JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Radioisotope Power Systems for Deep Space Exploration – Some Background

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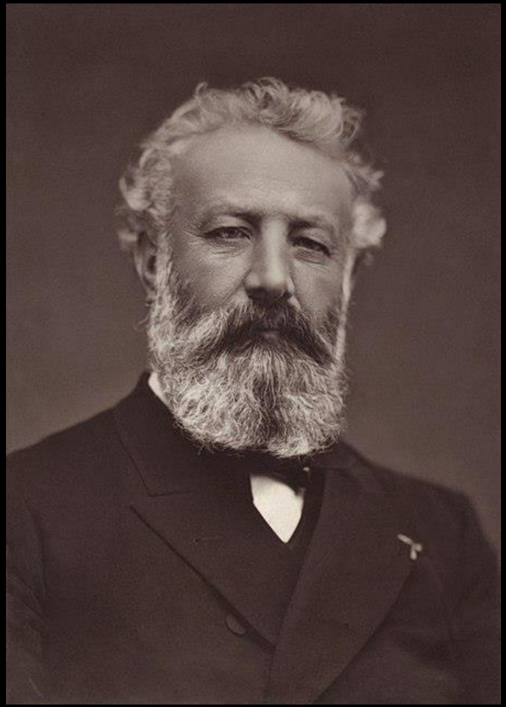
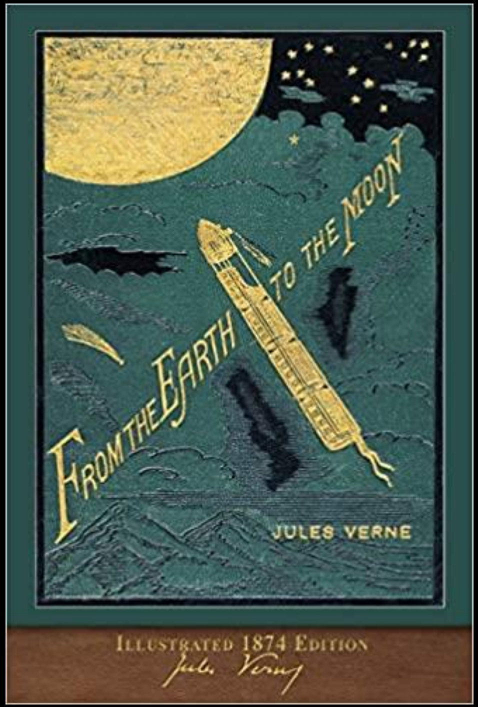
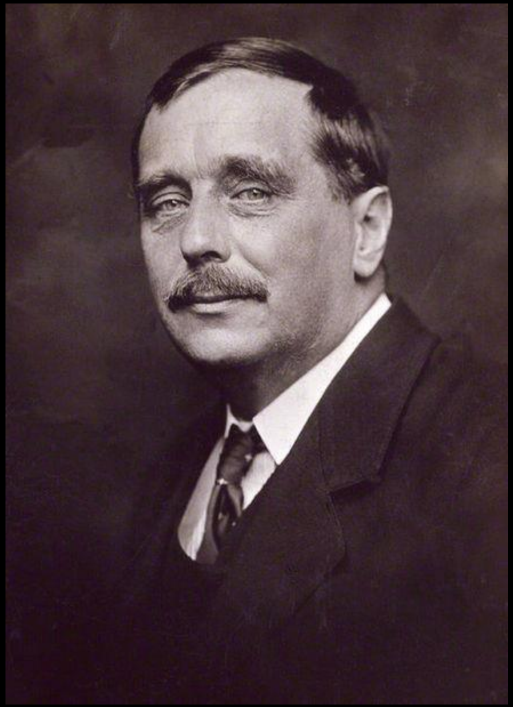
Planetary Science and Astrobiology Decadal Survey 2023-2032: Panel on Ocean Worlds and Dwarf Planets
Meeting 19

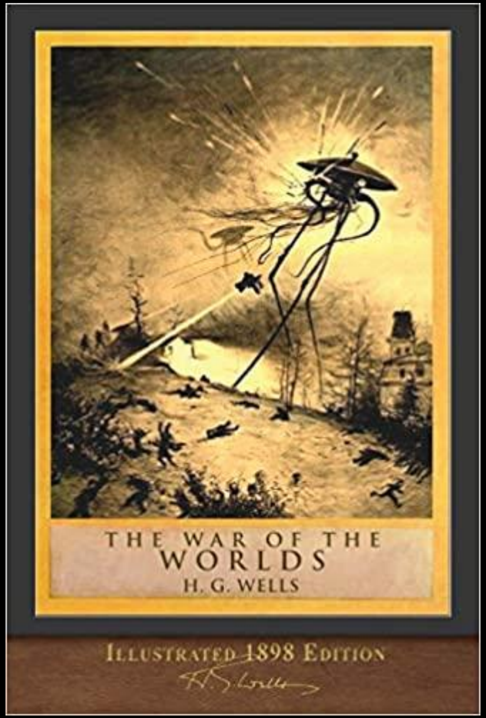
Friday 5 March 2021
20 minutes (withing 1:30 PM – 2:30 PM EST)

In the beginning, there is a confluence of ideas and people ("TRL 0") …









Jules Verne (1828 – 1905):
From the Earth to the Moon 1865

H. G. Wells (1866 – 1946):
The War of the Worlds 1898

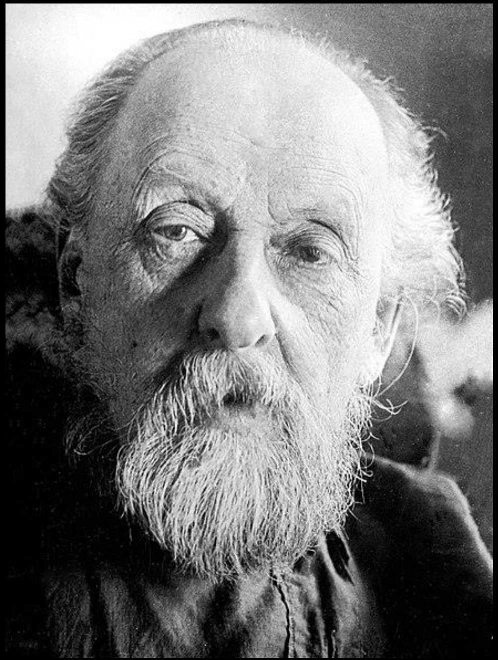
… and knowledge (TRL 1) …

Acc. 90-105 - Science Service, Records, 1920s-1970s, Smithsonian Institution Archives

Pierre Curie (1859-1906) and
Marie Sklodowska Curie (1867-1934

Jointly awarded the Nobel Prize for Physics in 1903 for discovery of the radioactive elements polonium and radium

…which inspire those who follow (TRL 2)



Konstantin Eduardovich Tsiolkovsky
Константин Эдуардович Циолковский
1857 - 1935

INVESTIGATION OF OUTER SPACES BY ROCKET DEVICES - 1911

…were it possible to accelerate sufficiently the disintegration of radium or other radioactive bodies, … then its use might give - in similar other conditions, … a velocity of the reactive device, by which access to the closest Sun (star) would come down to 10 – 40 years… a pinch of radium would be sufficient, to enable the rocket weighing a ton, to break all relations with the solar system."

"It may be, that with the help of electricity, it will be possible by and by, to impart tremendous velocity to the particles, being ejected from the reactive devices."

THE ULTIMATE MIGRATION – 14 January 1918

"Will it be possible to travel to the planets which are around the fixed stars, when the Sun and the Earth have cooled to such an extent that life is no longer possible on the Earth?
To answer this question, it is necessary to answer two others; first, will it be possible to unlock, and control, intraatomic energy?..."

"If it is possible to unlock, and to control, intra-atomic energy, or even to store up to great quantities of energy in artificial atoms, the transportation can be a comparatively simple matter."

Robert Hutchings Goddard
1882 - 1945

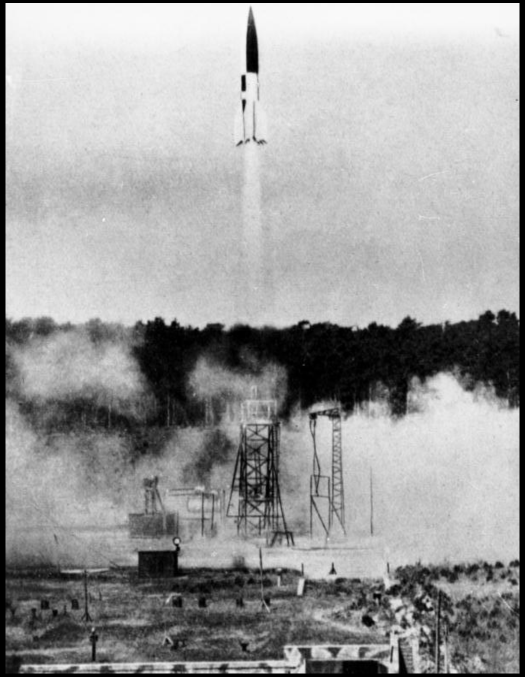
Mission Need + Demonstrated prototypes Led to Funds to go to the Next Level (TRL 3)

Parts from World War II

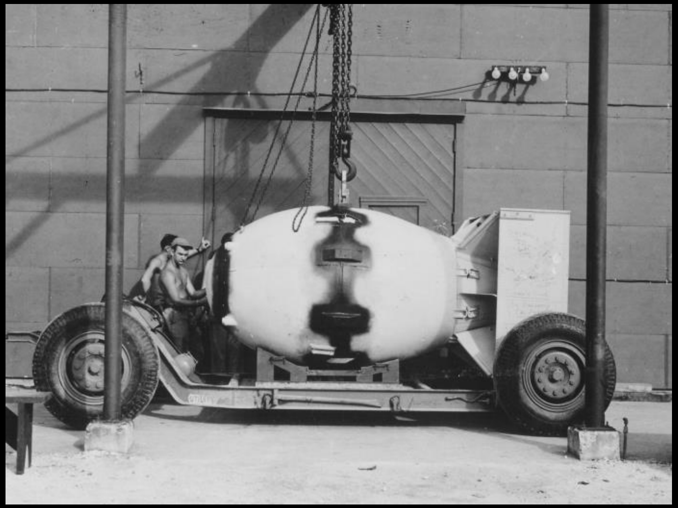
Rockets

Po-210 aka radium F "initiators"

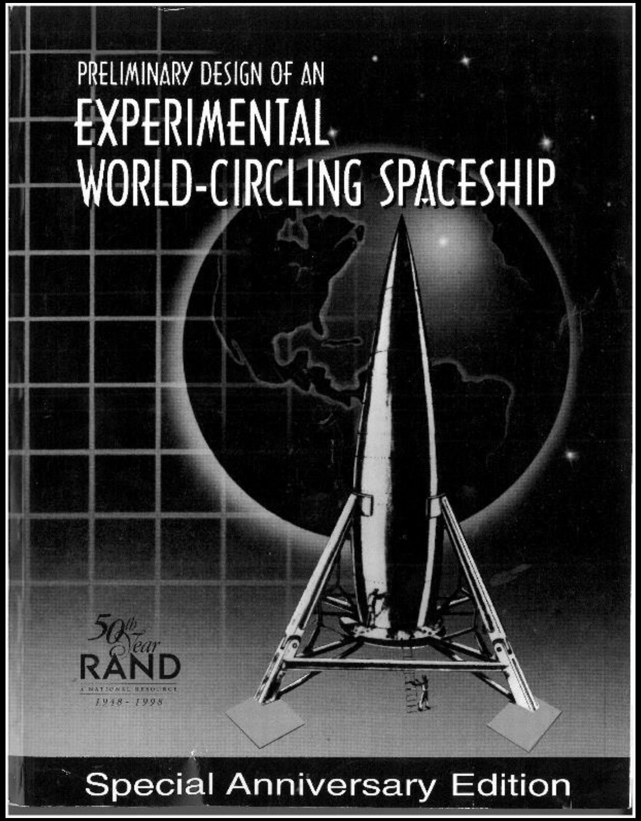
Mission need for "Cold War"
500 W electric power supply for satellite (SNAPs for Project Feed Back)

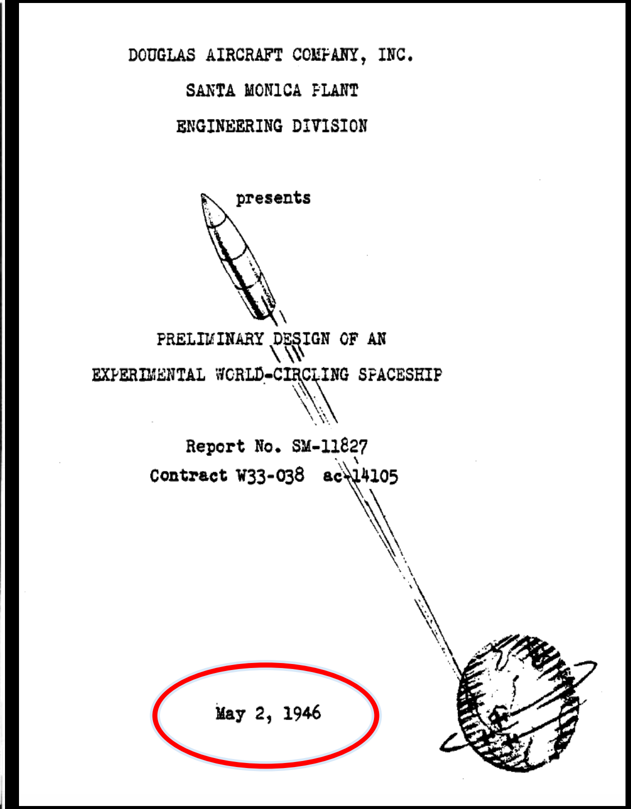


V2 (1943)
German



"Fat Man" (1945)
American





By-products of the Cold War

- Pu-239 is *NOT* what concerns NASA (or the rest of this talk)
- Production of transuranic elements is not a “clean” process – there are also other elements and/or isotopes produced that were not the point of production
  - Indeed such materials are effectively contaminants that need to be “filtered” out
  - Such “filtering” is typically done chemically, by trading production times in reactors (exposure to neutron fluxes), against isotope buildups and decay products
  - Direct physical separation of isotopes on an industrial scale is difficult – and has only been implemented for increasing the U-235 concentration with respect to U-238 in uranium ore
- Two by-products of Pu-239 production were the transuranic isotopes of neptunium (Np) and plutonium Np-237 and Pu-238

Origin of RPSs in the U.S. was with Po-210 fuel

- Research began at Mound Facility in Miamisburg, Ohio
  - Operated from 1948 to 2003
  - 182 acres

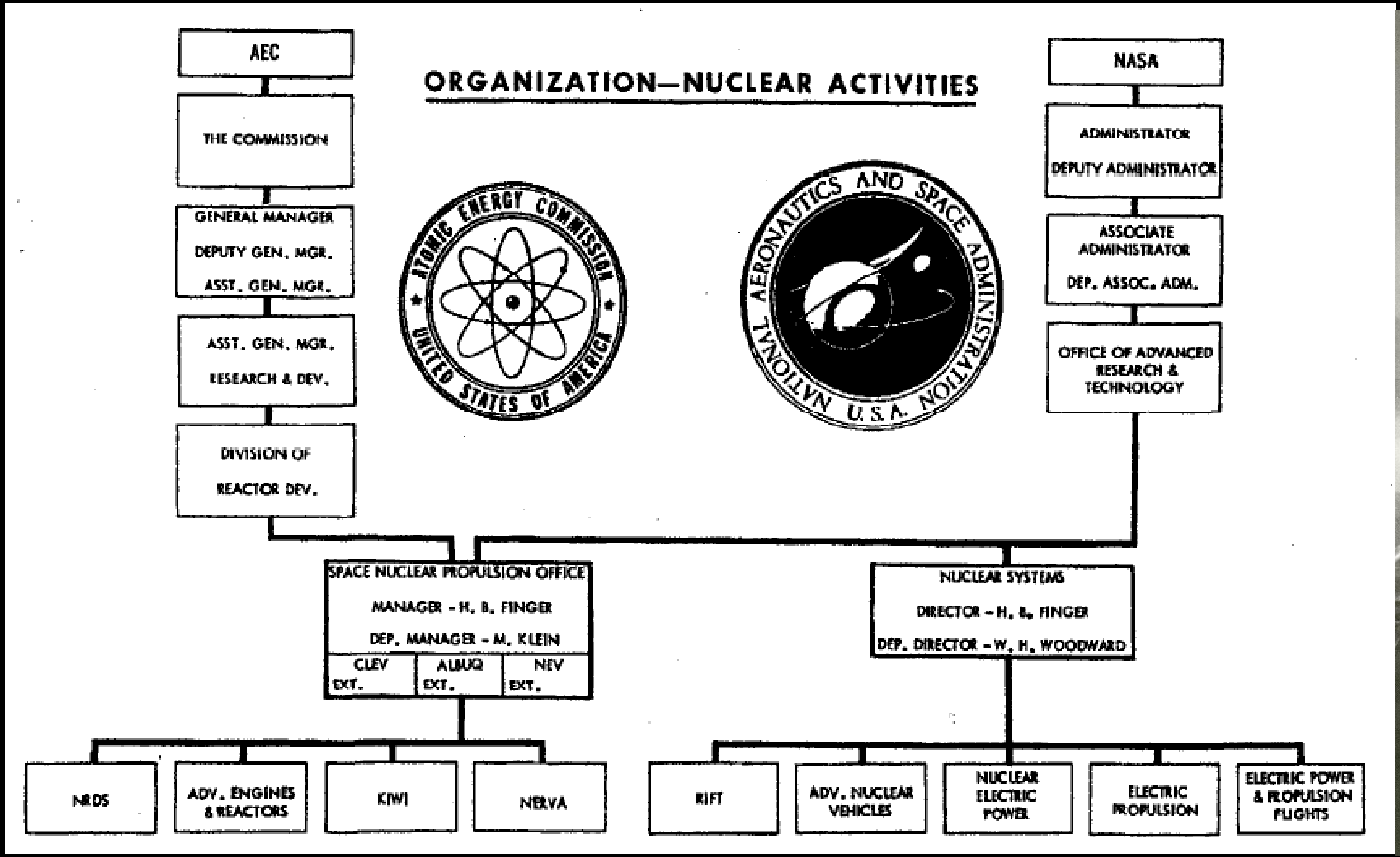
- Polonium-210 was investigated as an intense source of alpha particles beginning in 1942
  - 1954 – program to generate electricity from Po-210
  - 1956 - conceptual design using a mercury boiler
  - 1958 - RTG powered by polonium-210

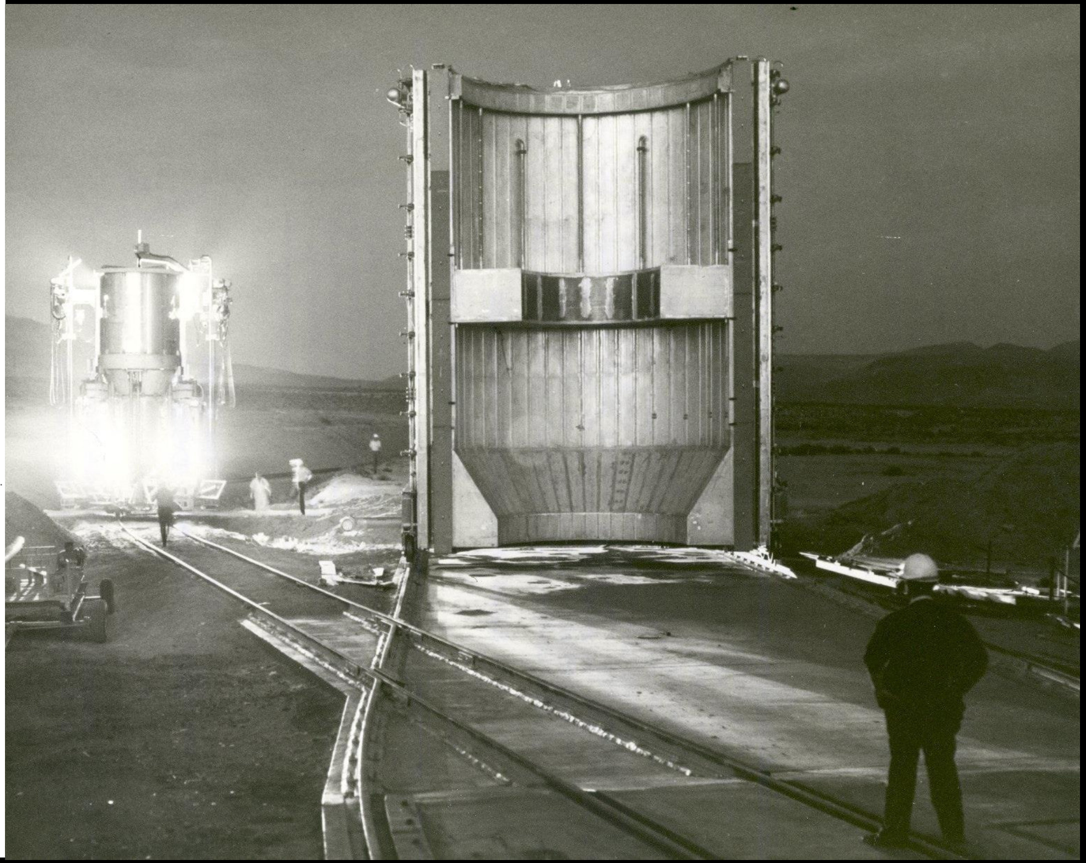
- Po-210
  - 120 watts per gram
  - Half-life of 138 days limited usefulness for space probe missions
  - Research and production at Mound phased out in 1971

- Gadolinium polonide (GdPo) developed as fuel

Space Nuclear Propulsion Office (SNPO): 1961 - 1973

- Main task: Nuclear Engine for Rocket Vehicle Application (NERVA) program
  - Nuclear thermal rocket engine development program that ran for roughly two decades. Its principal objective was to "establish a technology base for nuclear rocket engine systems to be utilized in the design and development of propulsion systems for space mission application"
- The RPS power program was a small part of SNPO through 1973





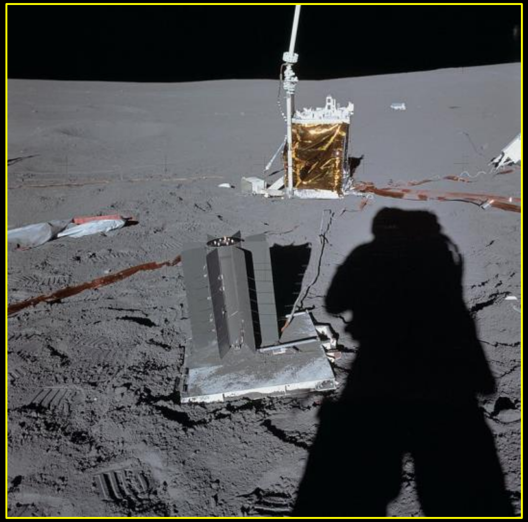
Radioisotope Power Systems (RPS)

- An **enabling technology for providing power** to satellite systems in cases for which solar power is impractical or absent altogether
  - Used in space as well as in naval and other applications

- Invented in the U.S. over 60 years ago and we have invested ~$4.7 billion (FY2011) to date in perfecting this technology

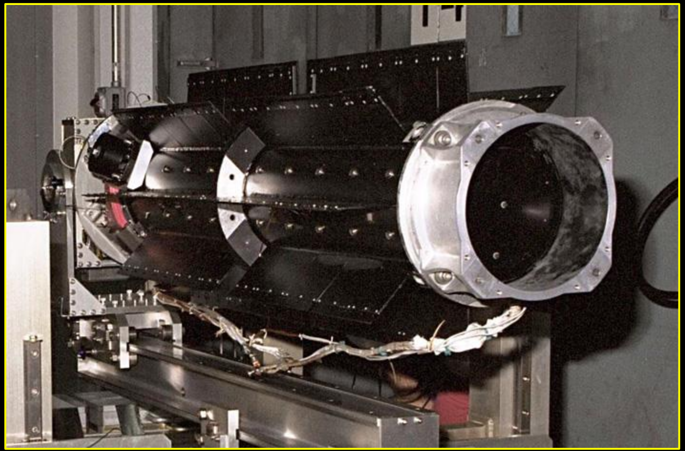
- Also radioisotope heater units (RHUs) used to keep spacecraft components warm

- **Development, infrastructure, and production now financially supported by NASA Planetary Science Division (~$150 M / year)**



Above left – RHUs
Above right – SNAP 27 on Moon (Apollo 14)
Below – RTG for Cassini

MHW–RTG



And the Pu-238?

- **Mid 1950s – Plutonium-238 research and development activity began at Mound**

- 1959 – Initial research concerning plutonium-238 was transferred to Mound from Lawrence Livermore National Laboratory

- 1960 – First reduction of metallic plutonium-238 achieved at Mound Research and development relating to the application of plutonium-238 as a radioisotopic heat source material followed
  - Materials research
  - Development of processes for the production of heat source materials
  - Development of fabrication and metallurgical technology to ensure the containment and stability of heat source materials
  - Research and development activities were on the design of RTG systems for the various applications of this technology

- Mound produced “well over” 500 RTG units

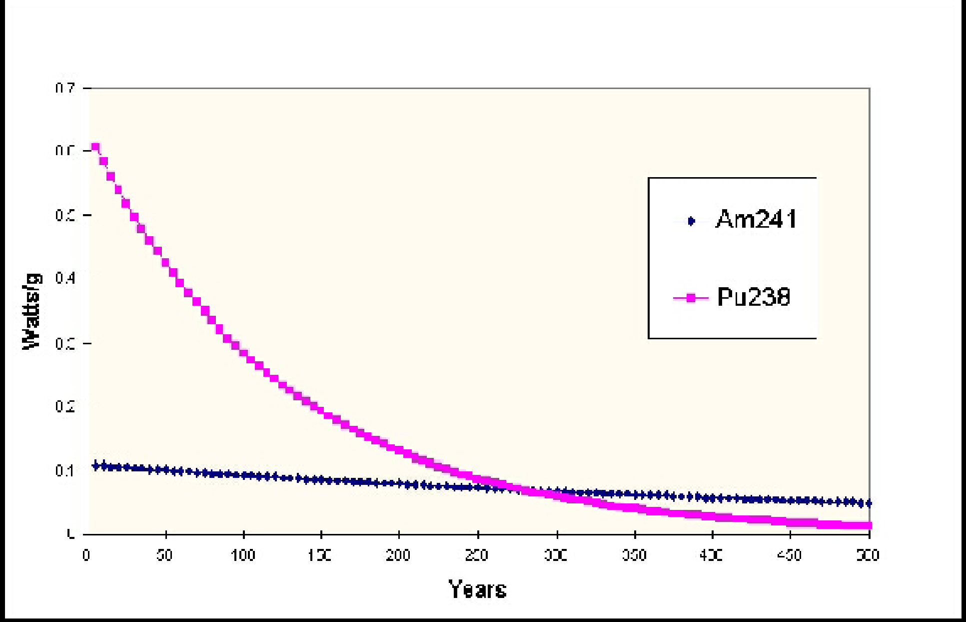
What About other isotopes?

- While there are over 3,175 nuclides, few are acceptable for use as radioisotopes in power supplies
- The five principal criteria include
  - (1) appropriate half-life,
  - (2) radiation emission considerations,
  - (3) power density and specific power,
  - (4) fuel form, and
  - (5) availability and cost.
- In practice, these criteria limit appropriate materials to radionuclides with half-lives from 15 to 100 years that decay by alpha-particle emission over 99% of the time, of which only five exist
  - ^{244}Cm has a relatively short half-life with associated production issues and also a high neutron background from spontaneous fission,
  - ^{243}Cm has a high gamma background,
  - ^{232}U has a very high gamma-ray background, and
  - ^{148}Gd can only be made in very small amounts in an accelerator.
  - **The fifth is ^{238}Pu**

What about longer-lived isotopes?

- **Isotopes that primarily decay by α-emission generally exhibit a half-life inversely proportional to their decay rate**

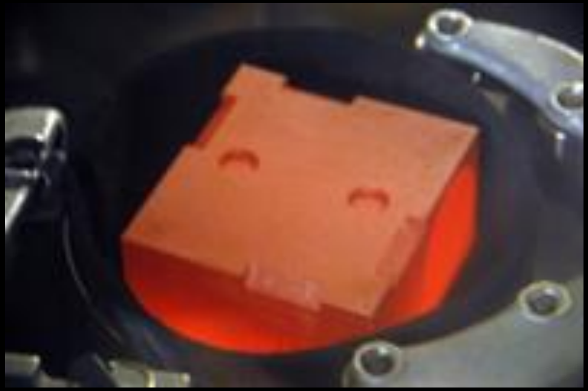
- **The "next" possibilities are**
  - **Po-209 (102 yr; 0.4855 W/g; bombardment of bismuth with protons in accelerator))**
  - **Cf-249 (351 yr; 0.1407 W/g; β-decay of berkelium-249 – made by intense neutron irradiation of plutonium)**
  - **Am-241 (433 yr; 0.1100 W/g; present in commercial spent fuel rods and "old" plutonium – from β-decay of Pu-241)**
  - **Cf-251 (900 yr; 0.0545 W/g; multiple intense neutron irradiations of plutonium and other transuranic elements)**



For the same initial mass, Am-241 exhibits an equivalent thermal power only after ~250 years of operations

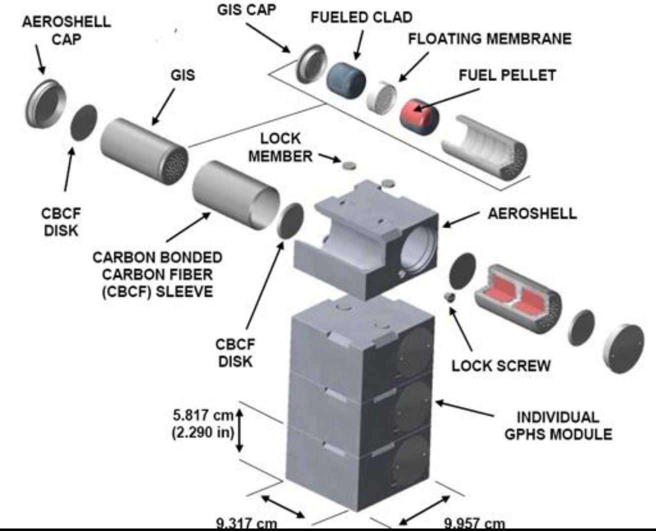
Lower thermal output earlier on also reduces conversion efficiency further

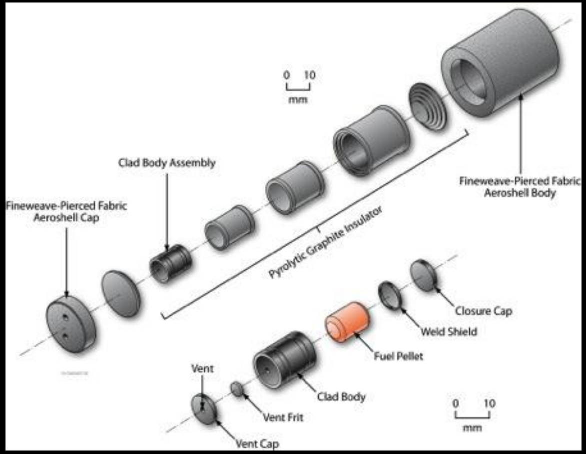
Pu-238 usage in space – U.S. standard packaging is a given



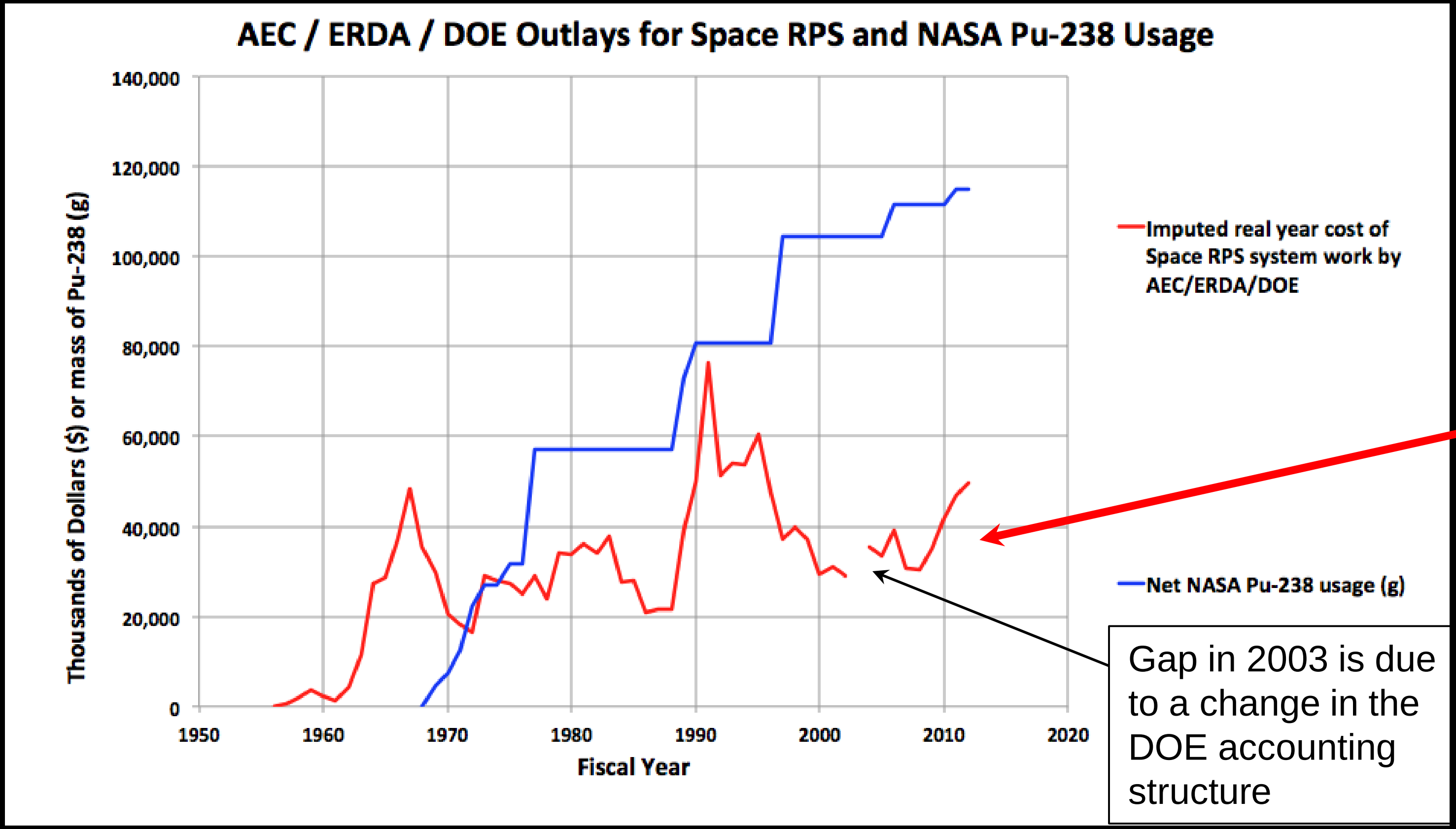
Usage has been standardized largely due to rigorous and comprehensive safety analyses

- **Power: General Purpose Heat Source (GPHS) Step-2, each containing 4 pellets of Pu-238 in the chemical form PuO_2 (nominal 150 g)**
- **Heating: Light Weight Radioisotope Heating Unit (LWHRU), each containing 1 pellet of Pu-238 in the chemical form PuO_2 (nominal 2.7 g)**





Pu-238 usage in space – Quantity

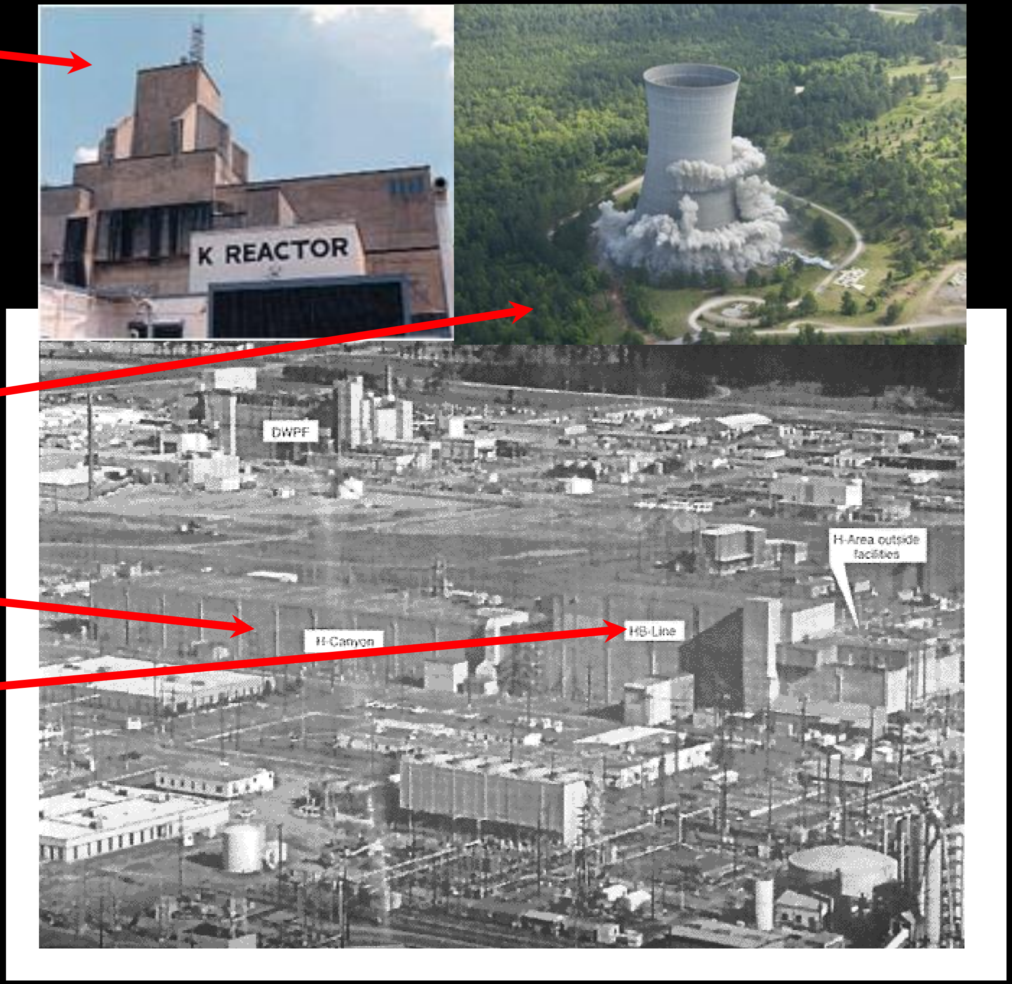


- No other isotope has been used by the U.S. to power spacecraft

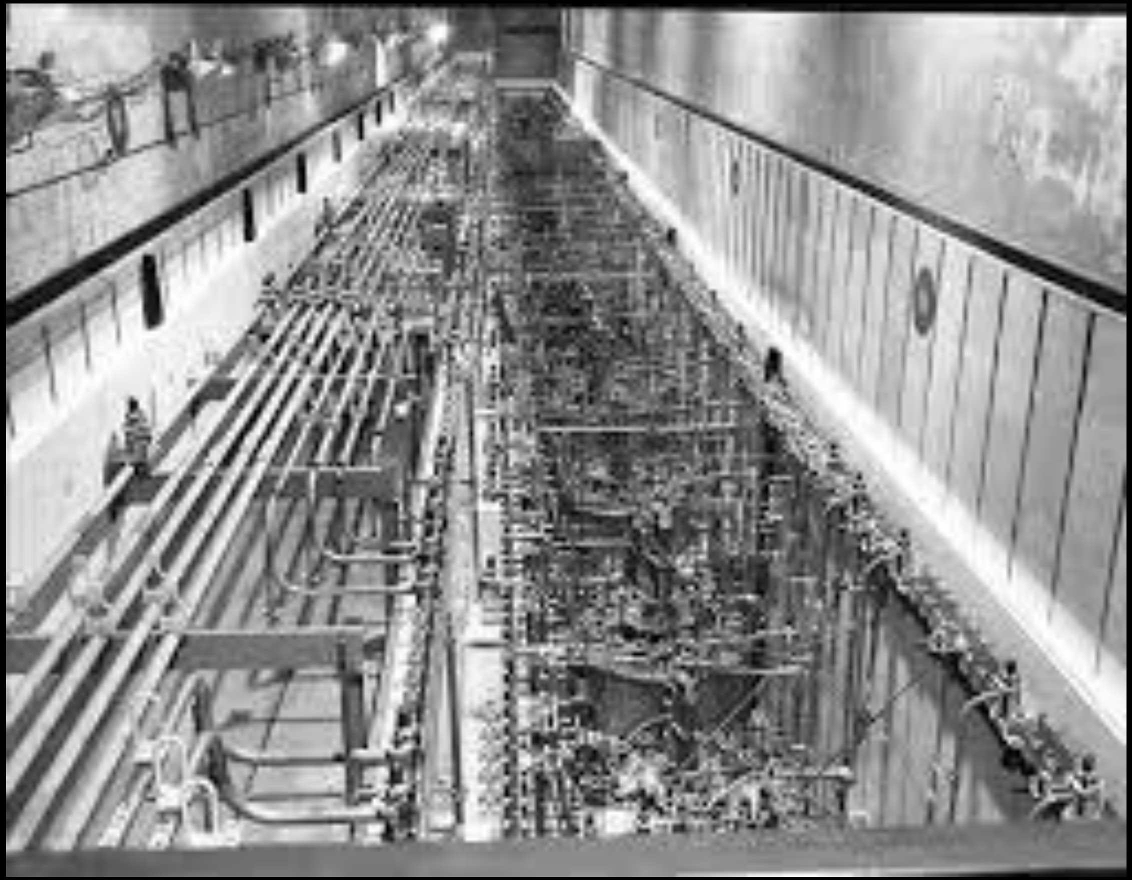
N.B. The costs directly supplied by DOD and NASA to these programs are *not* captured in these numbers

Production and separation of Pu-238 were carried out at the Savannah River facility in South Carolina – Industrial Scale

- K-reactor used for production
  - First went critical in 1954
  - To inactive status in 1988
  - Cooling tower built 1990
  - Operated with cooling tower in 1992
  - On cold standby 1993
  - Shutdown 1996
  - Reactor building converted to storage facility 2000
  - Cooling tower demolished 2010
- H-canyon used for fuel reprocessing
  - Only hardened nuclear chemical separations plant still in operation in the U.S.
  - Radioactive operations begin in 1955
- HB-line
  - Production begins of Pu-238 for NASA use 1985
- ~300 kg of Pu-238 produced 1959-1988



Savannah River Site – Used for Ulysses and Galileo RPS

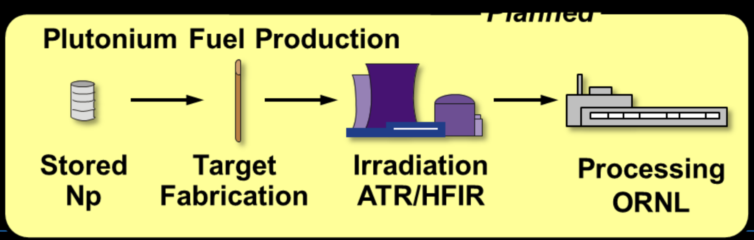


H Canyon interior

New Pu-238 Supply Project for NASA is more modest

- Production is targeted at ~1.5 kg “plutonium product” per year
- Facilities used include
  - Idaho National Laboratory (INL) – storage of NpO_2 and irradiation of targets at ATR (see below)
  - Oak Ridge National Laboratory (ORNL)
    - Remove Pa-233 (312 keV γ-ray is worker-dose issue)
    - Fabricate reactor targets
    - Irradiate at High Flux Intensity Reactor (HFIR) – or ship to INL for irradiation at the Advanced Test Reactor (ATR) –
    - Process in hot cells at ORNL Radiochemical Engineering Development Center (REDC)
    - Remove and purify Pu; change to oxide; and do O-16 exchange for processing by Los Alamos National Laboratory (LANL) into fuel pellets for GPHSs or LWRHUs

Hot Cell at ORNL REDC



10% conversion per campaign – to limit Pu-239 production
100 target per campaign to make 300 to 400 g of plutonium product
“Plutonium product” is NOT the same as Pu-238

Nuclear Isotope Production Issues (Physics)

- **When producing isotopes in a reactor, multiple channels as dictated by nuclear physics come into play – so no product is "clean"**

- **Once made, all isotopes begin decaying at physics-dictated rates and sometimes producing new radiological hazards**

- **The only "controls" are**
  - **Initial target composition**
  - **Reactor and target geometry**
  - **Exposure time**

- **Particular hazards in making Pu-238:**
  - **Protactinium-233 (Pa-233) – 312 keV γ, mitigate by chemical cleanup of Np-237 after removal from storage**
  - **Thallium-208 (Tl-208) – 2.61 MeV γ; mitigate by minimizing Pu-236**

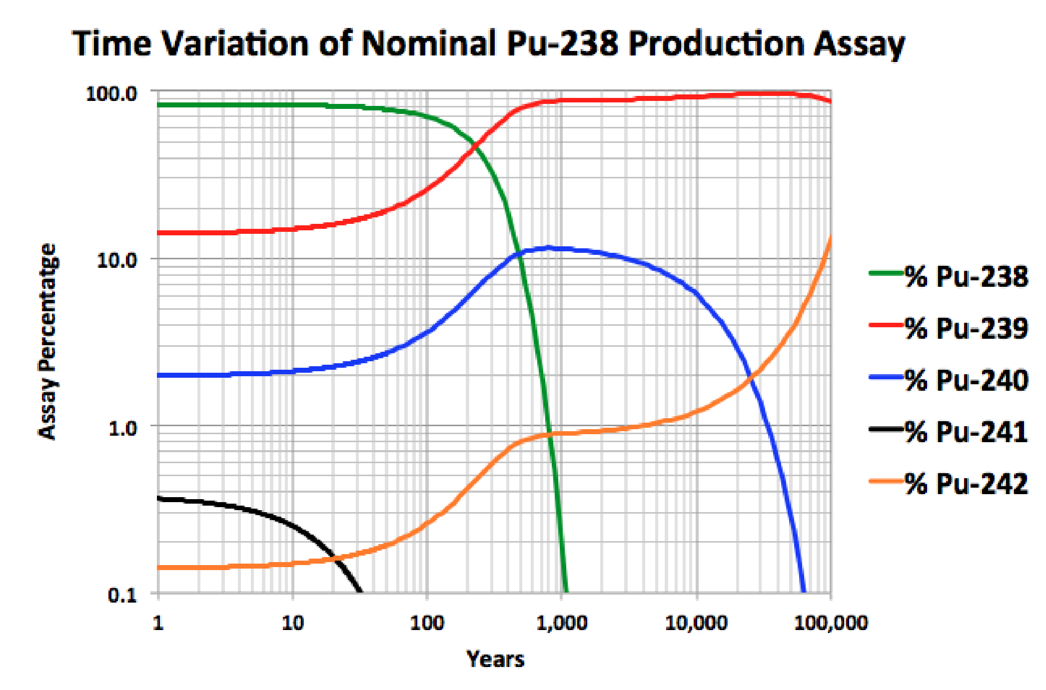
Isotope	Mass %
Pu-236	≤ 1 μg / g
Pu-238	83.50
Pu-239	14.01
Pu-240	1.98
Pu-241	0.37
Pu-242	0.14

- **Only chemical processing of plutonium is "practical" – isotopic separation is not**

- **Typical Pu-238 production at Savannah River – once reprocessed (Rinehart, 2001)**

Older Fuel has less power density

- Pu-239 in particular decays more slowly than Pu-238
- Once the Pu is produced, the initial fractions are "frozen in"
- As the fuel ages, the relative fraction of Pu-238 decreases and that cannot be changed



GPHS fuel clad design is driven by metallurgy of the iridium alloy of the clads

Nominal "plutonium product" loading is 150 g

Design thermal output is 62.5 W
➔ 62.5 W / 150 g = 0.42 W/g

Pu-238 isotope produces 0.56 W/g
Hence, a fuel clad contains roughly 0.42/0.56 x 150 g ~ 110 g of Pu-238 isotope

Details matter – this is the maximum thermal power available

Use in satellites

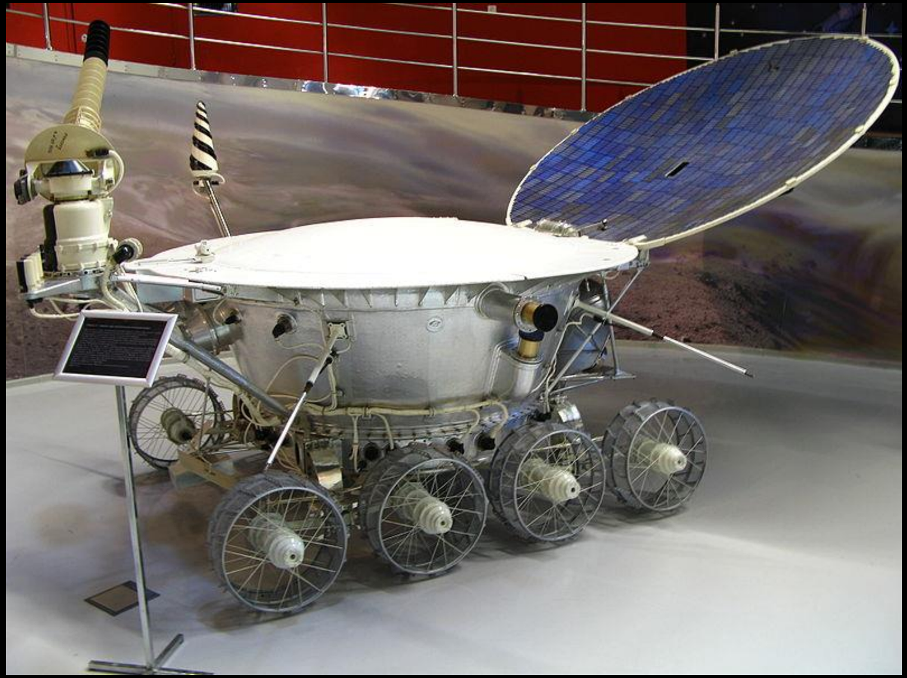
- RTGs found early use in satellites due to vulnerability of solar cells to radiation

- That problem was brought home by the Starfish detonation over Johnston Atoll in 1962

- Use in space in support of Apollo was also driven by the long lunar night.
  - Initial Surveyor designs were to make use of RTGs (SNAP 11)
  - Abandoned due to cost (and hence those spacecraft had limited lifetimes)
  - The RTG-powered ALSEP packages left on Apollo 12, 14, 15, 16, and 17 continued to function for many years and were finally turned off for budgetary reasons
  - The Apollo 13 RTG is somewhere in the Tonga Trench at and estimated 6,000 m (3.7 miles) of water depth
- But the first use was in Transit 4A – in the precursor to GPS

Russian RPS Missions

- Lunokhod 1 and 2 (Yttrium polonide using Po-210)
- Mars – 96 (“Angel” RHU and RTG using Pu-238)



RHUs ensure survival during lunar night and provide compact heater and power sources for small autonomous stations (SAS) and penetrators on planetary probes

8.5 W_{th} and 200 mW_e «Angel» RHU and RTG employed on Mars-96

Chinese RPS Missions

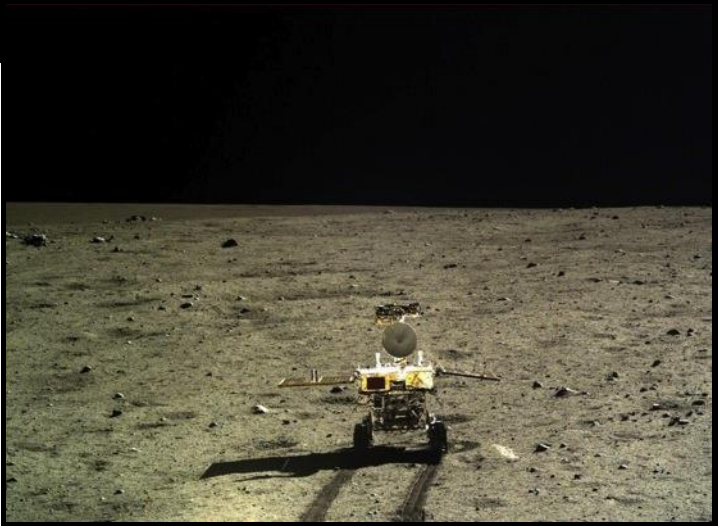
- Chang’e-3 and Yutu (Pu-238 RHUs)
- Lunar Lander and Rover

RHUs ensure survival during lunar night

Chang’e-3 lander from Yutu rover

RHU with APXS on Yutu –

image credited to CLEP at 2011-13
www.spaceflight101.com - Patrick Blau

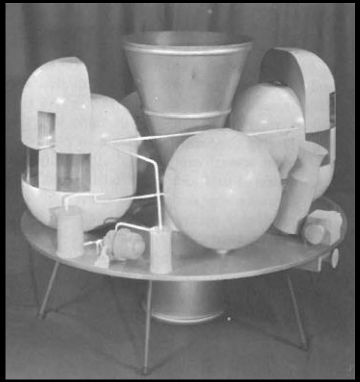


Yutu rover from Chang’e-3 lander

Convertor Technologies Have Proven Difficult to Develop

- **Requirements are high reliability and high thermal-to-electrical energy conversion**
  - **In the U.S. emergence of thermoelectric materials were chosen over dynamic systems (Rankine - cycle mercury boiler was baselined for SNAP-1) for reliability**
  - **PbTe and TAGS materials followed by higher efficiencies with SiGe couples operating at higher temperatures**

SNAP – 1 concept

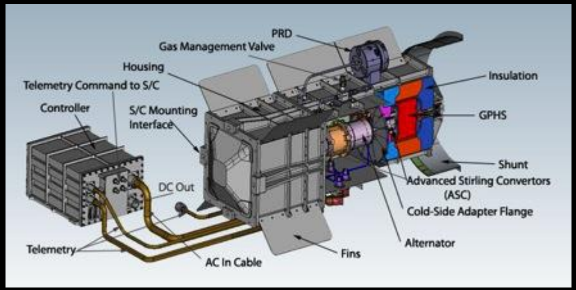


- **Other approaches were abandoned due to material difficulties**
  - Selenide thermoelectrics
  - Alkali metal thermal-to-electric converter (AMTEC)

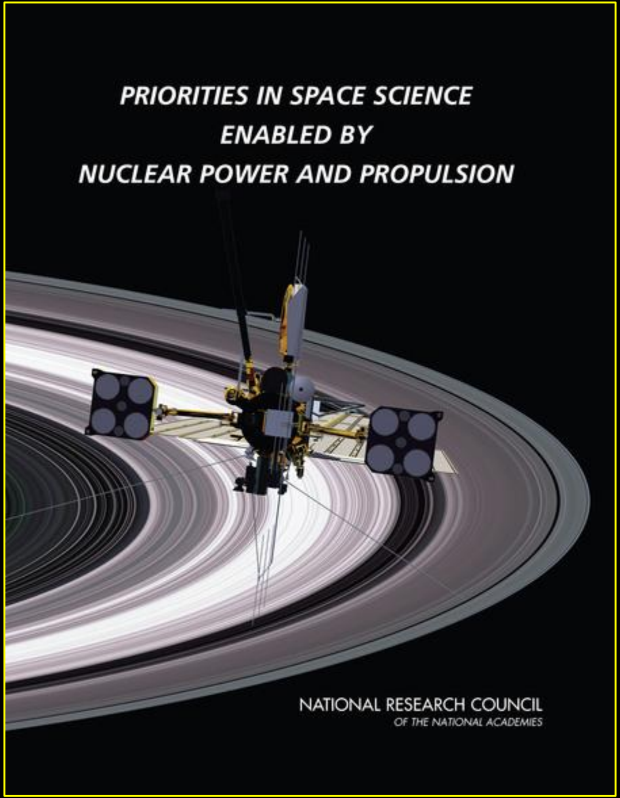
AMTEC cell

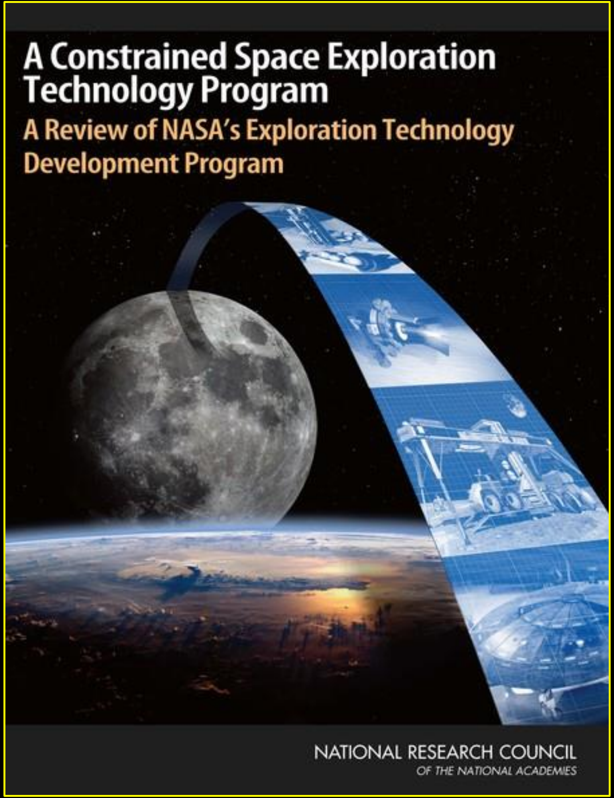
- **Still other approaches continue to show promise, but need larger infusions of research funds to further the technical readiness level of the the technology**
  - Skutterudites and other materials
  - Advanced Stirling Radioisotope Generator (ASRG) has been the most promising dynamic system to date

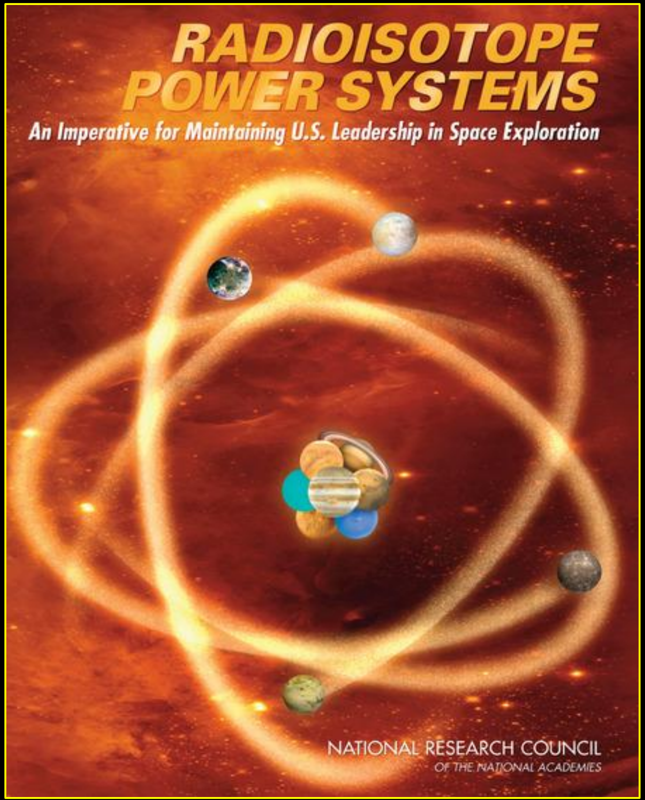
ASRG

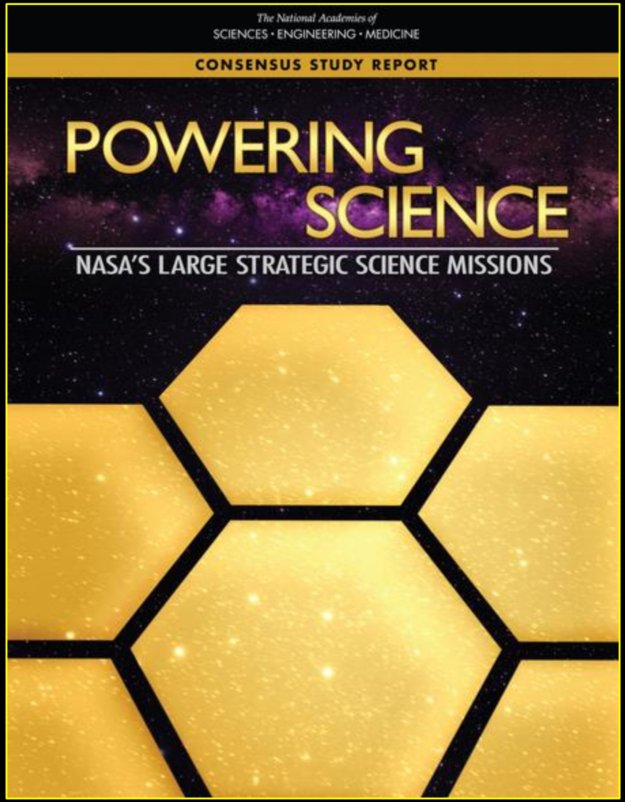


Space nuclear power remains a **major enabler** for NASA Robotic Science Missions



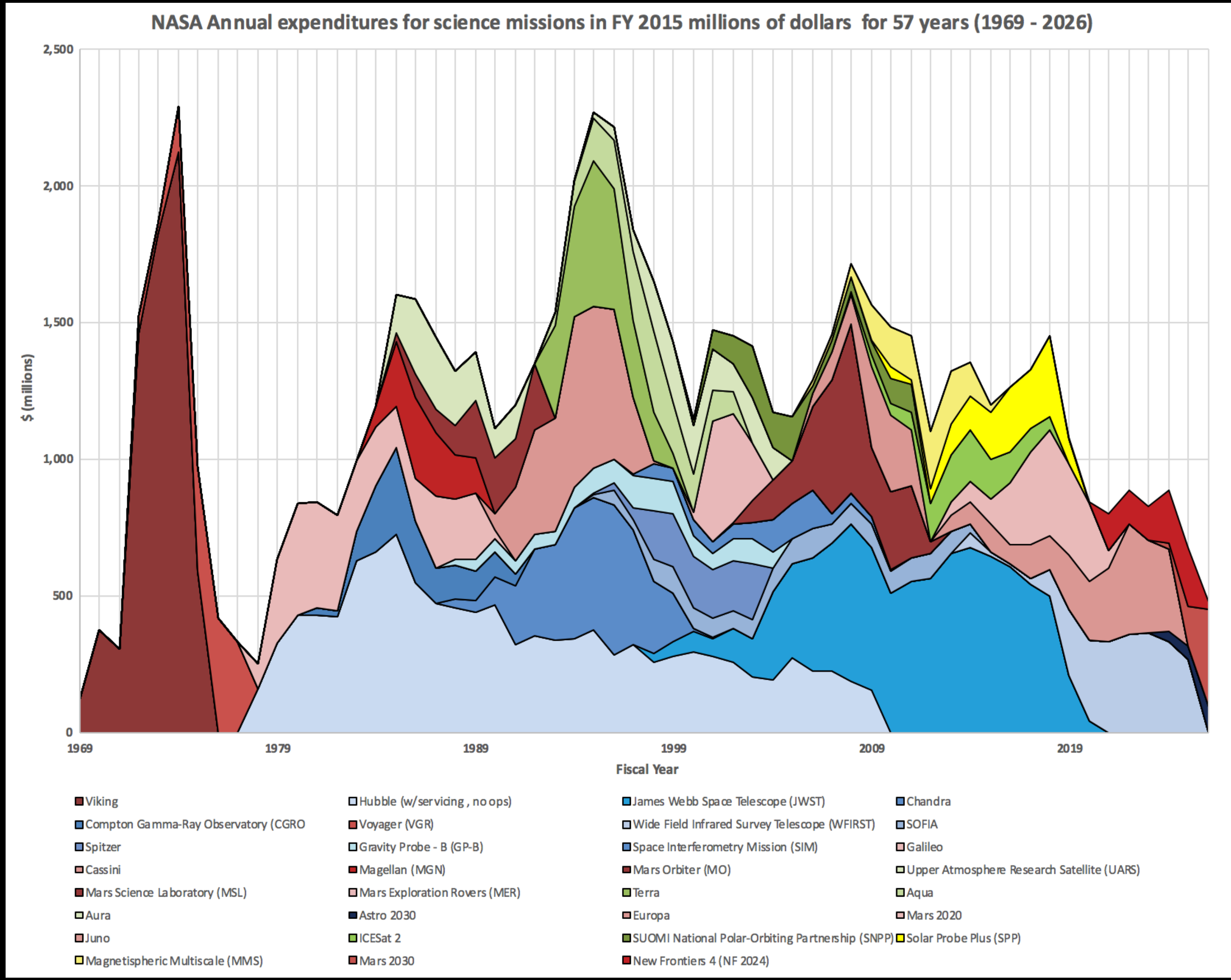






NASA Robotic Space: 31 Large Strategic Science Missions Across 57 Years

- Reconstructed figure using data from NASA
- Data corrected (by NASA) from actuals to FY 2015 base year
- Total is **$ 70,134,196k** FY15$

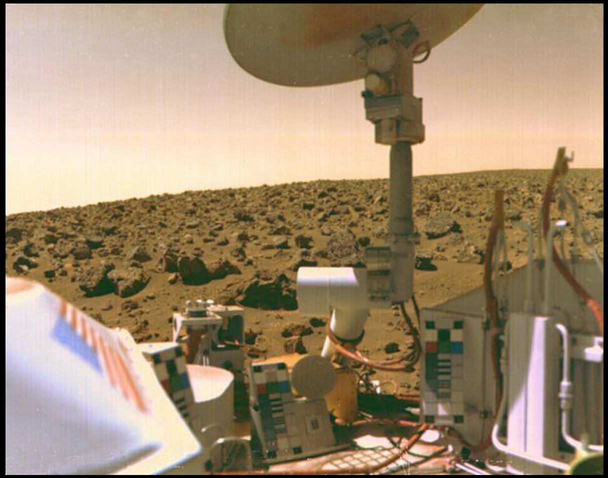


Most Expensive Flown Missions by Division (FY15 M$)

1. Hubble
$11,288.124
Astrophysics Division

RPS Enabled

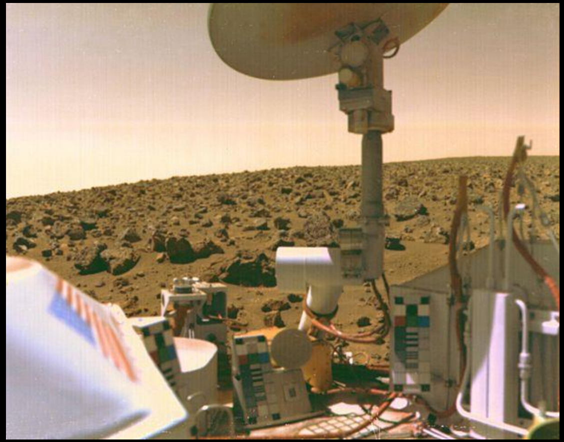
3. Viking
$6,790.746
Planetary Science Division



10. Terra
$2,224.832
Earth Science Division

23. Magnetospheric Multiscale
$1,074.350
Heliophysics Division

Top Five Missions by Cost FY 2015 $M



RPS Enabled

1. Hubble
$11,288.124
Astrophysics Division

2. JWST
$8,645.214
Astrophysics Division

3. Viking
$6,790.746
Planetary Science Division

4. Chandra
$3,440.968
Astrophysics Division

5. Cassini
$3,188.699
Planetary Science Division

Selectivity Remains Essential

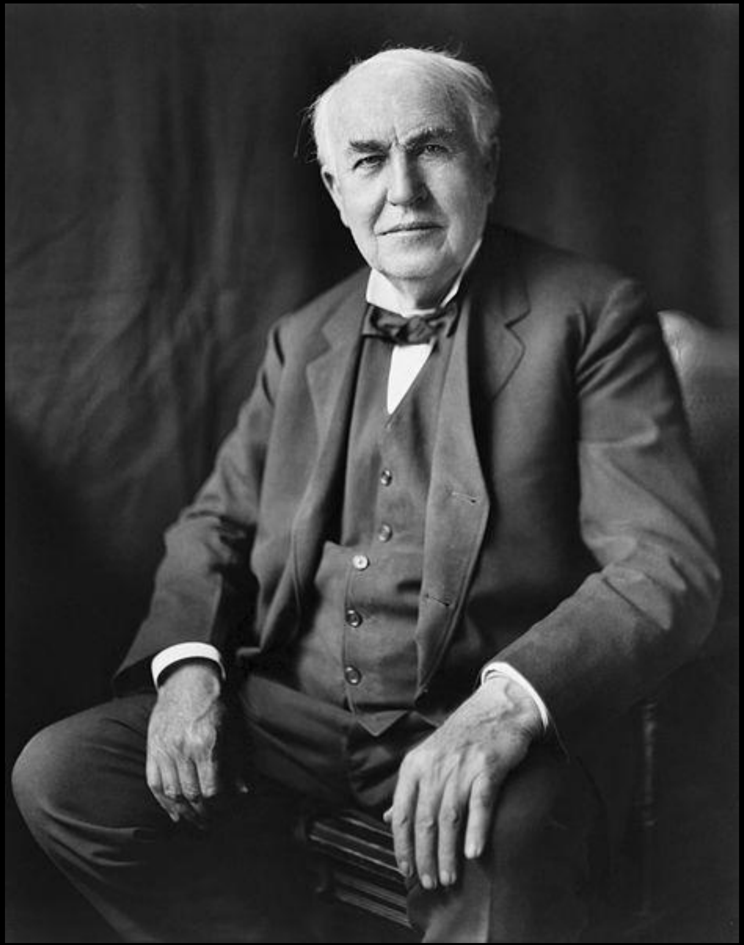
- The mission concepts from the last Decadal had estimated costs of $33.7 to $35.7 B
  - Based upon independent cost and technical evaluation (CATE) process
  - Project estimates average ~45% less
  - Almost ¼ of the cost is for the three robotic pieces of Mars Sample return (MSR)

	Vision and Voyages Mission (2013-2022)	Project Cost ($B)	CATE Cost ($B)	RPS Enabled
1	Venus Climate Mission	1.6	2.4	
2	Lunar Lander Network - Four Landers	0.9	1.3	YES
3	Mars Astrobiology Explorer - Cacher	2.2	3.5	
4	Mars Astrobiology Explorer - Cacher Descope		2.4	
5	Mars Sample Return Orbiter and Earth Entry Vehicle	1.8	2.1	
6	Mars Sample Return Lander and Mars Ascent Vehicle	2.5	4.0	
7	Io Observer	1.1	1.4	YES
8	Jupiter Europa Orbiter	3.4	4.7	YES
	Jupiter Europa Orbiter - descope			
9	Trojan Tour Rendezvous	1.0	1.3	YES
10	Saturn Probe	1.1	1.3	YES
11	Titan Saturn System Mission	4.5	6.7	YES
12	Enceladus Orbiter	1.6	1.9	YES
13	Uranus Orbiter with Solar Electric Propulsion and Probe	1.9	3.4	YES
14	Uranus Orbiter and Probe (no SEP)		2.7	YES
15	Comet Sample Return Orbiter	1.0	1.5	
	Total Nominal Cost (excludes 4 and 14)	**24.6**	**35.5**	
	Total Descoped Cost (excludes 3 and 13)	**N/A**	**33.7**	
	Total MSR only (nominal)	6.5	9.6	

Surface of Titan
from Huygens

The way forward is open…

With a caveat:



- **“Vision without execution is hallucination.”**
  - — Thomas A. Edison
- Requirements must be commensurate with realistic cost estimates and funds – a key element of any successful mission