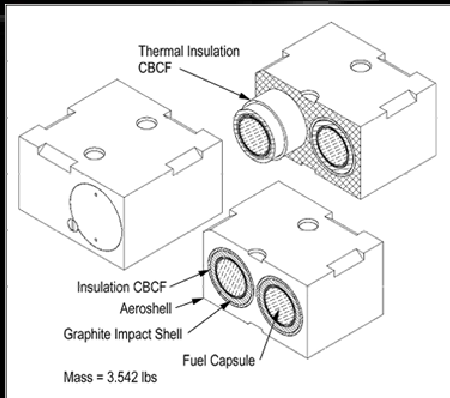




Radioisotope Power System Candidates for Unmanned Exploration Missions



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

- 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 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)

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.

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

- 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 than \$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



Planned, Candidate & In-flight Missions by Decade and Category	Class	2000-2005	2006-2010	2011-2015	2016-2020	2021-2025	2026-2030	2031-2035
Primitive Bodies								
Stardust (1999-2006)	D	Sample Return						
Deep Impact (2005)	D	In-Situ Exploration						
Dawn (2006-2015)	D		Orbiter					
Comet Surface Sample Return	NF			Sample Return				
Asteroid Rover Sample Return	NF				Sample Return			
Trojan/Centaur Recon Flyby	NF				Fly By			
Comet Cryogenic Sample Return	F					Sample Return		
Rosetta (ESA)			Orbiter					
BepiColombo (ESA/JAXA) (to Mercury)				Orbiter				

Earliest Flight Opportunities	2000-2005	2006-2010	2011-2015	2016-2020	2021-2025	2026-2030	2031-2035
		A-1	A-2	A-3	B-1	F-2	F-3
			F-1		I-1		

LEGEND

Class: NF - New Frontiers, D - Discovery, I - Intermediate, F - Flagship

- Fly By
- Orbiter
- In-Situ Exploration
- Sample Return

RPS Candidates for Unmanned Exploration Missions



Potential Mission Candidates: Giant Planets / Outer Planets



Planned, Candidate & In-flight Missions by Decade and Category	Class	2000-2005	2006-2010	2011-2015	2016-2020	2021-2025	2026-2030	2031-2035
Giant Planets/Outer Planets								
Galileo (with probe) (1989-2003)		Orbiter						
Cassini-Huygens (Saturn/Titan)('97-'08+6))		Orbiter	Orbiter	Orbiter				
Pluto-Kuiper Belt Explorer (New Horizons)	NF		Fly By	Fly By				
Jupiter Orbiter (JUNO)	NF			Orbiter				
Jupiter Flyby with Probes	NF					Fly By		
Neptune Flyby	NF					Fly By		
Uranus Flyby	NF					Fly By		
Neptune Flyby with Probes	I					Fly By	In-Situ Exploration	
Uranus Flyby with Probes	I					Fly By	In-Situ Exploration	
Saturn Flyby with Probes	I					Fly By	In-Situ Exploration	
Neptune Triton Orbital Tour	I					Orbiter		
Neptune Orbiter with Probes	F						Orbiter	In-Situ Exploration
Neptune Orbiter/Triton Explorer	F						Orbiter	In-Situ Exploration
Uranus Orbiter with Probes	F						Orbiter	In-Situ Exploration
Saturn Ring Observer	F						Orbiter	
Earliest Flight Opportunities			A-1	A-2	A-3	B-1	F-2	F-3
LEGEND								
		Class: NF - New Frontiers, D - Discovery, I - Intermediate, F - Flagship						
		Fly By						
		Orbiter						
		In-Situ Exploration						
		Sample Return						

RPS Candidates for Unmanned Exploration Missions

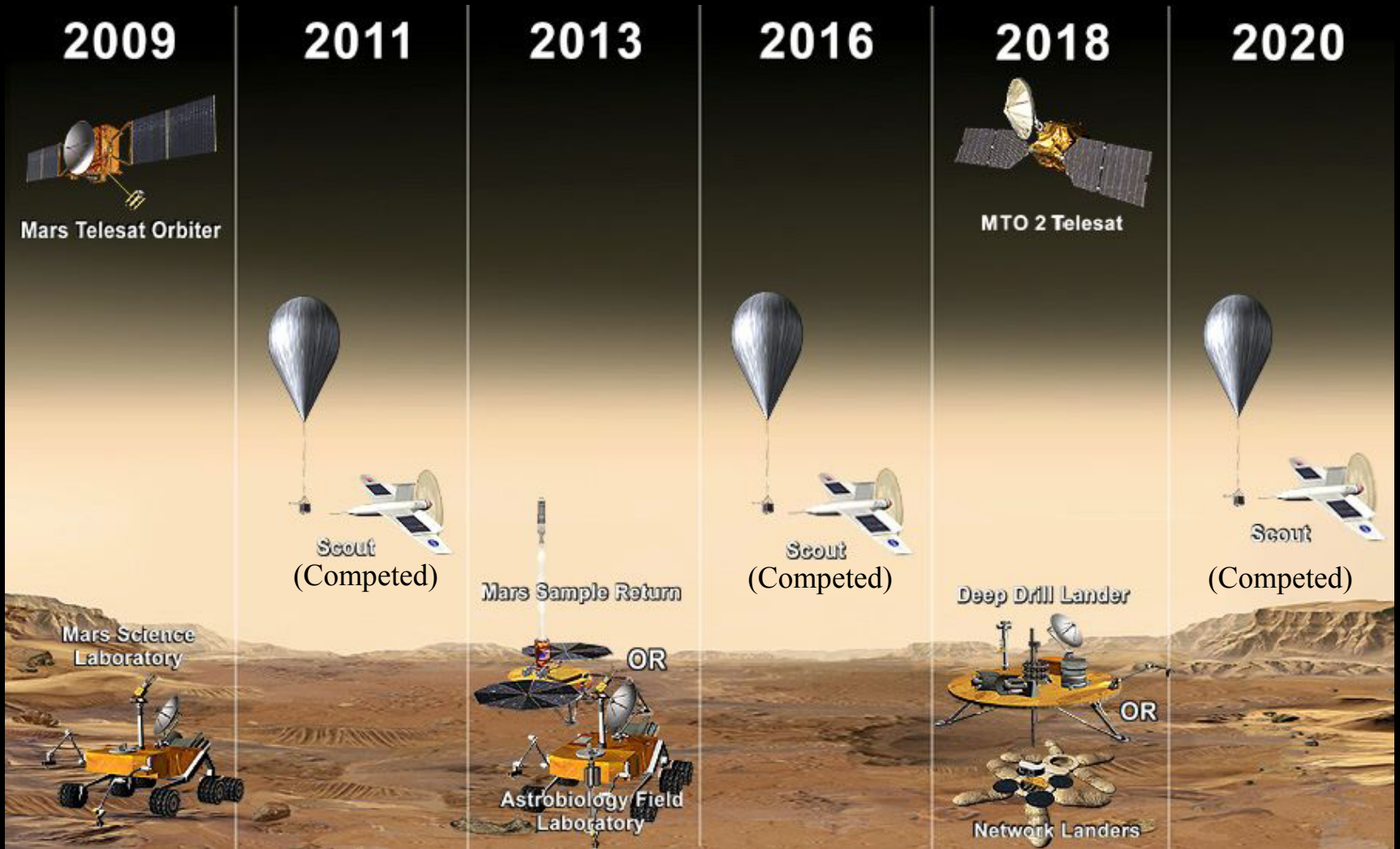


Potential Mission Candidates: Large Moons

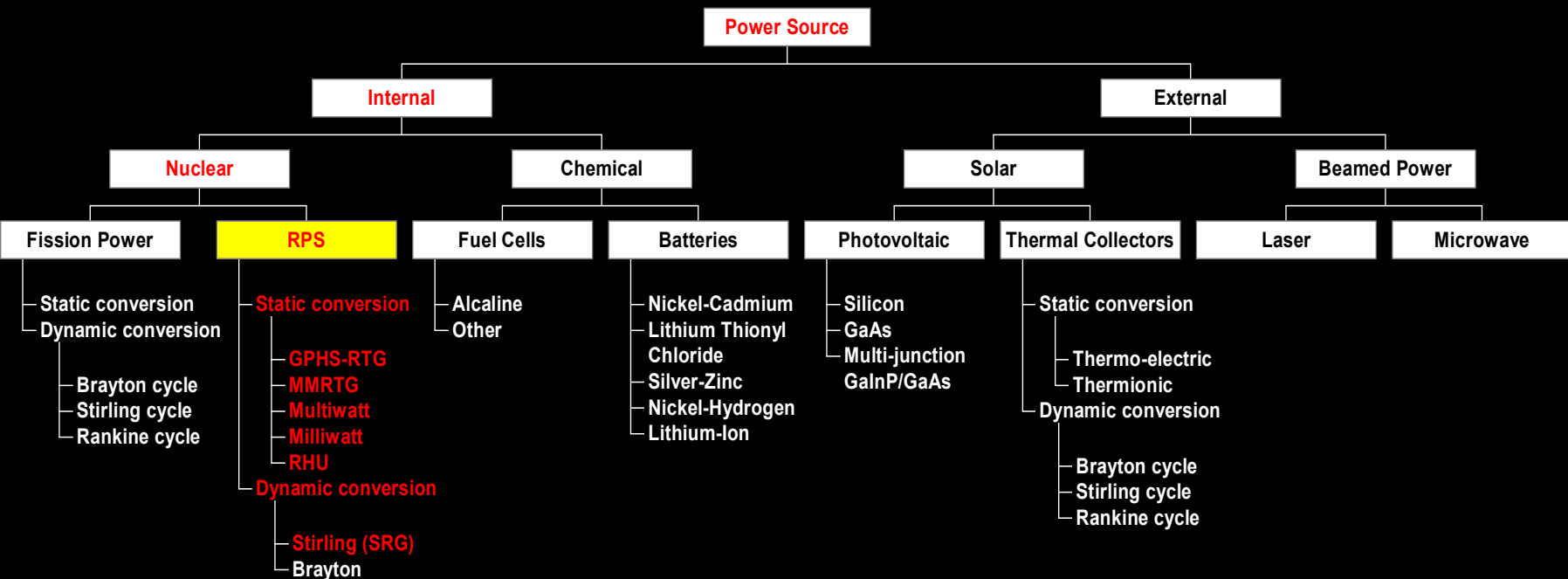


Planned, Candidate & In-flight Missions by Decade and Category	Class	2000-2005	2006-2010	2011-2015	2016-2020	2021-2025	2026-2030	2031-2035
Large Moons								
Io Observer	NF					Orbiter		
Ganymede Observer	NF					Orbiter		
Europa Geophysical Observer	F			Orbiter				
Jupiter Icy Moons Orbiter (JIMO)	F			Orbiter	Orbiter	Orbiter		
Europa (Astrobiology) Lander	F					In-Situ Exploration	In-Situ Exploration	In-Situ Exploration
Titan Explorer (no Orbiter)	I					In-Situ Exploration	In-Situ Exploration	
Titan Explorer (with Titan Orbiter)	F					Orbiter	Orbiter	
Earliest Flight Opportunities			A-1	A-2	A-3	B-1	F-2	F-3
				F-1		I-1		
LEGEND								
Class: NF - New Frontiers, D - Discovery, I - Intermediate, F - Flagship								
	Fly By							
	Orbiter							
	In-Situ Exploration							
	Sample Return							

RPS Candidates for Unmanned Exploration Missions



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



- 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

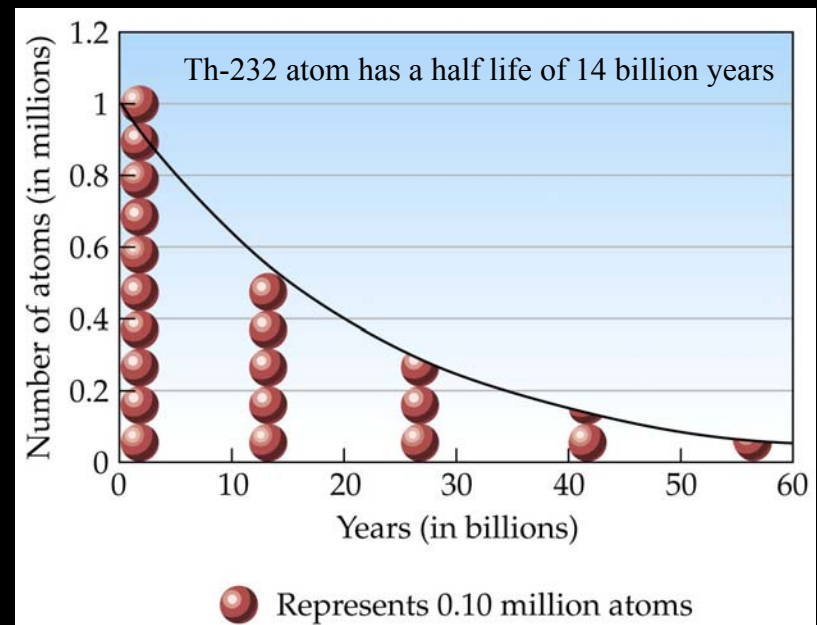
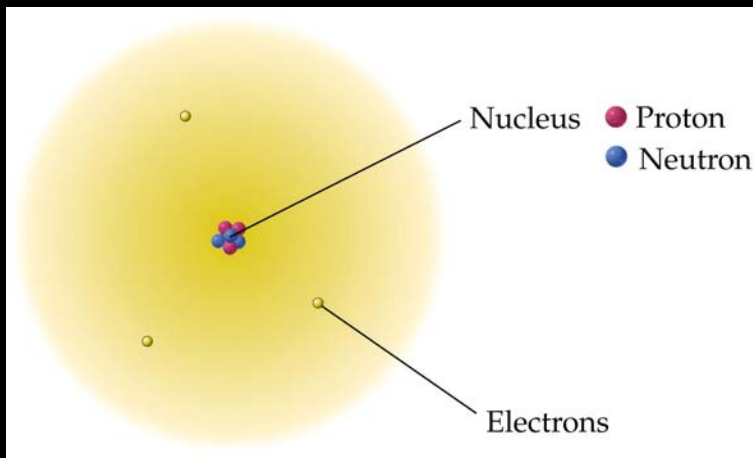
- short life measured in hours
 - E.g., to Venus, Jupiter, Titan
 - Would require batteries

- **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!

- 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.



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

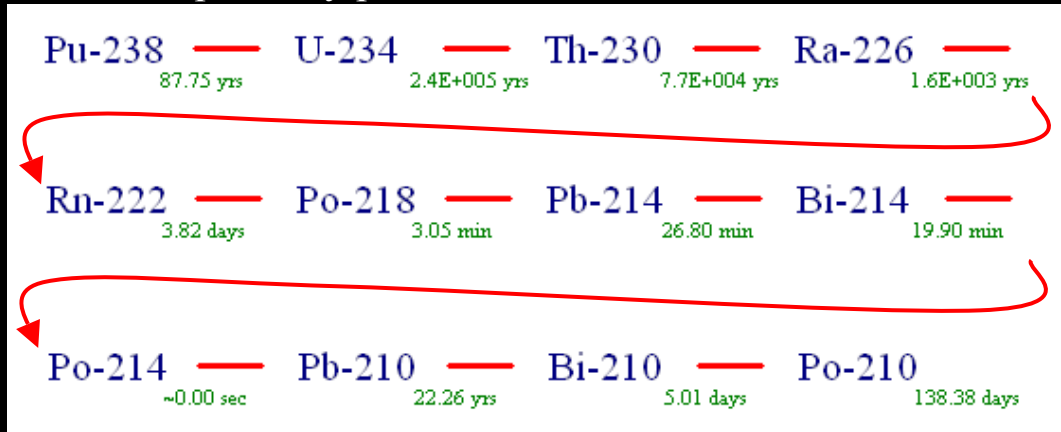
- | | Half life |
|---|------------------|
| • Curium-242 (Cm^{242}) | 162.8 days |
| • Polonium-210 (Po^{210}) | 138.4 days |
| • Curium-244 (Cm^{244}) | 18.1 year |
| • Plutonium-238 (Pu^{238}) | 87.7 year |
| • Promethium-147 (Pm^{147}) | 2.6 year |
| • Strontium-90 (Sr^{90}) | 28.78 year |



Note: Space applications only used Pu^{238}

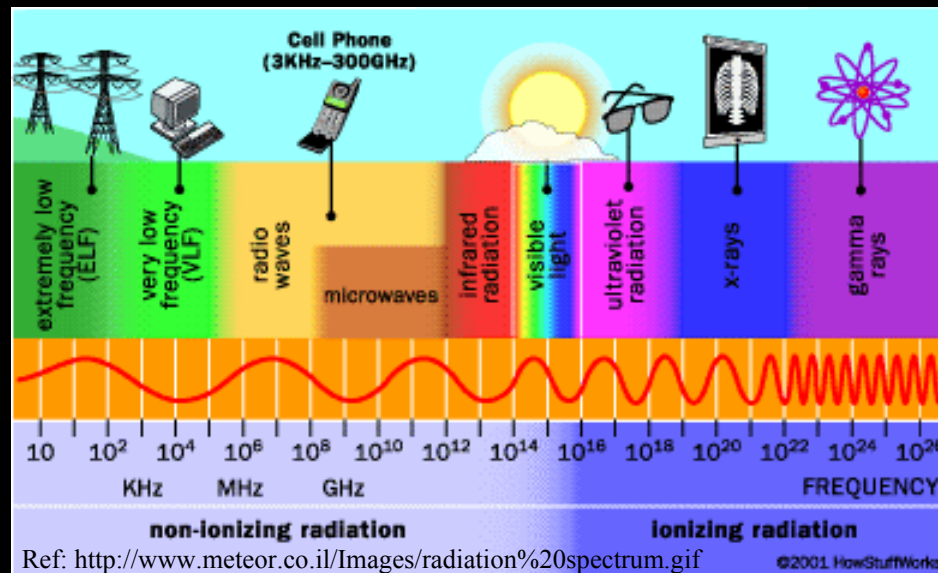


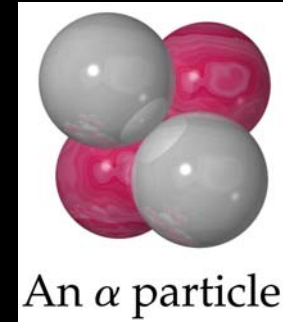
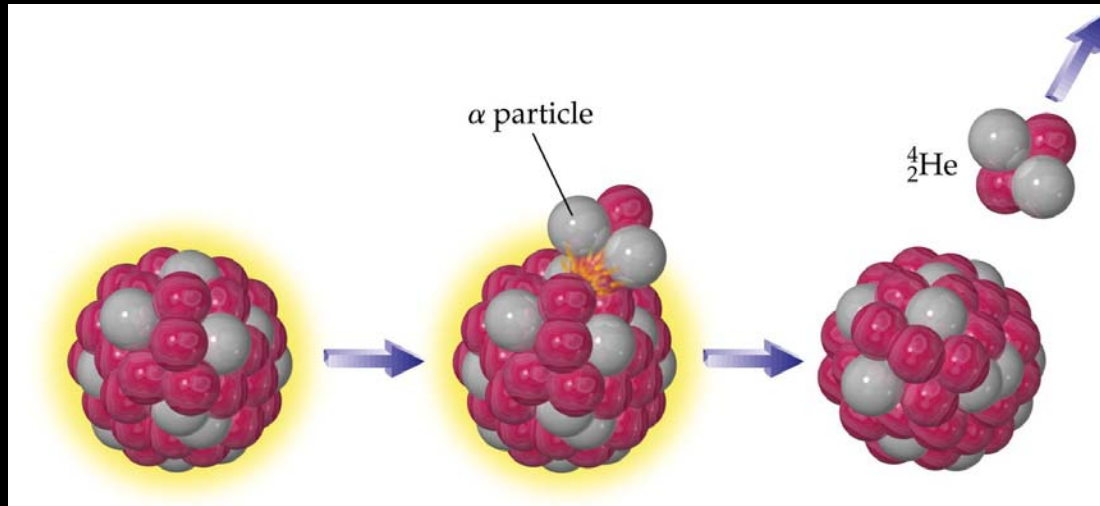
Radioisotope decay process of Pu^{238}



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

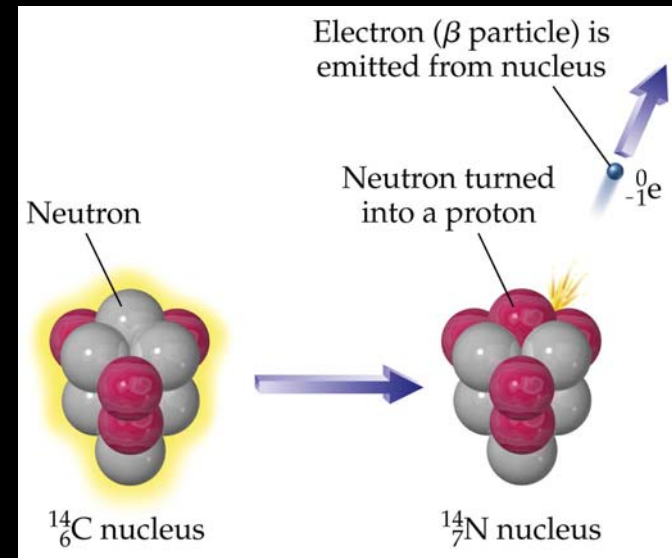
- **Non-Ionizing Radiation** (low energy)
radio frequency, microwave, infrared, visible, (lower frequency ultraviolet)
- **Ionizing Radiation** (high energy – damages DNA):
e.g., (higher frequency UV), X-ray, gamma ray;
Emitted by stars in the form of cosmic rays and by radioactive materials



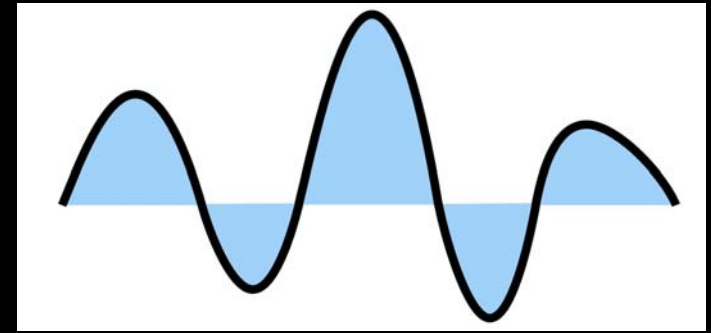


- A particle of two protons & two neutrons (i.e., **Helium nucleus**) is ejected from a usually heavy radioactive atom (e.g., Plutonium)
- (this results in the forming of a new parent atom with two less electrons and two less protons)
- Heavy, energetic and slow moving α -particle
- Can be blocked with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

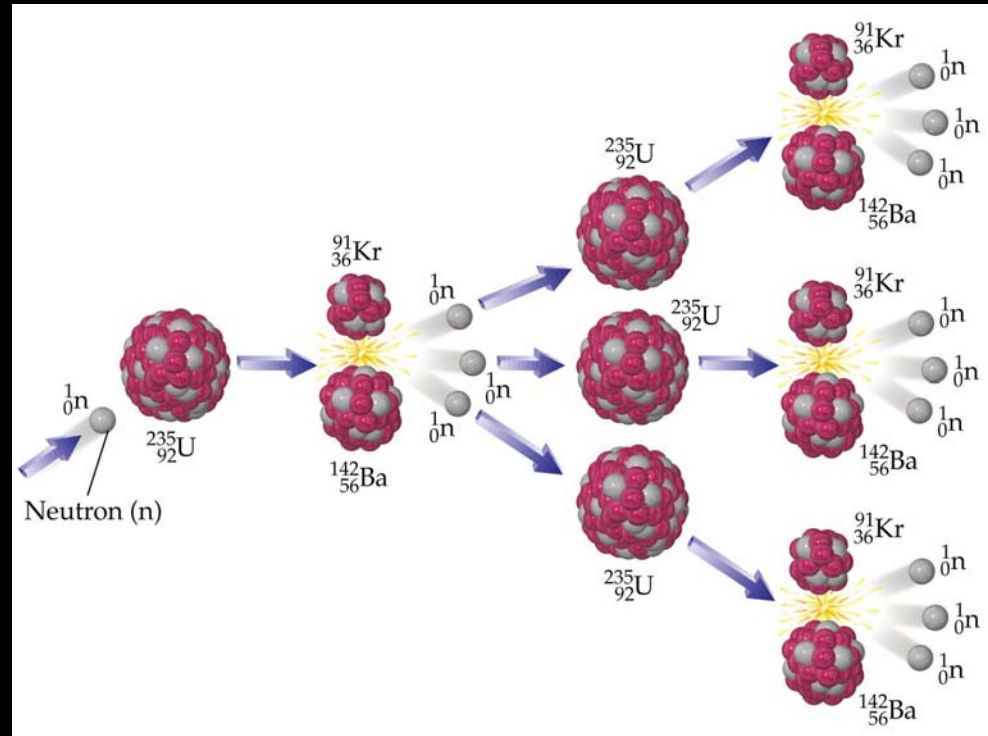
- From the nucleus of a radioactive atom an electron & an antineutrino are emitted
- Since the electron is from the nucleus, it is called β -particle to distinguish from the electrons orbiting the nucleus of the atom
- When the β -particle is ejected, one of the neutrons in the nucleus is transformed 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 than α -particles
- No particular shielding is required to guard against them



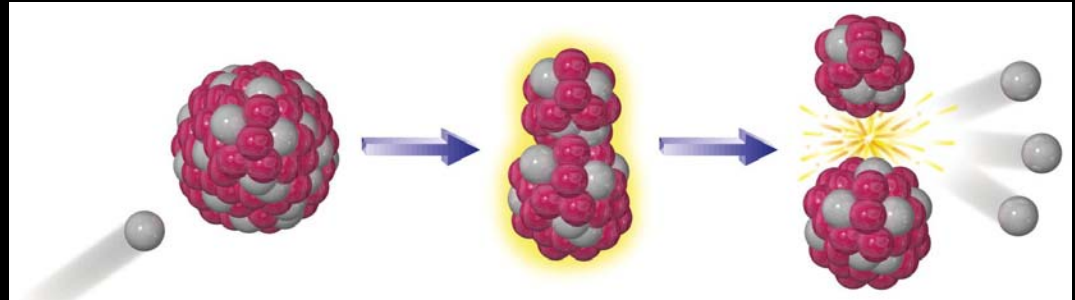
- Following a radioactive decay reaction the nucleus of the atom is still in an excited state with excess energy to emit
- This energy is then emitted in a **pulse of electromagnetic radiation** called γ -ray
- It has **no mass** and **no charge** and is a high energy short wavelength radiation
- High 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)



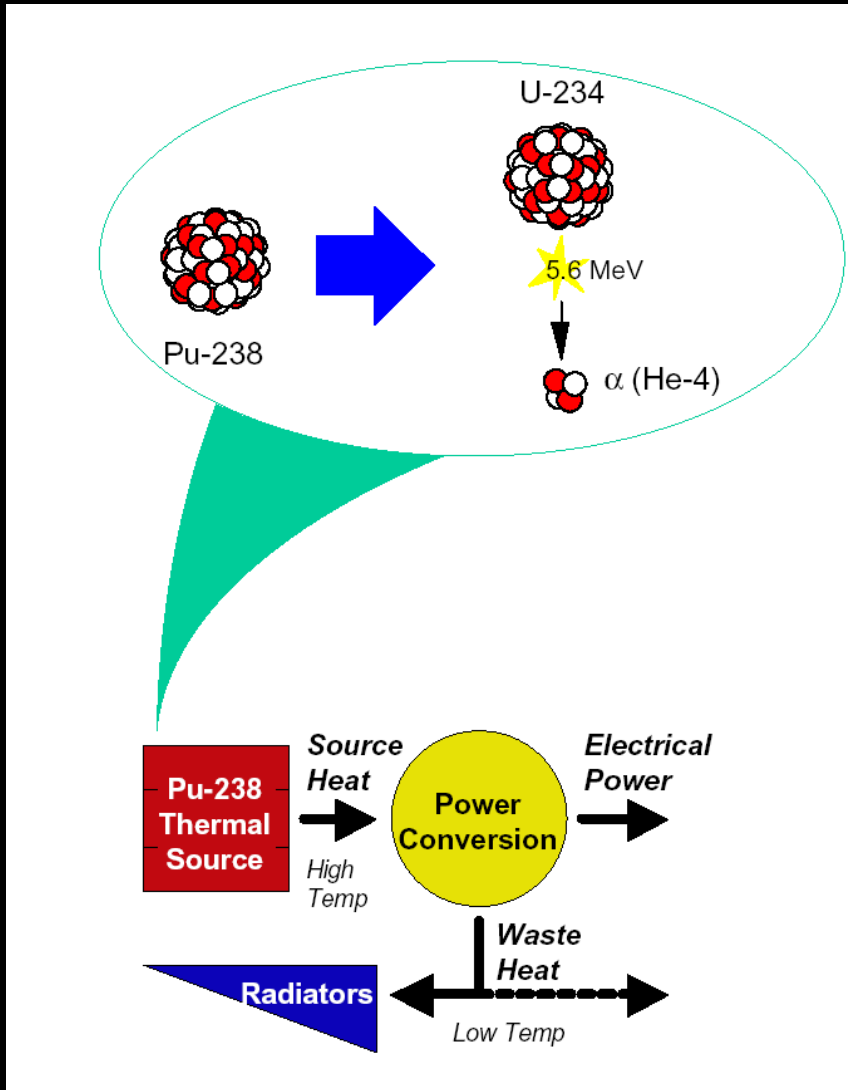
- Neutron collides with the nucleus of Uranium-235
- Nucleus splits, resulting in fission products such as two smaller nuclides and three free neutrons
- Each split (or fission) releases a large amount of energy
- Under favorable conditions the three new free neutrons could split other atoms
- A maintained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



- 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

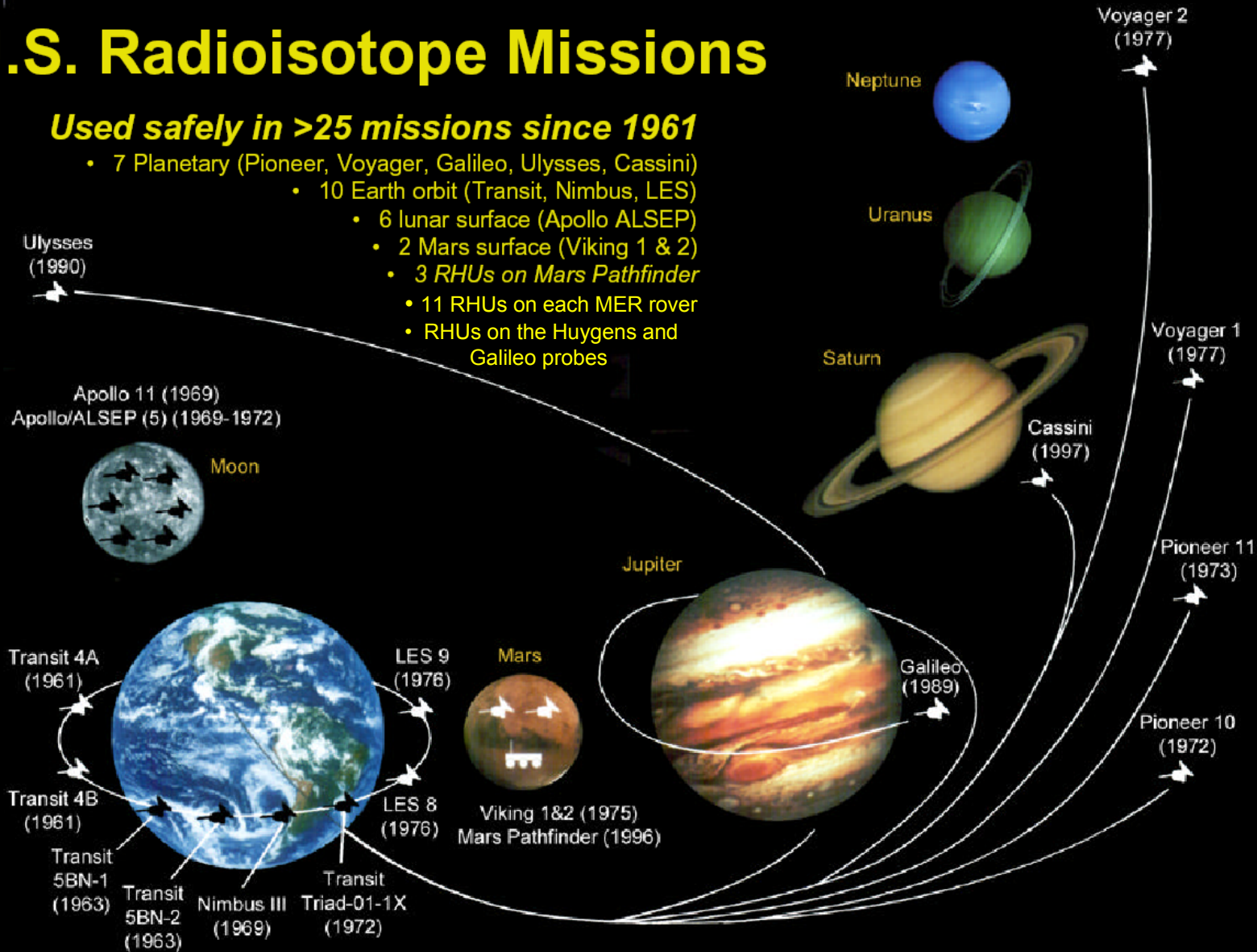


- The **Plutonium-238** fuel used in RPSs is a **radioisotope** with a half life of ~ 87.7 years
- It produces heat through natural alpha (α) **particle decay** (an α -particle is virtually a He nucleus)
- A small portion of the **heat** is converted **to electricity** using various conversion technologies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

U.S. Radioisotope Missions

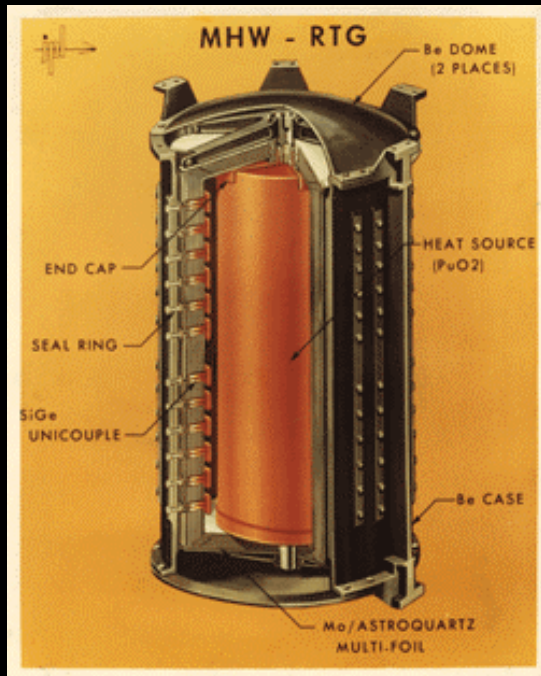
Used safely in >25 missions since 1961

- 7 Planetary (Pioneer, Voyager, Galileo, Ulysses, Cassini)
- 10 Earth orbit (Transit, Nimbus, LES)
- 6 lunar surface (Apollo ALSEP)
- 2 Mars surface (Viking 1 & 2)
- 3 RHUs on Mars Pathfinder
- 11 RHUs on each MER rover
- RHUs on the Huygens and Galileo probes

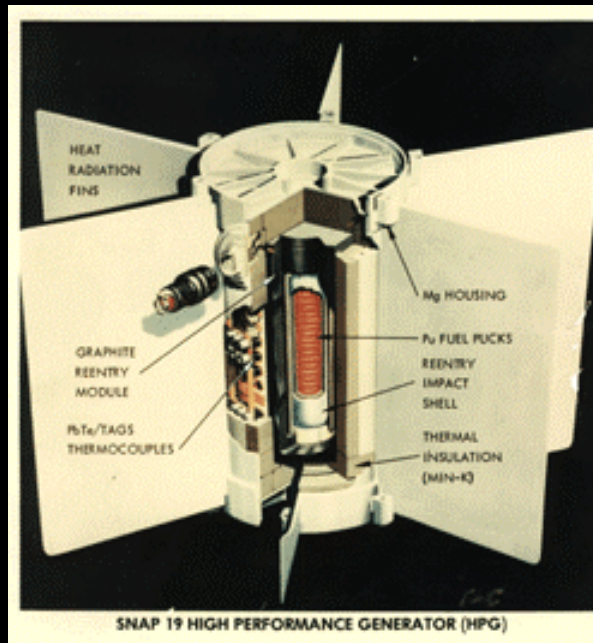


RPS Candidates for Unmanned Exploration Missions

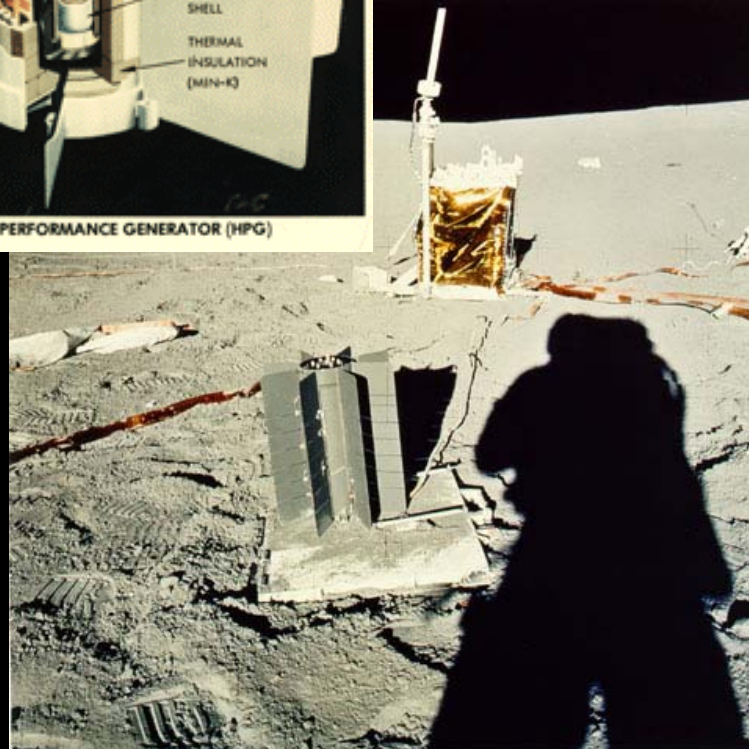
Distances & Planets Are Not to Scale



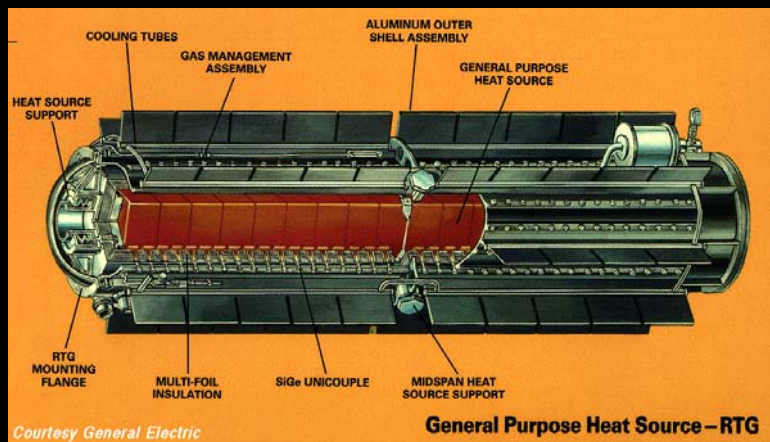
Voyager mission (in-space – vacuum), MHW-RTG (~150 We) (still providing power after 27 years)



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



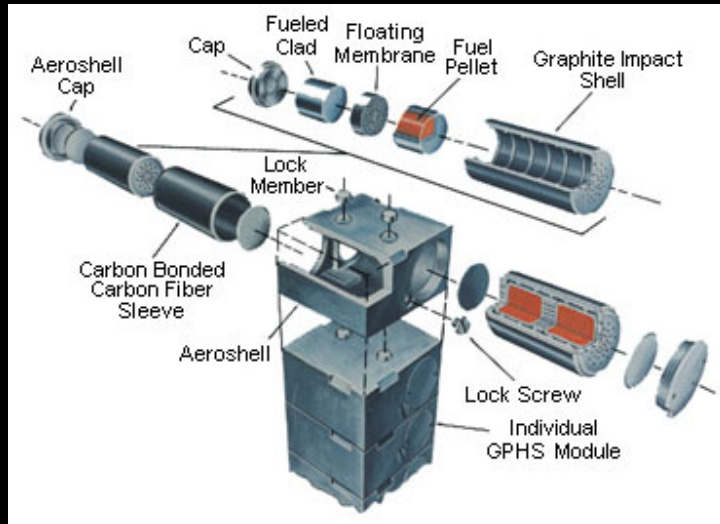
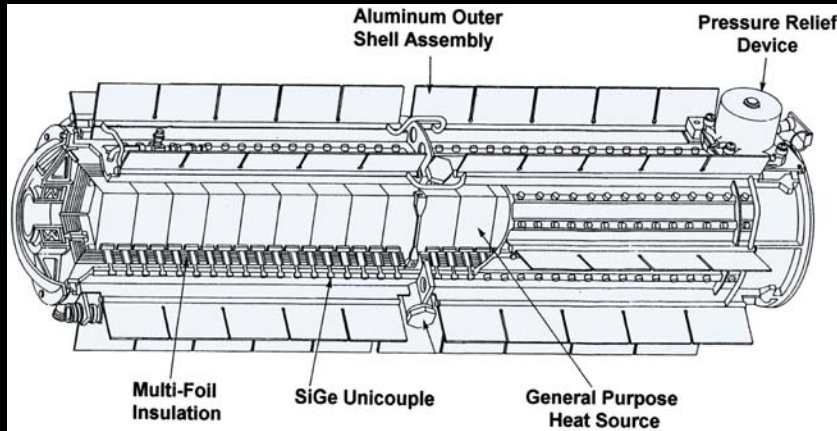
Apollo 12/14/15/16/17 missions (Moon – vacuum) SNAP-27 for ALSEP (Apollo Surface Experiments Package) (~70W) (still operated after 10 years on the Moon)



Courtesy General Electric

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

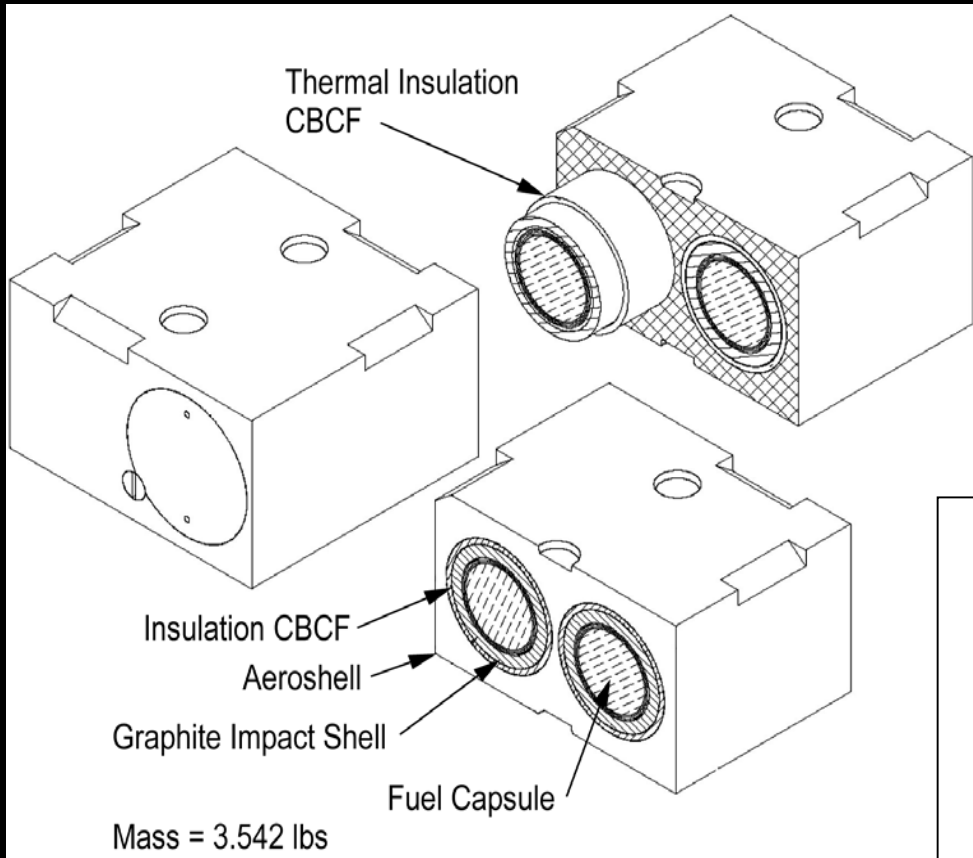
General Purpose Heat Source – Radioisotope Thermoelectric Generator (GPHS-RTG)



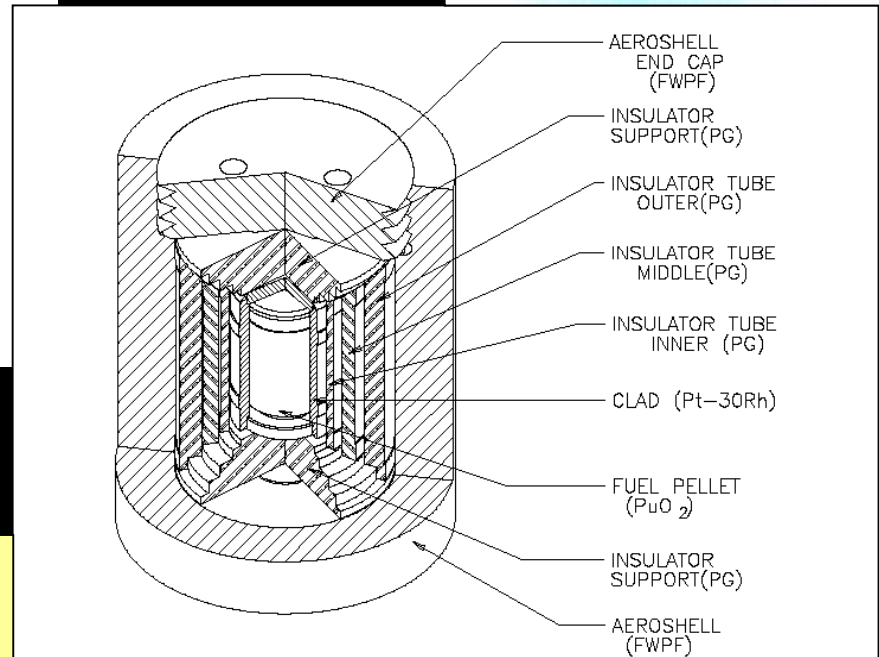
GPHS module stack

- 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)



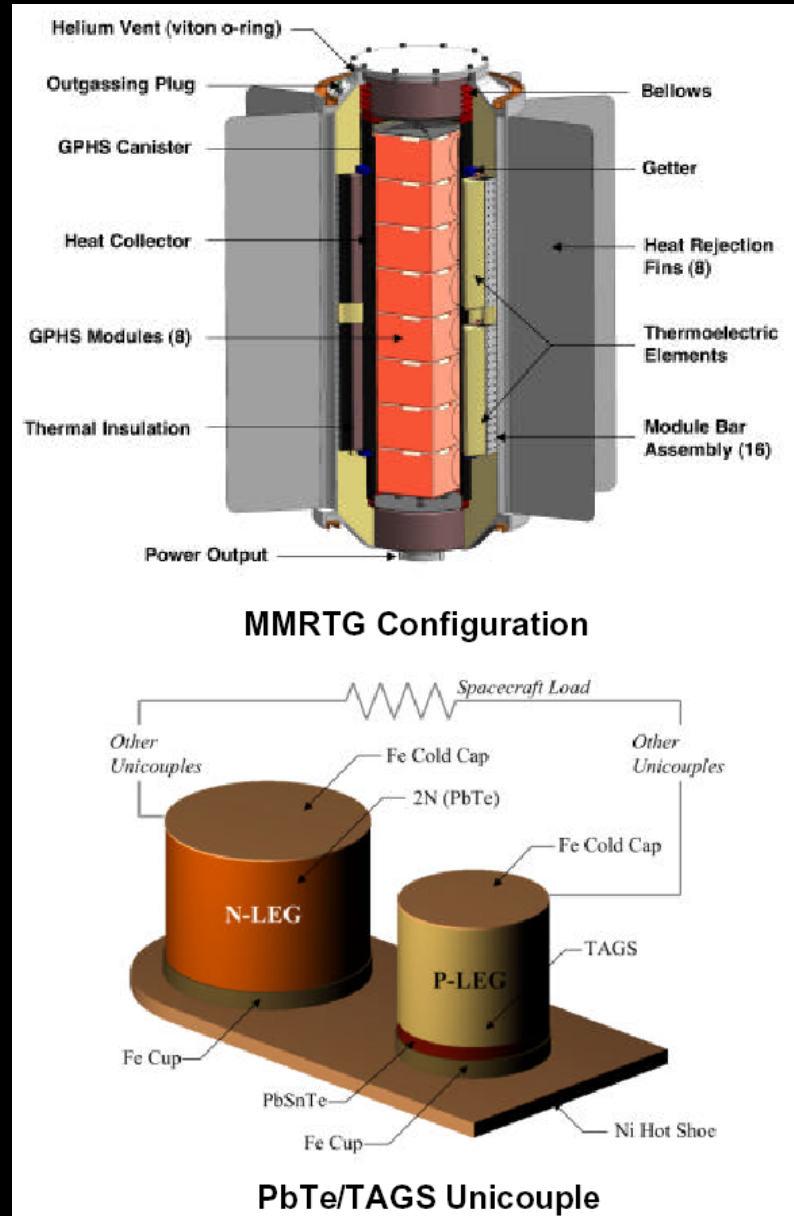
General Purpose Heat Source (GPHS) Module
[250 Wt BOL]; ~1.4kg



We have these at TRL 9

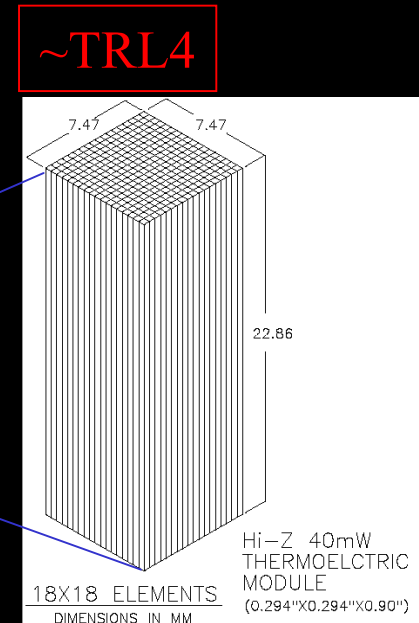
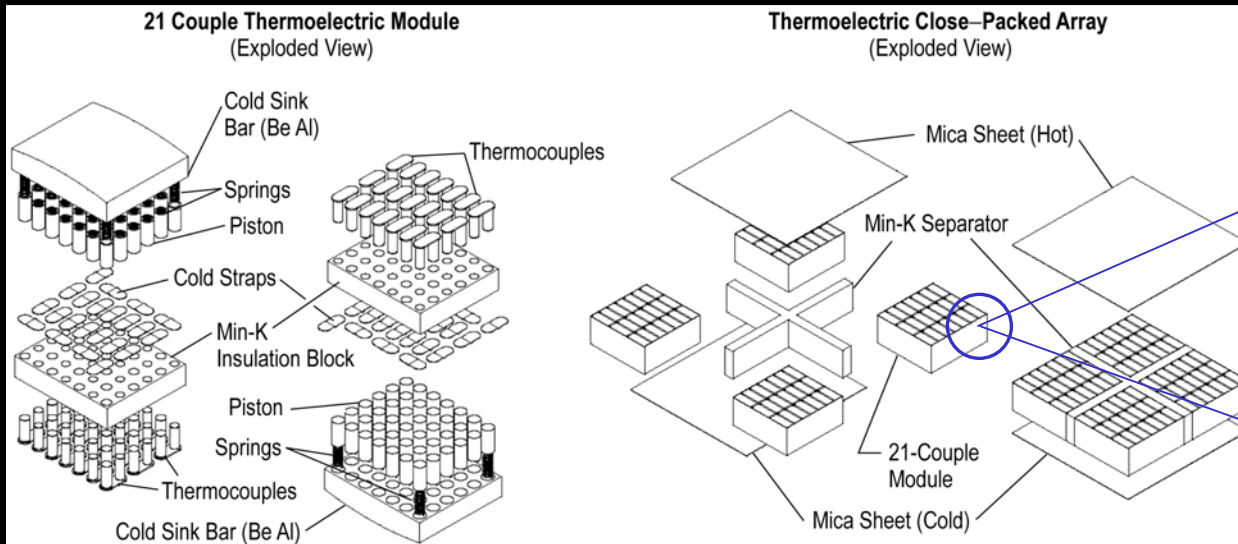
Radioisotope Heater Unit (RHU)
[1 Wt BOL]; ~40grams

- 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)
- Pu²³⁸ ~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



TAGS: Tellurides of Antimony, Germanium, Silver

MMRTG: Multi-Mission Radioisotope Thermoelectric Generator



- 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 $\eta \sim 13\%$
 - 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)

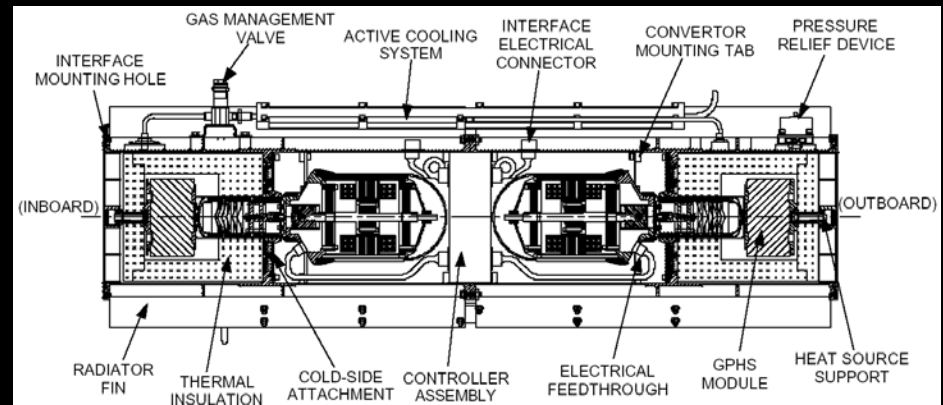
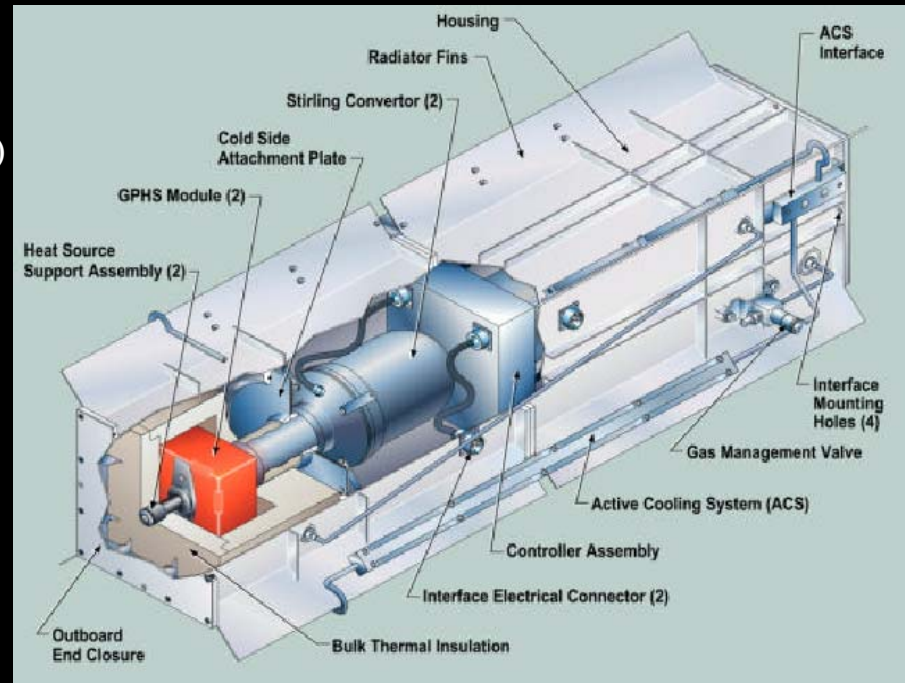
- 2 GPHS modules
- 2 Stirling converters ($\eta \sim 20.7\text{-}23.3\%$)
- Dimensions: 29 cm (W) x 38 cm (H) x 104 cm (L)
- Mass: 34 kg (CBE); $\text{Pu}^{238} \sim 1\text{kg}$
- Power: $\sim 116\text{W}$ (electric) (BOL);
 $\sim 500\text{W}$ (thermal) from 2 x GPHS (BOL)
- Specific Power: $\sim 3.4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

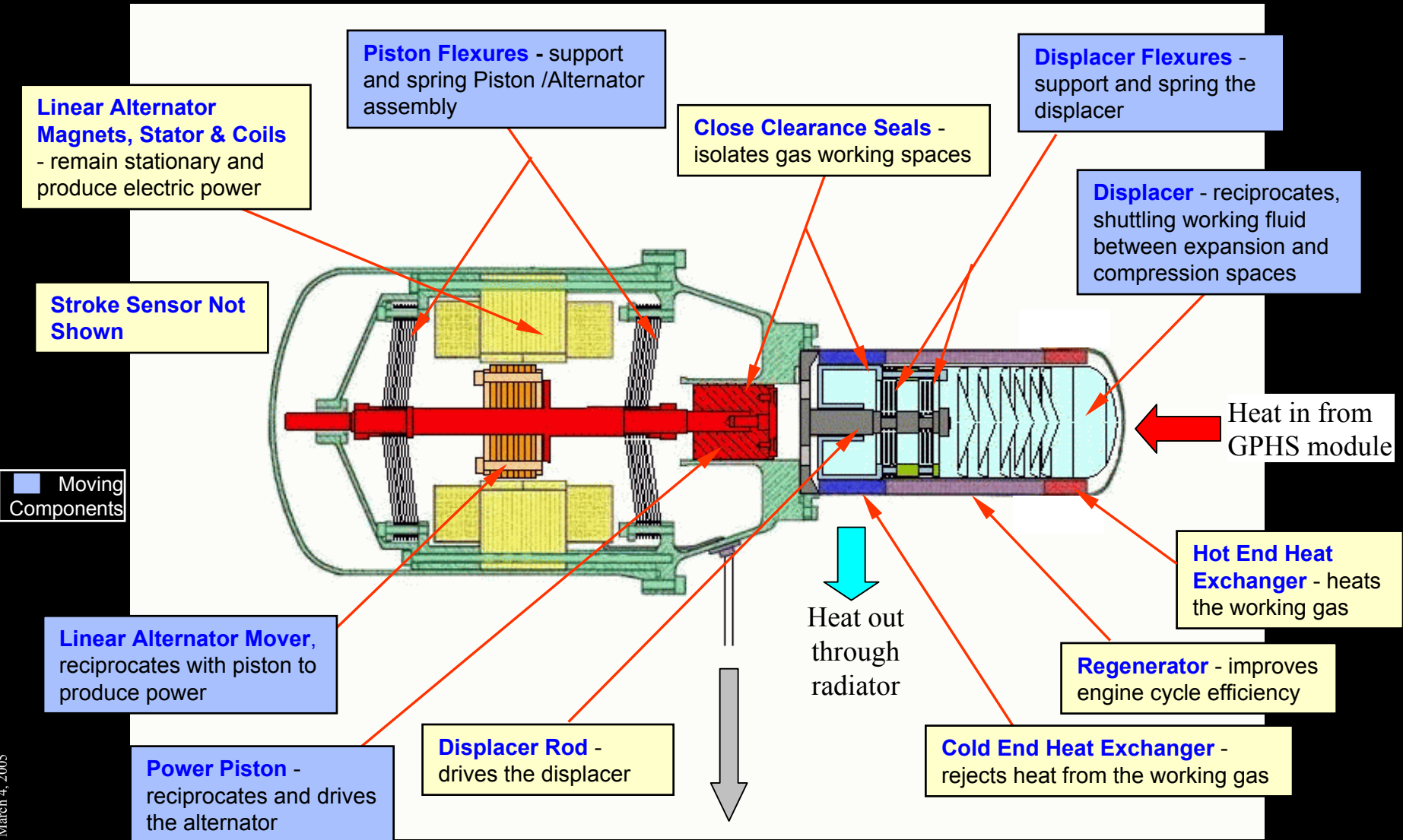
Availability:

- 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)





Key Stirling Converter Components and Functions

Dynamic conversion

e.g., Stirling shown here; has high power conversion efficiency (~20-25%)

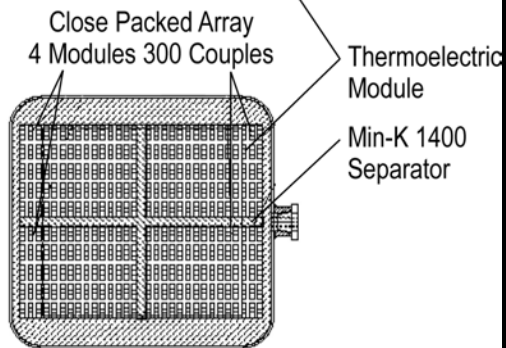
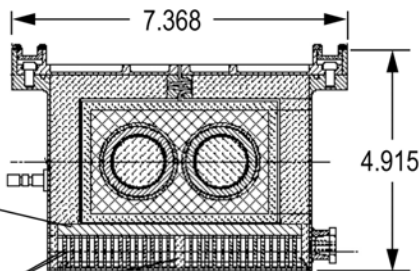
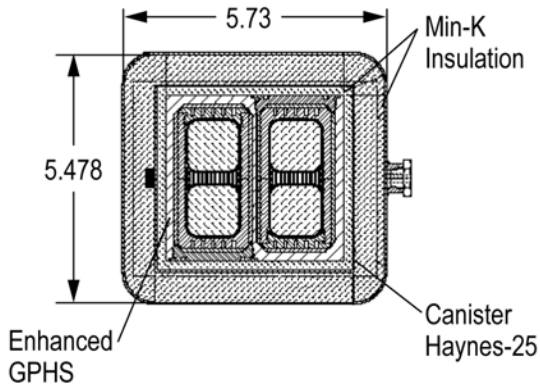
- Closed cycle
- Reversible thermodynamic processes
- Isothermal compression and expansion
- Constant volume displacement

DoE/OSC Study (2003)

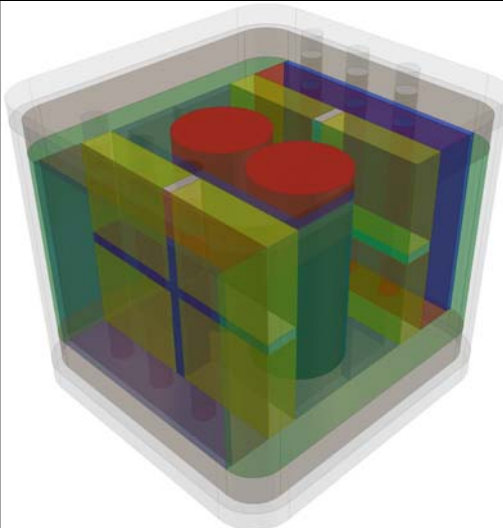
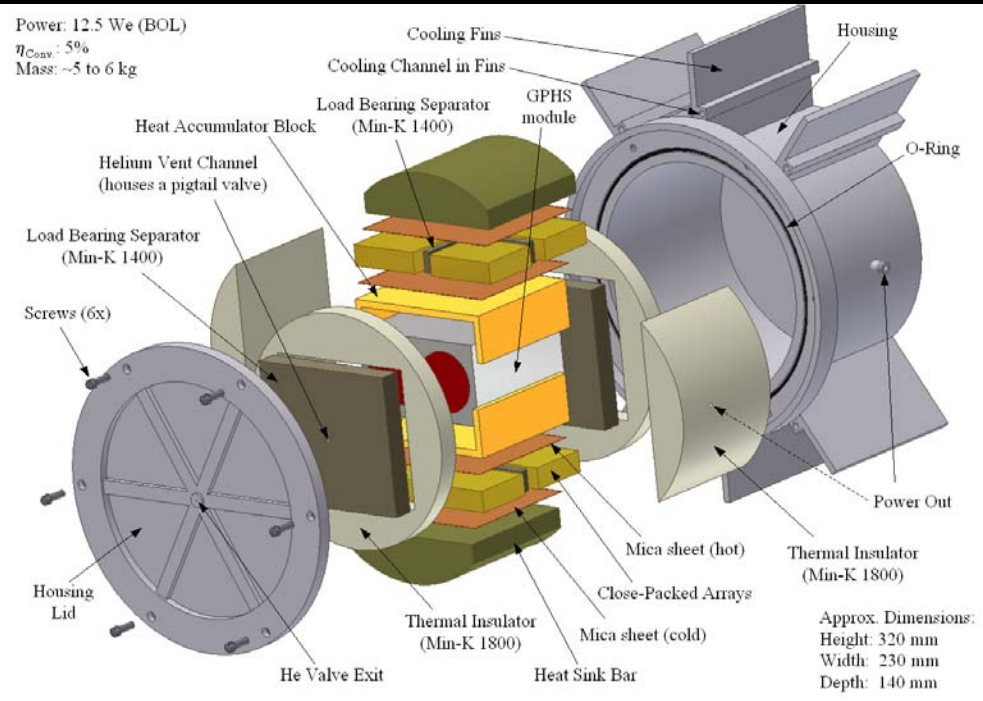
~TRL2

Power: 12.5 We (BOL)
 η_{conv} : 5%
 Mass: ~5 to 6 kg

Min-K Insulated Aeroshell
 (External Insulation)



Dimension in inches



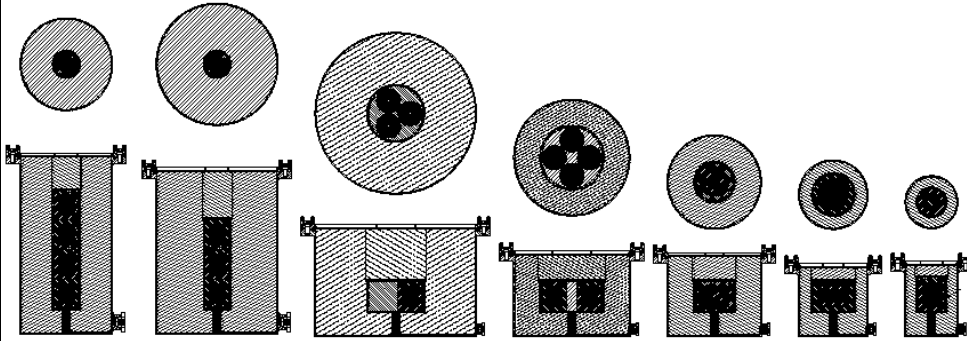
JPL Study (2004)
 [MER-A; -B; -C]

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

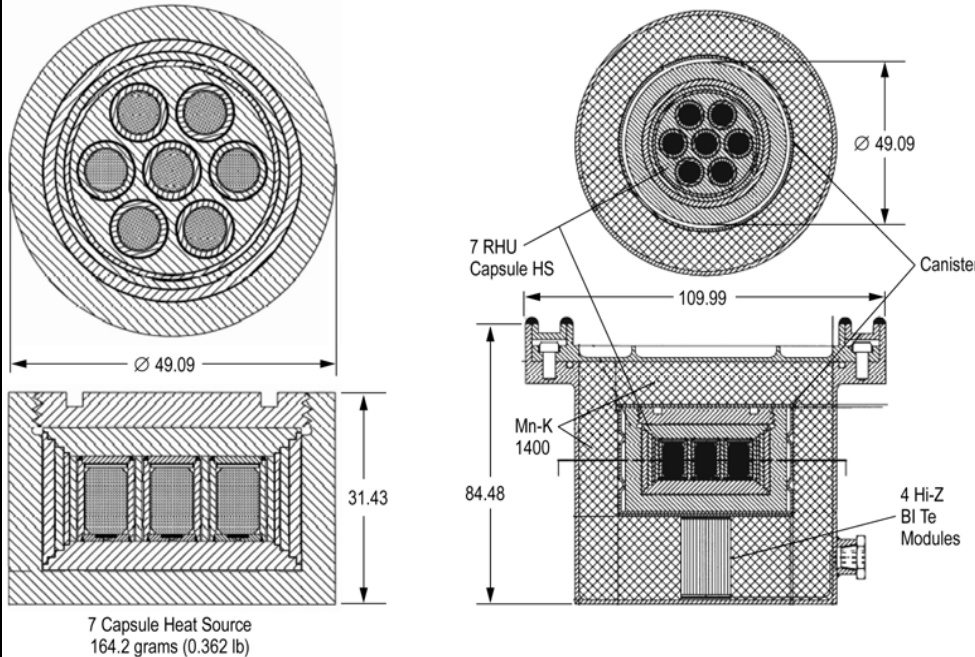
JPL Study (2004)
 [Mars Net Lander]

RPS Candidates for Unmanned Exploration Missions

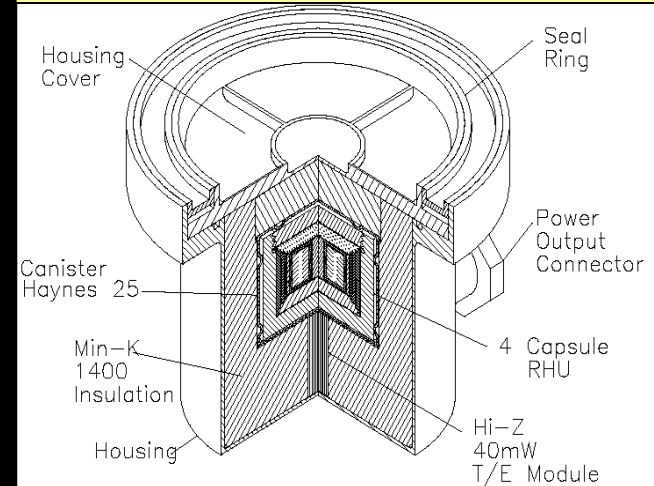
DoE/OSC Study (2003) [7 concepts; ~40mWe each]



Hi-Z [2 concepts ~160mWe each]



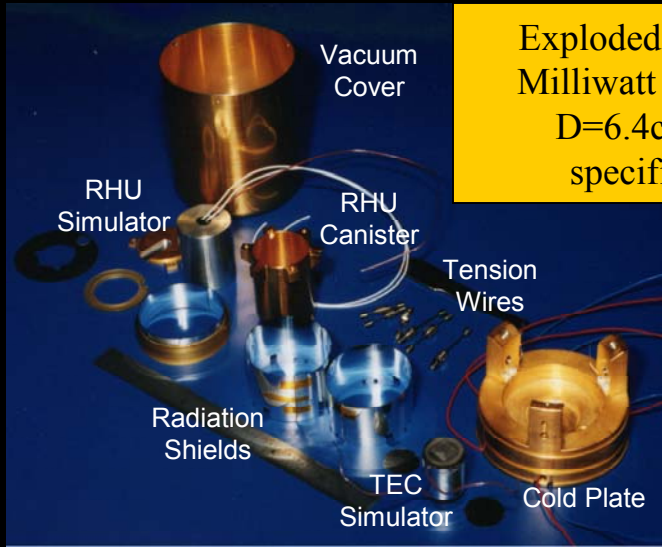
DoE/OSC Study (2003) [~40mWe]



RHUs in redesigned
Aeroshells

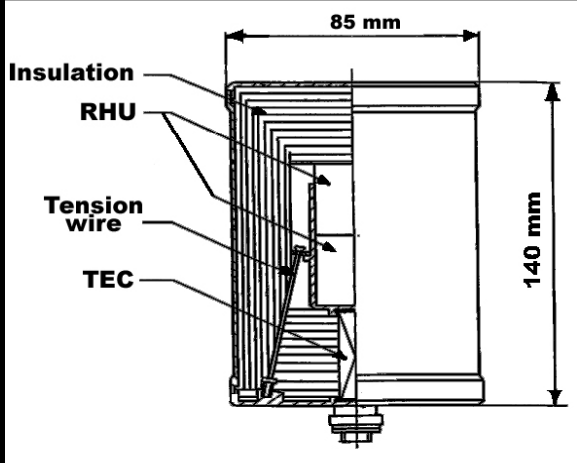
~TRL2

Potential
power range:
~40 to 160 mWe



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

**Potential
 power range:
 ~20 to 40 mWe**

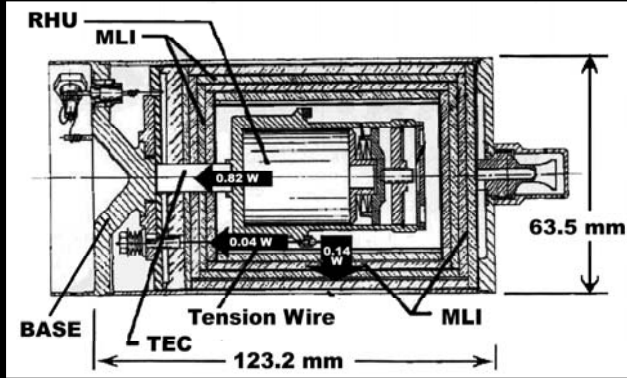


BIAPOS concept [2 RHUs70mWe]
 Built and tested in **Russia**; 2 RHUs;
 $D=8.5\text{cm}/L=13\text{cm}$; 0.37kg ; specific
 power: 0.189We/kg (also 1 RHU)

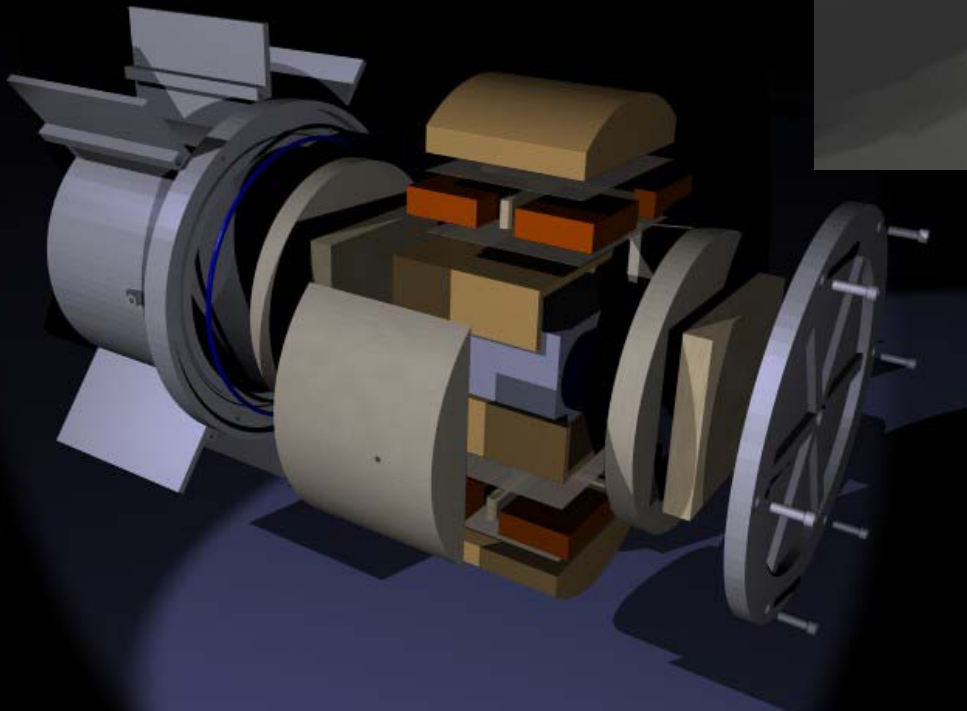
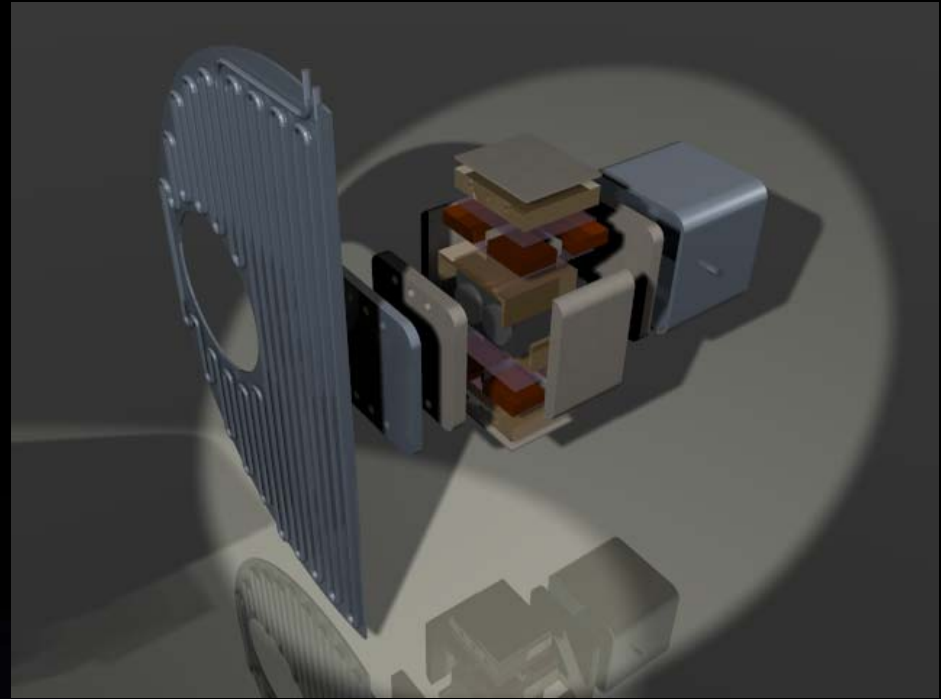
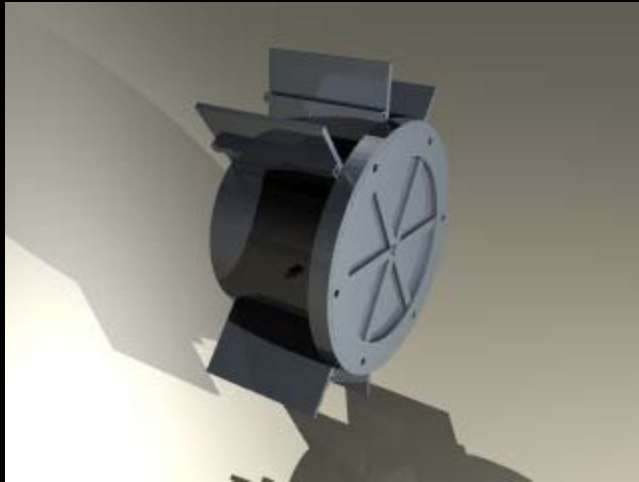
~TRL4



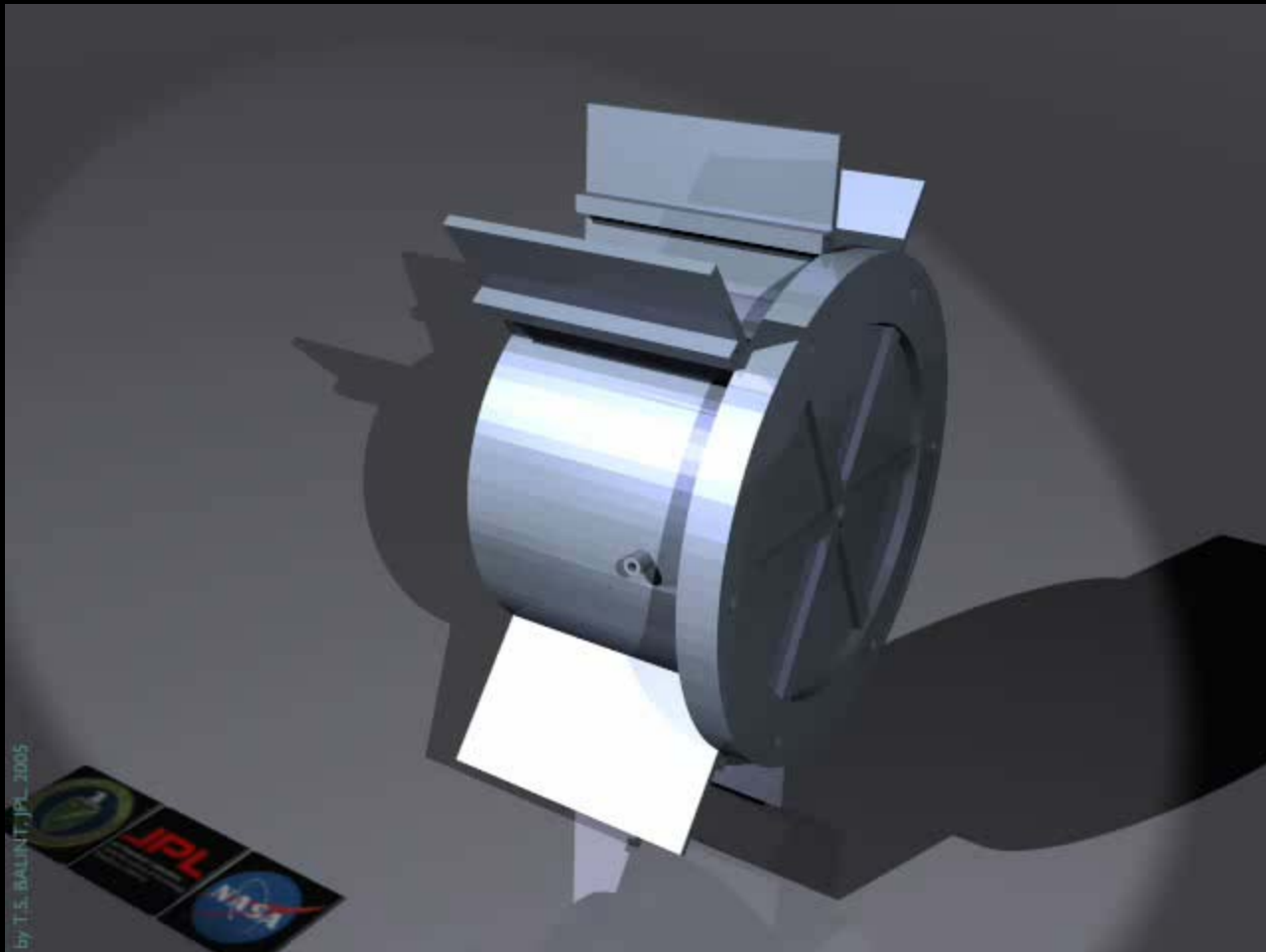
NASA ARC Milliwatt RPS concept;
 40 mWe; with higher g-load tolerance;
 $m=0.121\text{kg}$; spec.pwr: 0.33We/kg



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



- 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

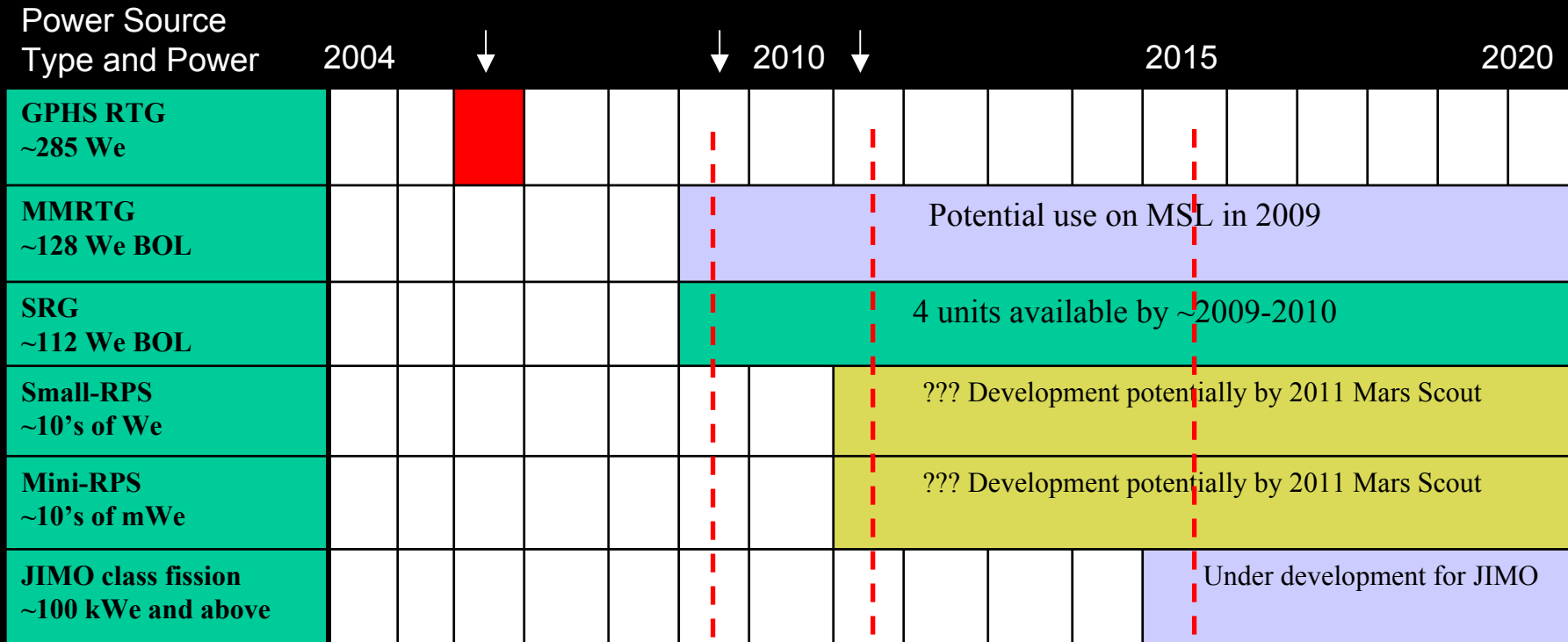


(animation)

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



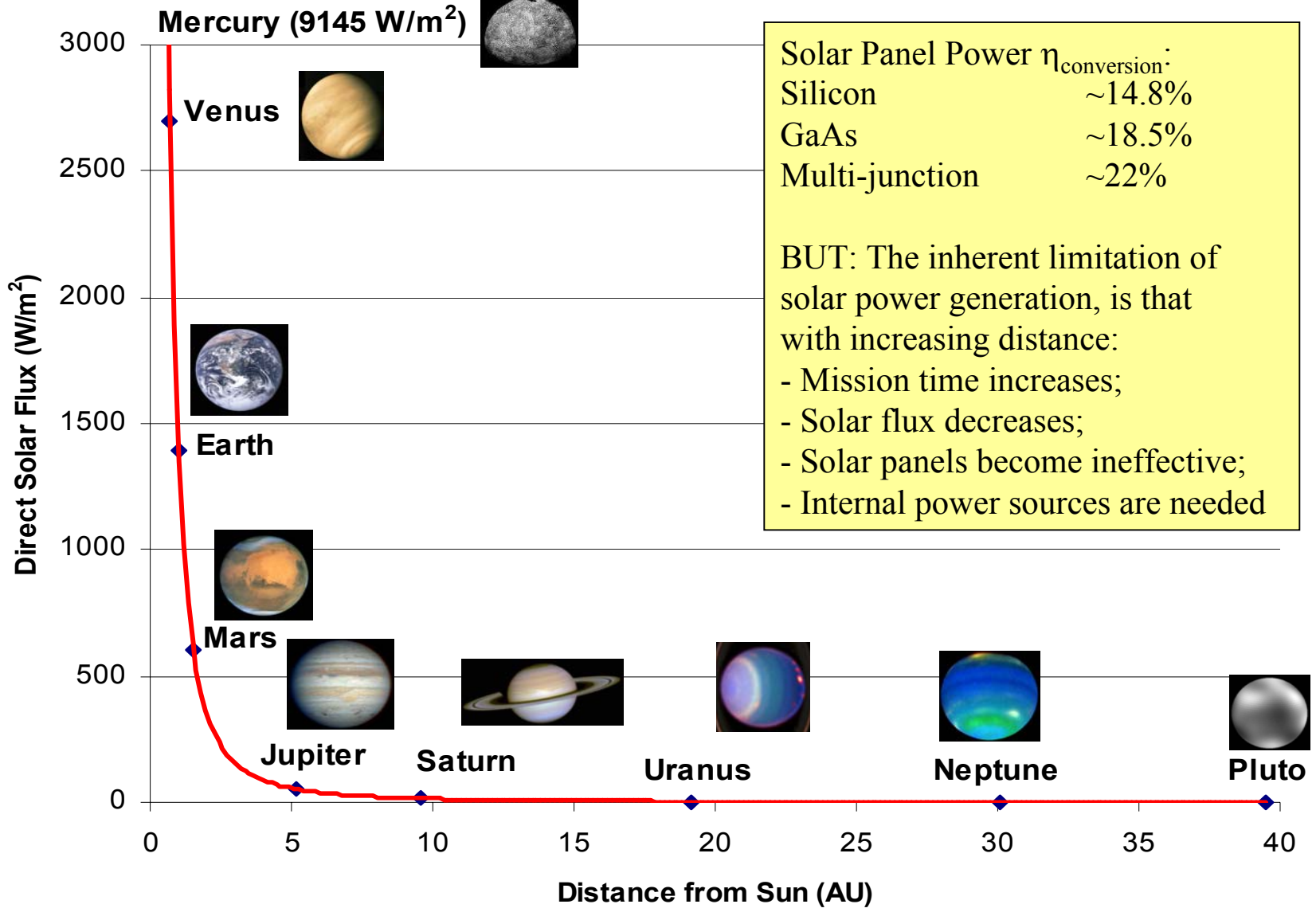
Predicted Nuclear Power System Availability

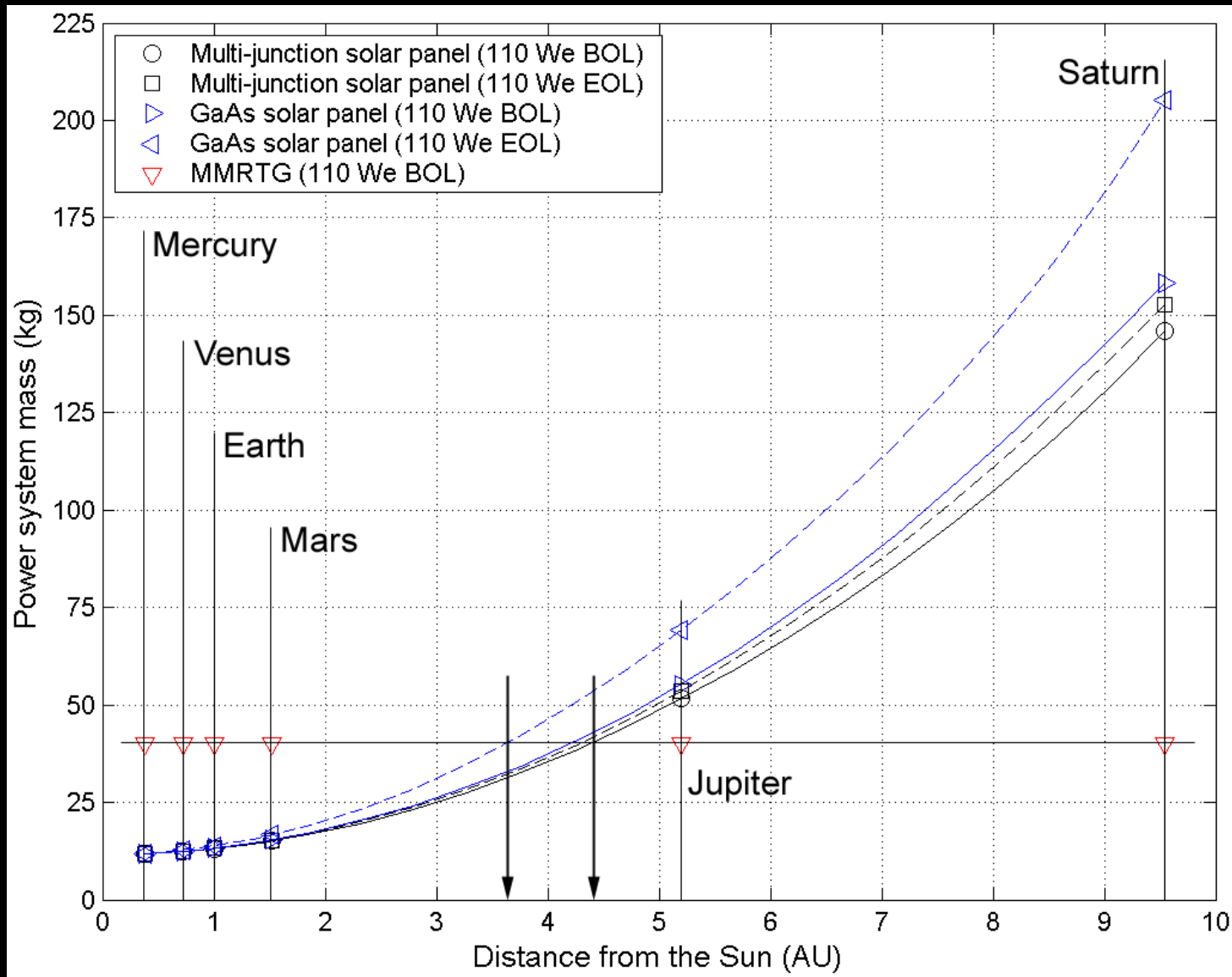


RPS Candidates for Unmanned Exploration Missions

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

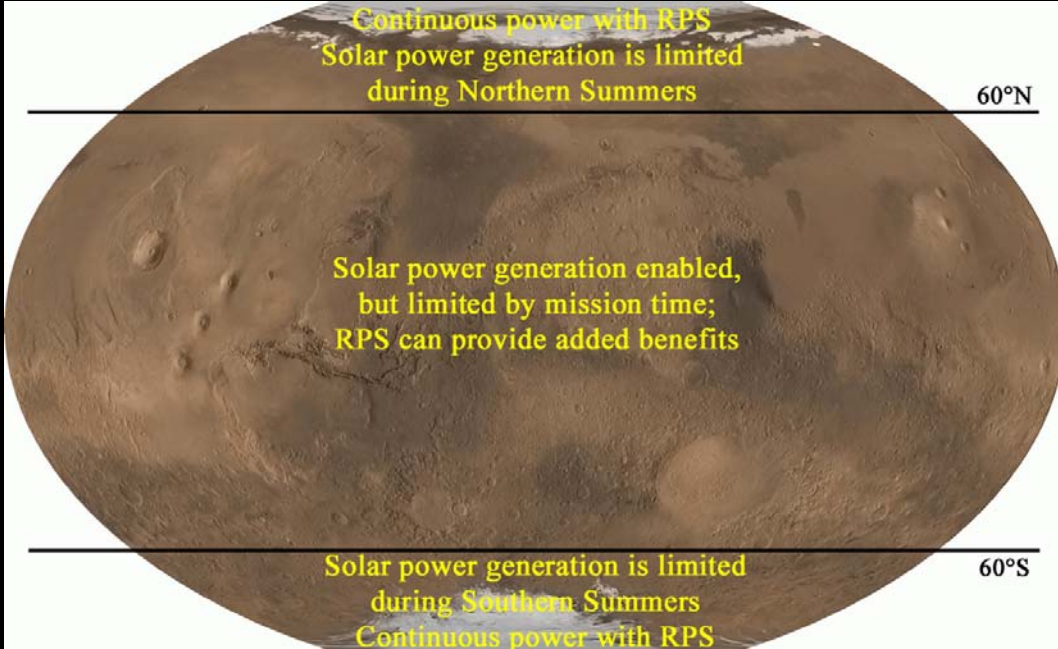
- Distance from the Sun (solar availability)
- Mission duration at low insolation locations
- In space (**vacuum**) vs. surface (**atmospheres**) operations
- Power level requirements (**mission class**)
- Power system sizing (**peak power** vs. **total energy**)
- **Thermal** environment through all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



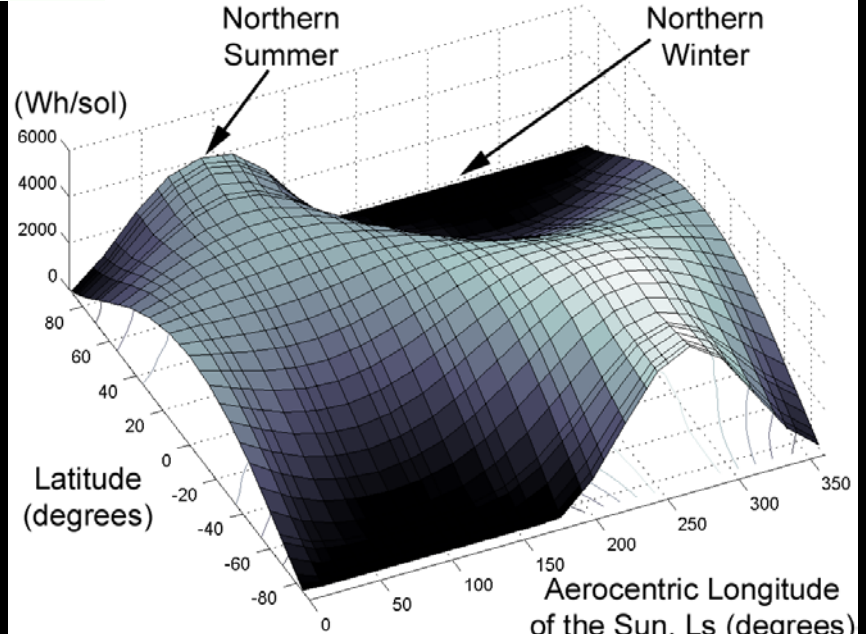
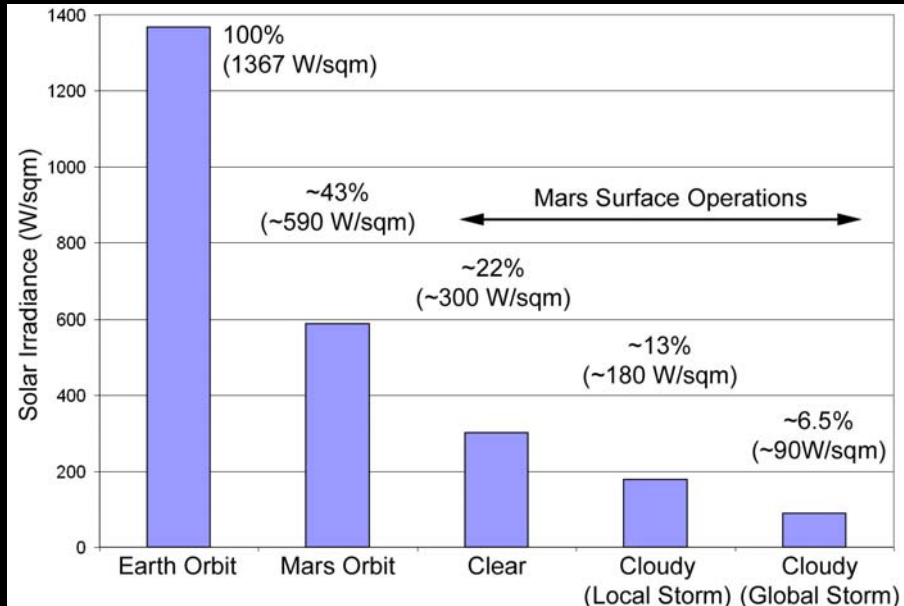


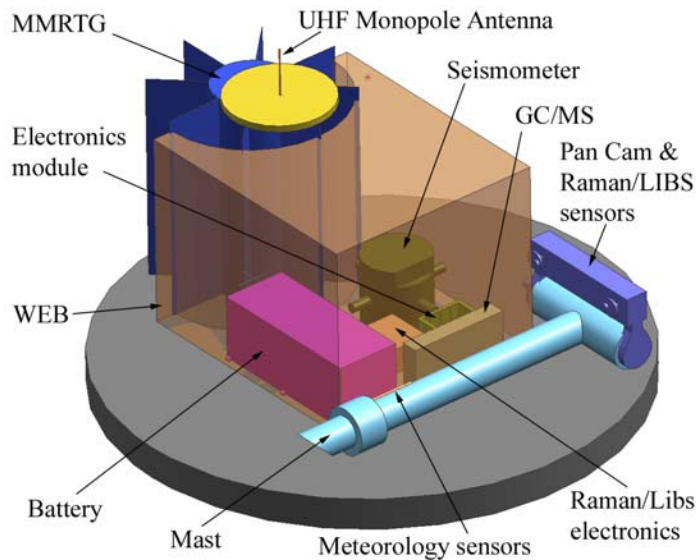
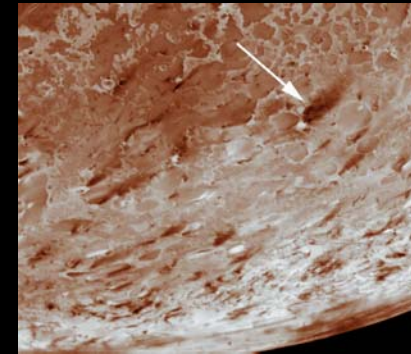
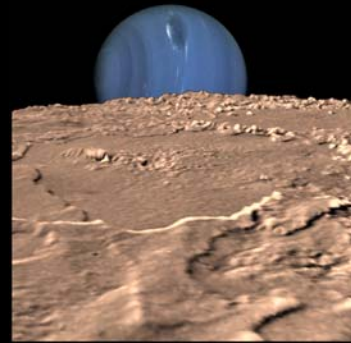
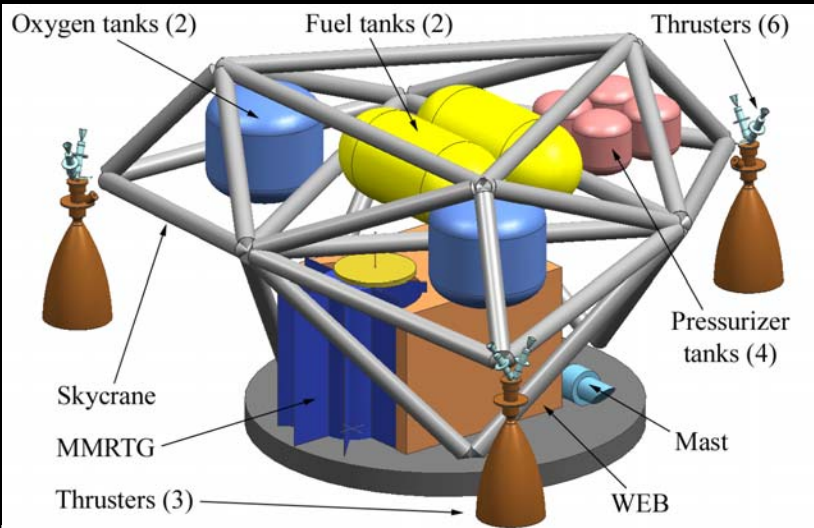
Beyond ~4AU RPS power generation is more mass efficient than solar power generation...

RPS Candidates for Unmanned Exploration Missions



- ### 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 Pu²³⁸ & less power is enough, or dynamic cycle based RPS for more power



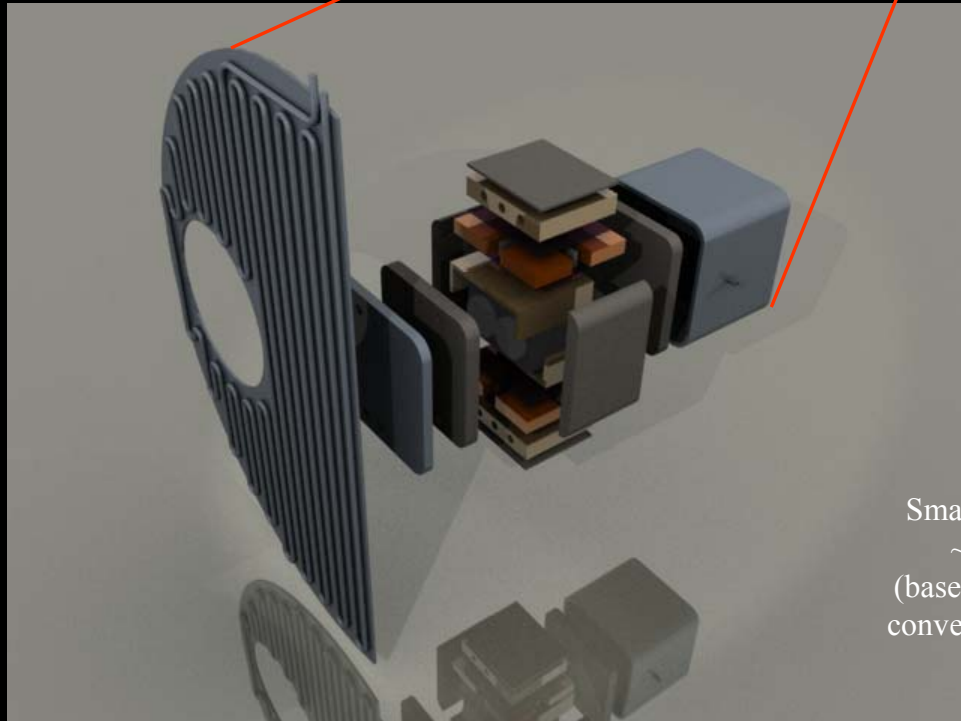
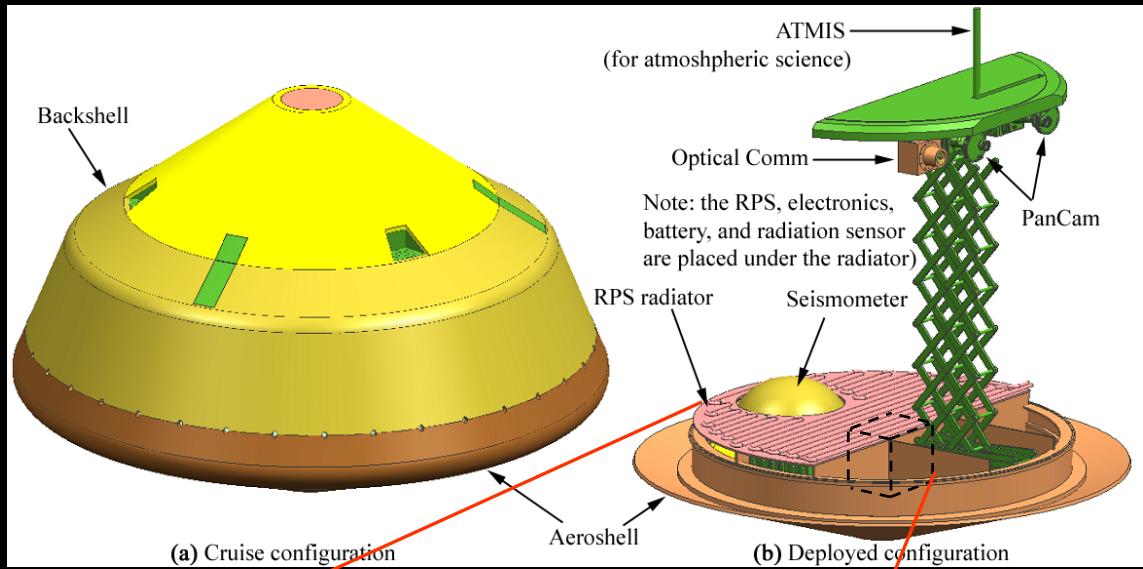


- Triton is the largest Moon of Neptune (D=2700km ; 22% smaller than the Moon)
- Coldest place in the Solar System (-235°C or 38°K)
- Thin atmosphere (mostly nitrogen gas with a small amount of methane, thin haze expands up to 5-10km) results in a low atmospheric pressure (~0.015 millibar, that is 0.000015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

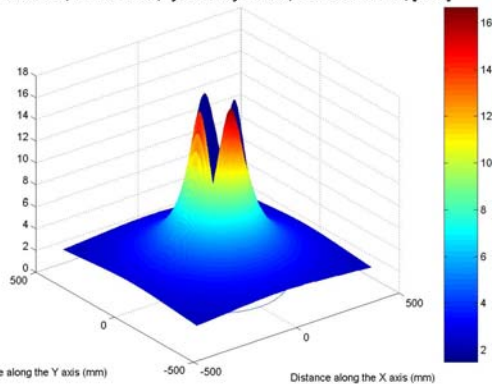
- 1 Small-RPS could enable the mission
- **High g-load tolerance** is needed during landing!
- **Thermal environment** should be addressed through all mission phases (Earth storage; Launch; Cruise; Entry/Descent/Landing; Mars surface operations)

- Monitor weather & environment
- Address MEPAG Goals 2 to 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

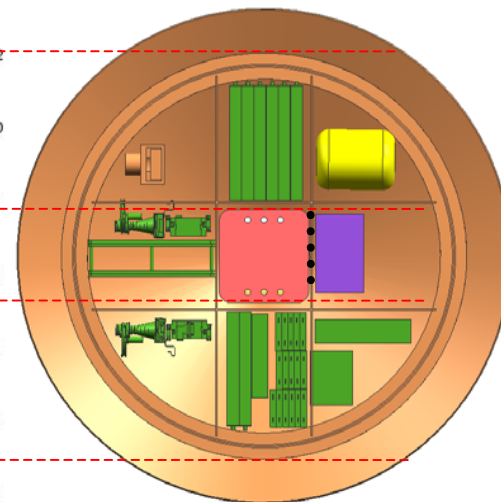
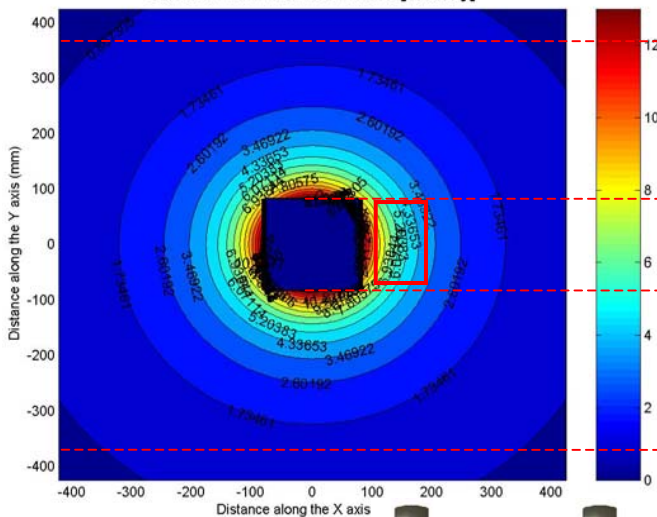


Small-RPS concept
 ~12.5-25We
 (based on 5% to 10% conversion efficiency)

TID Radiation: 1 GPHS-RPSs; 3yrs+360days-cruise; from RPS+natural; [kRad]



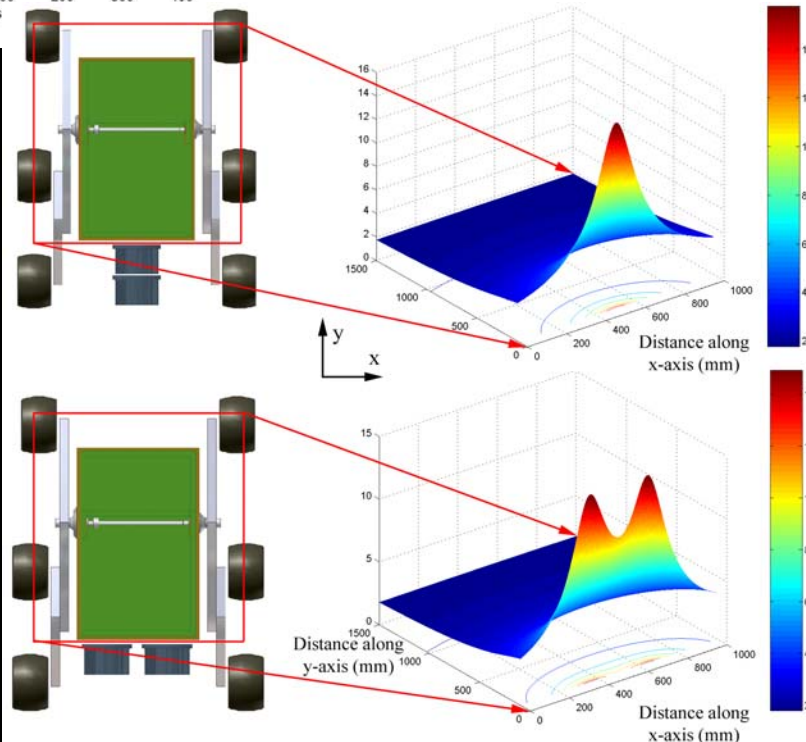
Radiation from 1 GPHS module [Rad/day]

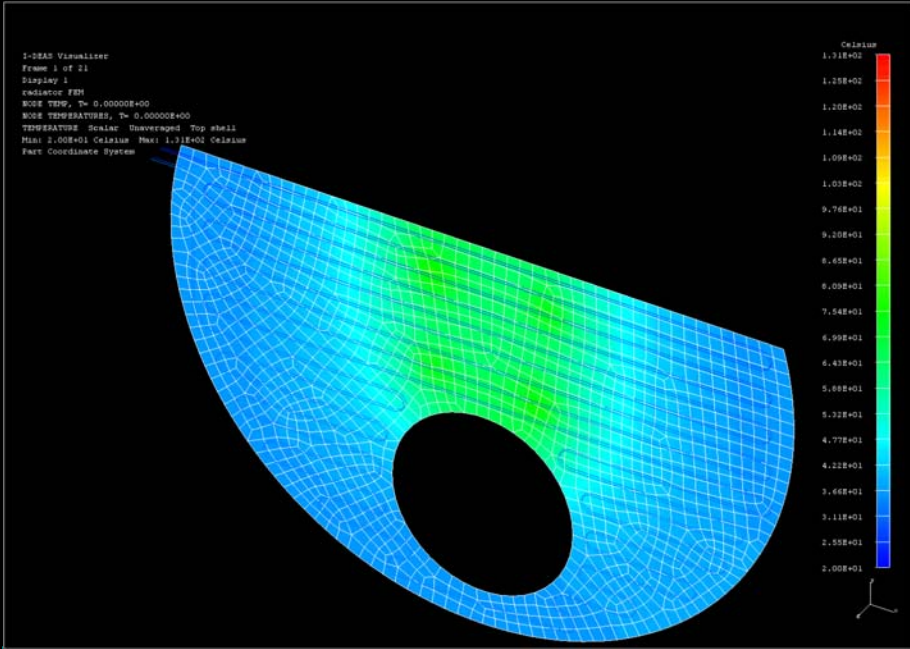


Total Ionizing Dose (TID)
Radiation from small-RPSs
after 4 years is less >20kRad

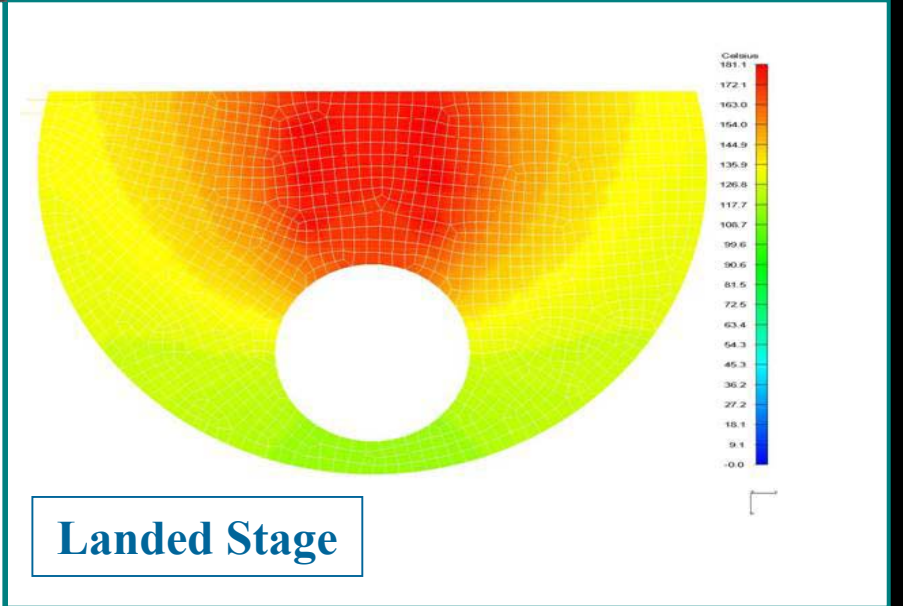
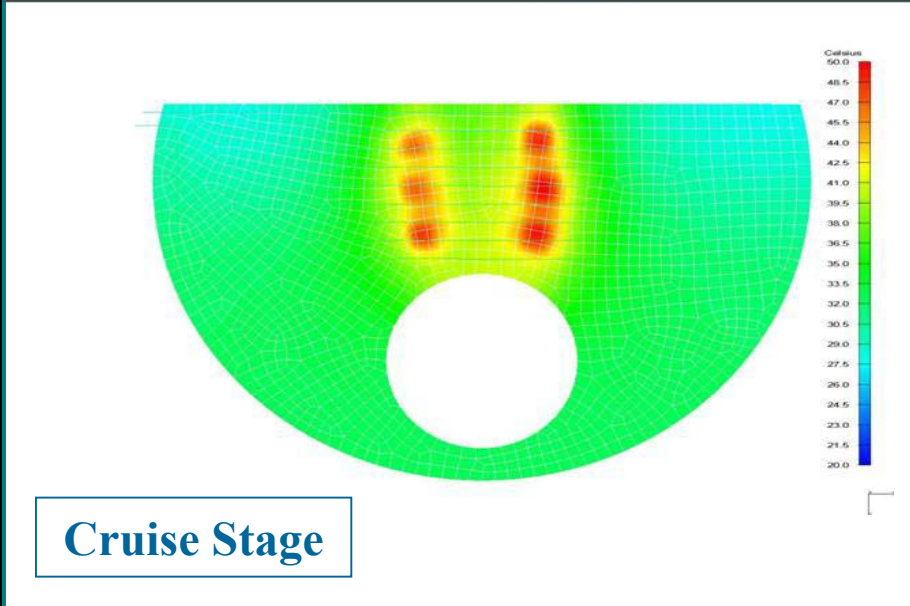
In comparison, state-of-the-art
electronics could tolerate up
to ~300-500kRad

Thus, radiation from small-RPSs
is not an issue

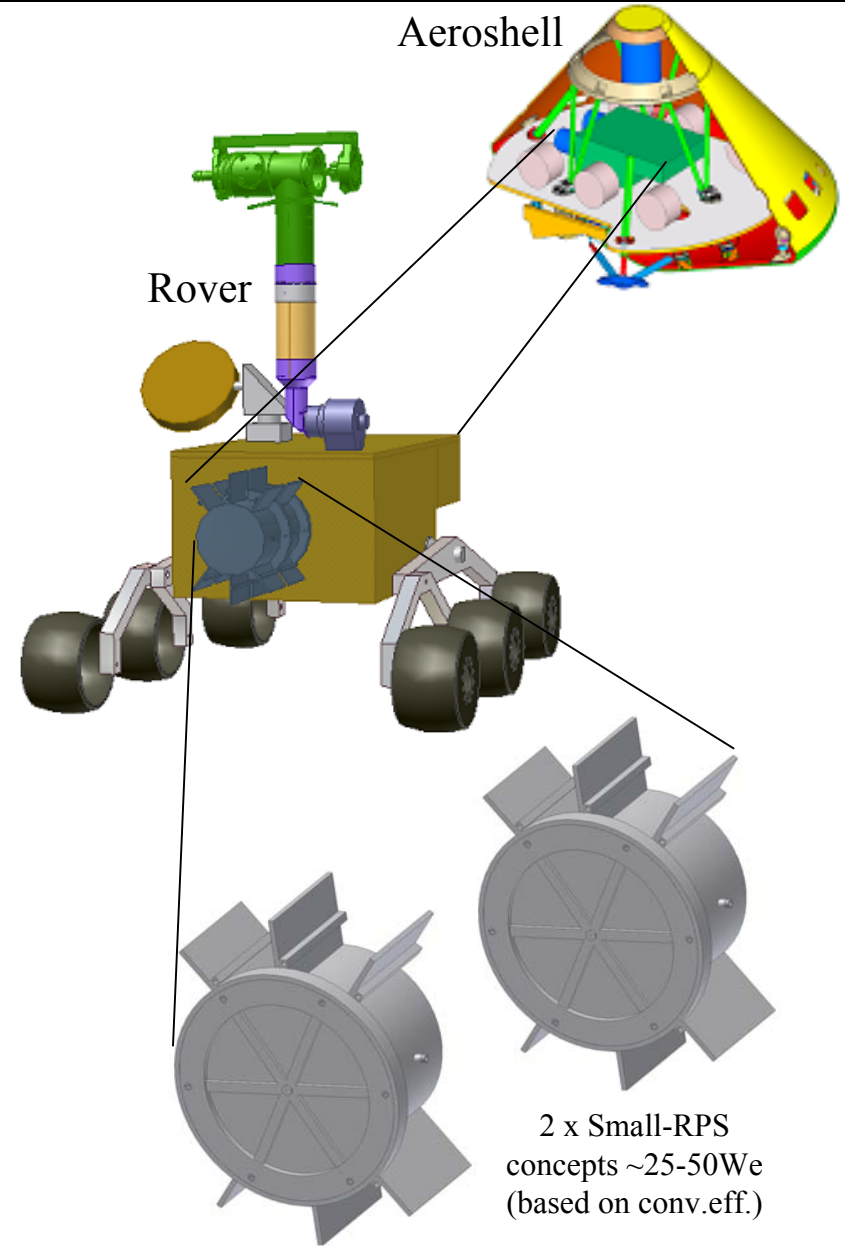
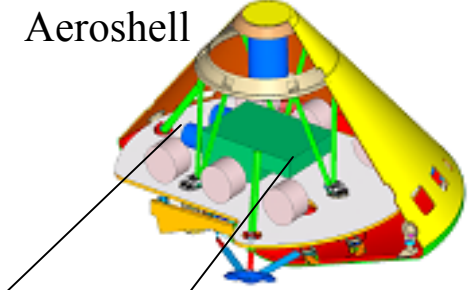




During cruise phase more heat is transferred to the pumped fluid, than it is radially conducted throughout the radiator



- 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

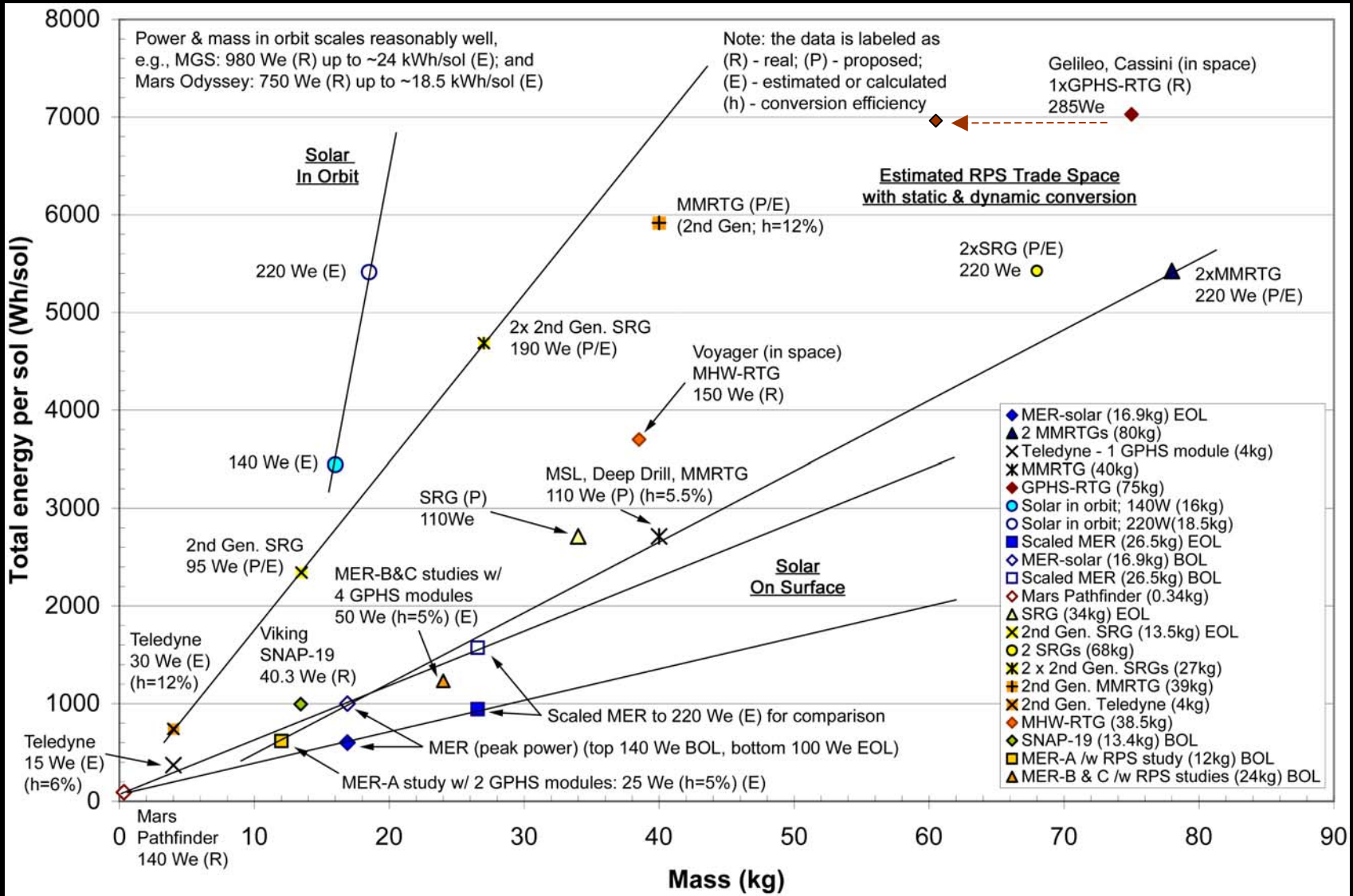


- **Hybrid power system** should be sized for **peak power** usage and **energy** usage (high power requirements by mobility, telecom)
- **Thermal environment** should be addressed through all mission phases

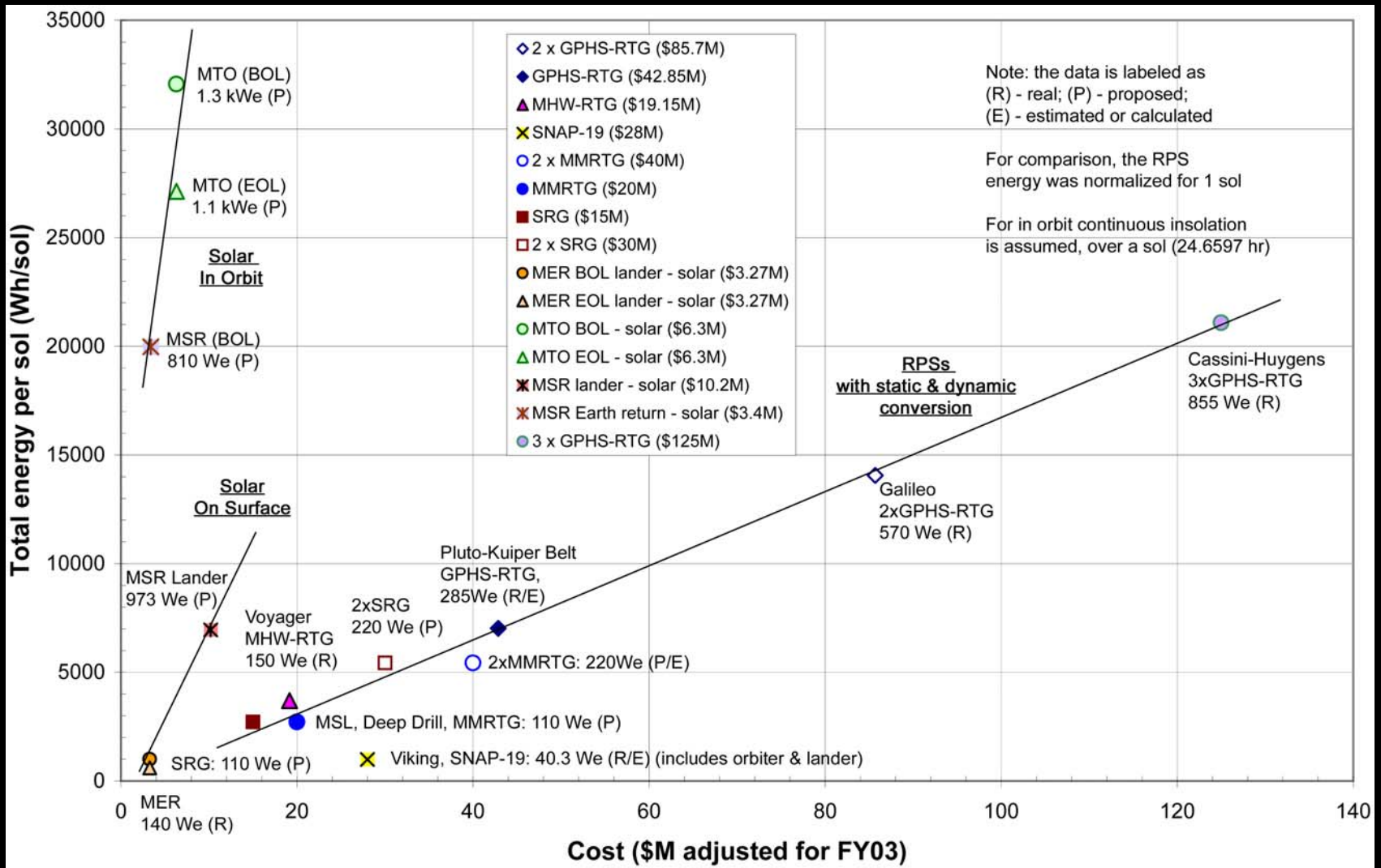
- An **active RPS research and development program** is in place by NASA / DoE
- Two systems are under development which could be used on SSE missions
 - **MMRTG** ≥ 110 We BOL
 - **SRG** ≥ 110 We BOL
 - Offered as early as **2009** (MSL down-selected an MMRTG)
- **Small-RPS** development is under consideration
 - **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**
 - **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 ~ 4 AU with high insolation, it allows to access locations on planetary surfaces where solar flux is not available: e.g., polar regions,
 - Beyond ~ 4 AU 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?





RPS Candidates for Unmanned Exploration Missions

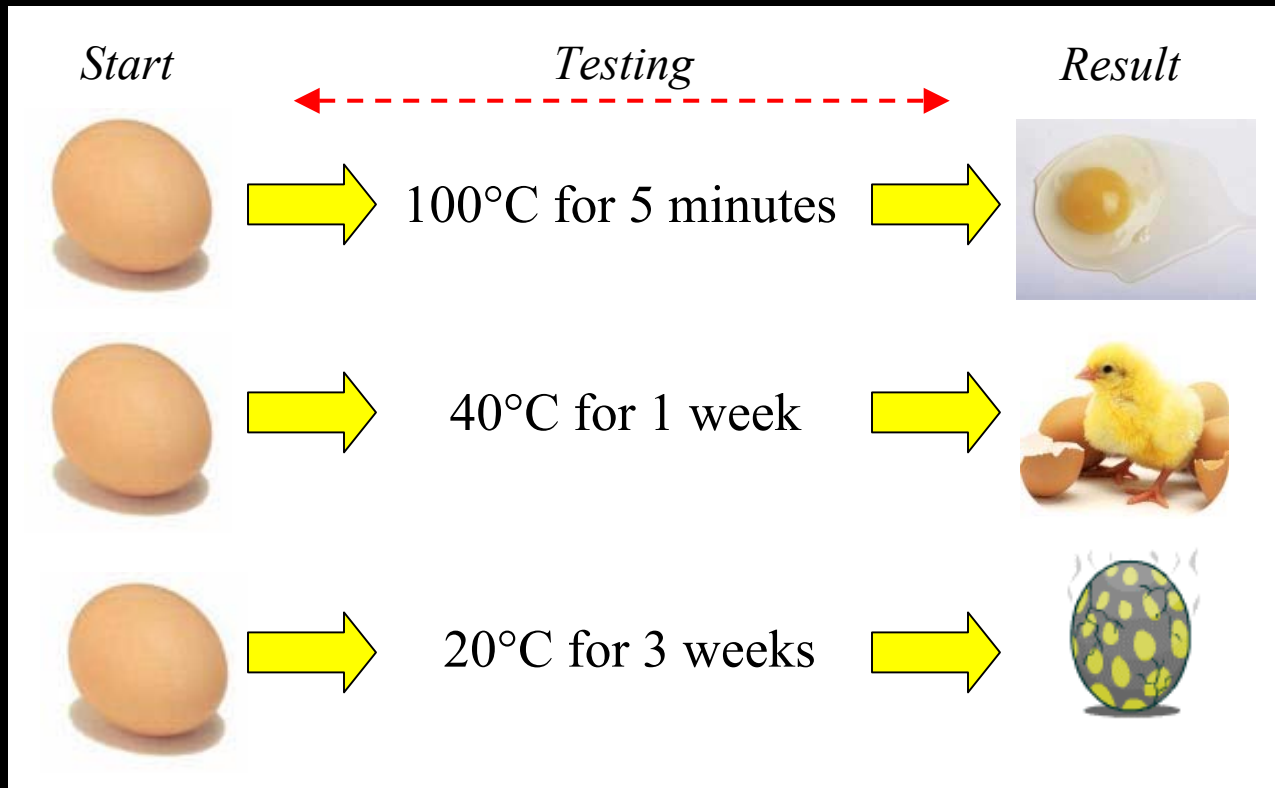


Mission (or Concept)	Power Source	Mass kg	Power We	Energy Wh/sol	Cost \$M FY03
Radioisotope Power Systems					
Cassini-Huygens	3 × GPHS-RTG	3x56	855	21084	125
Galileo	2 × GPHS-RTG	2x56	570	14056	85.7
Pluto/Kuiper Belt	1 × GPHS-RTG	56	285	7028	42.85
Voyager 1 & 2	MHW-RTG	38.5	150	3699	19.15
Viking	SNAP-19	13.4	40.3	994	28
MSL (early variant)	2 × MMRTG	80	220	5425	40
MSL (pre-decisional)	MMRTG	40	110	2713	20
-	SRG-110	34	110	2713	15
-	2 × SRG-110	68	220	5425	30
(2nd Generation, $\eta = 12\%$)	MMRTG	40	240	5918	N/A
(2nd Generation)	SRG	13.5	95	2343	N/A
(Small-RPS, $\eta = 5.5\%$)	1 × GPHS module	6	12.5	310	N/A
(Small-RPS, $\eta = 11\%$)	1 × GPHS module	6	25	620	N/A
(Teledyne, $\eta = 6\%$)	1 × GPHS module	4	15	370	N/A
(Teledyne, $\eta = 12\%$)	1 × GPHS module	4	30	740	N/A
Thermal power only					
Cassini-Huygens	157 × RHU	6.3	157Wt	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	-
MSG	GaAs & Si	-	980	24166	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	6950	10.2
MSR ERV (BOL)	triple junction	23	810	19974	3.4

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

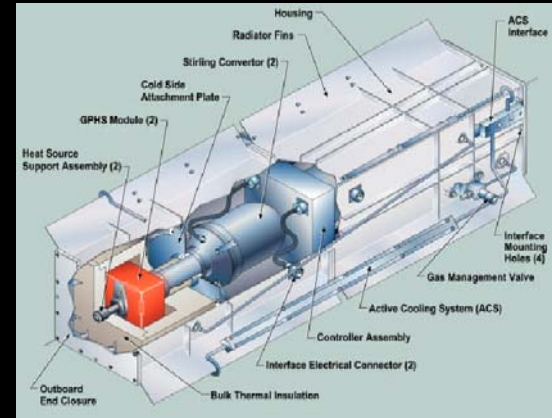
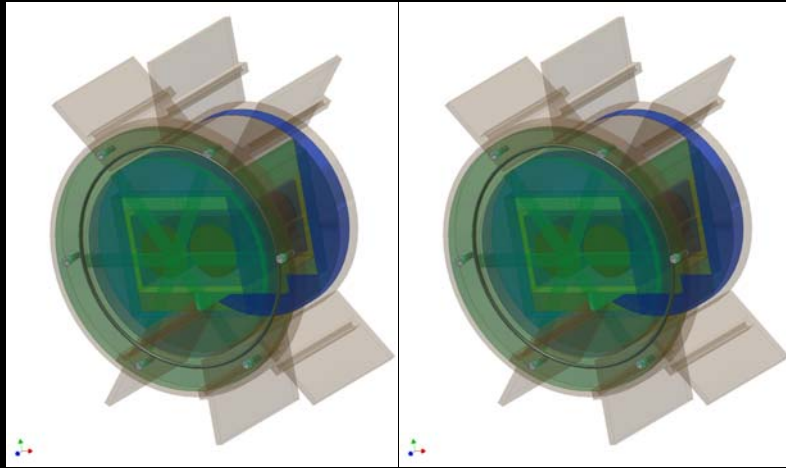
Near future RPS:
MMRTG (~2009)
SRG (~2009/2010)
(Small-RPS; ~2011?)

Solar panels:
GaAs/Ge
GaAs & Si
Triple junction



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!



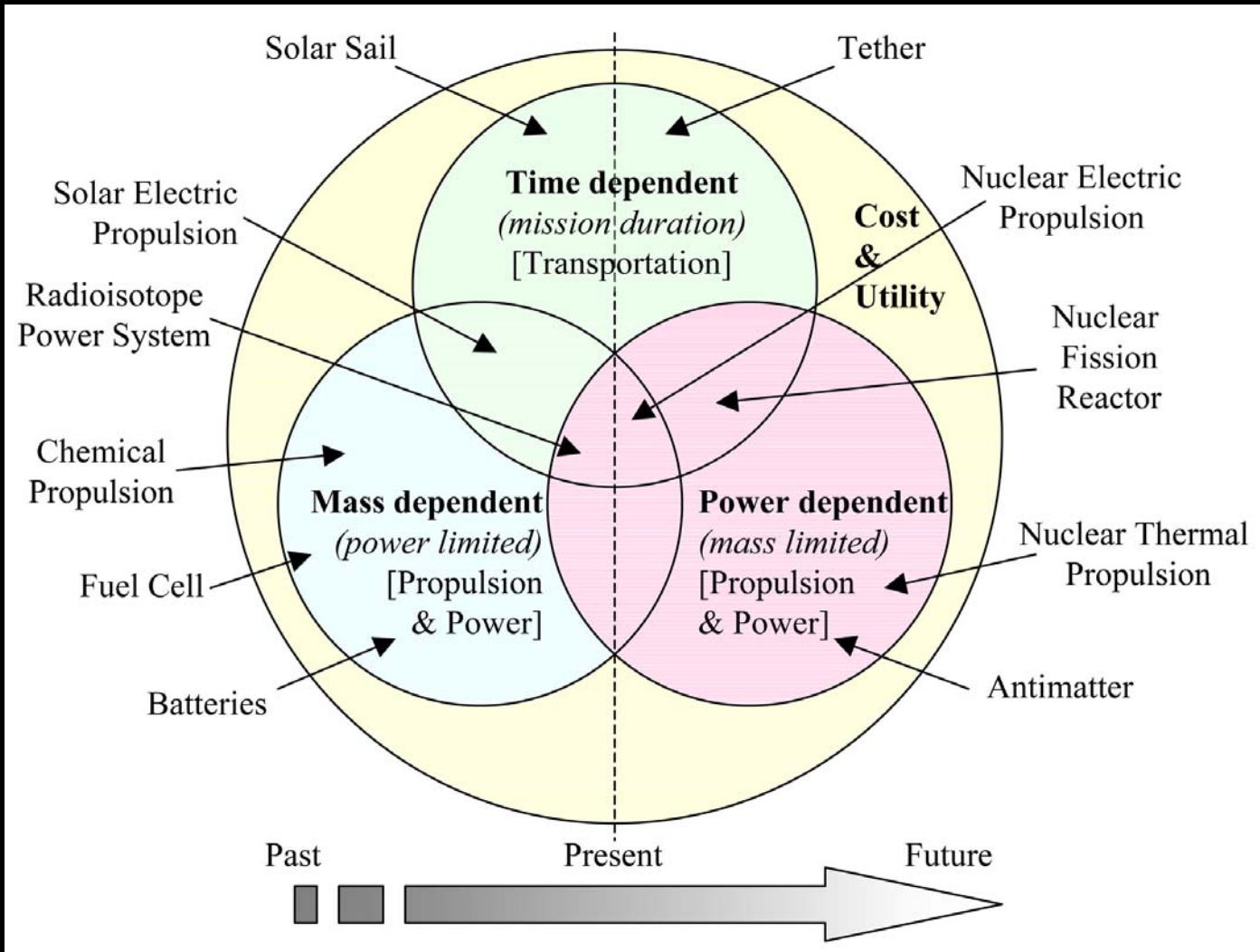
Small-RPS with 1 GPHS module

- 2 small-RPSs (1 GPHS each)
- Pu²³⁸ fuel mass: 2 x 0.5kg
- Static conversion (assumed $\eta \sim 5\%$)**
- Thermal power: 2 x 250Wt (BOL)
- Electric power: 2 x $\sim 12.5\text{We} = \sim 25\text{We}$
- System Mass: $\sim 2 \times \sim 7\text{-}8 \text{ kg} = \sim 16 \text{ kg}$
- Dimensions: $\sim \text{H}13'' \times \text{W}9'' \times \text{L}6''$ each
- Other: g-load tolerance (TBD)
- Low TRL: target 2011 Scout
- Development program: not yet started

Stirling Radioisotope Generator

- SRG110 (2 GPHS modules)
- ← Pu²³⁸ fuel mass: 2 x 0.5 kg
- Dynamic conversion ($\eta \sim 25\%$)
- ← Thermal power: 2 x 250Wt (BOL)
- Electric power: $\sim 110 \text{We}$ (BOL)
- ← System mass: $\sim 34 \text{ kg}$
- ← Dimensions: $\sim \text{H}15'' \times \text{W}11.5'' \times \text{L}37.5''$
- ← Other: g-load tolerance (TBD)
- TRL9 target: 2009
- Development program: ongoing

Note: ** efficiency up to $\sim 13\%$ would increase to power to $\sim 32.5\text{We}$ for each small-RPS, resulting in $\sim 65\text{We}$



RPSs

Fission Reactors

Power-plant	Type	Mass [kg]	Thermal power [kWt]	Power level [kWe]	Specific power [We/kg]	Lifetime
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 power system	Radioisotope/Brayton	905	25	6	6.6	Study
SNAP 10A (SNAPSHOT)	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	9,506	383	100	10.5	Study
SP-100 dynamic	Fission/Brayton	14,337	2,657	550	38	Study
SP-100 dynamic	Fission/Stirling	20,004	2,500	825	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