Radioisotope Power Systems: Pu-238 and ASRG status and the way forward

Ralph L. McNutt, Jr.

Space Department
Johns Hopkins University Applied Physics Laboratory
Laurel, MD 20723 USA

SBAG SMALL BODIES ASSESSMENT GROUP

OPAG Outer Planets Assessment Group

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

APL
The Johns Hopkins University
APPLIED PHYSICS LABORATORY

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**

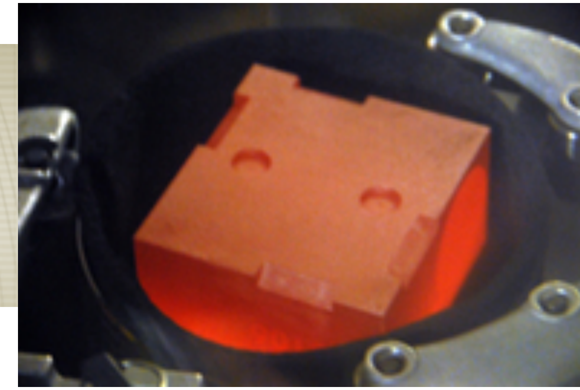
Origin of RPSs in the U.S. was with Po-210 fuel

- **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**

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

- **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

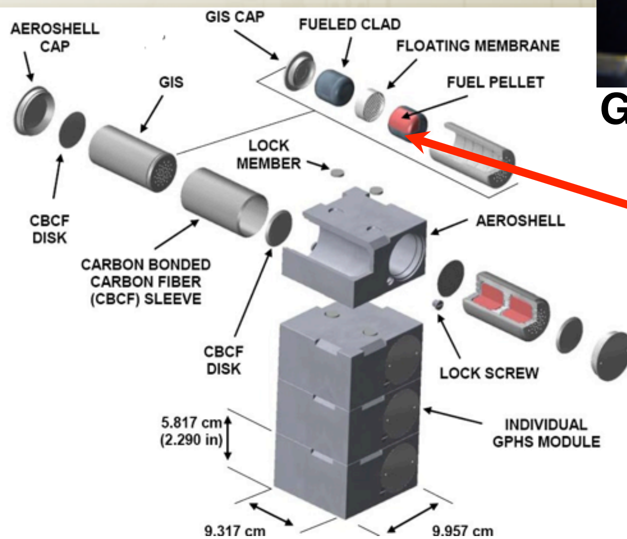
Pu-238 usage in space – U.S. standard packaging is a given

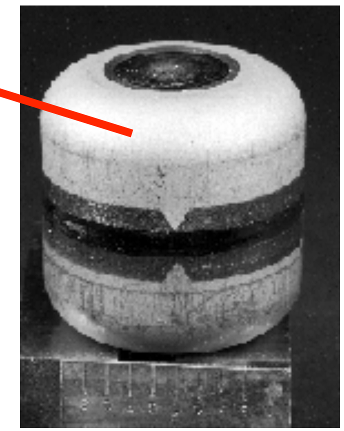


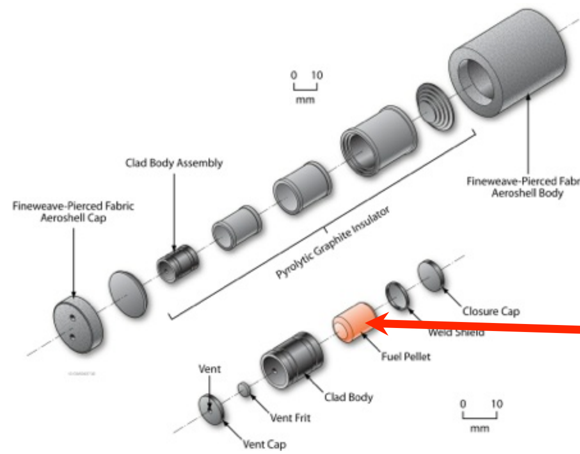
GPHS for Curiosity (from INL)

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

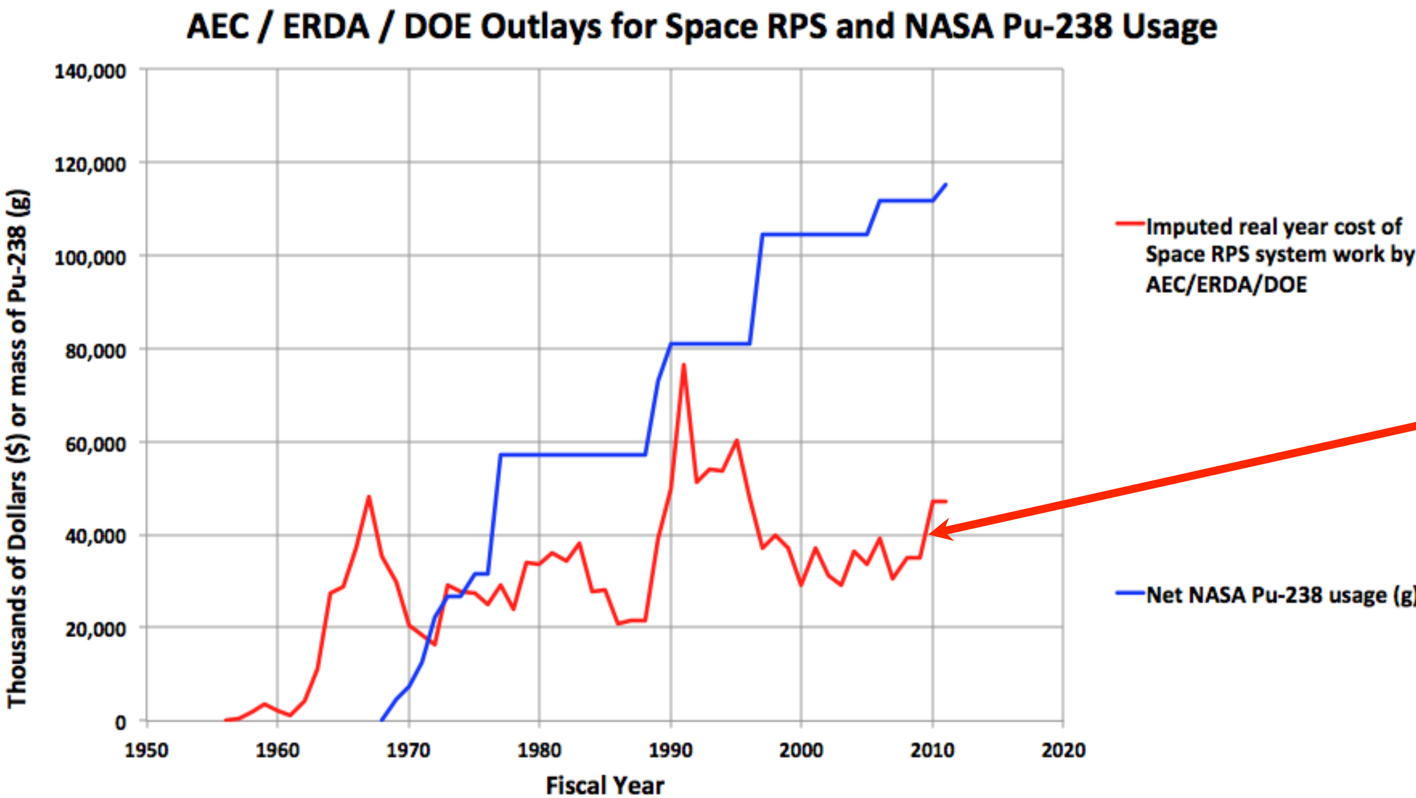
- **Power:** General Purpos Heat Source (GPHS) Step-2, each containing pellets of Pu-238 in the chemical form PuO_2 (nominal 150 g)
- **Heating**: Light Weight Radioisotope Heating Unit (LWHRU), each containing 1 pellet of Pu-238 in the chemical form PuO_2 (nominal 2.7 g)







Pu-238 usage in space – Quantity



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

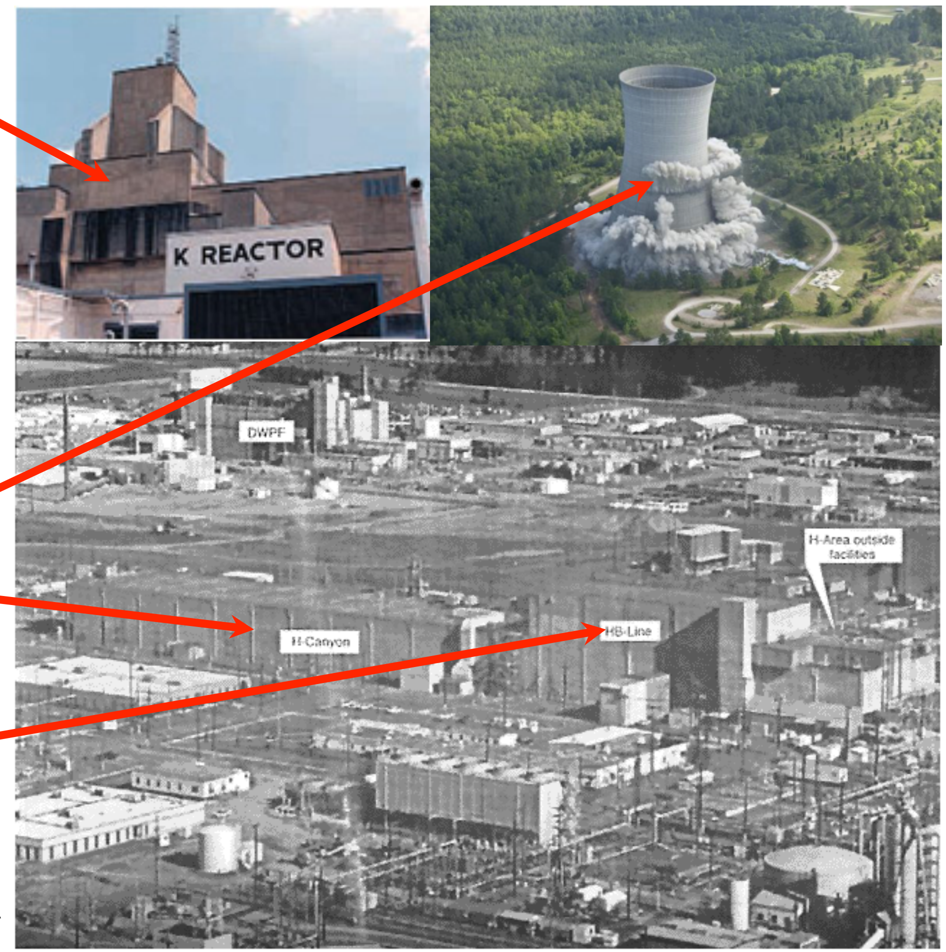
N.B. The costs directly supplied by DOD and NASA to these programs are ***not*** captured in these numbers

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

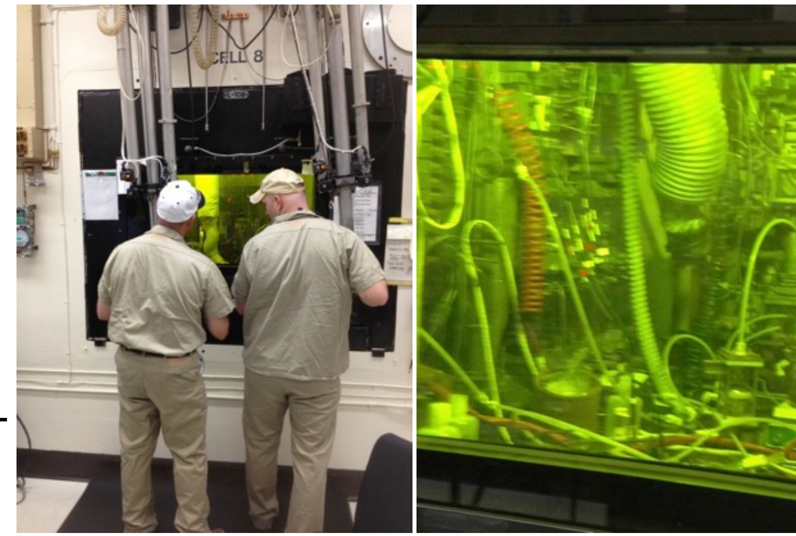
Production and separation of Pu-238 were carried out at the Savannah River facility in South Carolina – Industrial Scale

- **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**

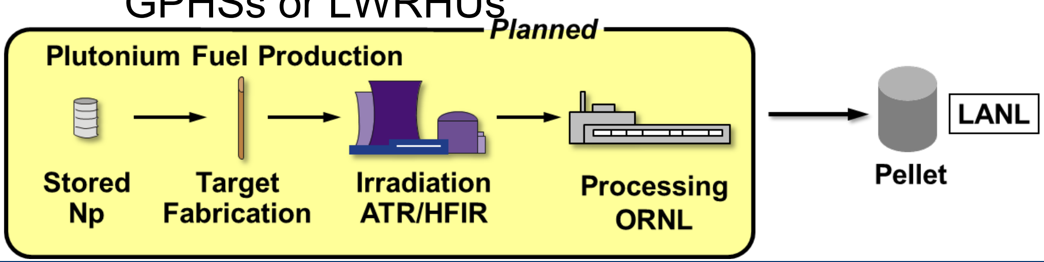


New Pu-238 Supply Project for NASA is more modest

- **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)

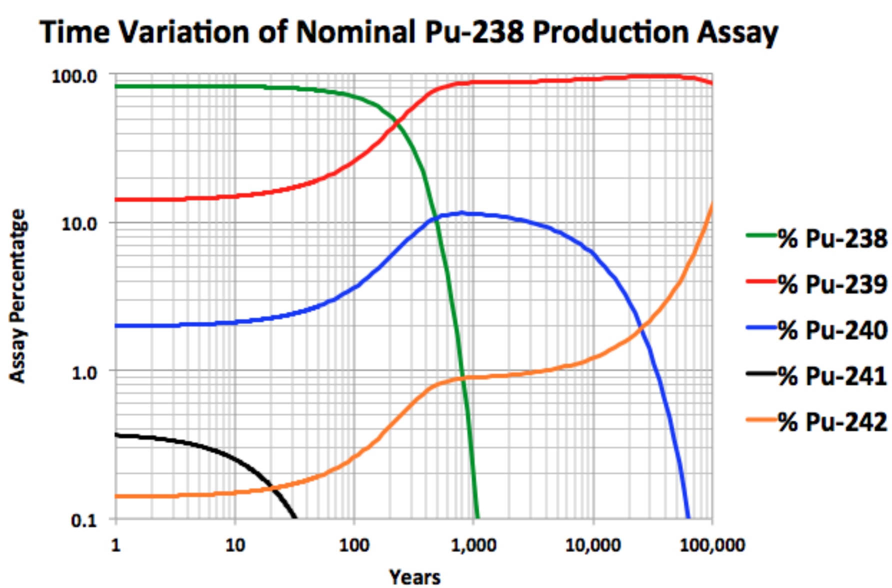
- **When producing isotopes in a reactor, multiple channels as dictated by nuclear physics come into play – so no product is “clean”**
- **Once made, all isotopes begin decaying at physics-dictated rates and sometimes producing new radiological hazards**
- **The only “controls” are**
  - Initial target 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 less 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

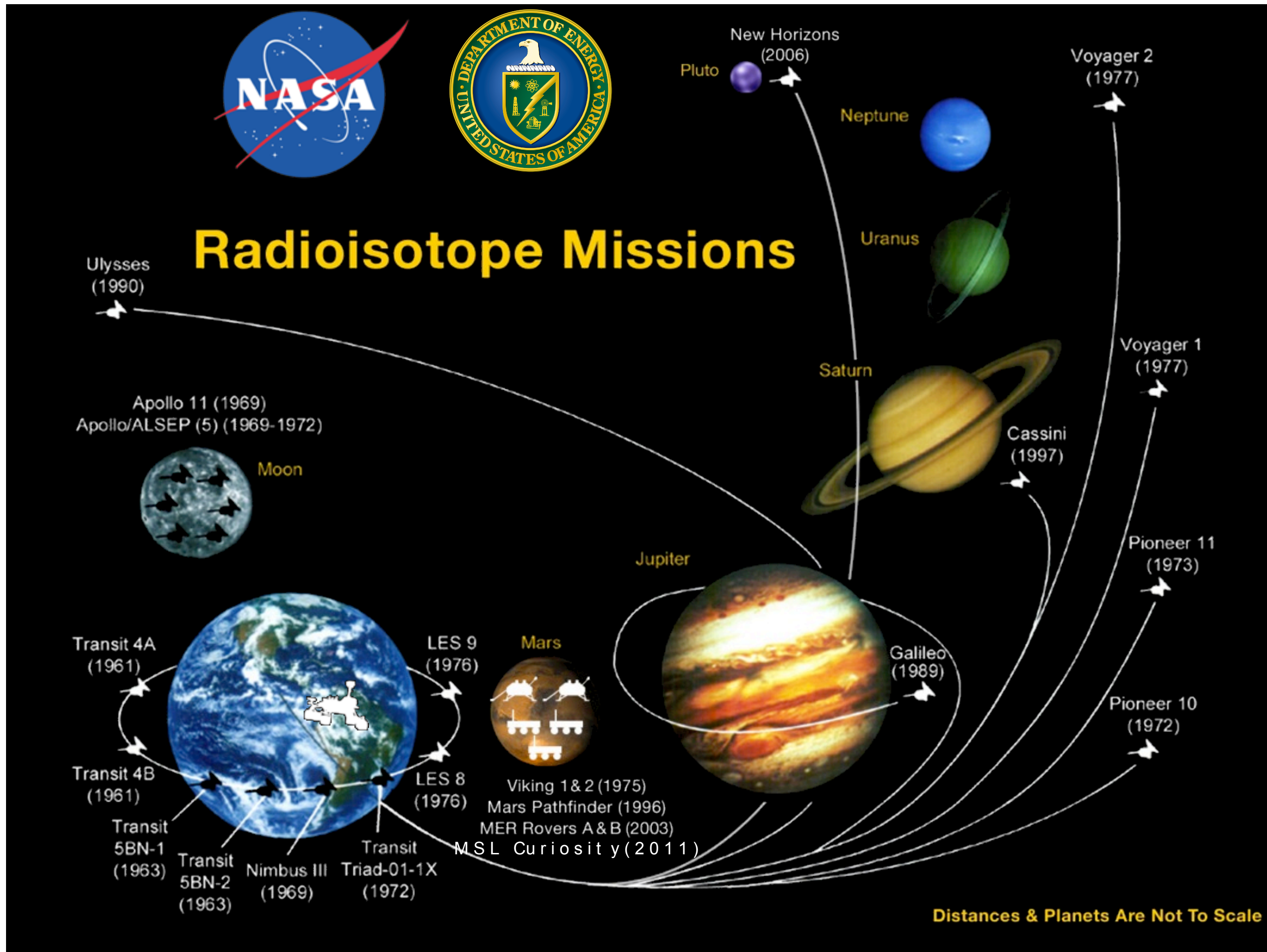
Hence, a fuel clad contains roughly 0.42/0.56 x 150 g ~ 110 g of Pu-238 isotope

Details matter – this is the maximum thermal power available

U.S. RPS Missions

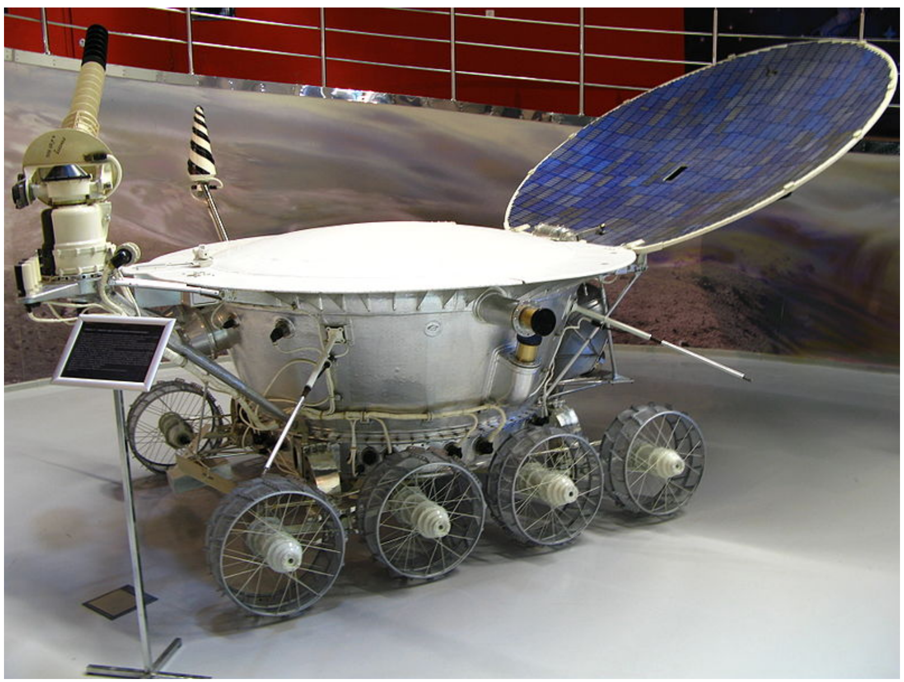
SBAG SMALL BODIES ASSESSMENT GROUP
OPAG Outer Planets Assessment Group

- 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

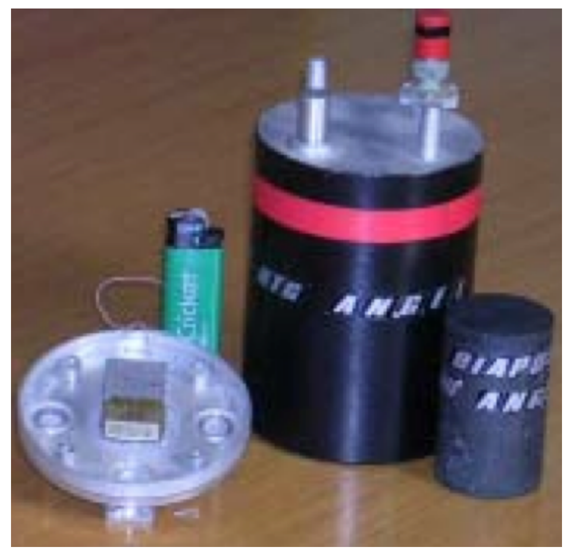


Russian RPS Missions

- 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

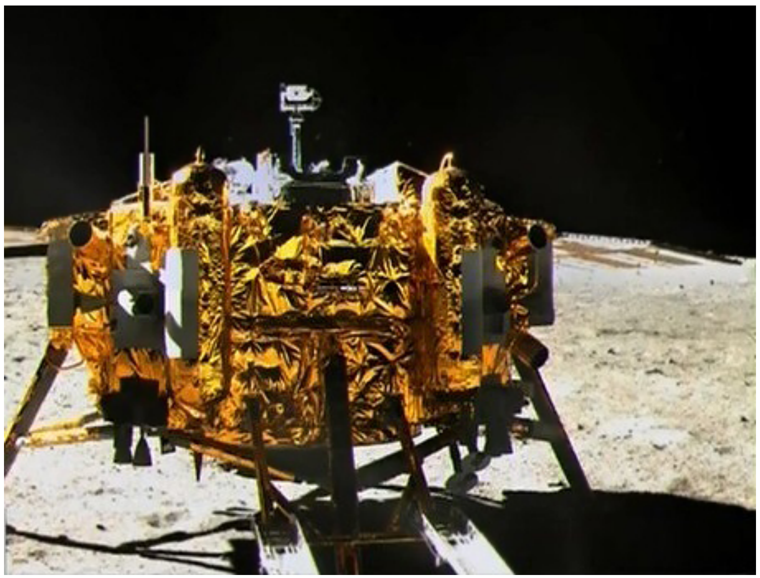


8.5 W_{th} and 200 mW_e «Angel» RHU and RTG employed on Mars-96

Chinese RPS Missions

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

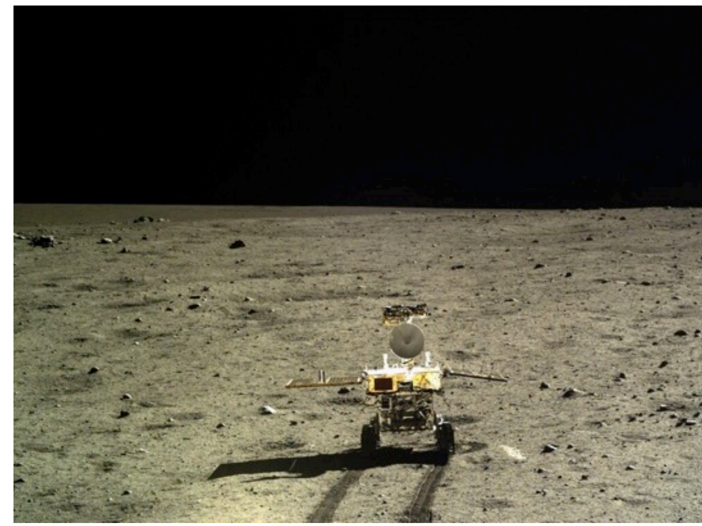
RHUs ensure survival during lunar night



Chang’e-3 lander from Yutu rover

RHU with APXS on Yutu –

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

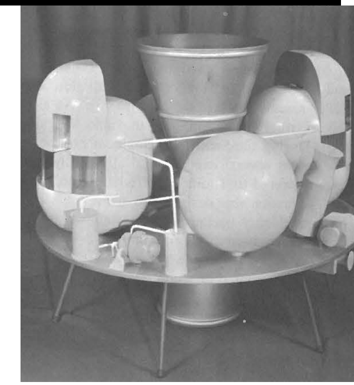


Yutu rover from Chang’e-3 lander

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

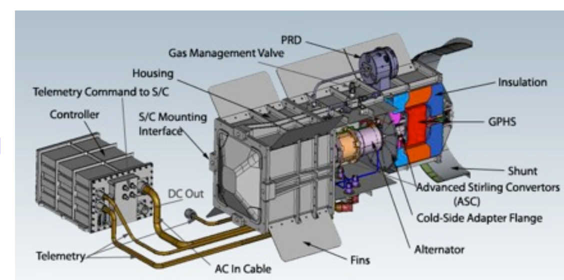


- **Other approaches were abandoned due to material difficulties**
  - Selenide thermoelectrics
  - Alkali metal thermal-to-electric converter (AMTEC)

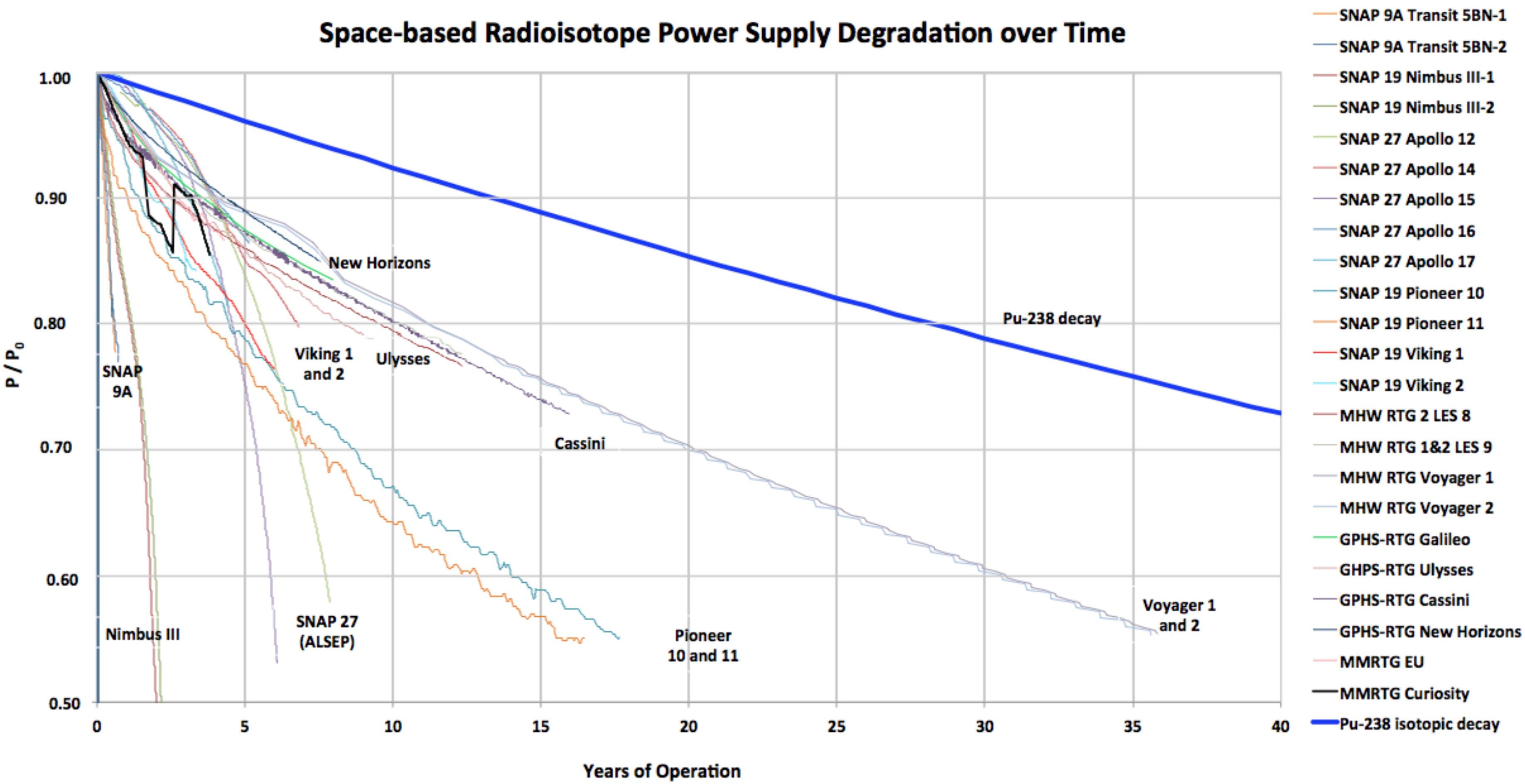
AMTEC cell

- **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

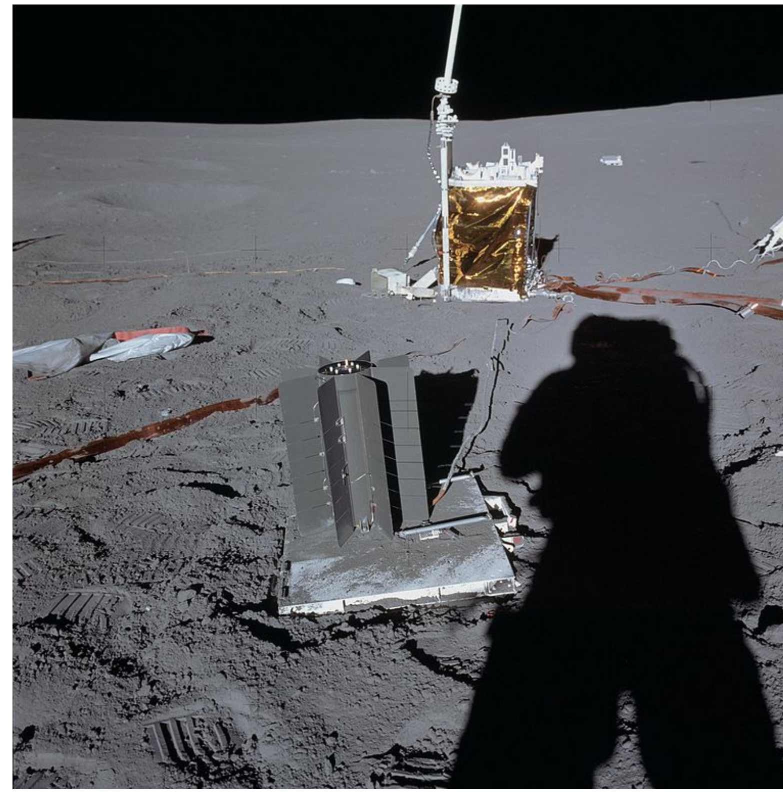


Long-lasting Electrical Power – with No Maintenance



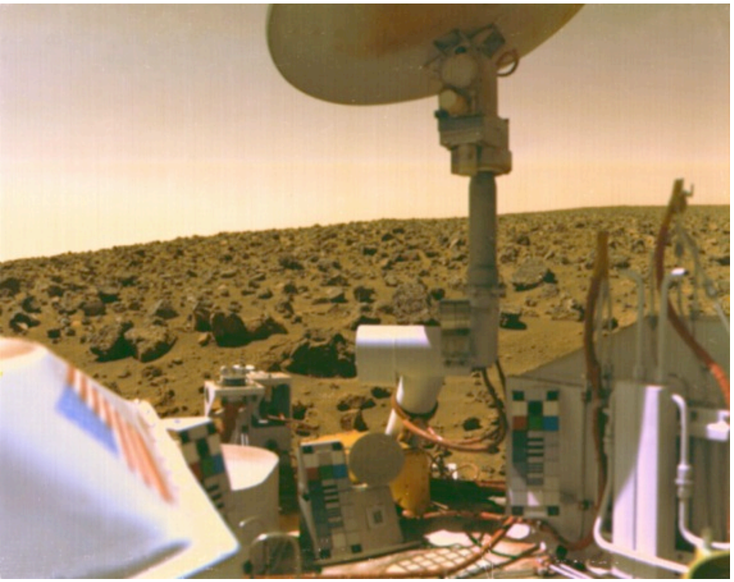
Missions Enabled: Long-Term Lunar Presence

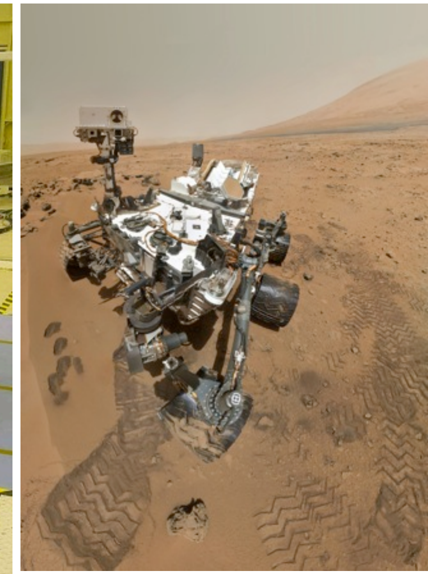
- **Surveyor was originally planned to employ RTGs so as to survive the lunar night**
  - The SNAP 11 was to use Curium-242 to allow the spacecraft to function for 130 days
  - Dropped due to cost
- **The Apollo Lunar Surface Experiment Package (ALSEP) was deployed on Apollo 12, 14, 15, 16, and 17**
  - 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:

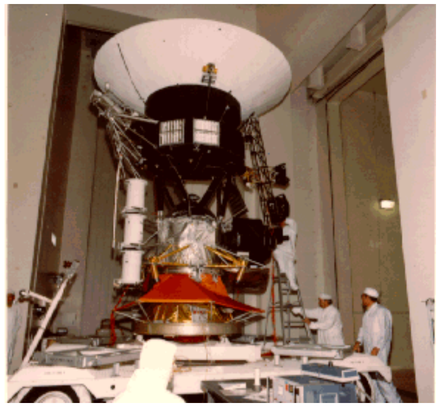
Sojourner, Spirit, and Opportunity

MMRTG for mobility:

Curiosity

Missions Enabled: The outer solar system …and beyond

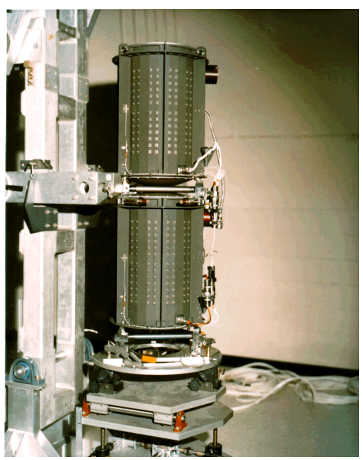
- **Multi-hundred watt (MHW) RTGs systems and evolution to GPHS-RTGs**



Voyager 1 and 2

Galileo

Ulysses w/ IUS



MHW RTGs for Voyager

Cassini GPHS RTGs

New Horizons

Cassini-Huygens

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