Radioisotope Power Systems Launch Safety and Space Science

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Radioisotope Power Systems

- Radioisotope Power Systems (RPSs) have played a crucial role in exploration of outer planets and deep space for almost 40 years since the Apollo missions to the moon
- Critical to continuing expansion of knowledge of the solar system in the 21st century
- VITAL to those past successes and continued existence of an outer planets science program is that these missions
  - Be done in a safe-reliable manner
  - Maintain the safety of the public

Topics

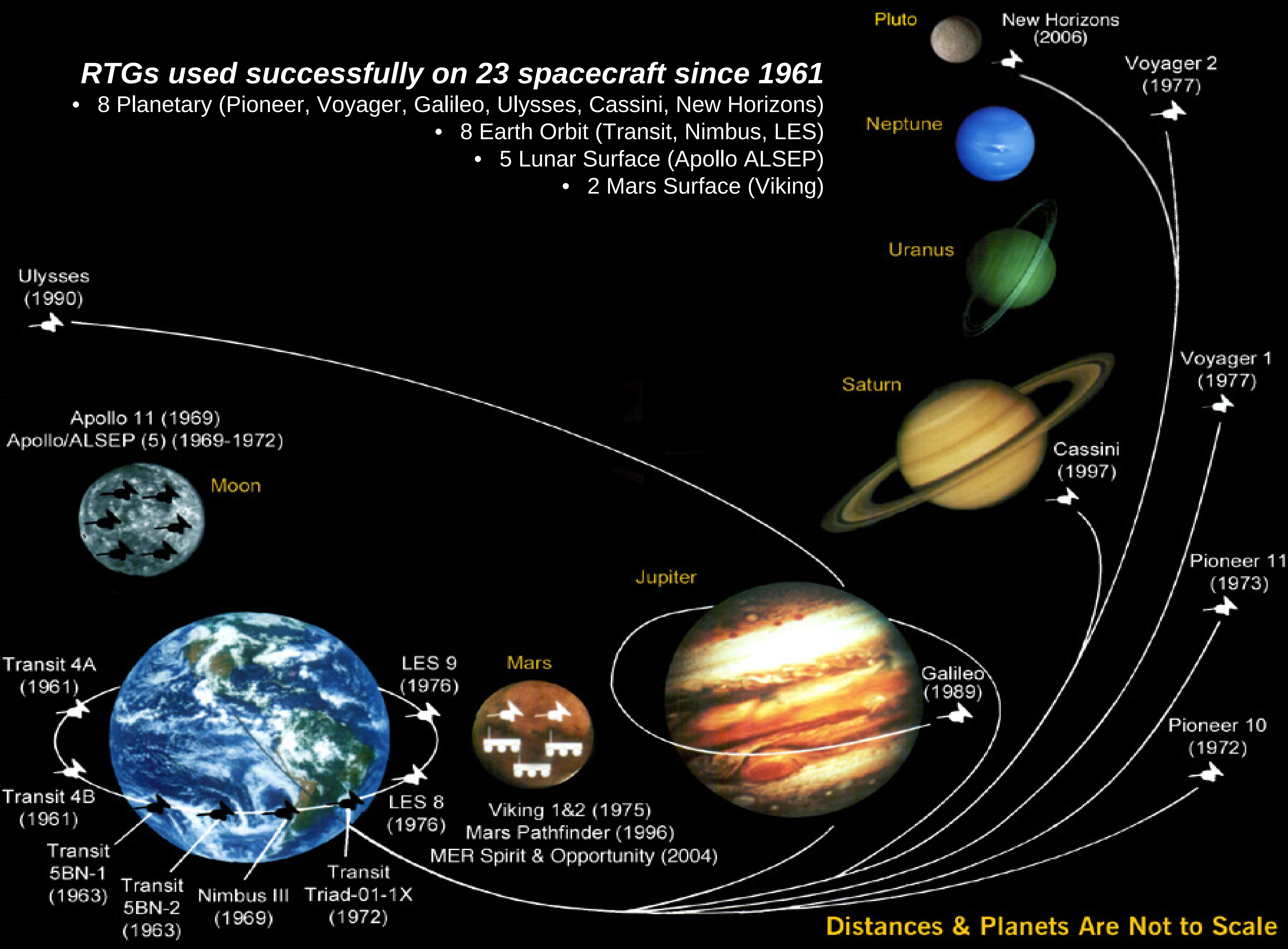
Why do we conduct missions with radioisotopes?

- To advance our knowledge of our solar system

- Review missions enabled using RPSs
  - A few brief highlights of knowledge collected through use of RPSs
- Processes in place to ensure public safety which permit the use of these systems

RTGs used successfully on 23 spacecraft since 1961

- 8 Planetary (Pioneer, Voyager, Galileo, Ulysses, Cassini, New Horizons)
- 8 Earth Orbit (Transit, Nimbus, LES)
- 5 Lunar Surface (Apollo ALSEP)
- 2 Mars Surface (Viking)



Explored in the Solar System

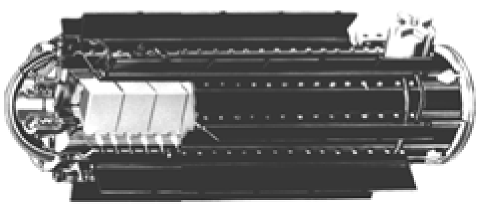
- Sun
- Venus
- Moon
- Mars
- Jupiter
- Saturn
- Uranus
- Pluto
- To and beyond the boundaries of the Solar System

Challenges to Exploration

- Severe thermal and radiation environments in space
- Severe surface conditions: hot or cold; caustic environments; rugged surfaces
- Shadowing from the sun, either on the surface or in-orbit
- Extreme distances to the sun
- Long durations missions driven by distances to the planets
- Desirable to operate without intervention or repair
  - For periods of a few years and even up to and beyond 30 years
- To do this safely

Successes: the Sun

- Ulysses: 1 General Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG); 283 watts
- Launched October 1990
  - Operated through 2008—17 years—4x expected mission life
- Solar polar orbit—first mission to survey space environment above and below the poles of the sun
- Changed the way scientists viewed our star and its effects



Courtesy NASA

Successes: Venus

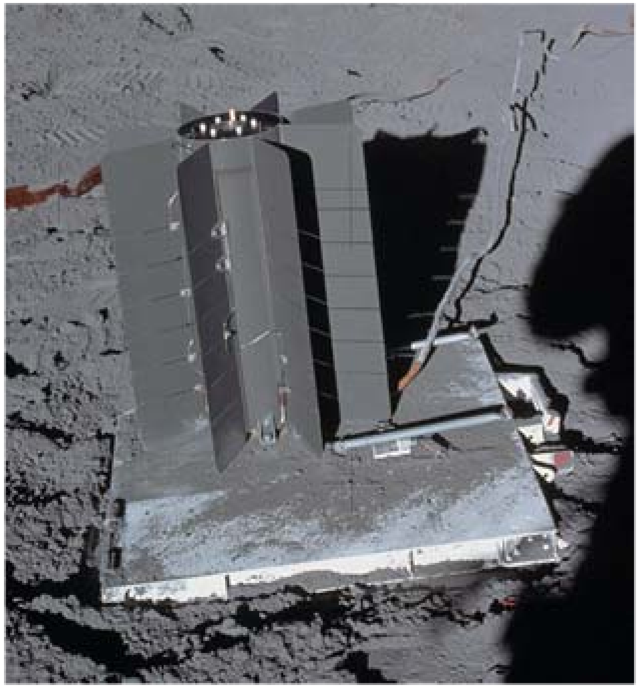
- Visited by Galileo and Cassini spacecraft during gravity assist flybys
  - Launched in 1989 and 1997
  - Galileo: 2 GPHS-RTGs; 283 watts each
  - Cassini: 3 GPHS-RTGs; 296 watts each

Galileo
Courtesy NASA

Cassini
Courtesy NASA

Successes: Moon

- Apollo Lunar Surface Experiments Package (ALSEP)
  - Apollo 12, 14, 15, 16, 17: Launched Nov 1969—Dec 1972
  - Space Nuclear Auxiliary Power 27 (SNAP-27) RTGs; 72 watts
  - Operated Nov 1969 through Sep 1977
    - » Design life 1 year; provided data 8 years
    - » Thermal environments: -169º C to 117º C
    - » Surface and atmospheric data



Courtesy NASA

Successes: Mars—Viking 1 and 2

- Viking 1 (launched 1975); Viking 2 (1975)
- Powered by 2 SNAP-19 RTGs; ~ 42 Watts
- Viking 1 lander operated for 6 years
- Viking 2 lander operated for 3.5 years

Viking 2 on Mars Utopian Plain
Courtesy NASA

Successes: Mars Rovers—Radioisotope Heater Units (RHUs)

- Mars Pathfinder-Sojourner Truth Rover (1996); Mars Exploration Rovers-Spirit and Opportunity (2003)
  - Mars Pathfinder and MER 2003 Rovers warmed by Radioisotope Heater Units (RHUs)
  - Mars Pathfinder operated for 3 months exceeding its design life by a factor of 12
  - MER 2003 rovers designed for 90 days operation are continuing to operate 4 years and 9 months after landing
    - In October 2007, Spirit had traveled 7.3 kilometers and Opportunity 11.6 kilometers
    - After climbing out of the Victoria crater, Opportunity's next goal is to drive 11.3 kilometers to the crater Endeavor which is 22 kilometers in diameter

Sojourner Rover
Courtesy NASA

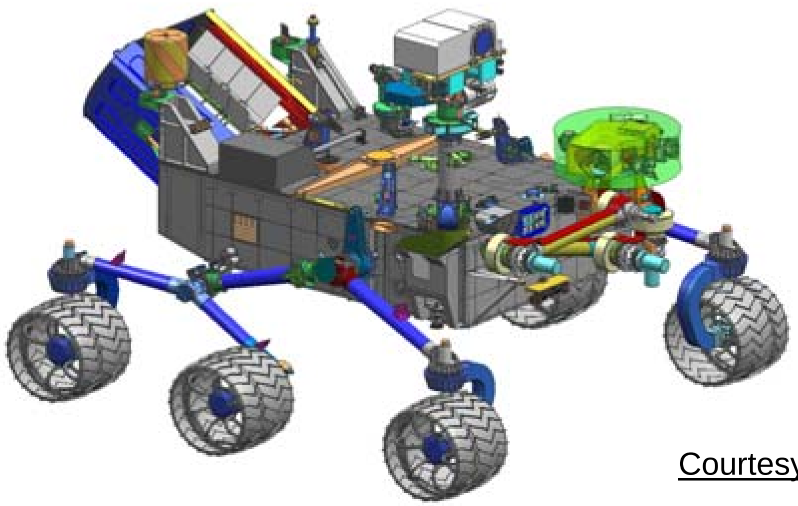
Radioisotope Heater Unit

MER 2003 Rover
Courtesy NASA

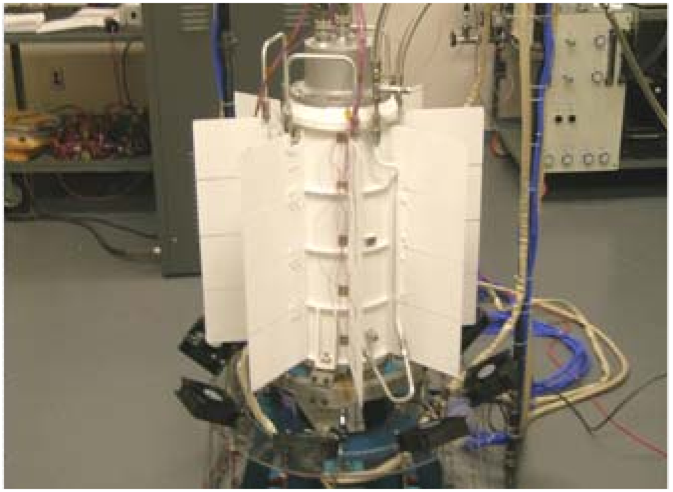
Mars Science Laboratory (MSL)

(Scheduled launch September 2009)

- MSL Rover size of a small car
- Powered by Multi-Mission RTG; 120 watts
- To operate 1 Martian year (1.8 years)
- Objectives include identifying organic compounds, inventorying the key building blocks of life, identifying features that may represent effects of biological processes, examining rocks and soil to see how they were formed, assessing how Mars atmosphere has changed over billions of years, and determining the distribution of cycles of water and carbon dioxide

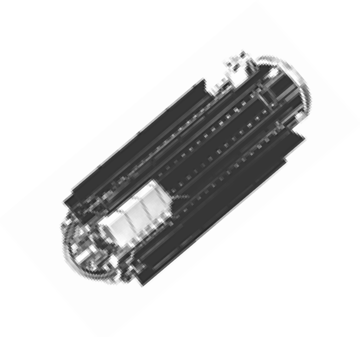


Courtesy NASA



Successes: Jupiter

- Multiplanet probes (Pioneer 10 and 11; Voyager 1 and 2) and Pluto New Horizons performed flybys of Jupiter on their way to edge of the solar system
- Galileo orbiter launch in 1989, arrived at Jupiter in 1995
- Powered by 2 GPHS-RTGs producing ~ 288 watts each
- Primary mission completed December 1997; extended 3 years; ended September 2003 for mission life from launch of 14 years
- Collected extensive data about Jupiter and its moons
  - Found evidence of saltwater on Europa, Ganymede and Callisto
  - Volcanic activity on Io



Courtesy NASA

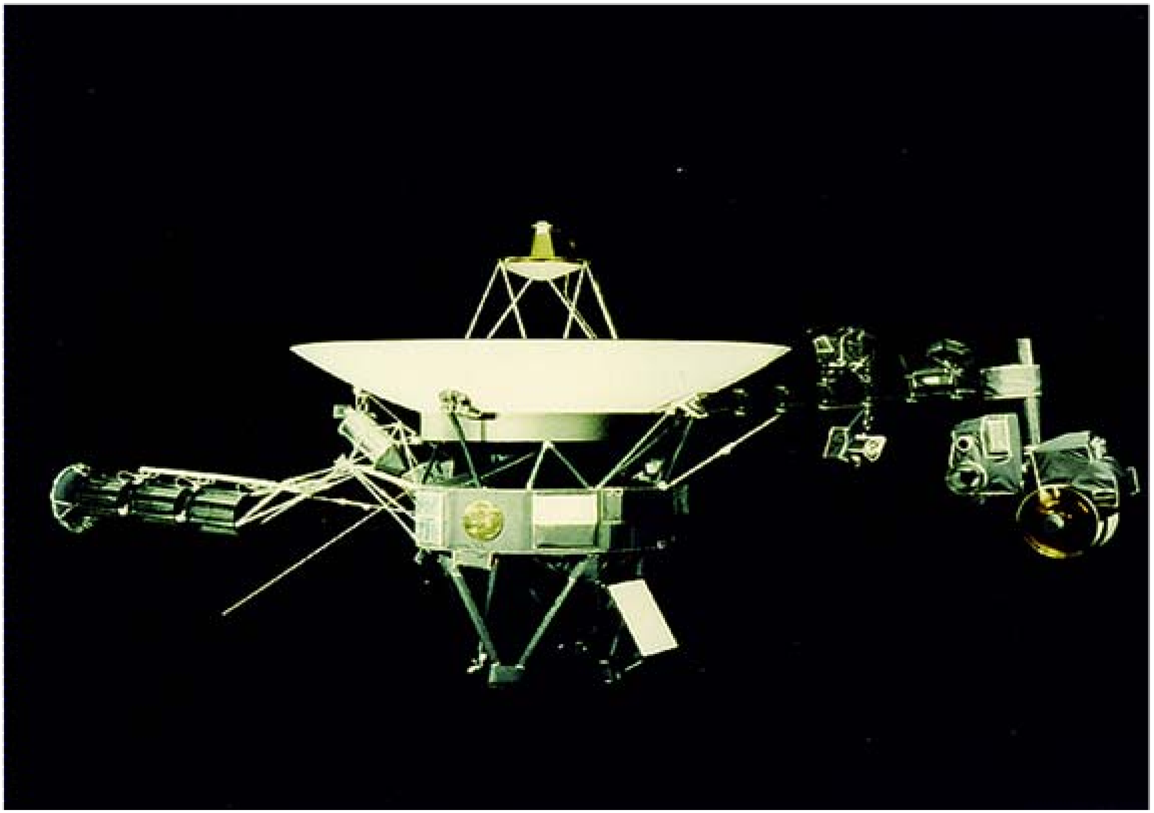
Successes: Saturn

- Cassini spacecraft with Huygens probe launched in October 1997, arrived at Saturn June 2004 with its 4-year prime mission ending in July 2008 and extended to September 2010 for a total 13 year life
- Powered by 3 GPHS-RTGs; ~295 watts each
- Selected accomplishments: Huygens probe landed on Titan; during first 4 years orbited Saturn 70 times; collected data about Saturn's rings, flew by a water plume from Enceladus
- Pioneer 10, Voyager 1 and 2 also flew by Saturn

Courtesy NASA

Successes: Uranus and Neptune

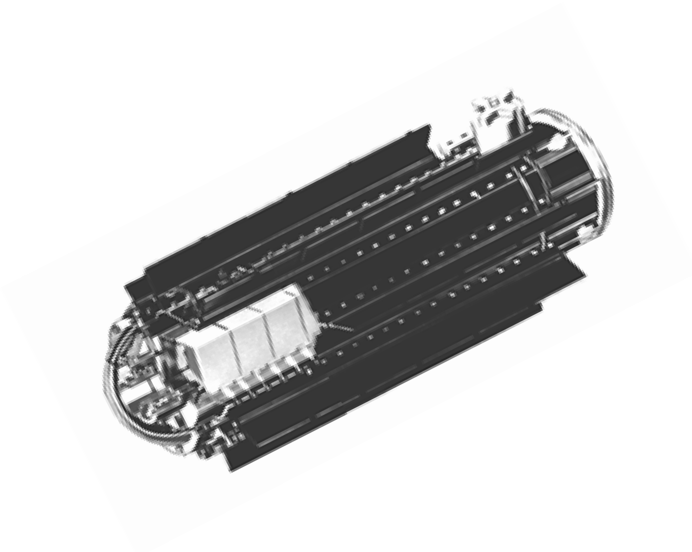
- Voyager 2, launched in 1977, flew by Uranus in 1986 and was at its closest approach to Neptune in 1989
  - 3 Multi-Hundred Watt RTGs; 159 watts each



Courtesy NASA

Pluto New Horizons

- PNH spacecraft launched January 2006 on its journey to Pluto with a Gravity Assist at Jupiter in February 2007
  - To flyby Pluto in July 2015
  - Will continue on to study objects in the Kuiper Belt
  - Powered by 1 GPHS-RTG; 250 watts



Courtesy Johns Hopkins University Applied Physics Laboratory

Deep Space Probes/Outer Planet Missions

- Pioneer 10 (1972) and 11 (1973) were each powered by 4 SNAP-19 RTGs; 40 watts each
  - At last contact, Pioneer 10 was 7.6 billion miles from Earth; originally designed for a 21 month mission and operated more than 30 years; mission ended 1997; Pioneer 11 mission ended 1995

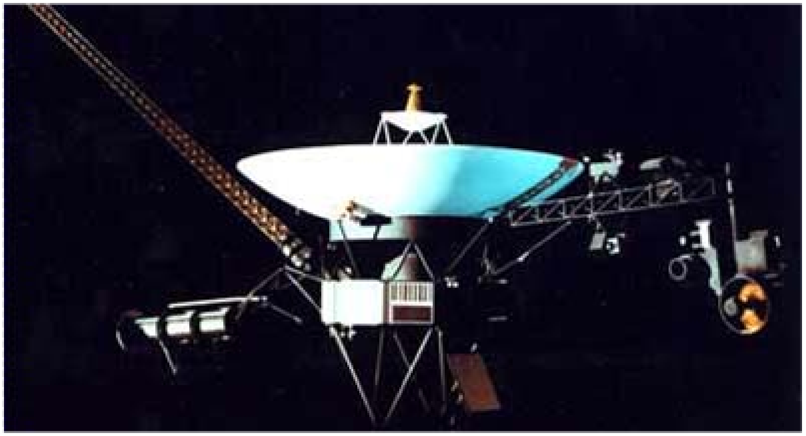
Pioneer 10

Courtesy NASA

SNAP-19 RTG
Courtesy NASA

Deep Space Probes/Outer Planet Missions

- Voyager 1 and 2 (launched 1977)
  - Powered by 3 Multi-Hundred Watt RTGs; ~155-159 watts each
  - Continuing to operate at this time
  - Voyager 1, 5.7 billion kilometers from Sun; Voyager 2, 12.7 billion kilometers
  - Crossed the heliosphere in December 2004 and August 2007
  - Found “that the ‘bubble’ formed around the Solar System was distorted by the supersonic solar wind is asymmetrical and dynamic.” Edward Stone, California Institute of Technology



Voyager 2

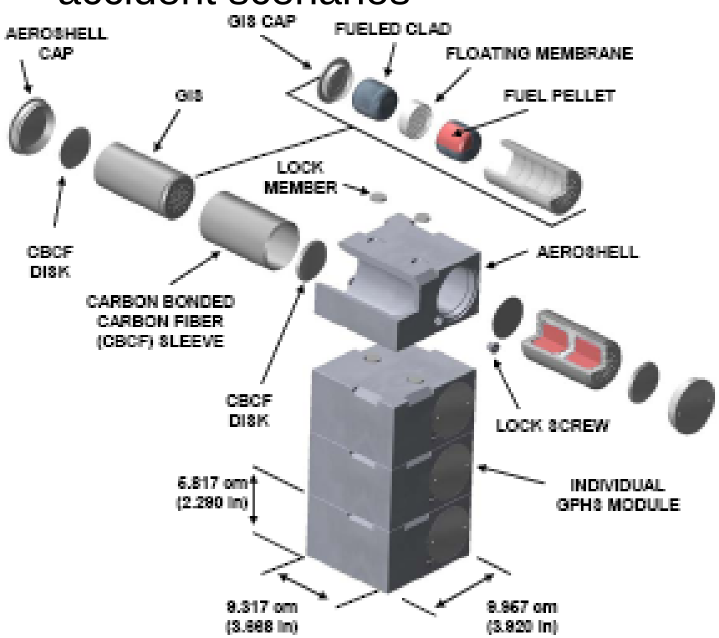
Courtesy NASA

Radioisotope Power Systems Launch Safety

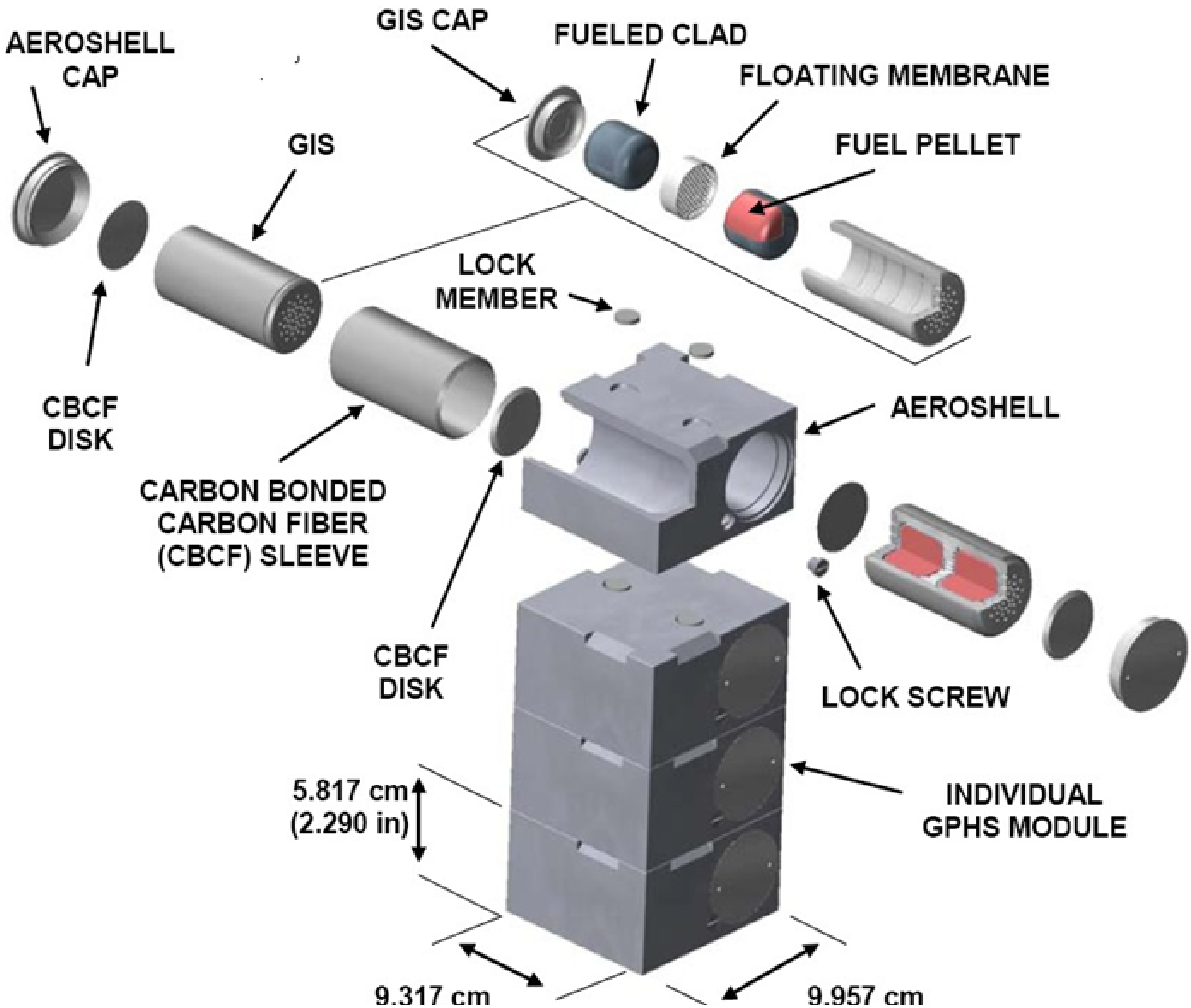
- RPS hardware design and mission execution
- Approval processes
  - National Environment Policy Act (NEPA)
  - Launch Approval Process
- Nuclear Safety Analyses
- International Organizations and Guidelines

Safety Designed into RPS Hardware

- Safety is intrinsic and inherent in power system design to contain and limit potential for dispersal
  - Isotope selected that is easily shielded—plutonium-238 (Pu-238) alpha particle radiation
  - Fuel form (plutonium dioxide, PuO_2) is rugged, chemically stable, and has a high melting temperature
  - Containment provided by multiple barriers: ductile iridium and temperature resistant carbon-carbon composites
- Safety features are complemented by safety testing to evaluate response to potential accident scenarios



RPS Hardware—GPHS RTG Module



Safety Inherent in Mission Design and Execution

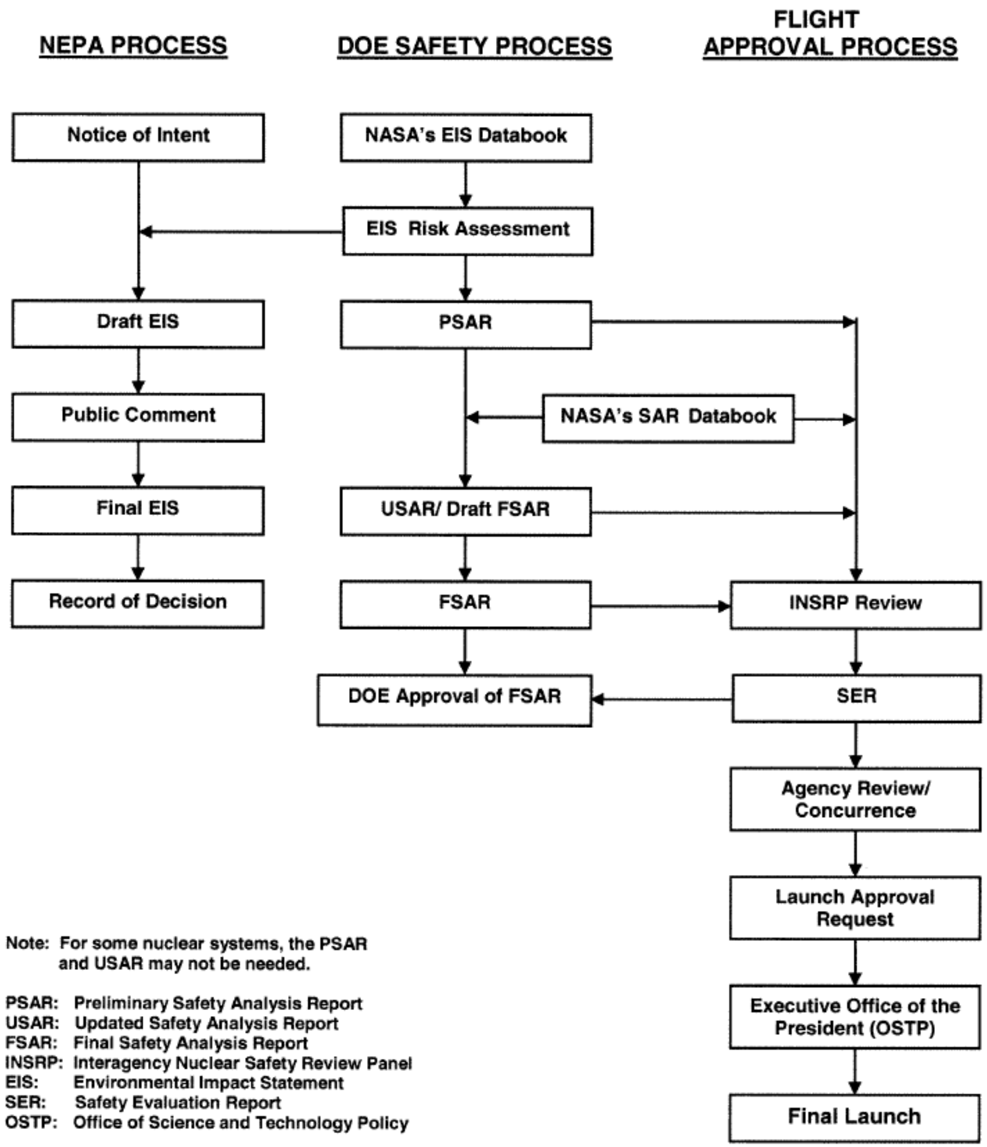
- Safety features are integrated into launch vehicle (LV), upper stage, flight termination system and mission profiles
  - National Aeronautics and Space Administration (NASA) has an extensive program to ensure reliability of the LV and the spacecraft
  - Integrated approach to range safety
  - Extensive contingency planning to deal with potential accidents

Courtesy NASA

Approval Processes

- National Environmental Policy Act (NEPA)
  - Formal process to evaluate the potential environmental impacts of proposed Federal actions, involving the preparation of Environmental Impact Statements (EISs) by the lead Federal agency, public review and a Record of Decision (ROD) by the agency
- Launch Approval Process—Presidential Directive/National Security Council Memorandum 25 (PD/NSC-25)
  - Establishes an ad hoc Interagency Nuclear Safety Review Panel (INSRP) for each mission to prepare a safety evaluation
  - Requires sponsoring agency request President's approval for flight

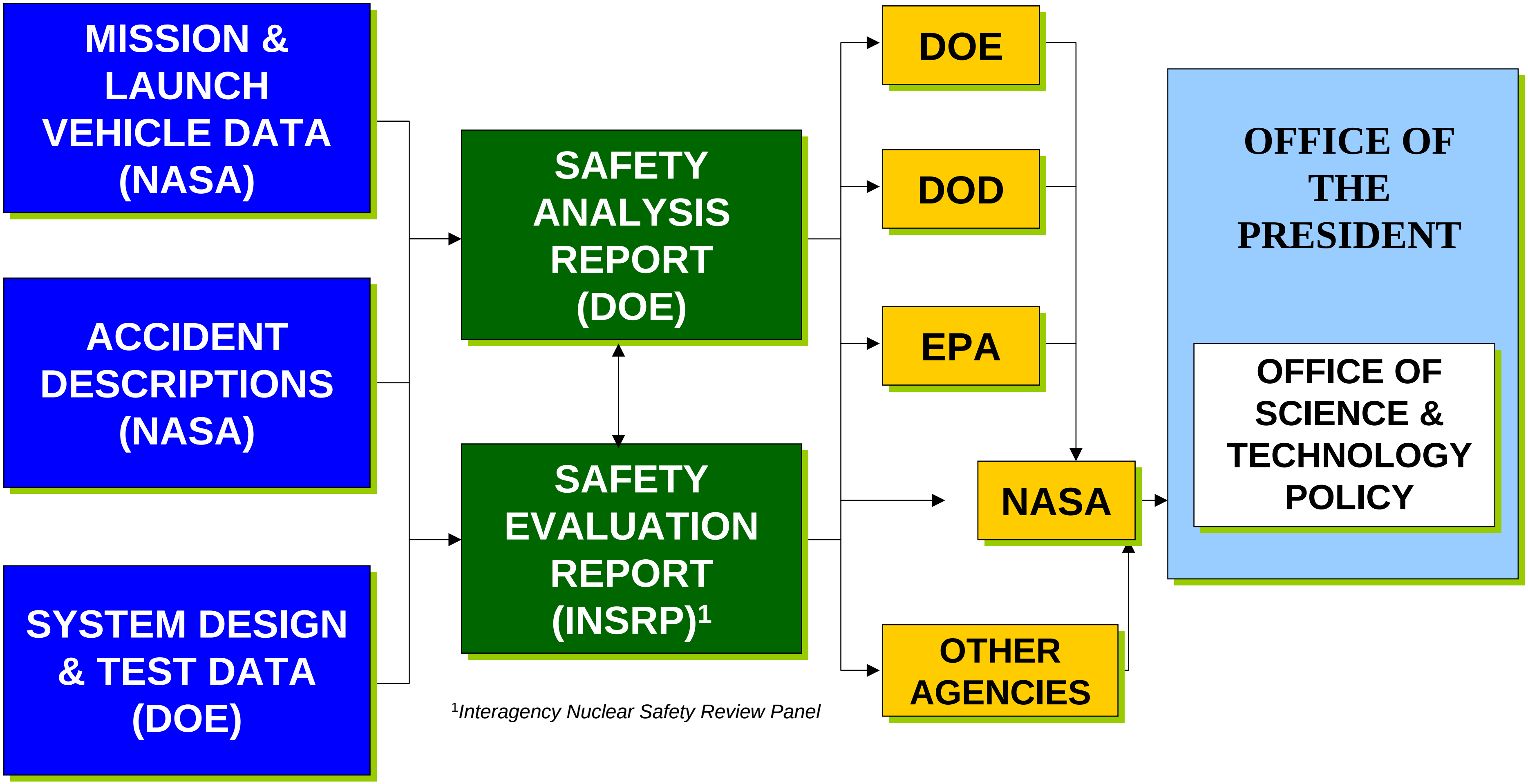
Approval Processes for Space Nuclear Power



Note: For some nuclear systems, the PSAR and USAR may not be needed.

PSAR: Preliminary Safety Analysis Report
USAR: Updated Safety Analysis Report
FSAR: Final Safety Analysis Report
INSRP: Interagency Nuclear Safety Review Panel
EIS: Environmental Impact Statement
SER: Safety Evaluation Report
OSTP: Office of Science and Technology Policy

Nuclear Safety Review and Launch Approval Process



DOE prepares a nuclear risk assessment which will be used by the Office of President to make a decision to authorize a launch using nuclear materials.

Sponsoring Agency -- Mission Definition/Databook

- **Databook describes mission, launch vehicle and payload**
- **Describes launch vehicle reliability and accident scenario environments**
  - Explosions/overpressures for solid and liquid propellants
  - Fragment environments
  - Fires: liquid and solid propellant
  - Surface impact conditions
  - Reentry environments: velocity and angle
- **Mission segments**
  - On-pad (pre-launch)
  - Early launch (near Launch Area)
  - Late launch (until Earth escape)
  - Earth gravity assist (EGA) swingby (if applicable)

DOE Safety Design and Test

- **RPS design--safety an integral part design**
- **Testing purposes**
  - Validate design
  - Calibrate deformation models
  - Develop source term models
- **Explosion overpressure**
- **Propellant fires**
- **Fragment impacts**
- **Reentry ablation**
- **Surface impact**
  - RTG converter
  - GPHS module
  - Fueled clad

Safety Analysis

- **Probabilistic risk analysis (PRA) and uncertainty analysis**
- **Accident scenarios and probabilities**
- **Accident environments**
- **Nuclear hardware response modeling**
  - Mechanical impact environments; solid propellant fire environments; reentry environments
- **Source terms**
- **Radiological consequence analysis**
  - Atmospheric transport and dispersion (ATD) modeling including meteorology; low altitude releases; high altitude releases (particulate); high altitude releases (small particles)
- **Exposure pathway modeling**
  - Inhalation (direct and resuspension); ingestion (vegetable, fruit, fish, seafood, water, other); external

Final Safety Analysis Report
(Illustrative Content)

- Volume I, Reference Design Document (RDD)
  - Provides information on the mission, launch vehicle, spacecraft, radioisotope hardware, launch site, and mission profile
- Volume II, Accident Model Document (AMD)
  - Describes the potential mission accidents, accident environments, and their probabilities; 2) evaluates the radioisotope hardware response to accident environments; and 3) provides estimates of PuO_2 source terms and probabilities
- Volume III, Nuclear Risk Analysis Document (NRAD)
  - Evaluates the radiological consequences and mission risks associated with potential PuO_2 releases identified in the AMD
- Volume IV, Uncertainty Addendum (UA)
  - Evaluates the uncertainty in the consequences.

Safety Evaluation Report (SER) —Interagency Process

- Interagency Nuclear Safety Review Panel (INSRP) reviews NASA Launch Vehicle Databook and DOE Safety Analysis Report (SAR)
- INSRP Performs an independent assessment of mission
- INSRP Prepares the Safety Evaluation Report (SER)
- SAR and SER reviewed by agencies and submitted to Office of Science and Technology Policy by mission sponsor as part of request for launch approval

Space Exploration--International

- Missions in the future are likely to have international cooperative participation
- United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS) and International Atomic Energy Agency formed Joint Expert Group (JEG)
  - JEG is a partnership that is developing a safety framework for nuclear power source applications in outer space.
  - United States is a participant
- International participation--examples
  - European Space Agency and Italian Space Agency participation in Cassini
  - Instruments on upcoming Mars Science Laboratory mission

Radioisotope Missions—Collectively 200+ Years of Space Science

- Probes have resulted in 20 planetary encounters
  - All planets except Mercury
  - Examined numerous moons
- Five Apollo experiments collected data for combined 30 years
- Mars landers/rovers operated for 17 years
- Planetary orbiters for 20 plus years
- Polar orbiting observation of the sun
  - Solar observations 19 years
- Five missions will reach beyond edge of solar system
  - Probes to deep space may operate for combined 120 to 150 years

Nuclear Power, Safety and Space Science

- The U.S. has safely conducted space science missions for 40 years
  - The U.S. has an extensive safety program in place to continue this record
- The missions described in this briefing were enabled through the use of radioisotope power
- Missions at Mars have often been enabled by radioisotopes or at least made easier and more successful through the life extension
- Missions beyond Mars to Outer Planets are exceedingly challenging or impossible without nuclear power
- Radioisotope power systems will be used to continue advancement of our knowledge of the Solar system.
- Radioisotopes have provided 200+ years of space science data

Without these systems and without doing these missions safely most of this knowledge would not exist.