Physics and Chemistry of Space-Certified Radioisotope Power Systems: What You Need to Know

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Space Studies Board
National Research Council

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11:30 AM - 12:30 PM EST

The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Disclaimer

- The view expressed herein are entirely those of the presenter and do not reflect any views explicitly or implicitly of The Johns Hopkins University Applied Physics Laboratory
- A condensed version of this talk was presented at

10th Meeting of the NASA Small Bodies Assessment Group

8 January 2014
Capitol Ballrooms A and B
Embassy Suites Washington DC
Convention Center Hotel

3:45 PM - 4:00 PM EST

Outer Planet Assessment Group Meeting

13 January 2014
Drake Building
University of Arizona
Tucson, AZ

10:40 AM - 11:00 AM

Why should you care?

- **"NASA" and "plutonium" are not usually juxtaposed – except for engineers working deep-space power supplies (and we will get to that)**

- **Some introduction is required (or at least useful)**
  - Plutonium comes in a variety of isotopes
  - The U.S. (and Soviet Union) went into full-scale industrial production of fissionable Pu-239 following the successes of the "Trinity" bomb test in Alamagordo, New Mexico and Nagasaki, Japan in July and August, 1945.
  - Many metric tons were produced
  - It is now being downblended to "burn" in power-production reactors to get rid of it

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**

The NASA – plutonium connection

- **As with the initial separation of gasoline in the 19th century – a contaminant in kerosene production and good for little except as a solvent for washing clothes – the advantages of Np-237 and Pu-238 were not readily appreciated**
- **The newly emerging Space Age of the late 1950s was ushered in by robotic spacecraft that needed longer-lived electrical power than could be supplied by chemical batteries**
  - Solar cells were vulnerable to radiation in the newly discovered Van Allen belts
  - Defense requirements meant something reliable was needed
  - Nuclear power had the potential for reliable power supply in space for both security (DoD) and civilian (NASA) use
  - The "easy" solution was to implement spacecraft power based upon radioisotope decay, aka radioisotope power systems (RPS)

RPS use and infrastructure costs are still emerging from the Cold War years

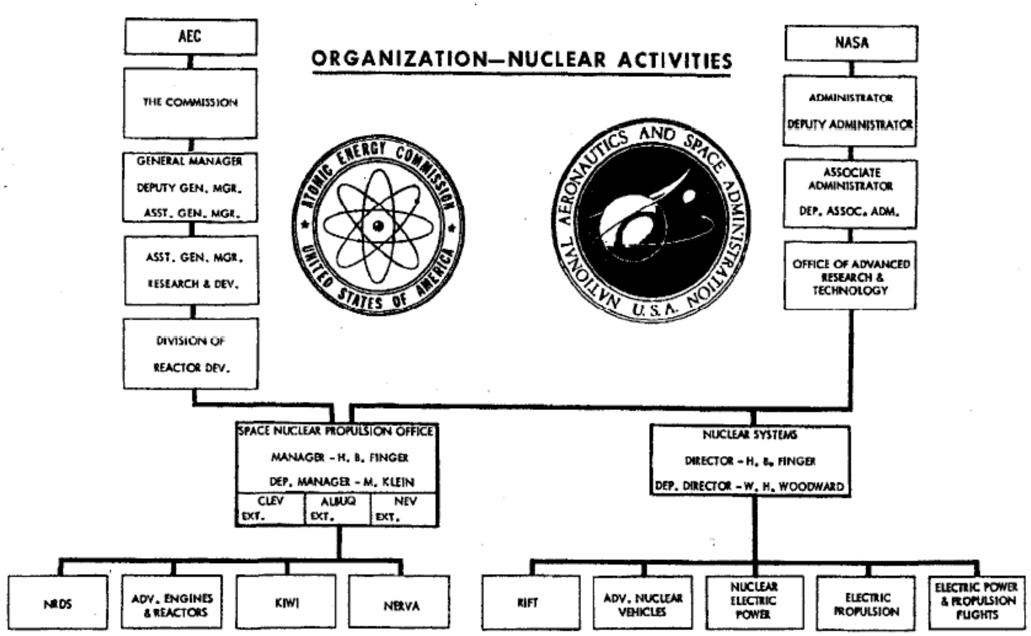
- **Radioisotope Power Systems (RPS) are an enabling technology for providing power to satellite systems in cases for which solar power is impractical or absent altogether**
    - They have been used in space as well other applications, in the U.S. and in Russia
    - Many other applications have been phased out
- **Their technical origins stretch back to research on the Manhattan Project**
- **They were invented in the U.S. about 55 years ago and we have invested ~$4.7 billion (FY2011) to date in perfecting this technology**
- **There are also in lightweight radioisotope heater units (LWRHUs) used to keep spacecraft components warm**

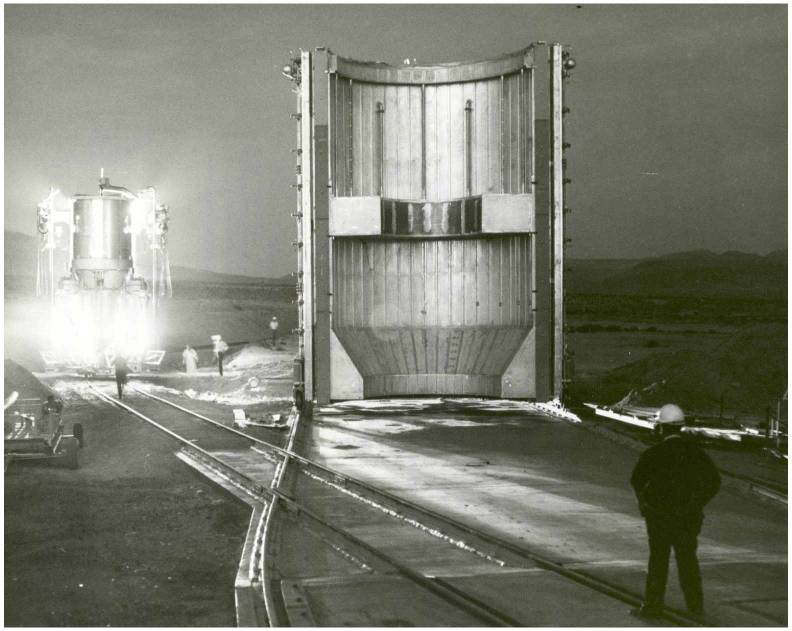
First use: Transit 4A in 1961

- **Bench check out and installation of the SNAP 3B7 radioisotope power supply**
- **Launch on Thor Able-Star 29 June 1961**

How did the program run?

- **The RPS program was only a small part of joint nuclear programs between NASA and the Atomic Energy Commission (AEC)**





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

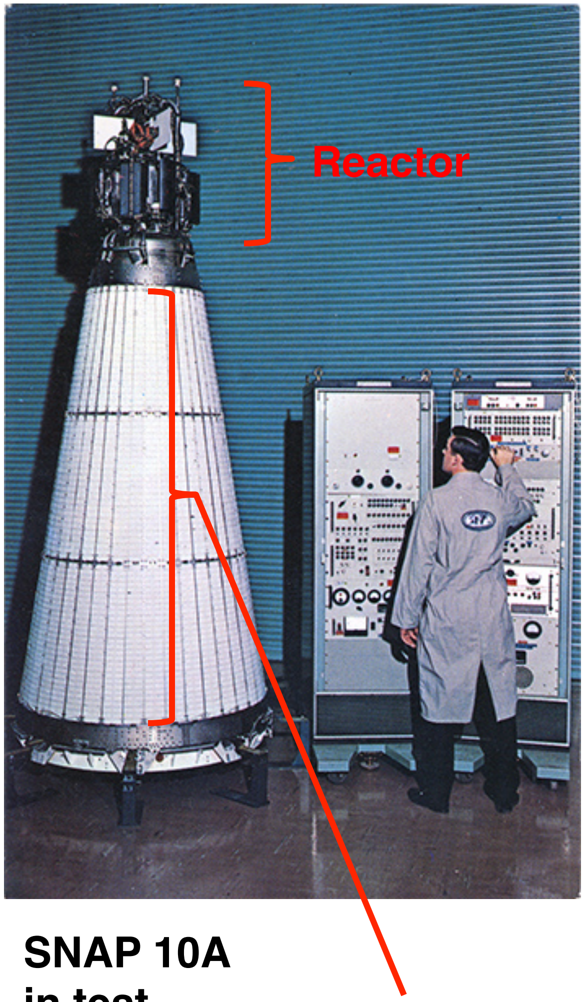
- **Polonium-210 was investigated as an intense source of alpha particles beginning in 1942**
  - 1954 – program to generate electricity from Po-210
  - 1956 - conceptual design using a mercury boiler
  - 1958 - RTG powered by polonium-210

- **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**

Are there alternative nuclear power supplies?

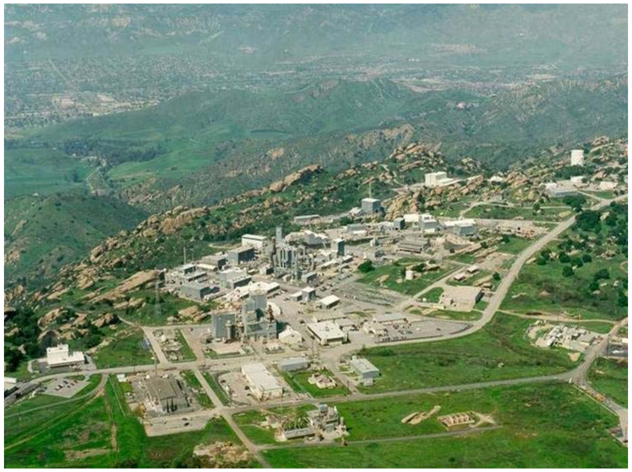
- **The short answer is “No”**
  - Over 30 Russian nuclear reactors (military and now off) are in Earth orbit
  - There have been many studies, including Prometheus for NASA
- **In the U.S., there was a development program for nuclear power supplies called Systems for Nuclear Auxiliary Power (SNAP)**
  - RTG supplies were odd-numbered SNAPs
  - Nuclear reactors (using nuclear fission and highly enriched uranium-235) were even-numbered SNAPs
- **The U.S. has flown one nuclear reactor in space: the SNAP 10A reactor**
  - ~500 watts, electric output
  - Launched from Vandenberg on 3 April 1965
  - Failed (non-nuclear electronics) after 43 days in orbit



SNAP 10A in test

Where was SNAP 10A developed?

- **SNAP 10A and other deemed “hazardous” items were developed at the Santa Susanna Field Laboratory in Simi Valley, CA**
  - Testing and development of liquid propellant rocket engines for the U.S. 1949 to 2006
  - Nuclear reactors from 1953 to 1980
  - Operation of a U.S. government-sponsored liquid metals research center from 1966 to 1998



Rocketdyne G-1 LF2/Hydrazine rocket engine for NOMAD Upper Stage System also developed at Santa Susanna

City of Los Angeles State of California

RESOLUTION

WHEREAS, the launching and successful operation of the world's first nuclear reactor power system in space, the

Snap 10A,

represents an historic milestone in the Nation's space and atomic energy programs; and

WHEREAS, since the nuclear system was launched on April 3, 1965, more than 700 miles into space, it has operated for more than a month generating electricity to power extensive test instrumentation and scientific apparatus aboard the spacecraft; and

WHEREAS, the SNAP program (Systems for Nuclear Auxiliary Power) is designed to develop reliable, long-lived sources of electrical power for satellites and space vehicles, and for other uses on land and at sea; and

WHEREAS, the SNAP 10 A was developed for the Atomic Energy Commission by a leading San Fernando Valley firm, Atomics International, of Canoga Park:

NOW, THEREFORE, BE IT RESOLVED by this action of the Los Angeles City Council, in behalf of all the people of Los Angeles, that Atomics International of Canoga Park, be heartily congratulated for its successful launch of the pioneering SNAP 10 A and be extended best wishes for success in all future operations in this challenging space age.

Resolution by

Councilman 12th District

Seconded by

Thomas D Shepard

Councilman 3rd District

I HEREBY CERTIFY that the foregoing resolution was adopted by the Council of the City of Los Angeles at its meeting held May 20, 1965.

President of the Council

ATTEST: Walter C Peterson

City Clerk

SNAP 10A Proclamation from the city of Los Angeles

Systems for Nuclear Auxiliary Power (SNAP):
- Atomics International (AI) program to develop space nuclear power systems.
- A system was launched from Vandenberg Air Force Base on April 3, 1965.
- Remains the only nuclear reactor placed in space by the U.S.

Switch from Po-210 to Pu-238 for Long-Lived Missions

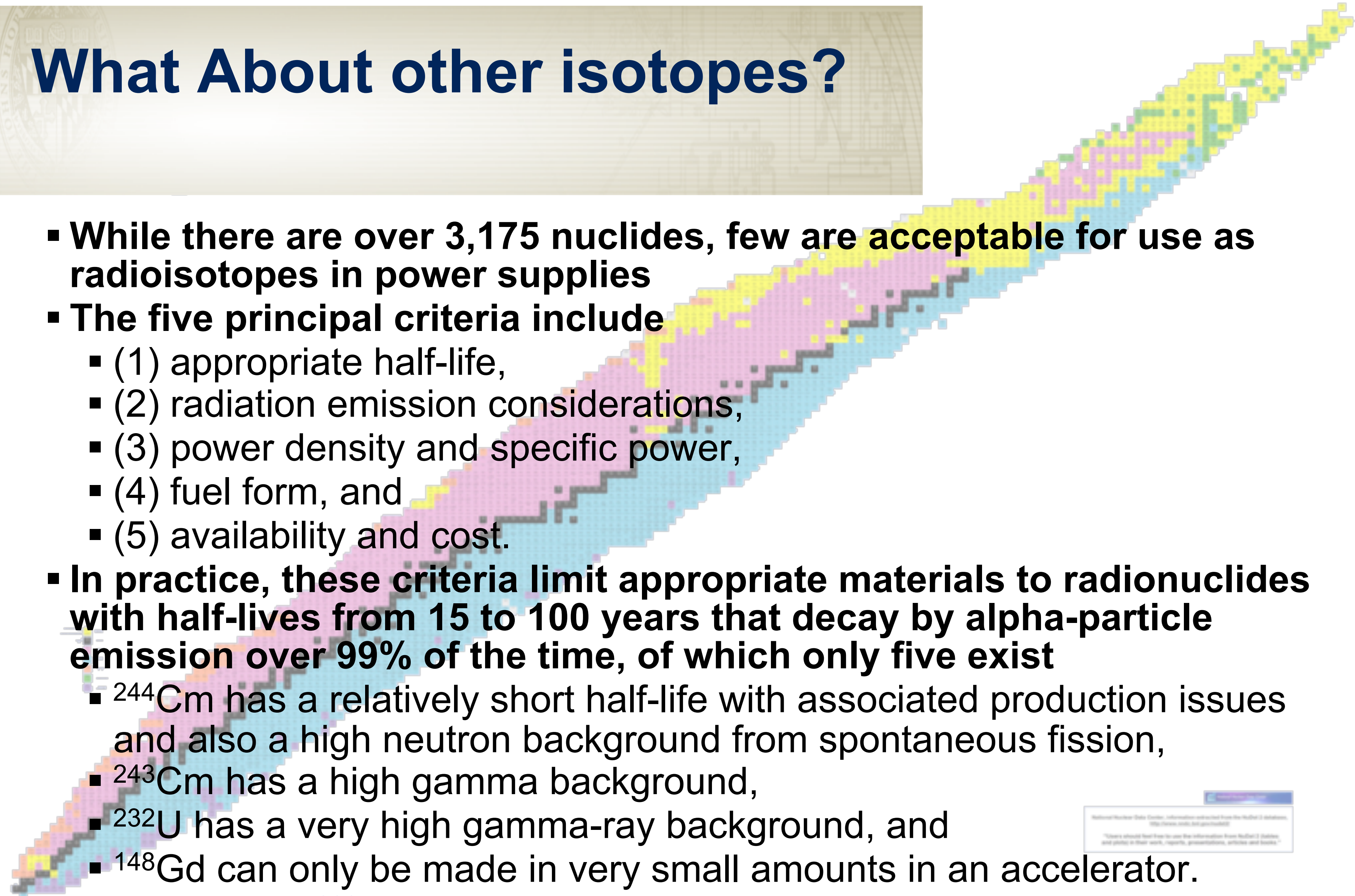
Pu-238 glowing under own heat

- **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

What About other isotopes?

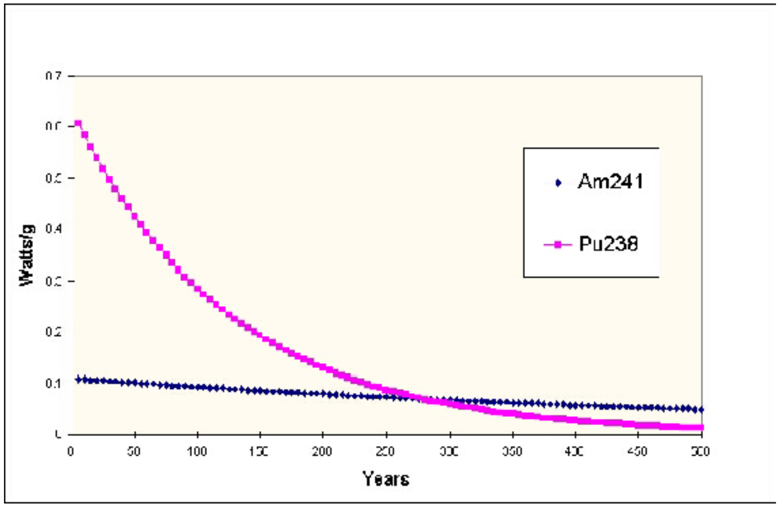


- **While there are over 3,175 nuclides, few are acceptable for use as radioisotopes in power supplies**
- **The five principal criteria include**
  - (1) appropriate half-life,
  - (2) radiation emission considerations,
  - (3) power density and specific power,
  - (4) fuel form, and
  - (5) availability 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)



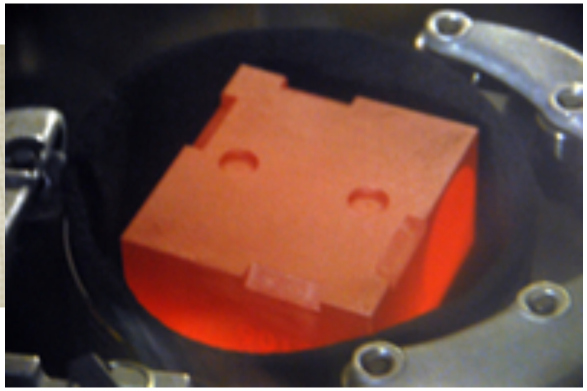
For the same initial mass, Am-241 exhibits an apparent power only after ~250 years of operations

Lower thermal output earlier on also reduces conversion efficiency further

And the Am-241?

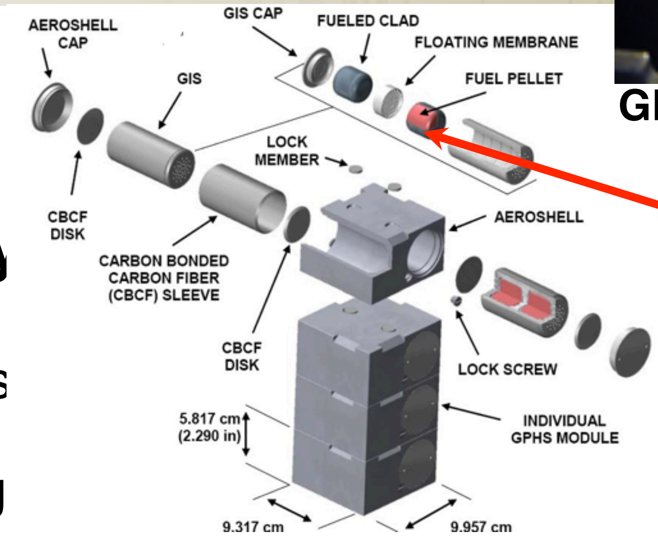
- **Responses (by the DOE) to Questions from the National Research Council, RPS Study Committee (asked by co-chair McNutt) Regarding Alternative Fuels (October 2008)**
    - …the 458 year half-life of Am-241 makes it a very poor power source. The gamma dose from Am-241 also requires shielding beyond what is required for the Pu-238 power source. While the majority of the gamma emissions are of low energy (59.7 keV), there are higher energy emissions on the order of 10^{-4} % that must be accounted for at the large quantities envisioned for an RPS. The U. S. government currently does not reprocess Am from spent fuel rods and is not considering a process that would. United States concepts for spent nuclear fuel processing address the recovery and recycle of unburned fissile material, but, for non-proliferation reasons, individual isotopes would not be isolated in the process. The recycled fuel would be a mixture U and Pu – no separation. The Np, Am, etc. would be in the waste stream with the fission products. To change this processing approach to recover a specific isotope like Am-241 would require an additional recovery plant that is not currently planned. **In addition, any Am recovered in such a way would be a mixture of Am-241, Am-242m, Am-243, etc. which would reduce the power density even further unless isotope separation methods (i.e. gaseous diffusion or centrifuges) were used. Cost and output estimates of such facilities are not available.**
- **There is a European effort being funded to reprocess spent fuel rods for recovering – and then using – Am-241 in RPSs.**

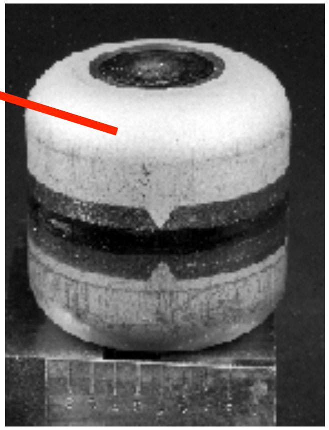
Pu-238 usage in space – U.S. standard packaging is a given

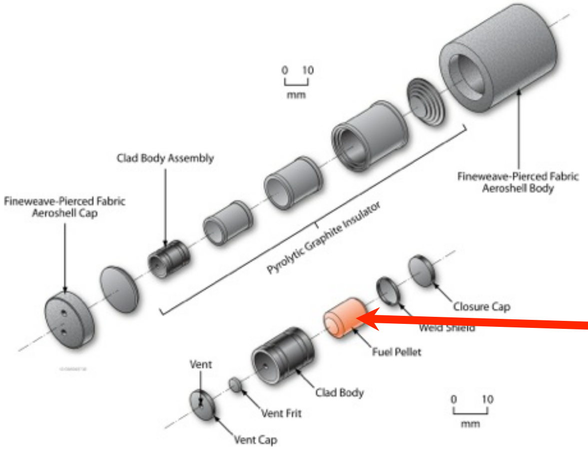

GPHS for Curiosity (from INL)

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

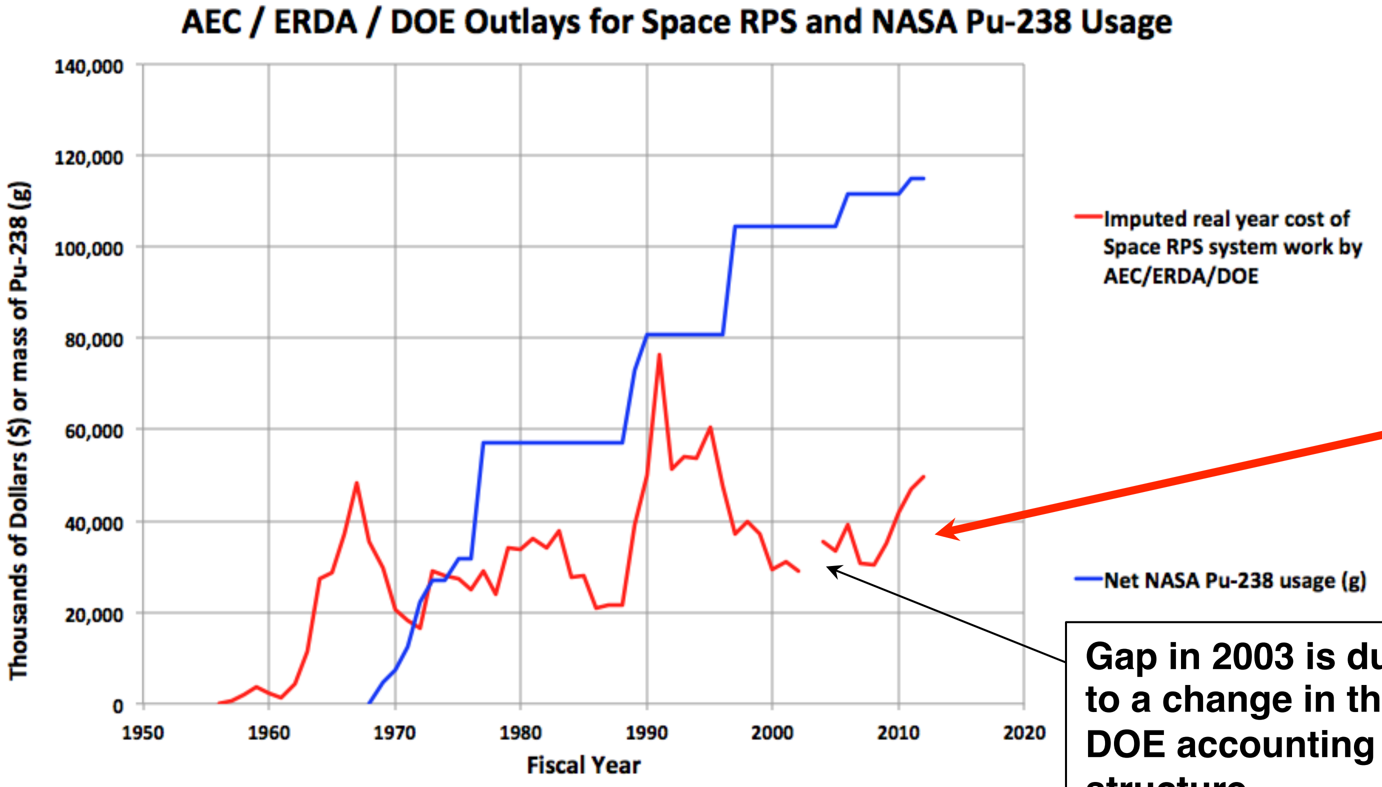
- **Power:** General Purpos Heat Source (GPHS) Step-2, each containing pellets of Pu-238 in the chemical form PuO_2 (nominal 150 g)
- **Heating**: Light Weight Radioisotope Heating Unit (LWHRU), each containing 1 pellet of Pu-238 in the chemical form PuO_2 (nominal 2.7 g)







Pu-238 usage in space – Quantity



Gap in 2003 is due to a change in the DOE accounting structure

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

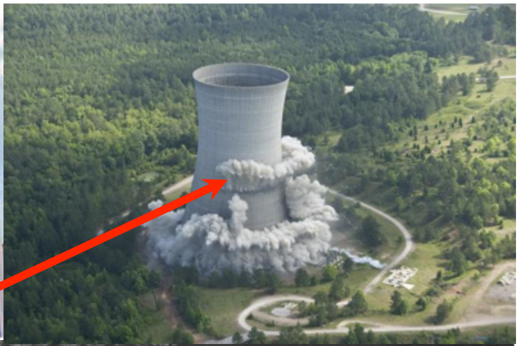
N.B. The costs directly supplied by DOD and NASA to these programs are ***not*** captured in these numbers

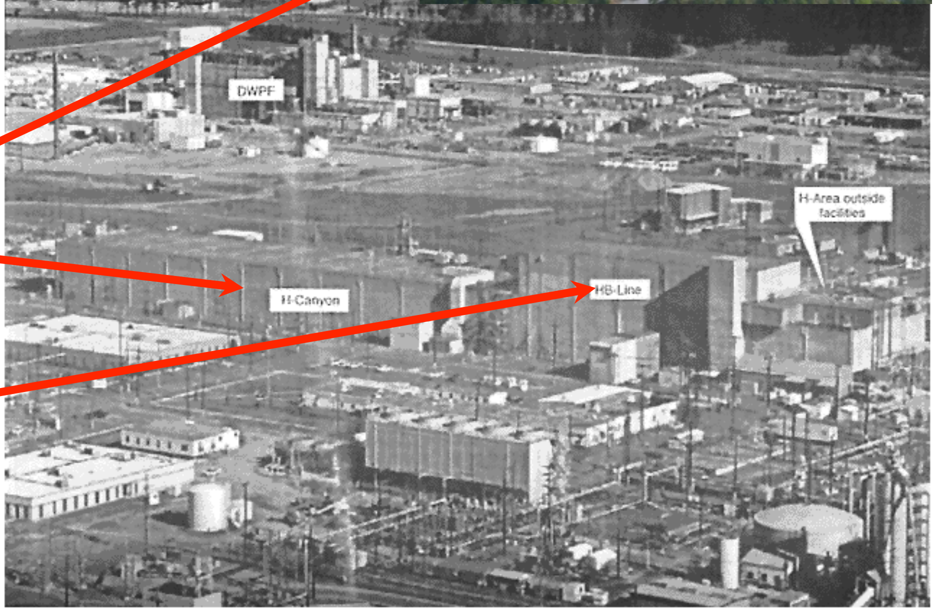
NASA usage: Nimbus B-1 through Curiosity 115 kg in 44 years = 2.6 kg/yr on average

Other U.S. spacecraft have also used Pu-238

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

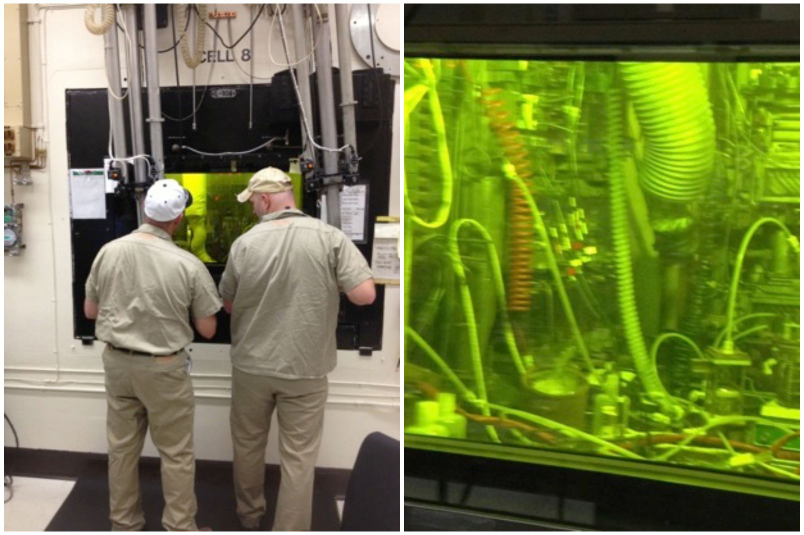
- **K-reactor used for production**
  - First went critical in 1954
  - To inactive status in 1988
  - Cooling tower built 1990
  - Operated with cooling tower in 1992
  - On cold standby 1993
  - Shutdown 1996
  - Reactor building converted to storage facility 2000
  - Cooling tower demolished 2010
- **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**



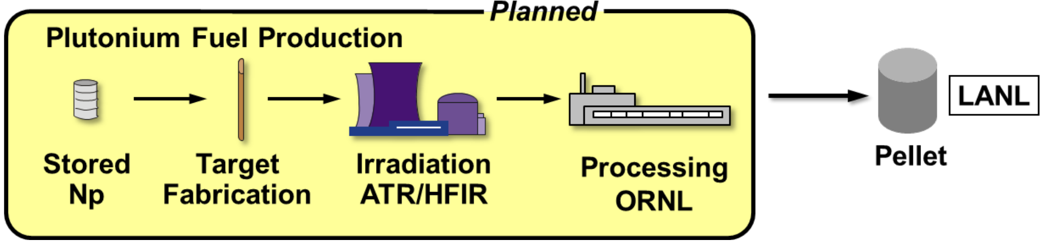


New Pu-238 Supply Project for NASA is more modest

- **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

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

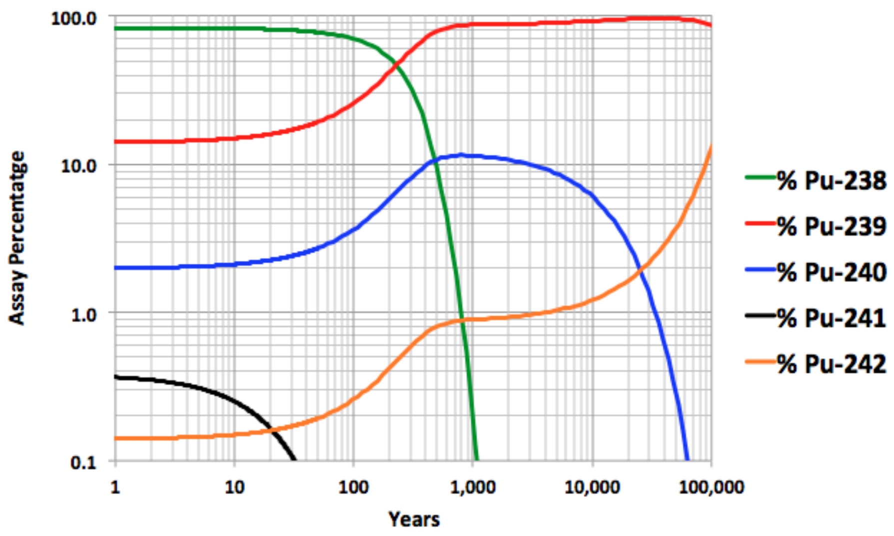
- **Typical Pu-238 production at Savannah River – once reprocessed (Rinehart, 2001)**

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

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

Time Variation of Nominal Pu-238 Production Assay



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

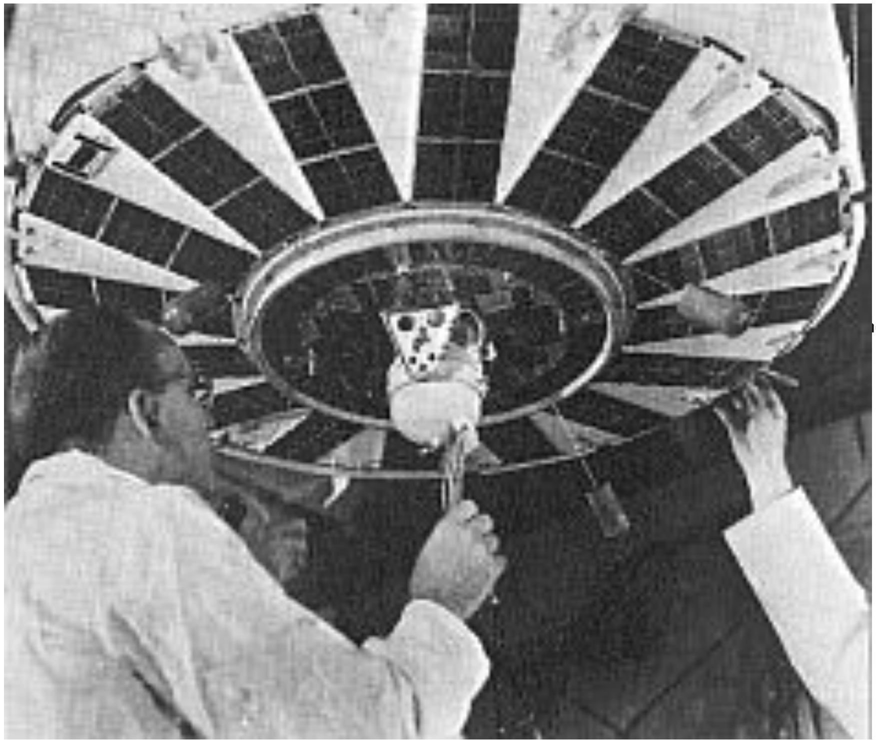
Use in satellites

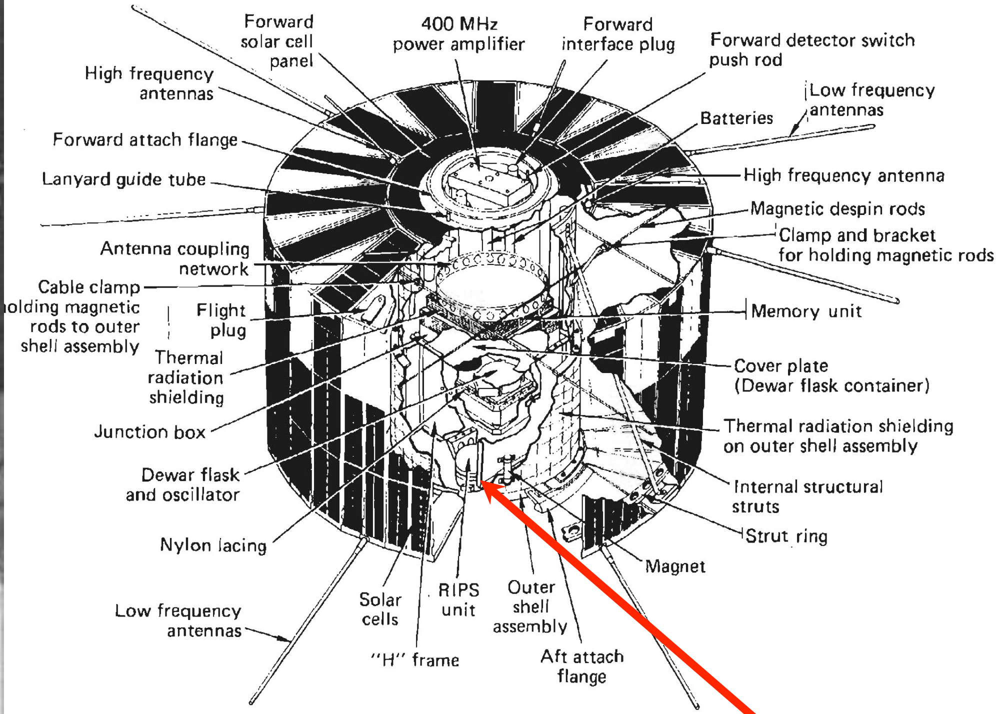
- **RTGs found early use in satellites due to vulnerability of solar cells to radiation**

- **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**

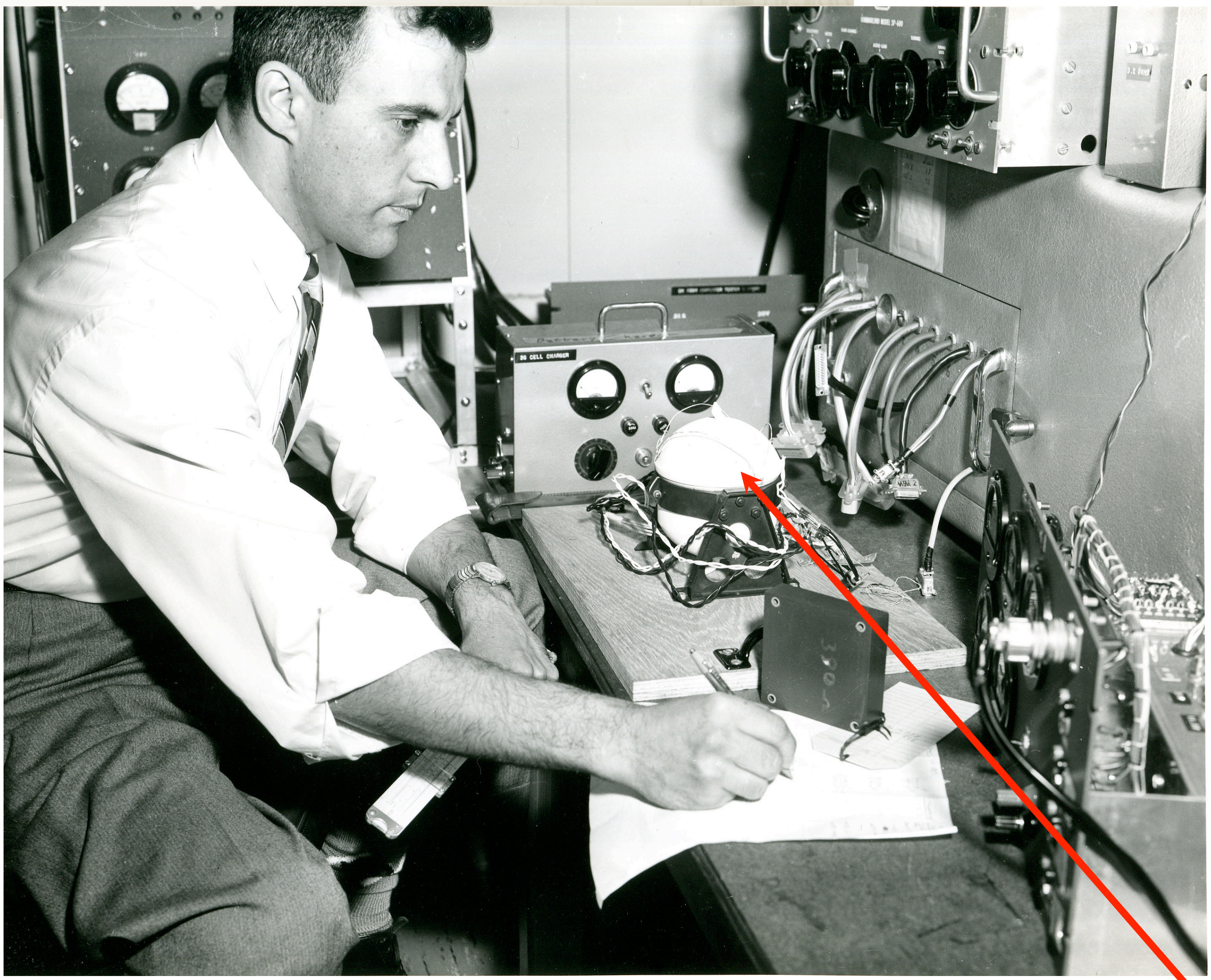
Transit 4A satellite – Built by APL





- Check out and installation of the SNAP 3 radioisotope power supply
- Transit 4A photo and schematic
- Power was switchable between solar cells and the RPS
- SNAP-3B7 power supply (SNAP-3B8 on Transit 4B launched 15 Nov 1961)

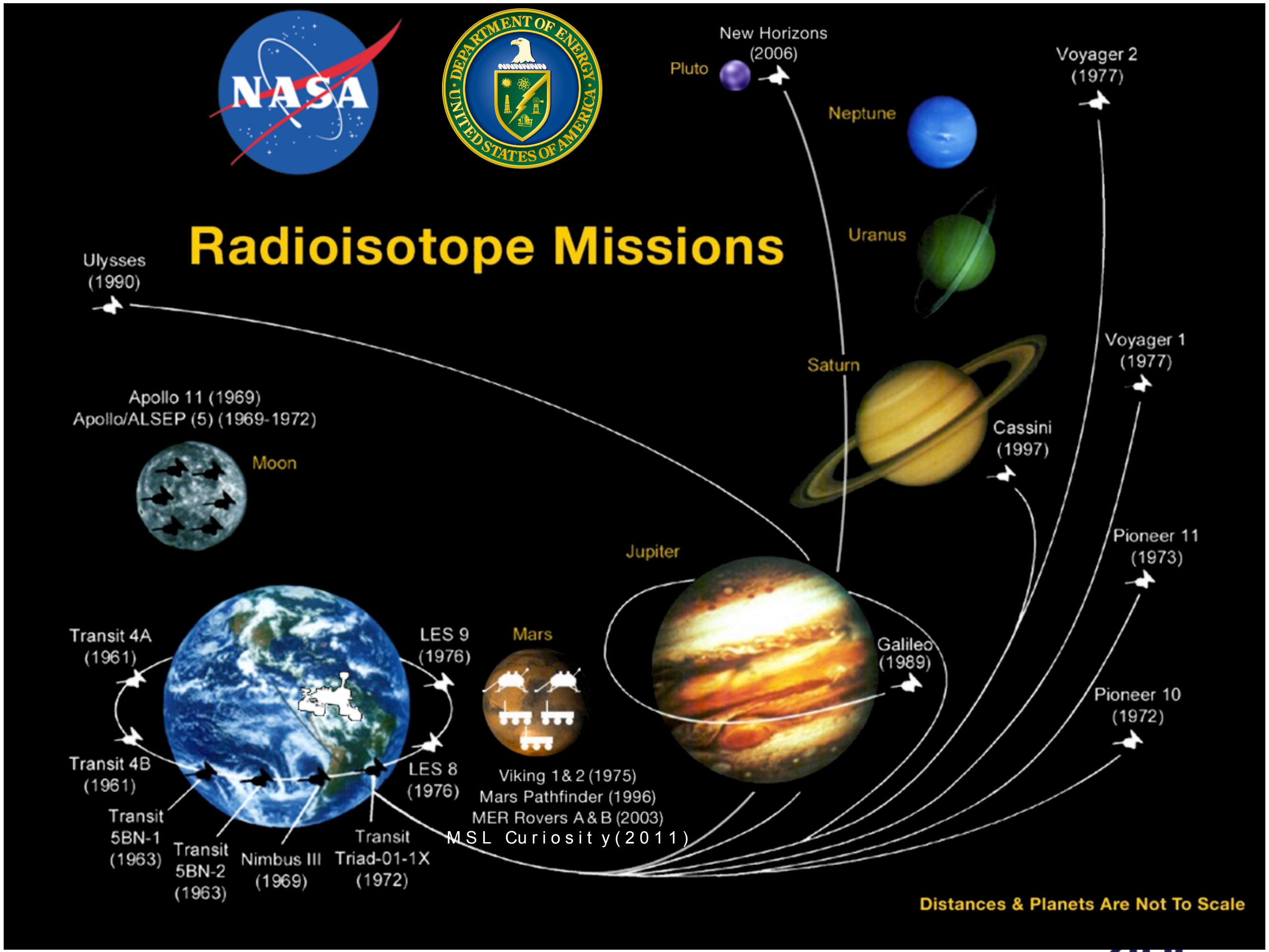
“It was easier done than said.”



Transit 4A Pu-238 power supply

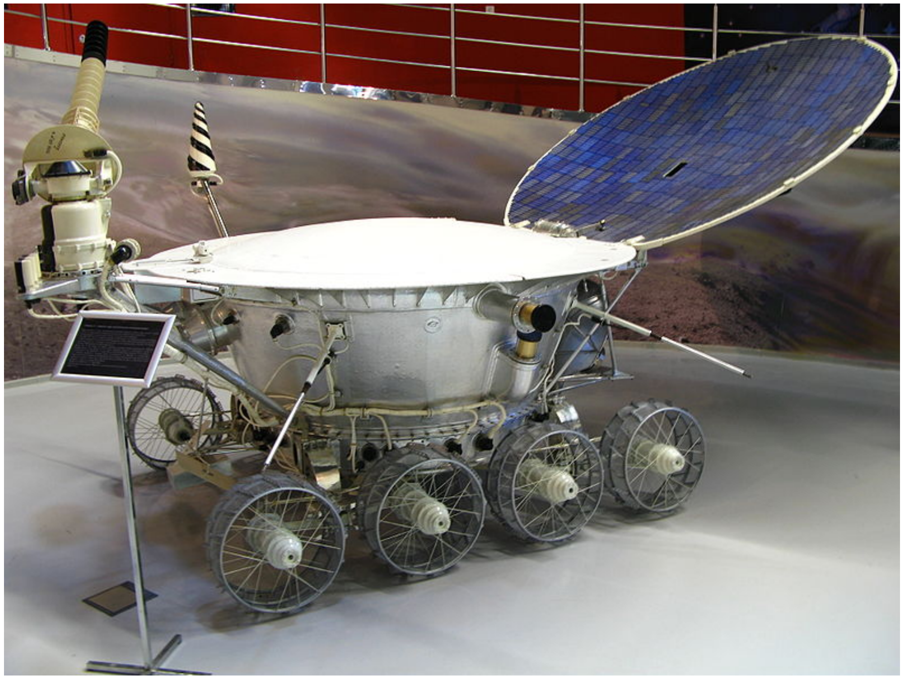
U.S. RPS Missions

- **The United States has launched 46 RTGs on 27 missions**
- **35 RTGs have been used on 18 NASA missions**
- **No mission has failed due to an RTG**



Russian RPS Missions

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



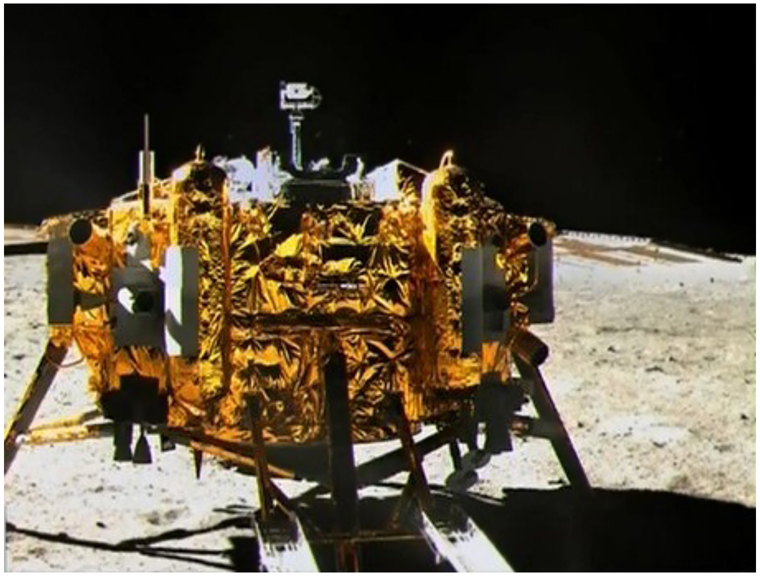
RHUs ensure survival during lunar night and provide compact heater and power sources for small autonomous stations (SAS) and penetrators on planetary probes

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

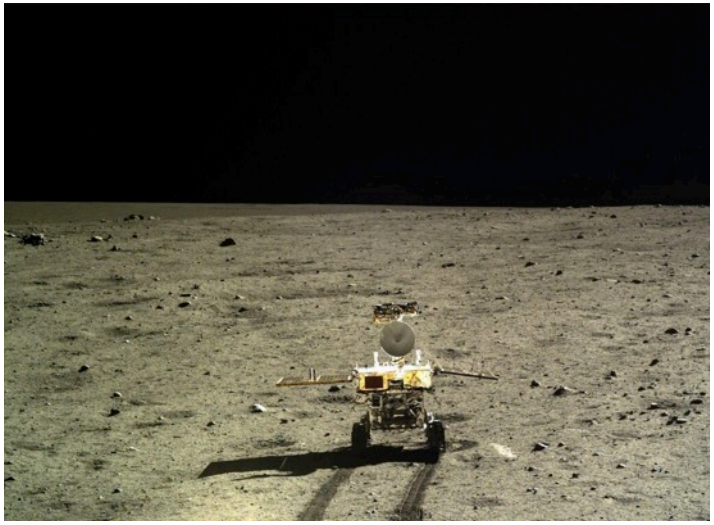
RHUs ensure survival during lunar night



Chang’e-3 lander from Yutu rover

RHU with APXS on Yutu –

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

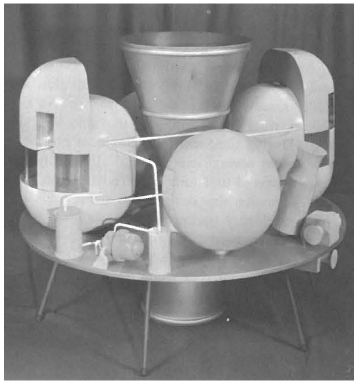


Yutu rover from Chang’e-3 lander

Convertor Technologies Have Proven Difficult to Develop

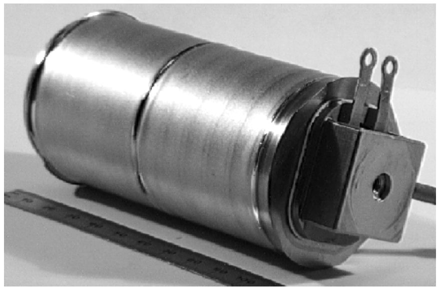
- **Requirements are high reliability and high thermal-to-electrical energy conversion**
  - In the U.S. emergence of thermoelectric materials were chosen over dynamic systems (Rankine - cycle mercury boiler was baselined for SNAP-1) for reliability
  - PbTe and TAGS materials followed by higher efficiencies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

SNAP – 1 concept



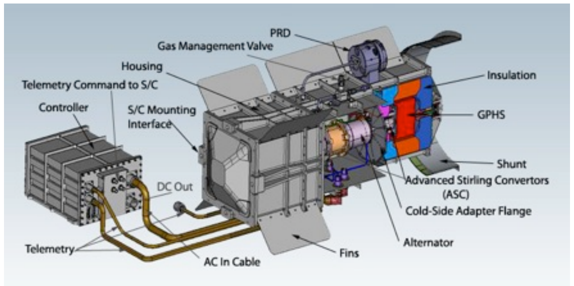
- **Other approaches were abandoned due to material difficulties**
  - Selenide thermoelectrics
  - Alkali metal thermal-to-electric converter (AMTEC)

AMTEC cell



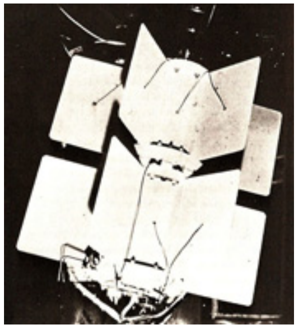
- **Still other approaches continue to show promise, but need larger infusions of research funds to further the technical readiness level of the the technology**
  - Skutterudites and other materials
  - Advanced Stirling Radioisotope Generator (ASRG) has been the most promising dynamic system to date

ASRG



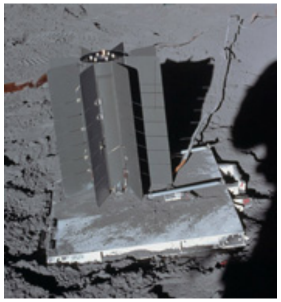
Types of RTGs

- **Space Nuclear Auxiliary Power (SNAP)-3 was the first nuclear launch on APL's Transit-4A satellite IN 1961**
- **SNAP-19B**
  - NIMBUS III; NASA's first launch and use of nuclear power (14 April 1969)
  - 28.2 W (BOL)
- **SNAP-19**
  - Pioneer 10 & 11; Viking 1 & 2
  - 40.3 W – 42.6 W (BOL); 5 years design lifetime
- **SNAP-27**
  - ALSEP (Apollo 12, 14-17)
  - 70 W (BOL); 2 years design lifetime
- **Multi-Hundred Watt (MHW)**
  - Voyager 1 & 2
  - 158 W (BOL)
- **General Purpose Heat Source (GPHS) RTG**
  - Galileo, Cassini, Ulysses, and New Horizons
  - 292 W (BOL)
  - 56 kg; 113 cm x 43 cm; 10.9 kg of Pu-238
- **Multi-Mission RTG (MMRTG)**
  - MSL
  - Designed for either vacuum of space or within atmosphere of a planet (i.e. Mars)
  - 110-120 W (BOL)
- **Advanced Stirling Radioisotope Generator (ASRG)**
  - No flight missions; proposed for TiME and CHopper

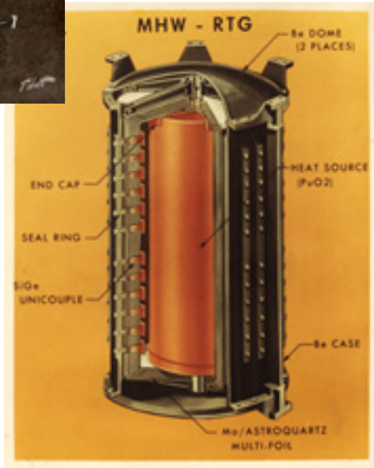


SNAP-19B

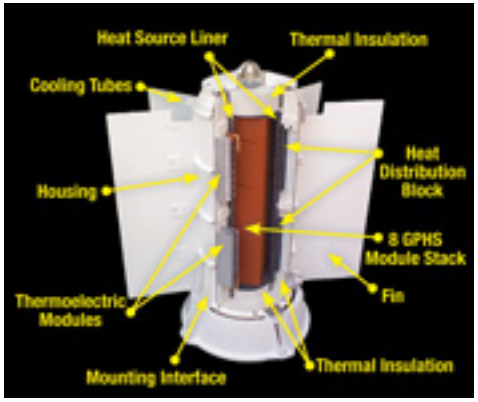
SNAP-19



SNAP-27



MHW RTG

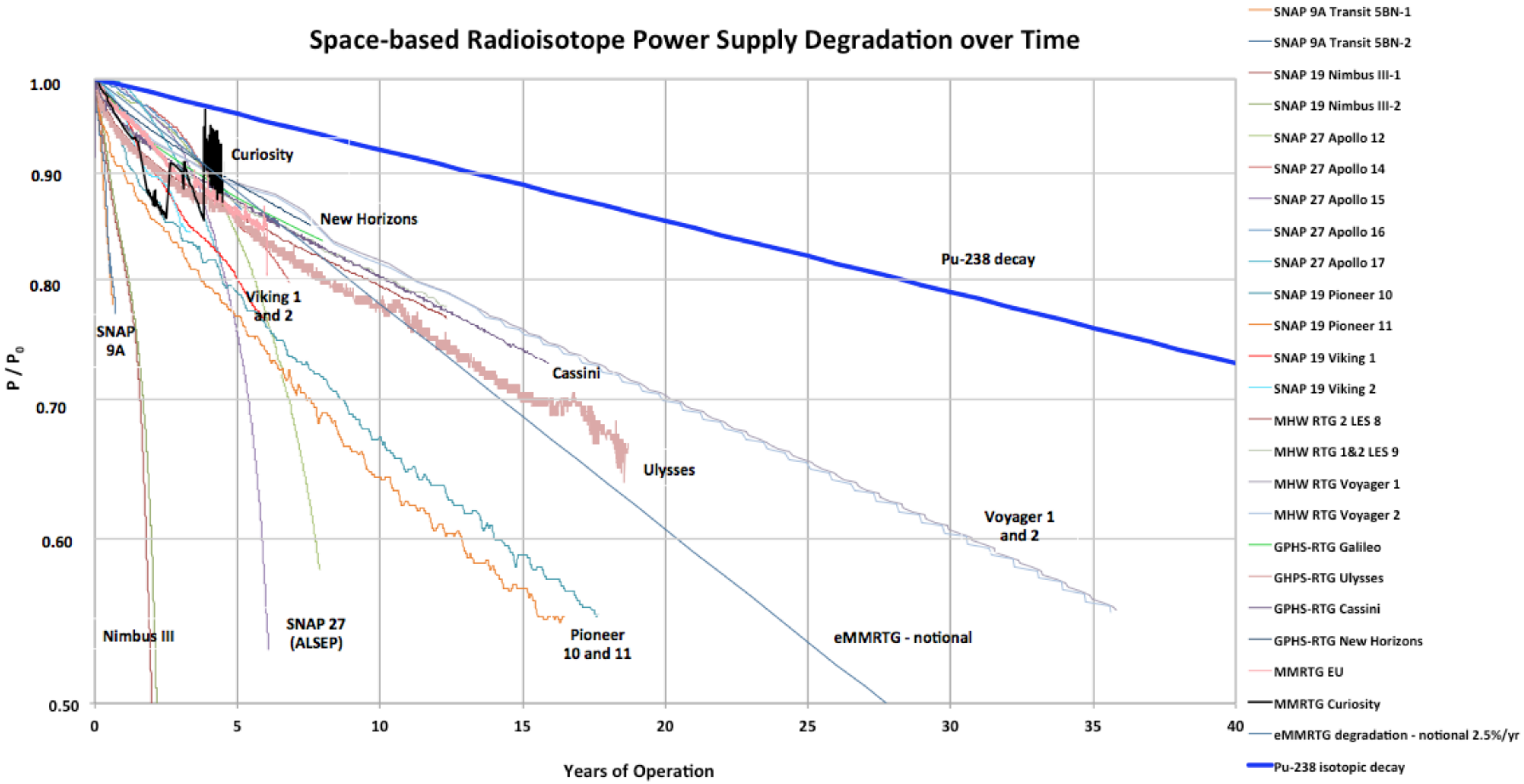


MMRTG

GPHS RTG

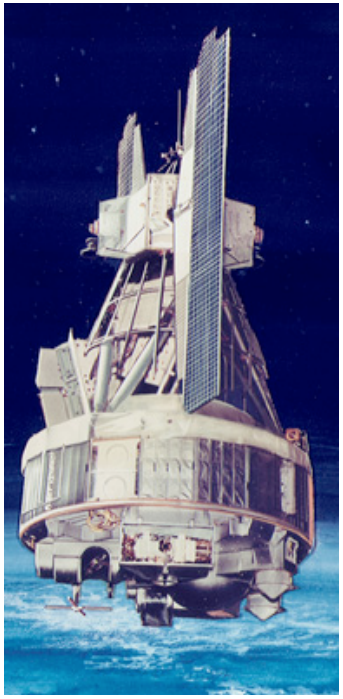
Long-lasting Electrical Power – with No Maintenance

Details matter: Output convolves Pu-238 decay, thermal environment, and convertor type



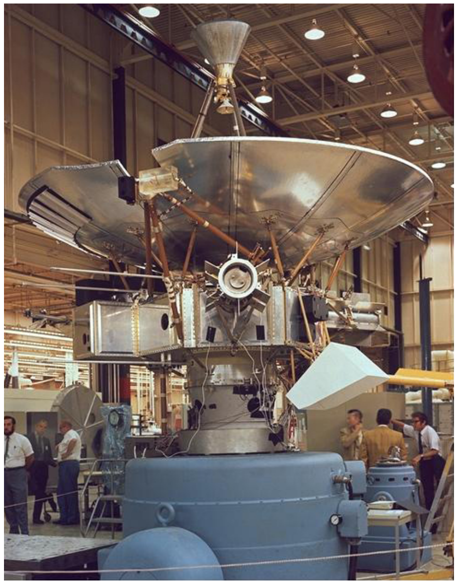
Missions Enabled: Getting started with SNAP 19

- Without RTGs and RHUs many of the most scientifically important and productive space missions of the last four decades (and counting) could not have happened

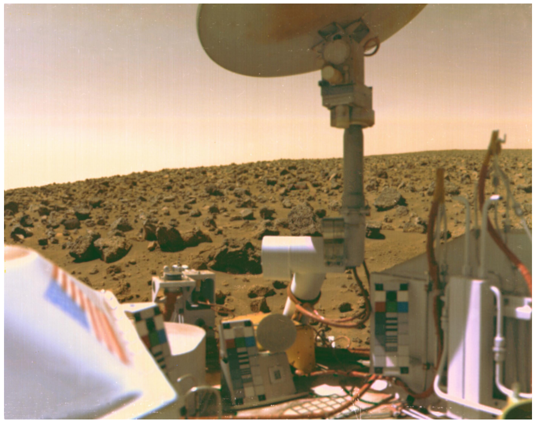


Nimbus B and Nimbus III: Meteorological Satellite and proof-of-concept for NASA

SNAP 19 cutaway



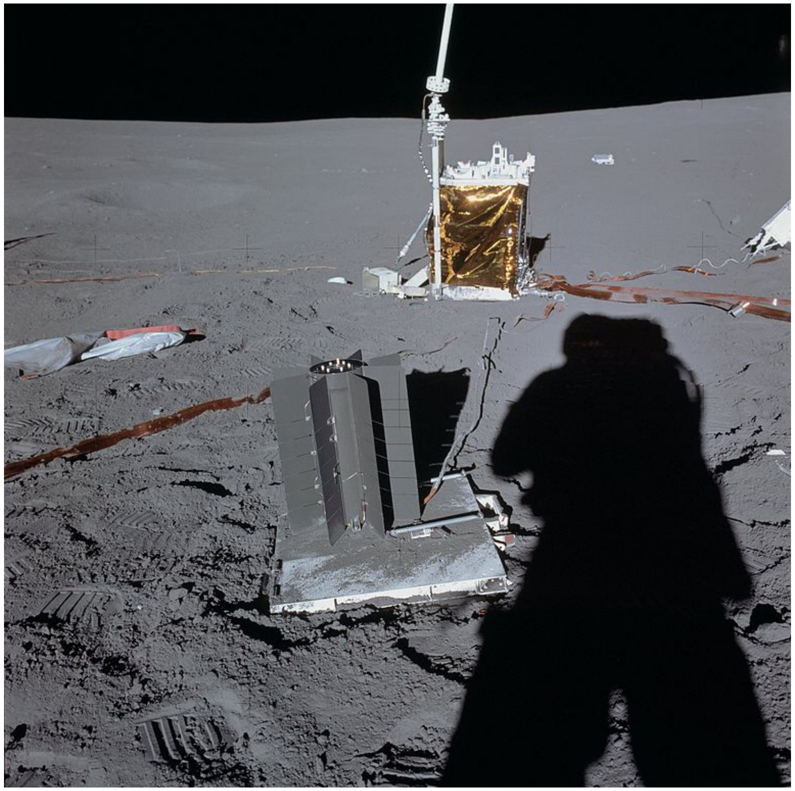
Pioneer 10 and 11



Viking 1 and 2

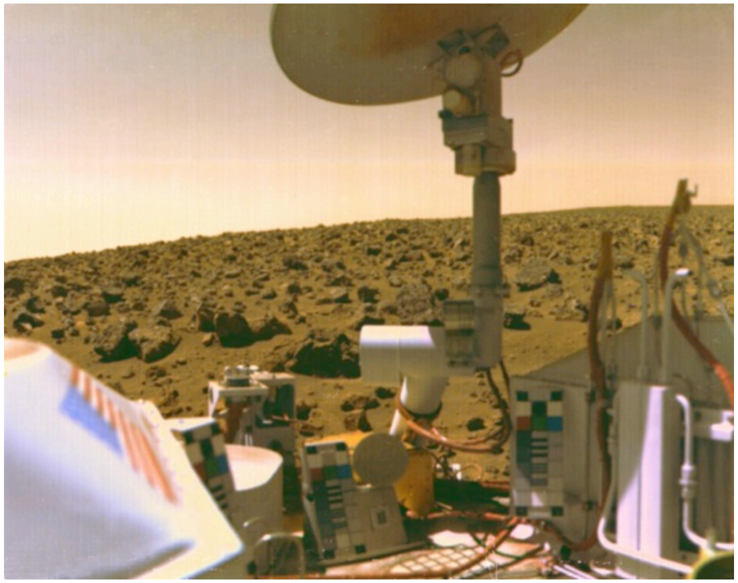
Missions Enabled: Long-Term Lunar Presence

- **Surveyor was originally planned to employ RTGs so as to survive the lunar night**
  - The SNAP 11 was to use Curium-242 to allow the spacecraft to function for 130 days
  - Dropped due to cost
- **The Apollo Lunar Surface Experiment Package (ALSEP) was deployed on Apollo 12, 14, 15, 16, and 17**
  - The SNAP 27 used Plutonium-238
  - Assembly by an astronaut was required following landing
  - The units were turned off long after the last landing due to cost constraints (30 Sep 1977)



ALSEP and SNAP 27 deployed on Apollo 14

Missions Enabled: The surface of Mars



SNAP 19 RTGs for power:

Viking 1 and 2 landers

RHUs for warmth:

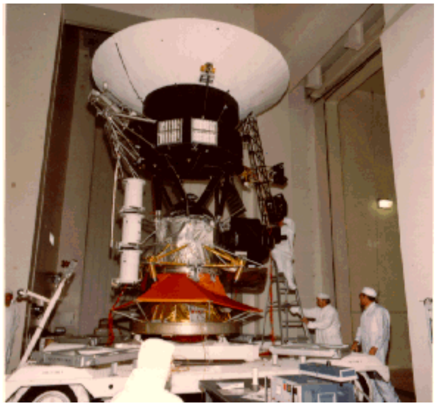
Sojourner, Spirit, and Opportunity

MMRTG for mobility:

Curiosity

Missions Enabled: The outer solar system …and beyond

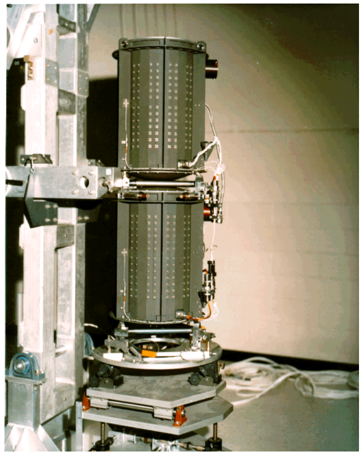
- Multi-hundred watt (MHW) RTGs systems and evolution to GPHS-RTGs



Voyager 1 and 2

Galileo

Ulysses w/ IUS



MHW RTGs for Voyager

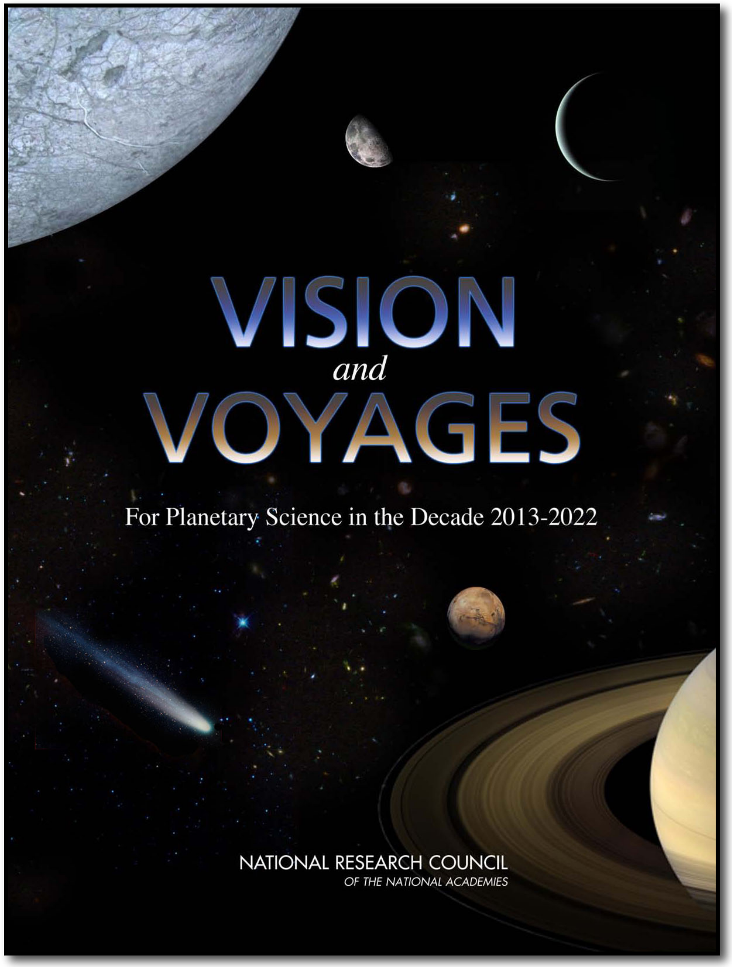
Cassini GPHS RTGs

New Horizons

Cassini-Huygens

RPS Systems Play a Fundamental, Enabling Role in the New Planetary "Decadal Survey"

- *Vision and Voyages for Planetary Science in the Decade 2013-2022* released in March 2011 after comprehensive planetary science community input and review
- THE document used as a guide in the U.S. by the Administration (NASA, OSTP, and OMB) as well as the Congress for guiding planetary science polity and initiatives for the coming decade

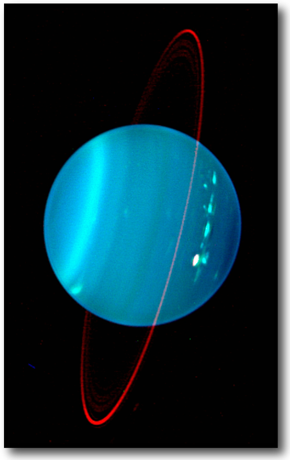

VISION and VOYAGES

For Planetary Science in the Decade 2013-2022

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

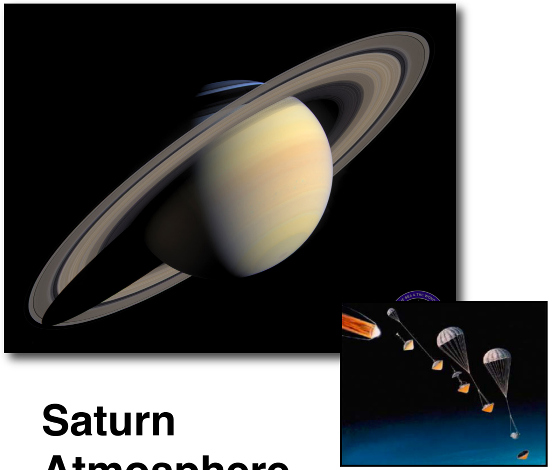
Over Half of the Notional Decadal Missions are Enabled by RPS

Jupiter Europa Orbiter

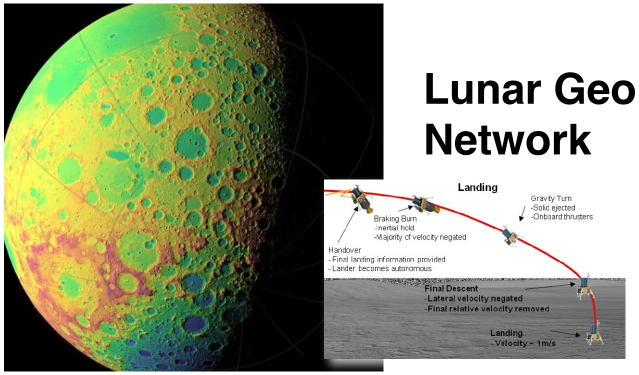


Uranus Orbiter/ Probe

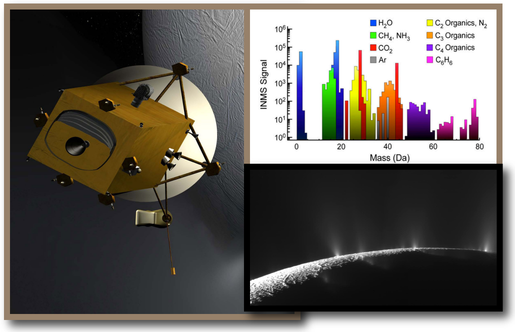
Trojan Tour and Rendezvous



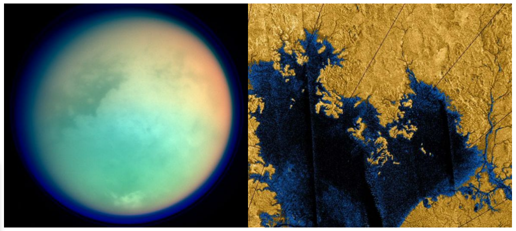
Saturn Atmosphere Probe



Lunar Geophysical Network

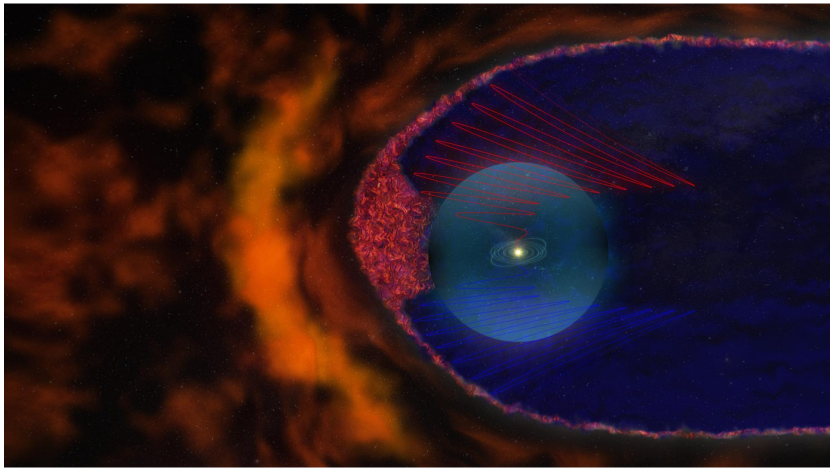


Enceladus Orbiter



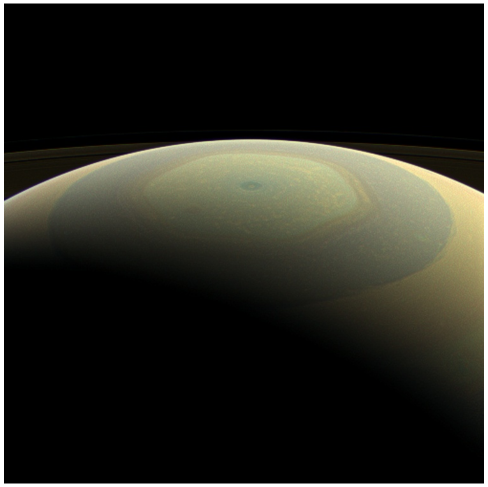
Titan Saturn System Mission

Meanwhile discoveries from past investments continue…



Voyager 1 in Interstellar Space

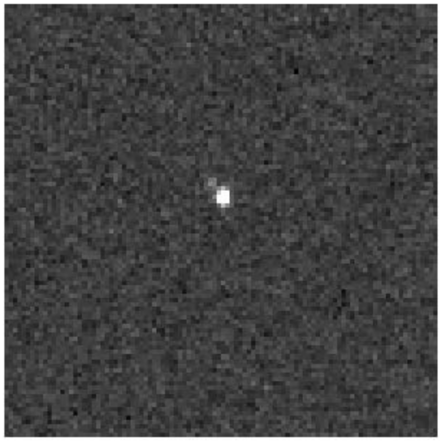
Curiosity on rocks on Mars



Cassini viewing jet stream of Saturn…

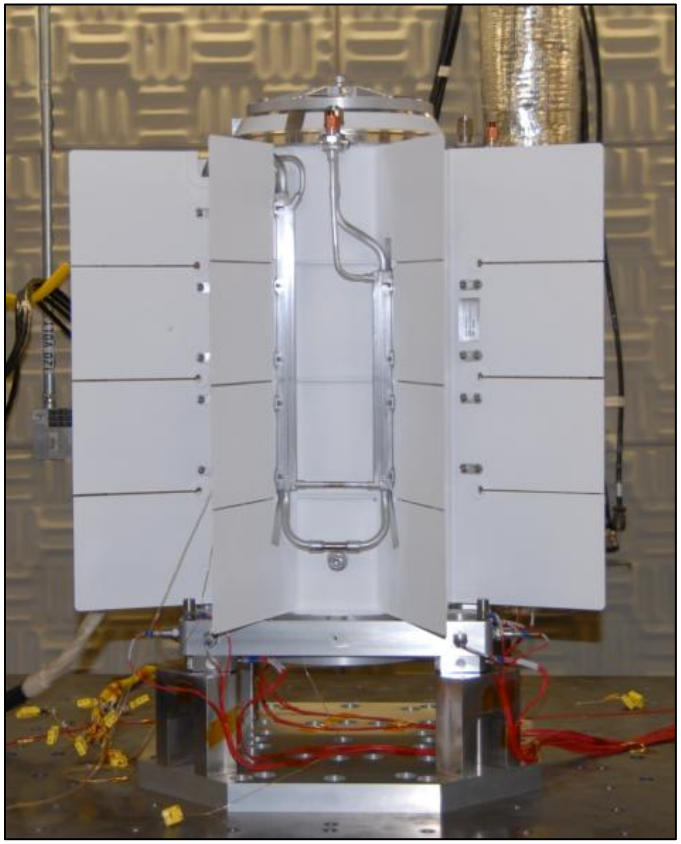
…and Huygens on the surface of Titan

New Horizons seeing Charon for the first time



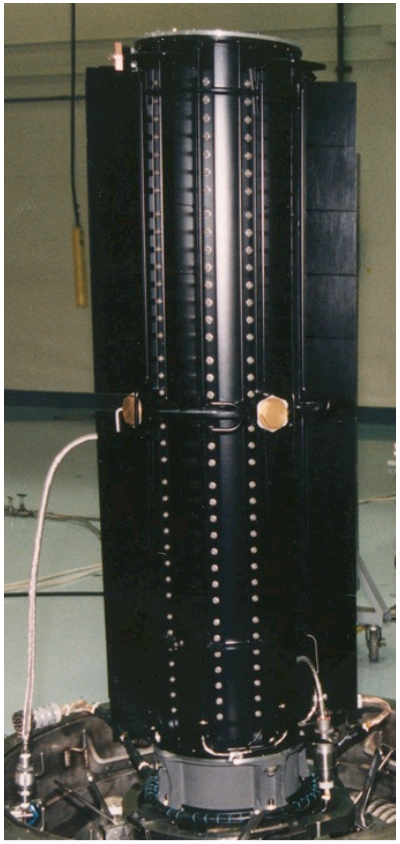
All Enabled by Pu-238 fueled Radioisotope Power Systems

Available for future use



MMRTG

Design abandoned



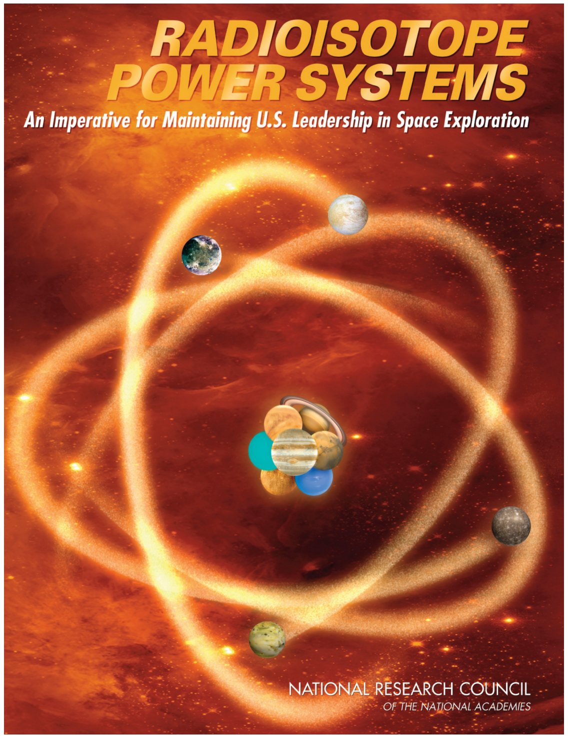
GPHS - RTG

Abandoned – safety issues

MHW - RTG

Status

- **How are we doing compared to 2009?**
- **At that time:**
  - **No domestic Pu-238 production since 1988 (K-reactor at Savannah River)**
  - **NASA has been relying on Russian purchases**
  - **Known world inventory is likely less than 30 kg**
  - **“Breeding stock” of U.S. Np-237 is ~300 kg**
  - **U.S. plans for new production were put on hold by 9/11**



RADIOISOTOPE POWER SYSTEMS

An Imperative for Maintaining U.S. Leadership in Space Exploration

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

NRC Finding (in 2009)

Domestic Production of ^{238}Pu

There are two viable approaches for reestablishing production of ^{238}Pu, both of which would use facilities at Idaho National Laboratory and Oak Ridge National Laboratory. These are the best options, in terms of cost, schedule, and risk, for producing ^{238}Pu in time to minimize the disruption in NASA’s space science and exploration missions powered by RPSs.

Approaches being pursued

HIGH-PRIORITY RECOMMENDATION (2009)

^{238}Pu Production

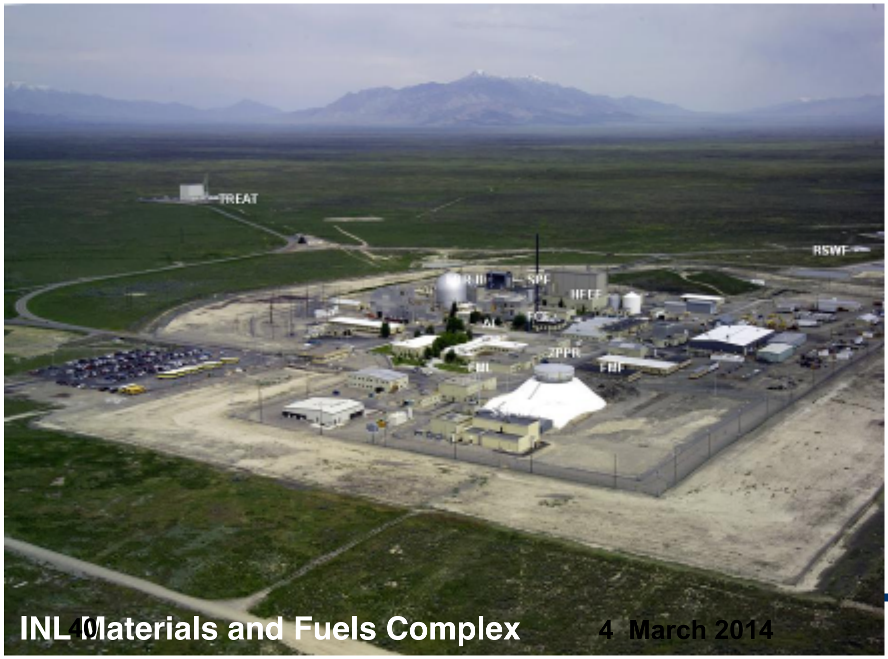
The FY 2010 federal budget should fund the DOE to reestablish production of ^{238}Pu.

- **As soon as possible, the DOE and the OMB should request–and Congress should provide adequate funds to produce 5 kg of ^{238}Pu per year.**

In process with lower goal

- **NASA should issue annual letters to the DOE defining future demand for ^{238}Pu.**

Last letter issued in 2010



INL Materials and Fuels Complex

NRC Finding in 2009

Multi-Mission RTGs

It is important to the national interest to maintain the capability to produce MMRTGs,

given that proven replacements do not now exist.

No change

NRC Recommendation in 2009
Multi-Mission RTGs

NASA and/or the DOE should maintain the ability to produce MMRTGs.

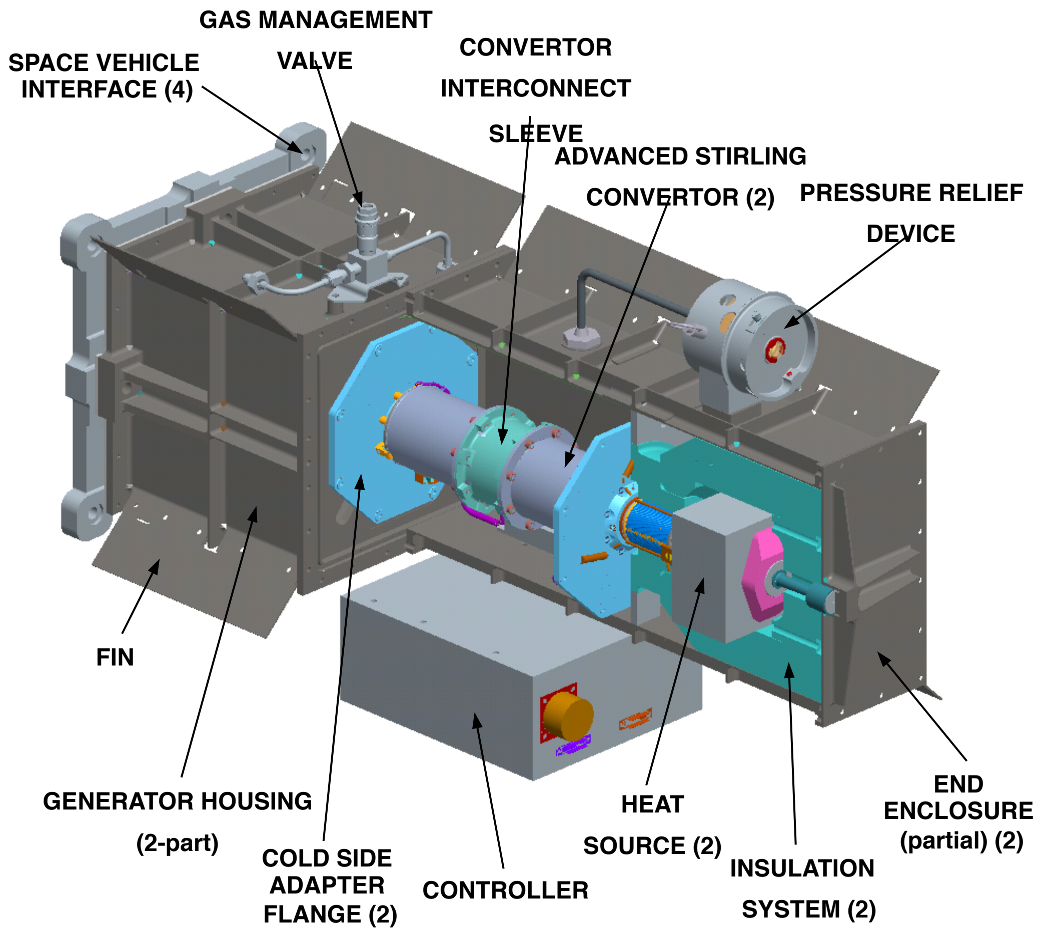
Implemented and continuing

MSL Rover

Advanced Stirling Radioisotope Generator (ASRG)

Approached initiated in 2001; SRG envisioned as power for 2007 MSL – MMRTG was the "backup"

New Stirling heat engine generators have ~30% conversion efficiency



Design Life: 17 Years

Power: BOM – 140 We
EOM Deep Space (14 Yrs) - 126 We

Mass: 20.2 kg

Size: 72.5 cm L x 41 cm H x 29.3 cm W

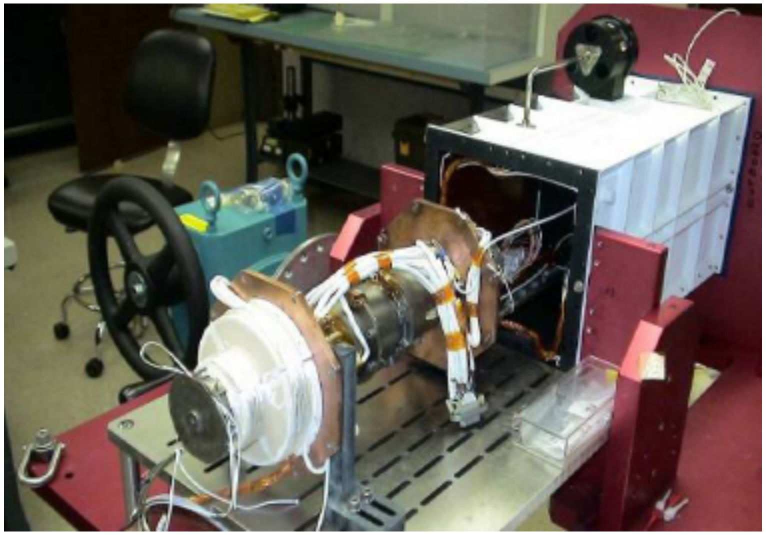
ATTRIBUTES

- Two Advanced Stirling Convertors
  - Co-Axially aligned for dynamic balance
  - One GPHS (Step 2) per convertor
- Integrated, Single-Fault Tolerant Controller
- Beryllium Housing
- Operates in vacuum or Martian atmosphere

HIGH-PRIORITY RECOMMENDATION (2009)

ASRG Development

NASA and DOE should complete the development of the ASRG with all deliberate speed, with the goal of demonstrating that ASRGs are a viable option for the Outer Planets Flagship 1 mission. As part of this effort, NASA and the DOE should put final design ASRGs on life test as soon as possible (to demonstrate reliability on the ground) as soon as possible (to demonstrate reliability on the ground) and pursue an early opportunity for operating an ASRG in space (e.g., on Discovery 12).



Not selected for Discovery 12

Development for flight on indefinite hold - $$ issues

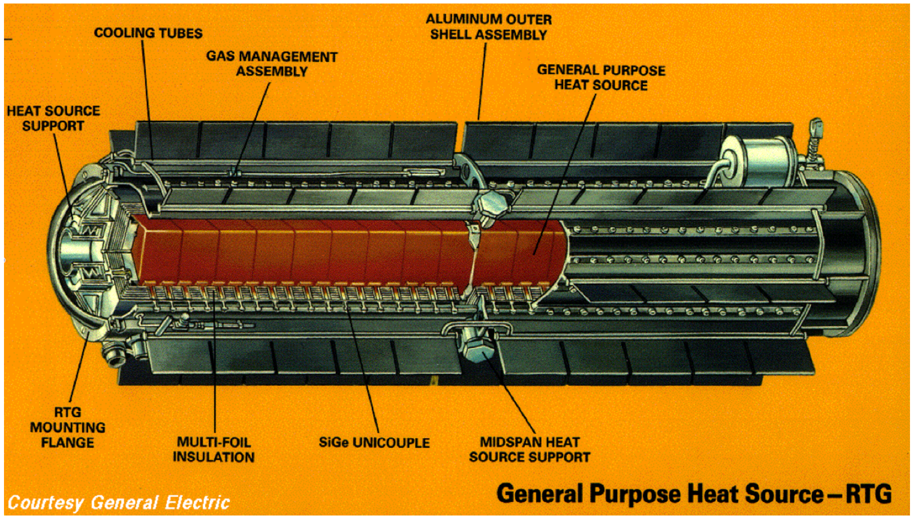
GPHS – RTG
Design Abandoned

Sufficient spare parts *may* exist to assembly one or two at lower power output

Would require direction from NASA and funds to investigate

- **Traditional RTGs use thermocouple converters**
  - Advantages: long life (more than a decade) and no moving parts
  - Disadvantage: low conversion efficiency (~5%); **(low compared to ASRG – high compared to MMRTG)**; requires more rare Pu-238
- **This previous design produced ~300W**

• 300 Watt generator class	
• used on Ulysses, Galileo, Cassini	
• Projected power	
• BOM (2006)	**249 We**
• EOM (2015)	**202 We**
• Mass	**57.8 kg**
• Overall length	**100.3 cm**



Courtesy General Electric

General Purpose Heat Source – RTG

Current (January 2014) Operations and Plans

- The President's proposed FY 2014 budget shifts fiscal responsibility and target budget for maintenance of NASA-required DOE infrastructure to NASA
- To improve transparency on DOE's planning basis to support NASA's mission DOE established in July 2013 an allocation of 35 kg of Pu-238 for Civil Space (NASA) use including both older U.S. supplies and previously purchased supplies from the Russian government
- In September 2013 NASA has deferred flight development of the ASRG
- Beginning in FY 2012 the Plutonium-238 Supply Project began at Oak Ridge National Laboratory to produce an average ~1 kg/yr of Pu-238 isotope (1.5 kg of PuO_2 product) by 2021
  - This effort is currently in a technology demonstration phase
- Any RPS-enabled flights for the next decade will use the flight-qualified MMRTG, as is the Mars 2020 mission – the only such future mission currently in Phase A study by NASA
- New for today – FY2015 budget will be indicative of current thinking