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An Introduction to Space Nuclear Power Systems

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An Introduction to Space Nuclear Power Systems

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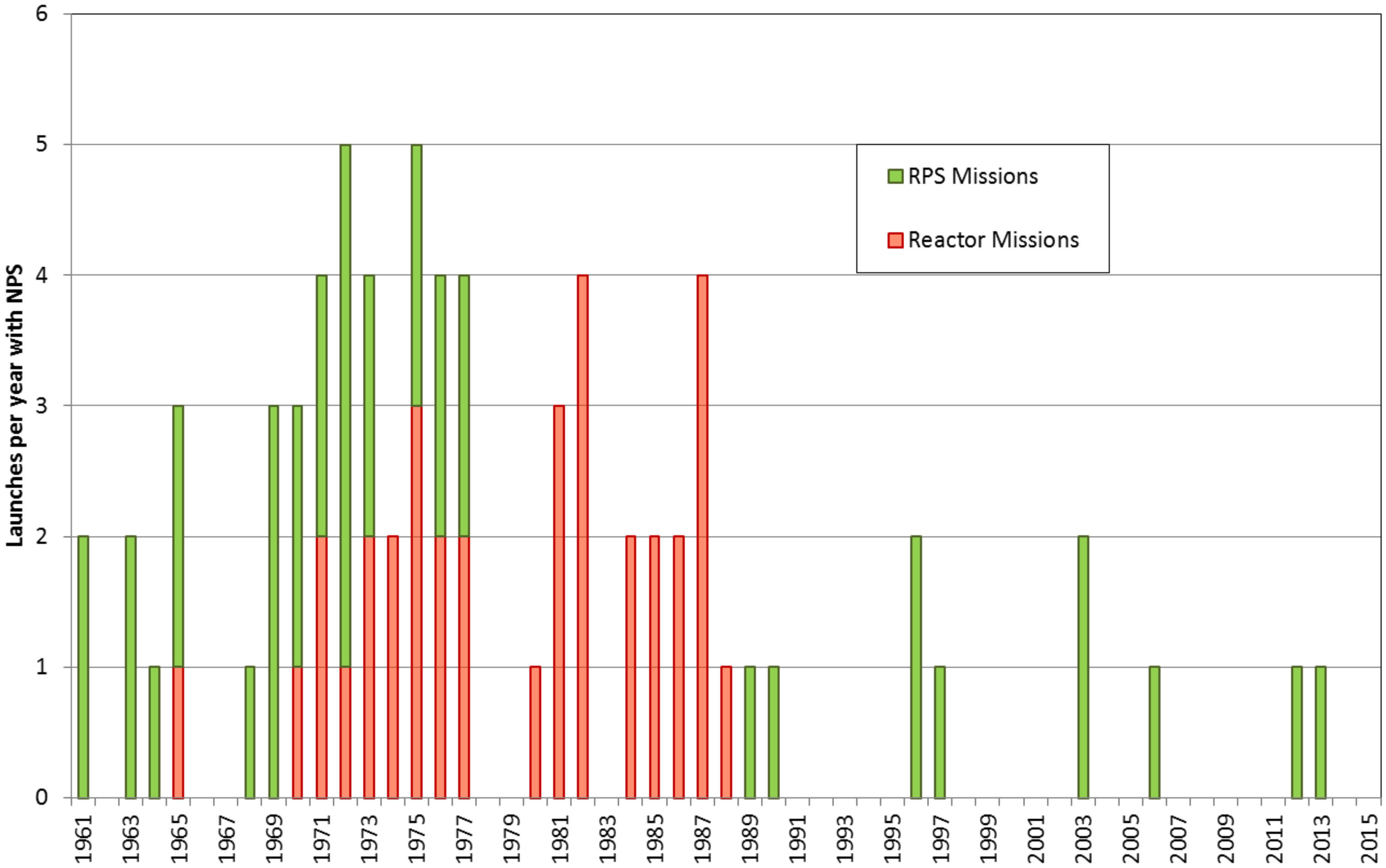
Presentation Outline

1. The history of, and requirement for, nuclear power in space.
2. Radioisotope heater units (RHU).
3. Radioisotope power systems (RPS).
4. Space reactor systems.

History of Nuclear Power in Space



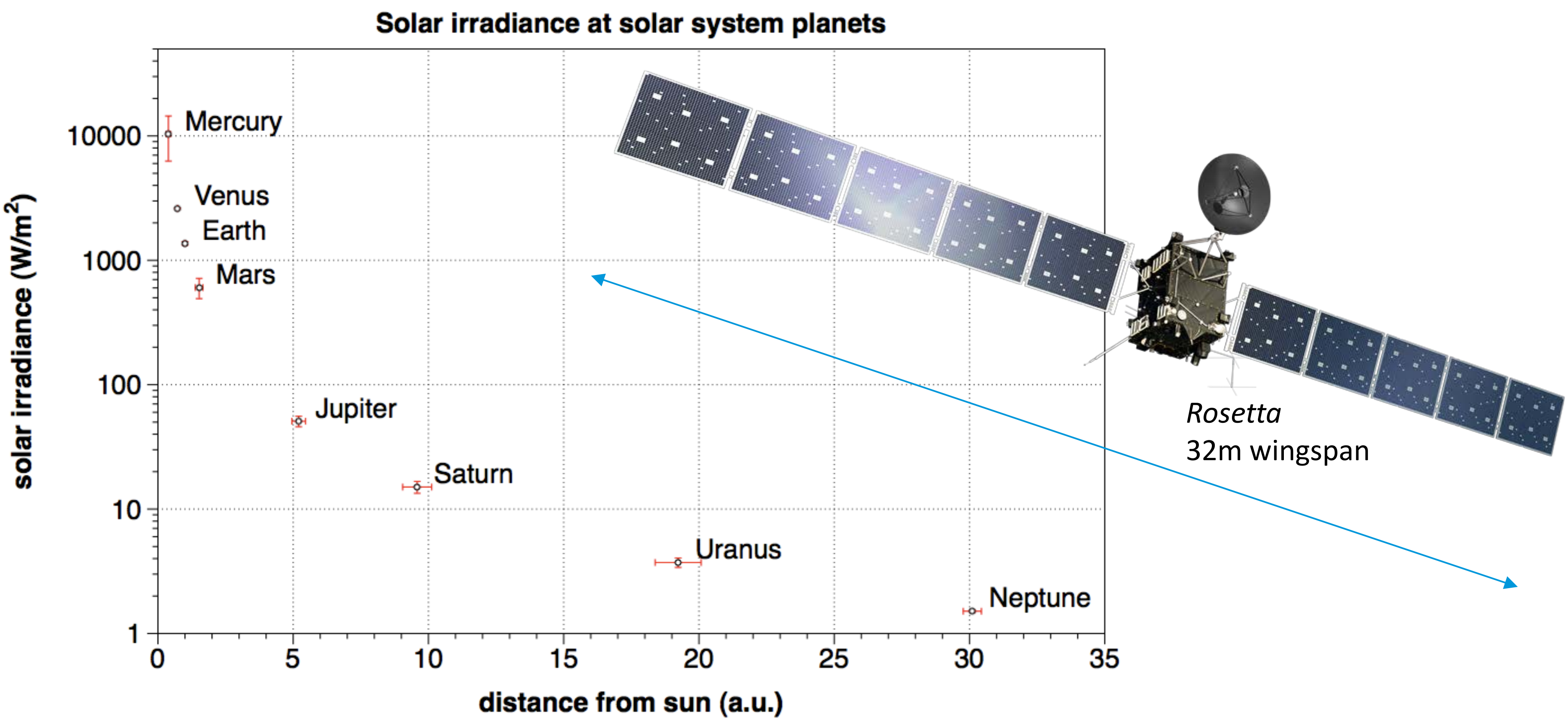
The Requirement for Nuclear Power Sources in Space

There are two important classes of *existing* space mission that cannot rely *only* on solar photovoltaics for power:

1. Outer solar system missions, due to the $1/r^2$ weakening of the solar flux.

    - ESA's *Rosetta* spacecraft requires 64m² of solar array to just *survive* at ~5 a.u.

2. Mars or moon lander/rover missions that wish to survive and/or operate through the night, or the Martian dust storms.



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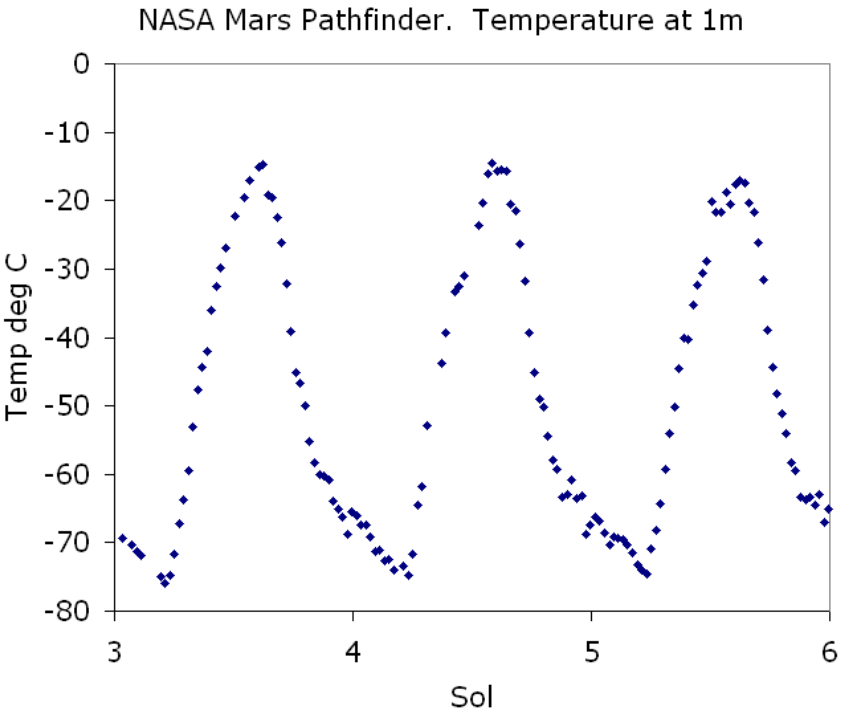


With the exception of the short-lifetime NASA *Phoenix* mission, all successful Mars landers and rovers have used nuclear power systems of some type:

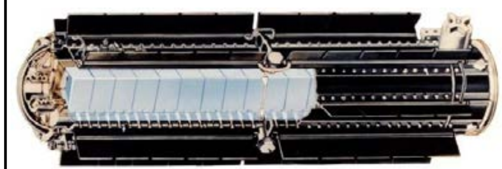
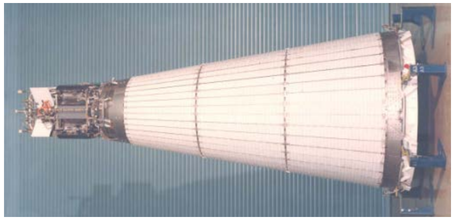
Mission	Mars Arrival Date	Country	NPS
Viking 1 Lander	July 1976	USA	2 SNAP-19 RTGs
Viking 2 Lander	September 1976	USA	2 SNAP-19 RTGs
Mars Pathfinder Rover	July 1997	USA	3 RHUs
MER Spirit Rover	January 2004	USA	8 RHUs
MER Opportunity Rover	January 2004	USA	8 RHUs
MSL Curiosity Rover	August 2012	USA	1 MMRTG

The Requirement for Nuclear Power Sources in Space

If solar power is unavailable, the spacecraft must carry its required energy from Earth.

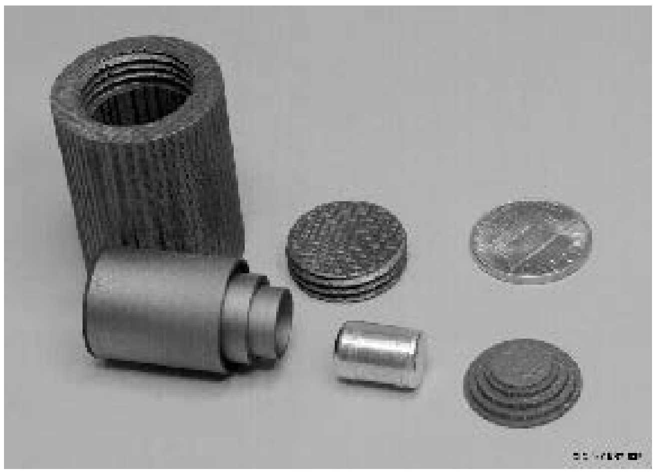
No chemical or electrochemical process can provide the energy density necessary for a multi-year mission.

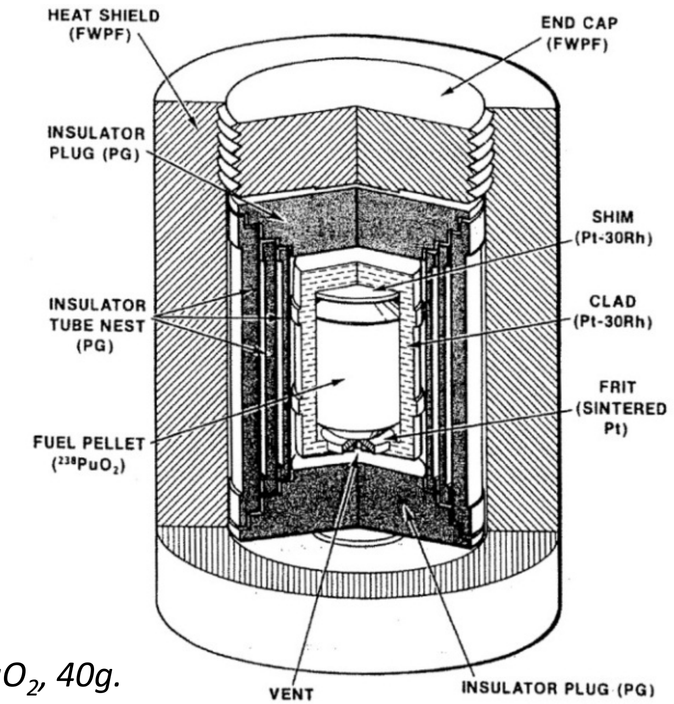
The only known solution is to use nuclear power, either from radioactive decay processes or a fission reactor.

		 USA GPHS-RTG (Pu-238)	 Generic Space Reactor
Power density	~100 W/kg	5 W/kg	2 ~ 30 W/kg
Energy Density (1 year mission)	10^6 J/kg	10^8 J/kg	$10^8 \sim 10^9$ J/kg
Energy Density (10 year mission)	10^6 J/kg	10^9 J/kg	$10^9 \sim 10^{10}$ J/kg

Radioisotope Heater Units

The simplest nuclear power systems used in space are Radioisotope Heater Units (RHUs). These devices contain an amount of radioactive material to generate heat directly via radioactive decay.

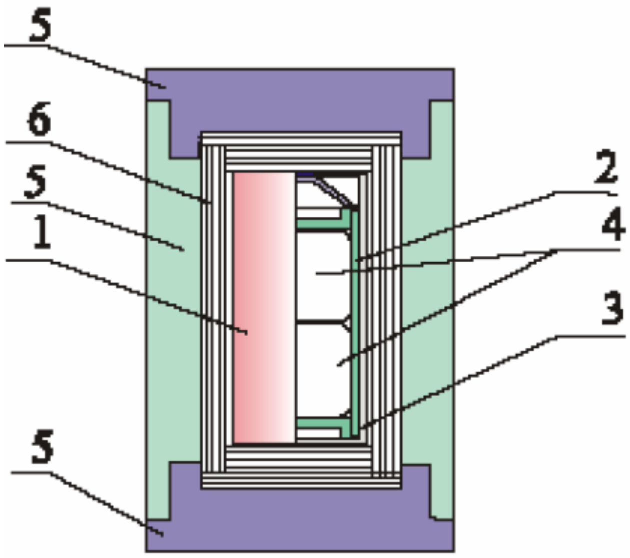




USA Light-Weight RHU (LWRHU), $1W_t$, $^{238}PuO_2$, 40g.

Typically, RHUs are low power devices, containing less than 100g of radioisotope, and producing less than $10W_t$ of heat. Whilst they do not *generate* electrical power, they provide power-budget savings by removing or reducing the requirement for electrical heaters.

Radioisotope Heater Units



1. Radioisotopic heat source (RHS).
2. Anticorrosive platinum-rhodium alloy shell.
3. Impact resistant tantalum-tungsten alloy shell.
4. Pellet of hot-pressed PuO_2 in iridium cladding.
5. Heat-protection casing.
6. Multi-layer heat-insulating insert.

Russian “Angel” RHU. $^{238}PuO_{2.}$ $8W_t$, 185 grams.

RHU Flights

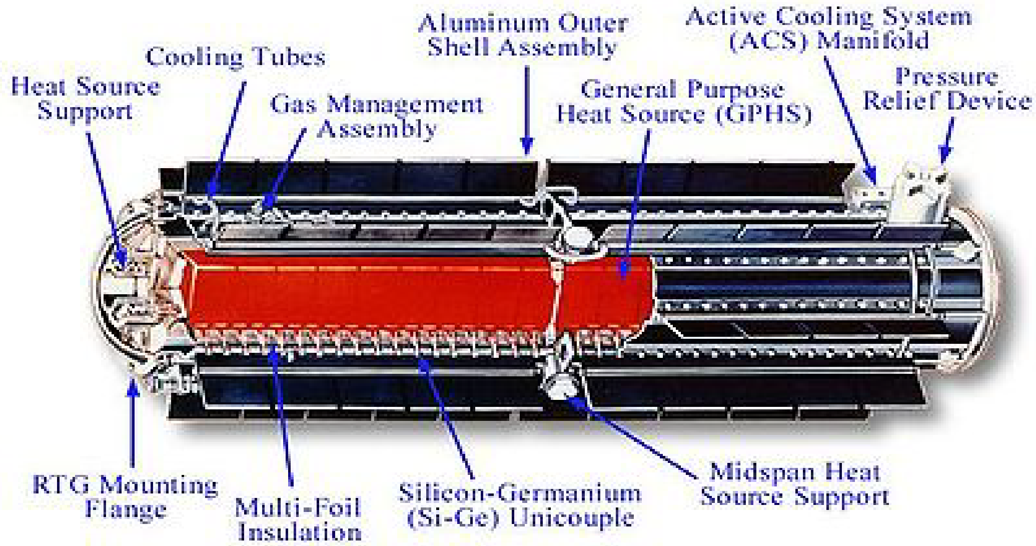
USA = Black USSR/Russia = Blue

China = Red

Year	Mission/ Spacecraft Name	Spacecraft Type	RHU Power (W_t) and quantity	Isotope
1969	Apollo 11	Lunar surface experiments package (EASEP)	15W x 2	^{238}Pu
1969,70,73	Lunokhod I and II. (Lunokhod "zero" was a launch failure)	Lunar Rover	800W x 1 per rover	^{210}Po
1972 & 73	Pioneer 10 and 11	Interplanetary - asteroid belt, Jupiter, Saturn.	1W x 12 per craft	^{238}Pu
1977	Voyager 1 and 2	Interplanetary – Jupiter, Saturn, Uranus, Neptune.	1W x 9 per craft	^{238}Pu
1989	Galileo	Interplanetary - Jupiter	1W x (103+17)	^{238}Pu
1990	Ulysses	Interplanetary - Sun	1W x 35	^{238}Pu
1996	Mars 96 (launch failure)	Mars Landers	8.5W x 2 per lander	^{238}Pu
1997	Cassini-Huygens	Interplanetary – Saturn/Titan	1W x (82+35)	^{238}Pu
1997	Mars Pathfinder Sojourner Rover	Mars Rover	1W x 3	^{238}Pu
2003	Mars Exploration Rovers (*Spirit* and *Opportunity*)	Mars Rovers	1W x 8 per rover	^{238}Pu
2013	Chang'e 3	Lunar lander & rover	8.5W? x ? (Russian?)	^{238}Pu

Radioisotope Power Systems

The heat generated by the decay of a radioisotope can be used to generate electricity. The usual way of doing this is via the thermoelectric (Seebeck) effect. Such a device is called a radioisotope thermoelectric generator (RTG).

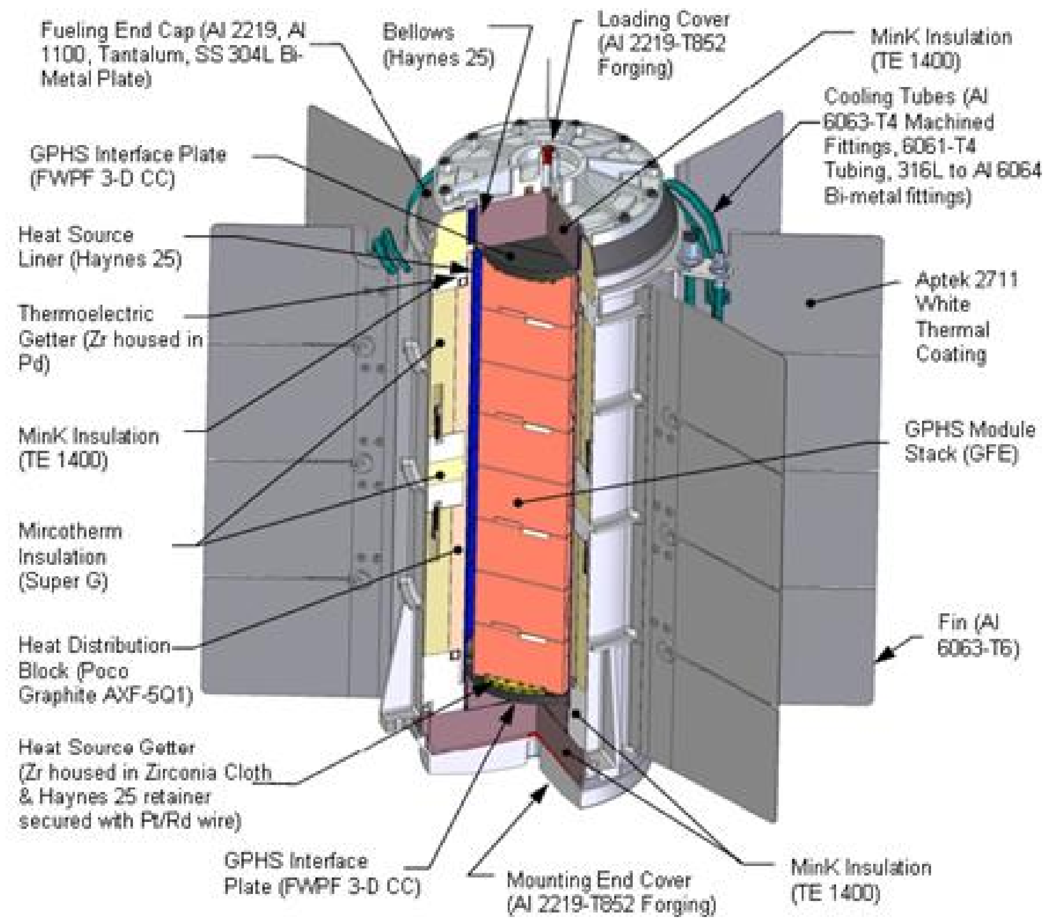


USA GPHS RTG (General Purpose Heat Source RTG). (1980s to 2000s.) 56kg. 295W_e. 572 Si-Ge thermolectric couples.

The main disadvantage of the RTG is the low power conversion efficiency (~6%), which leads to a large fuel requirement, and reduces the specific power (W/kg).

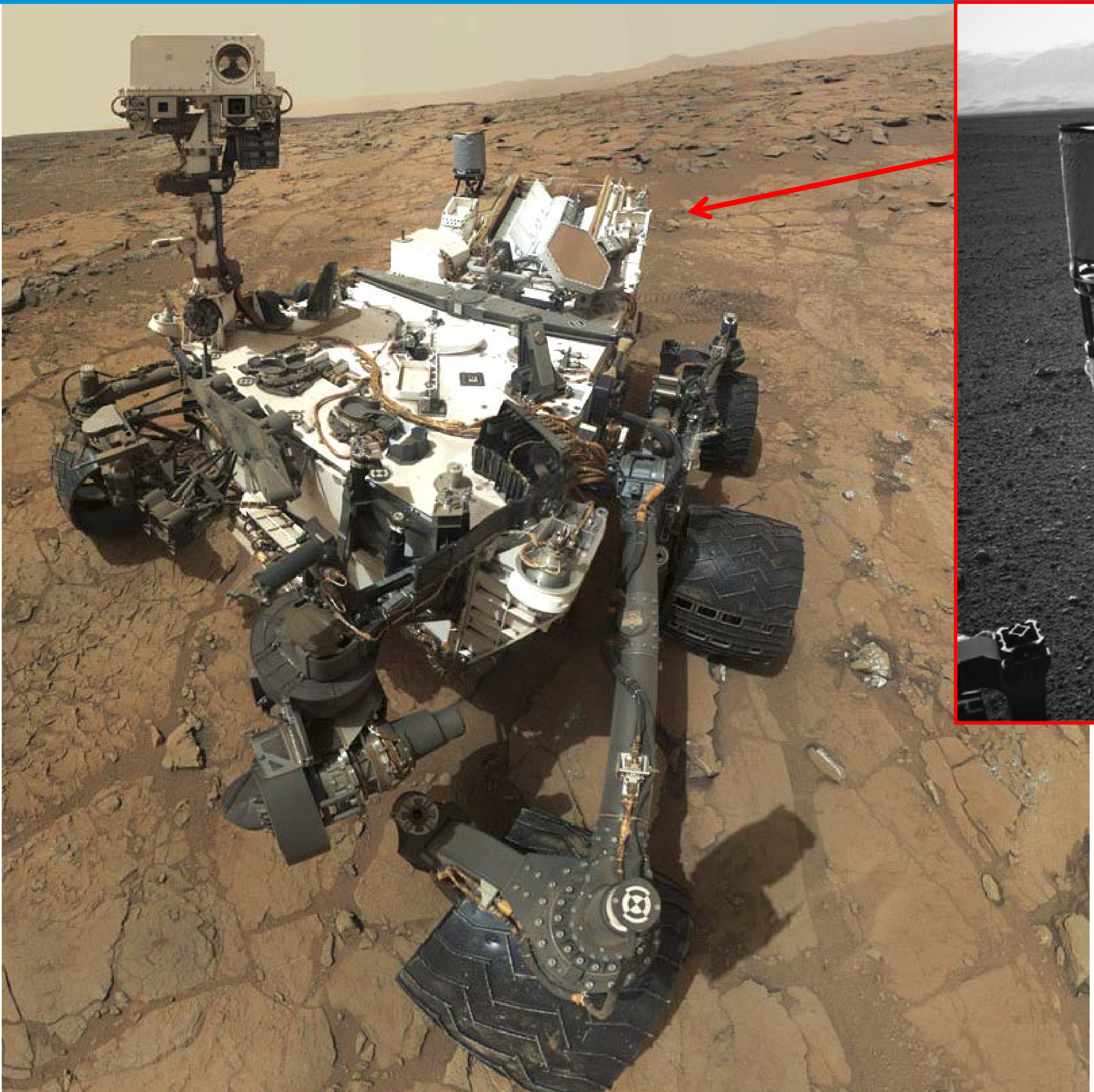
However, the advantages of motion-free operation, and proven long-term reliability mean that thermoelectric conversion is still the only power conversion method applied to radioisotope systems flown in space.

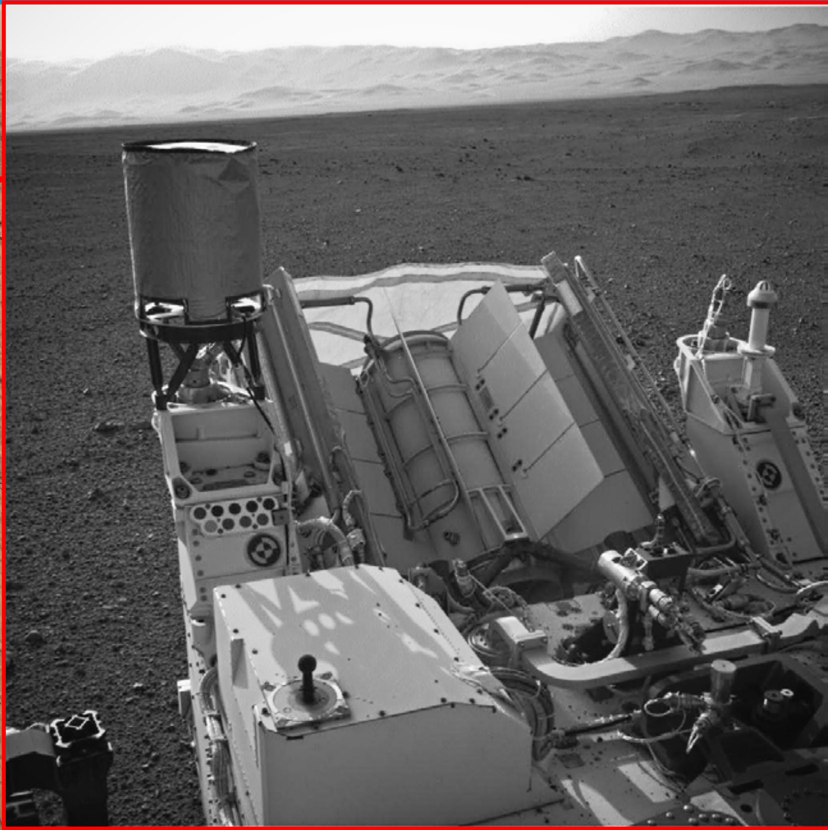
Radioisotope Power Systems



USA Multi-Mission RTG (2012 -) 44kg. 125W$_e$. 768 Pb-Te / TAGS thermocouples

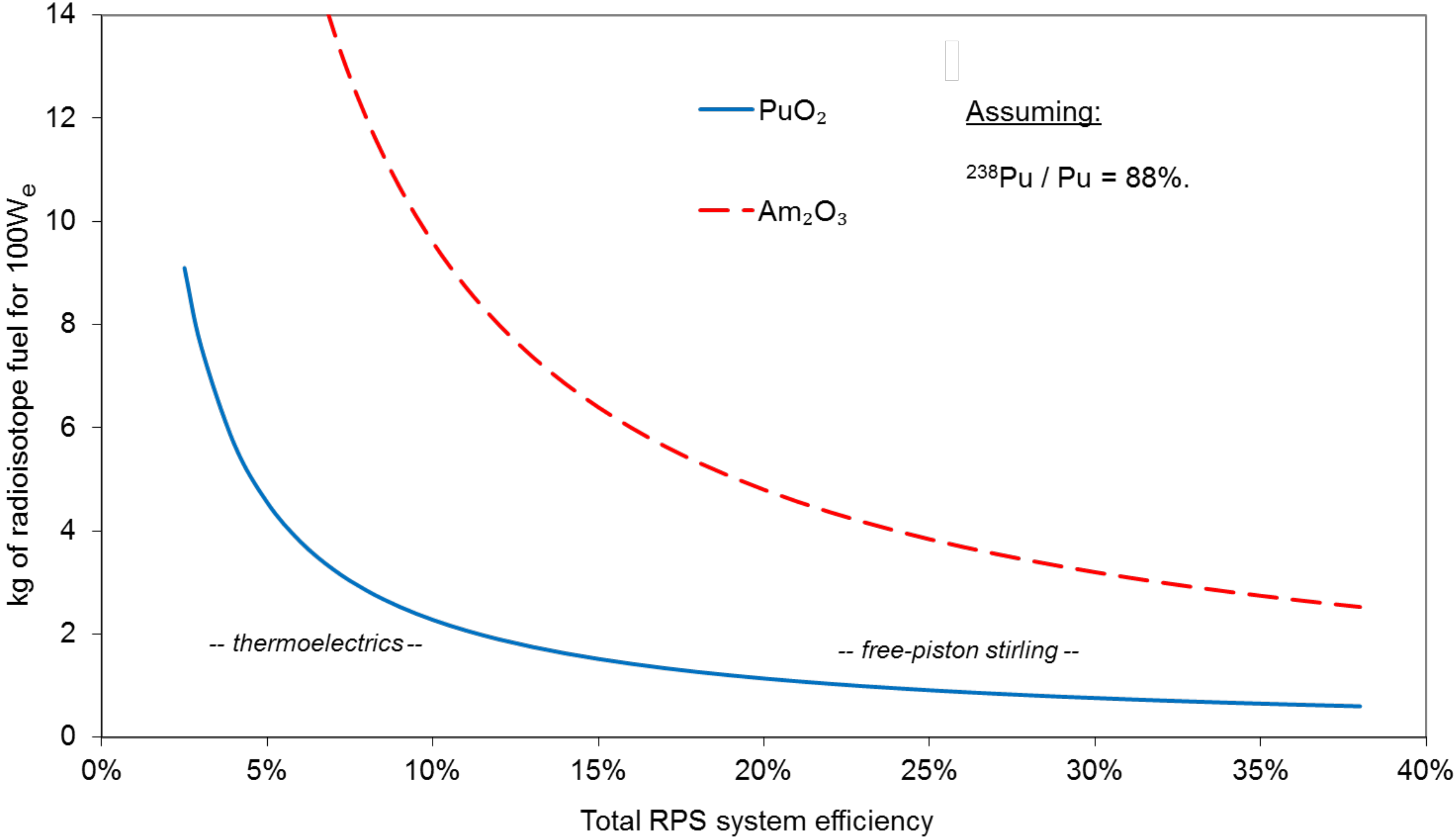
Radioisotope Power Systems





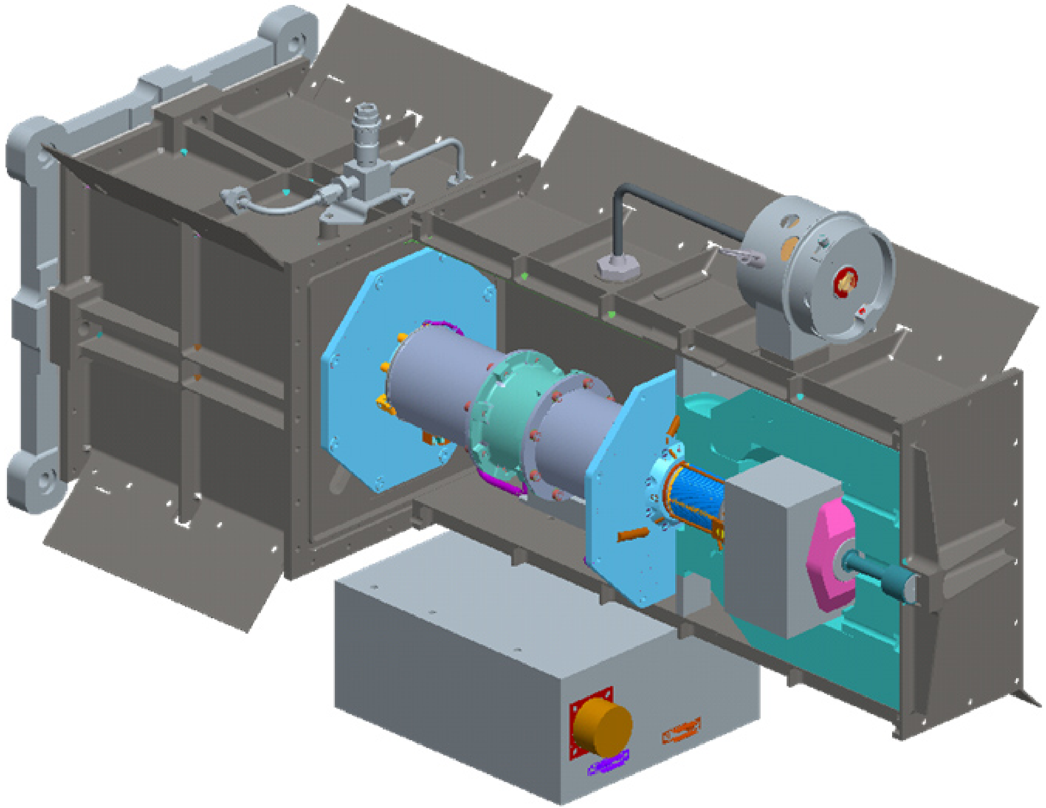
MMRTG in operation on Mars, powering NASA's Curiosity rover for the Mars Science Laboratory mission.

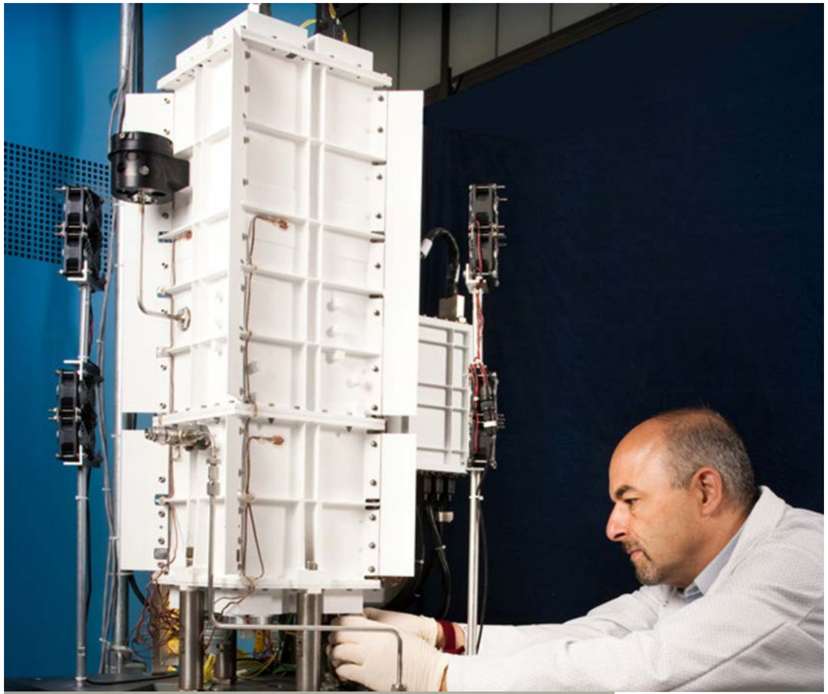
Radioisotope Power Systems

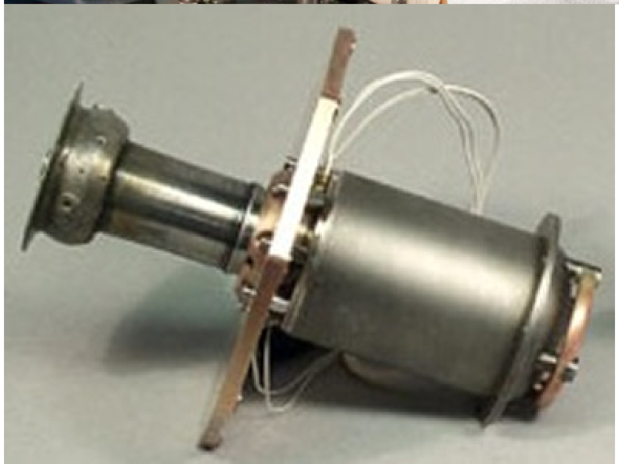


Radioisotope Power Systems

Hence the more recent development of Stirling engine conversion systems. The ASRG (pictured) has a conversion efficiency in the region of 26%.



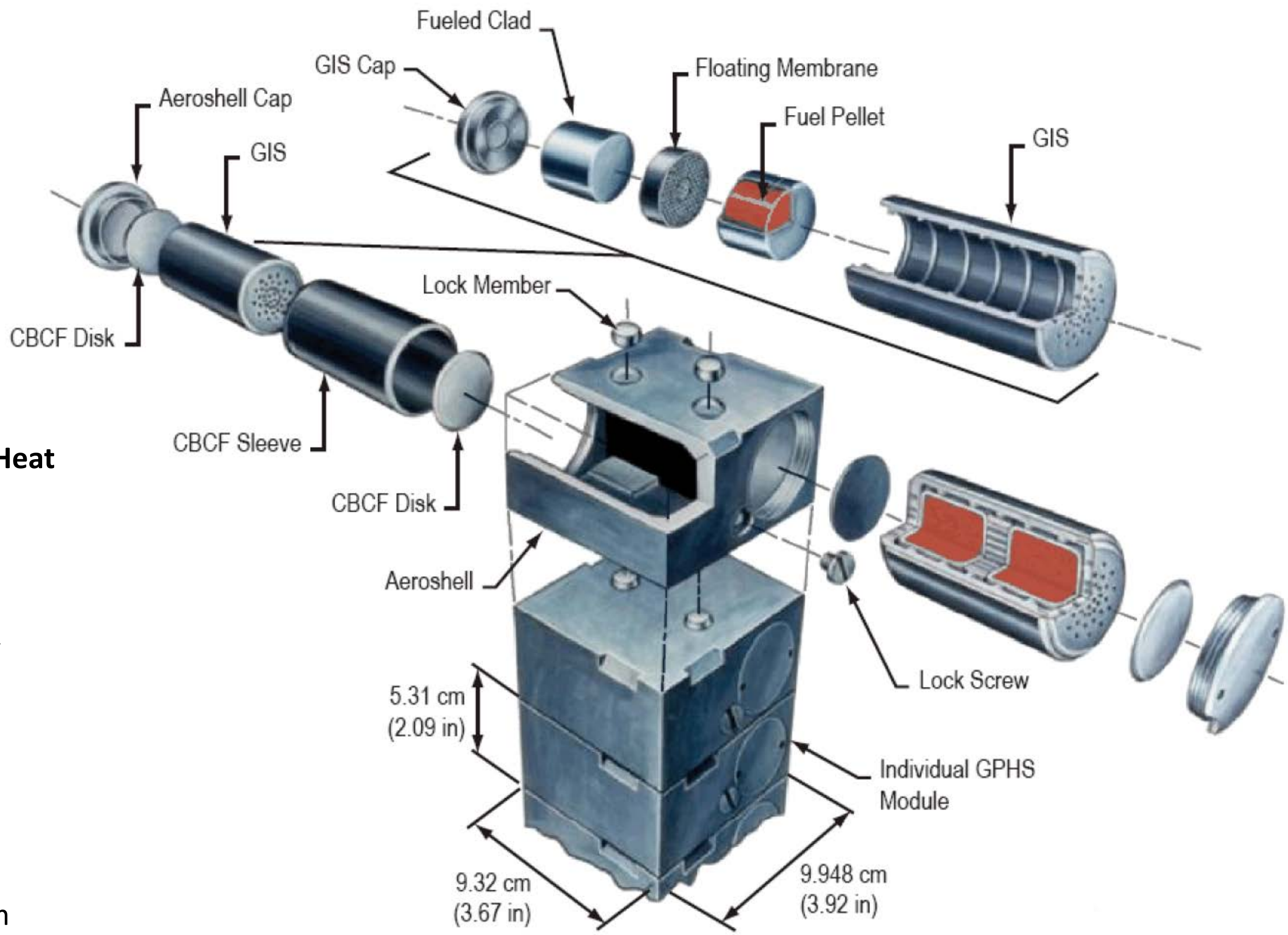




USA Advanced Stirling Radioisotope Generator (Not yet flown) 100 to 130W_e ~32kg.

Employs two Sunpower free-piston Stirling engines with linear alternators

Radioisotope Power Systems



USA General Purpose Heat Source (GPHS).

Per GPHS module:

Thermal power: 250 W

Mass: 1.6 kg

PuO_2 : 0.6 kg

Pu: 0.52 kg

^{238}Pu: 0.44 kg

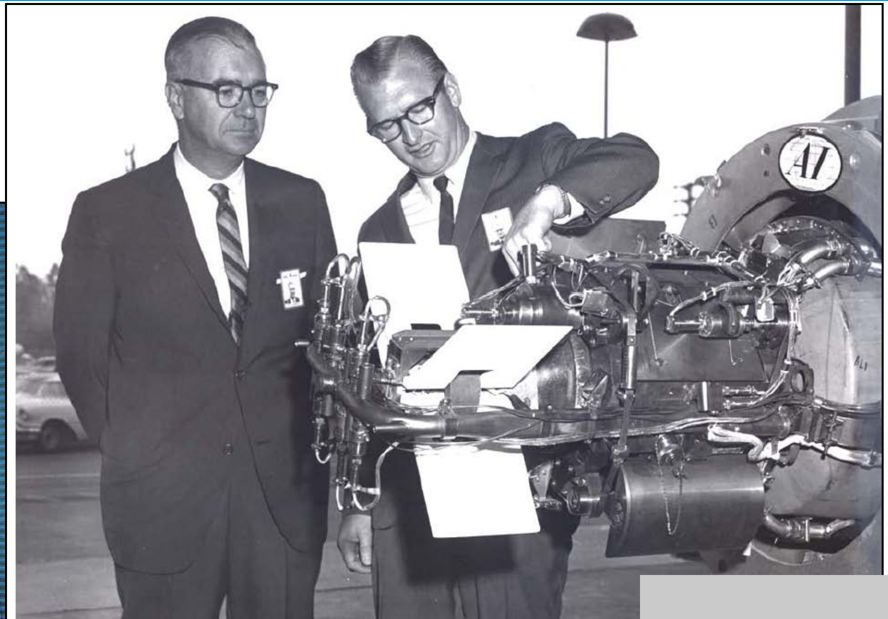
99mm x 93mm x 58mm

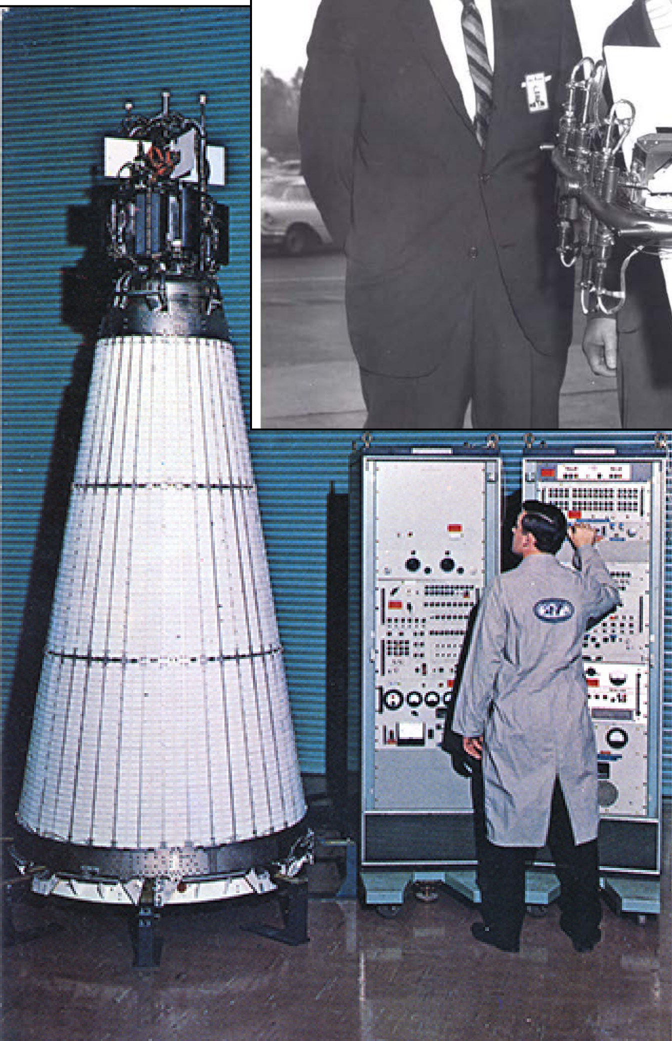
RTG Flights

USA = Black USSR/Russia = Blue

Year	Mission / Spacecraft Name	Spacecraft Type	RTG Type & Power (W_e)	Mass of one RTG (kg)	Spec. Power (W / kg)	Approx. Effic. (%)
1961	Transit 4A & 4B	Satellite (Navy Nav.)	SNAP-3B. 2.7W	2.1	1.3	5.1
1963-64	Transit 5BN-1 & 5BN-2 [5BN-3 = Launch fail]	Satellite (Navy Nav.)	SNAP-9A. >25W	12.2	2.0	5.1
1965	Cosmos 84 & 90 (USSR)	Satellite (Navigation?)	"Orion-1" RTG. ^{210}Po- 20W	14.8	1.35	Not known
1968	Nimbus-B1 (Launch failure)	Meteorological satellite	SNAP-19B. 2 x 25W	13.5	1.9	5.4
1969	Nimbus-3	Meteorological satellite	SNAP-19B. 2 x 25W	13.5	1.9	5.4
1969 - 1972	Apollo 12 thro'17 (Apollo 13 RTG re-entry)	Lunar Surface (Experiment Package)	SNAP-27. >70W	30.8 (without cask)	2.3	5.0
1972	Transit TRIAD	Satellite (Navy Navigation)	Transit RTG. 35W	13.5	2.6	4.2
1972-73	Pioneer 10 & 11	Interplanetary - asteroid belt, Jupiter, Saturn.	SNAP-19. 4 per sat. @ 40W each	13.6	2.9	5.4
1975	Viking 1 & 2	Mars Lander	SNAP-19. 2 per lander @ 42W each	13.6	3.1	5.4
1976	Lincoln LES 8 and LES 9	Comms. Satellite	MHW-RTG. 2 per sat. @ 154W each.	38.5	4.0	6.6
1977	Voyager 1 & 2	Interplanetary – Jupiter, Saturn, Uranus, Neptune.	MHW-RTG. 3 per S.C. @ 158W each.	38.5	4.1	6.6
1989	Galileo	Interplanetary - Jupiter	GPHS-RTG. 2@ 288W each	56	5.1	6.6
1990	Ulysses	Interplanetary - Sun	GPHS-RTG. 289W.	56	5.2	6.6
1996	Mars '96 (Russia). (Launch failure)	Mars Landers & penetrators	Angel RTG 150mW. 8 in total.	0.5	0.3	1.7
1997	Cassini	Interplanetary - Saturn, Titan	GPHS-RTG. 3@ 295W each	56	5.3	6.6
2006	New Horizons	Interplanetary – Pluto.	GPHS-RTG. 246W.	58	4.2	6.6
2012	Mars Science Laboratory - *Curiosity*	Mars Rover	MMRTG. 125W.	44	2.8	6.25

Space Fission Reactor Power Systems





The only U.S. fission reactor to fly in space was the SNAP-10A:

- Thermal reactor, U-ZrH_x fuel in Hastelloy-N cladding, NaK coolant.
- $40kW_t$, Si-Ge thermoelectric power converter, ~$550W_e$. ~ 440 kg.
- Launched 1965 on the SNAPSHOT spacecraft, which also contained an experimental ion thruster.

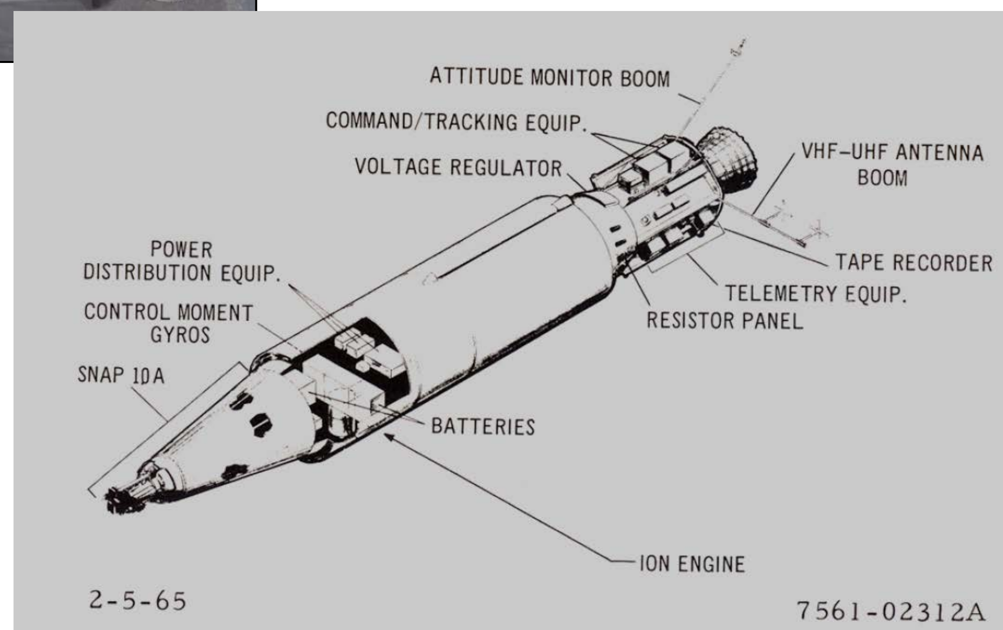


Figure 5. Spacecraft Configuration

Space Fission Reactor Power Systems

The USSR made more extensive use of fission reactors, all for military surveillance satellites, with lifetimes ranging from a few days to a few months. (Low orbits – at end of life the nuclear reactor module was ejected and boosted to a safe higher orbit – the rest of the satellite would re-enter)

- ~35 launched between 1967 and 1988.
- Earlier BUK / Romashka models (<1 kW_e)
  - Fast-spectrum, UC_2 fuel, Si-Ge thermoelectric power conversion. NaK cooled (?).
- Later TOPAZ models (5 – 10 kW_e)
  - Epithermal spectrum, NaK coolant, Hollow geometry UO_2 fuel incorporating in-core thermionic power conversion.
  - Were the subject of a technology transfer cooperation in the 1990s with USA, UK, France – some models tested in Albuquerque.
- KOSMOS 594
  - In January 1978, the reactor eject and orbit-boost function of this ocean recon satellite failed. The reactor re-entered over Canada, causing contaminated debris to be spread along a ~ 370 mile path.

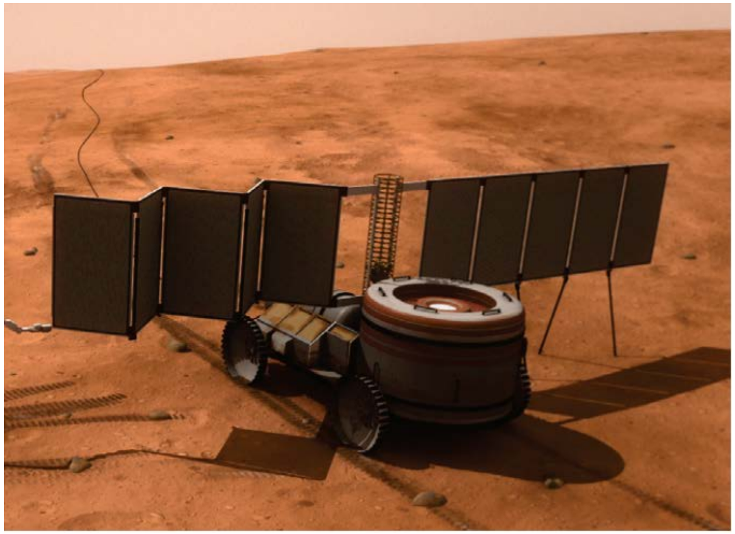
TOPAZ-II (USSR)

Space Fission Reactor Power Systems

Improved solar generation technology means reactors are no longer relevant for Earth orbit applications. In modern times, they are seen as an exciting enabling technology for large-scale exploration missions:

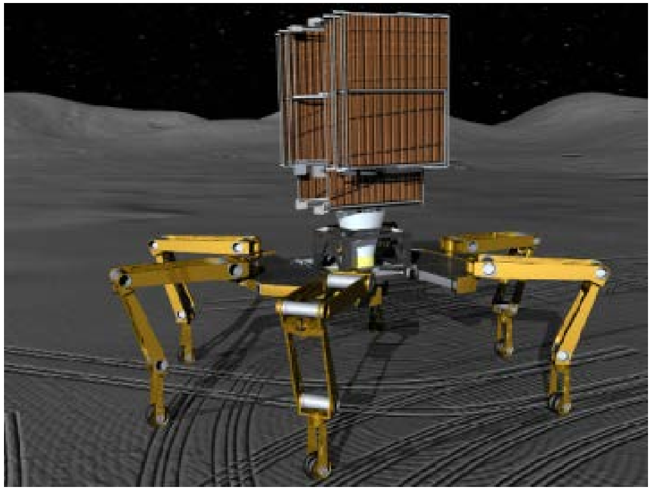
- Power for moon or Mars bases?
- Power for electrical thrusters on interplanetary craft?

Studies and design exercises have produced credible reactor concepts in the power range ~1kW ~ 1MW.



Moon and Mars surface reactor concepts are common in the literature. Use of the local material for shielding is a common assumption…

NASA's Fission Surface Power System is the most advanced development programme in this field:



Nuclear Rockets (Nuclear Thermal Propulsion)

This involves the direct heating of a propellant gas (such as H_2) within the reactor core, which is ejected from a nozzle to provide thrust.

From 1955 to 1973 the USA was engaged in development of nuclear rocket engines in the *Rover/NERVA* programme.

The development reactor families were known as KIWI, NRX, PHOEBUS and PEWEE. The PHOEBUS-2A reactor ran at over 4GW thermal power for 12 minutes in June 1968.

The low molecular mass of H_2 means that the *specific impulse* (propellant economy) of the NTP engine can be ~double that of chemical rockets.

NTP engines were foreseen to power spacecraft from LEO onwards, not for launch.

The programme was cancelled before a nuclear rocket was flown.

Pheobus NTP Engine (USA)

NERVA NTP Engine (USA)

Nuclear Rockets (Nuclear Thermal Propulsion)

Nuclear thermal propulsion has never been used in space, but continues to feature strongly in studies and mission concepts relating to "future generation" space exploration, such as human exploration beyond the Earth/Moon system.

Most (all?) credible concepts for human (return) travel to Mars include nuclear propulsion.

Nevada Test Site in 1962.