RADIOISOTOPE POWER SYSTEMS (RPS) FOR EMERGING POWER NEEDS OF DEEP SPACE CUBESATS, SMALLSATS, AND DEPLOYED PAYLOADS

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Why Low-Cost Small Mission Concepts?

- Considering NASA's increasingly constrained budgets, scientists and mission designers are exploring ways to develop effective, affordable planetary missions
  - Implementable at a fixed cost that includes spacecraft and science payload development, launch, operations, science data analysis and all relevant mission-specific technology development.
  - Low-cost, low-mass, and long-lived applications are being examined as a part of a wider study of standalone, piggy-backed, and landed missions that may not be feasible with available power options

- There are potential mission applications for small (10-100 W_e scale) RPS and very small (milliwatt scale) RPS for low-cost low-mass missions with:
  - Long mission durations and deep space destinations, particularly outer planet missions
  - Stricter mass and volume constraints
  - Lower power requirements

*Mission Classes Suitable for Small RPS**

- *Lander Missions*
  - Vehicles that land on another interplanetary body, to perform their mission from a fixed location
- *Rover Missions*
  - Mobile vehicles that operate on the surface, above the surface, and below the surface
- *Sub-satellite Missions*
  - Small orbiting spacecraft that perform standalone scientific measurements, but rely on a mother spacecraft for delivery and data relay
- *Deployable Mini-Payloads*
  - Small, simple, standalone instruments, that are deployed by a mother vehicle
- *SmallSat Free-Flyer Missions***
  - Small orbiting spacecraft (SmallSat or CubeSat) that perform scientific measurements and do not rely on a mother spacecraft

**http://solarsystem.nasa.gov/multimedia/downloads/Small_RPS_Report.pdf*
*** Identified new mission class suitable for Small RPS since 2004 Small RPS Study*

Mission Concept Study Team

- Recently, a pair of mission concepts were studied by the RPS Program Mission Analysis Team to explore mission need for low scale power options and determine optimal qualities of small and very small RPS.
  - Chiron SmallSat Mission Study with Small (GPHS-based) RPS*
    - » ~170 kg RPS powered SmallSat with ~ 60 W_e provided by RPS to deep space destinations (> 10 AU)
  - MASER Mars Hard Lander Mission Study with RHU-based RPS**
    - » ~ 19 kg landed packages (total 65 kg lander with 45 kg EDL system) with ~220 mW_e RPS power at Mars surface
- RPS Mission Analysis Team worked with COMPASS Team, JPL and APL to plan the studies and select the mission concepts for study
  - JPL team explored mission concepts for study, study goals, notional RPS characteristics, and participated in study
  - Collaborative Modeling for Parametric Assessment of Space Systems (COMPASS) Analysis Team at GRC, is a design team similar to JPL's Team X or A Team, and ran the studies.
  - APL provided science expertise for the studies

** http://arc.aiaa.org/doi/pdf/10.2514/6.2014-1629*
*** http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6836397*

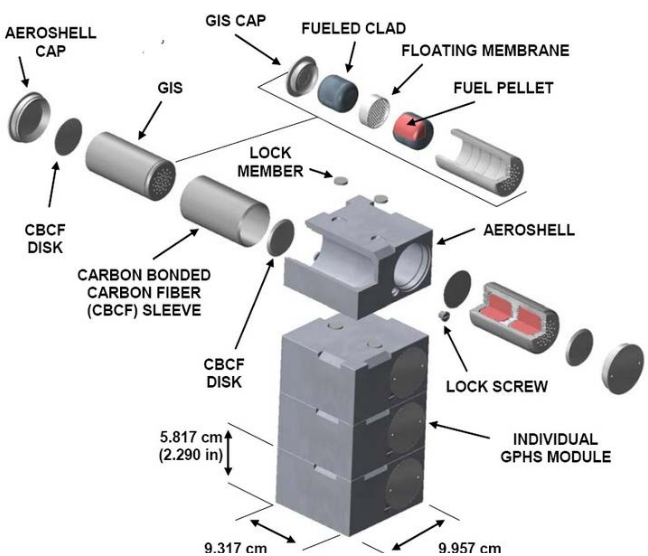
Example Study Questions

- Can Discovery-class science and a Discovery-class cost profile using multiple SmallSats, with mission duration of up to 14 years, be enabled by small RPS?
- Can mission concepts ‘close’ with one general purpose heat source (GPHS) module?
- What are the mission drivers for small RPS-enabled mission power needs? Number of spacecraft? Number of instruments? Or number of objects to fly by?
- What are the mission concept parameters that are key trade attributes when using small RPS in a Discovery-class mission?
- What are the optimal qualities of small RPS that could meet the needs of small RPS-enabled missions?

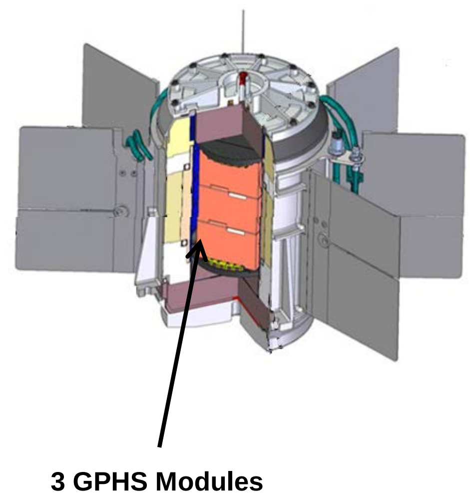
Two Concepts for Small RPS

- Small RPS: General Purpose Heat Source (GPHS) based RPS producing power in the 10-100 W_e range
  - Small RTG: GPHS-based Small Radioisotope Thermal Generator
  - Small SRG: GPHS-based Small Stirling Radioisotope Generator

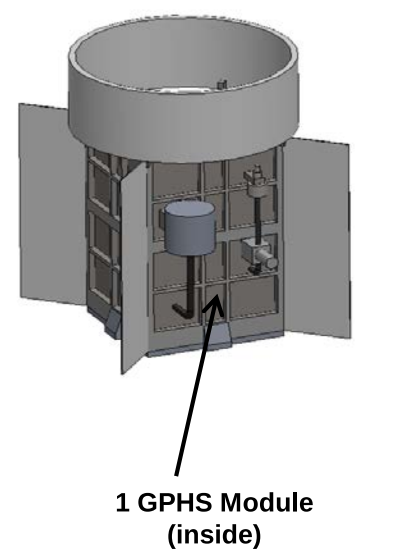
General Purpose Heat Source (GPHS) Components



Small RTG



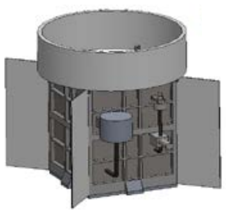
Small SRG



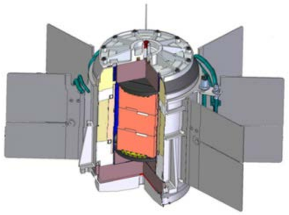
Representative Small RPS Attributes

(Used in Chiron SmallSat Mission Study)

Parameter	1-GPHS Small SRG	1-GPHS Small RTG	3-GPHS Small RTG
BOM Power	59 W_e	21 W_e	64 W_e
EOM Power	48 W_e	15 W_e	45 W_e
Mass	18 kg	10 kg	20 kg
Dimensions	49 x 39 x 38 cm	64 cm dia (inc fins) 17 cm height	64 cm dia (inc fins) 31 cm height
Voltage	28 +/- 6 V	5 +/- 1 V	28 +/- 8 V
Degradation	1.16 %/year	2.5 %/year	2.5 %/year
Efficiency (BOM)	24%	8.6%	8.7%



Small Stirling Radioisotope Generator Concept



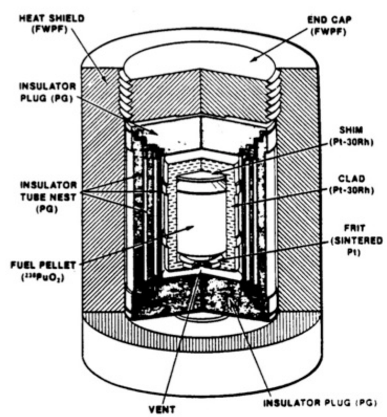
3-GPHS Small Radioisotope Thermoelectric Generator Concept

- *BOM values are at Beginning of Mission: at launch after 3 years in storage. EOM values at this table are at End of Mission after an additional 14 years of operations. Systems assumed qualified for this 17 year lifetime, including 3 years of storage.*
- *Small SRG Concept: One Advanced Stirling Radioisotope Generator (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.*
- *Small RTG Concept: Follows Multi-Mission Radioisotope Thermoelectric Generator* **(***MMRTG) design but with 1 or 3 GPHS modules and advanced PbTe/TAGS/BiTe thermocouples. Estimated 6 parallel strings for average 28 V power. Attributes are estimated requirements.*
- *GPHS stands for General Purpose Heat Source*

Very Small RPS Concept

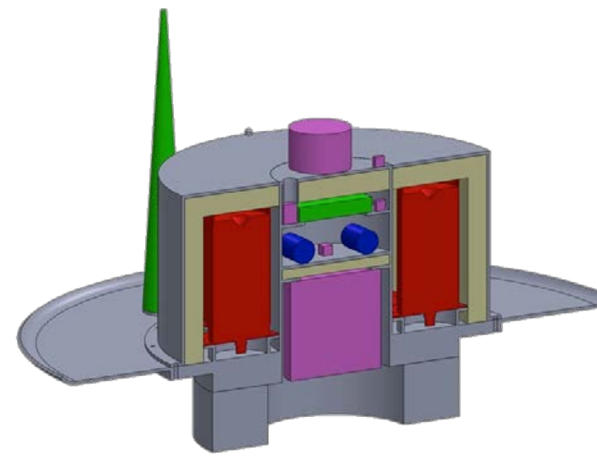
- Very Small RPS: Six, Single Radioisotope Heater Unit (RHU)-RPS (Hi-Z heritage) to provide >220 mW_e of continuous power
- Radioisotope Heater Units (RHUs) are an alternative heat source
  - Produce 1 W_t of heat
  - Requires validation to use as heat source for power
- Could provide power on a mW power level for very small missions or to supplement larger missions

Radioisotope Heater Unit



Light Weight Radioisotope Heater Unit

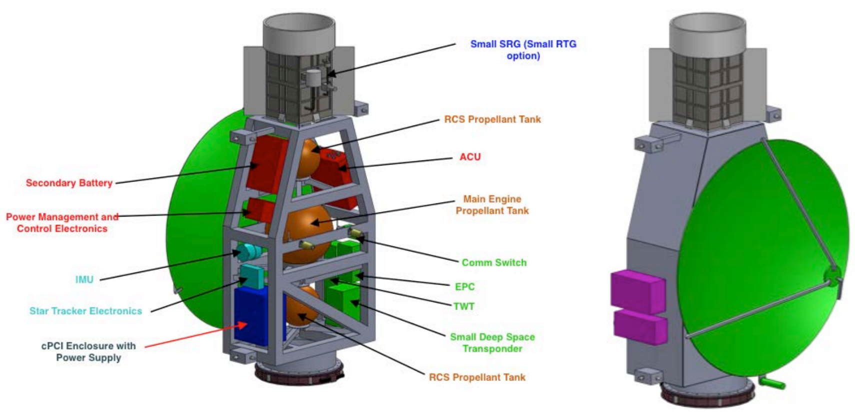
[From G. Rinehart, 6th Space Nuclear Power Systems (1989)]



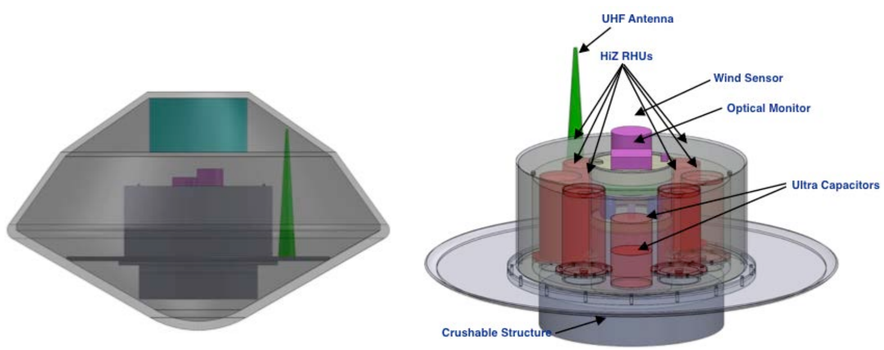
Meteorology And Seismology Enabled by Radioisotopes (MASER) concept

Findings from Two Deep Space Mission Concepts

- A SmallSat/CubeSat using a small Radioisotope Power System for deep space destinations could potentially fit into a Discovery class mission cost cap and perform significant science with a timely return of data.
  - RPS was considered as Government Furnished Equipment (GFE)
  - Costs for Nuclear Launch Safety aspects of mission would be one major challenge
  - Qualified heat source using RHU size a challenge, GPHS is within normal operations
  - RPS-based CubeSat would be ~5x more costly than a conventional CubeSat negating the premise of affording more low-cost mission concepts



Notional Chiron Small Spacecraft Diagrams with Interior Components



Notional MASER Configuration inside Aeroshell and notional MASER Hardlander Diagram with Interior Components

Two NASA CubeSat Studies

<u>STUDY #1:</u> Internal NASA Study of New Opportunities for Low-Cost Science Instruments, Platforms, and Mission Architectures
Chairs: Michael Seablom/SMD and Andy Petro/STMD

(a) Investigate current paradigm shifts in the miniaturization of science instruments and disruptive small satellite platform technologies;

(b) Determine the potential for novel approaches that could break the cycle of "larger but fewer" expensive missions;

(c) Identify key SMD science measurement requirements that could be satisfied through such paradigms;

(d) Identify technology gaps to address through solicitations to remove barriers to alternative paths.

<u>STUDY # 2:</u> SMD sponsored NAS Study Achieving Science Goals with CubeSats
SSB Ad Hoc Committee
Chair: Thomas H Zurbuchen, University of Michigan

(a) Review the current state of scientific potential and technological promise of CubeSats;

(b) Review the potential of CubeSats as platforms for obtaining high-priority science data;

- From recent decadal reviews, Science priorities in 2014 NASA Science plan

(c) Provide a set of recommendations on how to assure scientific return on future federal agency support of CubeSat programs;

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Note: Excerpt from the "CubeSats and Small Bodies Missions" presented by STMD and SMD Reps at the 14th Meeting of the NASA Small Bodies Assessment Group at Monrovia, CA on January 27-29

CubeSat Symposium

The National Academies of SCIENCES · ENGINEERING · MEDICINE

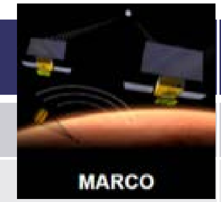
SPACE STUDIES BOARD
Division on Engineering and Physical Sciences

- Achieving Science Goals with CubeSats Symposium held in Irvine Sept 2015 by Space Studies Board under the auspices of the National Research Council
  - Held to gather information from the CubeSat community to develop a set of recommendations for NASA and others
- Discussed CubeSats technology, and use of CubeSats for heliophysics, planetary science, astronomy and astrophysics, earth science, and technology development
  - Agenda can be found at *http://sites.nationalacademies.org/SSB/CurrentProjects/SSB_160539*
- Wide participation, including:
  - Ames, Marshall, Goddard, JPL, APL, NASA HQ
  - SWRI, Aerospace Corporation, Lockheed Martin, Ball Aerospace, other industry
  - Many universities
- Discussed CubeSat paradigm:
  - Short development cycle
  - Frequent flights
  - High risk tolerances
  - Learn lessons from successes and failures and fly again

CubeSat Current and Upcoming Technologies

- **Power** – 10s of W_e for upcoming systems
  - Solar power limited by maximum area of deployed solar arrays and by ability to dissipate waste heat
  - Developing low temperature battery/ultracapacitor
- **Telecom** – 1 Mbps common now (for Earth orbiters), IRIS
  - Optical communication being developed – potential for Gbps communication
  - Developing inflatable antenna
- **Attitude Control System** – most CubeSats have 1-2 degree pointing accuracy
  - Upcoming missions achieving 0.1 degree or better
  - Developing miniaturized star trackers
- **Propulsion** – cold gas allows for ~10 m/s ΔV
  - Maturing chemical and electric propulsion (MEP) that is compatible with CubeSat requirements
- **Thermal** – most CubeSats have passive thermal systems

Representative Current Interplanetary CubeSats (free-flyers) Characteristics



	INSPIRE	Mars Cube One	NEAScout
Funding Org	SMD PSD	SMD PSD	HEOMD AES
No of CubeSat	2 s/c to beyond Low	2 s/c to Mars	1 s/c to Asteroid
Duration	~ 3 months	~ 6 months	~ 2.5 year lifetime
Size	3 U	6 U	6 U
Mass	3.8 kg	< 15kg (w/margin)	< 12kg (w/margin)
Power (mode)	17 W_e	17 W_e (safe), 35 W_e (telecom), 44 W_e (peak science)	~35 W_e @ 1AU solar distance
Power Source	2 deployable fixed solar arrays with batteries	2 deployable 1-axis gimbaled solar arrays with reflect array and batteries	4 deployable fixed solar arrays with batteries
Propulsion	No propulsion	Propulsion system to do 40 m/s ΔV	Solar Sail propulsion
Objective	Evaluate functionality, communications, navigation, and payload-hosting technologies.	To provide the real-time InSight Mars Lander landing phase data relay	Flyby/rendezvous and characterize one NEA that is candidate for a human mission

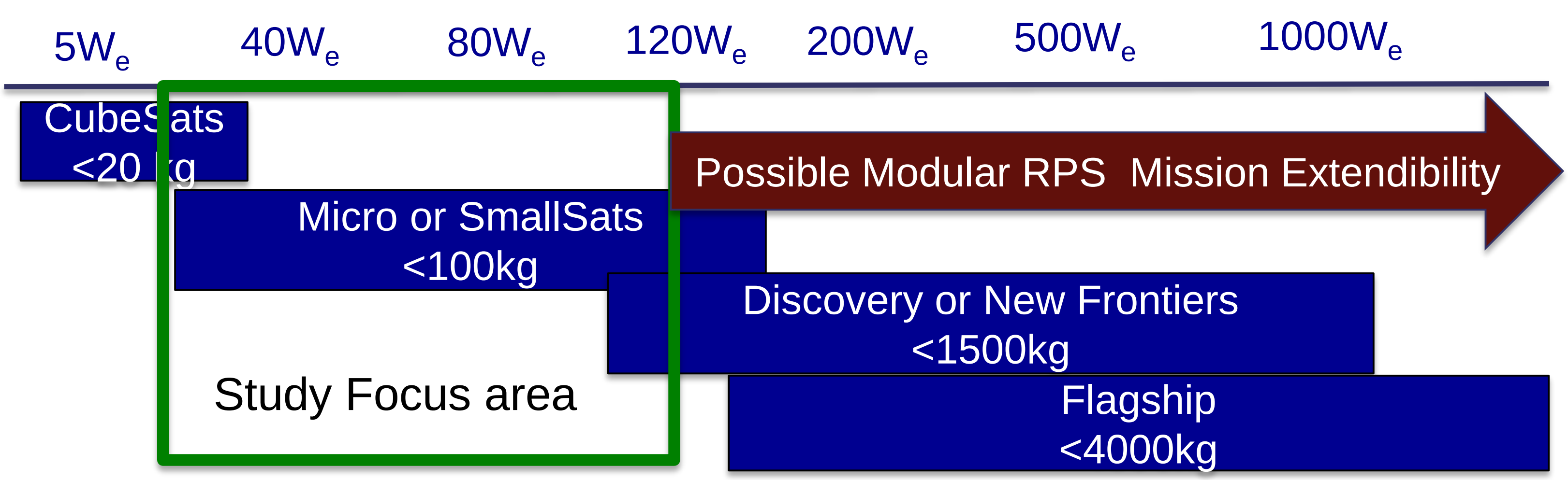
- 1 U is about 1.33 kg and 10 cm^3
- Each mission's power needs could be met by a GPHS-module based RPS
- **A new class of lower power, long-lived interplanetary CubeSat missions could potentially be enabled using small RPS.**

Motivation for Small-Sized RPS Mission Study

- The emergence of CubeSat technology is pointing the way to a future of very small spacecraft promising
  - Low cost, but high capability to yield science returns
- The solar system beyond Mars will prove very challenging to the use of such small vehicles without radioisotope power.
  - Solar power in the outer solar system requires very large arrays
  - Thermal management in the outer solar system is prohibitively power-expensive
  - Advanced power technology development needed for outer planet applications
- Small-sized RPS would very likely be an enabling technology for future small spacecraft exploration of the outer planets
  - Including investigating possible life-harboring environments of the moons of Jupiter and Saturn
  - Anticipation that micro (< 100 kg) and nano (< 10 kg) spacecraft could generate significant science returns at a reasonable cost
- The need to identify future RPS that could potentially meet a range of small spacecraft power is recognized

Considering Study Scope

- Examine anticipated small RPS capabilities for meeting the power needs of small outer solar system planetary missions, lunar and mars missions
  - Target from 15 kg/10 W_e CubeSats to 100 kg/100 W_e Micro or SmallSats
  - Devise a strawman S/C design that could use and accommodate the small RPS elements
  - Determine the strawman S/C design's applicability to the needs of important Decadal Survey missions, and define power and operational requirements on the small RPS
- Determine the nature of the applicable RPS elements
  - Trade among GPHS-based, fraction of GPHS-based, RHU-based or new heat-source based small RPS
- Determine if a modular approach could service needs of S/C even beyond the SmallSat range



Objectives of Study

- Examine CubeSats, NanoSats, and/or MicroSats less than 100 kg and determine their viability for planetary science missions
- Explore in specific RPS applications to sub-satellites, deployable mini-probes, and other free-flyers
- Investigate and quantify science benefits from use of RPS on small-sized mission concepts
- Determine the feasibility of applying modularity to RPS to be Modular RPS
- Study challenges specific to RPS on small spacecraft characteristics
  - Cost
  - Launch Approval / Launch Engineering
  - Mass
  - Volume / form factor / deployment / structure
  - Required mechanical/electrical interfaces
  - Etc.
- Define modular RPS technology needs that could inform RPS development planning

Why this study and why now?

- There is strong interests in small missions (either CubeSat or larger) beyond Earth by mission development community

- Many mission concepts will require power sources and heat beyond the capabilities of solar in the context of micro spacecraft

- Even close to home, the surface of the moon typically limits solar-powered missions to durations of 2 weeks. The possibility of micro-missions on the Moon increases almost daily with the advance of micro spacecraft technology and with increased capability to carry small ride-along payloads.

- Cost constraints within NASA, and interest within SMD demand a thorough look at how small spacecraft architectures could be accommodated.

- For many important (meaning Decadal Survey sanctioned) SMD applications, radioisotope power could be the only way to practically meet the objectives of small outer solar system planetary missions, lunar and mars missions