Space Nuclear Power & Propulsion

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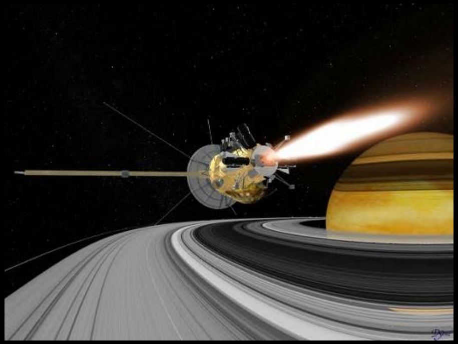

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KEY HISTORICAL EVENTS & DATES

- **The Setting: Post-WWII, the Cold War & the Space Race**
- **Key Events & Dates:**
  - **1 Aug 1946: Atomic Energy Act signed into law by President Truman**
  - **29 Aug 1949: USSR tests its first nuclear bomb**
  - **1 Nov 1952: US tests its first thermonuclear bomb**
  - **20 Aug 1953: USSR tests its first thermonuclear bomb**
  - **8 Dec 1953: President Eisenhower announces his "Atoms for Peace" program at meeting of UN General Assembly**
  - **15 Aug 1955: Startup of first US university research reactor**
  - **4 Oct 1957: Launch of Sputnik-1 by the USSR**
  - **31 Jan 1958: Launch of Explorer-1 by the US**
  - **29 Jun 1961: Nuclear-powered satellite, Transit-4A, launched by US**
  - **12 Sep 1962: President Kennedy's 'US is going to the Moon' speech at Rice University**
  - **Oct 1962: Cuban missile crisis**

PRESENTATION OVERVIEW

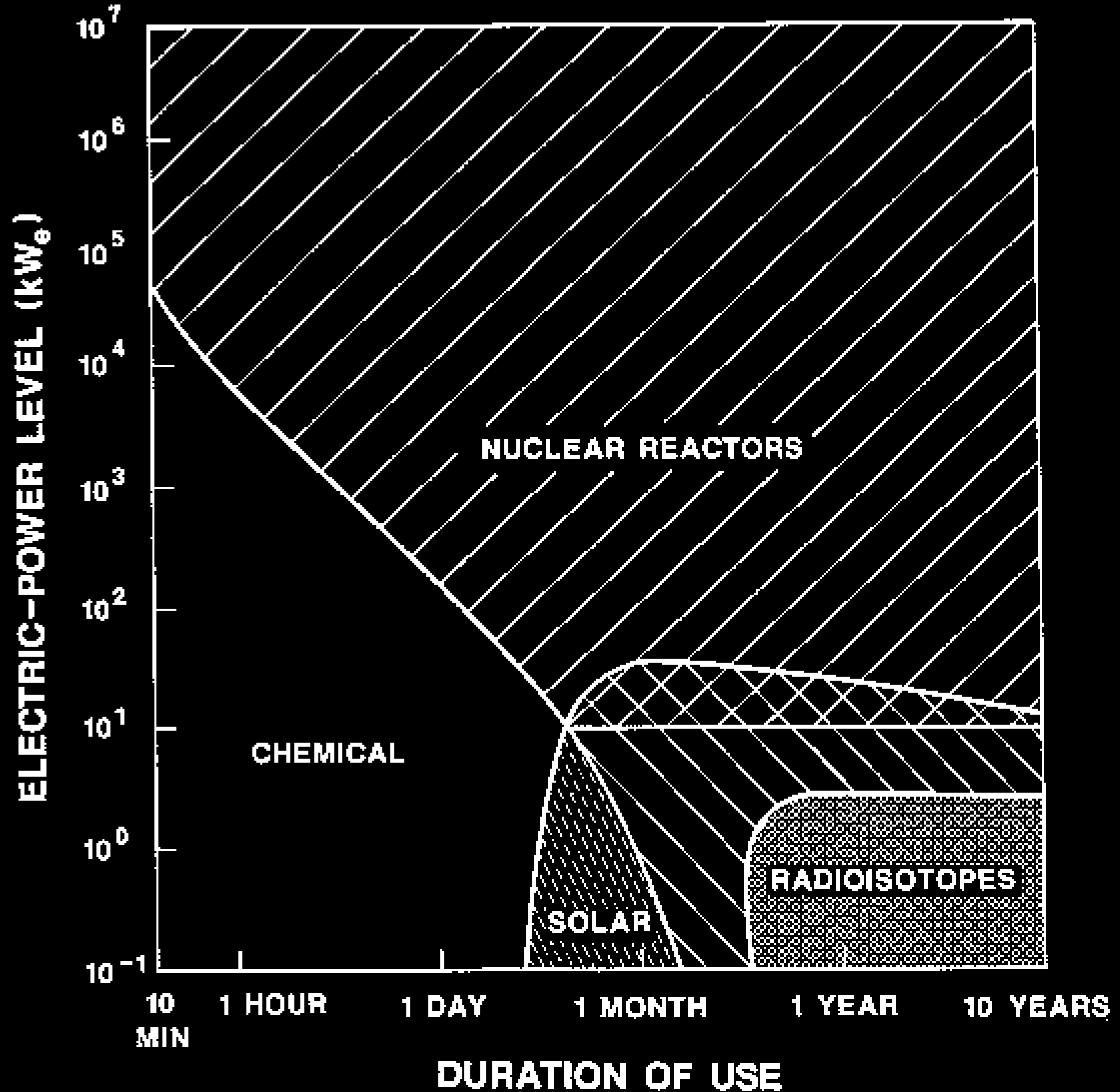
- **INTRODUCTION - The History, Promise & Challenge of Space Nuclear Technology**

- **HISTORICAL OVERVIEW OF U.S. & SOVIET / RUSSIAN SPACE NUCLEAR SYSTEMS**
  - U.S. RTGs, RHUs & Reactors Launched
  - U.S. Reactors Pursued for Space Power & Propulsion
  - Soviet / Russian Use of Space Nuclear Power Systems

- **FORMER & CURRENT/RECENT U.S. SPACE NUCLEAR SYSTEMS & MISSIONS**
  - Current U.S. Space Nuclear Systems
  - *The GPHS-RTG & the Cassini M*ission to Saturn & its Moons
  - *Mars Exploration Rovers A & B, "Spirit" & "Opportunity"* Rover Missions
  - *New Horizons – Pluto,* Pluto Flyby & Kuiper Belt Exploration Mission
  - *Mars Science Laboratory (MSL) "Curiosity"* Rover Mission
  - *Mars-2020 "Perseverance"* Rover Mission (July 2020 launch; Feb 2021 EDL)

- **PLANNED U.S. SPACE NUCLEAR SYSTEMS & FUTURE MISSIONS**
  - The NextGen RTG
  - A Dynamic Radioisotope Power System
  - The Kilopower Reactor Power System
  - Return to the Moon & Fission Surface Power
  - *Dragonfly*: An RTG-powered drone for exploration of Saturn's Titan
  - The *Trident* Mission to Neptune's Triton???
  - The *Interstellar Probe* Mission???
  - Onward to Mars & ??????

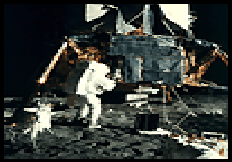
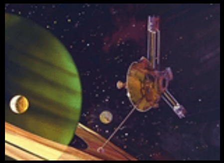
INTRODUCTION: WHY NUCLEAR??

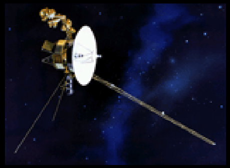


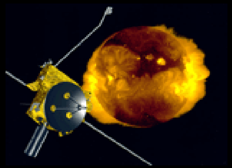
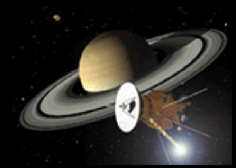
INTRODUCTION

- Nuclear systems have enabled tremendous strides in our country's exploration of space.

- Since 1961, the US has launched forty-eight nuclear power systems & three-hundred radioisotope heater units in support of thirty-three navigational, meteorological, communication, experimental, as well as lunar, solar, Martian, Jovian, Saturnian, and outer solar system exploration missions.



- One mission (*SNAPSHOT* in 1965) involved a small 500W(e) reactor power system (SNAP-10A); the remaining missions were powered by radioisotope thermoelectric generators (RTGs) &/or heated by radioisotope heater units (RHUs).

Space Nuclear Power Systems Launched by the US (1961 – 2020)

MISSION	MISSION TYPE	LAUNCH DATE	POWER SOURCE (#/power)	STATUS
TRANSIT 4A	Navigational	Jun 61	SNAP-3B7 (1/2.7W(e))	Successfully achieved orbit; ops terminated 1966
TRANSIT 4B	Navigational	Nov 61	SNAP-3B8 (1/2.7W(e))	Successfully achieved orbit; ops terminated 1967
TRANSIT 5BN-1	Navigational	Sep 63	SNAP-9A (1/25W(e))	Successfully achieved orbit; ops terminated 1970
TRANSIT 5BN-2	Navigational	Dec 63	SNAP-9A (1/25W(e))	Successfully achieved orbit; ops terminated 1971
TRANSIT 5BN-3	Navigational	Apr 64	SNAP-9A (1/25W(e))	Failed to achieve orbit; SNAP-9A burned up on reentry as then designed/intended
SNAPSHOT	Experimental	Apr 65	SNAP-10A (1/500W(e))	Successfully achieved orbit; S/C voltage regulator failed after 43 days; SNAP-10A reactor shutdown permanently in 3000+ year orbit
NIMBUS B-1	Meteorological	May 68	SNAP-19B2 (2/40W(e) ea)	Vehicle destroyed during launch; SNAP-19B2s retrieved intact; fuel used on later mission
NIMBUS III	Meteorological	Apr 69	SNAP-19B3 (2/40W(e) ea)	Successfully achieved orbit; ops terminated 1979
APOLLO 11	Lunar *exploration*	Jul 69	EASEP RHU (2/15W(t) ea)	Successfully placed on moon, ops terminated 1969
APOLLO 12	Lunar exploration	Nov 69	tSNAP-27 (1/70W(e))	Successfully placed on moon; ops terminated 1980
APOLLO 13	Lunar exploration	Apr 70	SNAP-27 (1/70W(e))	Mission aborted en route to moon; SNAP-27 survived reentry & in 7000+ ft of water in deep ocean
APOLLO 14	Lunar exploration	Jan 71	SNAP-27 (1/70W(e))	Successfully placed on moon; ops terminated 1980
APOLLO 15	Lunar exploration	Jul 71	SNAP-27 (1/70W(e))	Successfully placed on moon; ops terminated 1980
PIONEER 10	Solar system exploration	Mar 72	SNAP-19 (4/40W(e) ea)	Successfully placed on interplanetary trajectory; cks con't
APOLLO 16	Lunar exploration	Mar 72	SNAP-27 (1/70W(e))	Successfully placed on moon; ops terminated 1980
TRANSIT/TRIAD	Navigational	Sep 72	TRANSIT-RTG (1/30W(e))	Successfully achieved orbit; ops terminated 1977
APOLLO 17	Lunar exploration	Dec 72	SNAP-27 (1/70W(e))	Successfully placed on moon; ops terminated 1980
PIONEER 11	Solar system exploration	Apr 73	SNAP-19 (4/40W(E) ea)	Successfully placed on interplanetary trajectory; cks con't
VIKING 1	Mars exploration	Aug 75	SNAP-19 (2/40W(e) ea)	Successfully placed on Mars; ops terminated 1980
VIKING 2	Mars exploration	Sep 75	SNAP-19 (2/40W(e) ea)	Successfully placed on Mars; ops terminated 1980
LES 8	Communications	Mar 76	MHW-RTG (2/150W(e) ea)	Successfully achieved orbit; still operational
LES 9	Communications	Mar 76	MHW-RTG (2/150W(e) ea)	Successfully achieved orbit; still operational
VOYAGER 2	Solar system exploration	Aug 77	MHW-RTG (3/150W(e) ea)	Successfully placed on interplanetary trajectory; cks con't
VOYAGER 1	Solar system exploration	Sep 77	MHW-RTG (3/150W(e) ea)	Successfully placed on interplanetary trajectory; cks con't
GALILEO	Jovian exploration	Oct 89	GPHS-RTG (2/275W(e) ea) LWRHU (120/1W(t) ea)	Successfully placed in orbit around Jupiter; deorbited into atmosphere of Jupiter Sep 2003
ULYSSES	Solar polar exploration	Oct 90	GPHS-RTG (1/275W(e))	Successfully placed in solar polar orbit; ops ended 2009
MARS PATHFINDER	Mars rover demonstration	Dec 96	LWRHU (3/1W(t) ea)	Successfully placed on Mars; rover ceased ops in 1997
CASSINI	Saturnian exploration	Oct 97	GPHS-RTG (3/275W(e) ea) LWRHU (117/1W(t) ea)	Successfully placed in orbit around Saturn; deorbited into Saturn atmosphere Sep 2017
MER-A	Mars rover exploration	Jun 03	LWRHU (8/1W(t) ea)	Successfully placed on Mars; ops terminated 2010
MER-B	Mars rover exploration	Jul 03	LWRHU (8/1W(t) ea)	Successfully placed on Mars; ops ended 2018
NEW HORIZONS	Pluto/Kuiper Belt Exploration	Jan 06	GPHS-RTG (1/275W(e))	Successful Pluto Flyby in 2015; KBO flyby in 2019
MSL	Mars rover exploration	Nov 11	MMRTG (1/110W(e))	Successfully placed on Mars; still operational
Mars-2020	Mars rover exploration	Jul 20	MMRTG (1/110W(e))	Successfully placed on Mars; still operational

4 Accidents/Malfunctions Involving U.S. Space Nuclear Systems

TRANSIT 5BN-3: **US Navy navigational satellite launched 21 Apr 64. Failed to achieve orbit & reentered at ~120km over west Indian Ocean, N of Madagascar. SNAP-9A RTG burned up during reentry—as then designed). Release (17kCi of Pu-238) equivalent to Pu-238 released from all atmospheric weapons testing. As of Nov 70, only 5% of original Pu-238 released from SNAP-9A burnup remained in atmosphere (removal half life ~ 14mo). Using this value indicates that ~0.025 nCi remains in the atmosphere as of May 2021. [Note: ~10kCi still in biosphere]**

SNAPSHOT: **SNAP-10A reactor/electric propulsion experimental mission launched 3 Apr 65. Reactor successfully started & operated for 43days; S/C voltage regulator malfunction caused reactor permanent/irreversible shutdown; reactor in 3000+ year orbit.**

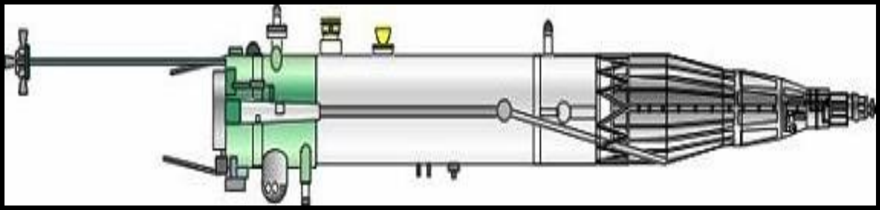
NIMBUS B-1: **Meteorological satellite launched 18 May 68 from WTR. RSO destroyed LV due to errant ascent; all debris fell into Santa Barbara channel. SNAP-19 RTG (34 kCi Pu-238) recovered intact at ~100m depth. No release; fuel used on later mission.**

APOLLO 13: **Manned lunar mission launched 11 Apr 1970. SNAP-27 fuel canister (44.5kCi Pu-238) reentered with LEM, canister survived reentry intact (no release) & rests in Tonga trench.**

Soviet / Russian Use of Space Nuclear Power Systems

- ~33 Russian space reactors launched during the period 1970 ***(KOSMOS 367)*** – 1987 ***(KOSMOS 1900),*** primarily to power Radar Ocean Reconnaissance Satellites (RORSATs), which kept watch over NATO naval activities at sea, especially during US & NATO naval exercises as well as times of global tension
  - 31 were BES-5 'BUK' reactor systems with out-of-core thermoelectrics at ~3kW(e) for operational RORSAT missions

  - 2 were TOPAZ-I 'TOPOL' in-core thermionic reactor systems at ~5kW(e) for ***KOSMOS 1818*** (Feb 1987) & ***KOSMOS 1867*** (Jul 87) experimental reactor and electric propulsion system testing

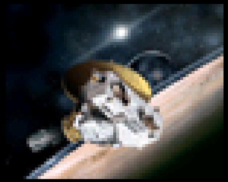


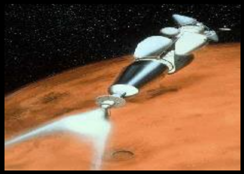
- Russian TOPAZ-II 'ENISEY' ~10kW(e) in-core thermionic space reactor prototype never launched/flown
- Only a few (~4) Russian RTGs (Po-210 & Pu-238 fueled) launched for lunar & solar system exploration

8 Accidents/Malfunctions Involving USSR/Russian Space Nuclear Power Systems

KOSMOS ?:	RORSAT launch attempted 25 Jan 69. Believed to be a launch failure on/at the pad.
KOSMOS 300:	Lunikhod S/C launched 23 Sep 69. Failed to achieve escape trajectory. S/C w/small Po-210 source reentered atmosphere and burned up on 27 Sep 69.
KOSMOS 305:	Lunikhod S/C launched 22 Oct 69. Failed to achieve escape trajectory. S/C w/small Po-210 source reentered atmosphere and burned up on 24 Oct 69.
KOSMOS ?:	RORSAT launched 25 Apr 73. Believed to fail to achieve orbit; falling into Pacific Ocean N of Japan.
KOSMOS 954:	RORSAT launched Sep 77. Reactor successfully separated from S/C following end of operations, but did NOT boost to a higher, long-lived orbit. Reactor reentered over Pacific Ocean and crashed near Great Slave Lake in northern Canada on 24 Jan 78. ~65kg of debris, radioactive objects & fuel recovered.
KOSMOS 1402:	RORSAT launched 30 Aug 82. Anomaly indicated; S/C intentionally separated into 3 parts. Reactor is believed to have reentered & fallen into the south Atlantic ~1600km E of Brazil on 7 Feb 83. Low levels of fission products detected in air from reentry.
KOSMOS 1900:	RORSAT launched 12 Dec 87. On 13 May 88, USSR reported that contact was lost in Apr 88 & reactor could not be boosted via ground signal to higher orbit. On 30 Sep 88, reactor automatically separated and boosted to higher (~720km) orbit.
MARS 96:	Mars explorer launched 16 Nov 96. Failed to achieve escape trajectory. S/C w/small Pu-238 fueled RTG reentered on 17 Nov 96 and fell near the coast of Chile/Bolivia. RTG designed to survive reentry; no radioactivity detected from reentry or impact.

U.S. SPACE NUCLEAR SYSTEMS: THE CHALLENGE




- While space nuclear systems have contributed greatly to our knowledge & understanding of Earth & our solar system, and offer promise for even greater advances in the future, their use poses unique safety challenges.
- These safety challenges, or issues, must be recognized and addressed in the design, deployment and use of each space nuclear system.
- In doing so, the system's planned & potential uses must be considered, and normal, off-normal, as well as potential, credible accident situations must be taken into account.
- Extensive safety analyses, buttressed by safety testing, must be conducted to determine the level & adequacy of safety built into the system for its intended use.
- Safety analyses also must establish the adequacy of safety for system ground testing prior to launch.
- Lastly, the risk for each US nuclear-powered space mission must be assessed so an informed launch decision can be made at the highest levels of our government, based on risk – benefit considerations.

Mandated & External Protocols & Processes For Space Nuclear Systems / Missions

- **UN Principles, RE: Nuclear Power Sources in Space**
  - Notification
  - Liability
  - Design & operational guidelines

- **U.S. National Environmental Policy Act (NEPA) Process**
  - *Federal Register* notice must be issued
  - EA or EIS w/public involvement required
  - Record of Decision required for action to proceed/occur

- **U.S. Safety Review & Launch Approval Process**
  - INSRB (DoD, DOE, NASA, EPA , DOT & NRC) provides oversight of safety & launch approval
  - SAR prepared by the mission-sponsoring agency
  - INSRB reviews SAR & conducts independent analysis/evaluation, as needed
  - INSRB prepares SER for mission-sponsoring agency, stakeholder agencies & decision-maker
  - Mission-sponsoring agency decides if it will request launch approval
  - Informed launch decision based on consideration of risks-benefits; SAR & SER are key inputs

BUILDING SAFETY IN AT THE OUTSET

Safety Issues & Strategies for Space Nuclear Systems

Space radioisotope systems:

- Safety issues:
  - Potential release of the radioactive fuel material into the Earth's biosphere as a result of a postulated pre-launch, launch, ascent, or reentry accident; and
  - Potential loss of physical security or positive control/cognizance over the system and its SNM.
- Safety strategies:
  - Design & build the system to be robust, with multiple containment barriers that are rugged—to prevent fuel release under normal, off-normal & credible accident situations; and
  - Take appropriate measures & incorporate special features into the design—to prevent sabotage & terrorism against, as well as theft, loss & diversion of the system & its SNM prior to achieving the planned orbit/trajectory in space.

Space reactor systems (for in-space power & propulsion):

- Safety issues (more complex than those for space radioisotope systems):
  - Potential inadvertent criticality as a result of a pre-launch, launch, ascent, or reentry accident prior to achieving the planned startup/operational orbit in space;
  - Potential reentry of a radioactively "hot" reactor into the Earth's atmosphere;
  - Potential release of fission & activation products, generated during reactor operation in space, into the Earth's biosphere; and
  - Potential loss of physical security or positive control/cognizance over the system and its SNM

ASSURING ADEQUATE SAFETY BY ANALYSIS & TESTING

- Hardware can be exposed to a number of threat environments – sequentially
- Difficult, if not impossible, to test all credible sequences of environments
- Testing
  - Extremely expensive & time consuming for nuclear hardware
  - Must be used sparingly/judiciously
    - Obtain materials property data
    - Verify response(s) of hardware (limited)
    - Benchmark analysis codes -- so that codes can be used to predict hardware response(s)
- Thus, benchmarked analysis, must be relied upon to project responses
- Analyses (very substantial in breadth & depth) required for:
  - NEPA compliance, i.e., EA/EIS
  - Ground test authorization
  - Launch approval (SARs & SER)

U.S. SPACE NUCLEAR SYSTEMS LAUNCHED

RTGs

Designation	W(e)	1st Use	Missions
SNAP-3	2.7	1961	*TRANSIT 4A &4B*
SNAP-9	25	1963	*TRANSIT 5BN-1,-2,-3*
TRANSIT-RTG	30	1972	*TRANSIT*
SNAP-19	40	1968	*NIMBUS B-1 & III, Pioneer 10 & 11, and Viking 1 & 2*
SNAP-27	70	1969	*Apollo 12 - 17*
Multi-Hundred Watt RTG (MHW-RTG)	150	1976	*LES 8 & 9 Voyager 1 & 2*
General Purpose Heat Source RTG (GPHS-RTG)	275	1989	*Galileo, Ulysses, Cassini & New Horizons*
Multi-Mission RTG (MMRTG)	110	2011	*MSL, Mars-2020*

RHUs

Designation	W(t)	1st Use	Missions
Light Weight Radioisotope Heater Unit (LWRHU)	1	1989	*Galileo, Ulysses, Mars Pathfinder, Cassini, and MER A & B*
RHU – Early Apollo Science Experiment Package	15	1969	*Apollo 11*

Reactors

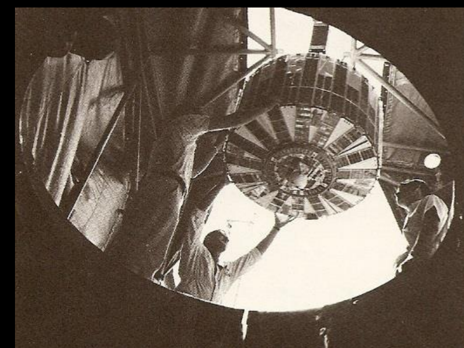
Designation	W(e)	1st Use	Missions
SNAP-10A	500	1965	*SNAPSHOT*

TRANSIT 4A, 4B, 5BN-1, 5BN-2, 5BN-3

U.S. Navy Navigational Satellites

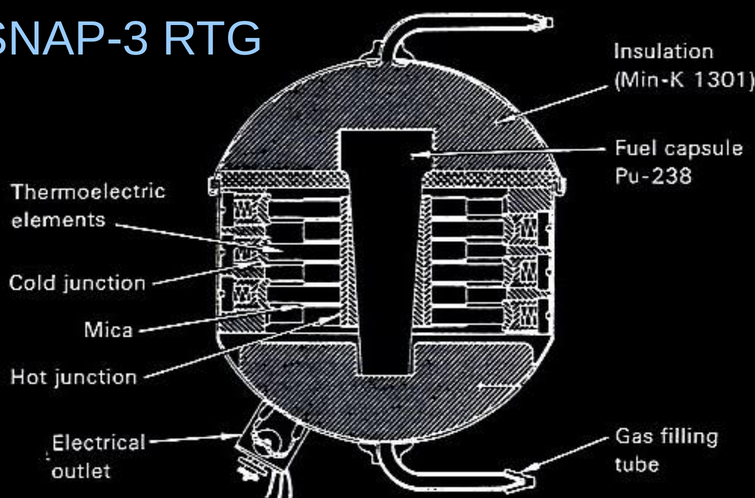
[2.7W(e) SNAP-3, 25W(e) SNAP-9 (1 each)]

SNAP-3 RTG

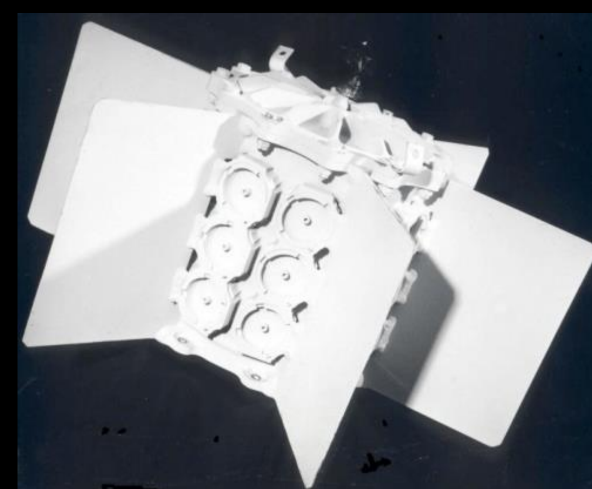


SNAP-3 & 9 RTGs

SNAP-3 RTG



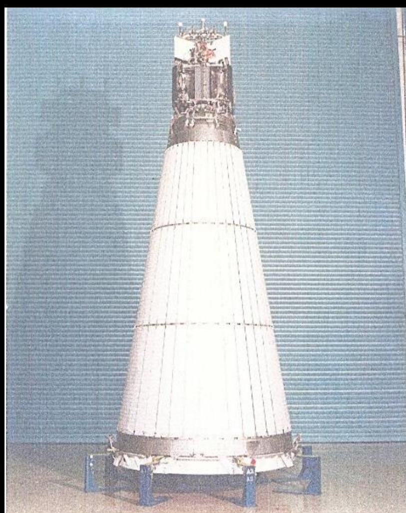
SNAP-9 RTG

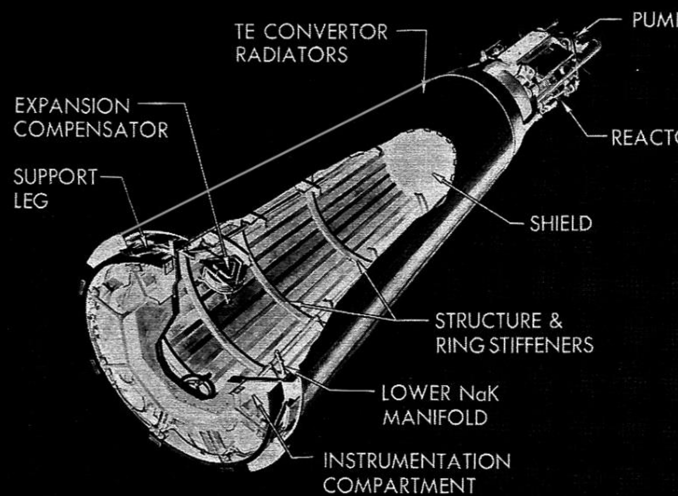


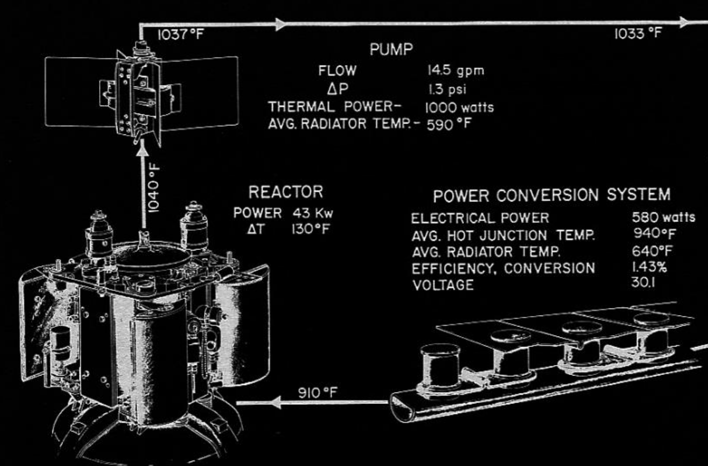
SNAPSHOT

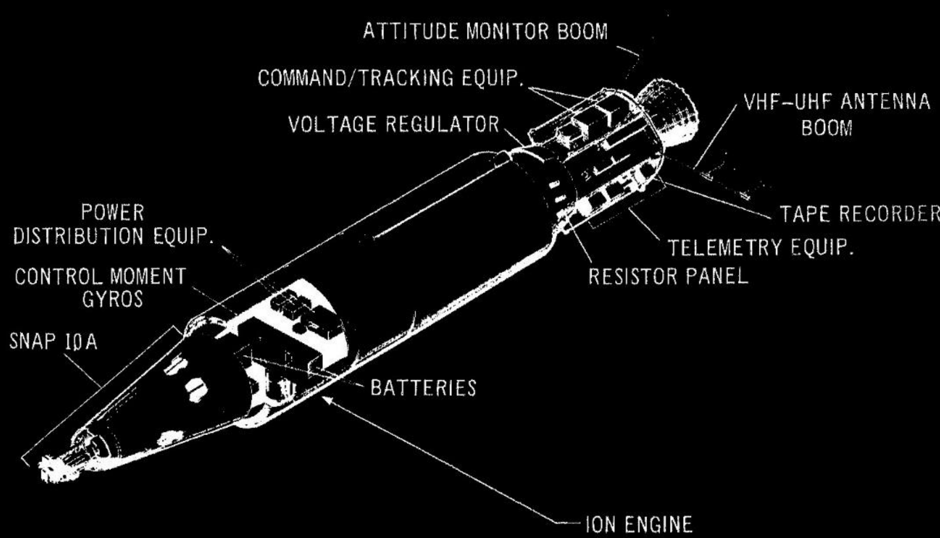
U.S. Air Force SNAP-10A Reactor & Ion Propulsion Technology Demonstration

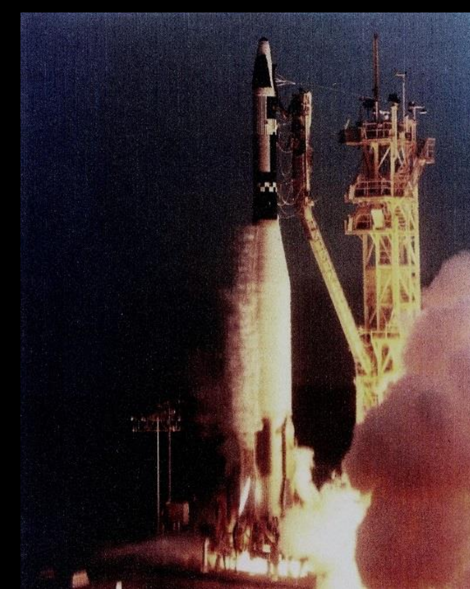
500W(e) SNAP-10A Reactor Power System (1 each)







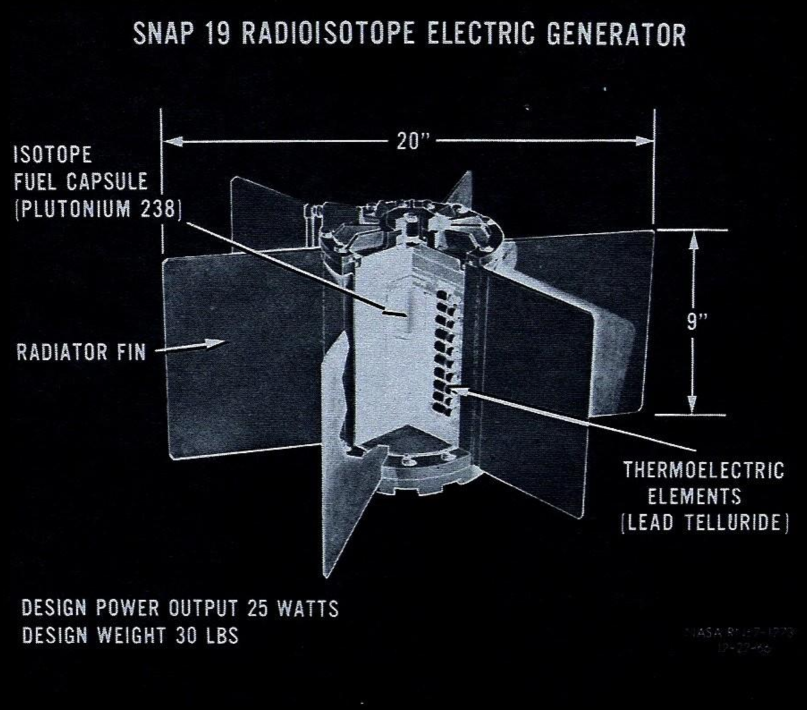




NIMBUS B-1 & III

NOAA Meteorological Satellites

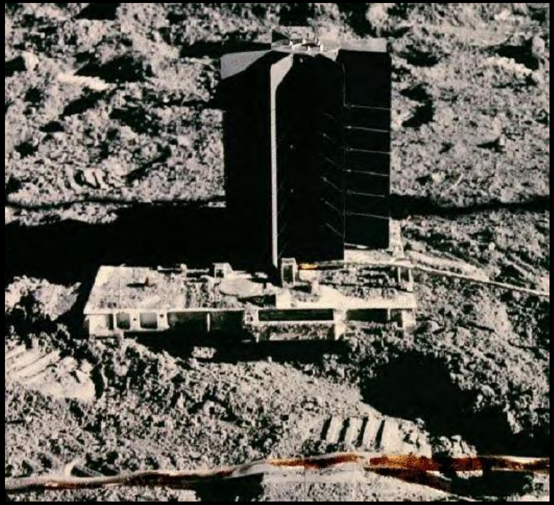
40W(e) SNAP-19 RTGs (2 each)

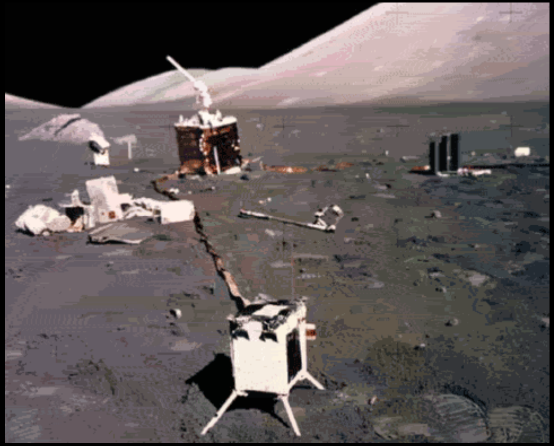


APOLLO 12, 13, 14, 15, 16 & 17

NASA Manned Missions to the Moon

70W(e) SNAP-27 RTGs (1 each); Apollo 11 only: 2, 15W(t) RHUs

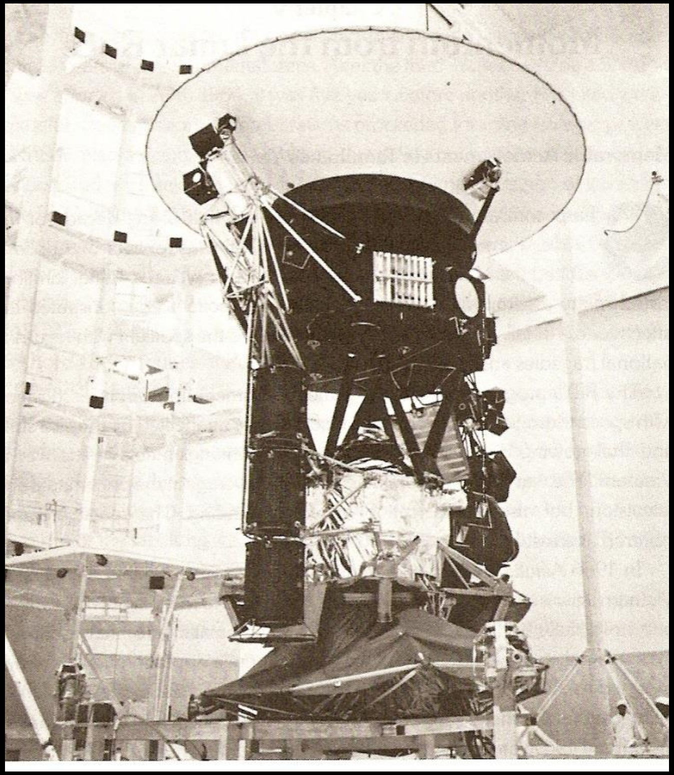


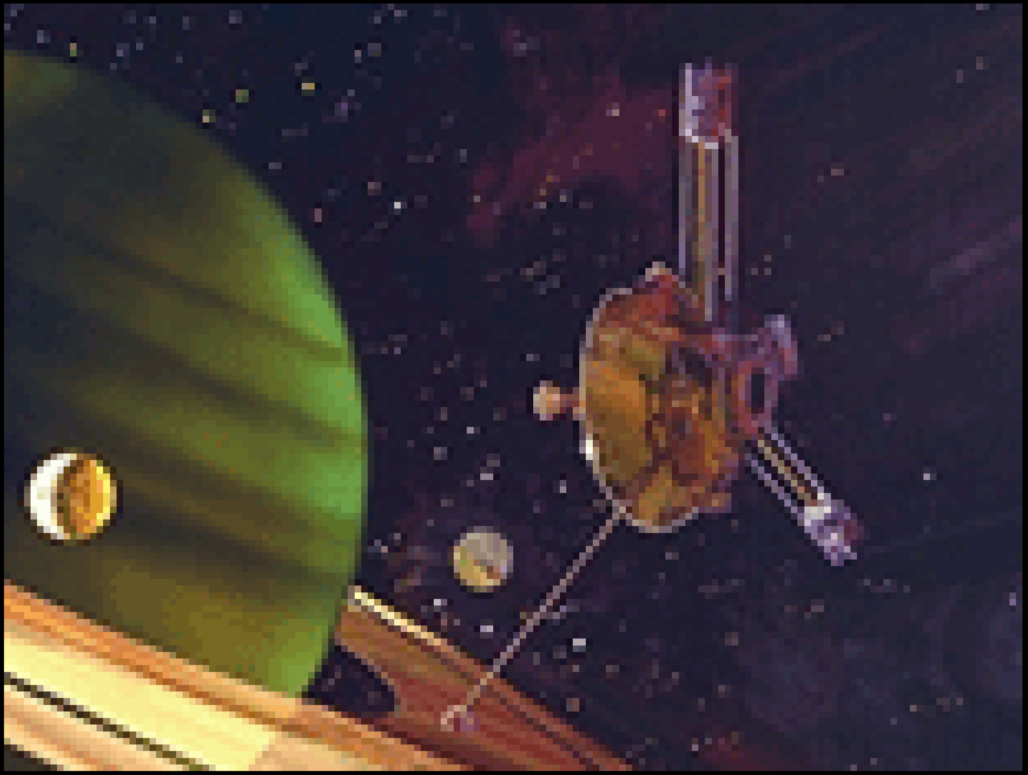


PIONEER 10 & 11

NASA Outer Solar System Exploration

40W(e) SNAP-19 RTGs (4 each)





VIKING 1 & 2

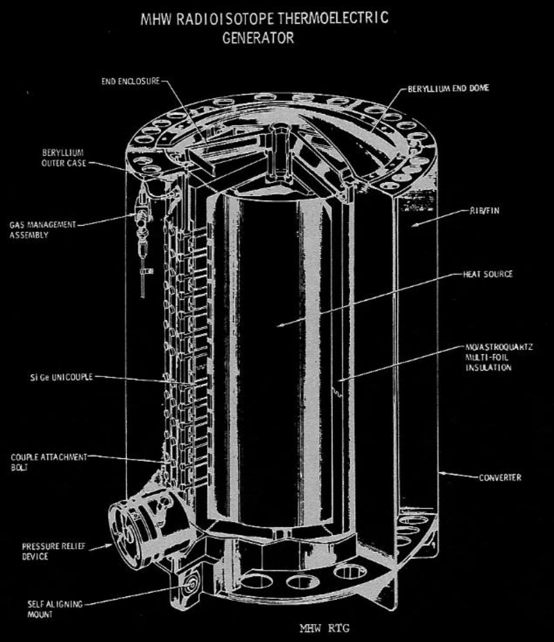
NASA Mission to Mars

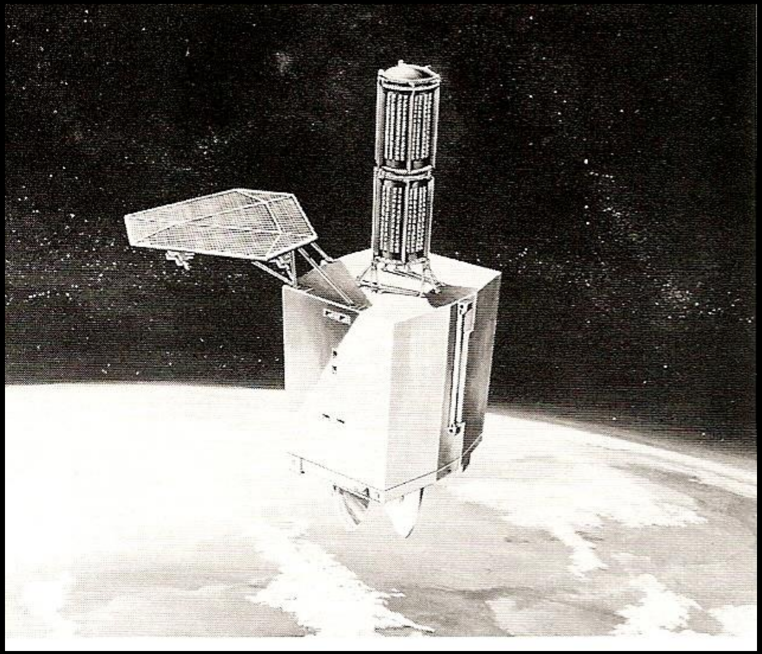
40W(e) SNAP-19 RTGs (2 each)

LINCOLN EXPERIMENTAL SATELLITES 8 & 9

U.S. Air Force Communication Tech Demonstrations

150W(e) MHW-RTGs (2 each)

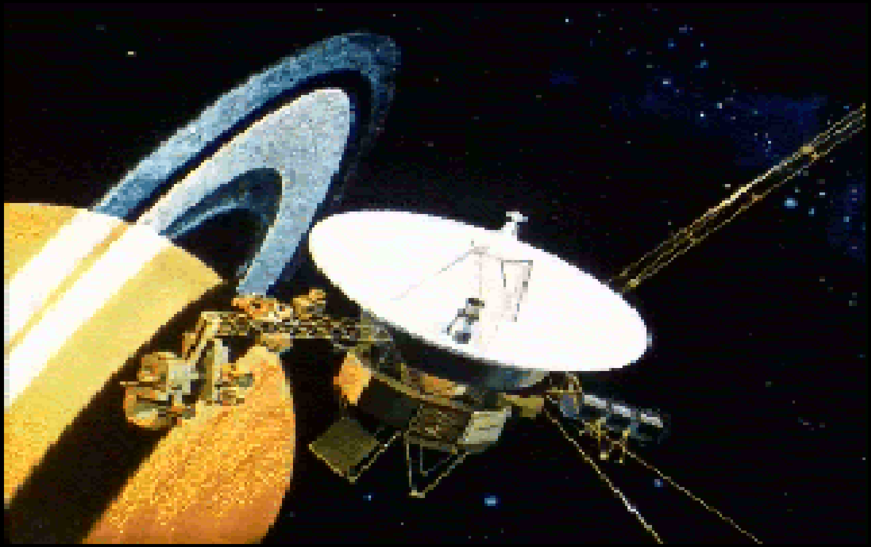




VOYAGER 1 & 2

NASA Outer Solar System Exploration

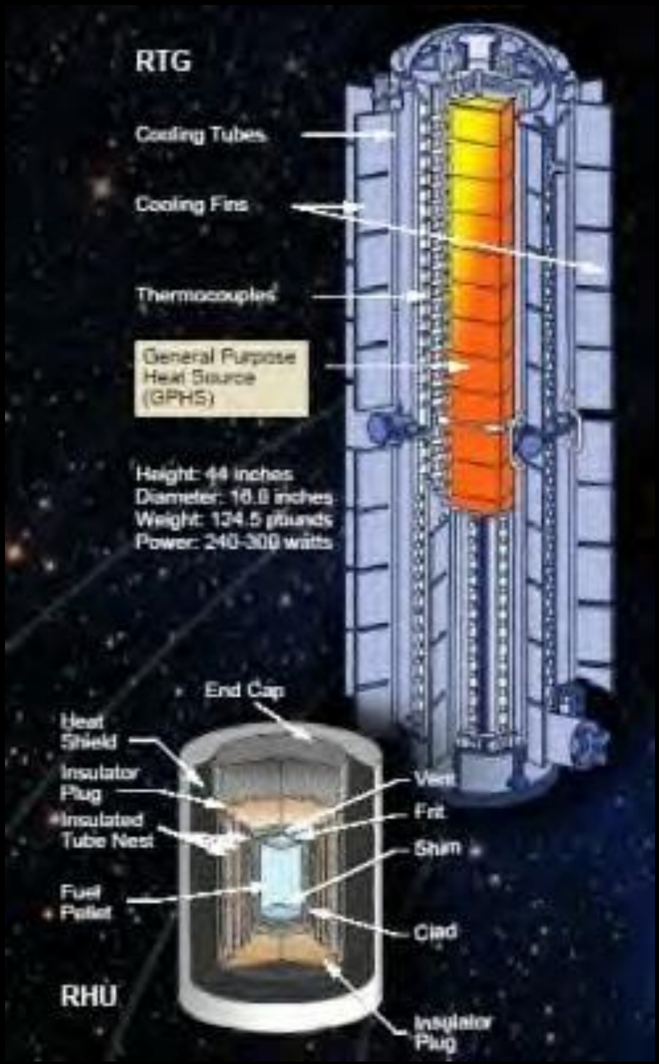
150W(e) MHW-RTGs (3 each)

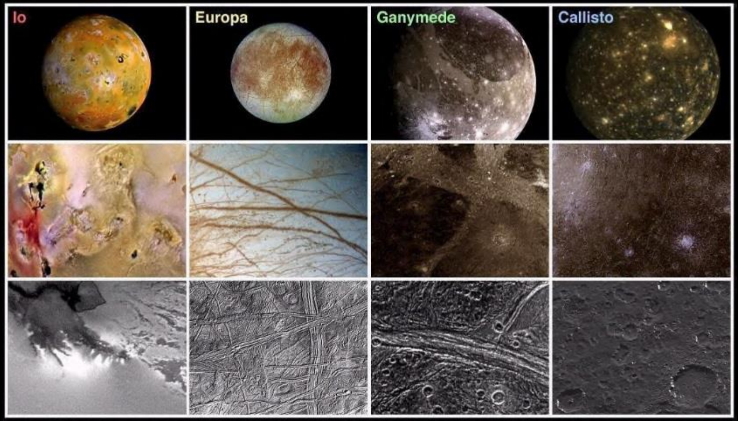


GALILEO

NASA/ESA Mission to Study Jupiter & its Moons

275W(e) GPHS-RTGs (2 each) & 1W(t) LWRHUs (120 each)

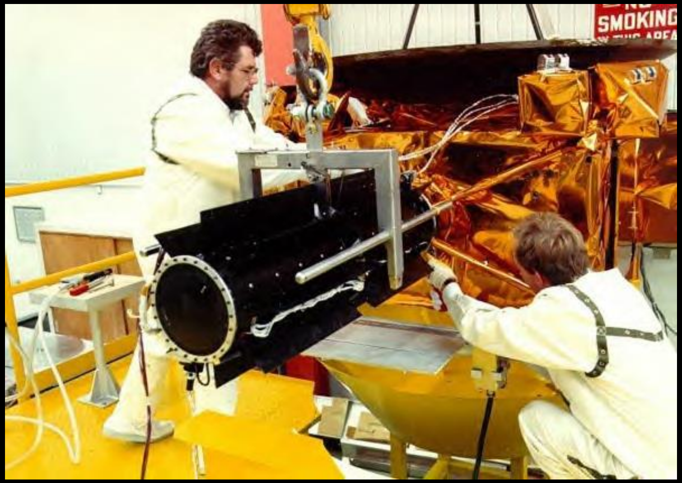


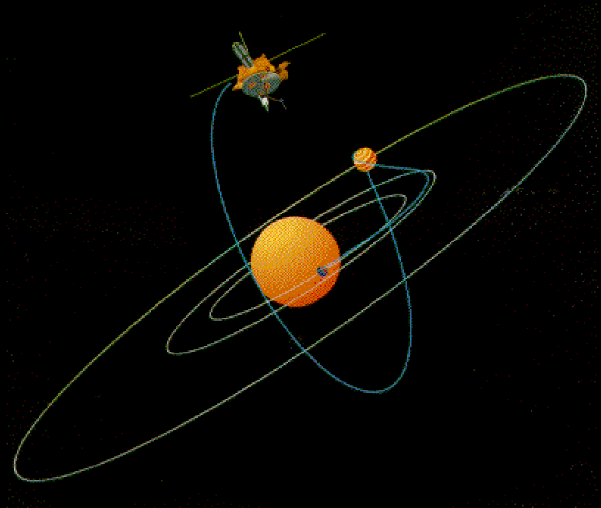


ULYSSES

NASA/ESA Mission to Study the Polar Regions of the Sun

275W(e) GPHS-RTG (1 each)

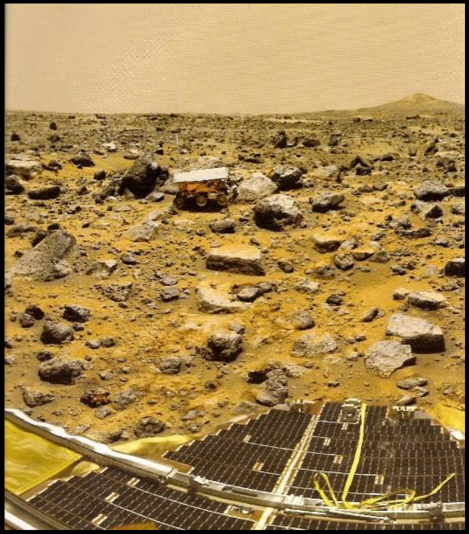


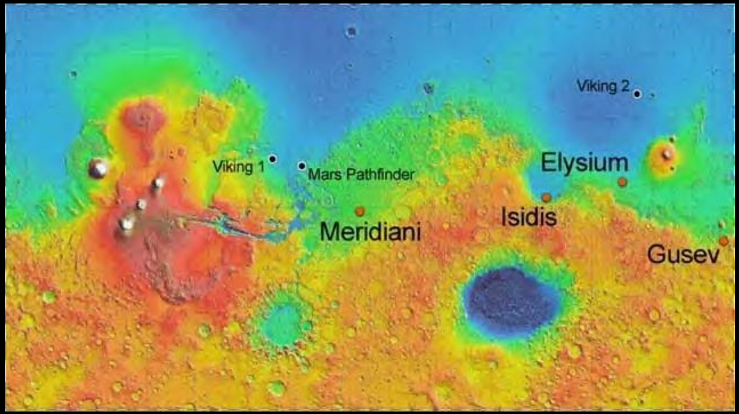


MARS PATHFINDER

NASA Robotic Tech Demonstration at Mars

1W(t) LWRHUs (3 each)

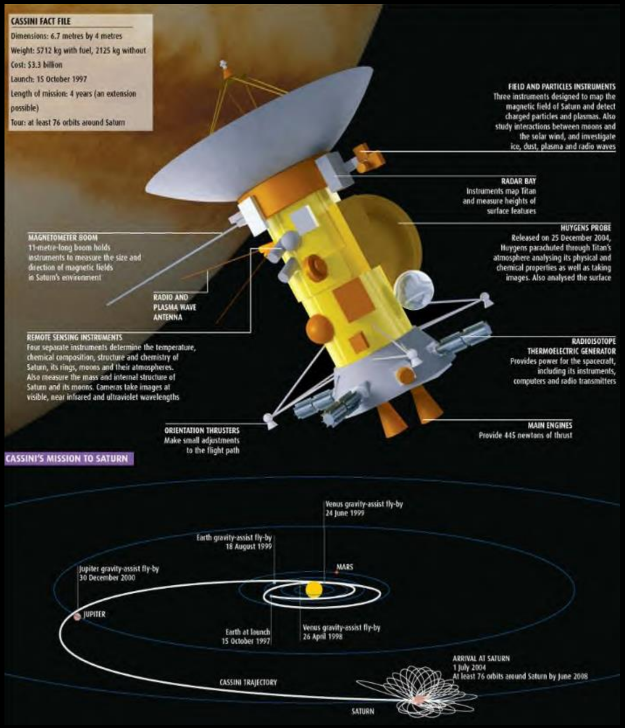



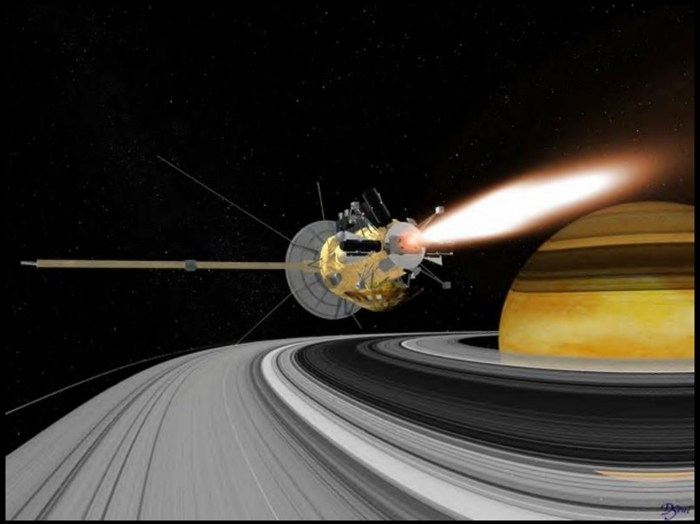


CASSINI

NASA/ESA Mission to Study Saturn & its Moons

275W(e) GPHS-RTGs (3 each) & 1W(t) LWRHUs (117 each)

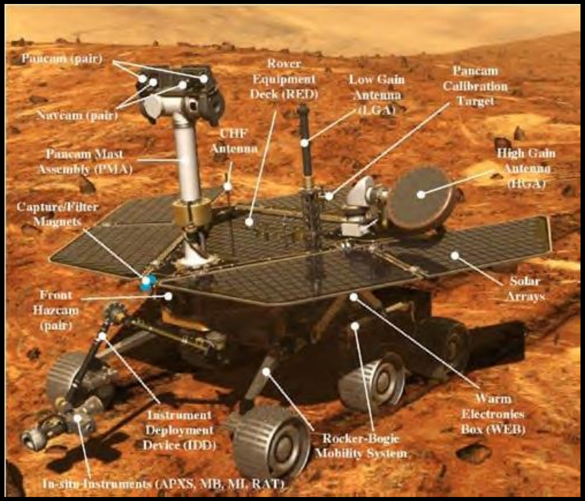


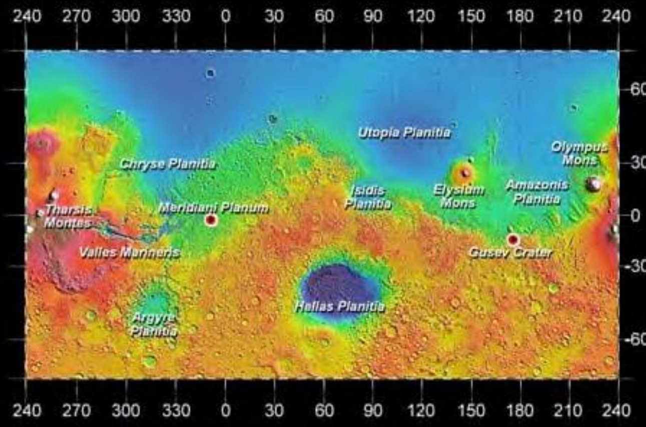


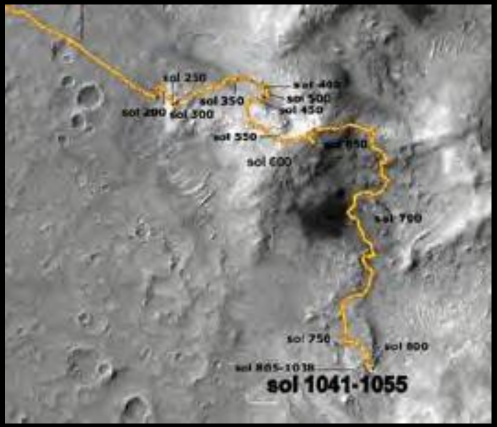
MARS EXPLORATION ROVERS A & B

NASA Robotic Exploration of Mars

1W(t) LWRHUs (8 each)



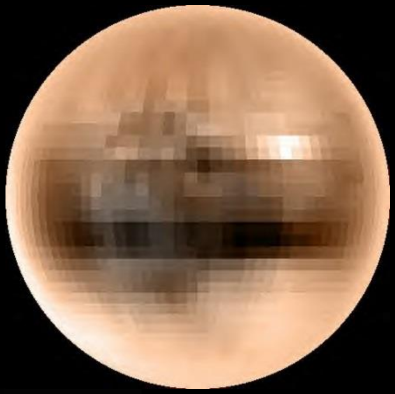


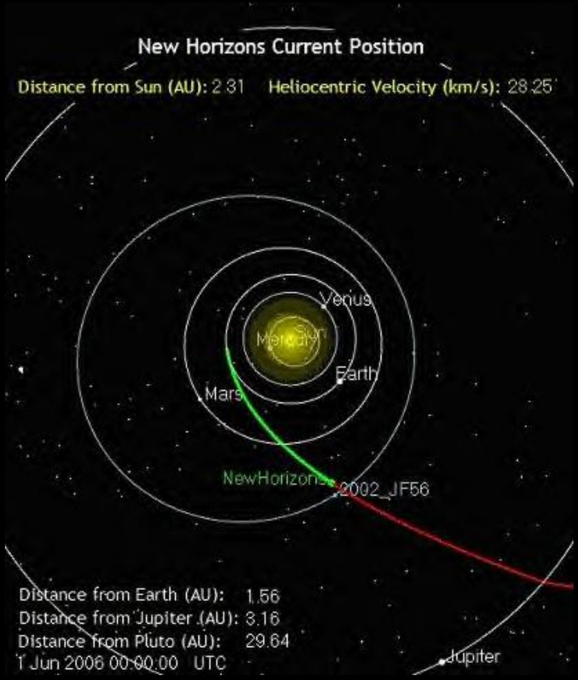


NEW HORIZONS – PLUTO

NASA Pluto Flyby & Kuiper Belt Encounters

~200W(e) GPHS-RTG (1 each)





PAST U.S. SPACE REACTOR SYSTEMS

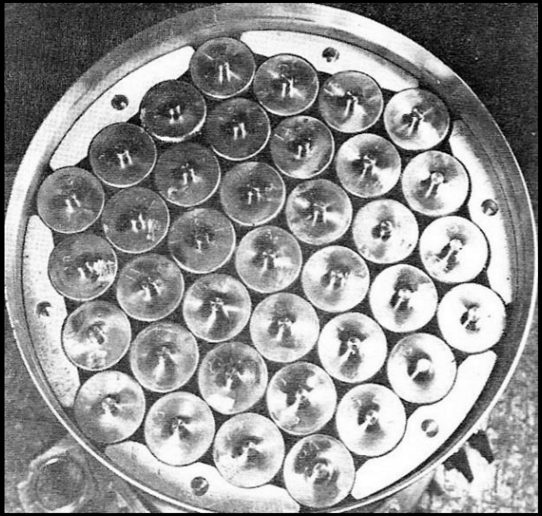
SNAP Space Power Reactors

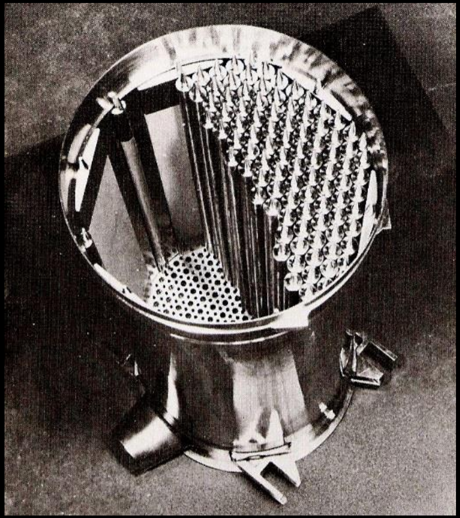
	SNAP 10A	SNAP 2	NASA SNAP 8	SPUR SNAP 50
Power (kwe)	0.5	5	35 to 50	350
Reactor Power (kwt)	30	55	600	2500
Efficiency (%)	1.6	9	8	14
Reactor Outlet Temperature (°F)	1000	1200	1300	+2000
Reactor	$U\text{-}ZrH_x$ Thermal	$U\text{-}ZrH_x$ Thermal	$U\text{-}ZrH_x$ Thermal	UC Fast
Primary Coolant	NaK-78	NaK-78	NaK-78	Lithium
Power Conversion	Ge-Si Thermoelectric	Hg Rankine	Hg Rankine	K Rankine
Boiling Temperature (°F)	-	930	1070	-
Turbine Inlet Temperature (°F)	-	1150	1250	1950
Condensing Temperature (°F)	-	600	700	1300 to 1400
Hot Junction Temperature (°F)	930	-	-	-
Cold Junction Temperature (°F)	615	-	-	-
Radiator Temperature (°F)	615	600	580	1300 to 1400
Radiator Area (ft^2)	62.5	120	1800	700
(ft^2/kwe)	125	40	45	2
System Unshielded Weight (lb)	650	1200	10,000	6000 (EST)
(lb/kwe)	1300	240	300	10 to 20
Available	1965		1972	
Development Agency	AEC	AEC	AEC/NASA	AEC/AF
Flight Test Agency	AEC(AF)	*	*	*
System Contractor	Atomics International	Atomics International	Aerojet General	Pratt & Whitney
Power Conversion Contractor	Radio Corp of America	Thompson Ramo Wooldridge	Aerojet General	AiResearch
Reactor Contractor	Atomics International	Atomics International	Atomics International	Pratt & Whitney
Flight Test Contractor	Lockheed			
Status	Complete	Cancelled	Continuing	Cancelled

*Flight Test Plans Undefined.

SNAP SPACE REACTORS

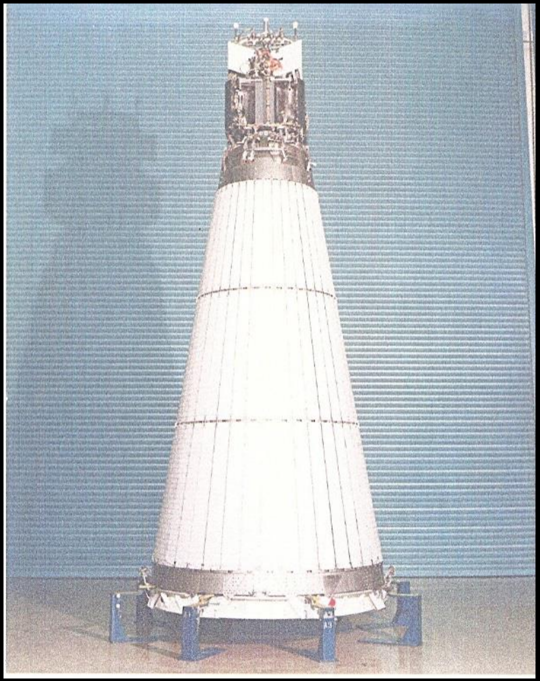
SNAP-10A/-2
Reactor Core

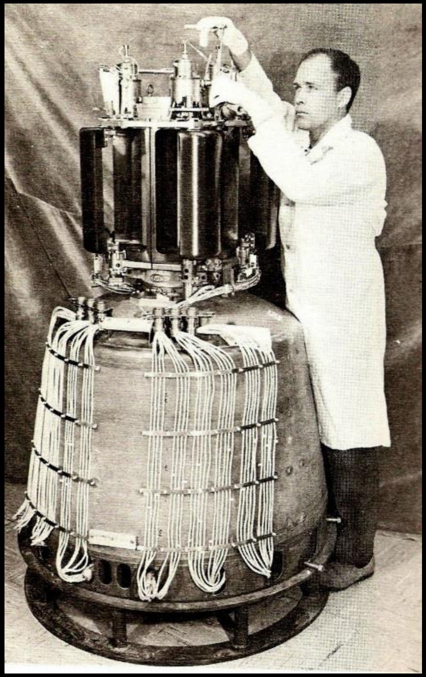




SNAP-8
Reactor Core

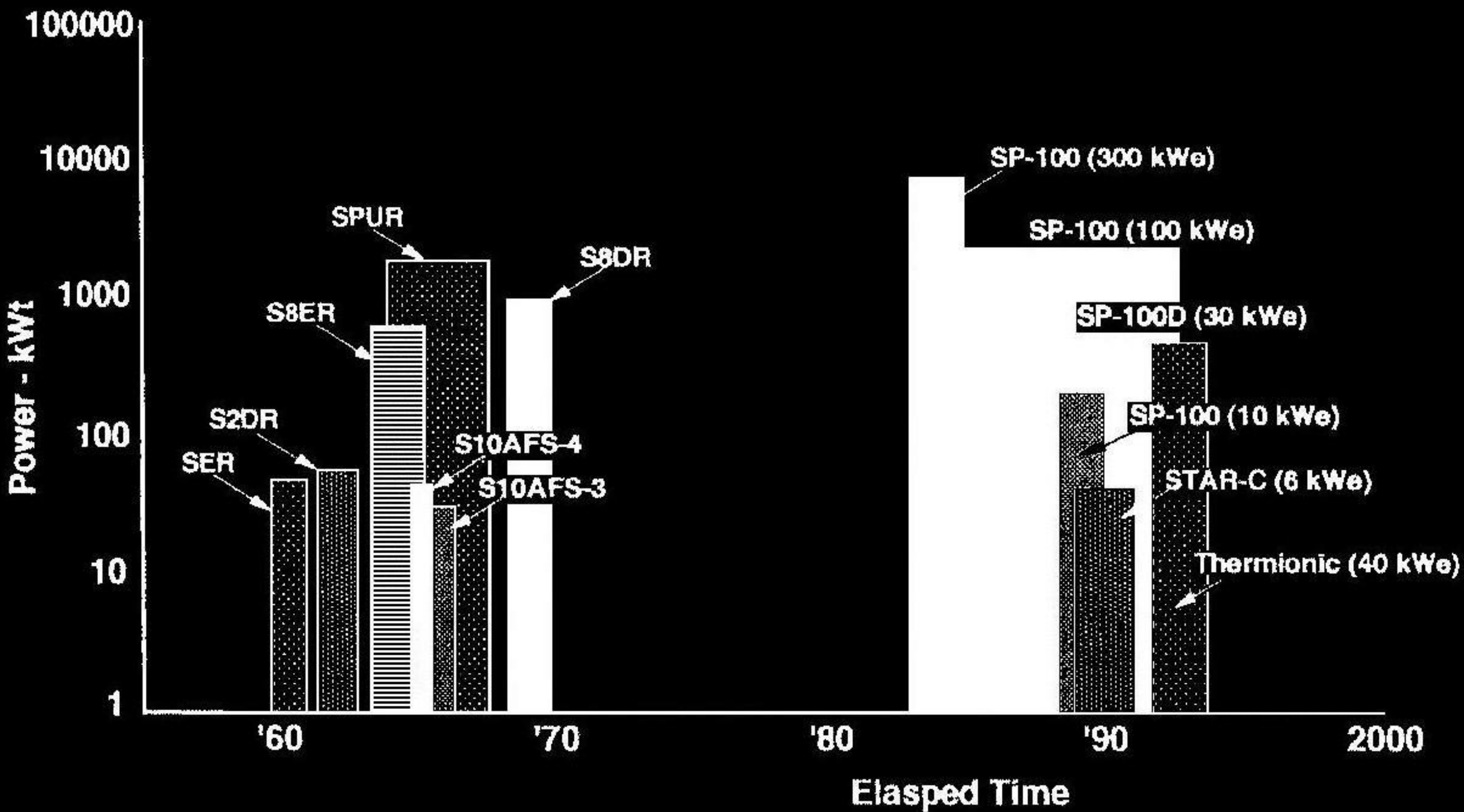
SNAP-10A
Power Sys





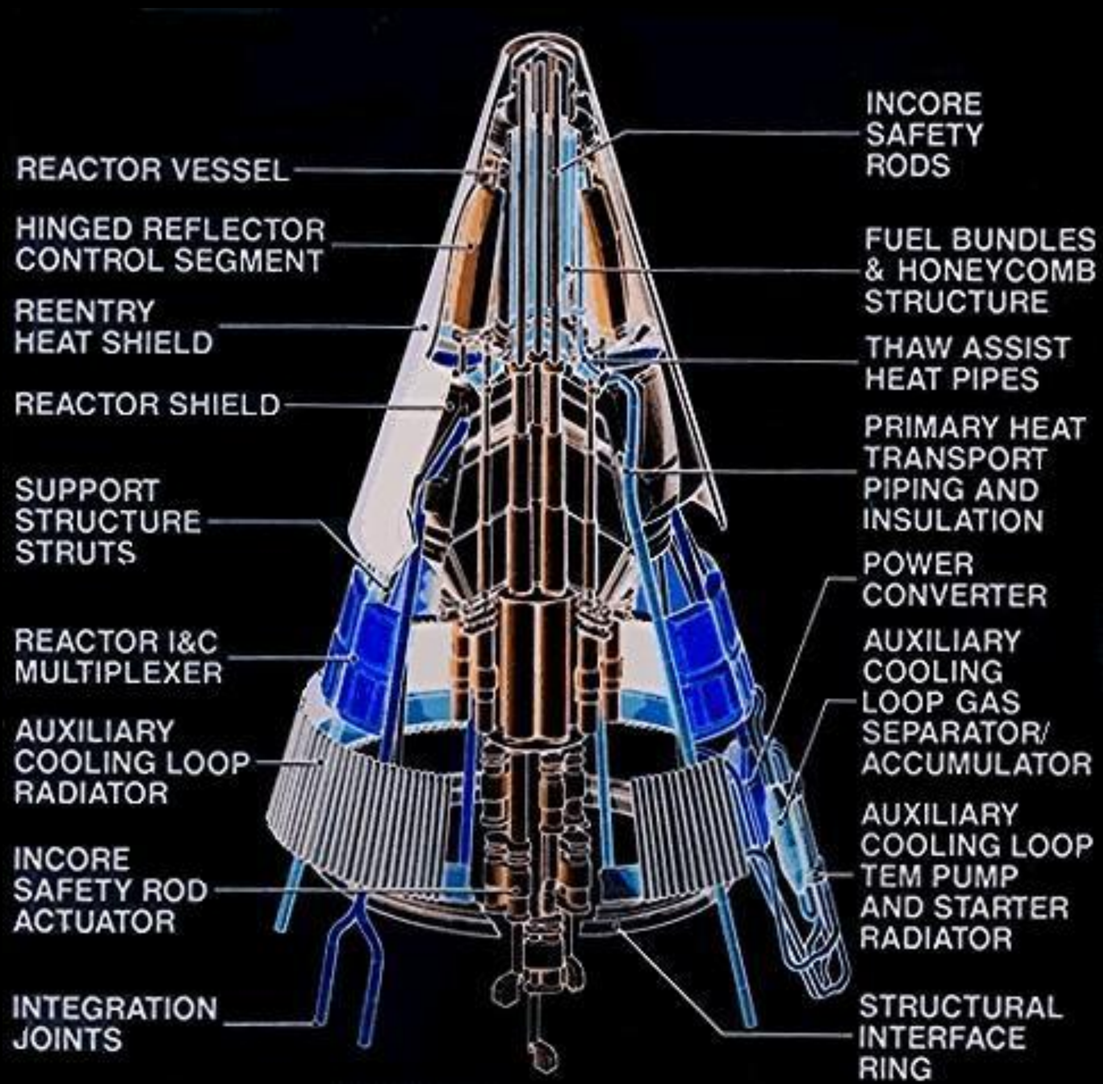
SNAP-8 Reactor
And Shield Assy

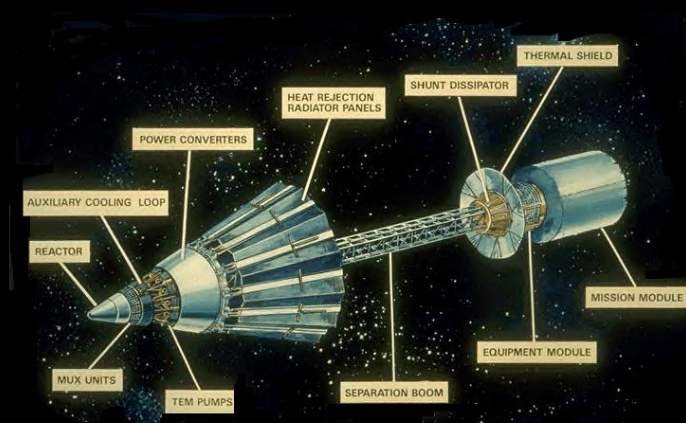
U.S. SPACE REACTORS PURSUED FOR POWER & ELECTRIC PROPULSION



PAST U.S. SPACE REACTOR SYSTEMS

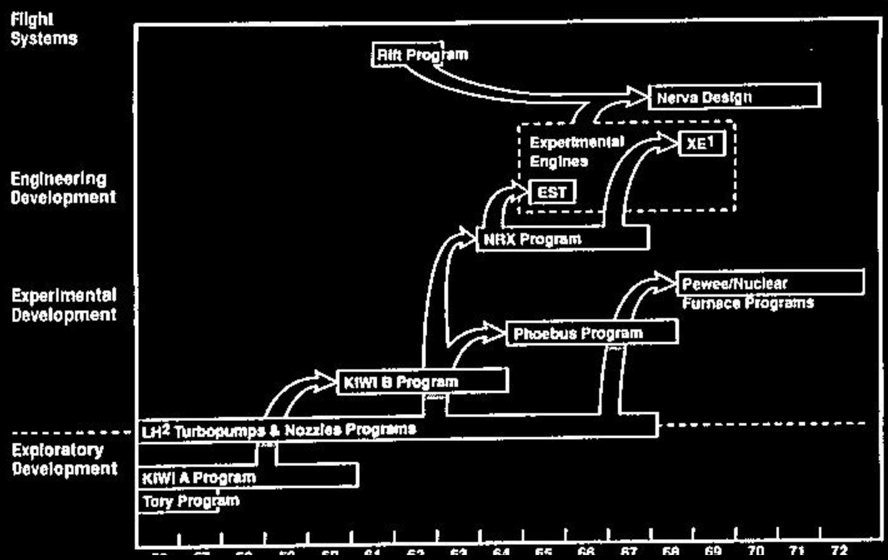
SP-100 Space Reactor Power System Development

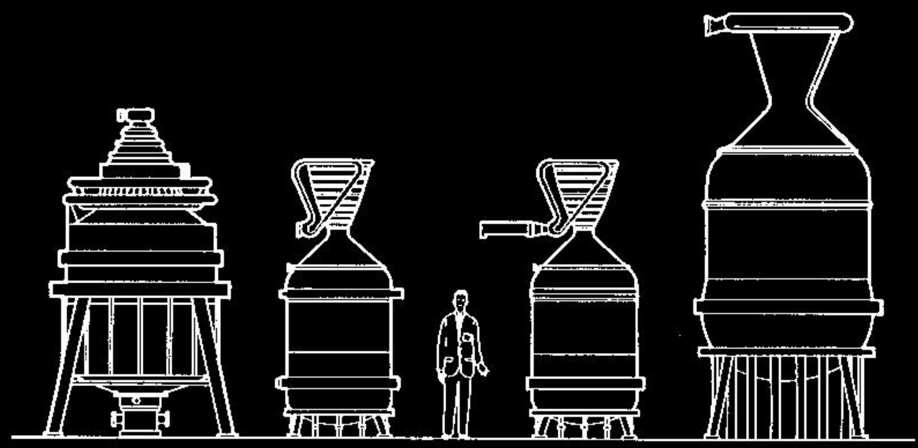




PAST U.S. SPACE NUCLEAR SYSTEMS

Rover / NERVA Space Reactors for Nuclear Thermal Propulsion





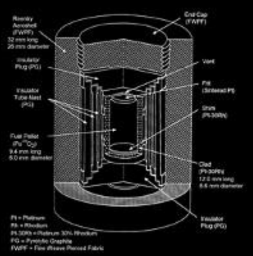
PAST U.S. SPACE NUCLEAR SYSTEMS

Rover / NERVA Space Reactors for Nuclear Thermal Propulsion

CURRENT & RELATIVELY RECENT U.S. SPACE NUCLEAR SYSTEMS & MISSIONS

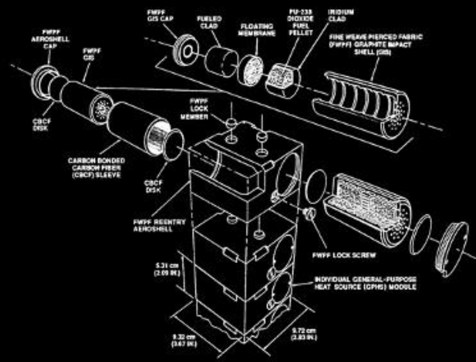
U.S. Space Nuclear Systems, 1986 - Present

1 W(t) LightWeight Radioisotope Heater Unit (LWRHU)



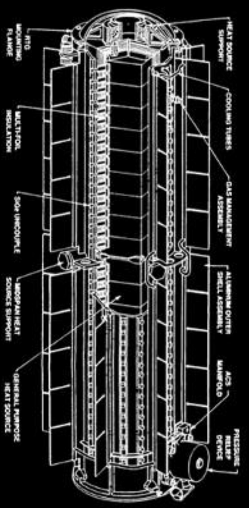
1W(t); 40g
~1in x 1.25in
0.37in x 0.25in fuel pellet
clad w/Pt-30Rh
2.7g Pu-238 oxide fuel;
~30Ci

250 W(t) General Purpose Heat Source (GPHS Module)



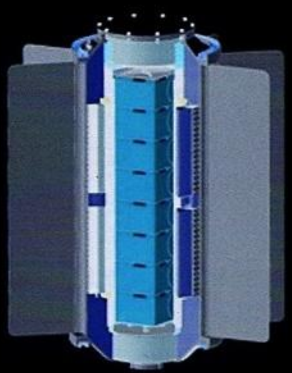
~4in x 4in x 2in aeroshell of
FWPF w/2 FWPF GISs
2FCs/GIS
FC: 1.1in x 1.1in fuel pellet
clad w/DOP-26 Ir alloy
~153g Pu-238 Oxide/FC
~612g Pu-238 Oxide/Module
~1860Ci/FC; ~7440Ci/Module

300 W(e) GPHS-Radioisotope Thermoelectric Generator



300 W(e); 56kg
~3.8ft x 1.4ft
18 GPHS Modules
~11kg Pu-238; ~134kCi

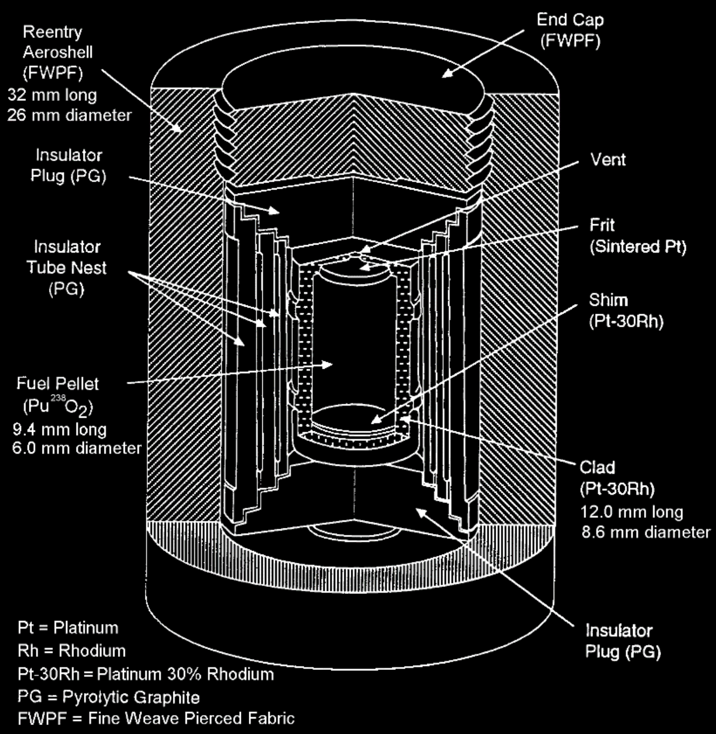
110 W(e) Multi-Mission Radioisotope Thermoelectric Generator



MMRTG Cross Section

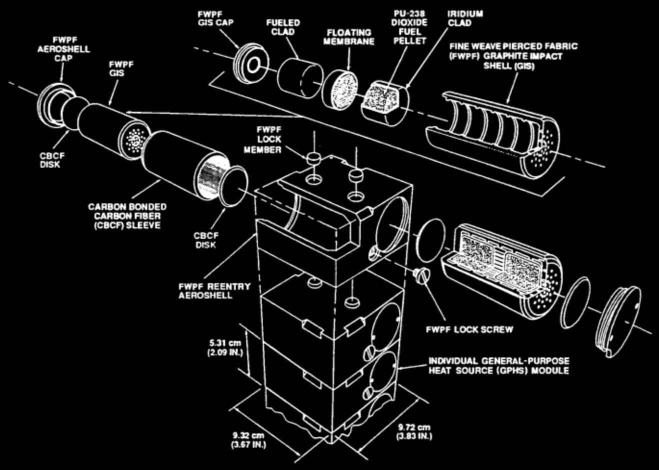
110 W(e); 33kg
~1.6ft x 1.4ft
8 GPHS Modules
~4.8kg Pu-238; ~58kCi

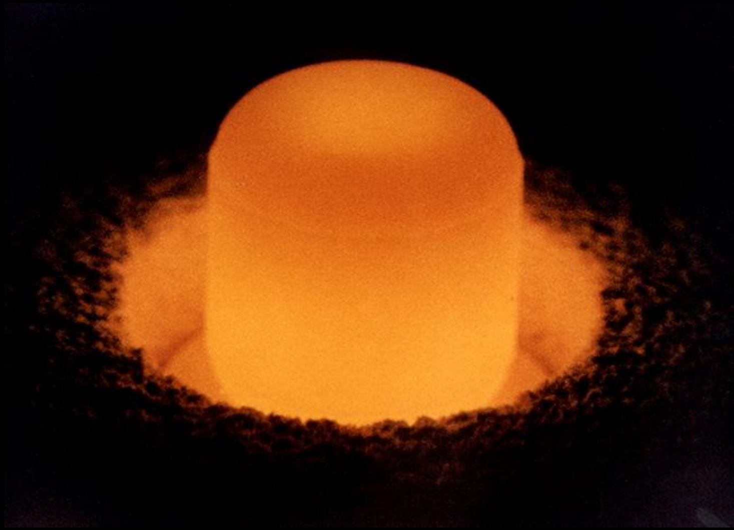
1 W(t) LWRHU



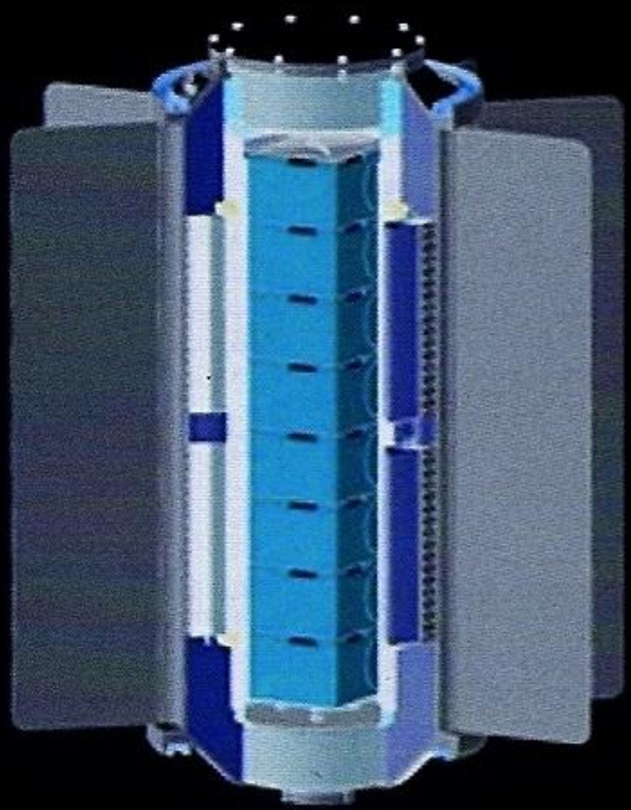
Reentry Aeroshell (FWPF) 32 mm long 26 mm diameter
End Cap (FWPF)
Insulator Plug (PG)
Vent
Frit (Sintered Pt)
Insulator Tube Nest (PG)
Shim (Pt-30Rh)
Fuel Pellet ($Pu^{238}O_2$) 9.4 mm long 6.0 mm diameter
Clad (Pt-30Rh) 12.0 mm long 8.6 mm diameter
Insulator Plug (PG)
Pt = Platinum
Rh = Rhodium
Pt-30Rh = Platinum 30% Rhodium
PG = Pyrolytic Graphite
FWPF = Fine Weave Pierced Fabric

GPHS-RTG

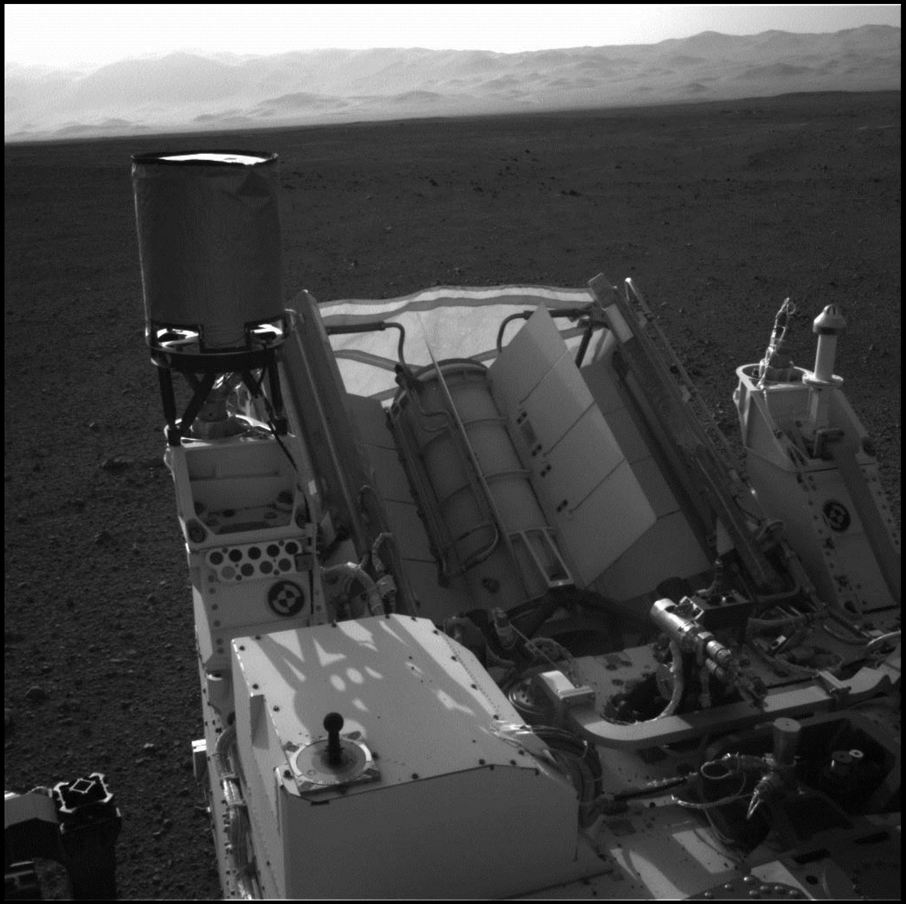

FWPF AEROSHELL CAP
FWPF GIS
FWPF GIS CAP
FUELED CLAD
FLOATING MEMBRANE
PU-238 DIOXIDE FUEL PELLET
IRIDIUM CLAD
FINE WEAVE PIERCED FABRIC (FWPF) GRAPHITE IMPACT SHELL (GIS)
CBCF DISK
FWPF LOCK MEMBER
CARBON BONDED CARBON FIBER (CBCF) SLEEVE
CBCF DISK
FWPF REENTRY AEROSHELL
FWPF LOCK SCREW
5.31 cm (2.09 IN.)
INDIVIDUAL GENERAL-PURPOSE HEAT SOURCE (GPHS) MODULE
9.32 cm (3.67 IN.)
9.72 cm (3.83 IN.)



Current U.S. RTG



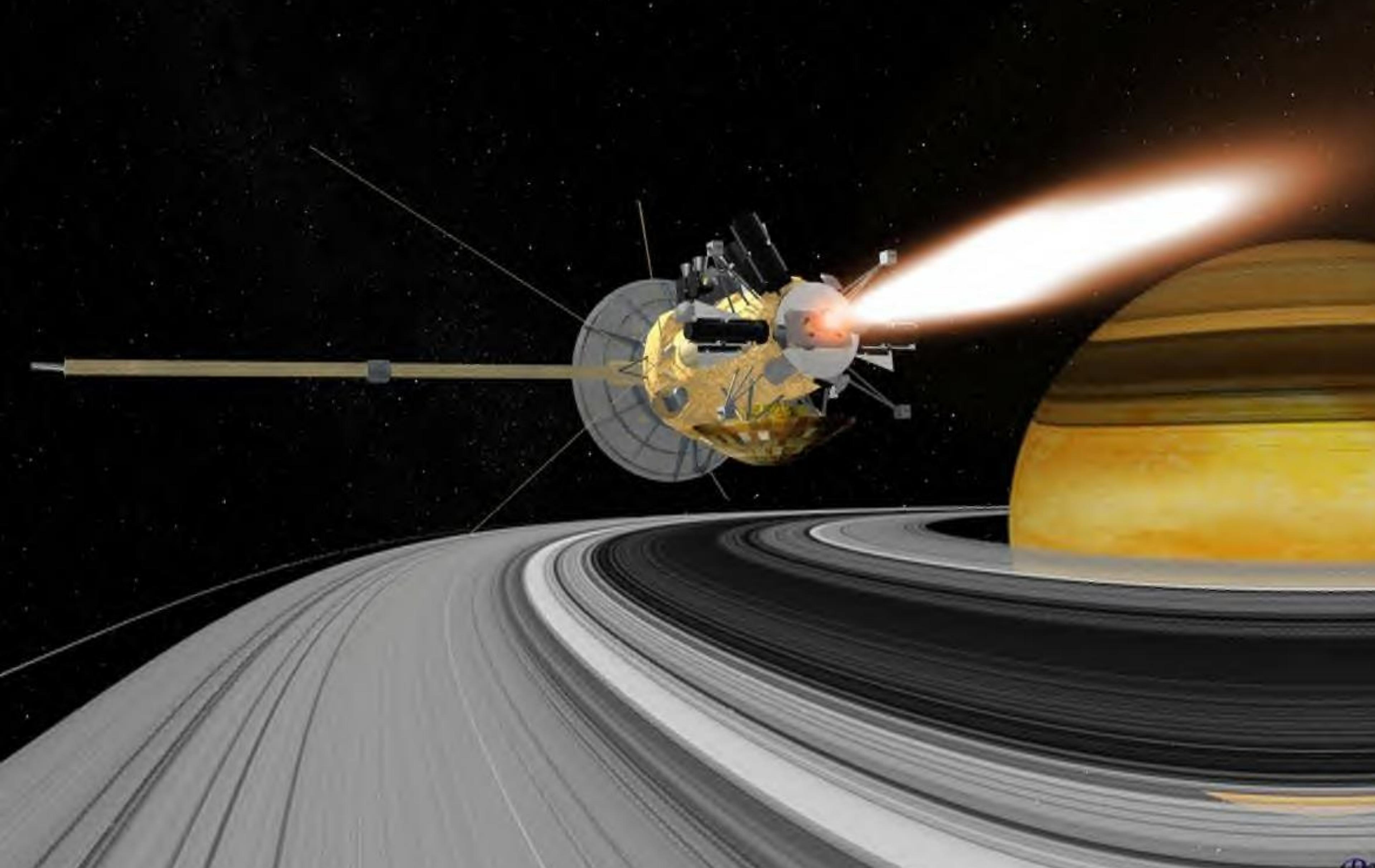
MMRTG Cross Section



Current & Relatively Recent U.S. Nuclear-Powered/Heated Space Missions

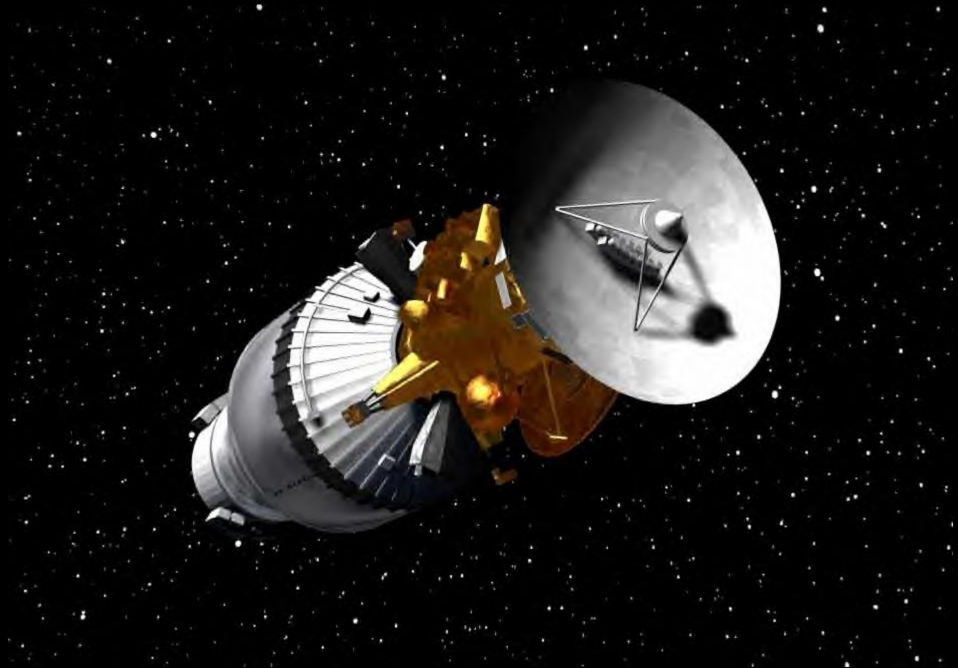
CASSINI: MISSION TO SATURN

Three 275 W(e) GPHS-RTGs



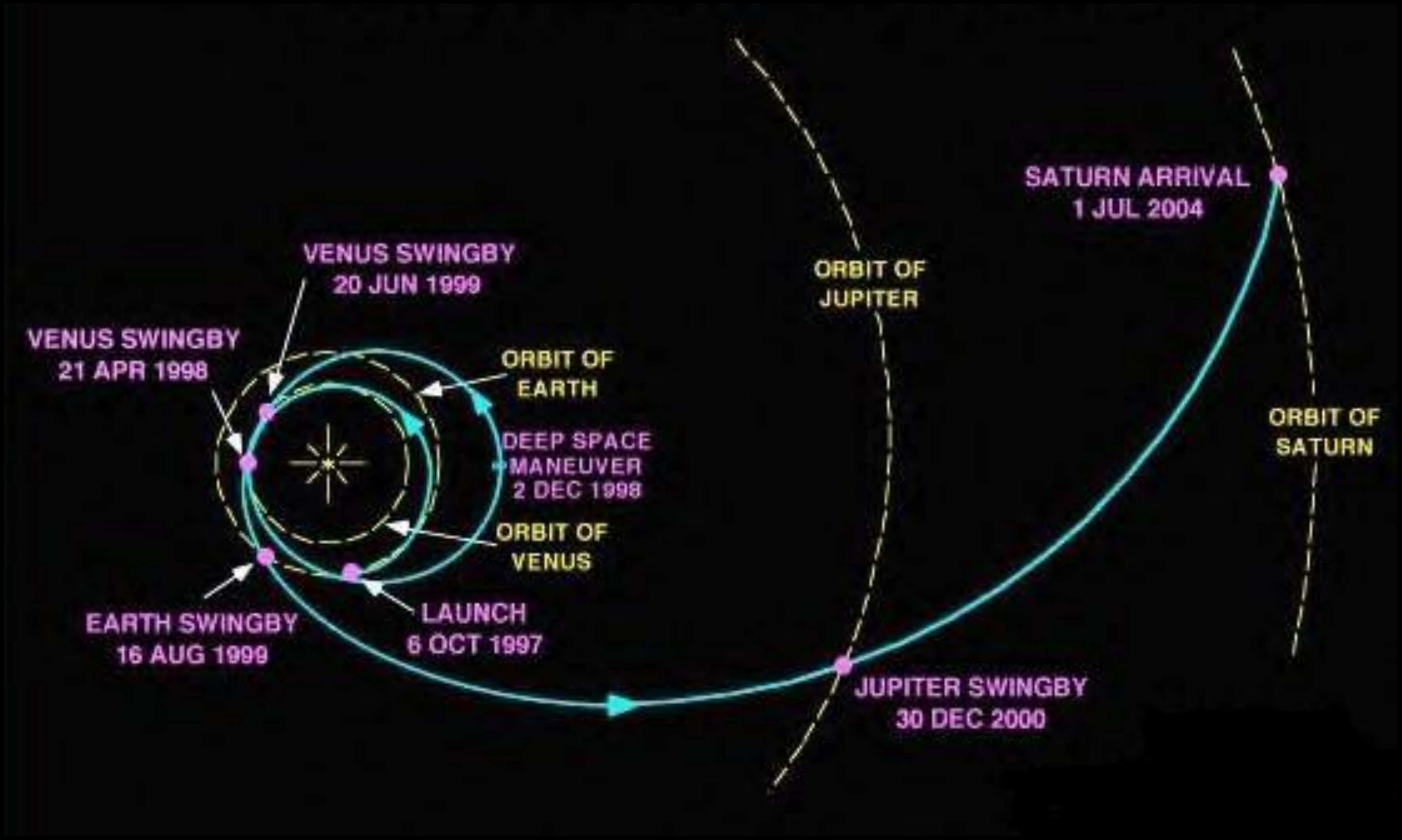
CASSINI Launch: 8 Oct 1997 on Titan IVB from LC40, CCAFS, FL

Cassini Earth Escape



CASSINI: Mission to Saturn

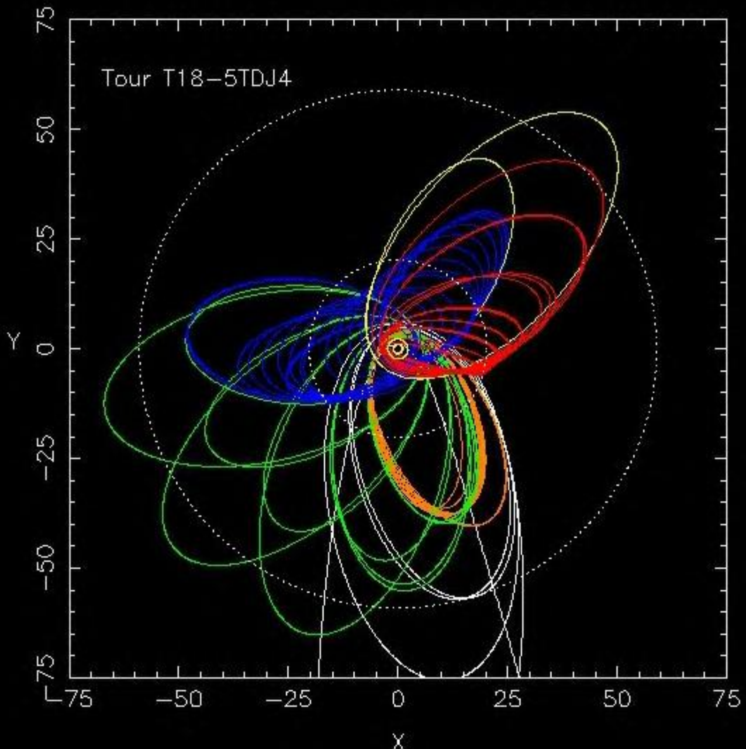
VVEJGA Interplanetary Trajectory



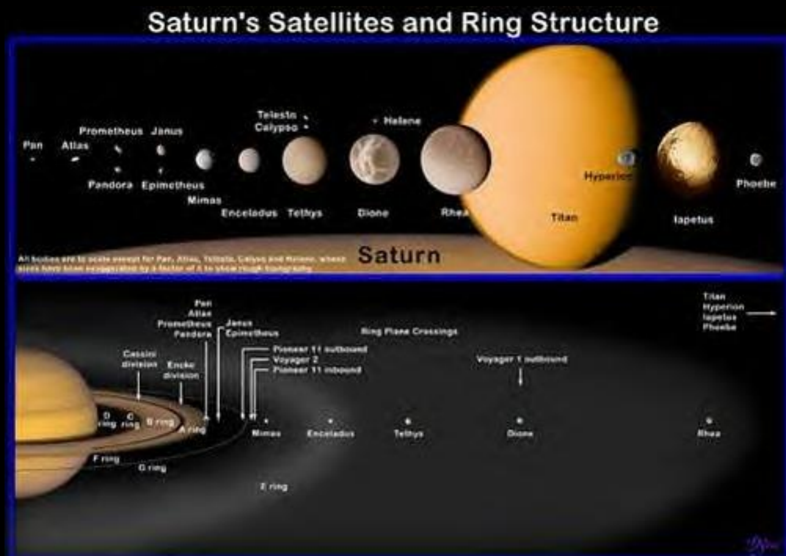
CASSINI: Mission to Saturn

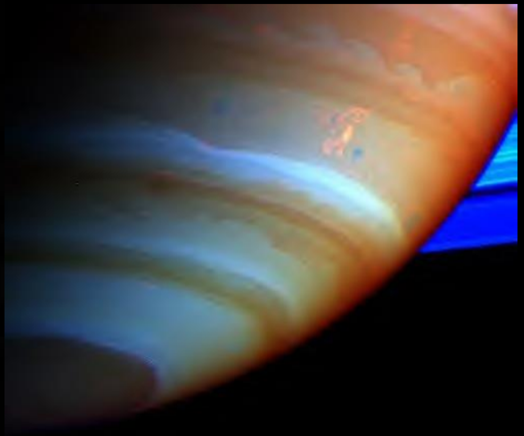
Operations at Saturn

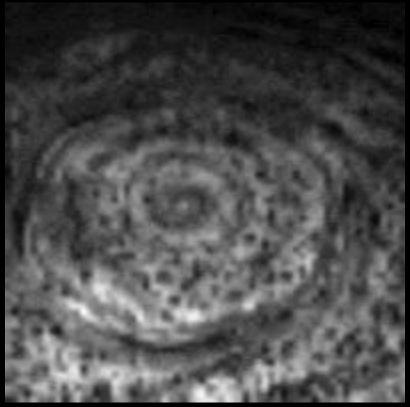
Video: Cassini's 13 year mission at Saturn

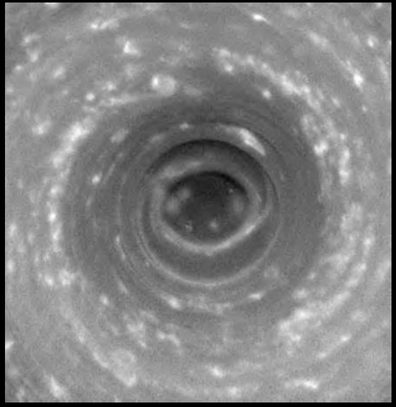


CASSINI: Mission to Saturn

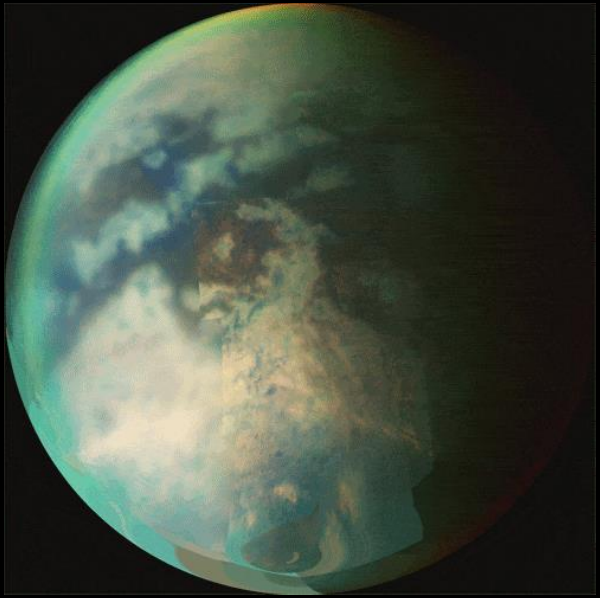


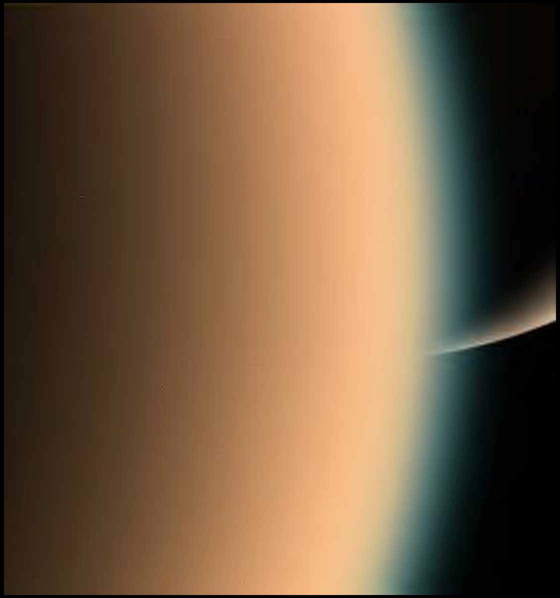


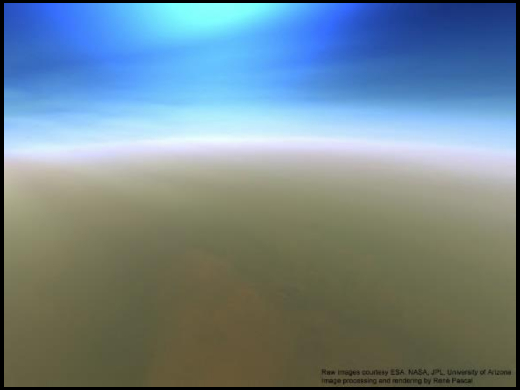


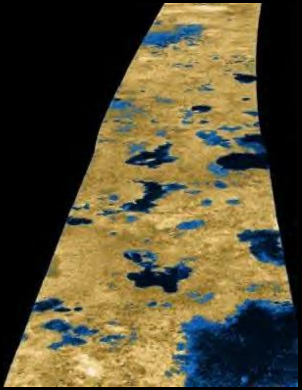


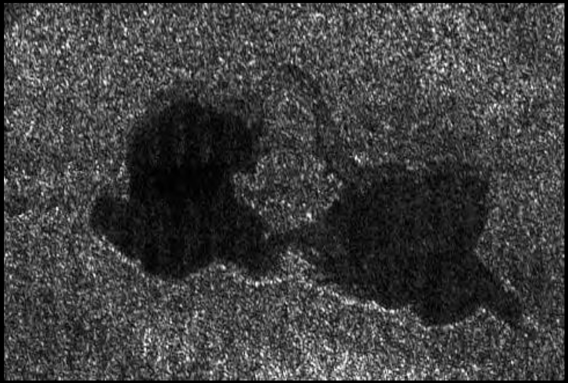
CASSINI: Mission to Saturn



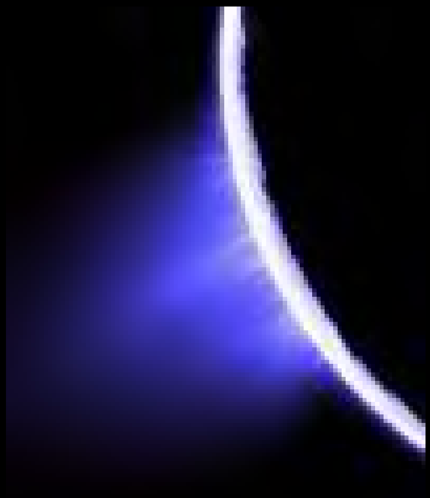


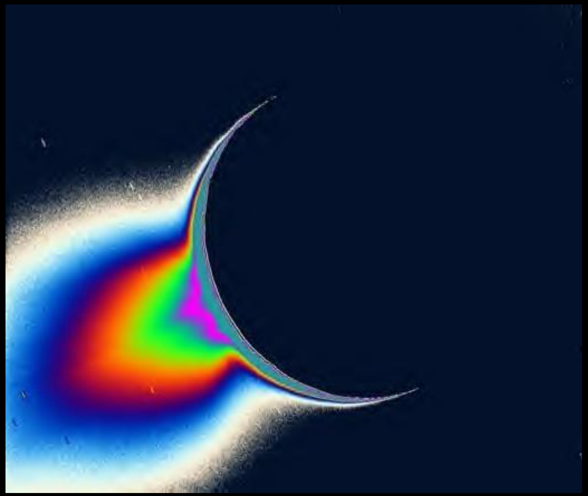


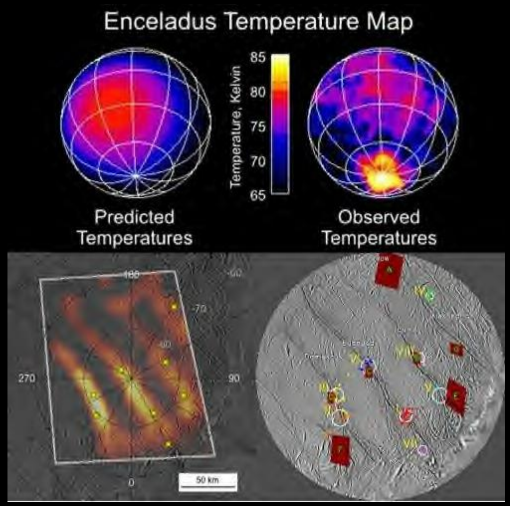


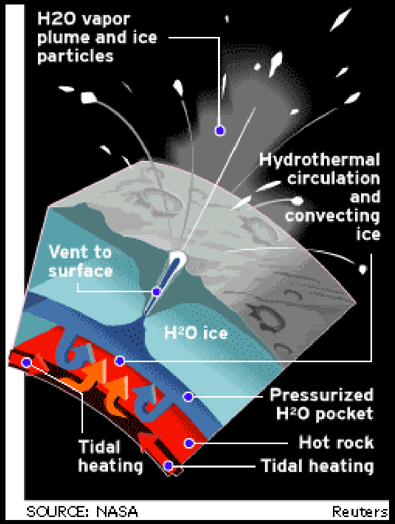


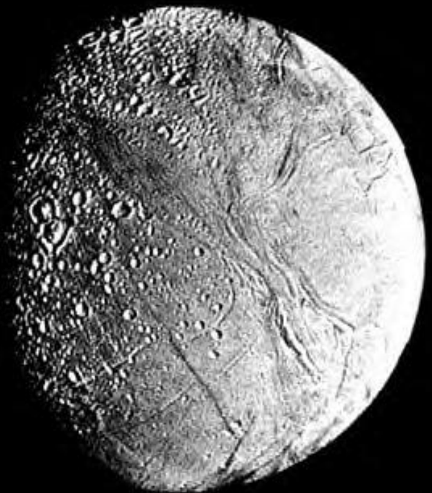
CASSINI: Mission to Saturn







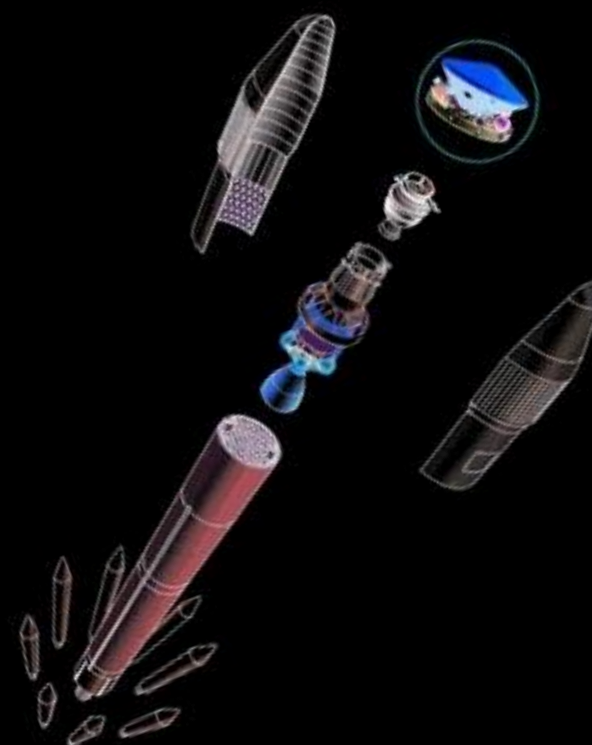




MARS EXPLORATION ROVER A & B MISSIONS

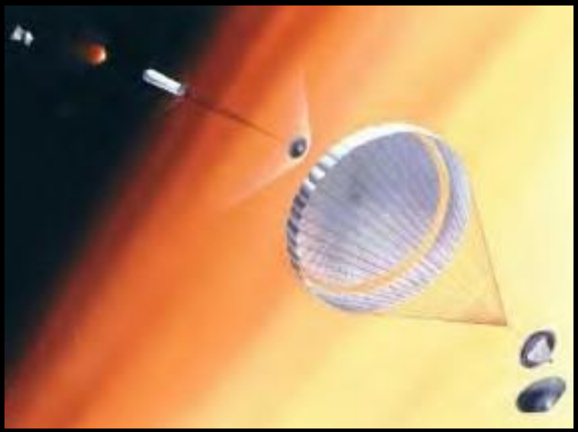
Eight 1 W(t) LWRHUs on each Rover

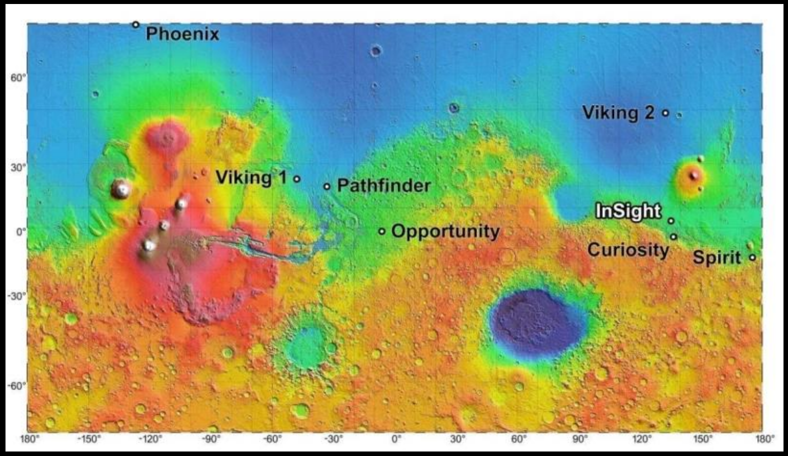
MER-A **Launch: Jun 03** ***MER-B*** **Launch: Jul 03**



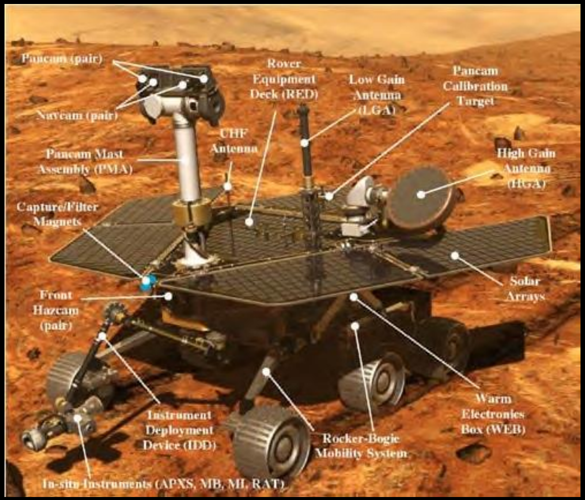
Mars Exploration Rovers "Spirit" and "Opportunity"

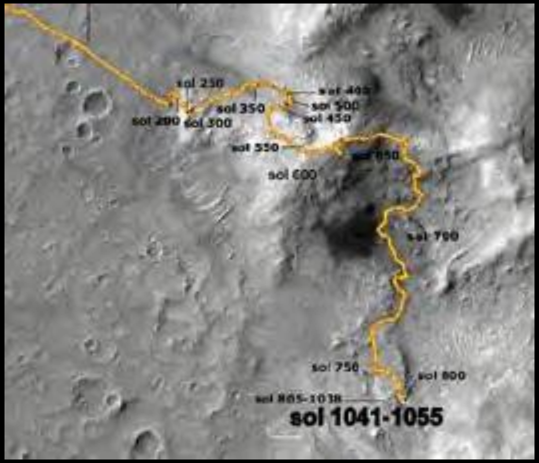
Video: Animation of MER Entry, Descent & Landing



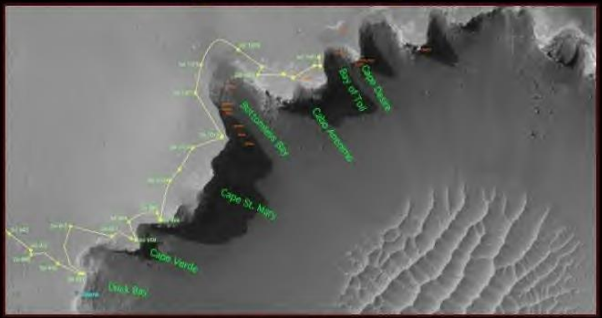


Mars Exploration Rovers “Spirit” and “Opportunity”



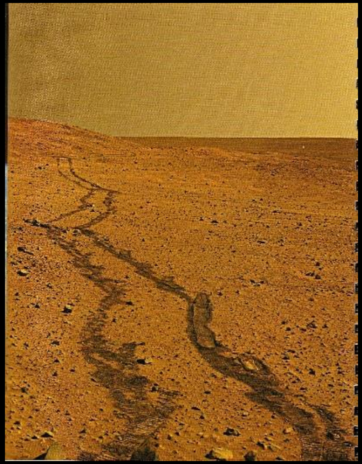


Opportunity is traversing “Victoria Crater” ridge by ridge, using autonomous navigation.

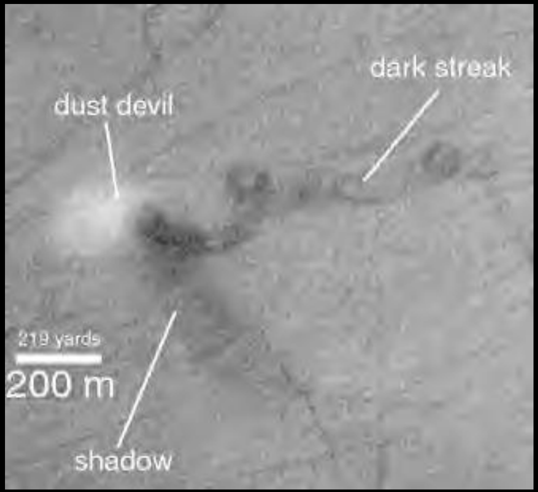


HiRISE image from Mars Reconnaissance Orbiter with graphic overlay of cliff names, Jan. 2007. NASA/JPL-Caltech/Univ. of Arizona

Science team members identify targets using names of places that 16th-century Earth explorer Magellan visited with his ship “Victoria.”

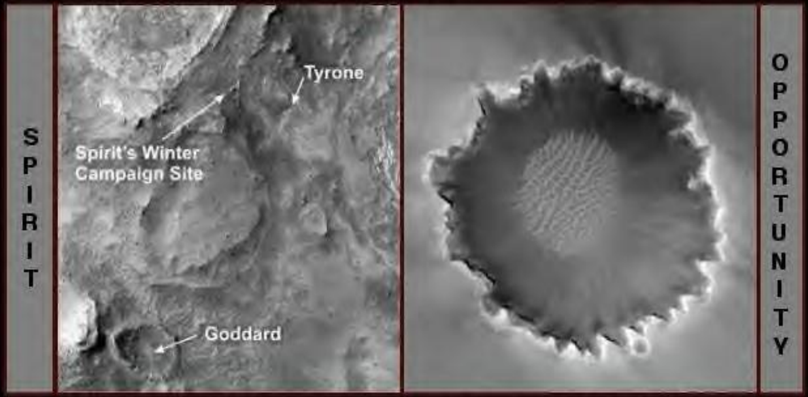


Mars Exploration Rovers "Spirit" and "Opportunity"

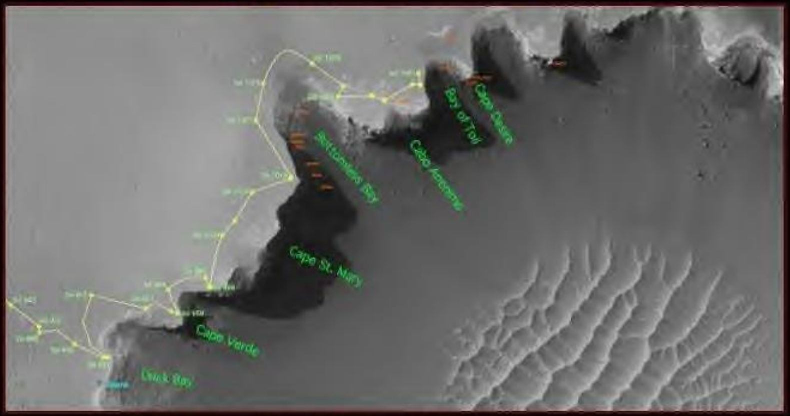


Mars Exploration Rovers “Spirit” and “Opportunity”

Spirit will drive toward Tyrone.
Opportunity will study rocks around the rim of Victoria and look for a safe spot to enter the crater.



Opportunity is traversing “Victoria Crater” ridge by ridge, using autonomous navigation.



HiRISE image from Mars Reconnaissance Orbiter with graphic overlay of cliff names, Jan. 2007 . NASA/JPL-Caltech/Univ. of Arizona

Science team members identify targets using names of places that 16th-century Earth explorer Magellan visited with his ship “Victoria.”

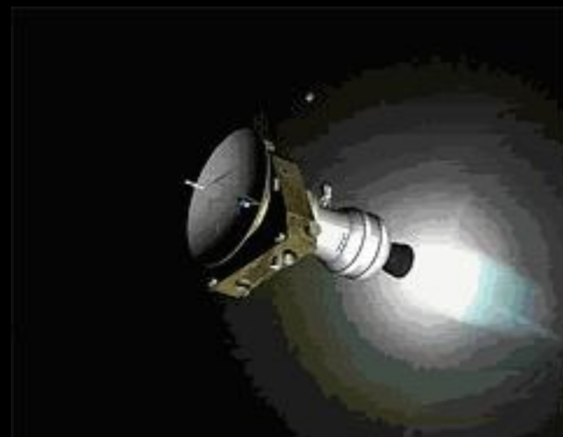
NEW HORIZONS – PLUTO

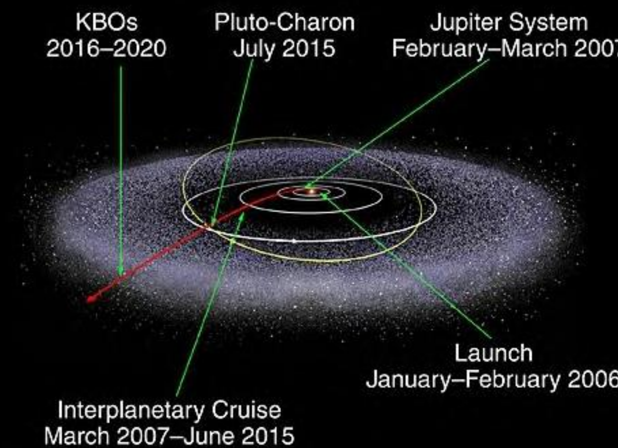
Pluto / Kuiper Belt Encounters

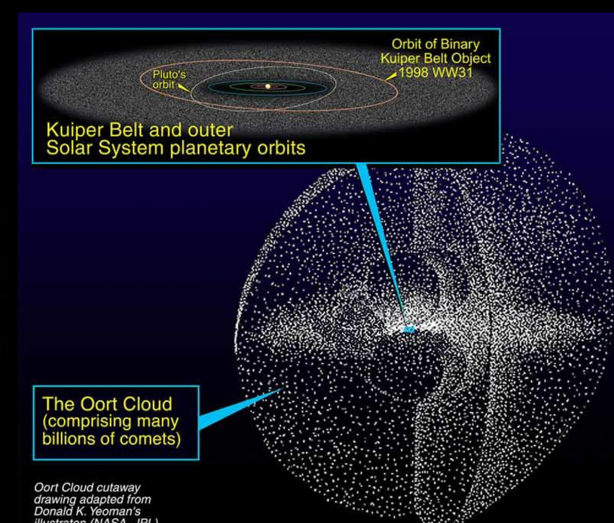
One 245 W(e) GPHS-RTG

New Horizons – Pluto: Pluto / Kuiper Belt Encounters

Video: New Horizons – Pluto Animated Mission







NEW HORIZONS – PLUTO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(See Page [illegible])

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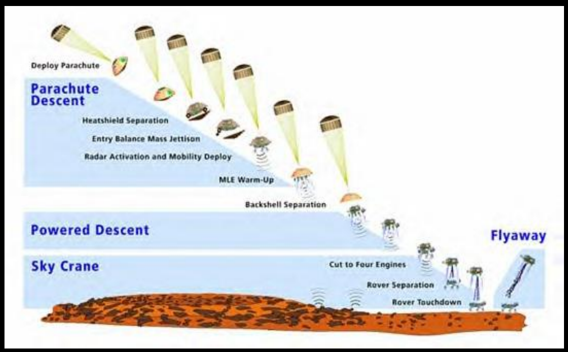
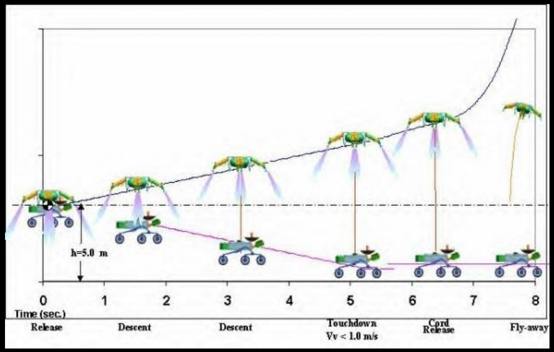
NEW HORIZONS – PLUTO & CHARON

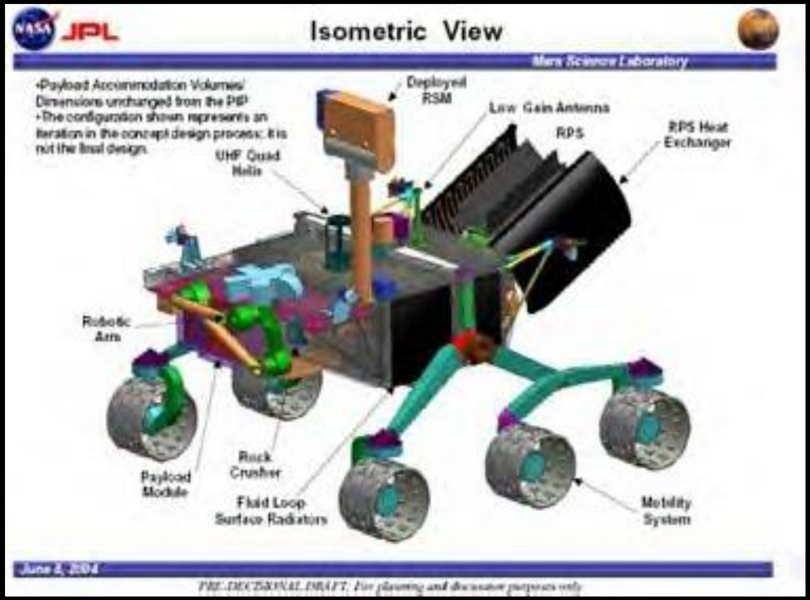
Video: New Horizons Flyover of Pluto

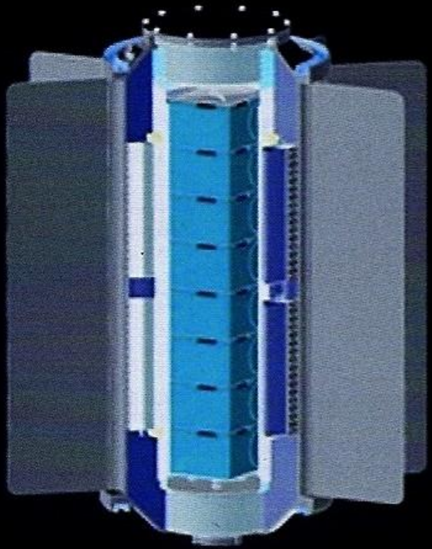
Ultima Thule

The *Mars Science Laboratory (MSL) & Mars-2020* Missions and the 110 W(e) Multi-Mission RTG (MMRTG)





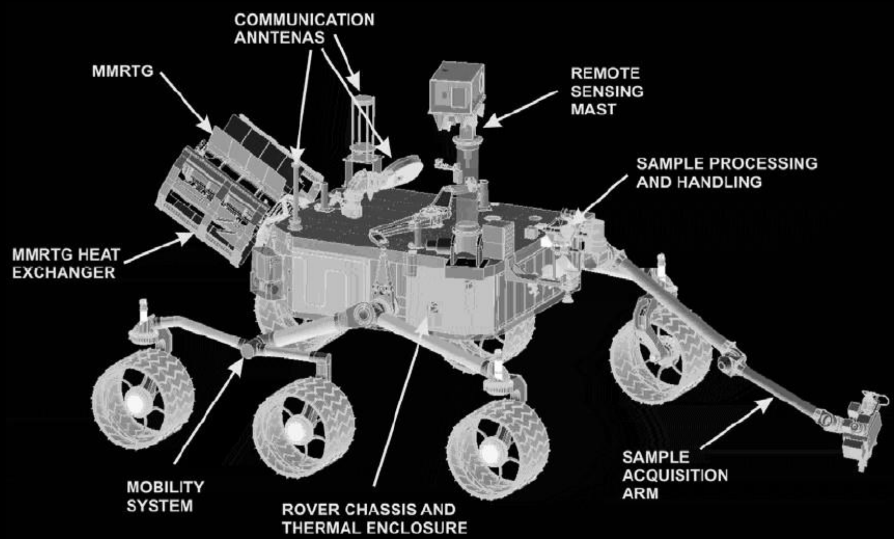


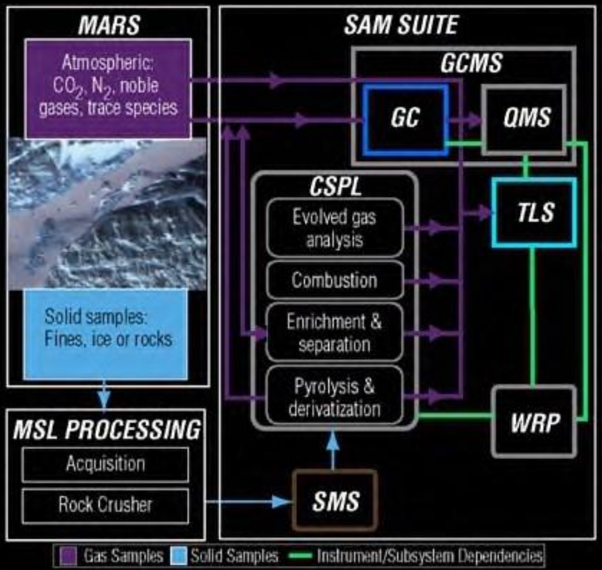


MMRTG Cross Section

Video: MSL Mission Animation

The *‘Curiosity” & “Perseverance” Mars Rovers*





The *Mars Science Laboratory (MSL)* Mission and Its 110 W(e) Multi-Mission RTG (MMRTG)

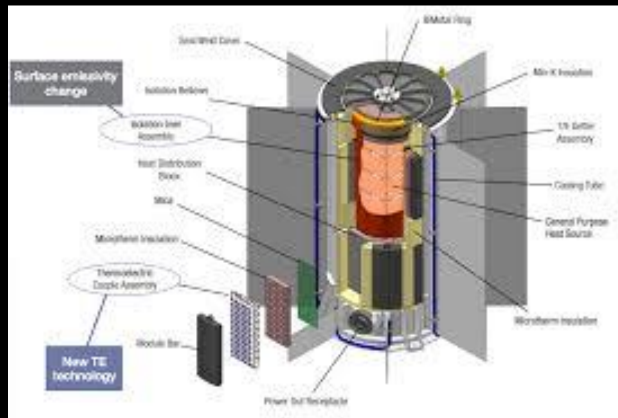
2012

2018

FUTURE U.S. SPACE NUCLEAR SYSTEMS AND MISSIONS

Future U.S. RTGs

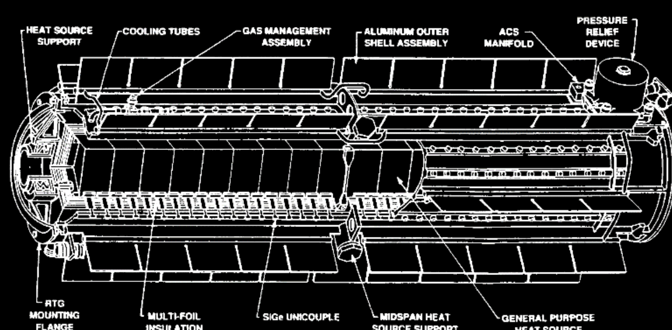
eMMRTG
(enhanced
MMRTG)



Enhancements over MMRTG
~140W(e) vs 110W(e)
Reduced degradation over time
Slightly higher operating temp

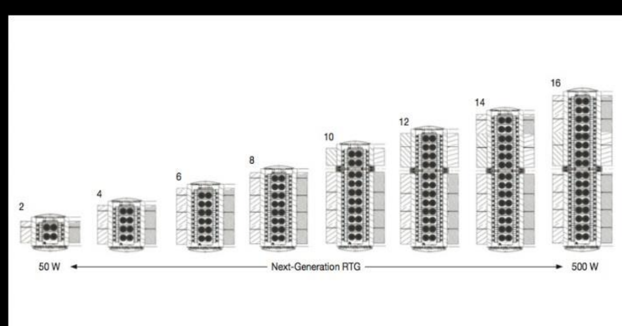
Changes to achieve enhancements
Higher efficiency TE w/lower degradation
Internal insulation changes

NextGen RTG



Recovery/Upgrade of GPHS-RTG with Si-Ge TE & Upgraded GPHS Modules to produce ~300 W(e) in-space RTG

SMRTG
(Segmented,
Modular RTG)

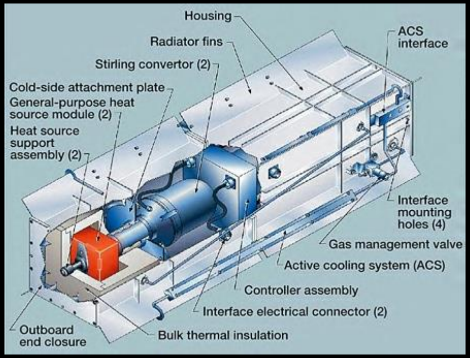


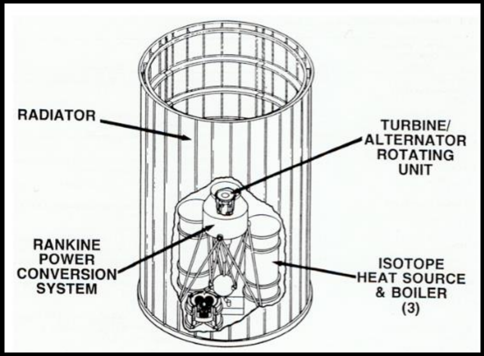
8 Different RTGs
Power levels: ~50-500W(e)
Incorporates advanced SKD TE
System efficiencies: ~12-16%
User chooses particular SMRTG(s)
Better S/C integration & mission fit

Development of a Dynamic RPS

Requirement: ~100-500W(e) high efficiency (~25-30%) RPS, with a 10-15+ year lifetime, for outer planetary exploration using the existing Step-II GPHS modules integrated into the RPS design

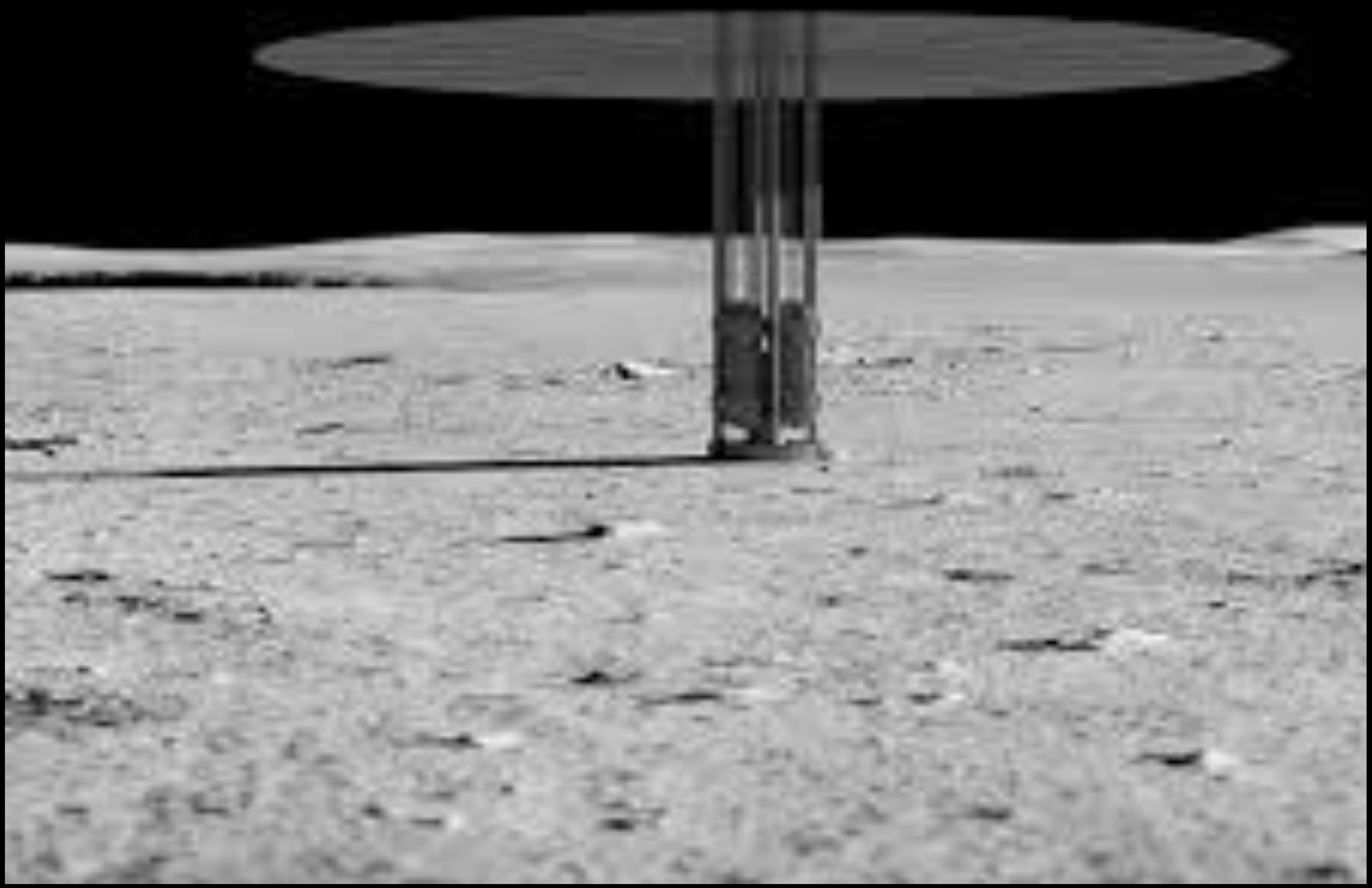
- **Consider dynamic energy conversion technologies in Phase I**
  - **Brayton rotating units**
  - **Free piston Stirling engines**
  - **Rankine cycle turbomachinery**
- **Downselect to one or, perhaps, two conversion technologies**
- **Advance selected conversion technologies in Phase II**
- **Select best conversion technology for development in Phase III**
- **Move to produce & qualify hardware for flight**



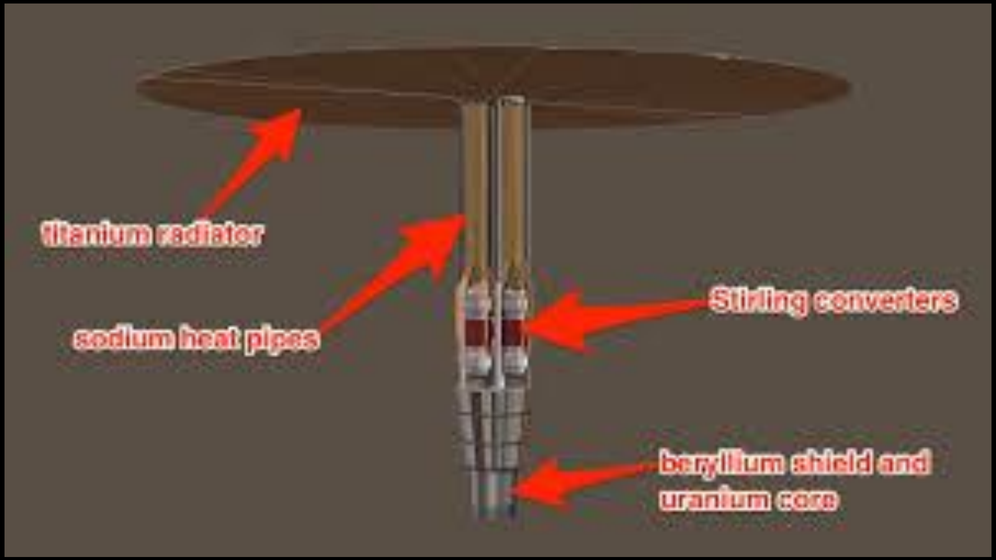


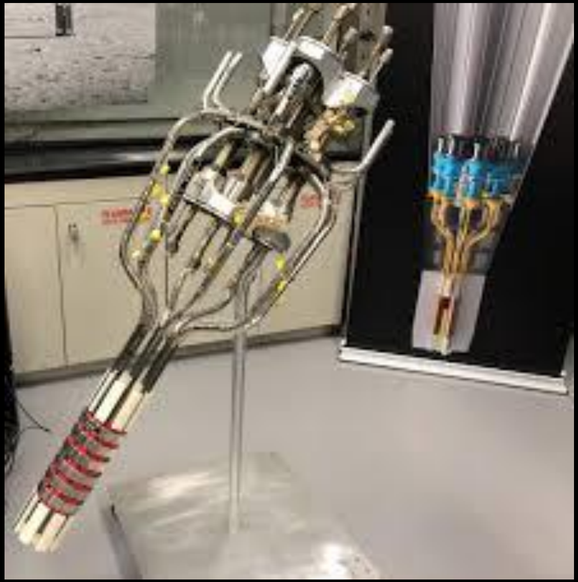
Return to the Moon

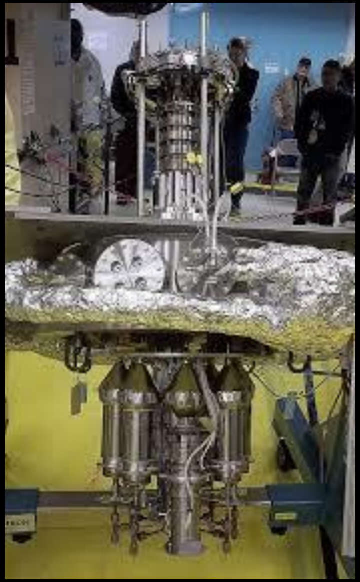
3-10 kW(e) Fission Surface Power System(s)



Kilopower Reactor Power System



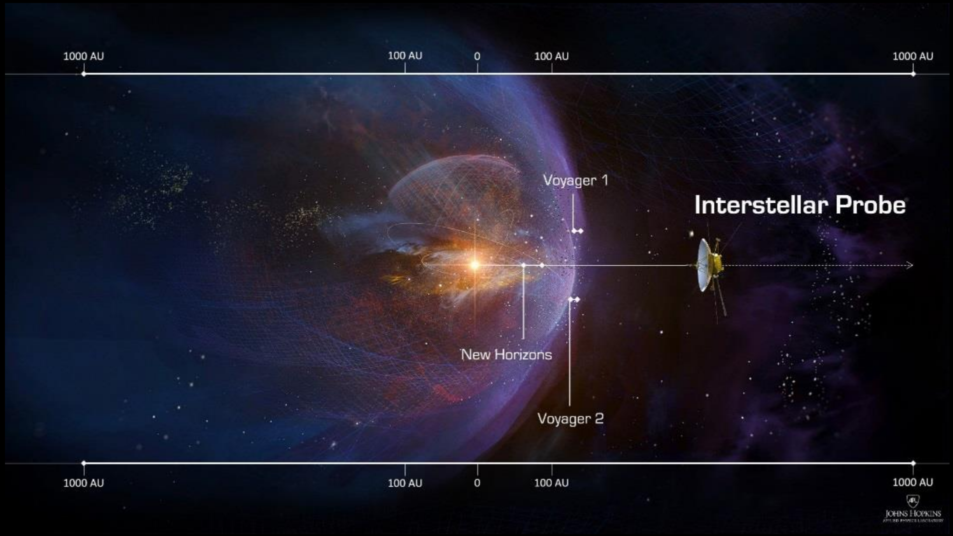




Near-Term Nuclear-Powered/Heated Space Missions

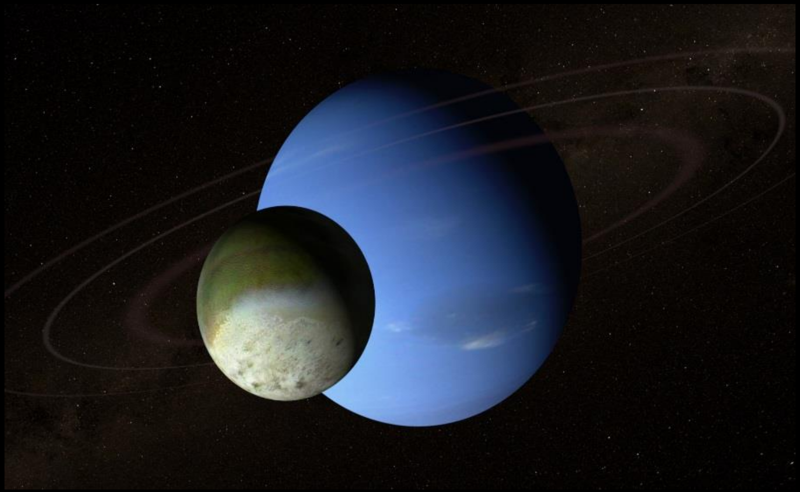
[Video: Titan Exploration - Dragonfly Animation]

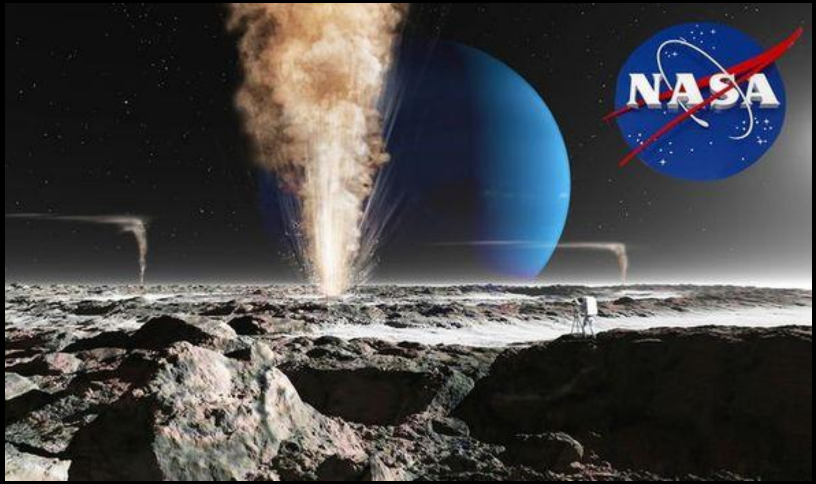
Interstellar Probe Mission

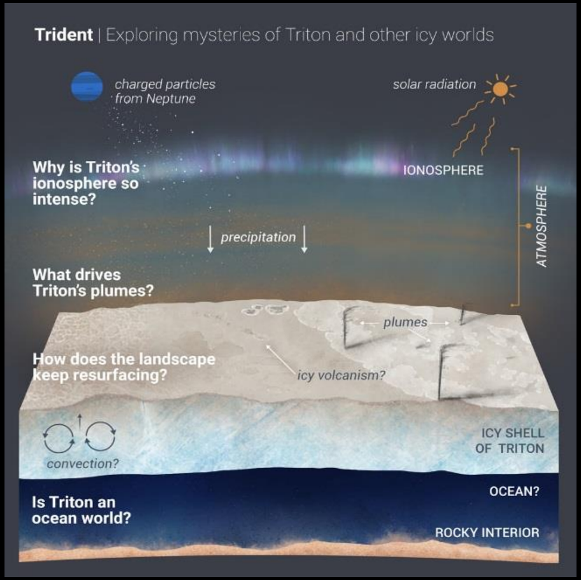


Near-Term Nuclear-Powered/Heated Space Missions

The Trident Mission to Triton??

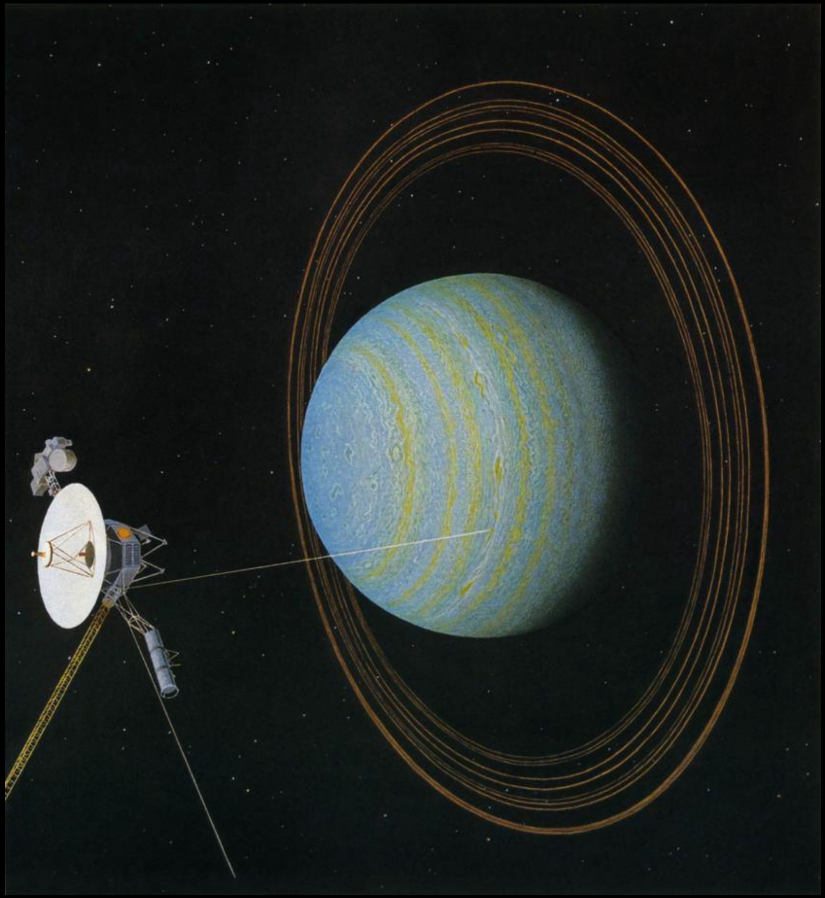






Future Nuclear Outer Planetary Missions

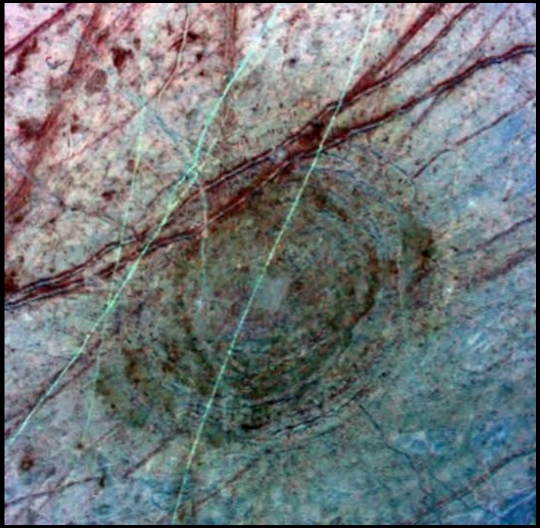
Uranus Orbiter Probe (UOP)



Neptune Orbiter

Ocean World Cryobots: Pursuit of New Future Heat Sources & RTG(s)

Provide heat & power necessary to get through the ice sheets of icy ocean worlds (like those of Europa, Enceladus, Pluto, etc) to permit access to their liquid oceans beneath - for cryobot exploration of the liquid oceans & their ice-ocean & ocean–oceanfloor interfaces. Also, acquire & transmit system status & science data during the mission.



Systems Needed:

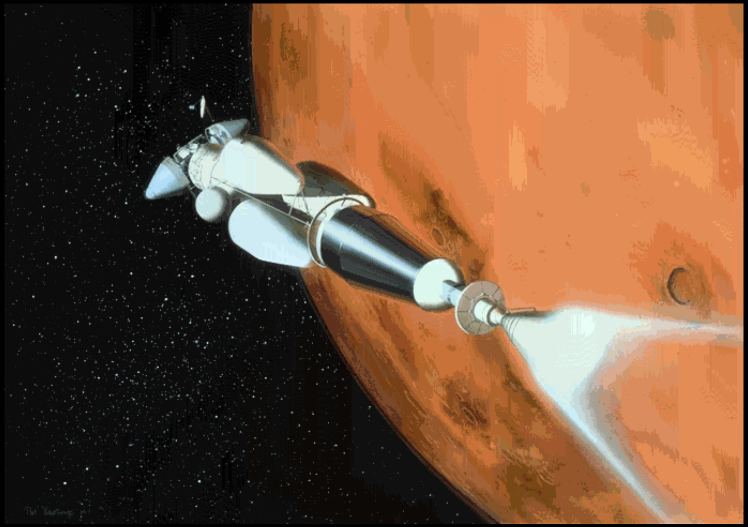
- New compact, high output (~8 kW(t)) cylindrical heat source
- Low-power ~40mW(e)-10W(e) RTG(s)

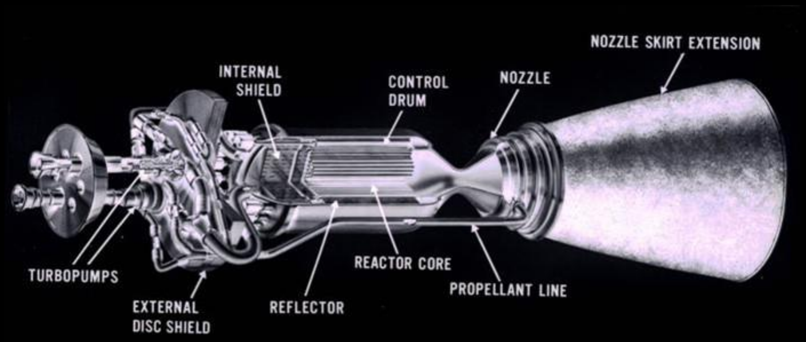
Onward to Mars

Nuclear Electric & Nuclear Thermal Propulsion: Getting to Mars & Beyond Quicker & Safer

Nuclear Electric Propulsion

Nuclear Thermal Propulsion

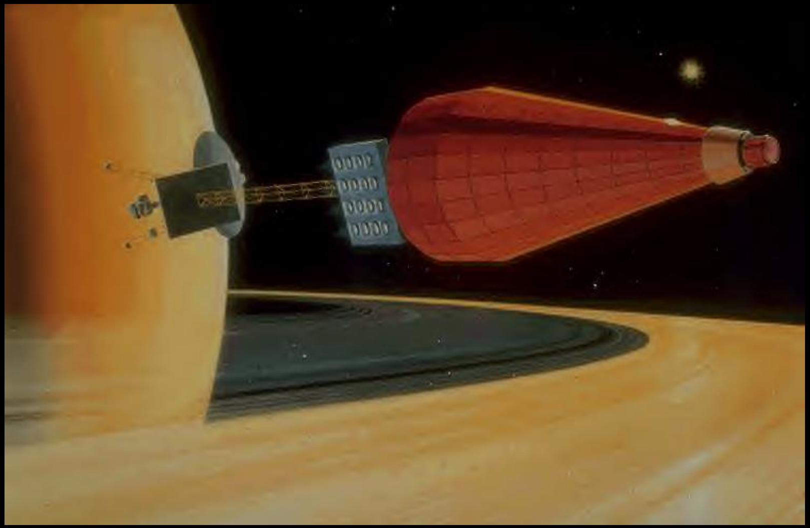


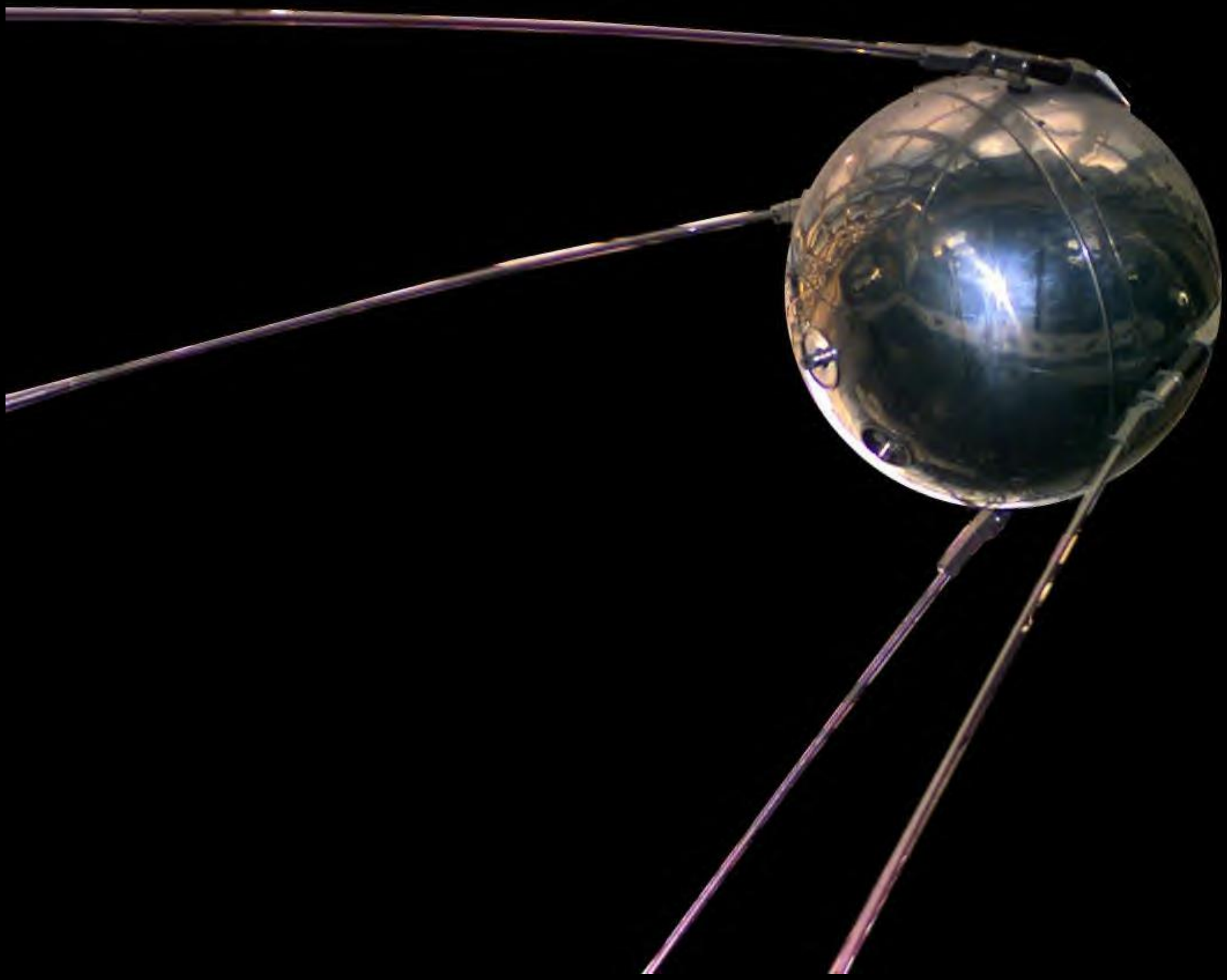


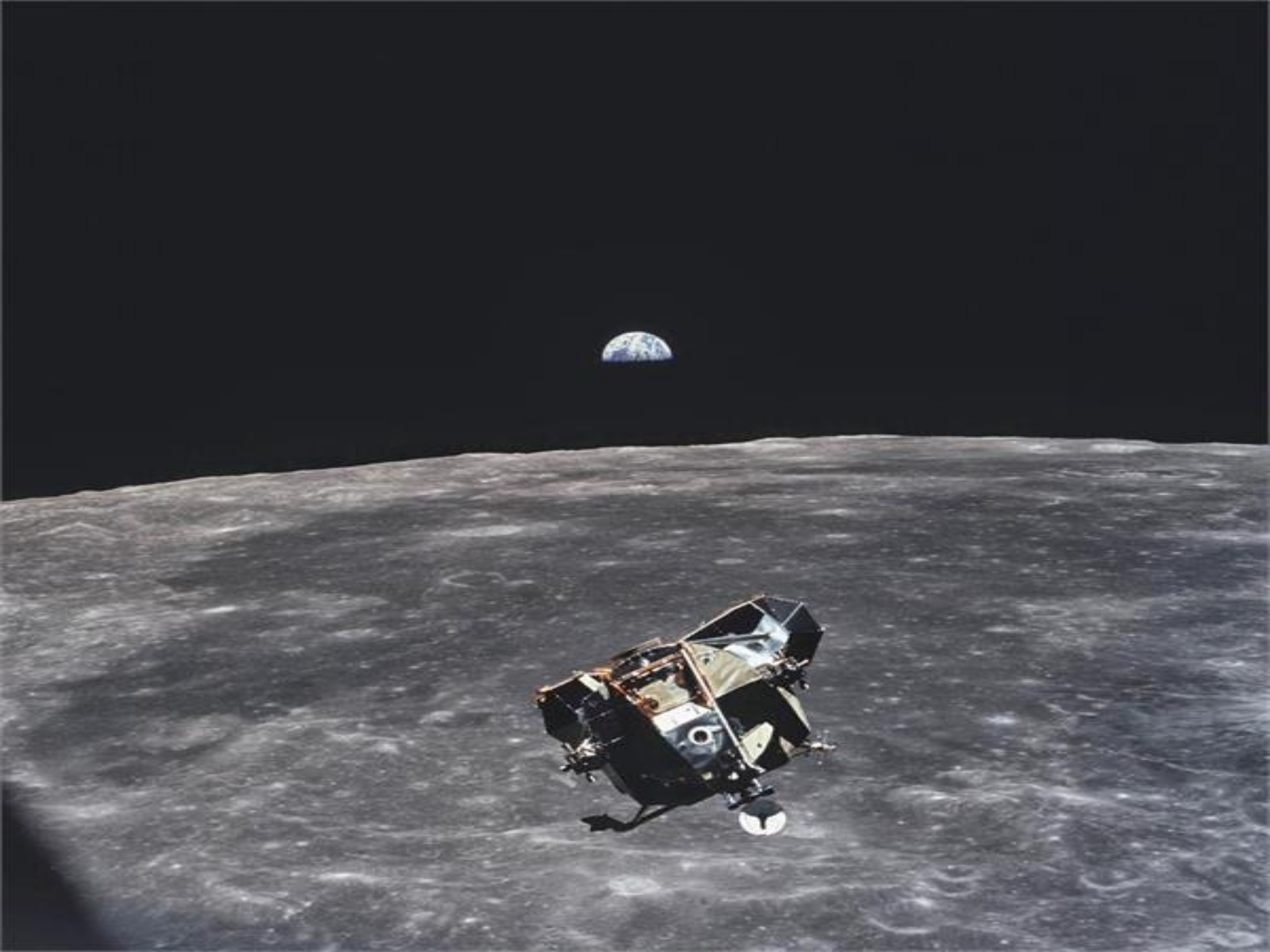
Onward to Mars

Four 10 kW(e) Fission Surface Power Systems

?????








Imagine the Possibilities