Radioisotope Power Systems and Their Applications for Solar System Exploration

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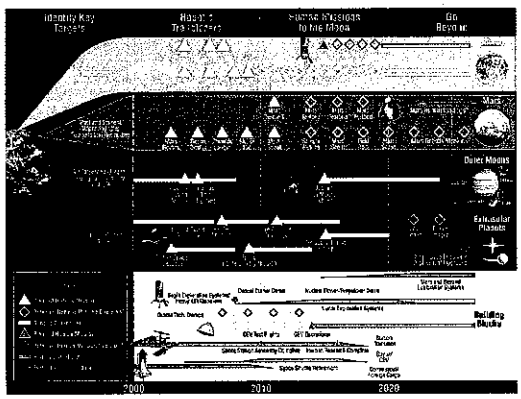
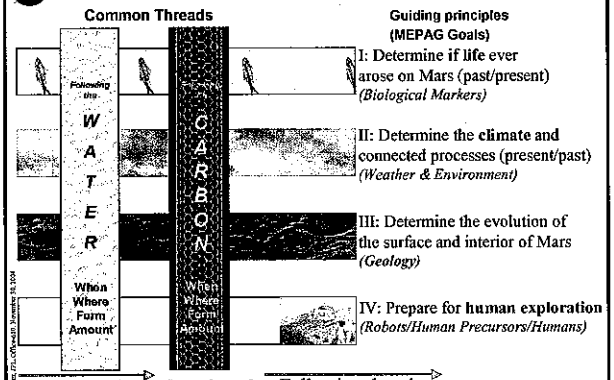
Outline

- Our Solar System Exploration Vision
- Power Source Classification & Brief Overview of the Options
- Introduction to Radioisotope Power Systems
- Implications of RPS Requirements through Mission Concepts
- Questions

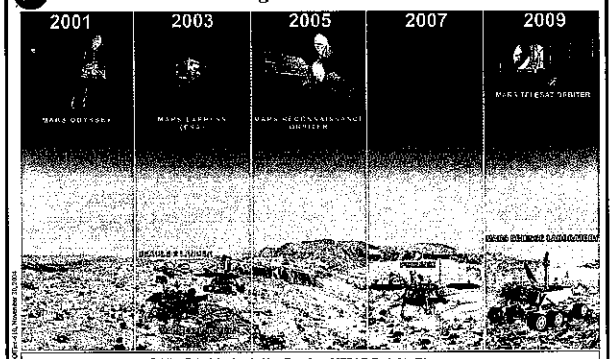
The Vision for Space Exploration



Mars Exploration Strategies



Mars Program in This Decade



Guiding Principles for the Next Decades – MEPAG Goals I to IV:

Goal I: Determine if life ever arose on Mars — Goal II: Determine climate on Mar

Goal III: Determine evolution of the surface and interior of Mars (Geology) — Goal IV: Prepare for Human Exploration

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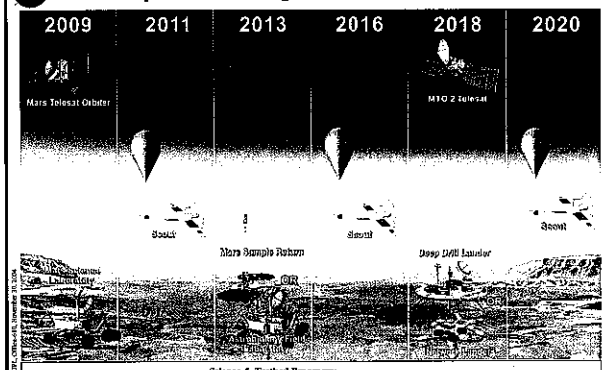
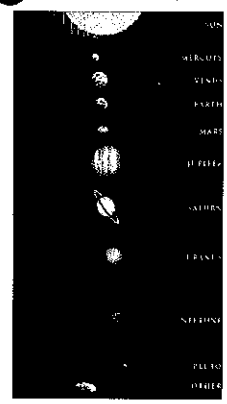
Proposed Mars Program for the Next Decade



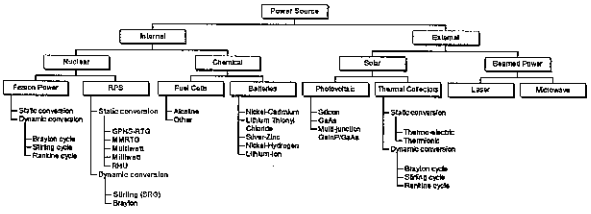
Science & Testbed Programs:
Science examples: AFL rover, Deep drill, NetLander, MSR
Testbed examples: Pinpoint landing; Increased landed mass; Subsurface access; Fission reactor on surface

Solar System Exploration (Beside Mars)



- Many scientifically interesting targets exist in our Solar System waiting to be explored
- A systematic exploration strategy could include a succession of orbiter, lander and sample return missions to these destinations
- A detailed roadmap with a full set of Design Reference Missions is currently under development. From these a set of missions could be selected based on science interest and other relevant considerations (e.g., affordability)

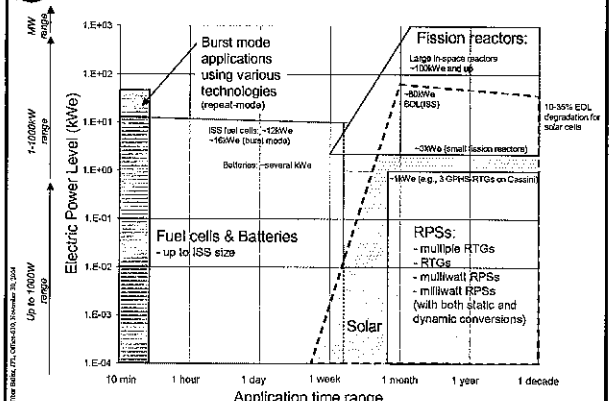
Power Source Classification



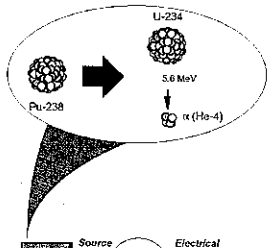
- Solar System Exploration includes
  - Orbital missions
    - From months (Earth) to years (any planetary destination)
    - Long missions beyond Mars could be RPS enabled
  - Entry probe missions into atmospheres
    - short life measured in hours
    - E.g., to Venus, Jupiter, Titan
    - Would require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

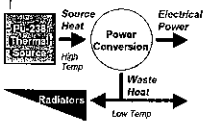
But no matter where we go, we will need power!

Power Regimes

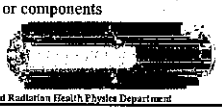


Power Options: Radioisotope Power Systems (RPS)

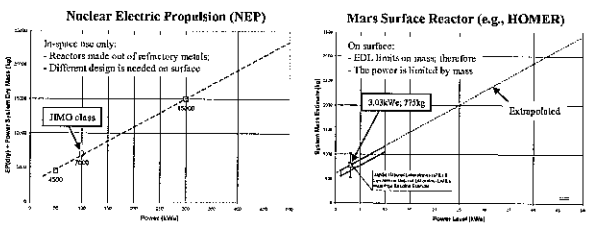




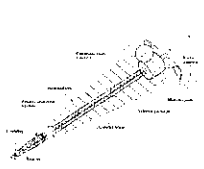
- The Plutonium-238 fuel used in RPSs is a radioisotope with a half life of ~87.7 years
- It produces heat through natural alpha (α) particle decay (an α-particle is virtually a He nucleus)
- A small portion of the heat is converted to electricity using various conversion technologies (η~ 2% to 25%)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

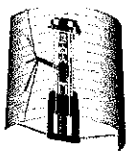


Power Options: Nuclear Fission Reactors

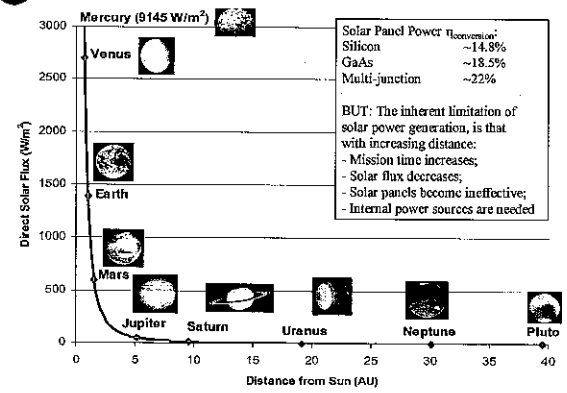


Suitable for SSE, but beyond the scope of this seminar.





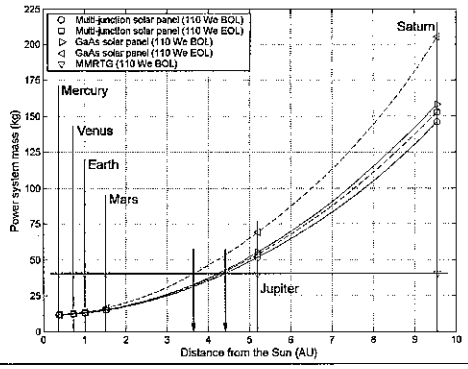
Power Options: Solar Power Generation



Solar Panel Power $\eta_{conversion}$:
Silicon ~14.8%
GaAs ~18.5%
Multi-junction ~22%

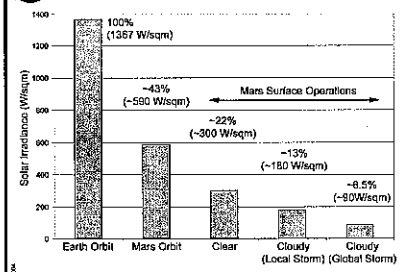
BUT: The inherent limitation of solar power generation, is that with increasing distance:
- Mission time increases;
- Solar flux decreases;
- Solar panels become ineffective;
- Internal power sources are needed

Comparison of Solar & RPS Power Generation



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

Solar Irradiation at Mars



Power Conversion Efficiencies:

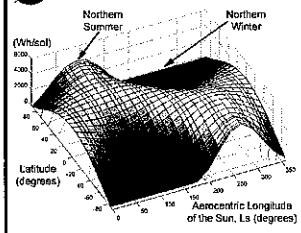
Silicon	~14.8%
GaAs	~18.5%
Multi-junction	~22%

Operation-life in years, but
- Mass scales with power
  100 W / 16.6 kg; 100kW / 16.6MT
- Panel area scales with power
  100W / 5.2m²; 100kW / 5200m²
- Power effected by
  Degradation (0.5-3.75%/year)
  Distance from the Sun

- Solar power generation on Mars is the function of:
  - Operating latitude
  - Sand storms
  - Eclipses
  - Solar panel degradation (dust; thermal cycling)
  - Seasons (aerocentric longitude of the Sun – Ls)
  - Atmospheric conditions
  - Terrain shadowing

… but even on Mars RPSs could present advantages

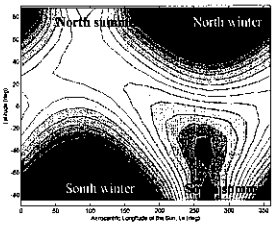
Solar Power Generation on Mars



When to use RPS?
- Long duty cycle (measured in years)
- High latitude operations
- 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

When to use solar?
- Short duty cycle
- Near equator
- High insolation
- Summer time

Insolation depends on:
-Seasons
-Latitude
-Environment
(e.g., dust in atm.)



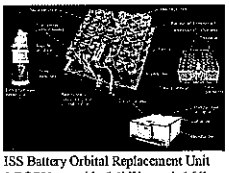
Power Options: Fuel Cells, Batteries, Flywheels

Fuel Cells

Space Shuttle
3 generators; η_{conv}~70%
each 12kWe (16kWe burst)
each 118kg; H_2O byproduct
But: 7-14 days of operation

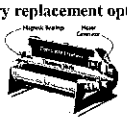
Apollo
3 in parallel; 110kg each
each 1.4kW (2.3kWe burst)
But: ~400 hours of operation

Batteries



ISS Battery Orbital Replacement Unit
2 BORUs provide 6.6kWe; each 166kg; <1 week

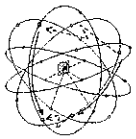
Battery replacement option

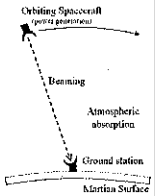


Flywheel unit under development for ISS
~60,000 rpm; greater capacity; clean; more economical than batteries

Power Options: Beamed Power

Power beaming options:
1) Orbit-to-orbit
2) Orbit-to-surface
3) Surface-to-orbit
4) Surface-to-surface



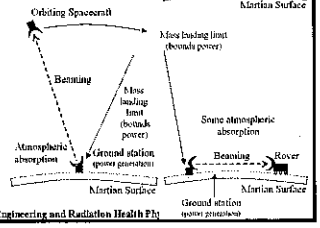


- Methods: laser & microwave
- Beaming efficiency very low

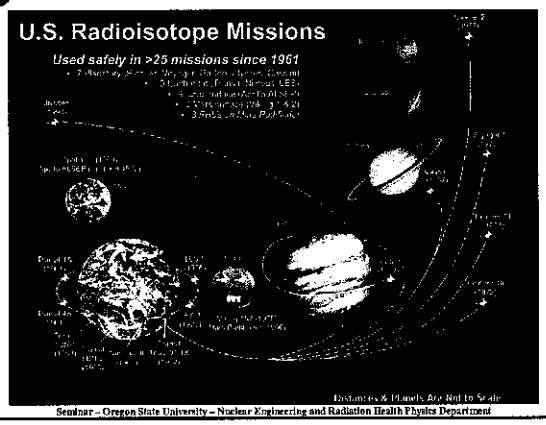
Example for Power Beaming*:
- GaAs laser diode array: D=2m
- Distance: 400,000km (~ Earth/Moon)
- Collector on Moon R~250m; A~0.2km²
- Power on Earth: 12MWe
- Power on Moon: 50kWe
- End-to-end conversion: 0.4%

*Landis, G.A., "Moonbeam Night Power by Laser Illumination", AIAA Journal of Propulsion and Power, 8, No.1, 1992

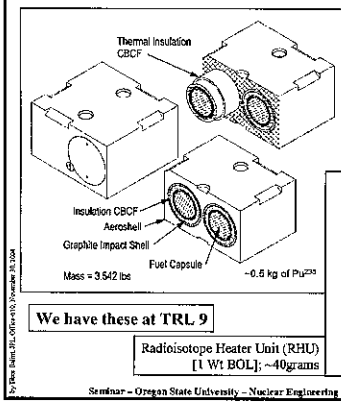
This technology is not mature enough to be used for SSE



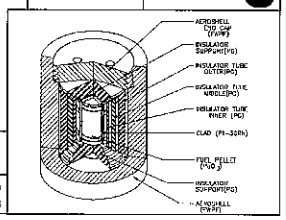
US RPS Enabled Missions



Building Blocks for Future Small-RPSs



General Purpose Heat Source (GPHS) Module [250 Wt BOL]; ~1.4kg



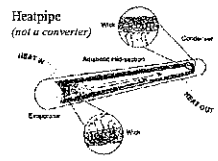
We have these at TRL 9

Radioisotope Heater Unit (RHU) [1 Wt BOL]; ~40grams

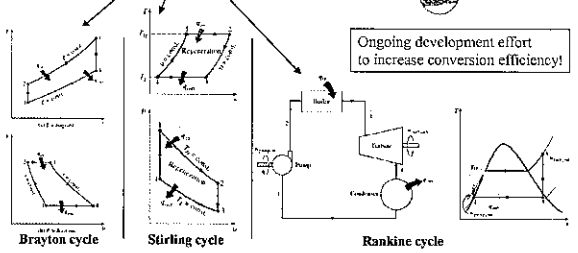
Heat-to-Electric Power Conversion

Converter	Type	Efficiency %	Comments
TEC	Conventional	~7-12	In Space
TIC		~10-20	In Space
AMTEC		~20-30	Development
TPV		~20-30	Development
Dynamic	Brayton	~20-35	Development
	Stirling	~25-30	Development
	Rankine	~15-25	Development

Heatpipe
(not a converter)

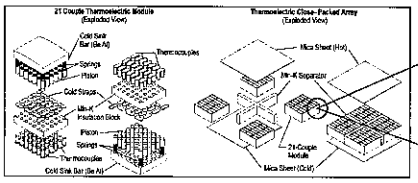


Ongoing development effort to increase conversion efficiency!

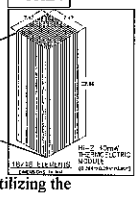


Brayton cycle **Stirling cycle** **Rankine cycle**

Conversion Technologies: Static



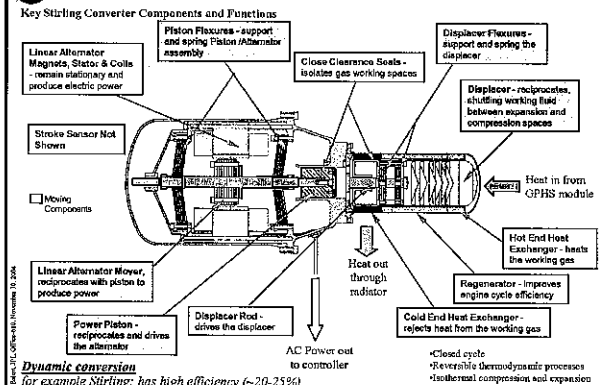
~TRL4



- 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**)

Conversion Technologies: Dynamic

Key Stirling Converter Components and Functions

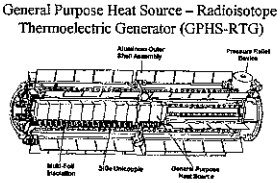


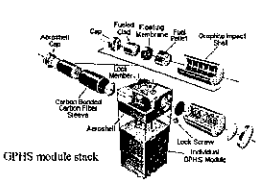
Dynamic conversion
for example Stirling: has high efficiency (~20-25%)

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

The Past – GPHS-RTG

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





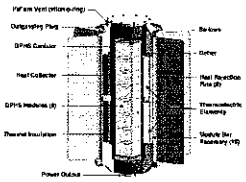
GPHS module stack

- 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 Pluto-Kuipter Belt mission**

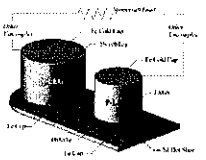
Note: Voyager used MHW-RTG (150We) (still operational after more than 27 years) Viking used Snap-19 (40.3We) on Mars (operated for over 7 years)

Multi-Mission Radioisotope Power System (MMRTG)

- 8 GPHS modules
- Thermoelectric conversion
  - Efficiency ~5.5-6.5%
- Dimensions (half that of GPHS-RTG),
  - Length ~55 cm
  - Diameter ~43 cm
- Mass: ~42 kg (CBE) (w/ not to exceed 45 kg)
- Pu^{238} ~4KG
- Power: ~128 W (electric) (BOL)
  ~2000 W (thermal) (BOL)
- 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



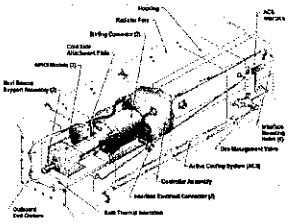
MMRTG Configuration



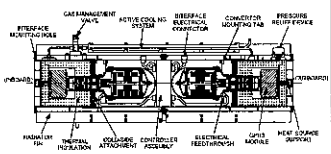
PbTe/TAGS Unicouple

Stirling Radioisotope Generator (SRG)

- 2 GPHS modules
- 2 Stirling converters (η~25%)
- Dimensions: 11.5"W x 15"H x 37.5"L
- Mass: 34 kg (CBE); Pu^{238} ~1kg
- Power: ~112W (electric) (BOL); ~500W (thermal) from 2 x GPHS (BOL)
- Voltage: 28V +/-0.2 VDC
- Design life requirement: 14 years
- In-space & surface operation

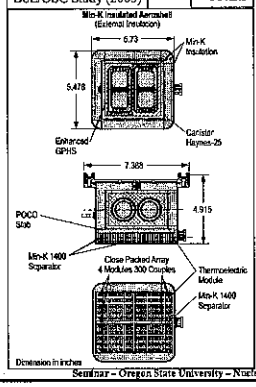


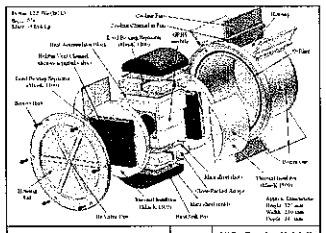
- Availability:
  - Development initiated as a backup to MMRTG
  - Broad application potentials e.g. lunar exploration
  - 4 units will be available by 2009-2010, our intention is to use them on upcoming missions
- Potential mission impact:
  - Vibration
  - Electromagnetic interference
  - Unknown reliability and lifetime for Stirling converters
  - Low g-load tolerance
  - Thermal design / heat rejection system (to a lesser extent than that of an MMRTG)

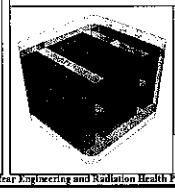


Small-RPS: "PaperWare" Concepts with 1 GPHS Module

DoE/OSC Study (2003) ~TRL2







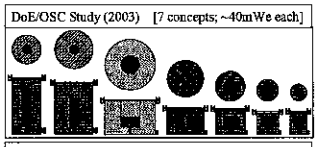
JPL Study (2004) *[MER-A; -B; -C]*

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

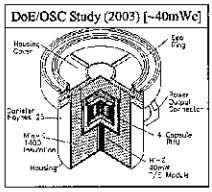
JPL Study (2004) *[Mars Net Lander]*

Small-RPS: "PaperWare" with Multiple RHUs

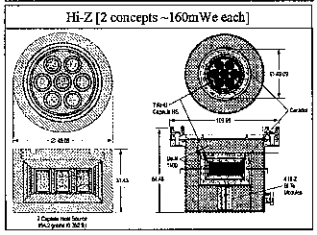
DoE/OSC Study (2003) [7 concepts; ~40mWe each]



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



Hi-Z [2 concepts ~160mWe each]



RHUs in redesigned Aeroshells

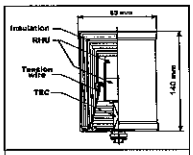
~TRL2

Potential power range: ~40 to 160 mWe

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: 0.067We/kg

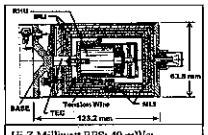
Potential power range: ~20 to 40 mWe



BIAPOS concept [2 RHUs70mWe] Built and tested in Russia; 2 RHUs, D=8.5cm/L=13cm; 0.37kg; specific power: 0.189We/kg (also 1 RHU)

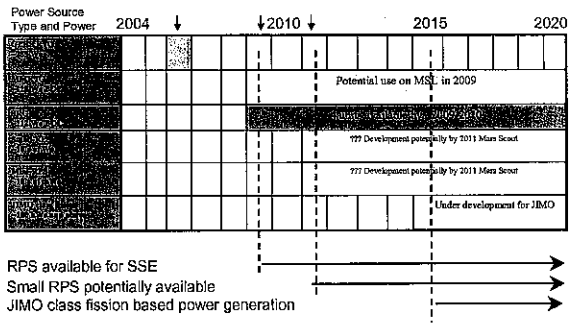
~TRL4

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

Predicted Nuclear Power System Availability



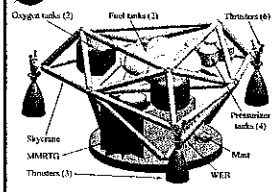
Note: the last GPHS-RTG will be used on the upcoming planned (2006) Pluto-Kuiper Belt mission

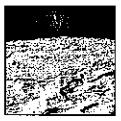
Mission Impact of RPS Requirements

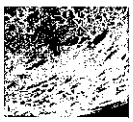
Requirements	Implications
Lifetime: >=14 years	Missions to Neptune could take 18 years, RPS is limited to Jupiter, Saturn, maybe Uranus
g-load tolerance: 40g	Missions limited to soft landing and to orbital / deep space
Operate in vacuum and in atmospheres	Will have the capability to operate on Mars and on other planetary bodies with or without atmospheres, in addition to orbital / deep space missions in vacuum
Operating temperatures	Cold outer planets region provides good ΔT between hot & cold sides of the TEs Venus environment is challenging due to high T (heat rejection) & pressure (Helium venting) Thermal issues should be addressed through all operational phases, e.g., for a landed mission on Mars it would include launch, cruise, EDL, surface operations
Other	Up to ~4AU solar power is more mass efficient in orbit, RPS missions out to Mars are limited to locations where long duration and independence from the sun is required
Requirements are not yet set	We could set requirements for longer lifetime and higher g-load tolerance to enable the largest number of missions
Radiation environment	Potential impact on S/C components should be addressed; (Material changing by RPS is not considered a problem, since the secondary gamma and neutron radiation impact is very limited)

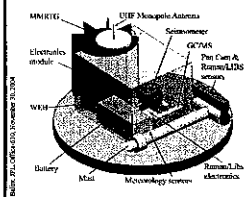
This incomplete list is shown to illustrate the impact of various requirements on potential missions

SSE Concept: Triton Lander









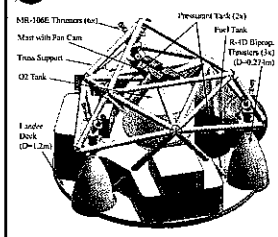
- Triton is the largest Moon of Neptune (D~2700km ; 22% smaller than the Moon)
- Coldest place in the Solar System (~235°C or 38°K)
- Thin atmosphere (mostly nitrogen gas with a small amount of methane, thin haze expands up to 5-10km) results in a low atmospheric pressure (~0.015 millibar, that is 0.000015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

- An MMRTG 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 landing could keep g-loads under 40g

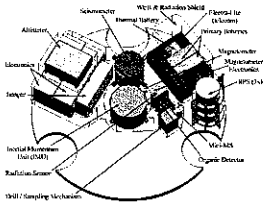
by Tibor Balint, JPL, Office 416, November 23, 2004

Seminar – Oregon State University – Nuclear Engineering and Radiation Health Physics Department

SSE Concept: Europa Surface Science Package



- Total mass: ~375 kg
- Total Power: ~50We
- 3 Small-RPSs (single GPHS module based)
- Plus a secondary battery
- Soft landing (total Δv~1.65km/s)
- Shielding mass can be significant, limiting mission duration (3-14 days)



- Small-RPSs could enable an ESSP mission
- Excess heat could be utilized for the WEB
- Development effort should address TE conversion efficiency

Ref: Balint, T., "To Europa and Beyond (Enabled by a Small-RPS)," IEEE05 Aerospace Conference, Big Sky, Montana, March 2005 (in appear)

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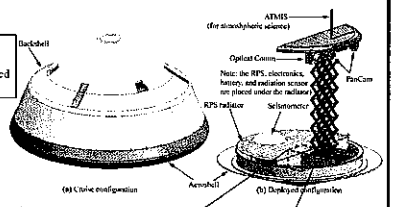
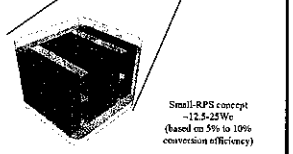
Mars Mission Concept: NetLander

- 1 Small-RPS could enable the mission
- High g-load tolerance during landing!
- Thermal environment should be addressed through all mission phases



- Monitor weather & environment
- Address MEPAG Goals 2 to 3
- 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



Small-RPS concept ~12.5-25We (based on 5% to 10% conversion efficiency)

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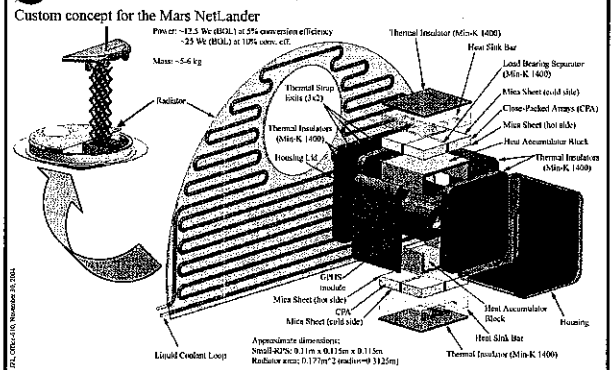
Small-RPS Concept for the NetLander

Custom concept for the Mars NetLander



Note: this small-RPS is highly conceptualized; various details and components are not shown, such as the heat straps connecting the RPS to the radiator; the helium vent; the power outlet; bolts; seals; etc.

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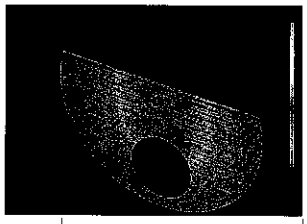
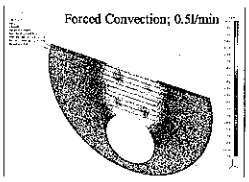
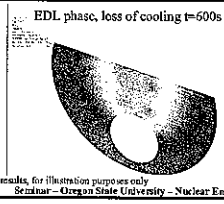
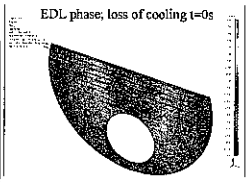
Mars NetLander Small-RPS Thermal Issues









Preliminary results, for illustration purposes only

Thermal analysis by Nick Ende

by Tibor Balint, JPL, Office 416, November 23, 2004

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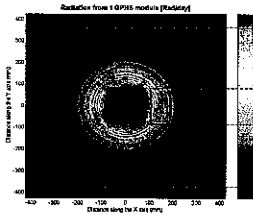
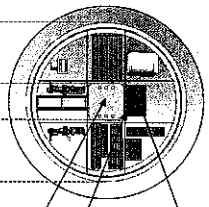
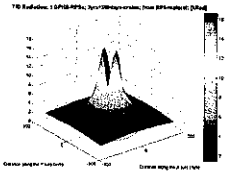
Radiation Environment for the NetLander Concept







by Tibor Balint, JPL, Office 416, November 23, 2004

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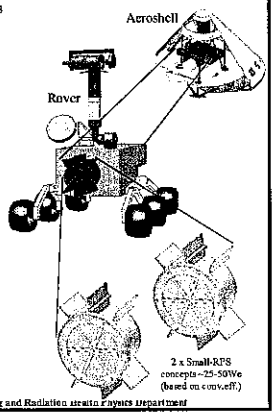
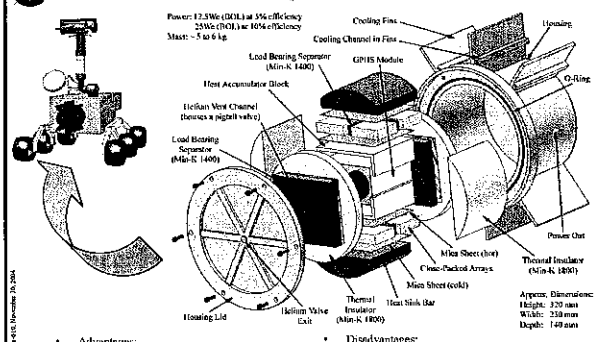
Mars Mission Concept: Small-RPS Powered Rover

- Astrobiology driven goals to address MEPAG Goals 1 to 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

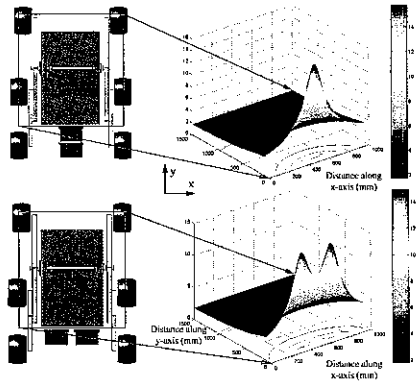


Small-RPS Concept for the Mars Rover



- Advantages:
  - Long mission duration and continuous
  - Works in vacuum and in atmospheres
  - Independent from the Sun (no insolation)
  - Waste heat could be utilized
- Disadvantages:
  - Cost
  - Approvals
  - Low g-load tolerance (to date)

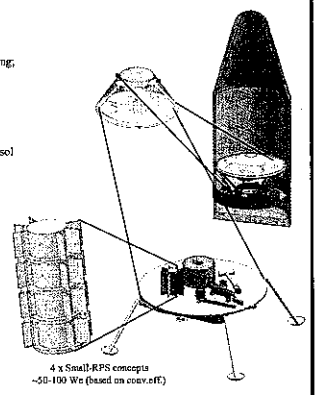
Radiation Environment for the Small Rover Concept



Mars Mission Concept: Deep Drill

- Deep Drill to 10 m or 50 m depth
- Key instruments: sample acquisition and processing; meteorology instrument; Pan Cam
- To address MEPAG Goals 1 to 3
- 10m drill could achieve mission goals with 4 small-RPSs, generating ~50We and ~1240 Wh/sol
- 50m drill would require an MMRTG (~110 We and ~2700 Wh/sol)
- High power requirements by drilling operations and telecom

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

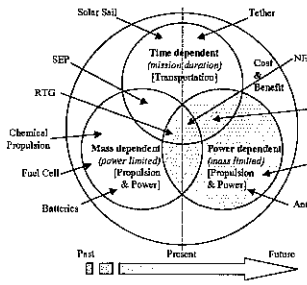


Summary

- An active RPS research and development program is in place by NASA / DoE
- Two systems are under development
  - MMRTG >=110 We BOL
  - SRG >=110 We BOL
  - Offered as early as 2009
- 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 likely to come out this month)
- Radioisotope Power Systems (RPS) could enable 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

Thanks for your attention. Any questions?

Power Generation Paradigm



Fission Power and RTG's to Date

	Power-plant	Type	Mass [kg]	Thermal power [kWt]	Power level [kWe]	Specific power [We/kg]	Lifetime
RTGs	SNAP 27 (Viking lander)	Radioisotope/TE	-	-	0.075	3.7	1 year 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 power system	Radioisotope/Brayton	905	25	6	6.6	Study
Fission Reactors	SNAP 10A (SNAP-10FM, FT)	Fission/TEC	435	46	0.5	1.9 (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	3,500	2,400	100	27.0	Study, 7 years (e)
	SP-100 dynamic	Fission/Brayton	9,500	383	100	10.5	Study
	SP-100 dynamic	Fission/Brayton	14,337	2,667	550	38	Study
	SP-100 dynamic	Fission/Stirling	20,064	2,509	824	41	Study
	Topaz (Cosmos 1818, ~1867)	Fission/TIC	1,200	150	5	4.2	342 days demonstr.
	Topaz II	Fission/TIC	1,060	135	5.5	~5.5	1.5-3 years (e)

73 W
285 W

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

Historical Overview (RPS & Solar)

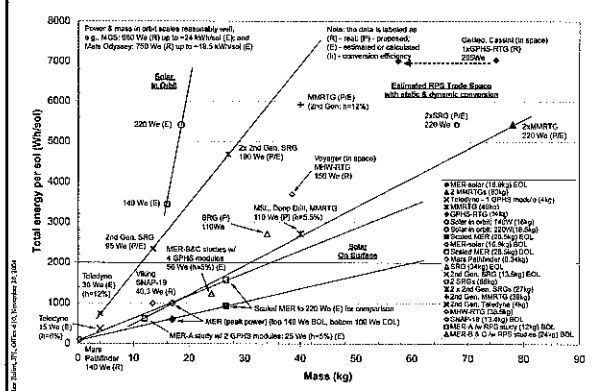
Past RPS:
MHW-RTG
Snap-19
GPHS-RTG

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

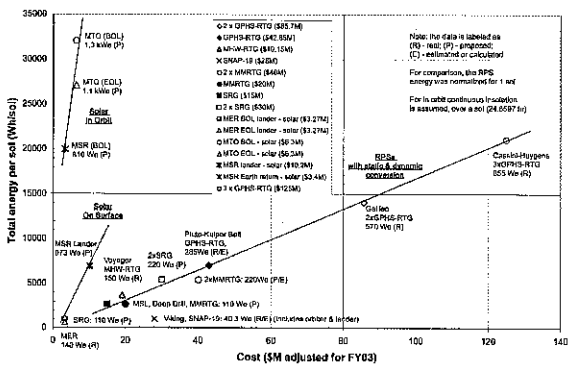
Solar panels:
GaAs/Ge
GaAs & Si
Triple junction

Mission (or Concept)	Power Source	Mass kg	Power We	Energy Wh/sol	Cost $M FY03
Radioisotope Power Systems					
Cassini-Huygens	3 × GPHS-RTG	2×56	885	21081	125
Galileo	2 × GPHS-RTG	2×56	570	11056	85.7
Pluto/Kuiper Belt	1 × GPHS-RTG	56	285	7028	12.85
Voyager 1 & 2	MHW-RTG	38.5	150	3600	19.15
Viking	SNAP-19	43.1	40.3	991	28
MSL (early variant)	2 × MMRTG	80	220	5425	40
MSL (pre-decisional)	MMRTG	40	110	2713	20
-	SRG-110	31	110	2713	15
-	2 × SRG-110	68	220	5425	30
(2nd Generation, $\eta = 12\%$)	MMRTG	40	200	5018	N/A
(2nd Generation)	SRG	13.5	95	2319	N/A
(Small-RPS, $\eta = 5.7\%$)	1 × GPHS module	6	12.5	310	N/A
(Small-RPS, $\eta = 10\%$)	1 × GPHS module	6	25	620	N/A
(Teledyne, $\eta = 6\%$)	1 × GPHS module	1	15	370	N/A
(Teledyne, $\eta = 12\%$)	1 × GPHS module	4	30	710	N/A
Thermal power only					
Cassini-Huygens	157 × RHU	0.3	47Wt	3872Wt	0.57
Solar powered missions					
MER (BOL)	triple-junction	16.9	140	1000	3.27
MER (EOL)	triple junction	16.9	~100	~600	3.27
Mars Pathfinder	GaAs/Ge	0.34	16.5	93	-
MGS	GaAs & Si	-	980	21196	10.1
Mars Odyssey	GaAs	58	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	6950	10.2
MSR ERV (BOL)	triple junction	23	810	19974	3.1

Power System Mass Summary

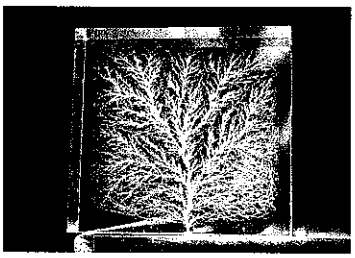


Power System Cost Summary



Radiation Exposure: Material Charging

- In radiation environments, high speed electrons could trap inside the material forming high voltage-potential charged regions
- If grounded, the charge could arc forming a permanently burned conductive path
- Internal charging could result in catastrophic breakdown of materials!



Example: Lucite acrylic, exposed to 4.5 MeV electrons, then shorted at the bottom to a ground point. (by P.B. Willis, JPL)

Radiation Tolerance: Testing vs. Accelerated Testing

Start ← *Testing* → *Result*

100°C for 5 minutes ⇨

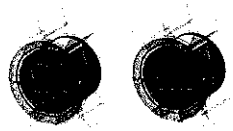
40°C for 1 week ⇨

20°C for 3 weeks ⇨

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!

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 D6" 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

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