td>48 W</td>
</tr>
<tr>
<td>Mass</td>
<td>18 kg</td>
<td>20 kg</td>
</tr>
<tr>
<td>Dimensions</td>
<td>49 cm high</td>
<td>17 cm high</td>
</tr>
<tr>
<td></td>
<td>39 cm dia</td>
<td>64 cm dia</td>
</tr>
<tr>
<td>Cold-side Temp (BOM, 4K sink)</td>
<td>38°C</td>
<td>50°C</td>
</tr>
<tr>
<td>Voltage</td>
<td>28 +/- 6 V</td>
<td>28 +/- 8 V</td>
</tr>
<tr>
<td>Degradation</td>
<td>1.16%/year</td>
<td>2.5%/year</td>
</tr>
<tr>
<td>Efficiency (BOM)</td>
<td>26%</td>
<td>8.5%</td>
</tr>
<tr>
<td># GPHS Modules</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

- BOM values are at Beginning of Mission: at launch after 3 years in storage. EOM values are at End of Mission after an additional 12 years of operations.
- SSRG: One ASRG engine with a passive balancer and a two-card controller. The controller is included in the mass above, but not in the volume or diagram. Attributes are based on ASRG current best estimate.
- SRTG: Follows MMRTG design but with 3 GPHS bricks and advanced PbTe/TAGS/BiTe thermocouples. Estimated 6 parallel strings for average 28 V power. Attributes are estimated requirements.
- Systems assumed qualified for 17 year lifetime, including 3 years of storage.
- GPHS stands for General Purpose Heat Source.
Mission Phased Power Requirements

- Battery Sizing Phase (One Discharge Cycle)
  - sSSRG (65 W BOM, 57 W EOM)
  - 3-GPHS sRTG (64 W BOM, 48 W EOM)
  - 1-GPHS sRTG (21 W BOM, 16 W EOM)

S/C Power Load We

Mission Phase

- Launch
- Check Out
- Cruise
- MCC
- Initial Sci. Ops
- Flyby Imaging
- Flyby Grav Sci
- Post Flyby Sci
- Data Return

Mission Phased Power Requirements

S/C Power Load We

Mission Phase

- Launch
- Check Out
- Cruise
- MCC
- Initial Sci. Ops
- Flyby Imaging
- Flyby Grav Sci
- Post Flyby Sci
- Data Return

Battery Sizing Phase (One Discharge Cycle)

- sSSRG (65 W BOM, 57 W EOM)
- 3-GPHS sRTG (64 W BOM, 48 W EOM)
- 1-GPHS sRTG (21 W BOM, 16 W EOM)
Microsat Summary

• Study showed that a small microsat using a compact radioisotope power system for deep space destinations could potentially fit into a Discovery class cost cap and perform meaningful science with a timely return of data.

• Commonality of hardware and science helps reduce costs.
MASER Mission

Technical considerations

Must be enabled by RPS - motivates high latitude target
Preference for low elevation – simplifies EDL
Avoidance of gully/rock hazards – northern plains have low rock density, low slopes, well-characterized following Phoenix mission

Science considerations

Desire to detect many events at multiple stations. Station separation should be small enough to assure intensity fall-off with distance

Mesoscale meteorology – waves, cyclonic systems propagation resolved by 50 degree longitude span.

15 deg latitude span will give insight into seasonal change (e.g. H2O release from subliming cap in spring; different crocus dates, thermal cracking of subsurface ice, etc.) 1km elevation span.
<table>
<thead>
<tr>
<th>Instrument</th>
<th>Measurement/Rationale</th>
<th>Basis</th>
<th>Mass (kg)</th>
<th>Dimensions/Configuration/Mounting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure / Temperature</td>
<td>Seasonal pressure cycle, atmospheric tides, cyclonic systems, dust devils. MEMS</td>
<td>Phoenix, Mars-96</td>
<td>0.07</td>
<td>Internal sensor, enclosure must be vented. Stable temperature essential. 1.5x2x2cm / 1x1x1cm</td>
</tr>
<tr>
<td></td>
<td>diaphragm pressure sensor or ion current gauge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seismometer</td>
<td>Seismic monitoring (short period seismic signals only). MEMS micro-seismometer or</td>
<td>Lunar-A, Ranger,</td>
<td>0.5</td>
<td>Forebody (for minimal wind effects and maximum seismic coupling). 10cm x 10cm diameter</td>
</tr>
<tr>
<td></td>
<td>Ranger/Lunar-A geophone type.</td>
<td>Insight</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optical Monitor</td>
<td>Set of windowed up-looking photodiodes/ filters to measure UV/near-IR light levels for</td>
<td>Beagle / Mars-96 / MSL</td>
<td>0.1</td>
<td>Top side, sky view 2x6x5cm</td>
</tr>
<tr>
<td></td>
<td>water vapor, cloud, dust loading</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accelerometer Package</td>
<td>MEMS. Atmosphere profile during entry/descent. Surface mechanical properties; post-impact tilt</td>
<td>DS-2</td>
<td>0.05</td>
<td>Entry/Tilt accel near c.g. Impact accel in forebody 1cm³ each.</td>
</tr>
<tr>
<td>Wind</td>
<td>Hot film anemometer. Seasonal, synoptic and diurnal weather systems, dust devils and gusts.</td>
<td>Beagle / MSL</td>
<td>0.15</td>
<td>Top side, minimal azimuthal obstruction 4cm x 6cm diameter</td>
</tr>
</tbody>
</table>
MASER EDL

- Acceleration Measurements Begin
- Release pilot chute & Backshell
- Deploy Parachute & Heat Shield Separation
- Impact @ 22 m/s
- Release pilot chute & Backshell
- Health Tone back to Orbiter
- Jettison Parachute
- Deploy Seismometer and Checkout
MASER Network and MRO

RPS1 RPS1 Data
Elevation Angle (deg): 46.2
Distance to MRO (km): 417.1

RPS2 RPS2 Data
Elevation Angle (deg): 11.6
Distance to MRO (km): 956.6

RPS3 RPS3 Data
Elevation Angle (deg): 19.1
Distance to MRO (km): 748.0

RPS4 RPS4 Data
Elevation Angle (deg): 28.7
Distance to MRO (km): 577.7
MASER Landed Operations

- **Pressure/Temp Continuous**
- **Seismometer Continuous**
- **Wind Sensor** 8% duty cycle
- **Optical - Hourly**
- ~ 5min UHF, 8 kbps Uplink to Orbiter twice a day

RHU power and thermal output enables nighttime and wintertime solstice operations at same level as daytime/summer.
Radioisotope Power Systems Program

- Current RPS use GPHS modules as a heat source
- Radioisotope Heater Units (RHUs) are an alternative heat source
  - Produce 1 W of heat
  - Flight qualified and extensive heritage
- Radioisotope Heater Unit (RHU) based RPS, producing power in the 40 mW_e range

Radioisotope Heater Unit (RHU) Components

- Plutonium Pellet

Hi-Z 1-RHU RHU-RTG

Radioisotope Power Systems Program
Power System Findings

- Power subsystem architecture:
  - Six RHU-RTGs producing 38 mW each.
  - Four ultra-capacitors (2 in series, with 2 series in parallel), to provide power at 5.4 V. Only 5% depth of discharge; this keeps voltage very steady.

- Operations are essentially steady state on a day-to-day basis:
  - Avionics a continuous draw
  - Pressure sensors, temperature sensors, and seismometer operated at 100% duty cycle
  - Charge capacitors for periodic operation of wind sensors, and telecom twice a day

---

### Energy Budget

<table>
<thead>
<tr>
<th>Component</th>
<th>Basic Power (mW)</th>
<th>Power with Margin (mW)</th>
<th>Duty Cycle</th>
<th>Total Energy Spent (mW-hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline - Six 1-RHU RHU-RPSs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuous Power for Electronics</td>
<td>50</td>
<td>65</td>
<td>100.0%</td>
<td>1560</td>
</tr>
<tr>
<td>Pressure + Temperature Sensors</td>
<td>2</td>
<td>2.6</td>
<td>100.0%</td>
<td>62</td>
</tr>
<tr>
<td>Seismometer</td>
<td>50</td>
<td>65</td>
<td>100.0%</td>
<td>1560</td>
</tr>
<tr>
<td>Wind Sensor</td>
<td>250</td>
<td>325</td>
<td>8.3%</td>
<td>650</td>
</tr>
<tr>
<td>Optical Monitor</td>
<td>20</td>
<td>26</td>
<td>8.3%</td>
<td>52</td>
</tr>
<tr>
<td>Transmitter</td>
<td>2500</td>
<td>3250</td>
<td>1.4%</td>
<td>1083</td>
</tr>
<tr>
<td>Capacitor Charge/Discharge Losses</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daily Energy Used</td>
<td></td>
<td></td>
<td></td>
<td>5477</td>
</tr>
<tr>
<td>Daily Energy Produced</td>
<td></td>
<td></td>
<td></td>
<td>5472</td>
</tr>
<tr>
<td># RHUs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EOM Power per RHU (mW)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

### Energy Storage Profile

---

### Periodic Wind Sensor measurement

---

### Data Transmission

2X per day

---
• Four sterilized landers encased in individual bioshield.
• Top portion of bag jettisoned prior to S/C Mars atmosphere trajectory insertion as done with Viking Landers
MASER: Study Conclusions

• Even at ¼ W of power mW RPS systems can enable hard landers that house long duration sensors in challenging environments
  – Power/heat enables night-time and year round operations
  – Power/heat simplifies in-space free flight (no solar arrays/batteries needed after carrier separation 1 Week before entry)

• The heat from the RPS combined with low temperature tolerable capacitor and electronics (-40°C) enable this mission concept

• RHU-RPS installation not typical for RTGs
  – Looked at installing at PHSF as done with RHU (e.g., Cassini, Huygens Probe)
  – Polar landing site might require Cat IVc Planetary Protection DHMR Standard (Viking Landers)
  – Future work would include more detailed ATLO conops and nuclear safety assessment
Acknowledgements

**Microsat Study:**
Brian Bairstow¹, Rashied Amini¹, Young H. Lee¹, Steven R. Oleson²,
Dr. Andrew Rivkin³, Dr. Julie Castillo¹, Robert. L Cataldo² and
COMPASS Team²

**MASER Study:**
Brian Bairstow¹, Dave Woerner¹, Young H. Lee¹, Steven R. Oleson²,
Dr. Ralph Lorentz³, Robert. L Cataldo² and COMPASS Team²

Jet Propulsion Laboratory¹, NASA Glenn Research Center², The Johns Hopkins University
Applied Physics Laboratory³