Jet Propulsion Laboratory, California Institute of Technology
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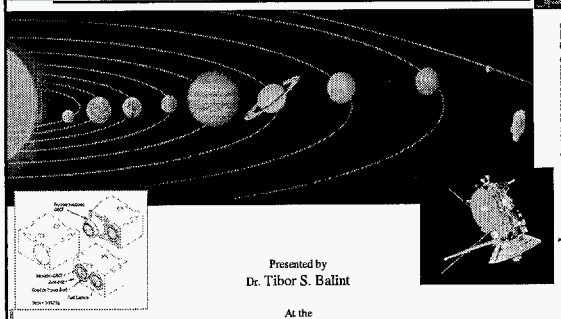


Presented by
Dr. Tibor S. Balint

At the
Aerospace Control & Guidance Systems Committee Meeting No.95

Sheraton City Centre, Salt Lake City, Utah
March 2-4, 2005

Outline

- NASA's Roadmapping Activities & Potential Candidate Design Reference Missions (DRM)
- Power source classification
- Types of radiation (a brief introduction)
- Past, Present and Future of RPS technology
- RPS requirements through mission concept examples
- Summary

NASA's Roadmapping Activities – Overview

- NASA's Advanced Program and Integration Office (APIO) established two teams for roadmapping activities,
  - **Strategic Roadmaps**: will explore options and establish pathways for achievement of NASA's strategic objectives
  - **Capability Roadmaps**: will recommend approaches for providing certain technical capabilities, judged to be critical to NASA's future programs
- Additional inputs to the planning process:
  - Decadal Survey by the National Academies / NRC (2003)
  - MEPAG – Mars Exploration Program Assessment Group
  - OPAG – Outer Planets Assessment Group
  - SSES – Solar System Exploration Subcommittee
- Preliminary results for NASA's Space Exploration Roadmap are expected by late summer (2005)

NASA's Roadmapping Activities – SRM

The NASA Strategic Roadmap teams cover 12 focus areas:

1. Robotic and human lunar expeditions.
2. Sustained, long-term robotic and human exploration of Mars.
3. Robotic exploration across the solar system.
4. Advanced telescope searches for Earth-like planets and habitable environments.
5. Development of an exploration transportation system.
6. Completion of the International Space Station and focusing its use on supporting space exploration goals.
7. Exploration of the Universe.
8. Exploration of the dynamic Earth system.
9. Exploration of the Sun-Earth system.
10. Advanced aeronautical technologies for next-generation aviation systems.
11. Using NASA missions to inspire, motivate, and educate.
12. Utilization of nuclear systems for the advancement of space science and exploration.

NASA Roadmapping Activities – CRM

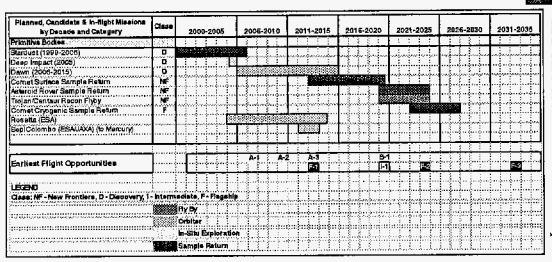
The NASA Capability Roadmap teams cover 15 focus areas:

1. High-Energy Power and Propulsion
2. In-Space Transportation
3. Advanced Telescopes and Observatories
4. Communication and Navigation
5. Robotic Access to Planetary Surfaces
6. Human Planetary Landing Systems
7. Human Health and Support Systems
8. Human Exploration Systems and Mobility
9. Autonomous Systems and Robotics
10. Transformational Spaceport/Range
11. Scientific Instruments/Sensors
12. In Situ Resource Utilization
13. Advanced Modeling, Simulation, Analysis
14. Systems Engineering Cost/Risk Analysis
15. Nanotechnology

Solar System Exploration Roadmap Candidates

- Potential SSE candidate Design Reference Missions could be grouped into four target categories (ref. Decadal Survey):
  - Primitive Bodies: Comets / Asteroids / Trojans / Centaurs / Kuiper Belt Objects
  - Inner Planets: Moon / Mars / Mercury / Venus
  - Gas Giants: Jupiter / Saturn; Ice Giants: Uranus / Neptune
  - Large Moons: Europa / Titan / Triton
- Mission categories by cost cap:
  - Discovery Class – competitive – less than $370M
  - New Frontiers Class – competitive – less than $700M
  - (Large Mission Class – program directed – less then $1.5B)
  - Flagship Class – program directed – greater than $1.5B
- The future NASA roadmap should be driven by science objectives and should fit into NASA's spending profile

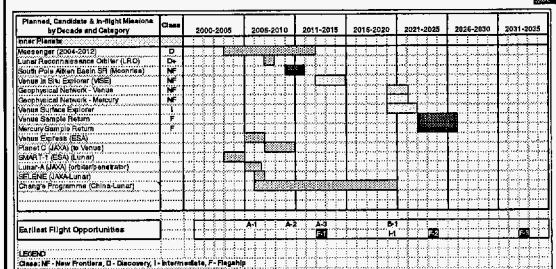
Potential Mission Candidates: Primitive Bodies



RPS Candidates for Unmanned Exploration Missions

7

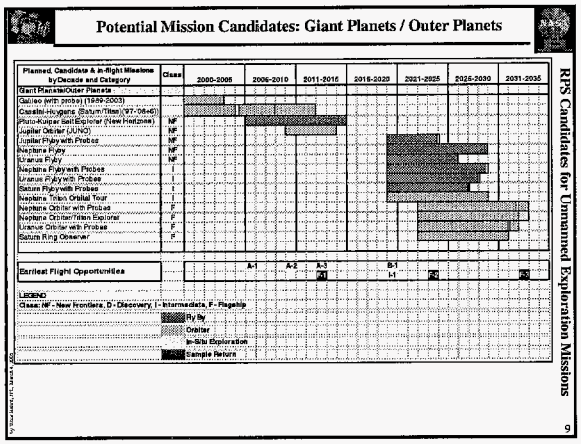
Potential Mission Candidates: Inner Planets



RPS Candidates for Unmanned Exploration Missions

8

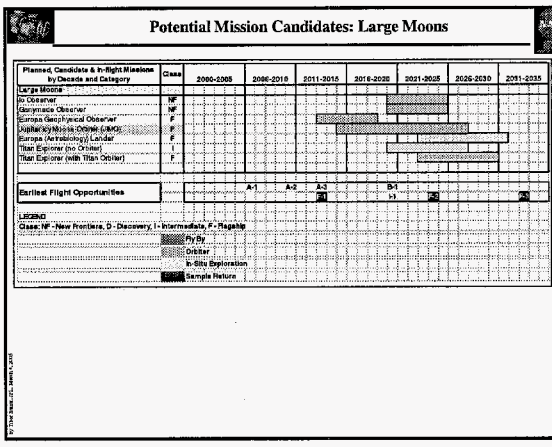
Potential Mission Candidates: Giant Planets / Outer Planets



RPS Candidates for Unmanned Exploration Missions

9

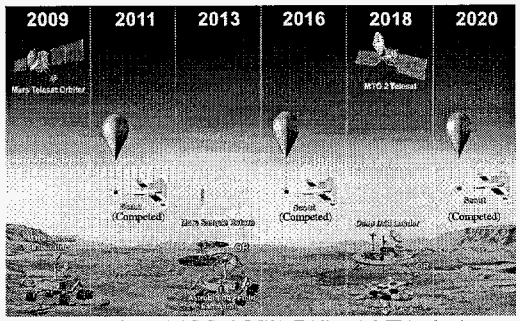
Potential Mission Candidates: Large Moons



RPS Candidates for Unmanned Exploration Missions

10

Potential Mission Candidates: Mars Program for the next decade

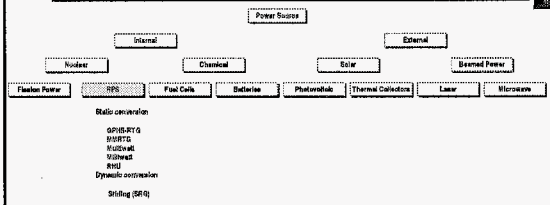


Addressing MEPAG Goals I (life), II (climate) & III (geology)
"Follow the water" turns into "Follow the Carbon"

RPS Candidates for Unmanned Exploration Missions

11

Power Source Classification



- Solar System Exploration includes
  - Orbital missions
    - From months (Earth) to years (any planetary destination)
    - Long missions beyond Mars could be RPS enabled
  - Entry probe missions into atmospheres
    - short life measured in hours
    - E.g., to Venus, Jupiter, Titan
    - Would require batteries
  - In-situ Surface missions
    - hours: Venus, Titan;
    - days: Mars Pathfinder;
    - weeks/months: Mars Exploration Rovers;
    - year(s): could be RPS enabled

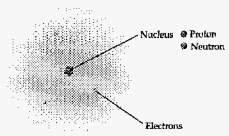
But no matter where we go, we will need power!

RPS Candidates for Unmanned Exploration Missions

12

Types of Radiation: Atoms and Isotopes

- An atom consists of a nucleus (with protons and neutrons) orbited by electrons
- Almost all of the mass is included in the atom's nucleus
- The volume of an atom is determined by the electrons' paths
- Isotopes of an atom have the same number of protons but different number of neutrons (same atomic number – same number of protons – thus similar chemical behavior, but different atomic mass)
- Radioactivity is a process where radioactive materials – composed of unstable atoms – emit excess energy in the form of radiation until becoming stable.
- During the half-life of a radioisotope half of the radioactive sample decays. The half-life is different for each isotope.



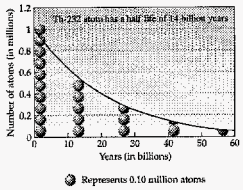


Illustration reference: http://wps.prenhall.com/wps/media/objects/476/488316/index.html

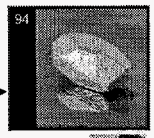
RPS Candidates for Unmanned Exploration Missions

13

Types of Radiation: Radioisotopes

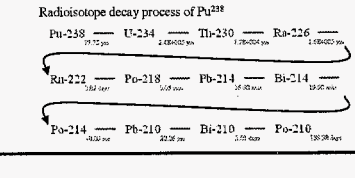
For example, the Pu^{238} isotope has a half life of ~87.74 years; during this time the generated heat output reduces by 50%

Radioisotopes	Half life
Curium-242 (Cm^{242})	162.8 days
Polonium-210 (Po^{210})	138.4 days
Curium-244 (Cm^{244})	18.1 year
Plutonium-238 (Pu^{238})	87.7 year
Promethium-147 (Pm^{147})	2.6 year
Strontium-90 (Sr^{90})	28.78 year



Note: Space applications only used Pu^{238}

Radioisotope decay process of Pu^{238}



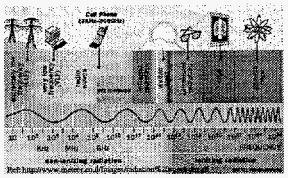
Reference:
C. Hacker, "Radiation Decay Version 3.5", Free Wars, October 25, 2000

RPS Candidates for Unmanned Exploration Missions

14

Types or Radiation: Ionizing / Non-Ionizing

- Non-Ionizing Radiation (low energy)
  radio frequency, microwave, infrared, visible, (lower frequency ultraviolet)
- Ionizing Radiation (high energy – damages DNA):
  e.g., (higher frequency UV), X-ray, gamma ray;
  Emitted by stars in the form of cosmic rays and by radioactive materials

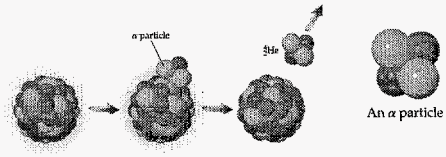


Ref: http://www.nuvet.com/dr/image/radiation/%20spectrum/index.htm

RPS Candidates for Unmanned Exploration Missions

15

Types of Radiation: α (alpha) Particle Radiation



- A particle of two protons & two electrons (i.e., Helium nucleus) is ejected from a usually heavy radioactive atom (e.g., Plutonium)
- (this results in the forming of a new parent atom with two less electrons and two less protons)
- Heavy, energetic and slow moving α–particle
- Can be blocked with a piece of paper or the skin
- No shielding material is required
- Radioisotope Power Systems predominantly radiate α–particles

Illustration reference: http://wps.prenhall.com/wps/media/objects/476/488316/index.html

RPS Candidates for Unmanned Exploration Missions

16

Types of Radiation: β (beta) Particle Radiation

- From the nucleus of a radioactive atom an electron & an antineutrino are emitted
- Since the electron is from the nucleus, it is called β-particle to distinguish from the electrons orbiting the nucleus of the atom
- When the β-particle is ejected, one of the neutrons in the nucleus is transformed into a proton
- The new daughter atom has one less neutron and one more proton than the parent
- β decay occurs in heavy isotopes
- β-particles have a single negative charge, they are smaller, lighter, faster and more penetrating than α-particles
- Traveling and depositing energy over a greater distance, thus less harmful then α-particles
- No particular shielding is required to guard against them

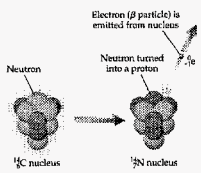


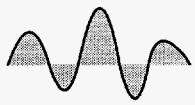
Illustration reference: http://wps.prenhall.com/wps/media/objects/476/488316/index.html

RPS Candidates for Unmanned Exploration Missions

17

Types of Radiation: γ (gamma) Radiation

- Following a radioactive decay reaction the nucleus of the atom is still in an excited state with excess energy to emit
- This energy is then emitted in a pulse of electromagnetic radiation called γ-ray
- It has no mass and no charge and is a high energy short wavelength radiation
- High atomic number, high density materials are best for shielding against γ -radiation
- In space, Aluminum could be used effectively, since it is relatively light
- (X-rays are similar to γ-rays, but with lower energies. They are produced when electrons change orbits within an atom or electrons from an external source are deflected around the nucleus, thus emitted from processes outside the nucleus)



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RPS Candidates for Unmanned Exploration Missions

18

Fission Chain Reaction in Reactors

- Neutron collides with the nucleus of Uranium-235
- Nucleus splits, resulting in fission products such as two smaller nuclides and three free neutrons
- Each split (or fission) releases a large amount of energy
- Under favorable conditions the three new free neutrons could split other atoms
- A maintained chain reaction generates a large amount of thermal power continuously (that is, until no atoms left to split)

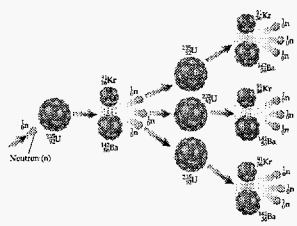
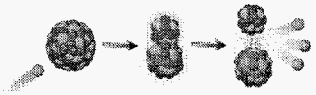


Illustration reference: http://wps.prenhall.com/wps/media/objects/476/488316/index.html

Types of Radiation: *Neutron* Radiation

- When a high energy neutron collides with a proton, it transfers its energy to it
- The charged proton causes ionizing radiation, which is damaging to DNA
- Low energy neutrons (less than 0.1MeV) could be shielded with low mass number materials such as water (due to the high cross sectional interaction with hydrogen)
- At higher energies (over 10MeV) cross sectional interaction with hydrogen is not effective to slow down the neutrons. Efficient shielding could be achieved with inelastic materials, such as iron to initially reduce the high energy neutrons through collisions, then water could be used to further reduce the neutron's energy and diffuse the thermal energy



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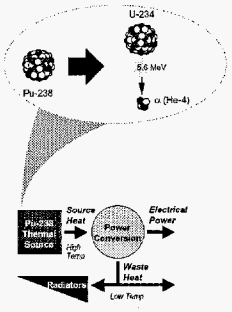
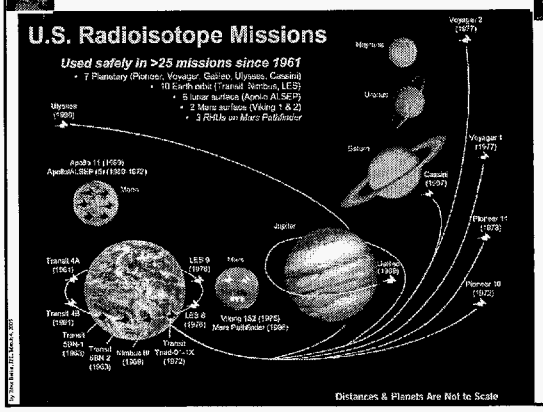
Power Options: Radioisotope Power Systems

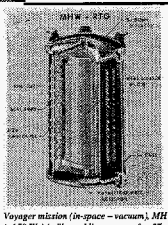


- The Plutonium-238 fuel used in RPSs is a radioisotope with a half life of ~87.7 years
- It produces heat through natural alpha (α) particle decay (an α-particle is virtually a He nucleus)
- A small portion of the heat is converted to electricity using various conversion technologies (η~ 2% to 25%)
- Waste heat is rejected through radiators or utilized for thermal control of spacecraft subsystems or components

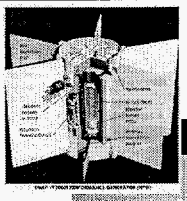
Past US RPS Enabled Missions



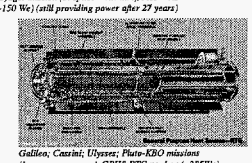
Past US Radioisotope Power Systems



Voyager mission (in-space – vacuum), MHW-RTG (~150 We) (still providing power after 27 years)



Pioneer 11; Viking 1 & 2 missions (In-space vacuum & Mars atmosphere) SNAP-19 (~40 We) (operated for ~7 years)

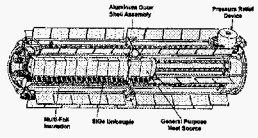


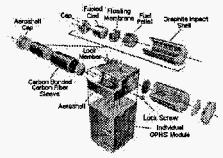
Galileo, Cassini; Ulysses; Pluto-KBO missions (In-space – vacuum), GPHS-RTG used on (~285We)

Apollo 12/14/15/16/17 missions (Moon – vacuum) SNAP-27 for ALSEP (Apollo Surface Experiments Package) (~70W) (still operated after 10 years on the Moon)

Present: GPHS-RTG

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



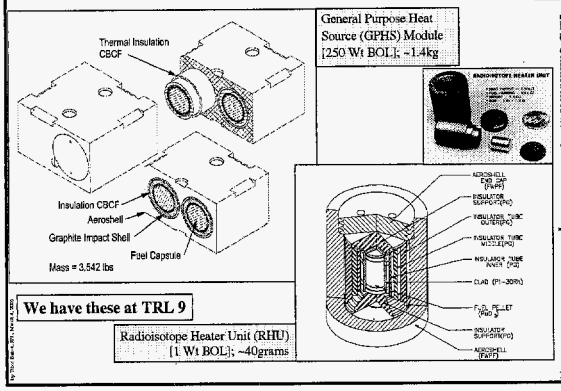


GPHS module stack

- 18 GPHS modules
- Dimensions
  - Length 113 cm
  - Diameter 43 cm
- Mass 56 kg
- Pu^{238} ~8KG
- Power ~240We
- Voltage 28V +/-0.2 VDC
- Mission life ~14 years
- Missions:
  Galileo (2 units)
  Cassini (3 units)
- Will be discontinued after the planned 2006 New Horizons Pluto-Kuiper Belt mission

Note: Voyager used MHW-RTG (150We) (still operating after more than 27 years) Viking used Snap-19 (40.3We) on Mars (operated for over 7 years)

Present and Future: Building Blocks for Proposed Small-RPSs



RPS Candidates for Unmanned Exploration Missions

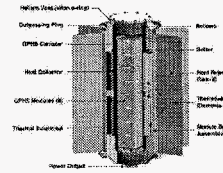
25

Under Development: MMRTG

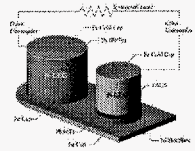
- 8 GPHS modules
- Thermoelectric conversion (PbTe/TAGS)
  - Efficiency ~6.3%
- Dimensions (half that of GPHS-RTG),
  - Length ~64 cm
  - Diameter ~64 cm
- Mass: ~42.7 kg (CBE) (w/ not to exceed 45 kg)
- Pu^{238} ~4KG
- Power: ~123 W (electric) (BOL)
  ~2000 W (thermal) (BOL)
- Specific power: ~2.9 We/kg
- Voltage 28V +/-0.2 VDC
- Mission life ~14 years
- In-space & surface operation

- Availability:
  - Under development
  - Down-selected for the 2009 MSL mission

- Potential mission impact:
  - Low g-load tolerance
  - Thermal design / heat rejection system



MMRTG Configuration



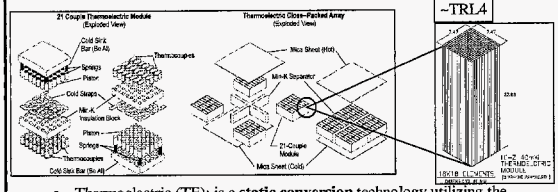
PbTe/TAGS Unicouple

TAGS: Tellurides of Antimony, Germanium, Silver
MMRTG: Multi-Mission Radioisotope Thermoelectric Generator

RPS Candidates for Unmanned Exploration Missions

26

Conversion Technologies: Static



- Thermoelectric (TE): is a **static conversion** technology utilizing the Seebeck effect
  - Low efficiency (~2% with RHUs & ~6% with GPHS)
  - Thermocouples (to be used in MMRTGs, high TRL)
  - Closed Packed Arrays (CPA) (under development, prototype only)
  - JPL is working on segmented thermocouples with a demonstrated η~13%
  - Variety of TEs: SiGe; PbTe – TAGS; Segmented TE; Skudderudites; etc.
  - Long missions should account for TE degradation (~0.8%/year)
    (Note: there is a ~0.8%/year degradation due to the radioisotope decay resulting in a total degradation of ~1.6%/year)

RPS Candidates for Unmanned Exploration Missions

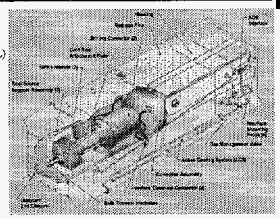
27

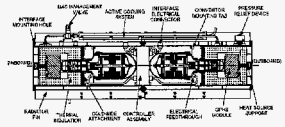
Under Development: Stirling Radioisotope Generator (SRG)

- 2 GPHS modules
- 2 Stirling converters (η~20.7-23.3%)
- Dimensions: 29 cm (W) x 38 cm (H) x 104 cm (L)
- Mass: 34 kg (CBE); Pu^{238} ~1kg
- Power: ~116W (electric) (BOL);
  ~500W (thermal) from 2 x GPHS (BOL)
- Specific Power: ~3.4 We/kg
- Voltage: 28V +/-0.2 VDC
- Design life requirement: 14 years
- In-space & surface operation

- Availability:
  - Development initiated as a backup to MMRTG
  - Broad application potentials e.g. lunar exploration
  - 4 units will be available by 2009-2010, our intention is to use them on upcoming missions

- Potential mission impact:
  - Vibration
  - Electromagnetic interference
  - Unknown reliability and lifetime for Stirling converters
  - Low g-load tolerance
  - Thermal design / heat rejection system (to a lesser extent than that of an MMRTG)

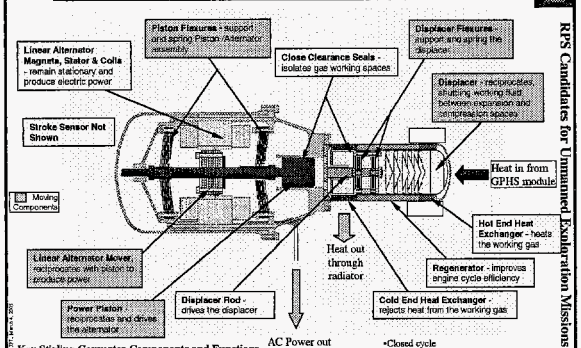




RPS Candidates for Unmanned Exploration Missions

28

Conversion Technologies: Dynamic (Stirling)



Key Stirling Converter Components and Functions
Dynamic conversion
e.g., Stirling shown here; has high power conversion efficiency (~20-25%)

- Closed cycle
- Reversible thermodynamic processes
- Isothermal compression and expansion
- Constant volume displacement

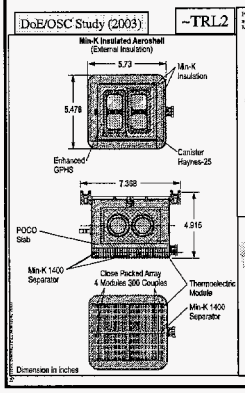
RPS Candidates for Unmanned Exploration Missions

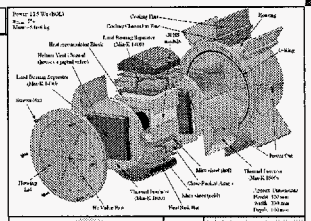
29

Small-RPS: "PaperWare" Concepts with 1 GPHS Module

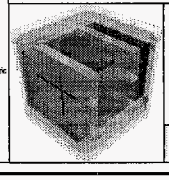
DoE/OSC Study (2003)

~TRL2





JPL Study (2004) [MER-A; -B; -C]



Potential power level: ~12-32We
Mass: ~6-8 kg (est.)

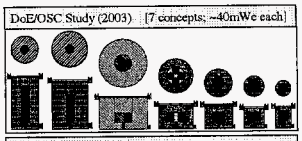
JPL Study (2004) [Mars Net Lander]

RPS Candidates for Unmanned Exploration Missions

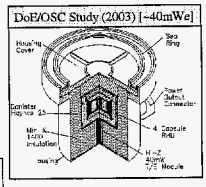
30

Small-RPS: "PaperWare" with Multiple RHUs

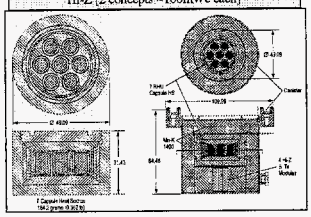
DoE/OSC Study (2003) [7 concepts; ~40mWe each]



DoE/OSC Study (2003) [~40mWe]



Hi-Z [2 concepts ~160mWe each]



RHUs in redesigned Aeroshells

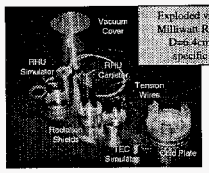
~TRL2

Potential power range: ~40 to 160 mWe

RPS Candidates for Unmanned Exploration Missions

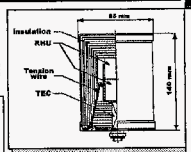
31

Small-RPS: Prototypes Built & Tested Around RHUs



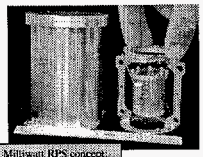
Exploded view of the JPL/Swales Milliwatt RPS 20 mWe in vacuum; D=6.4cm/L=8.1cm; m=0.3kg; specific power: 0.067 We/kg

Potential power range: ~20 to 40 mWe

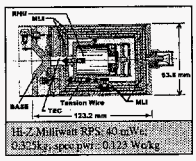


BIAPOS concept [2 RHUs?0mWe] Built and tested in Russia; 2 RHUs; D=8.5cm/L=15cm; 0.37Kg; specific power: 0.189We/kg (also 1 RHU)

~TRL4



NASA ARC Milliwatt RPS concept; 40 mWe; with higher g-load tolerance; m=0.121kg; spec pwr: 0.33We/kg

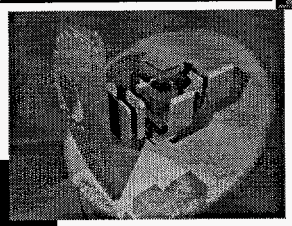


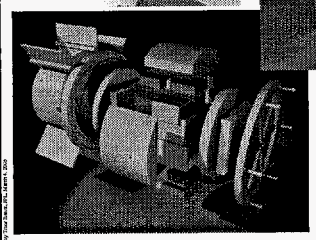
Hi-Z Milliwatt RPS: 40 mWe; 0.325kg; spec pwr: 0.123 We/kg

RPS Candidates for Unmanned Exploration Missions

32

Status of Small-RPS Development



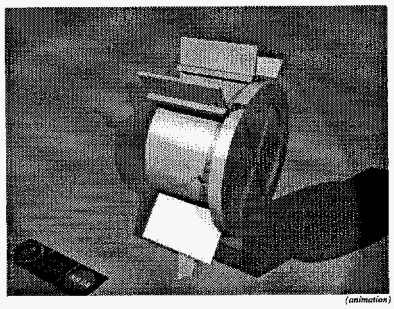


- Small-RPSs are under consideration by the US DoE and by NASA
- Notice of Intent (NOI) to develop them was issued in September 2004
- Request for Proposals (RFP) from the DoE is expected in early 2005
- Could be made available as early as the 2011 Mars Scout launch opportunity

RPS Candidates for Unmanned Exploration Missions

33

Anatomy of a Small-RPS Concept



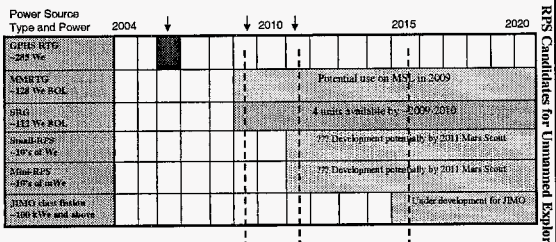
(animation)

Note: This small-RPS concept was inspired by the works of R. Wiley (DoE) and R. Carpenter (OSC)

RPS Candidates for Unmanned Exploration Missions

34

Predicted Nuclear Power System Availability



RPS available for SSE
Small RPS potentially available
JIMO class fission based power generation

Note: the last GPHS-RTG will be used on the upcoming planned (2006) New Horizons Pluto-Kuiper Belt mission
JIMO is deferred from 2015; a tech demo mission with a fission reactor might be possible ~2013-2014

RPS Candidates for Unmanned Exploration Missions

35

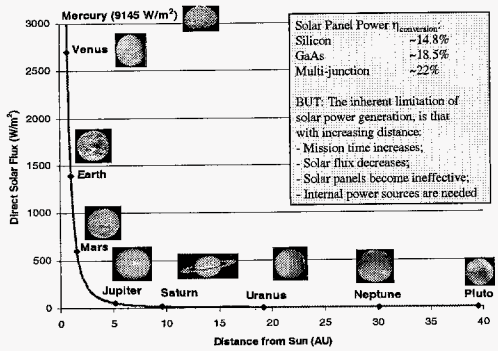
Considerations for RPS Enabled Missions

- Distance from the Sun (solar availability)
- Mission duration at low insolation locations
- In space (vacuum) vs. surface (atmospheres) operations
- Power level requirements (mission class)
- Power system sizing (peak power vs. total energy)
- Thermal environment through all mission phases
- Radiation environment
- EMI environment
- Vibration environment (e.g., Stirling – dynamic systems)
- Landing method (g-load tolerance)
- Cost considerations (unit cost + approval cost = $$$)

RPS Candidates for Unmanned Exploration Missions

36

Considerations: Solar Availability



Solar Panel Power $\eta_{conversion}$:

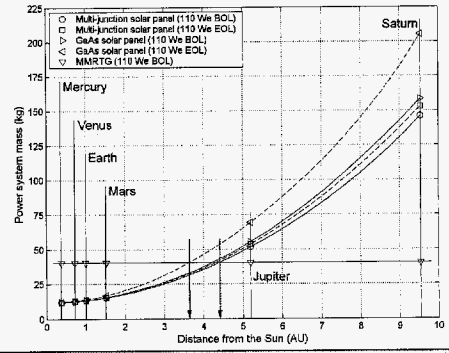
Silicon	~14.8%
GaAs	~18.5%
Multi-junction	~22%

BUT: The inherent limitation of solar power generation, is that with increasing distance:
- Mission time increases;
- Solar flux decreases;
- Solar panels become ineffective;
- Internal power sources are needed

RPS Candidates for Unmanned Exploration Missions

37

Considerations: Comparison of Solar and RPS Power Generation

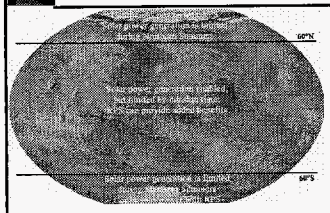


Beyond ~4AU RPS power generation is more mass efficient than solar power generation...

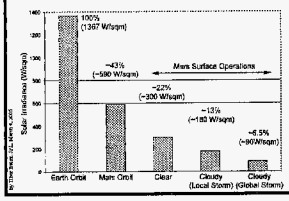
RPS Candidates for Unmanned Exploration Missions

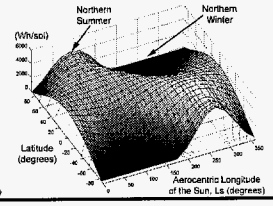
38

Considerations: RPS Power Generation on Mars



When to use RPS?
- Long duty cycle (measured in years)
- High latitude operations (for long duty cycle missions)
- No insolation (polar winter)
- Thermal death (utilize excess heat)
- Small-RPS when trying to save Pu^{238} & less power is enough, or dynamic cycle based RPS for more power

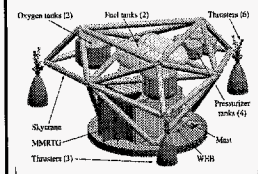


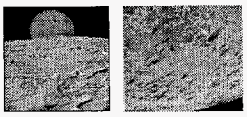


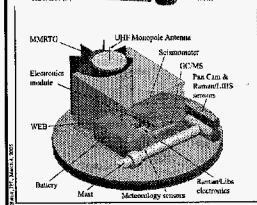
RPS Candidates for Unmanned Exploration Missions

39

Considerations: SSE Concept for a Triton Lander (lifetime/thermal)







- Triton is the largest Moon of Neptune (D=2700km ; 22% smaller than the Moon)
- Coldest place in the Solar System (-235°C or 38°K)
- Thin atmosphere (mostly nitrogen gas with a small amount of methane, thin haze expands up to 5-10km) results in a low atmospheric pressure (~0.015 millibar, that is 0.000015 times sea level pressure on Earth)
- It circles Neptune in a retrograde direction

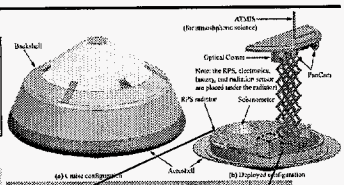
- An RPS enabled mission; could utilize excess heat
- Power system sizing should account for degradation
- The ~18 years trip time would require changes to the MMRTG lifetime requirements
- Skycrane type landing could keep g-loads under 40g

RPS Candidates for Unmanned Exploration Missions

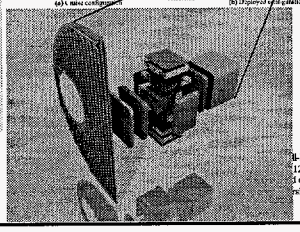
40

Considerations: Mars NetLander Concept (g-loads/thermal)

- 1 Small-RPS could enable the mission
- High g-load tolerance is needed during landing!
- Thermal environment should be addressed through all mission phases (Earth storage; Launch; Cruise; Entry/Descent/Landing; Mars surface operations)



- Monitor weather & environment
- Address MEPAG Goals 2 to 5
- Instruments could include: seismometer; mini-MS; Pan Cam; meteorology station
- Use up to 10 landers
- Hybrid power system: small-RPS & battery
- High power requirement by telecom
- Long life (up to several years)
- Independent from solar flux
- Capable to operate at any location

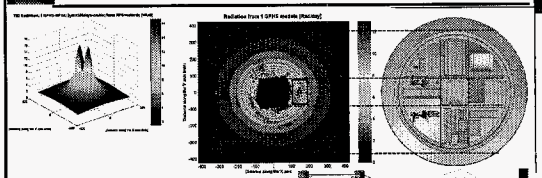


...l-RPS concept
...12.5-25We
...d on 5% to 10%
...sion efficiency)

RPS Candidates for Unmanned Exploration Missions

41

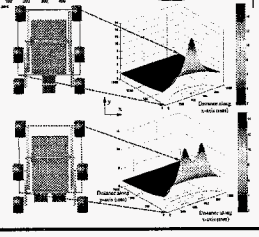
Considerations: Radiation Environment for Small-RPS Concepts



Total Ionizing Dose (TID) Radiation from small-RPSs after 4 years is less >20kRad

In comparison, state-of-the-art electronics could tolerate up to ~300-500kRad

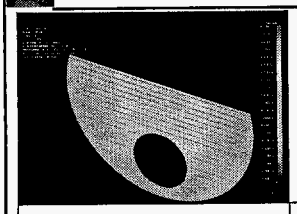
Thus, radiation from small-RPSs is not an issue



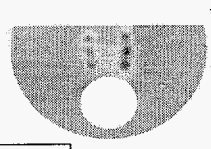
RPS Candidates for Unmanned Exploration Missions

42

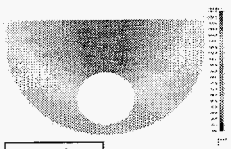
Considerations: Mars NetLander Small-RPS Thermal Issues



During cruise phase more heat is transferred to the pumped fluid, than it is radially conducted throughout the radiator



Cruise Stage



Landed Stage

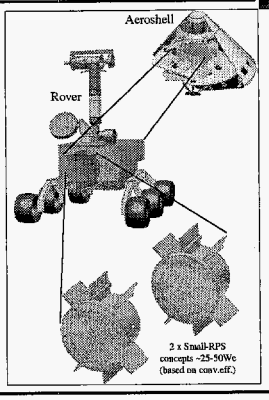
RPS Candidates for Unmanned Exploration Missions

43

Considerations: Small-RPS Powered Mars Rover Concept (peak power)

- Astrobiology driven goals to address MEPAG Goals 1-3
- Instruments could include: Microscopic imager; Raman spectrometer; APXS; Mini-TES; Pan Cam, RAT; TEGA; GC/MS etc.
- Could operate up to 2-3 years on Mars
- MER solar power generation: ~600 Wh/sol EOL; Small-RPS enabled concepts with 2 GPHS modules: ~620 Wh/sol BOL; 4 GPHS modules: ~1240 Wh/sol BOL.
- Electric power: 2 x 12.5We at BOL (based on 5% conversion efficiency, this could increase to as high as ~10% by the next decade)
- Each of the two GPHS modules produces ~250 Wt thermal power at BOL
- Waste heat could be utilized to heat components, motors, actuators, etc.
- High power requirements by mobility, telecom

- **Hybrid power system** should be sized for **peak power** usage and **energy** usage (high power requirements by mobility, telecom)
- **Thermal environment** should be addressed through all mission phases



RPS Candidates for Unmanned Exploration Missions

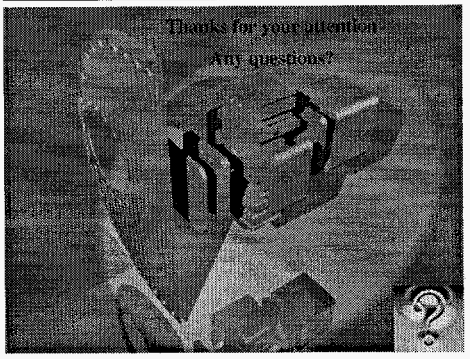
44

Summary

- An active RPS research and development program is in place by NASA / DoE
- Two systems are under development which could be used on SSE missions
  - MMRTG >=110 We BOL
  - SRG >=110 We BOL
  - Offered as early as 2009 (MSL down-selected an MMRTG)
- Small-RPS development is under consideration
  - GPHS based small-RPS in the 10's of watts
  - RHU based small-RPS in the 10's to 100's of milliwatts
  - Potential small-RPSs could be made available as early as the 2011 Scout mission
  - NOI (out in September 2004) & RPF (is planned for the early part of 2005)
- Next generation RPSs are planned, providing
  - Higher conversion efficiency; lower mass; higher specific power; TE, TPV, dynamic conversion technologies
- Radioisotope Power Systems (RPS) could enable potential future Solar System Exploration missions
  - Long mission duration & continuous power generation
  - Works in orbit (vacuum) & in atmospheres
  - Independent from solar flux
  - Within ~4AU with high insolation, it allows to access locations on planetary surfaces where solar flux is not available: e.g., polar regions,
  - Beyond ~4AU for long missions nuclear power generation may represent the only viable option
  - Excess (or waste) heat could be utilized for thermal management

RPS Candidates for Unmanned Exploration Missions

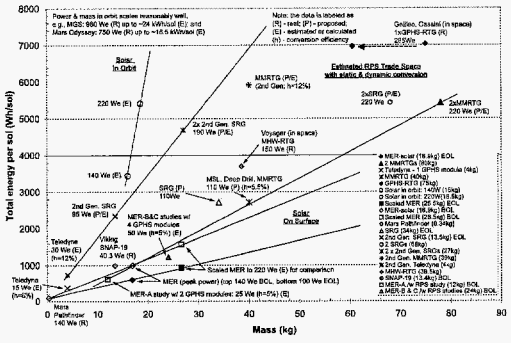
45



RPS Candidates for Unmanned Exploration Missions

46

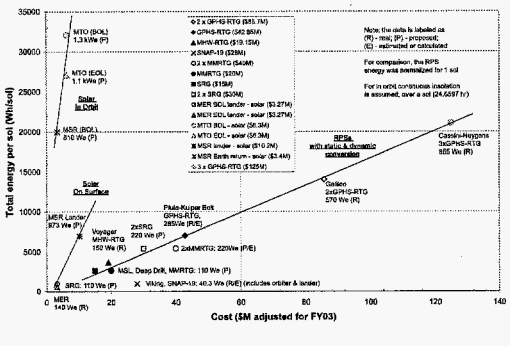
Power System Mass Summary



RPS Candidates for Unmanned Exploration Missions

47

Power System Cost Summary



RPS Candidates for Unmanned Exploration Missions

48

Historical Overview (RPS & Solar)

Mission (or Concept)	Power Source	Mass kg	Power We	Energy Wh/sol	Cost $M FY04
Radioisotope Power Systems					
Cassini/Huygens	3 × GPHS-RTG	3x56	855	21484	128
Galileo	2 × GPHS-RTG	2x56	570	14056	85.7
Pluto/Kuiper Belt	1 × GPHS-RTG	56	285	7028	42.85
Voyager 1 & 2	MHW-RTG	38.5	130	3600	10.15
Viking	SNAP-19	13.4	40.8	994	28
MSL (early variant)	2 × MMRTG	80	220	5426	40
MSL (pre-decisional)	MMRTG	40	110	2713	39
-	SRG-110	34	110	2713	18
-	2 × SRG-110	68	220	5426	30
(2nd Generation, η = 12%)	MMRTG	40	240	5918	N/A
(2nd Generation)	SRG	34.5	96	2368	N/A
(Small-RPS, η = 5.5%)	1 × GPHS module	6	12.5	310	N/A
(Small-RPS, η = 11%)	1 × GPHS module	6	25	620	N/A
(Teledyne, η = 6%)	1 × GPHS module	4	15	370	N/A
(Teledyne, η = 12%)	1 × GPHS module	4	30	740	N/A
Thermal power only					
Cassini-Huygens	157 × RHU	6.8	157Wt	3872Wt	0.57
Solar-powered missions					
MER (BOL)	triple-junction	16.9	140	1060	3.27
MER (EOL)	triple-junction	16.9	~400	~400	3.27
Mars Pathfinder	GaAs/Ge	0.31	16.5	92	-
MGS	GaAs & Si	-	980	24168	10.4
Mars Odyssey	GaAs	86	750	18500	27.7
MTO (BOL)	triple junction	78	1300	32058	6.3
MTO (EOL)	triple junction	78	1100	27126	6.3
MSR lander (BOL)	triple junction	77	973	6880	10.2
MSR ERV (BOL)	triple junction	23	810	19673	4.4

Past RPS:
MHW-RTG
Snap-19
GPHS-RTG

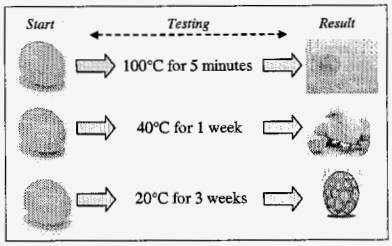
Near future RPS:
MMRTG (~2009)
SRG (~2009/2010)
(Small-RPS; ~2011?)

Solar panels:
GaAs/Ge
GaAs & Si
Triple junction

RPS Candidates for Unmanned Exploration Missions

49

Radiation Tolerance: Testing vs. Accelerated Testing



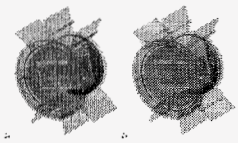
Accelerated testing is only meaningful if the mechanisms to be tested remain consistent through ranges of time, temperature, rate, energy etc.

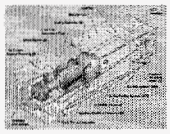
Therefore, equal "dose" may not result in the same outcome!

RPS Candidates for Unmanned Exploration Missions

50

Power System Trade for the Same Amount of Pu^{238}





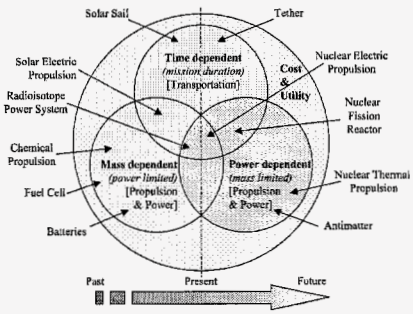
Small-RPS with 1 GPHS module	Stirling Radioisotope Generator
2 small-RPSs (1 GPHS each)	SRG110 (2 GPHS modules)
Pu^{238} fuel mass: 2 x 0.5kg	Pu^{238} fuel mass: 2 x 0.5 kg
Static conversion (assumed η ~5%)**	Dynamic conversion (η ~25%)
Thermal power: 2 x 250Wt (BOL)	Thermal power: 2 x 250Wt (BOL)
Electric power: 2 x ~12.5We = ~25We	Electric power: ~110 We (BOL)
System Mass: ~ 2 x ~7-8 kg = ~16 kg	System mass: ~34 kg
Dimensions: ~H13" x W9" x L6" each	Dimensions: ~H15" x W11.5" x L37.5"
Other: g-load tolerance (TBD)	Other: g-load tolerance (TBD)
Low TRL: target 2011 Scout	TRL9 target: 2009
Development program: not yet started	Development program: ongoing

Notes: ** efficiency up to ~13% would increase to power to ~32.5We for each small-RPS, resulting in ~65We

RPS Candidates for Unmanned Exploration Missions

51

Power Generation Paradigm



RPS Candidates for Unmanned Exploration Missions

52

Examples of Fission Power and RPSs (dated information)

	Power-plant	Type	Mass [kg]	Thermal power [kWt]	Power level [kWe]	Specific power [We/kg]	Lifetime
RPSs	SNAP 27 (Apollo-14)	Radioisotope/TE	-	-	0.073	3.7	10 years & demonstrated
	RTG (Galileo/Ulysses)	Radioisotope/TE	55	4.2	0.285	5.1	~20 demonstr.
	Radioisotope-AMTEC (1)	Radioisotope/AMTEC	~21	-	0.105	~5	Development
	Radioisotope-AMTEC (2)	Radioisotope/AMTEC	-	-	1	18.5	Study
	Dynamic isotope [illegible]	Radioisotope/Brayton	905	25	6	6.6	Study
Fission Reactors	SNAP 10A (SNAP-10A/X)	Fission/TEC	435	46	0.5	1.15 (e)	43 days demonstr.
	SP-100 (10 kWe)	Fission/TEC	-	-	10	5.3	Study
	SP-100 baseline	Fission/TEC	4,518	2,400	100	21.8	Development, 7 years (e)
	SP-100 advanced	Fission/TEC	3,900	2,400	100	27.0	Study, 7 years (e)
	SP-100 dynamic	Fission/Brayton	9,505	383	100	10.5	Study
	SP-100 dynamic	Fission/Brayton	14,337	2,667	450	38	Study
	SP-100 dynamic	Fission/Stirling	20,604	2,500	835	41	Study
	Topaz (Cosmos 1818, +1867)	Fission/TIC	1,200	150	5	4.2	342 days demonstr.
	Topaz II	Fission/TIC	1,000	135	5.5	~5.5	1.5-3 years (e)

73W

285W

500 W (US)
10 kW
One US reactor have been flown (but 45 RTG's)

5 kW (USSR)
~37 Russian reactors have been launched to LEO (6 RTG's)

RTG: Radioisotope Thermoelectric Generator
SNAP: Space Nuclear Auxiliary Power
SP: Space Power
AMTEC: Alkali-Metal Thermo-to-Electric Cells
TEC: Thermo-Electric Converter
TIC: Thermo-Ionic Converter
(e): estimated
demonstr.: demonstrated

RPS Candidates for Unmanned Exploration Missions

53