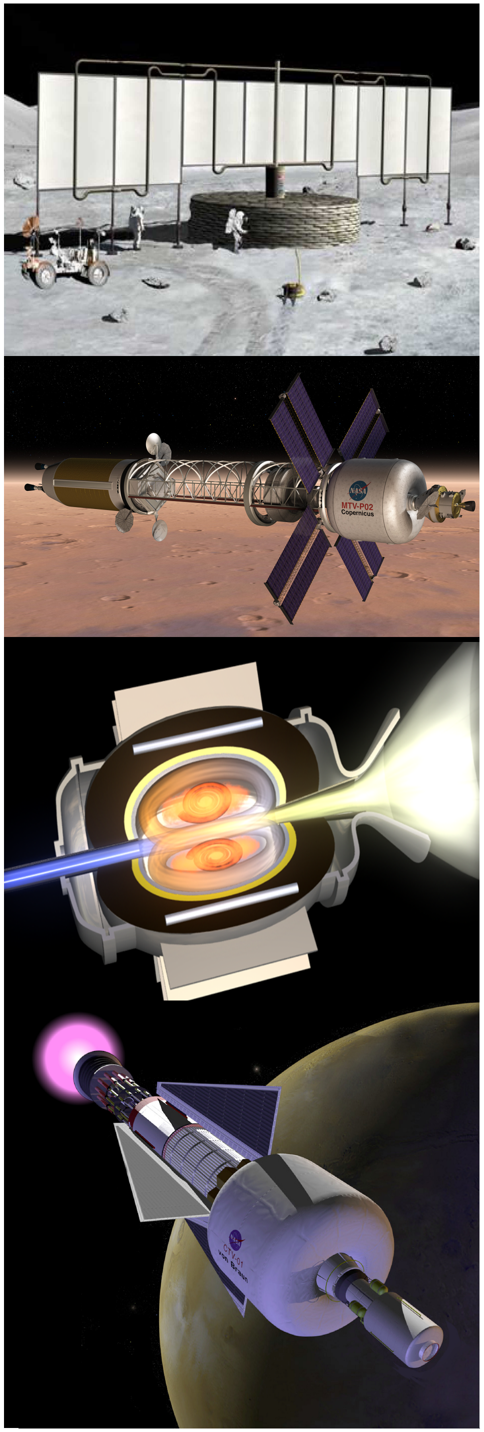


Nuclear Systems for Space Propulsion and Power

FISO Seminar
8 December 2010

George Schmidt
NASA Glenn Research Center

Outline

- Why Nuclear?
- Radioisotope Power Systems
- Fission-based Power and Propulsion
- Advanced Concepts and Technologies
- Conclusions

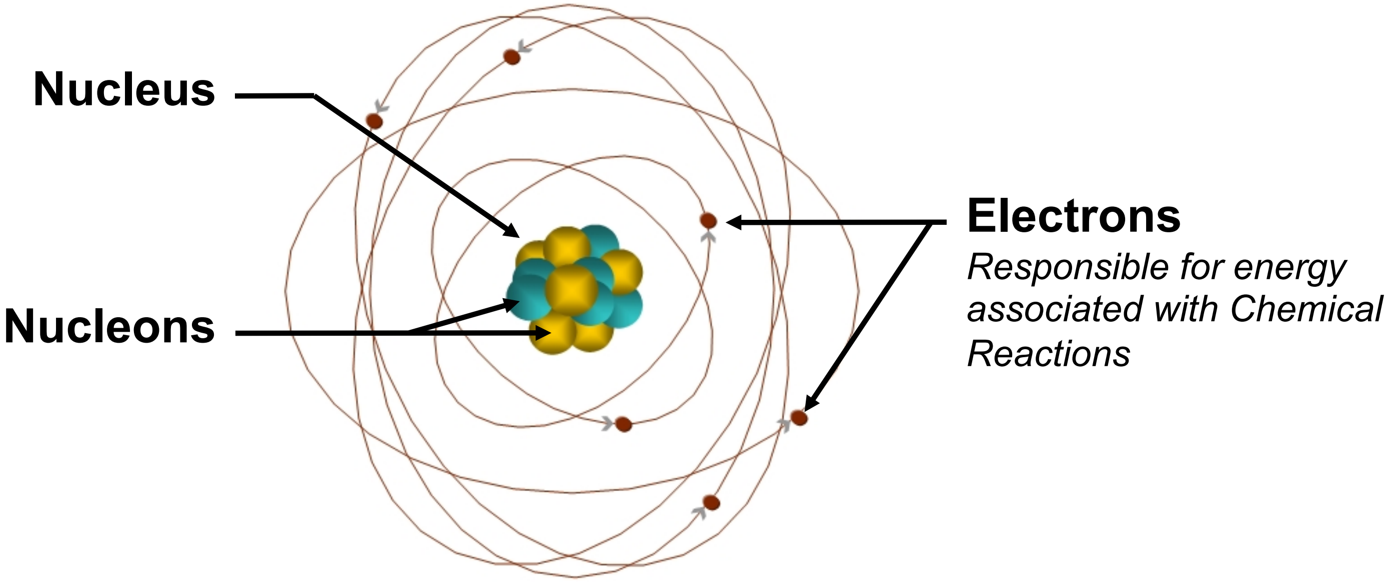
“…the navigation of interplanetary space depends for its solution on the problem of atomic disintegration…”

Robert H. Goddard, 1907

Robert H. Goddard, Father of American Rocketry

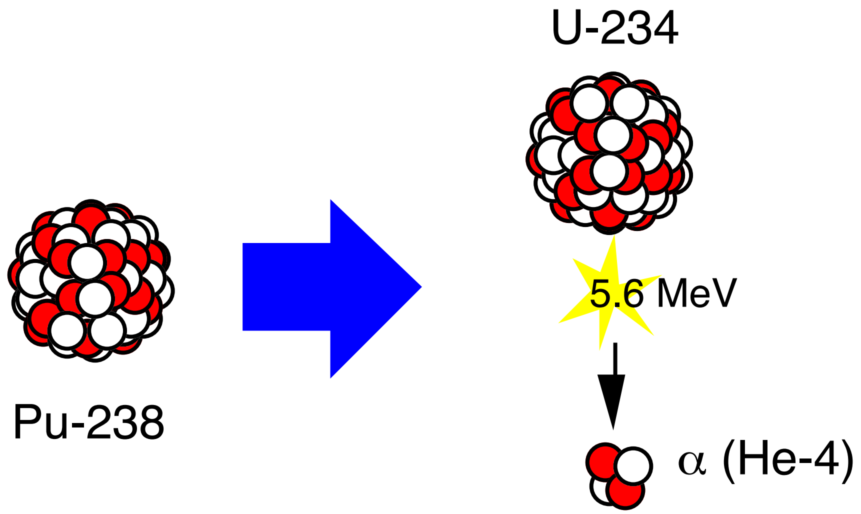
What is a Nuclear System?

A power or propulsion system that relies on energy released from the transformation of atomic nuclei and/or nucleons as its principal energy source.



Basic Structure of the Atom

Radioisotope Decay

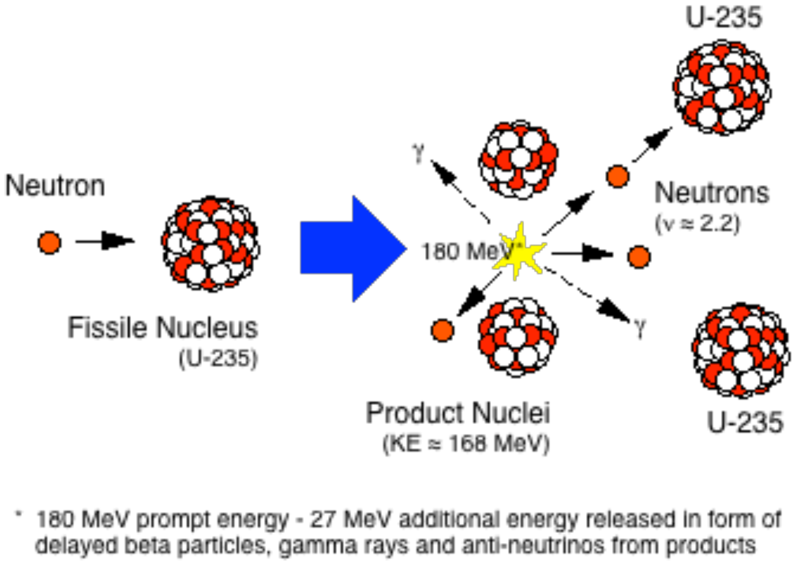


Radioisotope decay of Plutonium-238

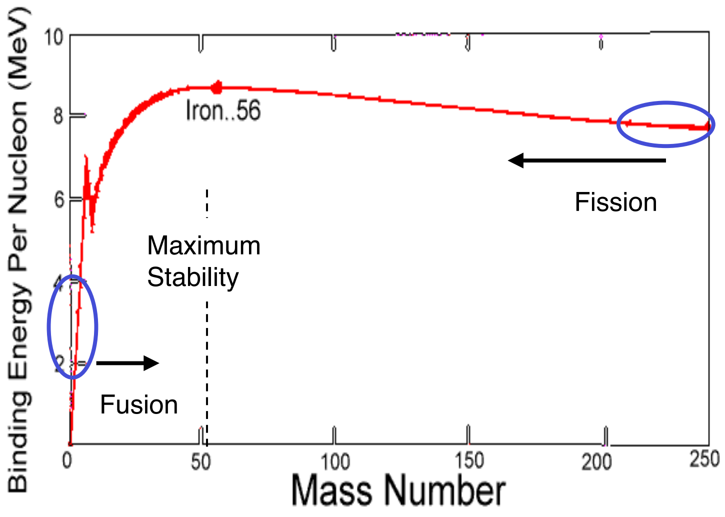
- 0.024 MeV produced per nucleon.
- Decay via Alpha Particle (α) emission – 87.7 year half-life (t1/2).
- Plutonium-238 (Pu-238) considered best fuel for space applications. Current supply very limited.
- Other isotopes considered:
  - Cerium (Ce-144) β/electron-emitter with t1/2 ≈ 285 days
  - Polonium (Po-210) α-emitter with t1/2 ≈ 138 days
  - Curium (Cm-242) α-emitter with t1/2 ≈ 163 days
  - Strontium (Sr-90) β-emitter with t1/2 ≈ 28.8 years
  - Americium (Am-241) α-emitter with t1/2 ≈ 432.5 years

Glenn Seaborg, Discoverer of Plutonium (1941), Nobel Laureate and Chair of the Atomic Energy Commission (AEC)

Nuclear Fission



Fission of Uranium-235

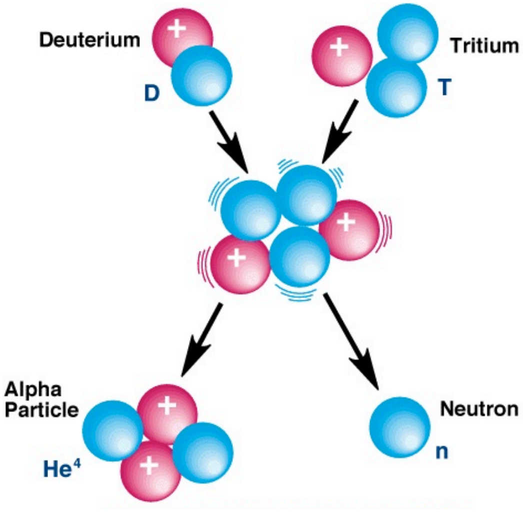


Curve of Binding Energy

- 0.720 MeV produced per nucleon (U-235).
- Neutron absorbed by heavy nucleus, which splits to form two highly energetic daughter products and more neutrons.
  - Fissile isotopes (U-233, U-235 and Pu-239) fission at any neutron energy
  - Other actinides (U-238, Th-232, Pu-240) fission at only high neutron energies
- Heat manifested as product kinetic energy and reabsorbed energy from delayed betas, gammas, and neutrons (average of 0.851 MeV per nucleon).
- For steady power production (criticality), 1 of the 2 to 3 neutrons from each reaction must cause a subsequent fission in a *chain reaction* process. (<1 neutron subcritical, >1 neutron supercritical)

Nuclear Fusion

Deuterium-Tritium Fusion

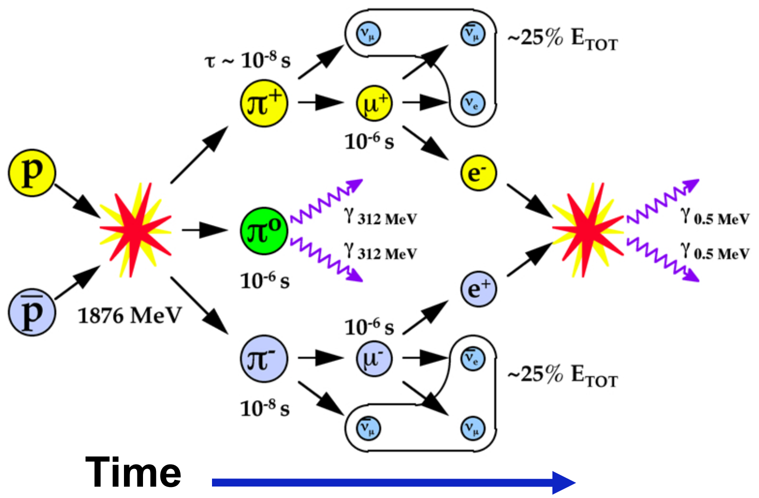


- Energy ranges from 0.73 to 3.66 MeV per nucleon.
- Relative advantages and disadvantages:
  - —D-T is easiest to ignite and yields high energy, but it produces a high-energy neutron (14.1 MeV) in each reaction.
  - —D-D uses plentiful fuel, but still produces a neutron (fewer and at lower energy than D-T).
  - —D-He3 has highest specific energy, but requires scarce fuel (He3). It also produces neutrons in side D-D reactions.
  - —p-B11 is completely aneutronic and yields three iso-energetic α particles. But it is hardest to ignite and has low specific energy.
- Demonstration of practical energy gain is still decades off, but large gains have been demonstrated using nuclear explosives.

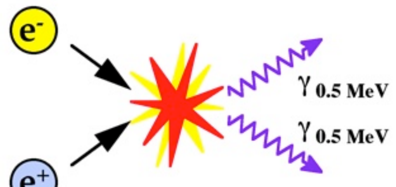
Fuel Comb	Nuclear Reaction	Optimum Temp (keV)	Norm τNT Product	Energy/ Nucleon (MeV)
Deuterium/ Tritium	${}^2_1D + {}^3_1T \rightarrow {}^4_2He + {}^1_0n + 17.49\ MeV$	13.6	1	3.50
Deuterium/ Deuterium	${}^2_1D + {}^2_1D \rightarrow {}^3_2He + {}^1_0n + 3.27\ MeV$ $\rightarrow {}^3_1T + {}^1_1p + 4.03\ MeV$	15.0	30	0.93
Deuterium/ Helium-3	${}^2_1D + {}^3_2He \rightarrow {}^4_2He + {}^1_1p + 18.3\ MeV$	58.0	16	3.66
P/Boron-11	${}^1_1p + {}^{11}_2B \rightarrow 3{}^4_2He + 8.7\ MeV$	123.0	500	0.73

Antimatter Annihilation

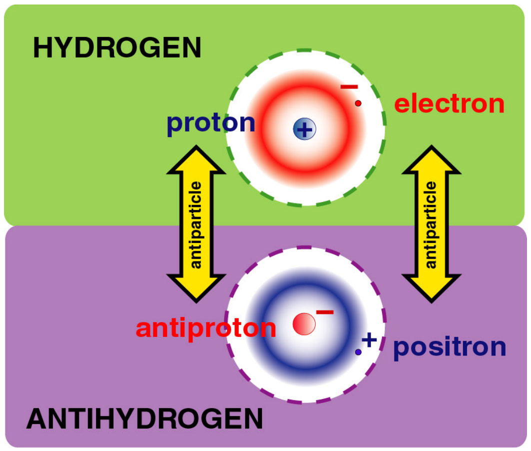
Proton-Antiproton Annihilation Process



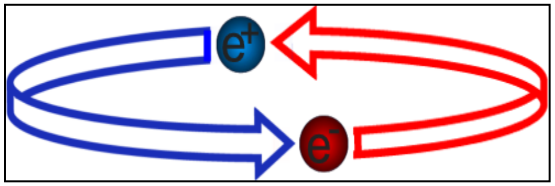
Electron-Positron Annihilation Process



Possible Stable Storage States



Antihydrogen Atoms/Molecules

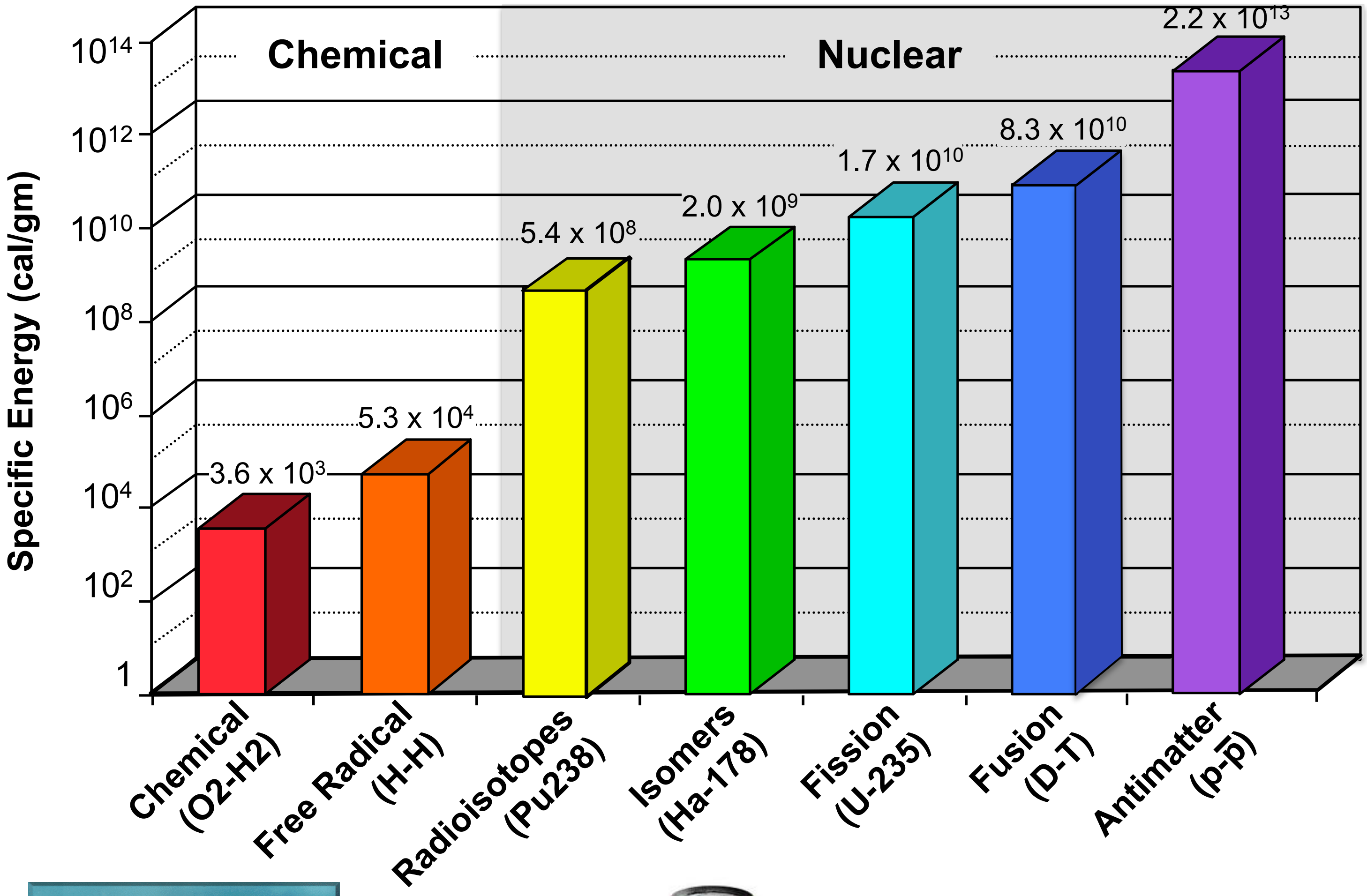


Positronium

- 938 MeV produced per nucleon ($p\text{-}\bar{p}$ reaction). Highest energy yield of any reaction known in physics
- Topic of active physics research since its prediction in 1928 (Dirac) and discovery in 1932 (Anderson)
- Used in Positron Emission Tomography (PET) and could find more use in future medical applications
- Key challenges
  - —Production (low efficiency and high costs)
  - —Storage (stable states and containment systems)
  - —Application (controlled reaction and energy release)

Why Nuclear?

Specific Energy for Different Reactions



50 x

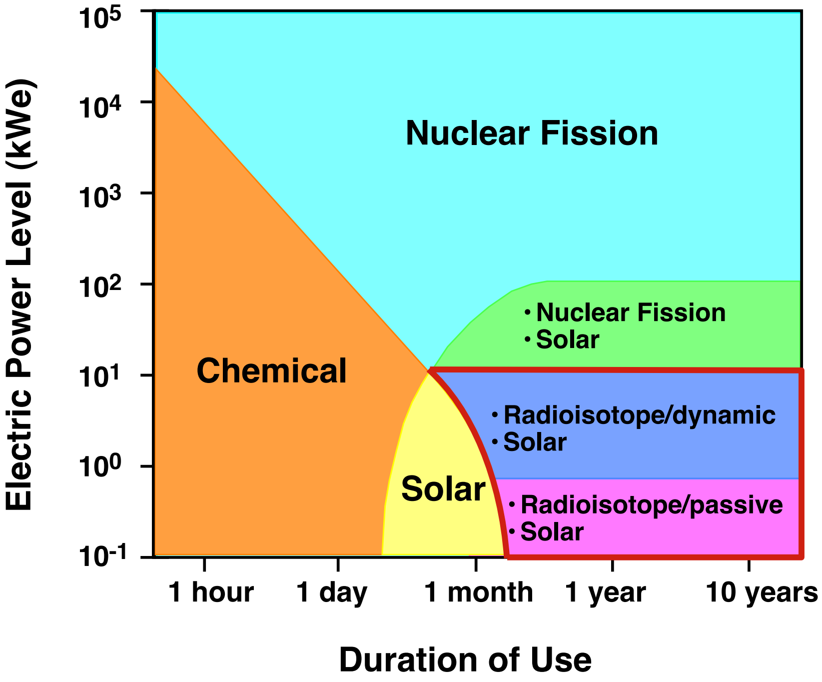
Chemical energy in Shuttle External Tank ≈

Energy in 12 fl oz (355 ml) of Uranium-235
(assumes total consumption) ≈

Energy in 3 gm (~3 raisins) of antimatter
(assumes total consumption)

Why Nuclear?

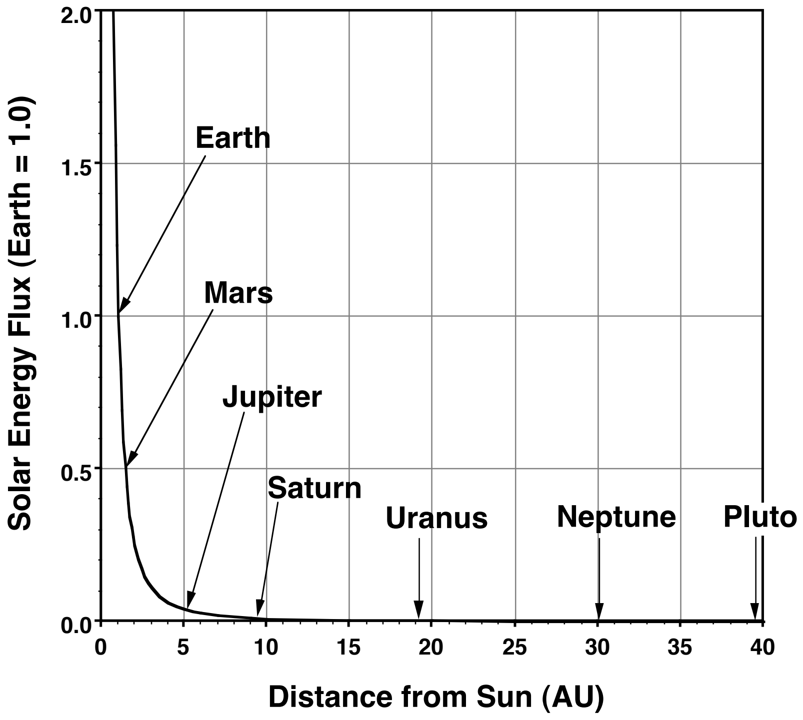
Best Power Technologies for Different Power Levels and Periods of Use



- **Vast amount of energy available for missions of long duration**
- **Continuous power independent of distance and orientation with respect to Sun**

- **Ideal for applications in…**
  - Deep space
  - Shadowed surface regions
  - Thick planetary atmospheres, including extreme environments (e.g., Venus, Titan)
  - High-radiation environments (e.g., Jovian system)

Solar Insolation versus Distance from Sun



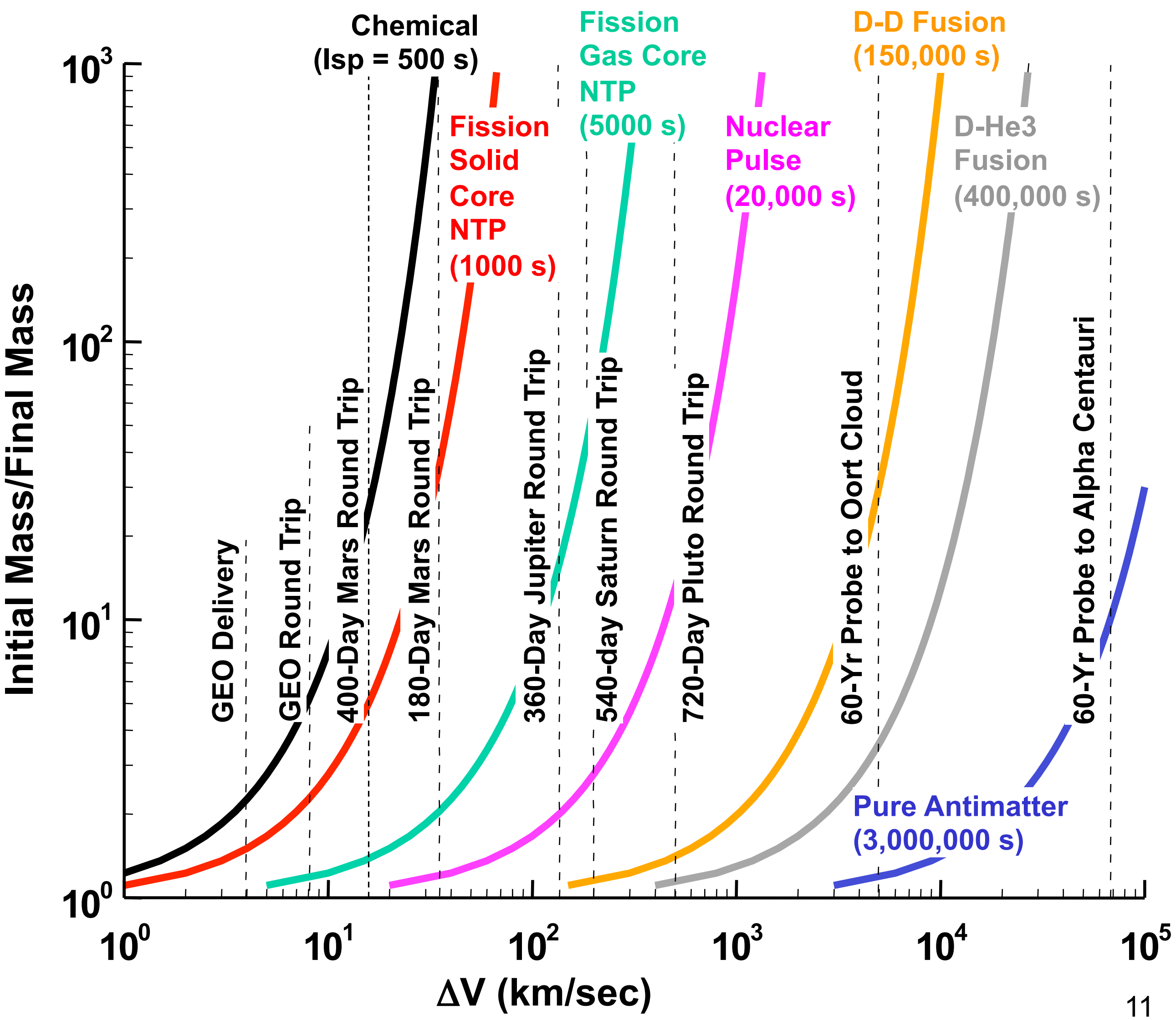
Why Nuclear?

- **High Capability Propulsion**
  - High Specific Impulse (Isp)
  - Moderate-High Specific Power (Thrust/mass)
- **Enables high ΔV missions**
  - More rapid interplanetary flight
  - Science missions beyond solar system
- **Reduces propellant mass and/or increases mass margins**

$$Isp_{\substack{max\\ideal}} = \frac{\sqrt{2 \cdot Specific\ \ Energy}}{g}$$

Applicable only for non-relativistic exhaust velocities (g•Isp ≤ 0.1c)

Spacecraft Mass Ratio as Function of ΔV (Mission) for Different Propulsion Technologies



Outline

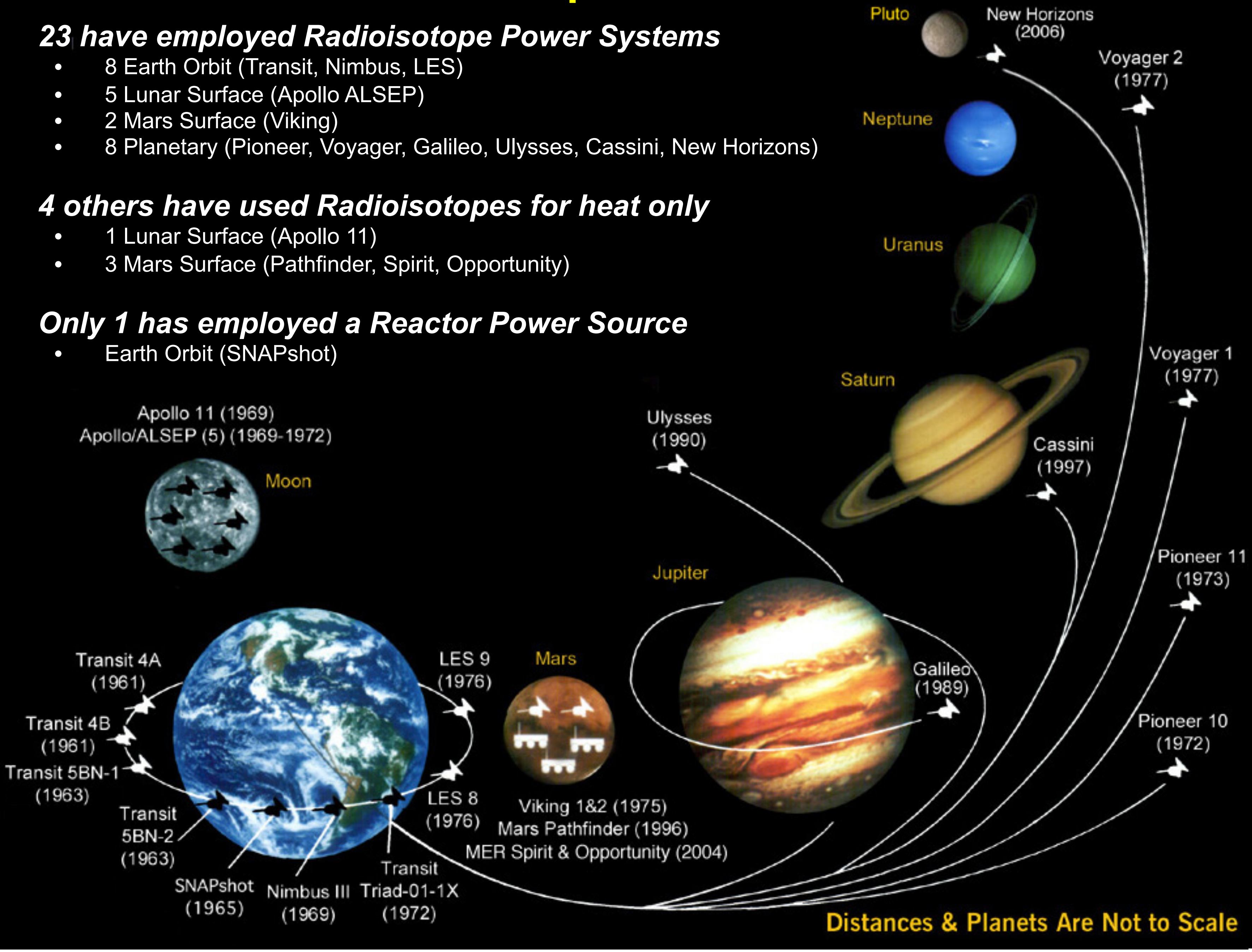
- Why Nuclear?
- Radioisotope Power Systems
- Fission-based Power and Propulsion
- Advanced Concepts and Technologies
- Conclusions

28 successful U.S. nuclear spacecraft since 1961

- ***23 have employed Radioisotope Power Systems***
  - 8 Earth Orbit (Transit, Nimbus, LES)
  - 5 Lunar Surface (Apollo ALSEP)
  - 2 Mars Surface (Viking)
  - 8 Planetary (Pioneer, Voyager, Galileo, Ulysses, Cassini, New Horizons)

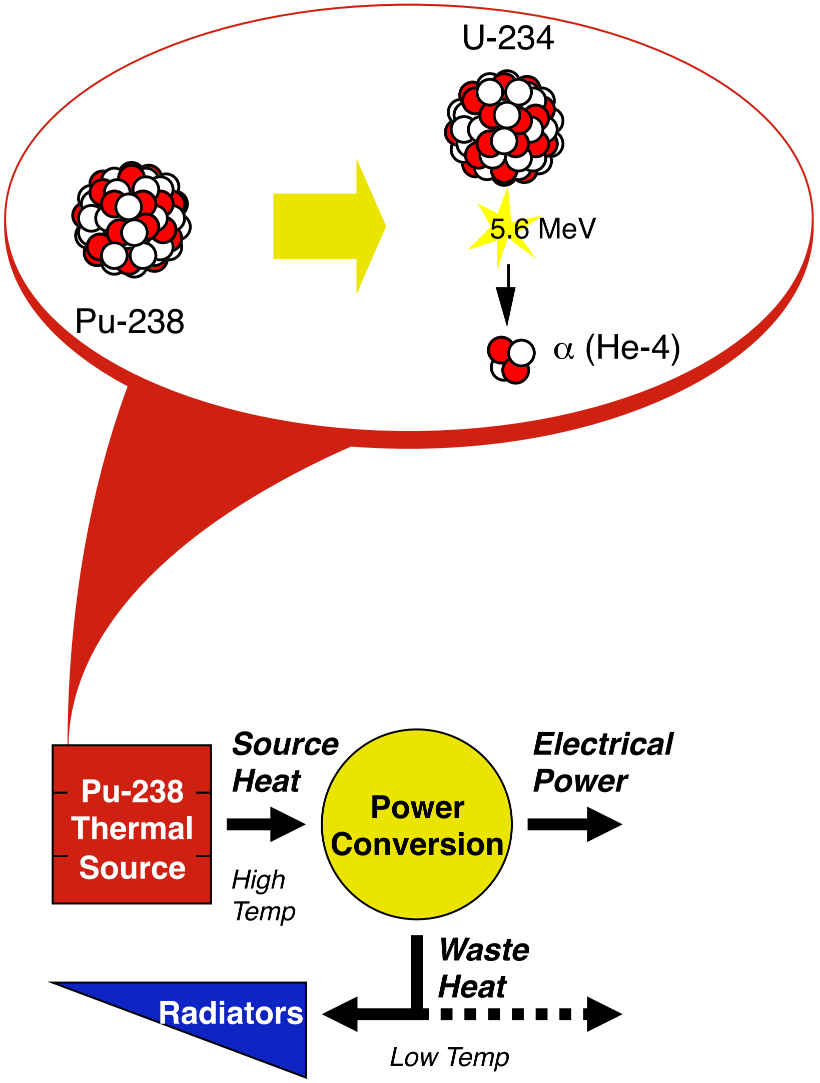
- ***4 others have used Radioisotopes for heat only***
  - 1 Lunar Surface (Apollo 11)
  - 3 Mars Surface (Pathfinder, Spirit, Opportunity)

- ***Only 1 has employed a Reactor Power Source***
  - Earth Orbit (SNAPshot)



Radioisotope Power Systems (RPS)

- **Heat produced from natural alpha (α) particle decay of Pu-238 (87.7-y half-life)**
- **Small portion of heat energy (6%-35%) converted to electricity**
  - Thermoelectric (existing and advanced technology)
  - Stirling (under development)
  - Brayton, TPV, etc. (future candidates)
- **Waste heat rejected through radiators**



U-234

Pu-238

5.6 MeV

α (He-4)

Pu-238 Thermal Source

Source Heat

High Temp

Power Conversion

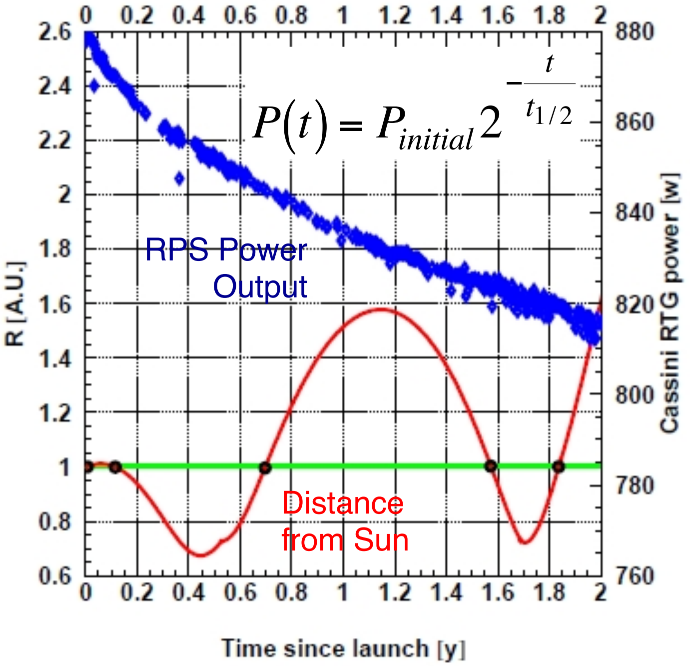
Electrical Power

Waste Heat

Radiators

Low Temp

Functional Schematic



Cassini RPS Power after Launch

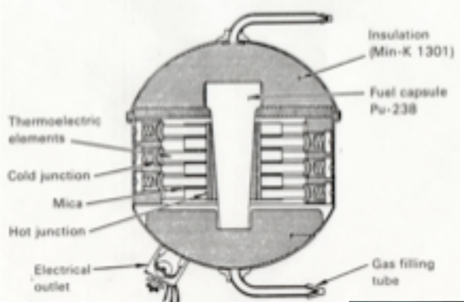
SNAP-3 – The First RTG

Oval Office Presentation of SNAP-3 in January 1959

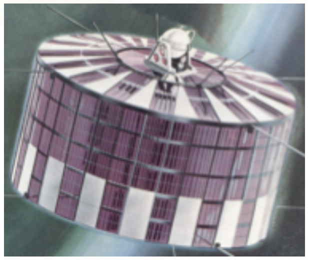
- SNAP-3* project developed thermoelectric-based device using Polonium-210 fuel.
- President Eisenhower used SNAP-3* to advocate expanded use of space nuclear power, particularly for NASA. Became marketing centerpiece of “Atoms for Peace.”

* *SNAP = Systems for Nuclear Auxiliary Power. Odd numbers assigned to Radioisotope unit developments while even numbers given to reactors*

Early Flight Units



SNAP-3B RTG



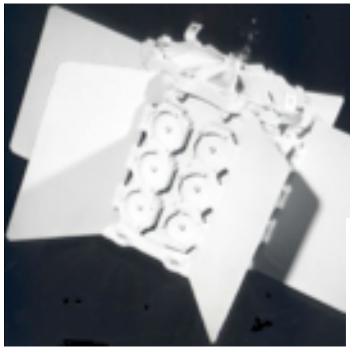
Transit-4A Satellite

SNAP-3B

- Supplemental power source for Transit 4A and 4B navigational satellites
  - Launched in June and Nov 1961 to 1,100 km altitude
  - RTG powered crystal oscillator and other sensitive electronic components
- Features:
  - Pu-238 metal fuel and Pb-Te thermoelectrics
  - 2.7 We BOM, 2.1 kg, **1.3 We/kg specific power**
  - 5-year design lifetime: 4A and 4B RTGs operated for 9 and >15 years, respectively

SNAP-9A

- Primary power source on Transit 5BN-1 and 5BN-2 navigational satellites
  - Launched in Sept and Dec 1963
  - Unit on 5BN-3 lost due to launch abort in April 1964
- Features:
  - SNAP-3B fuel form and thermoelectrics
  - 25 We BOM, 12.3 kg, **2.0 We/kg specific power**
  - 6-year design lifetime: 5BN-1 failed in 9 months due to electrical problems, 5BN-2 RTG operated >6 years

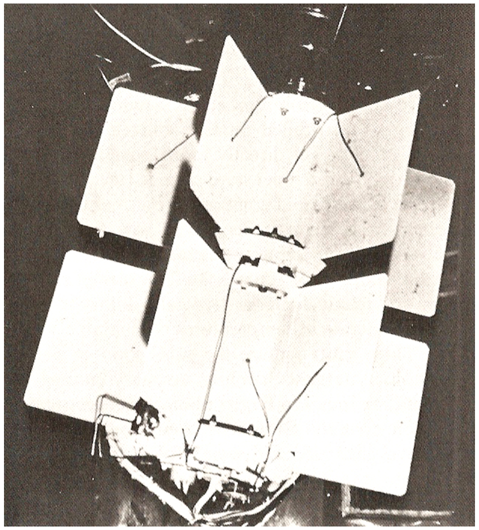


SNAP-9A

Transit-5BN-1 Satellite

SNAP-19B

Nimbus III Satellite

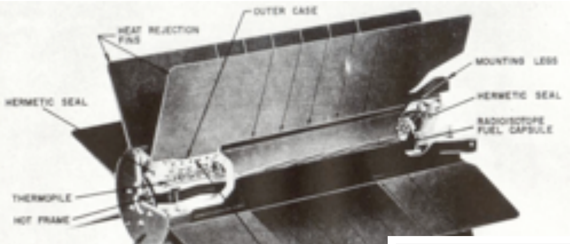


Assembly of 2 SNAP-19B RTGs

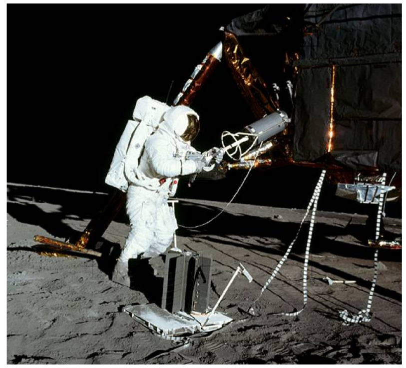
Nimbus Meteorological Satellite

- First NASA application of RPS
- 2 RTGs served as primary power source
- Nimbus B-1 launch on 18 May 1968
    - Launch vehicle failure forced destruction by Range Safety Officer
    - Agena Upper Stage in Santa Barbara Channel
    - RTGs recovered and fuel reused
- Nimbus III (B-2) launch on 14 April 1969
    - Operated fine for ~2.5 years
    - Sharp degradation in performance due to sublimation of thermoelectric materials and loss of hot junction bond due to internal cover gas depletion
- Features:
    - Intact Impact Heat Source (IIHS)
    - PuO2 microspheres in capsules for fuel - microspheres too big for inhalation
    - Pb-Te thermoelectrics (6.2% efficiency)
    - 23.5 We BOM, 13.4 kg, **2.1 We/kg specific power**
    - 2-year design lifetime

Specialty Units



SNAP-27



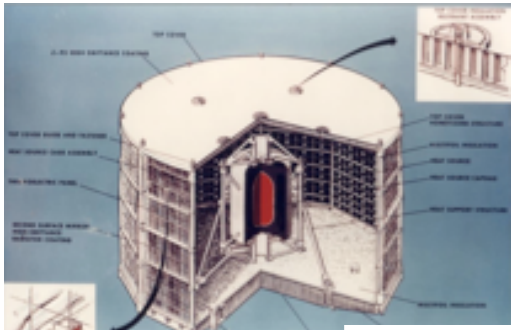
Alan Beam removing SNAP-27 fuel container from LEM

SNAP-27

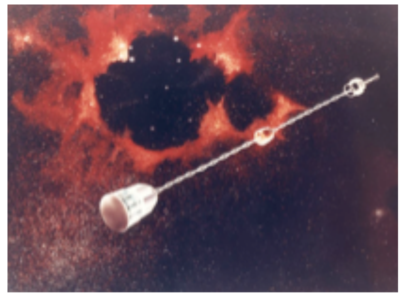
- Power source for Apollo Lunar Surface Experiment Package (ALSEP)
  - Deployed on Apollo missions 12, 14, 15, 16 and 17
  - Apollo 13 unit at bottom of Tonga Trench
- Features:
  - 238PuO2 fuel and Pb-Te thermoelectrics
  - 63.5 We BOM, 19.6 kg, **3.2 We/kg specific power**
  - 2-year design lifetime: All deployed units operated 5-8 years until ALSEP station shutdown

Transit RTG

- Used on Transit Triad satellite
  - Launched in Sept 1972
  - Served as primary source with PV/battery auxiliary power
- Features:
  - 238PuO2/Mo Cermet fuel
  - Radiatively-coupled Pb-Te thermoelectrics
  - 35.6 We BOM, 13.6 kg, **2.6 We/kg specific power**
  - 5-year design lifetime: RTG still operating as of Feb 2008



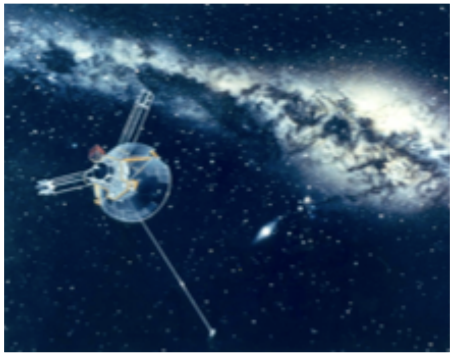
Transit RTG



Transit Triad Satellite

SNAP-19

SNAP-19 Stack on Pioneer Spacecraft



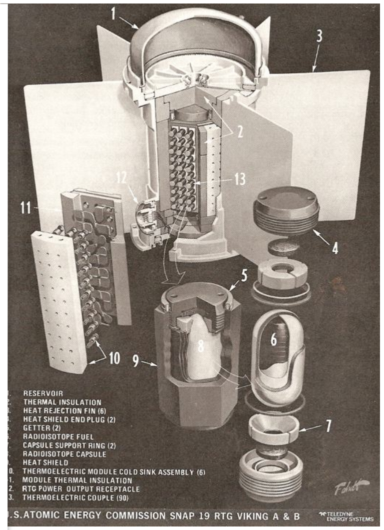
Pioneer Spacecraft

Pioneer Deep Space Probes

- Pioneer 10 and 11 each had 4 SNAP-19 RTGs for primary power source
- Modified version of SNAP-19B
  - Incorporation of TAGS/Sn-Te material for thermoelectrics – increased efficiency (6.2%) and lifetime
  - Longer, narrower generator size
  - 40.3 We BOM, 13.6 kg, **3.0 We/kg specific power**
  - 5-year design lifetime
- Launch on 2 March 1972 and 6 April 1973
  - Last signal from Pioneer 10 in 2003
  - Last signal from Pioneer 11 in 1995

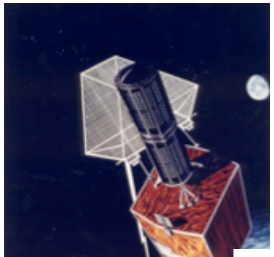
Viking Landers

- Vikings 1 and 2 each had 2 RTGs for primary power
- Modified for Mars environment
  - Larger and more massive than Pioneer
  - 42.6 We BOM, 15.2 kg, **2.8 We/kg specific power**
  - 90-day operational requirement
- Launch on 20 Aug 1975 and 9 Sept 1975
  - Last data from Viking 1 in 1982
  - Relay link from Viking 2 lost in 1979



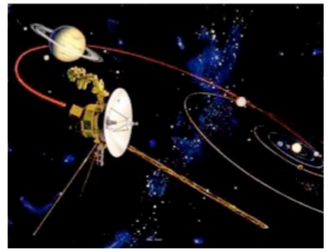
Viking Lander and SNAP-19 Modified for Mars Operation

High-Performance RTGs



LES 8

MHW RTG



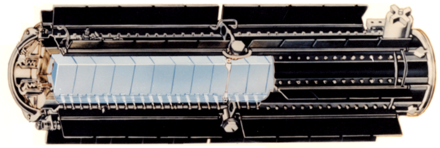
Voyager

Multi-Hundred Watt (MHW) RTG

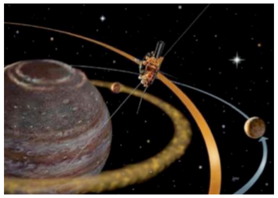
- Primary Power on four Spacecraft
  - Lincoln Experimental Satellites (LES) 8 and 9 (Launched in 1976)
  - Voyager 1 and 2 Space Probes (Launched in 1975)
- Features:
  - 238PuO2 Fuel and Si-Ge Thermoelectrics (6.6% efficiency)
  - 37.6 kg, 158 We BOM, **4.2 We/kg specific power**
  - RTGs still operating as of Feb 2008
  - Designed for operation in space only

General Purpose Heat Source (GPHS) RTG

- Primary Power on 4 Most Recent Deep Space Spacecraft
  - Galileo (May 1989)
  - Ulysses (1990)
  - Cassini (1997)
  - Pluto New Horizons (2006)
- Features:
  - 238PuO2 Fuel and Si-Ge Thermoelectrics (6.8% efficiency)
  - 56.1 kg, 292 We BOM, **5.2 We/kg specific power**
  - All RTGs, except Galileo's, operating as of Feb 2008
  - Designed for operation in space only

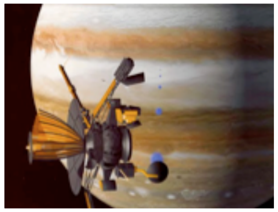


GPHS RTG

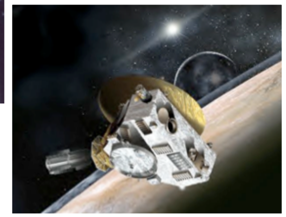


Ulysses

Cassini



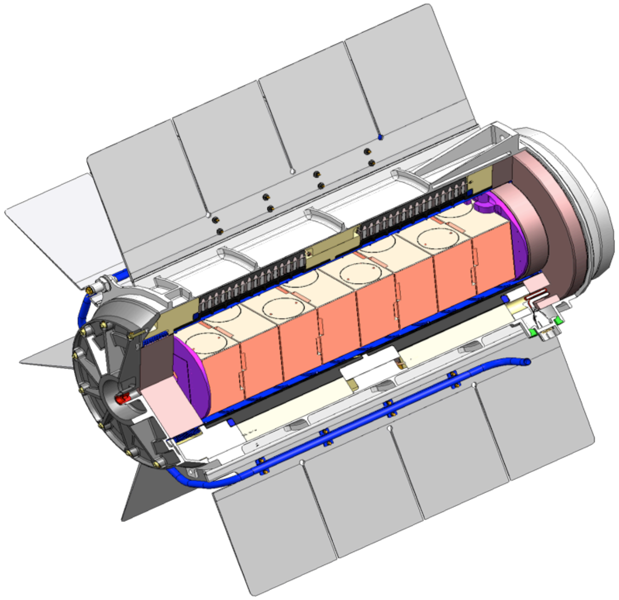
Galileo



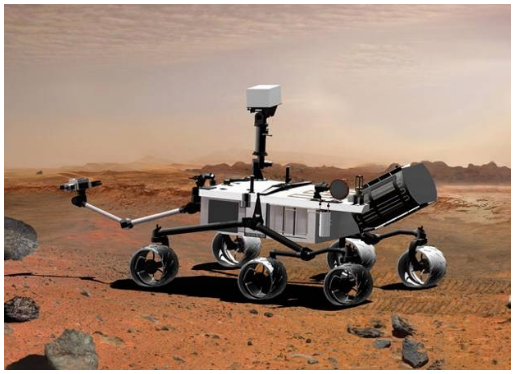
New Frontiers

Multi-Mission RTG (MMRTG)

- **Developed for upcoming Mars Science Laboratory (MSL) mission with launch in 2011**
- **Design Features:**
  - 123 We @ BOM; 99 We @ 14 yrs
  - 8 GPHS heat sources per MMRTG
  - Pb-Te/TAGS thermoelectrics (6.3% efficiency)
  - 44 kg, **2.8 We/kg specific power**
  - Lifetime: 3-year storage + 14-year mission
  - Approx Dimensions: 66 cm (length) x 60 cm (dia)
  - Designed for use on Mars and in space
- **Status:**
  - Project Start in July 2003
  - Completed Qualification Unit tests in 2007
  - Flight unit currently under storage – will be shipped to Cape Canaveral about 6 months prior to launch

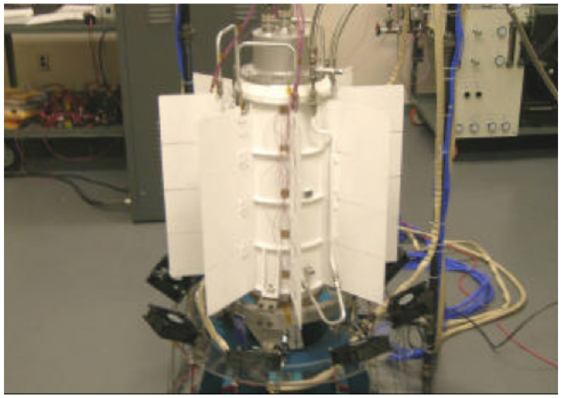


MMRTG Configuration



MSL Concept

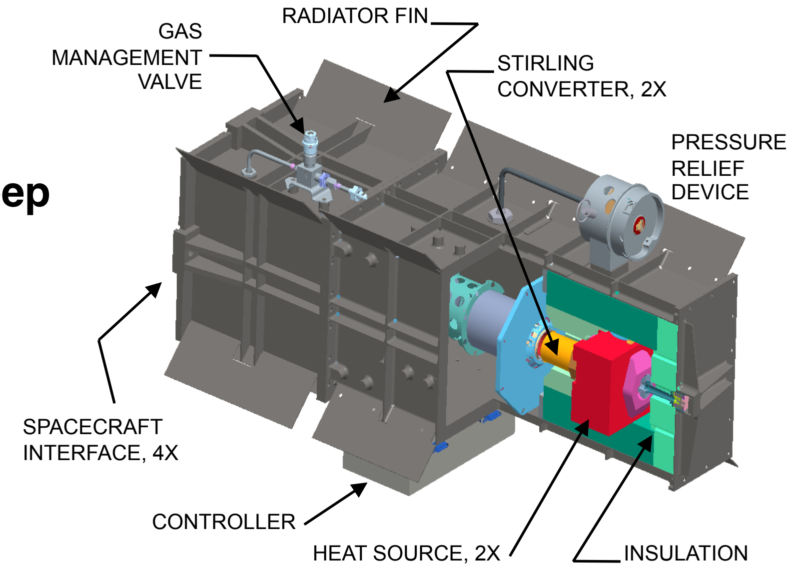
Potential Aerobot Applications



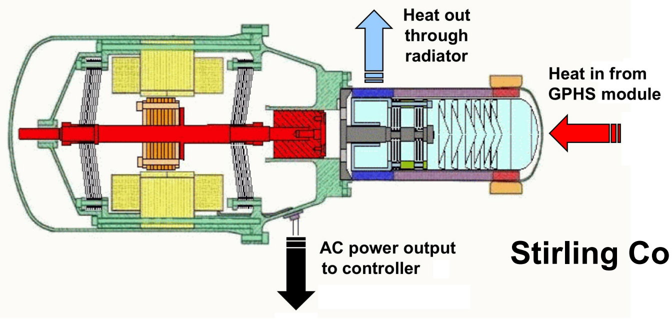
MMRTG Qualification Tests in 2007

Advanced Stirling Radioisotope Generator (ASRG)

- **Dramatic advancement in RPS capability**
  - High efficiency Stirling power conversion (≥30%)
  - Increase in specific power (2-3x greater than MMRTG)
- **Compatible for use on planetary surface and deep space missions – 14-year design lifetime**
- **Engineering Unit Features:**
  - >140 We (650 C heater head temp)
  - 2 simulated GPHS heat sources per ASRG
  - 22 kg, **6 - 7 We/kg specific power**
- **Flight Unit Features:**
  - ~160 We (850 C heater head temperature)
  - 2 GPHS heat sources per MMRTG
  - ≥20 kg, **≤8 We/kg specific power**
  - Lifetime: 3-year storage + 14-year mission
- **Potential Missions:**
  - 2015-2016 Discovery mission – ASRG offered as GFE
  - Europa Flagship mission (≥2016)?



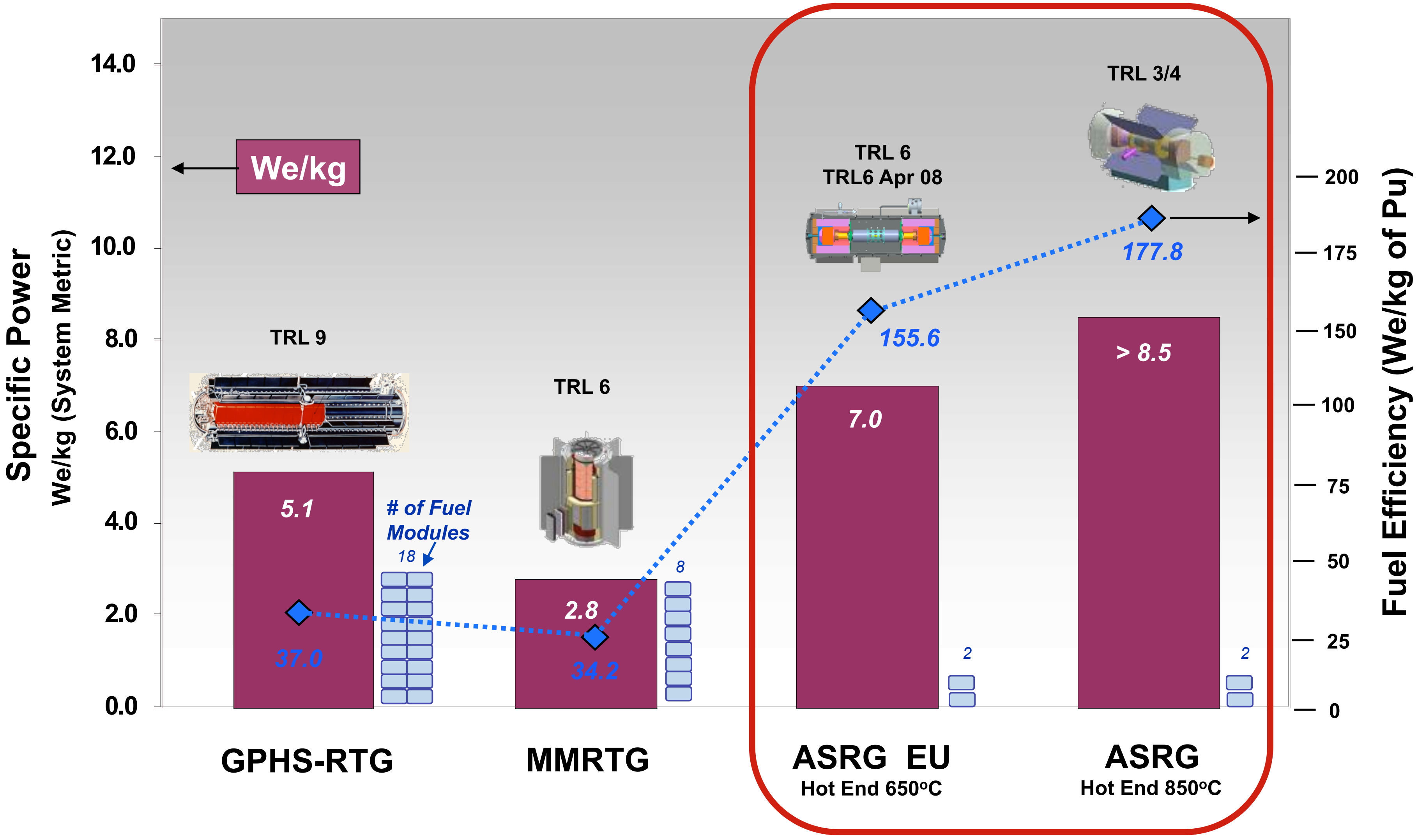
ASRG Configuration



Stirling Converter

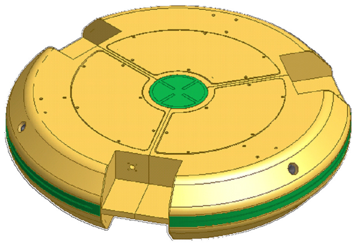
ASRG Engineering Unit under Test at NASA GRC

Recent Advancement in RPS Performance

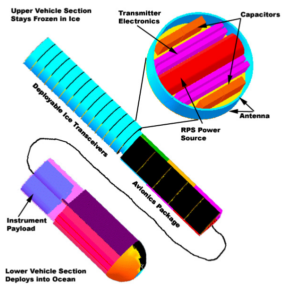


Images not to scale

Potential New Applications for RPS



Transponder/ Sensor Unit



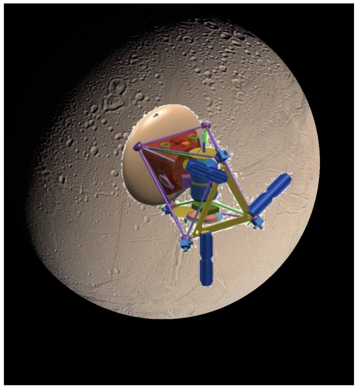
Cryobot Probe with Deployable Transceivers (JPL)

Small RPS (mWe to several We)

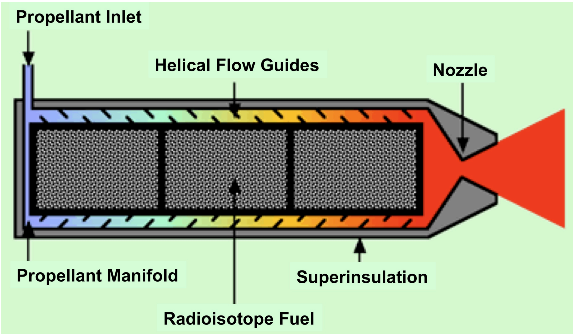
- Many potential surface and space applications (e.g., networked science stations, deployable mini-payloads)
- 3 general size ranges using existing Pu-238 thermal sources
  - 40-80 mW (based on 1-few RHUs)
  - 0.1-few W (based on multiple RHUs or fractional GPHS)
  - 10-20 W (based on single GPHS module)

Radioisotope Electric Propulsion (REP)

- Low-power Nuclear Electric Propulsion (NEP) based on RPS as principal power source (1-3 kWe evaluated)
- Enables use of high-performance electric propulsion independent of distance from Sun (i.e., deep space)
- Compatibility on small spacecraft permits launch injection into C3 > 0 and offsets disadvantage of low specific power



REP Spacecraft Concept (NASA GRC)



Radioisotope Thermal Thruster Concept

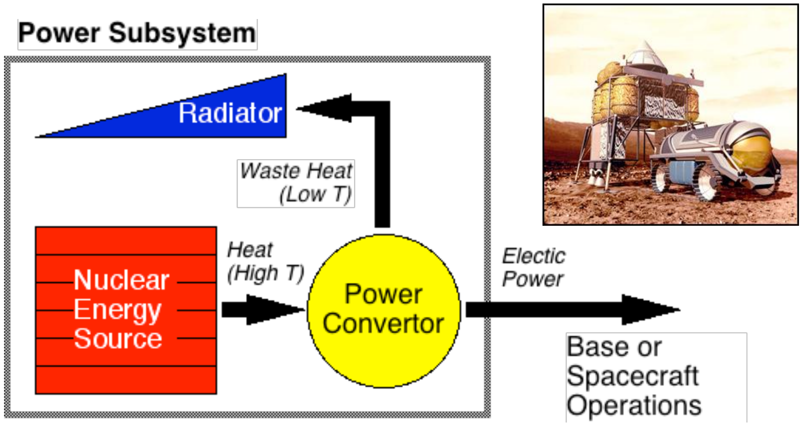
Radioisotope Thermal Propulsion

- Active development program by TRW from 1961 to 1965, known as “Poodle.” (Used Polonium-210 fuel)
- Tests achieved Isp of 650 to 700 s. Isp > 800 s possible with advanced fuel forms (Idaho National Laboratory)
- New approaches in heat shunt design and encapsulated fuel forms may hold some promise for small applications

Outline

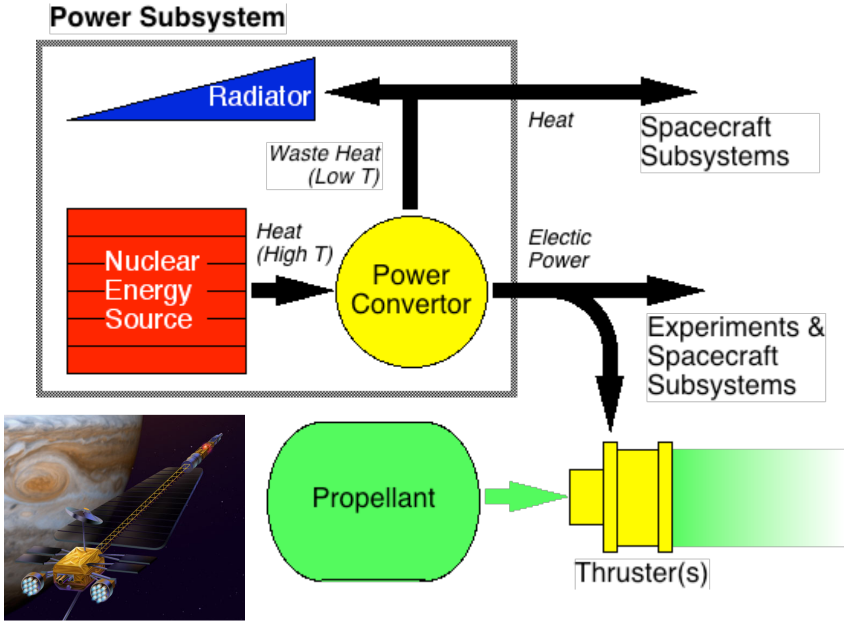
- Why Nuclear?
- Radioisotope Power Systems
- Fission-based Power and Propulsion
- Advanced Concepts and Technologies
- Conclusions

Fission-based Propulsion and Power



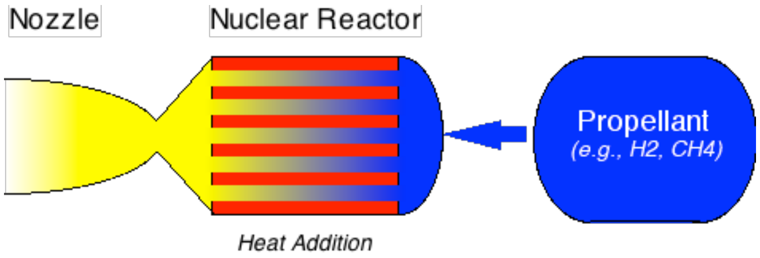
Power Generation

- Provide power for human spacecraft and surface operations
- Small reactor units for space science?
- Best for power applications >10-100 kWe



Nuclear Electric Propulsion (NEP)

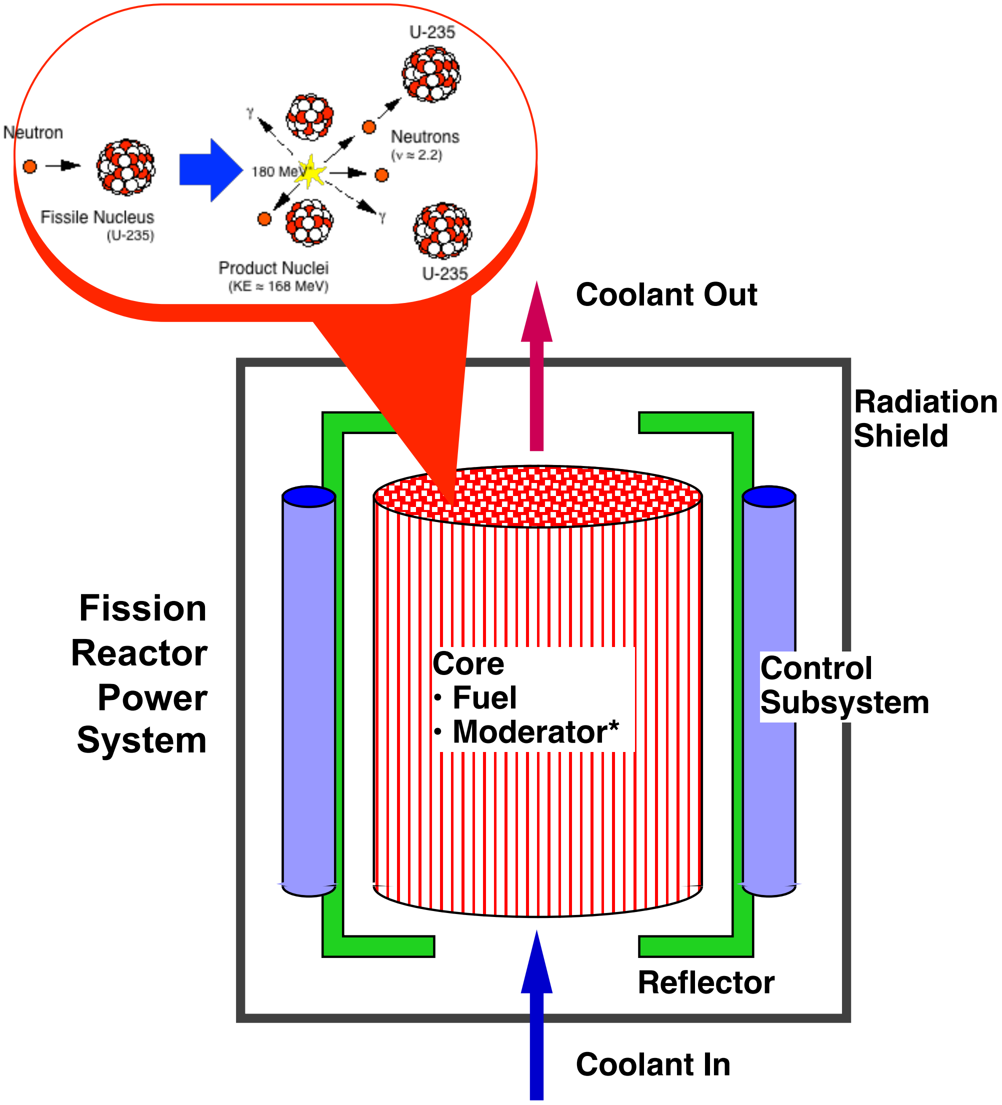
- High Isp electric propulsion and power-rich environment for deep space missions
- Specific power of current technology too low for near-term applications. Requires significant advancement.



Nuclear Thermal Propulsion (NTP)

- Propulsion for crewed missions to Mars and other destinations in inner solar system
- Isp = 900 to 1000 sec.

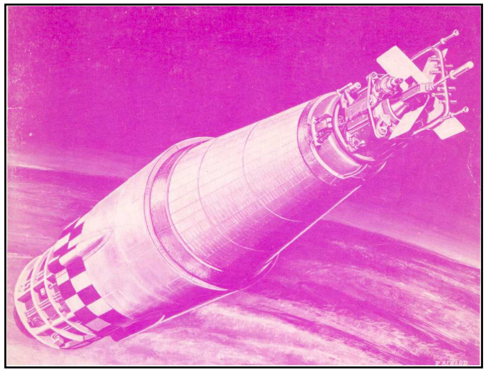
Fission Power System Elements



* Thermal reactors only

- **Core**
  - Central reactor region
  - Contains fuel, moderator, suitable structural materials, and coolant passages or heat removal devices (heat pipes)
- **Fuel**
  - Fissile material
  - Productive absorption produces heat and neutrons for sustained chain reaction
  - Non-productive absorption (still produces heat)
- **Moderator (if needed)**
  - Reduces neutron velocity (depends on system) to increase absorption cross-section
- **Control Subsystem**
  - Actively controls neutron population in core via absorption and/or reflection
- **Reflector**
  - Scatters neutrons back into core, thus reducing critical mass and power peaking
- **Radiation Shield**
  - Reduces radiation dose to sensitive components near core

Fission Flight Systems



SNAP-10A and Agena upper stage approaching orbit

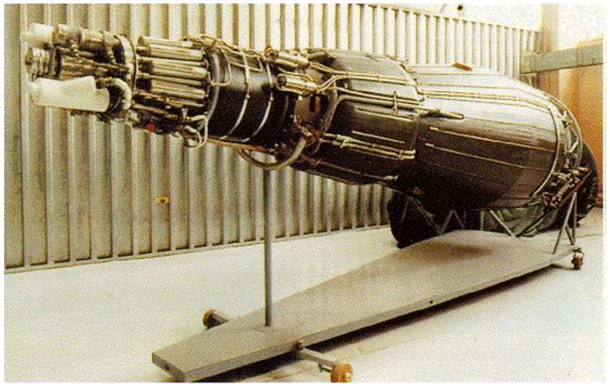
SNAP-10A Checkout

SNAP-10A

- 30 kW thermal output produced 500 watts of electrical power using thermoelectrics (1.67% efficiency)
- Launched by an Atlas Agena D rocket on April 3, 1965
- SNAP-10A maintained a low earth orbit for 43 days
- An onboard voltage regulator within the spacecraft – unrelated to the SNAP reactor – failed causing the reactor core to be ejected into high earth orbit

Russian Systems

- Radar Ocean Reconnaissance Satellite (RORSAT)
  - 33 radar satellites powered by nuclear reactors in low earth orbit (~255 km) altitude) from 1967 to 1988
  - NaK-cooled reactor cores separated and disposed into higher (600 yr) orbit
  - Several accidents. Most notable was Kosmos 954 in 1978 which crashed in Canada
- TOPAZ
  - More powerful reactors for higher-altitude surveillance satellites. Two flown.
  - 2nd Generation TOPAZ used thermionic conversion. Acquired by U.S. for study in 1980s.

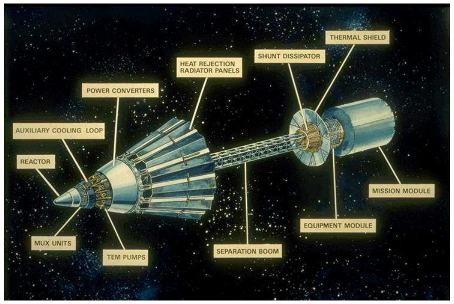


5 kWe TOPAZ Thermionic Reactor Power system

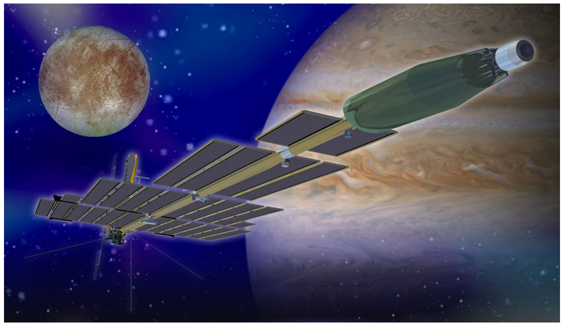
Recent U.S. Activities

SP-100

- NASA/DOE technology program from early 1980’s to mid-1990’s
- Liquid metal cooled reactors with thermoelectrics or Brayton conversion cycles
- 20-100 kWe output and ~7-year life
- Mature system design and extensive component tests



100 kWe SP-100 Thermoelectric



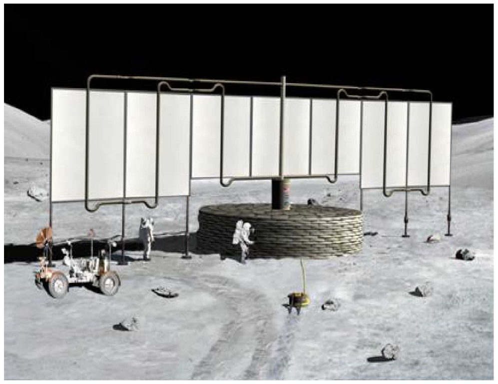
Jupiter Icy Moons Orbiter (JIMO)

Project Prometheus

- NASA/DOE technology program started in 2002 as Nuclear Systems Initiative and terminated in 2005
- RPS research, technology and flight system development
- Nuclear Electric Propulsion (NEP) system technology development
- Preliminary design and system analysis of Jupiter Icy Moons Orbiter (JIMO) NEP mission

Fission Surface Power Demonstration

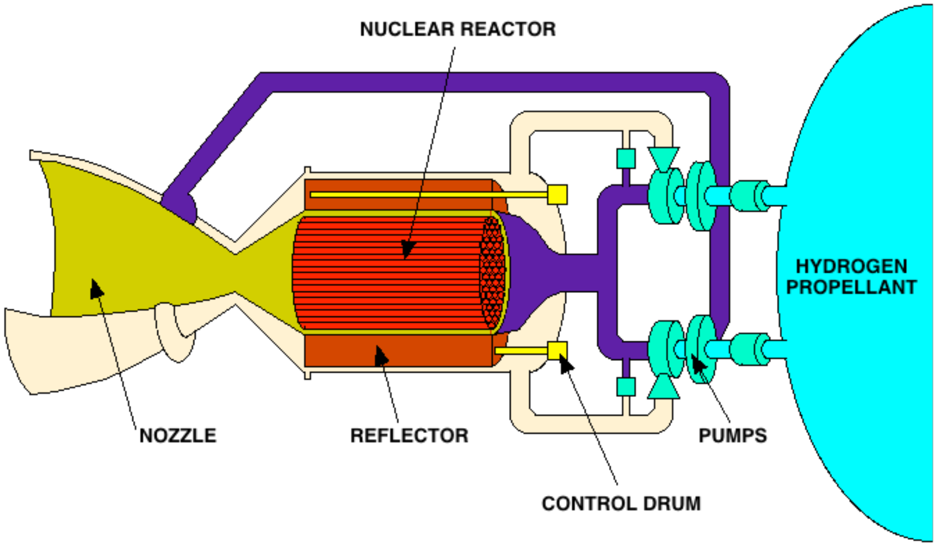
- Technology program for low-power (≤50 kW) reactor systems started at end of Prometheus program (>2005)
- Featured test and evaluation of kW-class Stirling converters using simulated electrically-heated reactor cores
- Liquid metal cooling loops for reactor core and Stirling head heat exchanger
- Tests at NASA GRC and MSFC



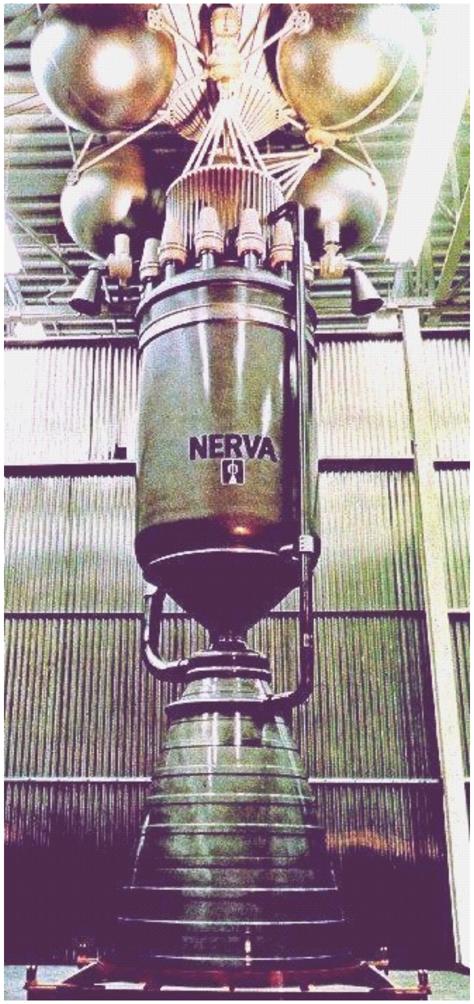
Fission Power System on Surface of Moon

Nuclear Thermal Propulsion (NTP)

- Propellant heated directly by a nuclear reactor and thermally expanded/accelerated through a nozzle
- Low molecular weight propellant – typically Hydrogen
- Thrust directly related to thermal power of reactor: 50,000 N ≈ 225 MW_{th} at 900 sec
- Specific Impulse directly related to exhaust temperature: 830 - 1000 sec (2300 - 3100K)
- Specific Impulse improvement over chemical rockets due to lower molecular weight of propellant (exhaust stream of O2/H2 engine runs much hotter than NTP)



Major Elements of a Nuclear Thermal Rocket



XE-Prime Nuclear Thermal Rocket Prototype

Rover/NERVA Nuclear Rocket Program

NTP Reactors Tested in the Rover Nuclear Rocket Program

KIWI A	KIWI B	Phoebus 1	Phoebus 2
1958-1960	1961-1964	1965-1966	1967
100 MW	1,000 MW	1,000 & 1,500 MW	5,000 MW
0 lbf Thrust	50,000 lbf Thrust	50,000 lbf Thrust	250,000 lbf Thrust

NERVA engines based largely on the KIWI B reactor design.

Culmination of NERVA Program

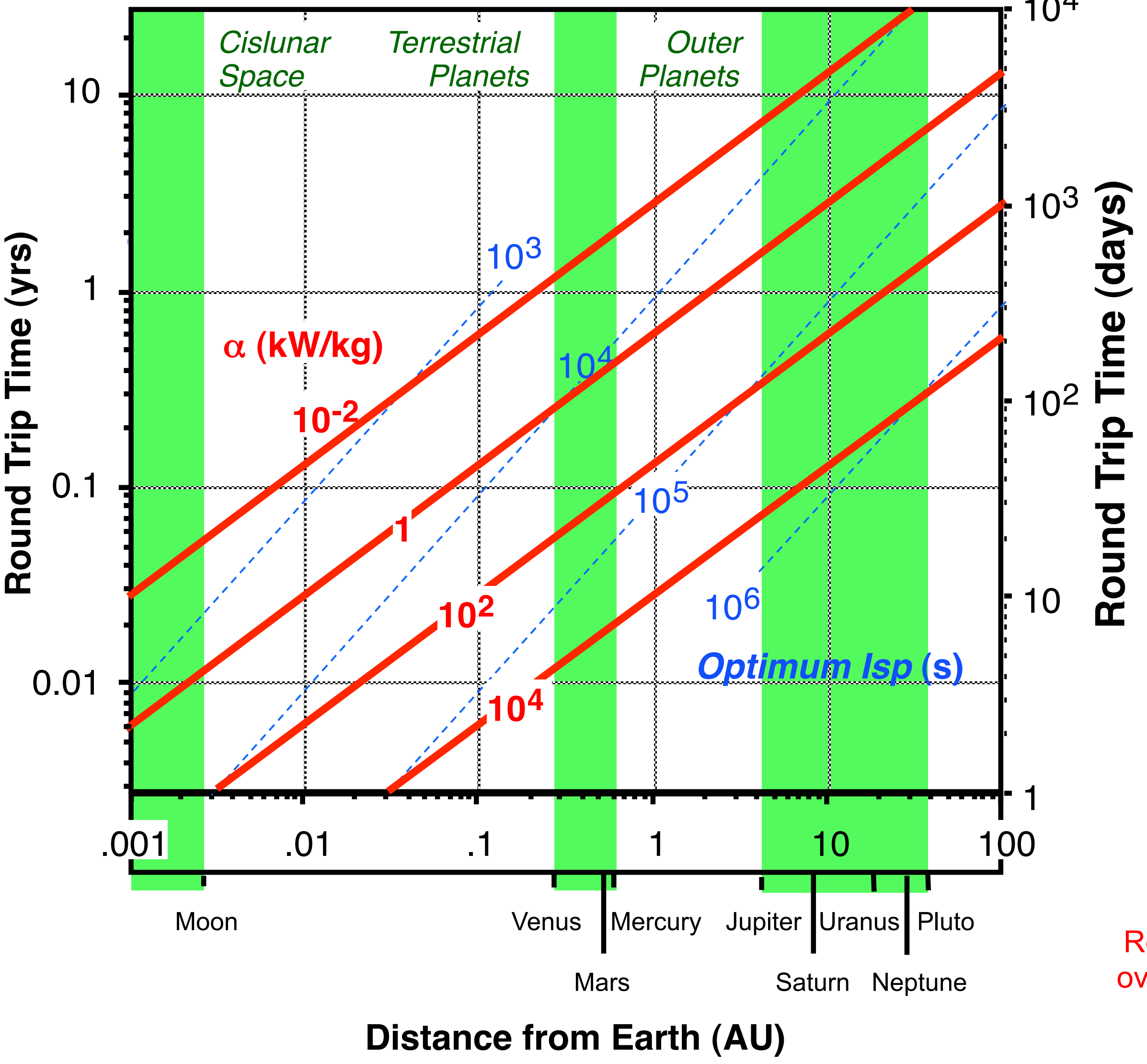
XE-Prime
1969
1,140 MW
55,400 lbf Thrust
28 engine restarts
115 minutes total run time
11 minutes at full power

Outline

- Why Nuclear?
- Radioisotope Power Systems
- Fission-based Power and Propulsion
- Advanced Concepts and Technologies
- Conclusions

Ambitious Exploration Demands High Specific Power (α) and High Specific Impulse (Isp)

Round Trip Time to Destinations in the Solar System as a Function of Isp and α



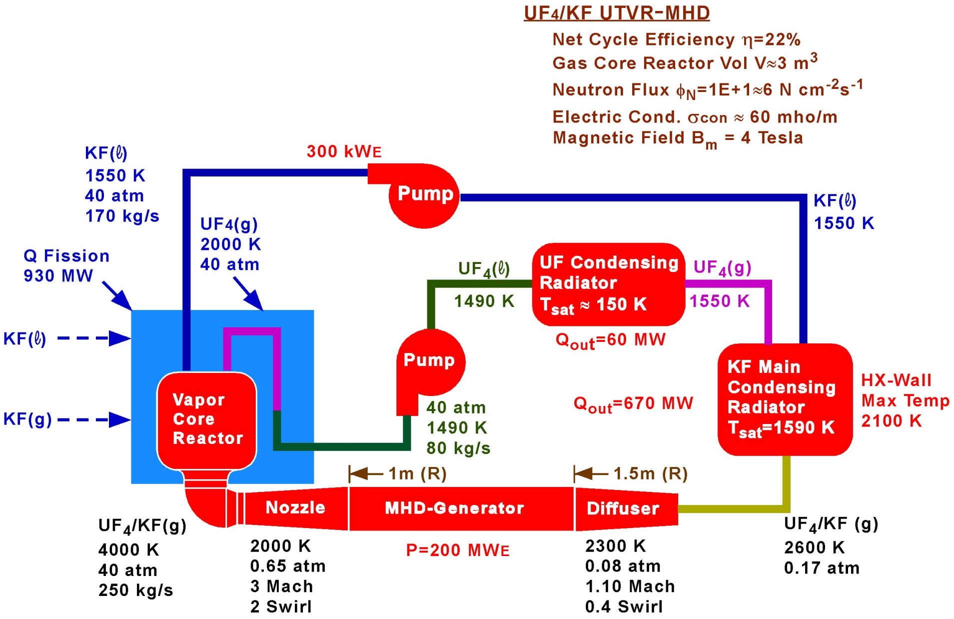
System	α (kW/kg)
JIMO – SOA Nuclear Electric Prop (NEP)	~0.01
Multi-MW NEP	~0.03
FAST-based SEP (Earth – Mars)	~0.1
VASIMR and other Plasma Systems (~100 day Round Trip to Mars)	≥1.0

Requires ≥2 Order of Magnitude increase over JIMO-class nuclear power systems – a very ambitious goal!

Advanced Power System Technology

High-Temperature Vapor Core Reactor with MHD Energy Conversion

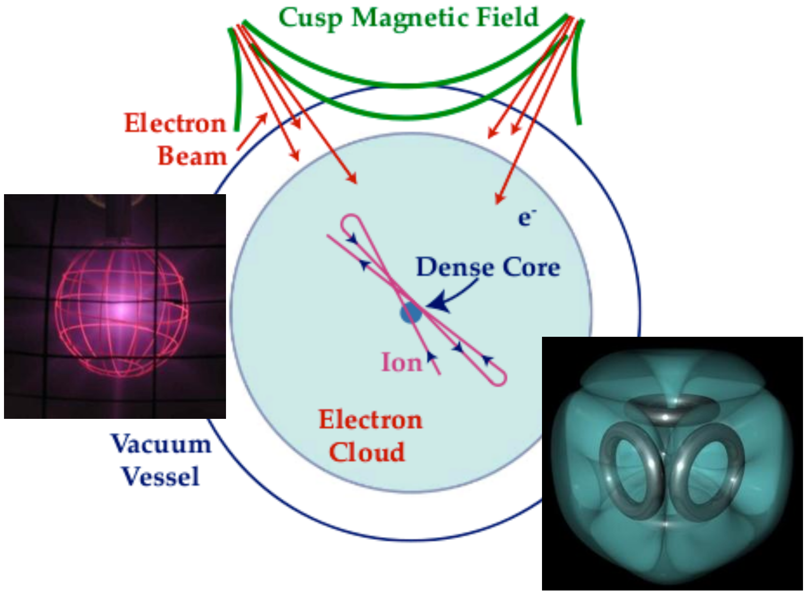
- Several different concepts involving high temperature gas core reactors
- Studies indicate that system specific powers >1.0 kWe/kg could be possible
- Common reactor gas and MHD working fluid reduce inefficiencies in having different conversion processes



Vapor Core Reactor/MHD Power System

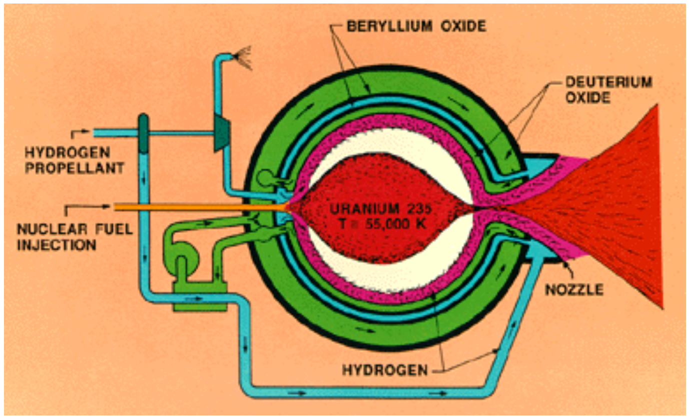
Inertial Electrostatic Confinement (IEC) Fusion Generator

- Conceived by Filo Farnsworth (inventor of TV). Several university and industry research activities underway.
- Relies on spherically configured electrostatic and magnetic fields to accelerate ions into center region of high density.
- Specific powers ≥10 kWe/kg may be possible
- Potential use of true aneutronic p/B-11 fuel and direct conversion into electrical power.



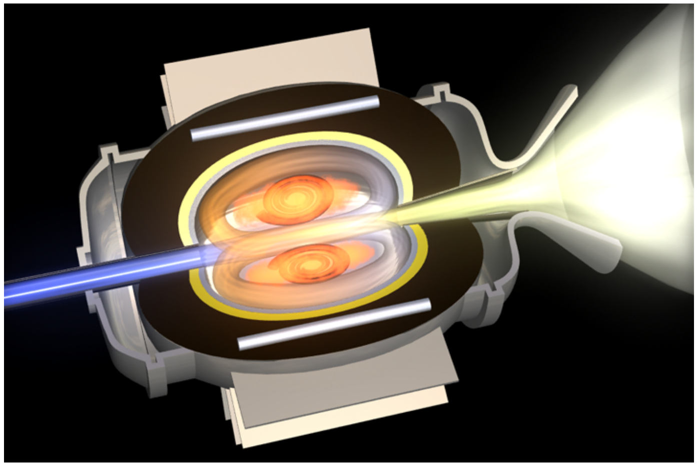
IEC Confinement Concepts

Gas Core Nuclear Thermal Rockets (GCNTR)

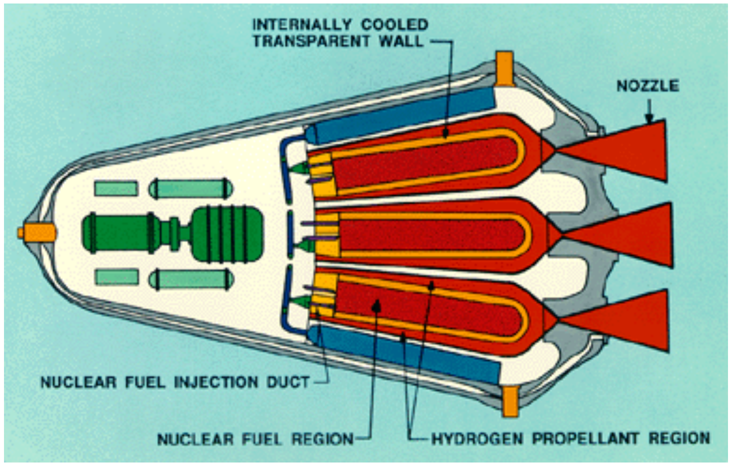


Early concept for open cycle GCTR

- Nuclear reactions take place in open or closed gaseous core. Enables operation at much higher temperatures than solid core rockets.
- Tests of “gaseous” fuel elements performed in 1975 and 1979. Equivalent Isp of 1350 secs demonstrated.
- CFD analyses periodically since then.
- Isp ≥ 2000 secs

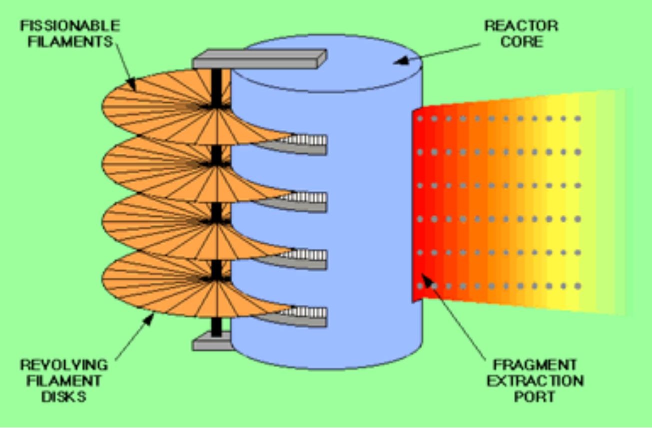


LANL (Howe) Vortex-stabilized GCTR from late-1990’s to early-2000’s



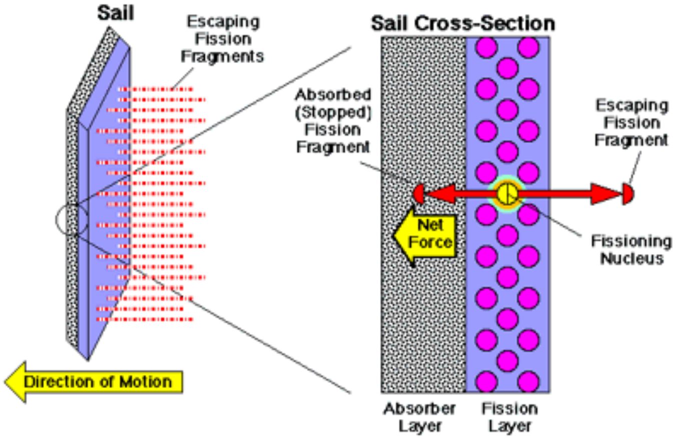
Closed cycle Nuclear Light Bulb Concept

Fission Fragment Rockets

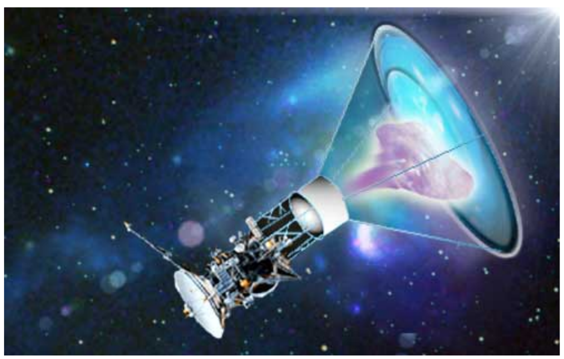


Rotating Filament Concept

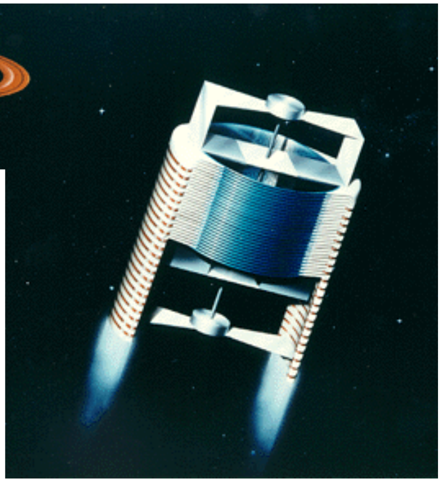
- Kinetic energy of fission fragments used directly to produce thrust
- Eliminates inefficiencies arising from thermalization in a core or other materials
- Most concepts based on highly-fissile isotopes, such as Americium-242
- Very high Isp of 100,000 to 1,000,000 sec appear to be possible



Fission Sail Concept (R. Forward)

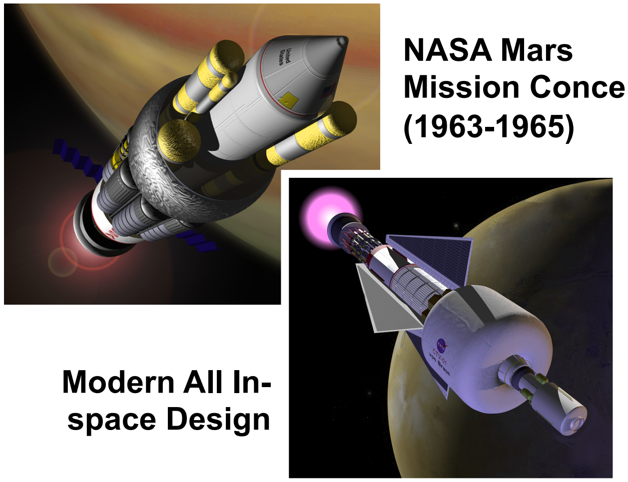


Antimatter-Facilitated Fission Sail (S. Howe)



Directed Fragment Exhaust (Lawrence Livermore)

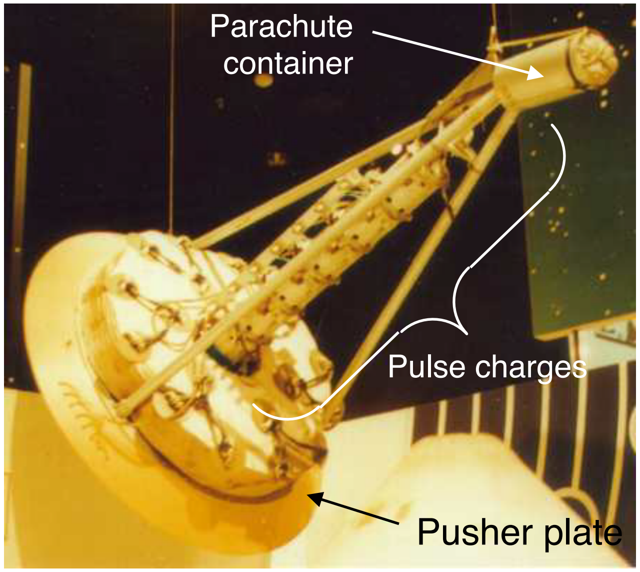
Nuclear Pulse Propulsion



NASA Mars Mission Concept (1963-1965)

Modern All In-space Design

NPP Vehicle Concepts



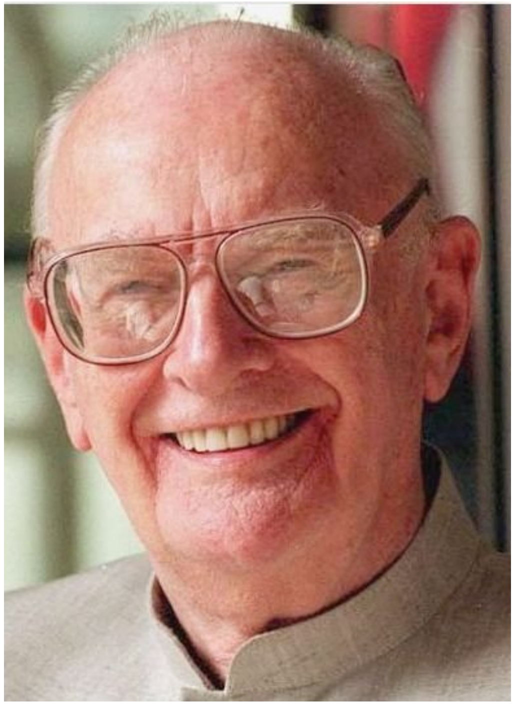
"Put-Put" Flight Test Vehicle on Display in Smithsonian Air & Space Museum

- Small nuclear bombs provide thrust via large pusher plate at rear of spacecraft
- First studied in 1950's and early 1960's for ARPA and then NASA as Project Orion
- Data from nuclear tests, analyses and subscale flights with chemical explosives pointed to feasibility for launch and in-space
- High Isp (~10,000 s) and high thrust (~1 g) attracted NASA interest as follow-on to Rover/NERVA technology
- More advanced politically-palatable versions have been studied since that could enable even higher performance
  - External compression/initiation using lasers, z-pinches, electron beams
  - Fusion and/or antimatter boosters/initiators

"Even now, the only way we could get large payloads around the solar system is with something like Orion…So when you talk of sending hundreds of tons or even thousands of tons of payload, including human beings to Mars, that's the only way we could do it."

Arthur C. Clarke
2009

Propulsion Trivia: In Clarke's original screenplay for "2001: A Space Odyssey," the interplanetary spacecraft Discovery used an Orion-based Nuclear Pulse Propulsion system.

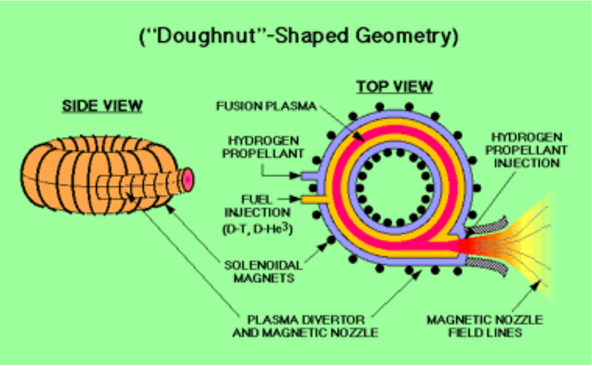


Arthur C. Clarke, Inventor of the GEO Communications Satellite, Author and Space Age Thought Leader

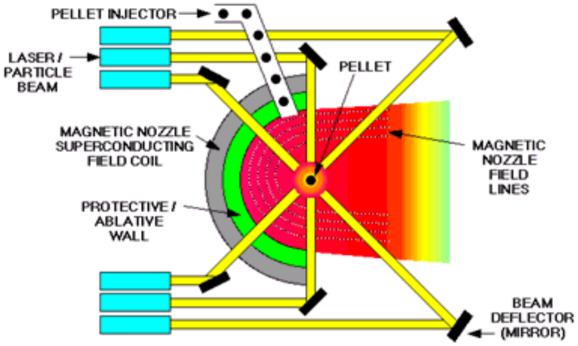
Project Orion - The Legacy

- **Large fission/fusion pulse vehicles for interstellar missions (Dyson, 1968)**
- **Laser-ignited Fusion Concepts**
  - BLASCON - Oak Ridge, 1969
  - Project SIRIUS - Los Alamos, 1970 - 1971
  - High-Isp - Lawrence Livermore, 1971 - 1972
  - Project ICARUS - USSR, 1976
- **Electron Beam Initiation - Winterberg**
  - Non-compressive method, 1970 - 1971
  - Compressive method, 1976 – 1977
- **Project DAEDALUS (British Interplanetary Society, 1973 – 1978) – electron beam compression of D-He3 targets**
- **VISTA (Lawrence Livermore, 1985 – 1995) – laser**
- **Pulsed Fission Assessment - UK (Bond), early-1990's**
  - Electron beam compression of fissile target
- **ICAN (Penn State, 1990's) – antiproton-catalyzed microfission/fusion**
- **Exploratory Work for NASA Decadel Planning Team/ NASA Exploration Team (1998-2001)**
- **Mini-Mag Orion (Andrews Aerospace, 1999-2003)**
  - Z-pinch compression of fissile target (fusion augment)
- **Project ICARUS (British Interplanetary Society, Tau Zero Foundation, 2009 – present)**

Fusion Propulsion

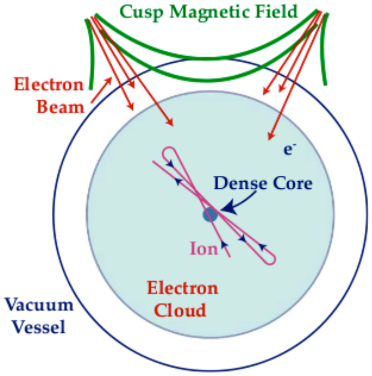


Magnetic Confinement Fusion



Inertial Confinement Fusion

Inertial Confinement Fusion



Magnetic Confinement

- Steady continuous energy production in a tokamak or magnetically confined plasma configuration
- Fusion research over last 50 years (TFTTR, ITER) indicates that this approach would be very large and massive
- Most recent studies by NASA GRC in 2005 suggest Isp of up to 45,000 s

Inertial Confinement

- Second main thrust of U.S. fusion research over last 60 years. Uses powerful lasers to implode fuel pellets and achieve high gain.
- National Ignition Facility (NIF) at Lawrence Livermore represents most recent research
- Studies suggest Isp's of 10,000 to 100,000 sec possible

Magnetized Target Fusion

- New concept that was explored by Los Alamos and NASA Marshall in late-1990's and early 2000's
- Pulsed inertial compression of magnetized plasma targets. Could represent easier implosion technique and higher performance than classic inertial confinement
- Isp's of up to 70,000 sec appear possible

Inertial Electrostatic Confinement

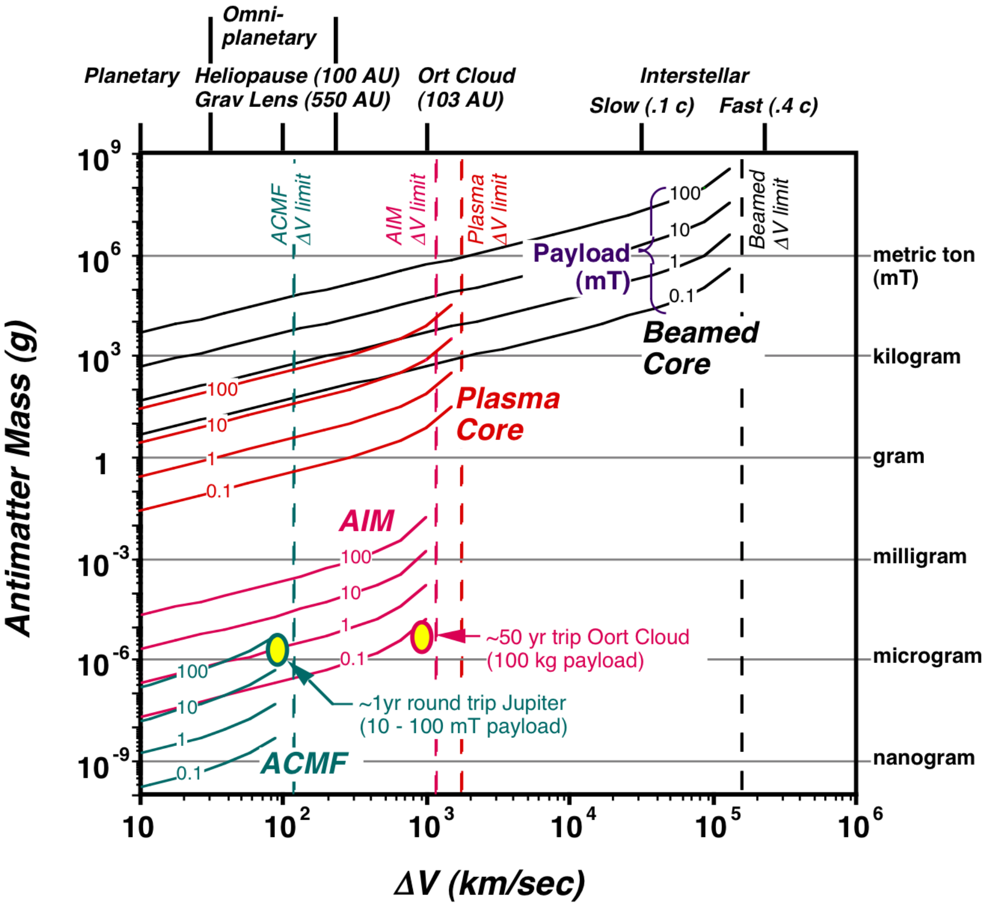
- Spherical chamber with radial electric field. Ions accelerated to center where they encounter high densities and tempertures.
- Pioneered by Philo Farnsworth (inventor of TV) and continued today by seveal universities and industry

Antimatter-catalyzed Fusion

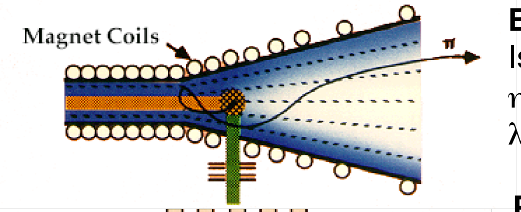
- Conceived at Penn State, antiproton annihilation used to promote fusion.
- Most promising application for inertial confined techniques

Antimatter Propulsion

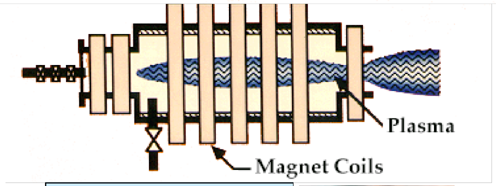
Antimatter Requirements for Various Missions and Propulsion Technologies



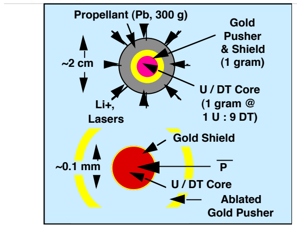
Antimatter-based Propulsion Technologies



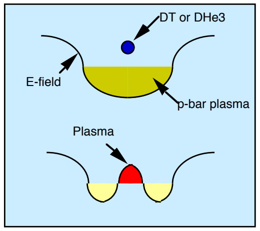
Beam Core
Isp $\approx 10^7$ s
$\eta_p \approx 60\%$
$\lambda \approx 0.2$

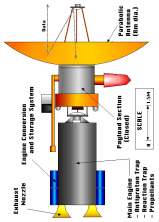


Plasma Core
Isp $\approx 10^5$ s
$\eta_p \approx 10\%$
$\lambda \approx 0.2$



Antimatter-Catalyzed Micro-Fusion (ACMF)
Isp $\approx 13{,}500$ s
$\eta_p \approx 15\%$
$\lambda \approx 0.7$
$\beta \approx 1.6 \times 10^7$





Antimatter-Initiated Micro-fusion (AIM)
Isp $\approx 67{,}000$ s
$\eta_p \approx 84\%$
$\lambda \approx 0.2$
$\beta \approx 10^5$

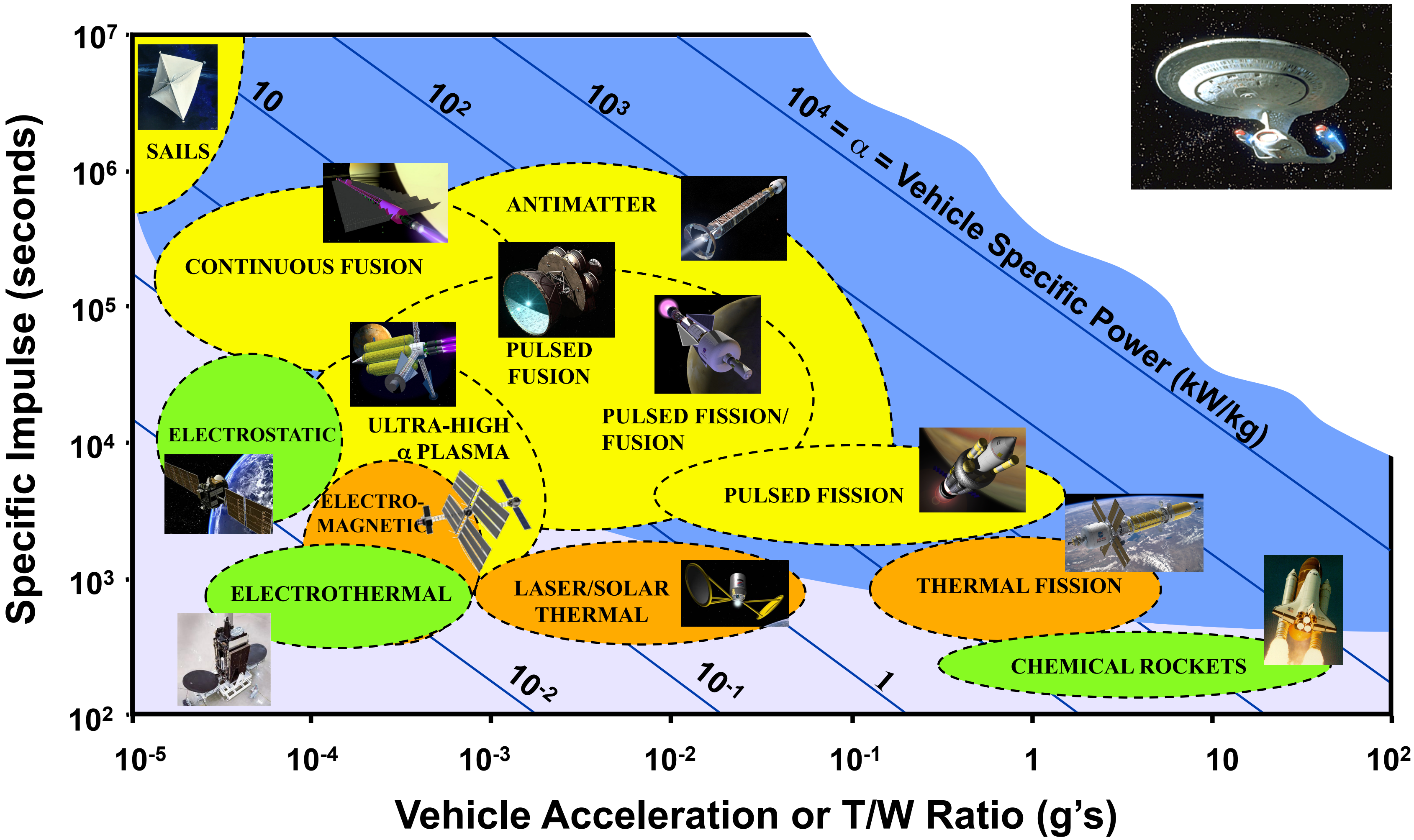
Isp Specific Impulse
η_p Propulsive energy utilization
λ Vehicle struct/prop mass ratio
β Fusion/annihilation energy ratio

- “Pure” antimatter propulsion not practical due to large antimatter requirement (≥ 1 gram). Current “cost” for 1 μg of p-bars is $63 million.
- With near-term improvements (x100 increase in efficiency) costs drop to $0.6 million/$\mu$g. This translates to antimatter costs of $0.6 million to $60 million for antimatter-assisted fission/fusion missions.

Outline

- Why Nuclear?
- Radioisotope Power Systems
- Fission-based Power and Propulsion
- Advanced Concepts and Technologies
- Conclusions

Capabilities of Candidate Propulsion Technologies



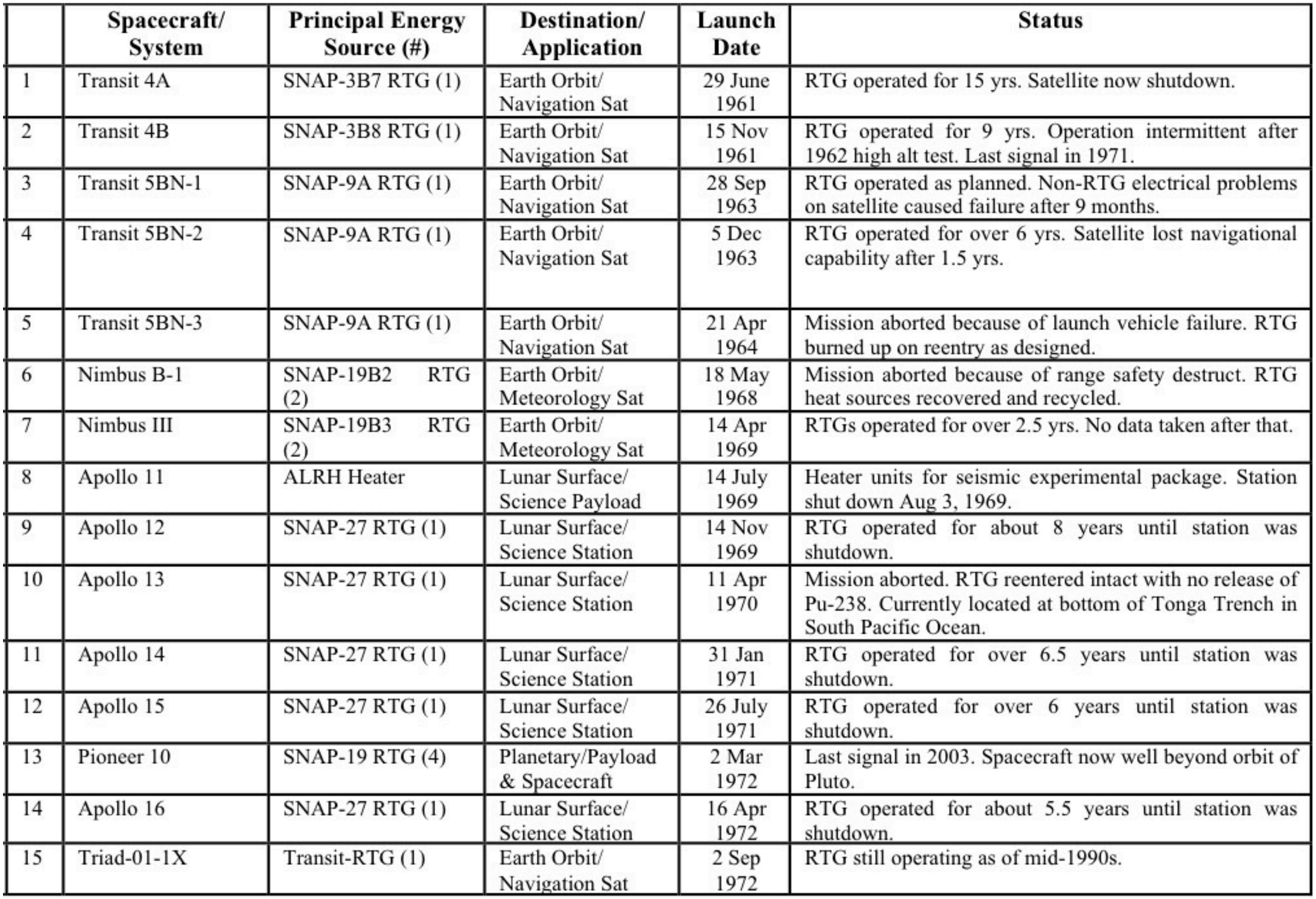
🟨 Unproven Technology (TRL 1-3) 🟧 Demonstrated Technology (TRL 4-6) 🟩 Operational Systems (TRL 7-9)

Conclusions: Recommended Areas of Emphasis

	Pull	Push
Radioisotope Technology	• Complete development of ASRG • Continue development of improved power conversion technologies • Develop Small RPS and Radioisotope Electric Propulsion (REP)	• Advanced fuel forms and isotopes (e.g., universal encapsulation) • Far-term alternative Pu-238 production techniques • Radioisotope Thermal Propulsion
Fission Technology	• ~10 kWe power system for crewed spacecraft and surface ops • NTP reactor fuel development and testing	**Power** • High specific power systems (≥1 kWe/kg) (e.g., Vapor/gas core, MHD, IEC) • Proof-of-principle demonstrations **Propulsion** • Proof-of-principle of fundamental energetics and key subsystems (e.g., GCNTP, antimatter-initiated fission/ fusion) • Concept and mission studies
Advanced Concepts and Technologies		

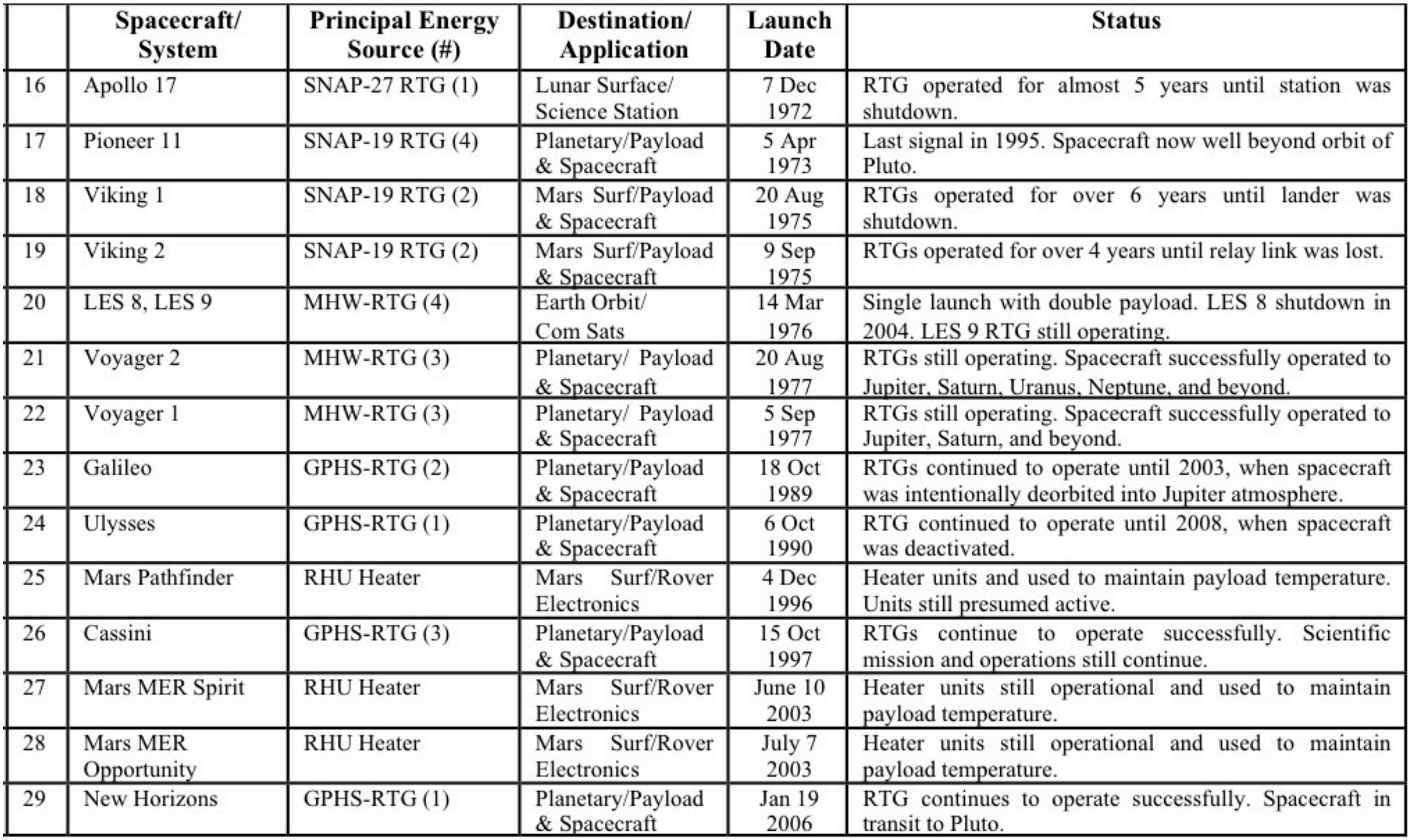
Backup Charts

U.S. Missions Using Radioisotopes



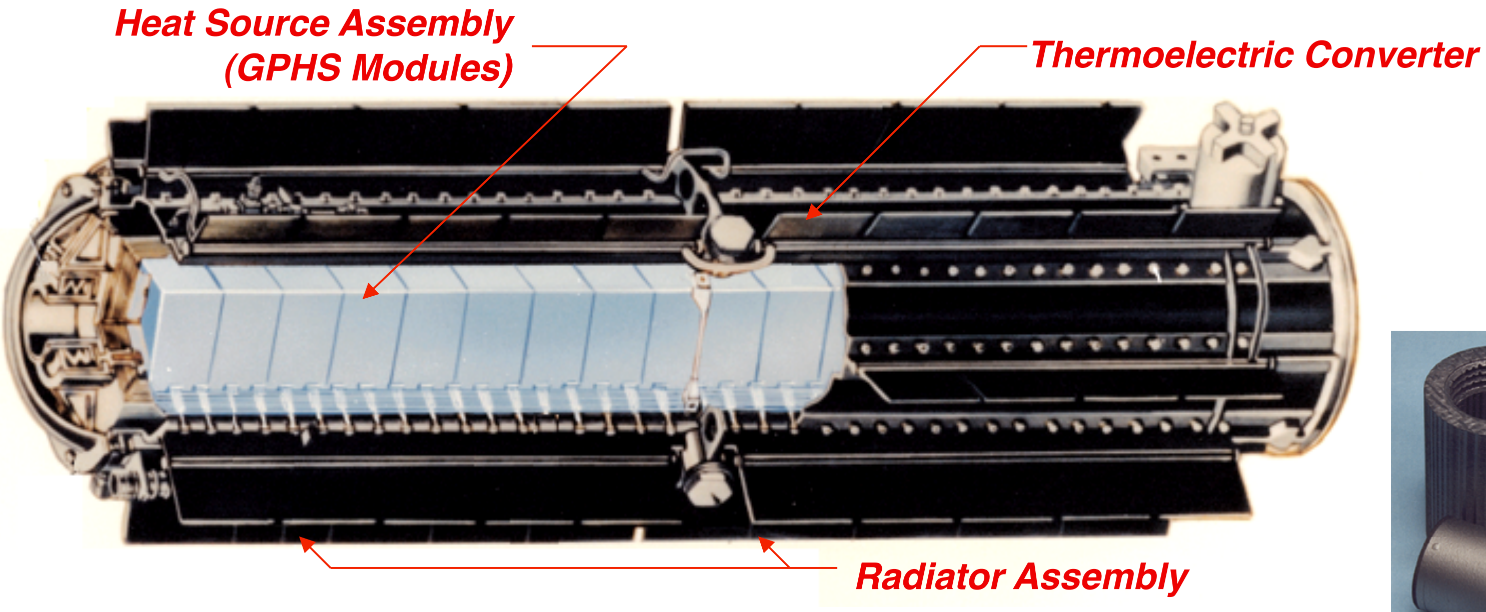
	Spacecraft/ System	Principal Energy Source (#)	Destination/ Application	Launch Date	Status
1	Transit 4A	SNAP-3B7 RTG (1)	Earth Orbit/ Navigation Sat	29 June 1961	RTG operated for 15 yrs. Satellite now shutdown.
2	Transit 4B	SNAP-3B8 RTG (1)	Earth Orbit/ Navigation Sat	15 Nov 1961	RTG operated for 9 yrs. Operation intermittent after 1962 high alt test. Last signal in 1971.
3	Transit 5BN-1	SNAP-9A RTG (1)	Earth Orbit/ Navigation Sat	28 Sep 1963	RTG operated as planned. Non-RTG electrical problems on satellite caused failure after 9 months.
4	Transit 5BN-2	SNAP-9A RTG (1)	Earth Orbit/ Navigation Sat	5 Dec 1963	RTG operated for over 6 yrs. Satellite lost navigational capability after 1.5 yrs.
5	Transit 5BN-3	SNAP-9A RTG (1)	Earth Orbit/ Navigation Sat	21 Apr 1964	Mission aborted because of launch vehicle failure. RTG burned up on reentry as designed.
6	Nimbus B-1	SNAP-19B2 RTG (2)	Earth Orbit/ Meteorology Sat	18 May 1968	Mission aborted because of range safety destruct. RTG heat sources recovered and recycled.
7	Nimbus III	SNAP-19B3 RTG (2)	Earth Orbit/ Meteorology Sat	14 Apr 1969	RTGs operated for over 2.5 yrs. No data taken after that.
8	Apollo 11	ALRH Heater	Lunar Surface/ Science Payload	14 July 1969	Heater units for seismic experimental package. Station shut down Aug 3, 1969.
9	Apollo 12	SNAP-27 RTG (1)	Lunar Surface/ Science Station	14 Nov 1969	RTG operated for about 8 years until station was shutdown.
10	Apollo 13	SNAP-27 RTG (1)	Lunar Surface/ Science Station	11 Apr 1970	Mission aborted. RTG reentered intact with no release of Pu-238. Currently located at bottom of Tonga Trench in South Pacific Ocean.
11	Apollo 14	SNAP-27 RTG (1)	Lunar Surface/ Science Station	31 Jan 1971	RTG operated for over 6.5 years until station was shutdown.
12	Apollo 15	SNAP-27 RTG (1)	Lunar Surface/ Science Station	26 July 1971	RTG operated for over 6 years until station was shutdown.
13	Pioneer 10	SNAP-19 RTG (4)	Planetary/Payload & Spacecraft	2 Mar 1972	Last signal in 2003. Spacecraft now well beyond orbit of Pluto.
14	Apollo 16	SNAP-27 RTG (1)	Lunar Surface/ Science Station	16 Apr 1972	RTG operated for about 5.5 years until station was shutdown.
15	Triad-01-1X	Transit-RTG (1)	Earth Orbit/ Navigation Sat	2 Sep 1972	RTG still operating as of mid-1990s.

U.S. Missions Using Radioisotopes (cont)



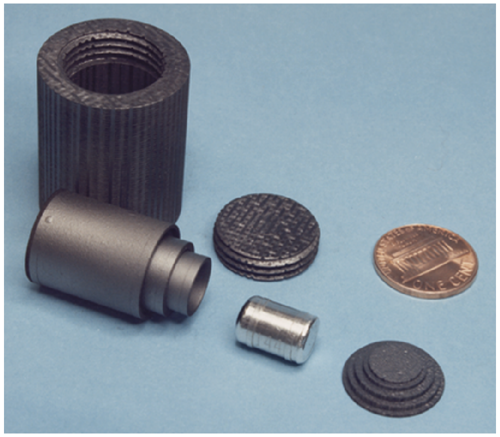
	Spacecraft/ System	Principal Energy Source (#)	Destination/ Application	Launch Date	Status
16	Apollo 17	SNAP-27 RTG (1)	Lunar Surface/ Science Station	7 Dec 1972	RTG operated for almost 5 years until station was shutdown.
17	Pioneer 11	SNAP-19 RTG (4)	Planetary/Payload & Spacecraft	5 Apr 1973	Last signal in 1995. Spacecraft now well beyond orbit of Pluto.
18	Viking 1	SNAP-19 RTG (2)	Mars Surf/Payload & Spacecraft	20 Aug 1975	RTGs operated for over 6 years until lander was shutdown.
19	Viking 2	SNAP-19 RTG (2)	Mars Surf/Payload & Spacecraft	9 Sep 1975	RTGs operated for over 4 years until relay link was lost.
20	LES 8, LES 9	MHW-RTG (4)	Earth Orbit/ Com Sats	14 Mar 1976	Single launch with double payload. LES 8 shutdown in 2004. LES 9 RTG still operating.
21	Voyager 2	MHW-RTG (3)	Planetary/ Payload & Spacecraft	20 Aug 1977	RTGs still operating. Spacecraft successfully operated to Jupiter, Saturn, Uranus, Neptune, and beyond.
22	Voyager 1	MHW-RTG (3)	Planetary/ Payload & Spacecraft	5 Sep 1977	RTGs still operating. Spacecraft successfully operated to Jupiter, Saturn, and beyond.
23	Galileo	GPHS-RTG (2)	Planetary/Payload & Spacecraft	18 Oct 1989	RTGs continued to operate until 2003, when spacecraft was intentionally deorbited into Jupiter atmosphere.
24	Ulysses	GPHS-RTG (1)	Planetary/Payload & Spacecraft	6 Oct 1990	RTG continued to operate until 2008, when spacecraft was deactivated.
25	Mars Pathfinder	RHU Heater	Mars Surf/Rover Electronics	4 Dec 1996	Heater units and used to maintain payload temperature. Units still presumed active.
26	Cassini	GPHS-RTG (3)	Planetary/Payload & Spacecraft	15 Oct 1997	RTGs continue to operate successfully. Scientific mission and operations still continue.
27	Mars MER Spirit	RHU Heater	Mars Surf/Rover Electronics	June 10 2003	Heater units still operational and used to maintain payload temperature.
28	Mars MER Opportunity	RHU Heater	Mars Surf/Rover Electronics	July 7 2003	Heater units still operational and used to maintain payload temperature.
29	New Horizons	GPHS-RTG (1)	Planetary/Payload & Spacecraft	Jan 19 2006	RTG continues to operate successfully. Spacecraft in transit to Pluto.

Most Recent Flight Radioisotope Systems



GPHS Radioisotope Thermoelectric Generator (RTG)

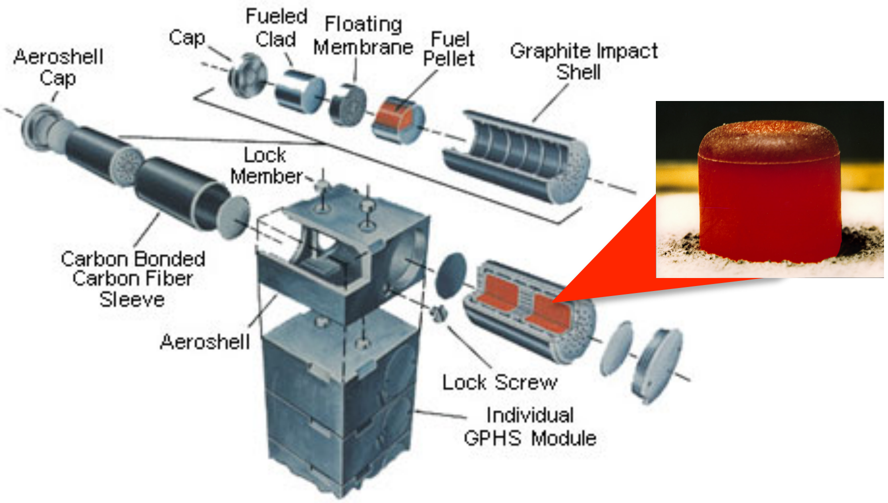
Heat Source:	18 GPHS modules
Power:	292 We (BOL)
Mass:	56 kg
Efficiency:	6.8%
Specific Power:	5.2 We/kg



Radioisotope Heater Unit (RHU)

- Compact 1 W thermal source containing ~2 g Pu-238 fuel
- Total mass ~40 g
- Used extensively on many space missions

Key Elements of GPHS RTG

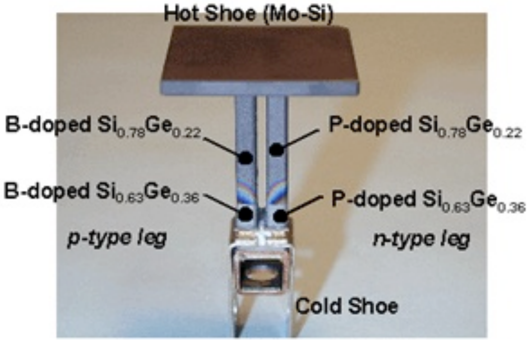


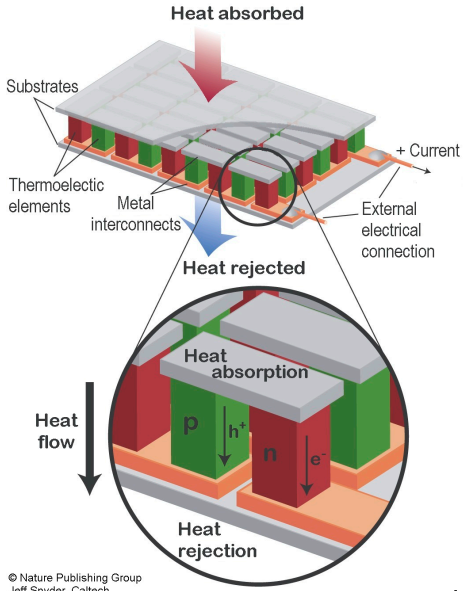
General Purpose Heat Source (GPHS)

- Each GPHS module contains four Ir-clad $^{238}PuO_2$ fuel pellets
- Each pellet contains ~150 g $^{238}PuO_2$ and generates ~62.5 W_{th} heat
- Iridium clad operation of 660-1273 K to maintain ductility and limit grain growth
- Dimensions: 9.32 cm x 9.72 cm x 5.31 cm (≤ Cassini); 9.32 cm x 9.96 cm x 5.82 cm (enhanced)
- Mass: 1.45 kg (≤ Cassini); 1.60 kg (enhanced)
- Thermal Power: ~250 W_{th} (Beginning of Life)

Thermoelectric Converter

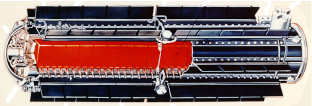
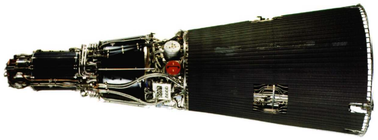
- Subsystem consists of 572 Silicon-Germanium (Si-Ge) thermoelectric unicouples
- Si-Ge enables operation at higher temperature, thus improving efficiency and reducing radiator mass
- 6.8% efficiency
- >27 year lifetime of unicouple operation demonstrated in space
- Hot Side Temp: 1273 K
- Cold Side Temp: 573 K





© Nature Publishing Group
Jeff Snyder, Caltech

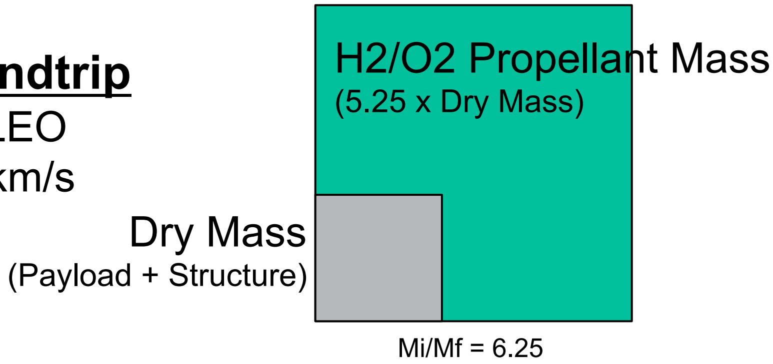
Comparing Radioisotope and Fission Systems

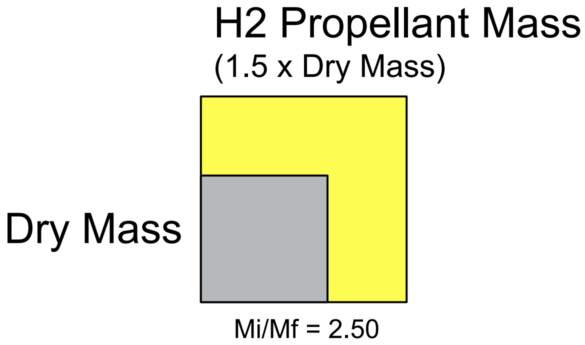
	Radioisotope Power System 	**Fission Power System** 
Power/Unit	≤1,000 Watts electric (We). Larger sizes possible but may not be practical with limited Pu-238 supply.	>10 kilowatts electric (kWe). Smaller powers possible at expense of very low specific powers.
Specific Power (We/kg)	~3 - 8 We/kg. 10 We/kg may be possible with advanced technology.	~10 We/kg (Near-term) ~100 We/kg may be possible for large (MW) advanced systems.
Radioactivity at launch	Considerable (~100,000 Curies) but very low penetration energy and easily shielded.	Very little (<10 Curies). Inventory does not increase until reactor activated in orbit or space.
Advantages	• High reliability – fewer active control components • Extensive flight history - 45 units launched over last 50 yrs • Small size provides flexibility in design of science spacecraft.	• Higher power density – increases with larger units (>1 MW) • Low radiation concerns prior to startup. • Relatively constant power output for longer durations
Disadvantages	• Safety considerations for handling Pu-238 during assembly, pre-launch and flight phases of mission • Very limited worldwide supply of Pu-238. • Waste heat handling systems required before use.	• Security in handling enriched Uranium (U-235) prior to launch • Safety considerations to avoid inadvertent startup at launch • Release of radioactive products after extended operations (with crew operations)

NTP versus Chemical Propulsion

Chemical (Isp = 450 sec) **Nuclear Thermal (Isp = 900 sec)**

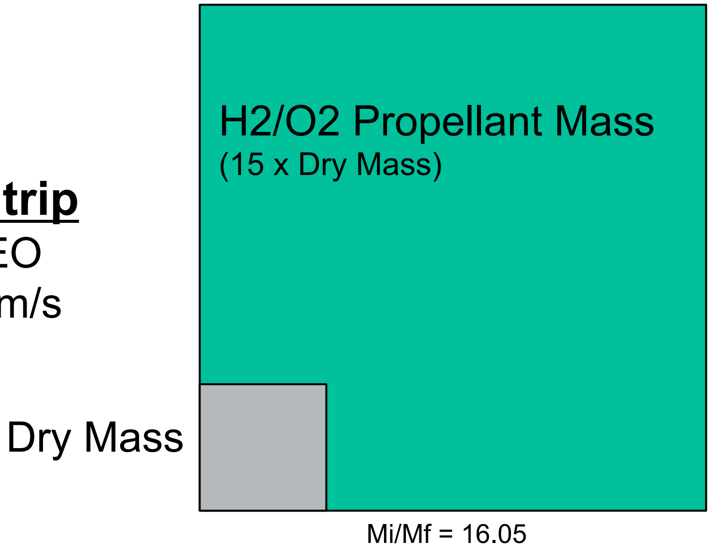
Moon Roundtrip
- LEO-LLO-LEO
- ΔV = 8.08 km/s

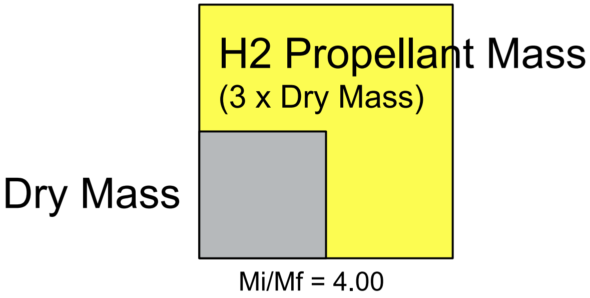




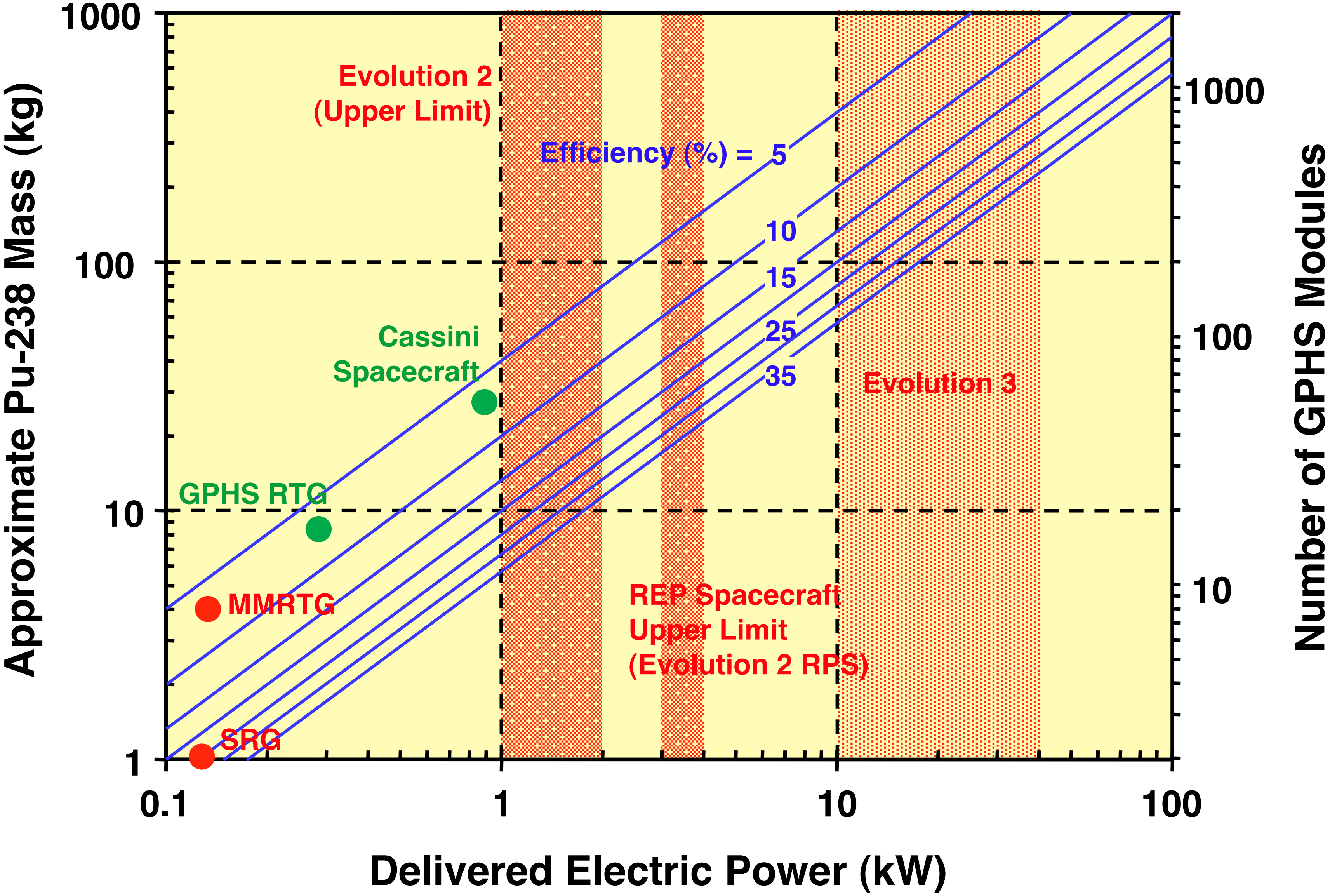
$$\frac{\text{Initial Mass}}{\text{Final Mass}} = \exp\left(\frac{\Delta V}{g \cdot Isp}\right)$$

Mars Roundtrip
- LEO-LMO-LEO
- ΔV = 12.24 km/s

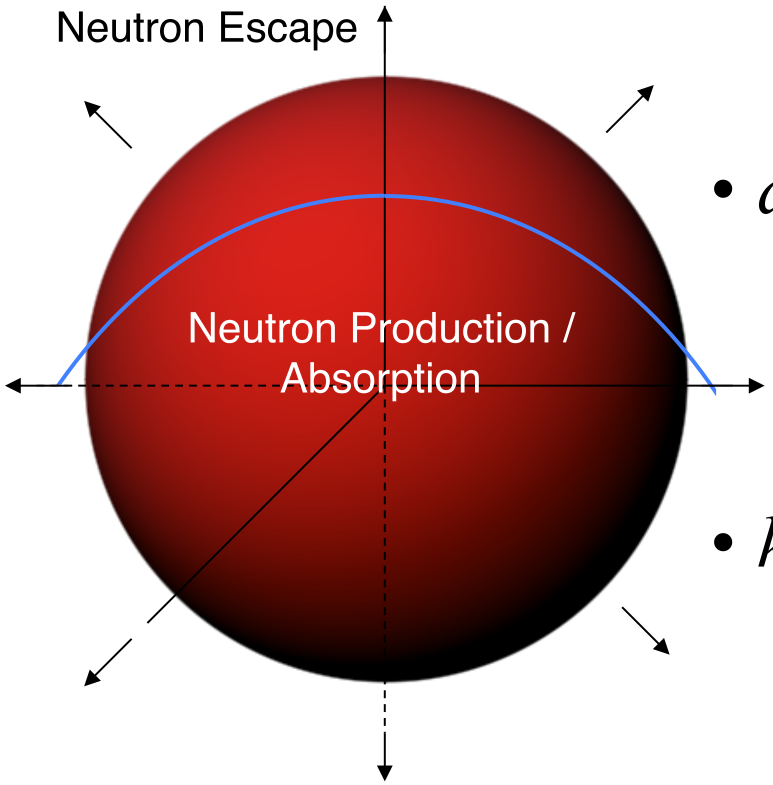




Plutonium-238 Requirements Versus Power Level



The Fission Chain Reaction



Radial neutron flux distribution in idealized spherical core

- $\text{Thermal Power}(t) = \underbrace{N(t)}_{\text{Core neutron population}}$
- $dN/dt = \underbrace{\text{Production Rate}}_{\text{Fission neutrons}} - \underbrace{\text{Loss Rate}}$
  - Absorption (fission, nonproductive capture)
  - Leakage (boundaries)
- $k = \text{Multiplication Factor}$

  $= \text{Production Rate/Loss Rate}$

$$
\begin{aligned}
&< 1 \quad (\text{subcritical},\ dN/dt < 0) \\
&= 1 \quad (\text{critical},\ dN/dt = 0) \\
&> 1 \quad (\text{supercritical},\ dN/dt > 0)
\end{aligned}
$$

Control of Reactor Conditions