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Title: Mission: Space Plutonium-238 Heat Sources for NASA

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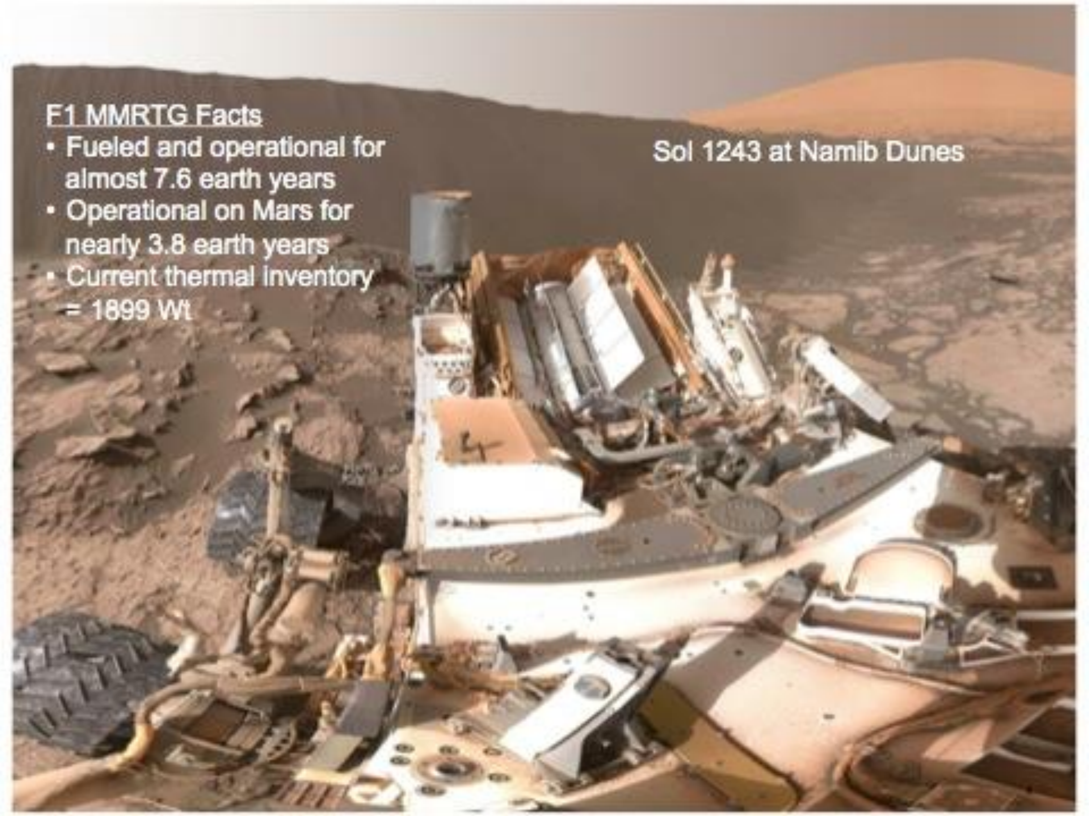

Mars Rover Selfie

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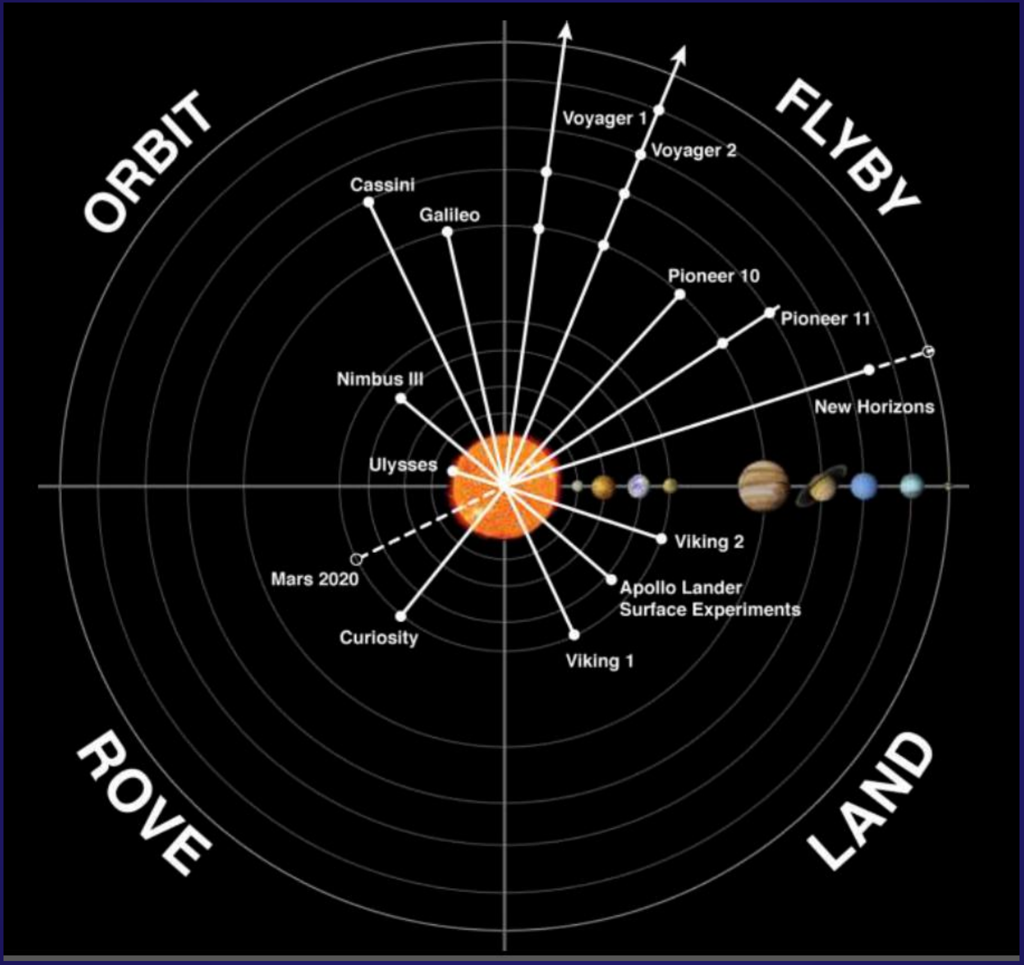
Mission: Space Plutonium-238 Heat Sources for NASA

Pu-238 Engineering & Manufacturing Team

<iframe width="560" height="315" src="https://www.youtube.com/embed/UajVjnYiPvA" frameborder="0" allowfullscreen></iframe>

Date: June 6, 2016

NASA Missions Powered by Radioactive Power Sources



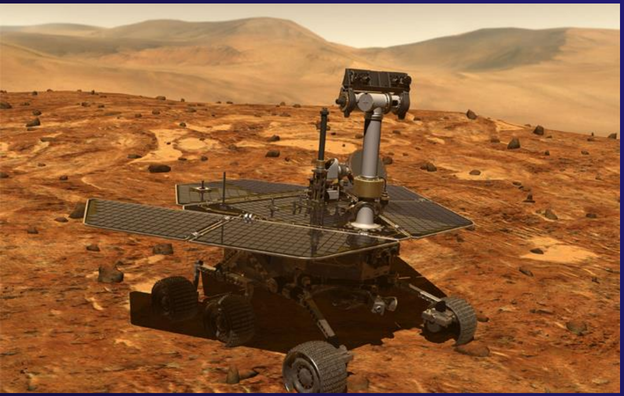
Source:
http://sites.nationalacademies.org/cs/groups/ssbsite/documents/webpage/ssb_087114.pdf

NASA Missions Powered by Radioactive Power Sources

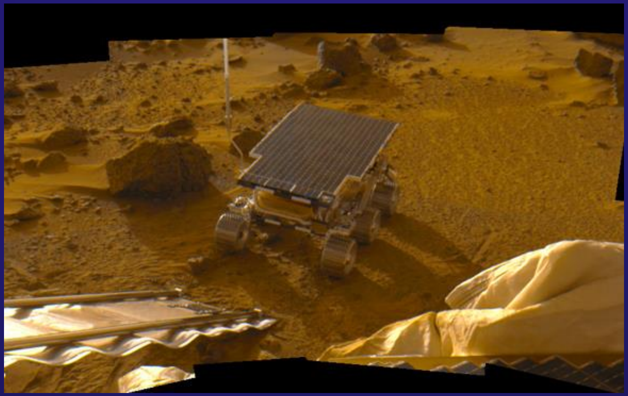
- Nimbus III

- Apollo Surface Experiments

- Viking Mars Landers



- Mars Exploration Rovers

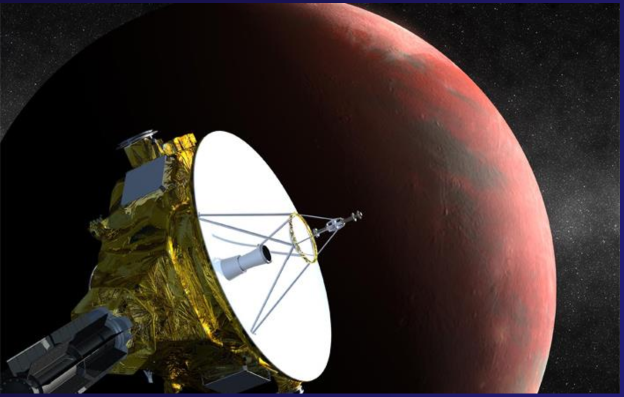


- Mars Pathfinder Rover

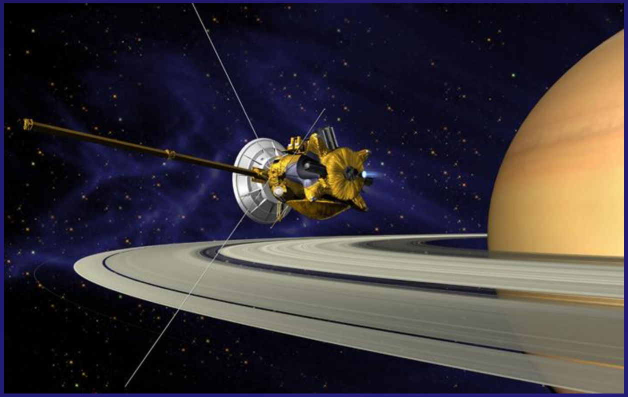
- Mars Science Laboratory

Source: https://solarsystem.nasa.gov/rps/discovery.cfm

NASA Missions Powered by Radioactive Power Sources



- New Horizons

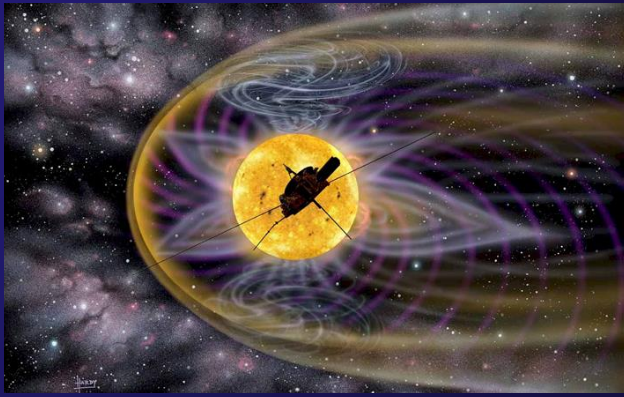


- Cassini

- Pioneer 10 & 11

- Galileo

- Voyager 1 & 2



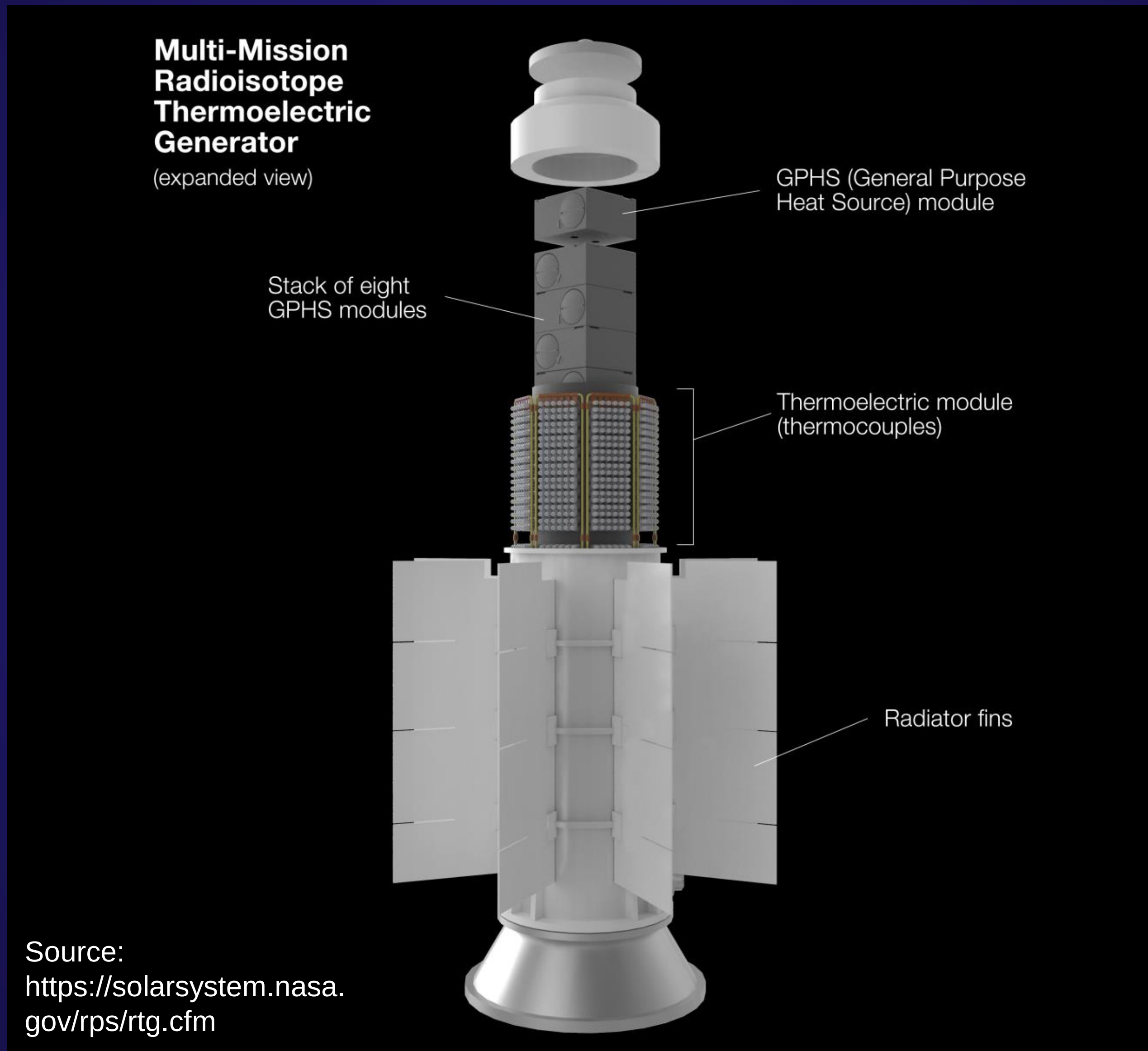
- Ulysses

Source: https://solarsystem.nasa.gov/rps/discovery.cfm

New Horizons’ Radioisotope Power System (RPS)

The New Horizons spacecraft, with its radioisotope power system attached (circled), is prepared for its January 2006 launch to explore Pluto and the Kuiper Belt, starting in 2015.
Source: https://solarsystem.nasa.gov/rps/docs/APP%20RPS%20Safety%20Fact%20Sheet%205-21-12%20v2.pdf

Multi-Mission Radioisotope Thermoelectric Generator



Seebeck Effect

- https://www.youtube.com/watch?v=OuSNlk7JnBc
- <iframe width="420" height="315" src="https://www.youtube.com/embed/OuSNlk7JnBc" frameborder="0" allowfullscreen></iframe>

Demo – Thermoelectric Generator

Criteria for selection of isotopes

The radioactive material used in radioisotope thermal generators (RTGs) must have several characteristics:

- **Have a high specific power**
- **Half-life between 15 to 100 years**
- **Radiation easily absorbed and transformed into thermal radiation, preferably alpha radiation.**
- **Low neutron, beta, and gamma radiation emissions**
- **Insoluble form, not readily absorbed into the body**
- **Be stable at high temperatures**

Table of Possible Radioisotopes

Primary Emission Produced BY Radioisotopes with Half-lives of 15 to 100 Years

Isotope	Half-Life (years)	Type of Primary Emissions
Promethium-145 (Pm-145)	18	gamma
Halfnium-178m (Hf-178m)	31	gamma
Bismuth-207 (Bi-207)	33	gamma
Europium-150 (Eu-150)	37	gamma
Titanium-44 (Ti-44)	47	gamma
Platinum-193 (Pt-193)	50	gamma
Terbium-157 (Tb-157)	99	gamma
Actinium-227 (Ac-227)	22	beta, some alpha
Niobium-93m (Nb-93m)	16	beta, gamma
Lead-210 (Pb-210)	22	beta, some alpha
Strontium-90 (Sr-90)	29	beta
Cesium-137 (Cs-137)	30	beta, gamma
Argon-42 (Ar-42)	33	beta
Tin-121m (Sn-121m)	55	beta
Samarium-151 (Sm-151)	90	beta
Nickel-63 (Ni-63)	100	beta
Curium-244 (Cm-244)	18	alpha, spontaneous fission
Curium-243 (Cm-243)	29	alpha, gamma
Uranium-232 (U-232)	72	alpha, spontaneous fission
Gadolinium-148 (Gd-148)	75	alpha
Plutonium-238 (Pu-238)	88	alpha, spontaneous fission

SOURCE: Department of Energy, information memorandum and associated transmittal memorandum to S-1 from NE-1 on the subject of "Alternatives to Plutonium-238 for Space Power Applications," dated August 4, 1992, Office of Nuclear Energy, Science, and Technology, Washington, D.C., Table 1, updated.

Characteristics of Pu-238 and Cm-244 Isotope Fuels

Isotope	Plutonium-238	Curium-244
Half-life	87	18.1
Type of emission	Alpha	Alpha
Activity (curies/watt)	30.73	29.12
Fuel form	PuO_2	Cm_2O_3
Melting point (°C)	2,150	1,950
Specific power (watt/g)	0.40	2.42
Power density (watt/cc)	4.0	26.1
Radiation levels		
Gamma dose rate (mR/hr @ 1m)	~5	~900
Gamma shield thickness[a] (cm of uranium)	0	5.6
Fast neutron flux @ 1m (n/cm^{2}sec)	260	116,000

NOTE: mR, milliroentgen.
[a] Gamma shielding to reduce dose rates to ~5 mR/hr @ 1m (equivalent to Pu-238)
SOURCE: Department of Energy, information memorandum and associated transmittal memorandum to S-1 from NE-1 on the subject of "Alternatives to Plutonium-238 for Space Power Applications," dated August 4, 1992, Office of Nuclear Energy, Science, and Technology, Washington, D.C., Table 2.

What is a half-life?

Half-Life Equation:

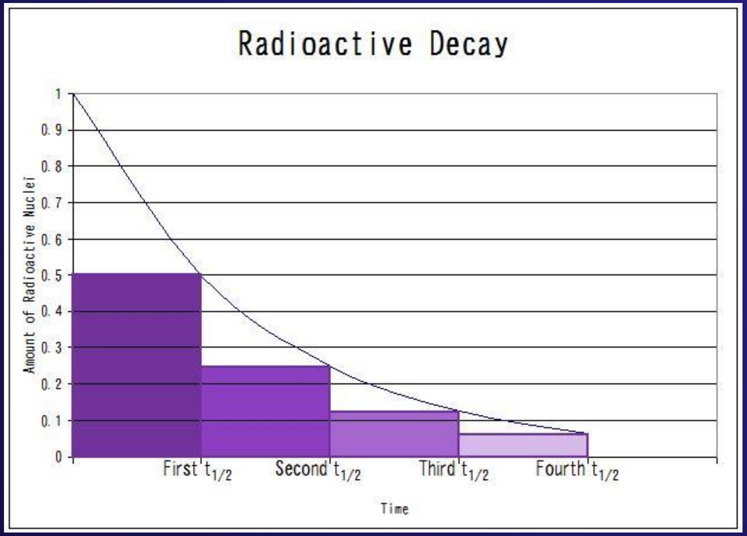
$$T_{1/2} = \ln 2/\lambda$$

$T_{1/2}$: half-life
λ: Decay constant

Radioactive Decay Equation:

$$A = A_0 e^{-\lambda t}$$

A: Activity
A_0: Initial activity

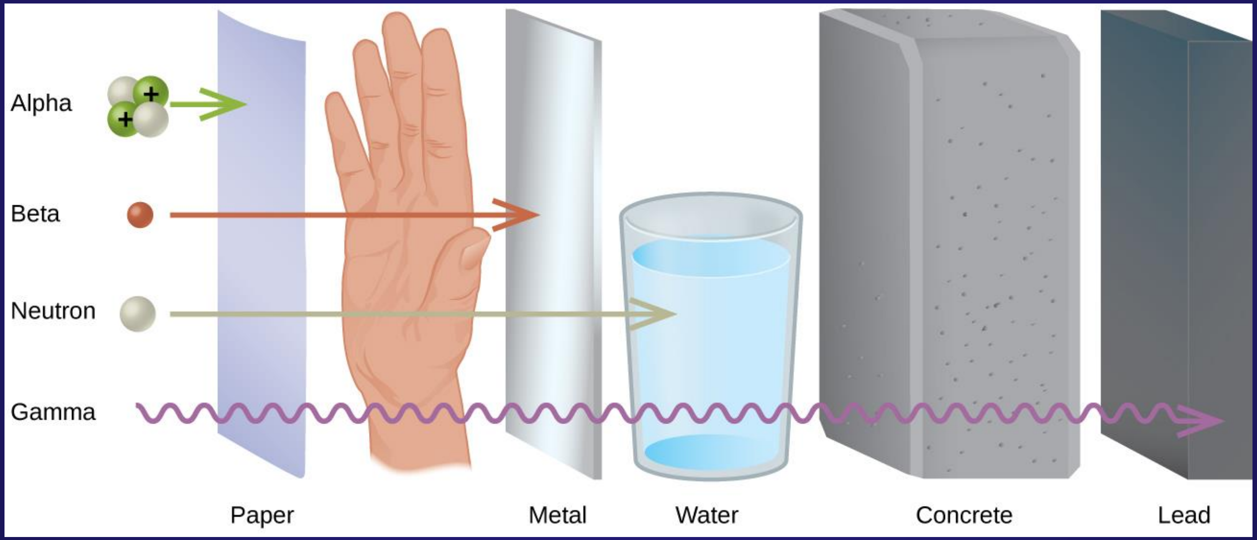


Source: http://chemwiki.ucdavis.edu/Core/Physical_Chemistry/Nuclear_Chemistry/Radioactivity/Radioactive_Decay_Rates

Number of half-lives elapsed	Fraction remaining	Percentage remaining
0	$^1/_1$	100
1	$^1/_2$	50
2	$^1/_4$	25
3	$^1/_8$	12.5
4	$^1/_{16}$	6.25
5	$^1/_{32}$	3.125
6	$^1/_{64}$	1.563
7	$^1/_{128}$	0.781
...	...	...
n	$^1/_{2^n}$	$100/(2^n)$

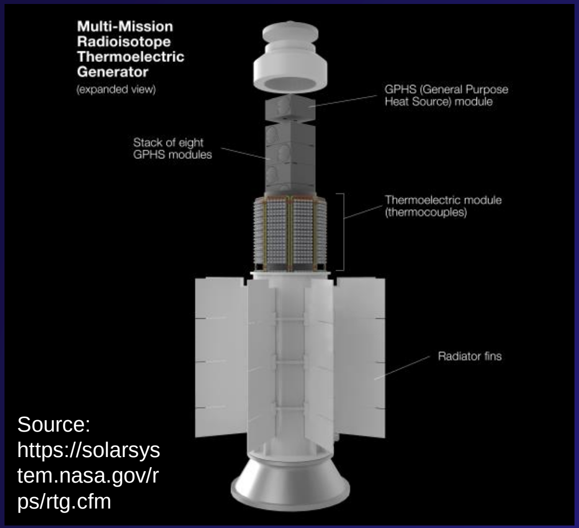
Source: https://en.wikipedia.org/wiki/Half-life

Types of Radiation

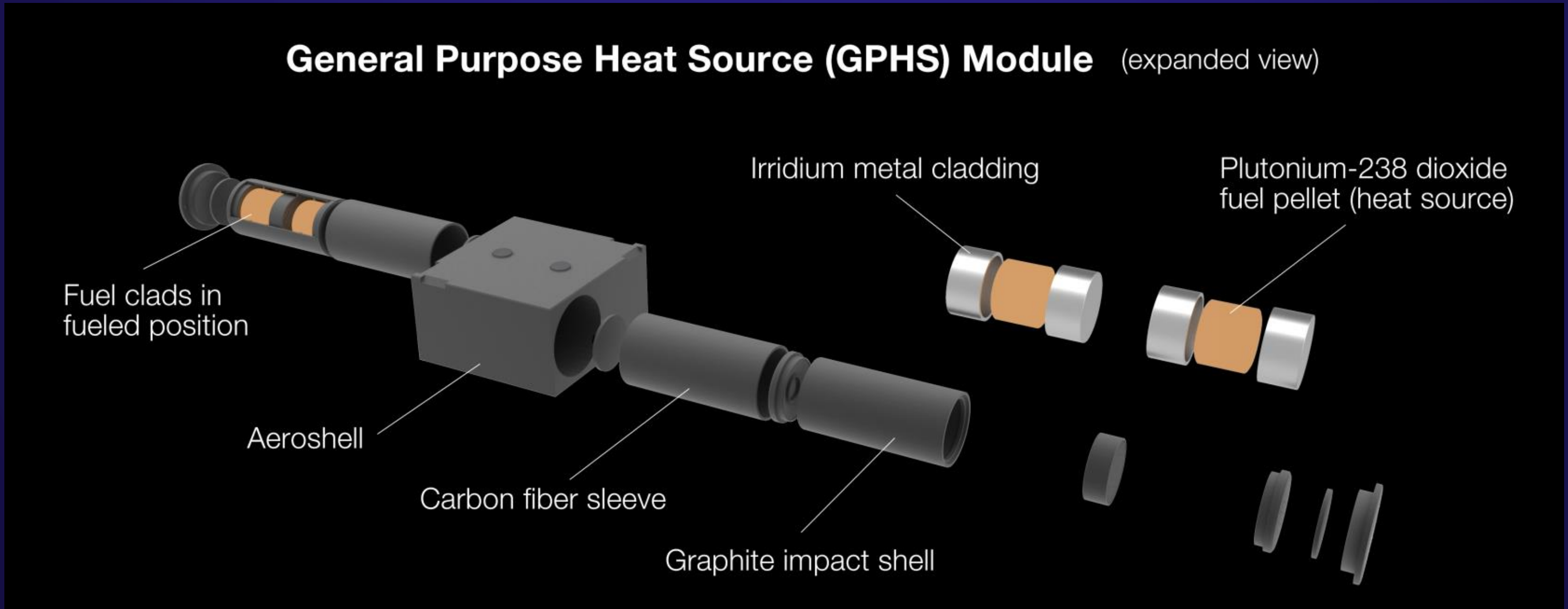


Source: http://chemwiki.ucdavis.edu/Textbook_Maps/General_Chemistry_Textbook_Maps/Map%3A_General_Chemistry_%28Petrucci_et_al.%29/25%3A_Nuclear_Chemistry/25.10%3A_Effect_of_Radiation_on_Matter

General Purpose Heat Source (GPHS) Module



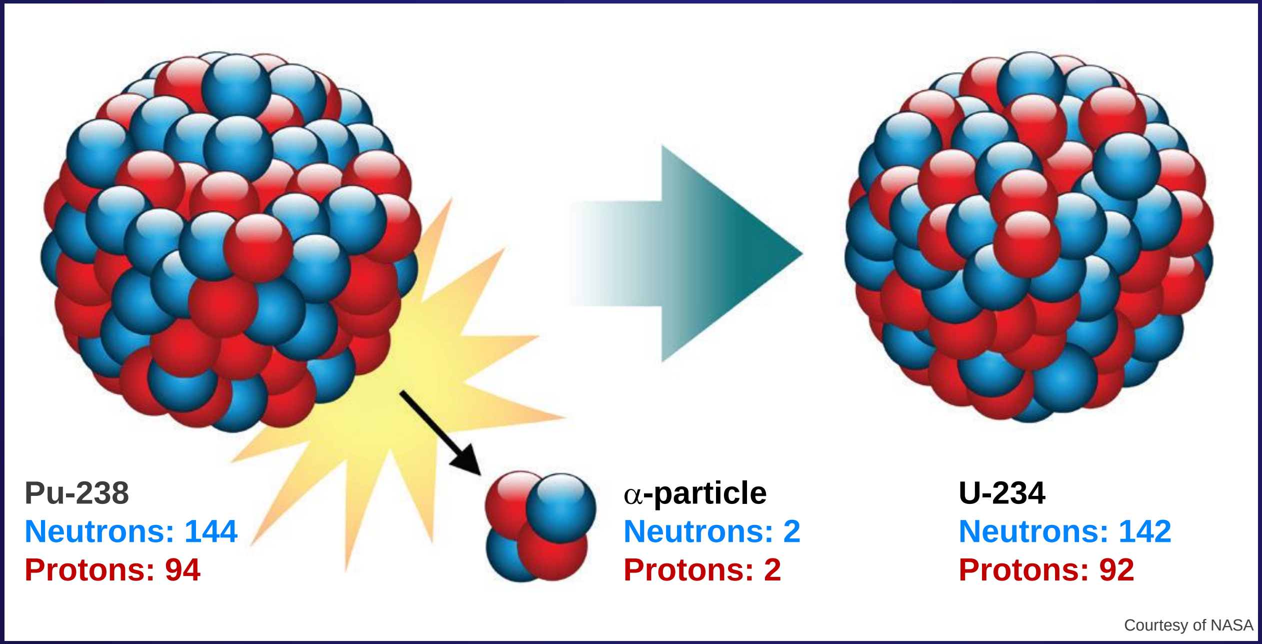
Source: https://solarsystem.nasa.gov/rps/rtg.cfm



Source: https://solarsystem.nasa.gov/rps/types.cfm

Why is plutonium dioxide used

- Fractures in large, non-inhalable chunks
- Highly insoluble
- Non-reactive
- Decays by α emission

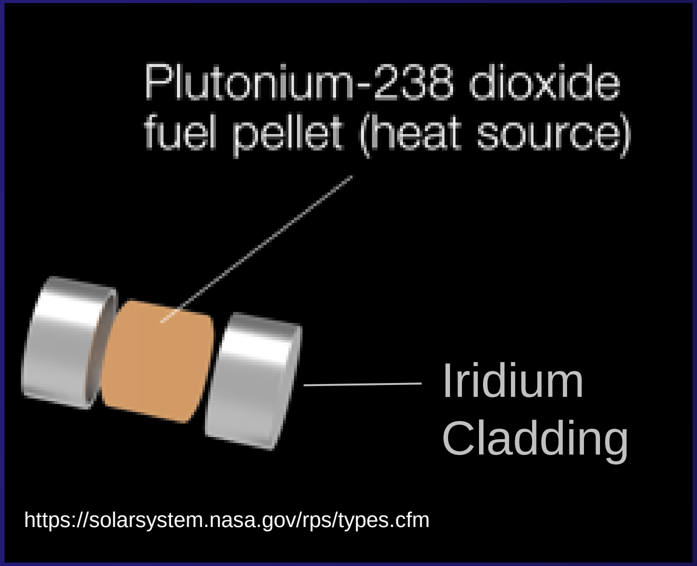


Radioactive decay of a Pu-238 atom emits an alpha particle (identical to a helium nucleus).This process, occurring constantly within a sample of plutonium, heats the material.

Source: https://solarsystem.nasa.gov/rps/docs/APP%20RPS%20Pu-238%20FS%2012-10-12.pdf

Why use iridium cladding?

- Chemically compatible with plutonium dioxide fuel pellet and graphite impact shell
- Strong and ductile at high temperatures (deforms before it breaks)
- Corrosion-resistant
- High melting point



Courtesy of NASA

Other Safety Features

- **Plutonium oxide is a highly insoluble, heat resistant ceramic**
- **Fuel is stored in individual modular units with their own heat shielding**
- **Fuel is surrounded by iridium cladding and graphite block which are corrosion and heat resistant**
- **Graphite block is surrounded by aeroshell designed to protect from heat from reentering Earth's atmosphere**

Photo showing the Nimbus B-1 spacecraft's power source on the seafloor where its fuel was recovered intact, as designed, and reused on NASA's Nimbus III spacecraft.
Source: https://solarsystem.nasa.gov/rps/safety.cfm

Working with Pu-238

- Processing done in glovebox
- Small viewing windows required for structural stability of gloveboxes
- Special gloves used to reduce exposure
- Tantalum coated vessels needed to prevent reactions with Pu
- Insulated gloves needed for some operations

Demo – Glovebox Simulations

Can depleted uranium be used as heat source?

Isotope	*E*	$T_{1/2}$	*M*	*P'*
Uranium -238	4.27	1.41×10^{17}	238	8.50×10^{-09}
Plutonium-238	5.60	2.77×10^{09}	238	5.67×10^{-01}
Plutonium-239	5.24	7.61×10^{11}	239	1.93×10^{-03}

$$P' = \frac{6.68 \times 10^{36}\, E}{T_{1/2} M}$$

P': specific power in Watts/gm

E: energy released per disintegration in MeV

$T_{1/2}$: half-life of radioisotope in seconds

M: molar mass of radioisotope in g/mol

Source:http://mragheb.com/NPRE%20402%20ME%20405%20Nuclear%20Power%20Engineering/Radioisotopes%20Power%20Production.pdf

Mars Missions

- https://www.youtube.com/watch?v=Ki_Af_o9Q9s