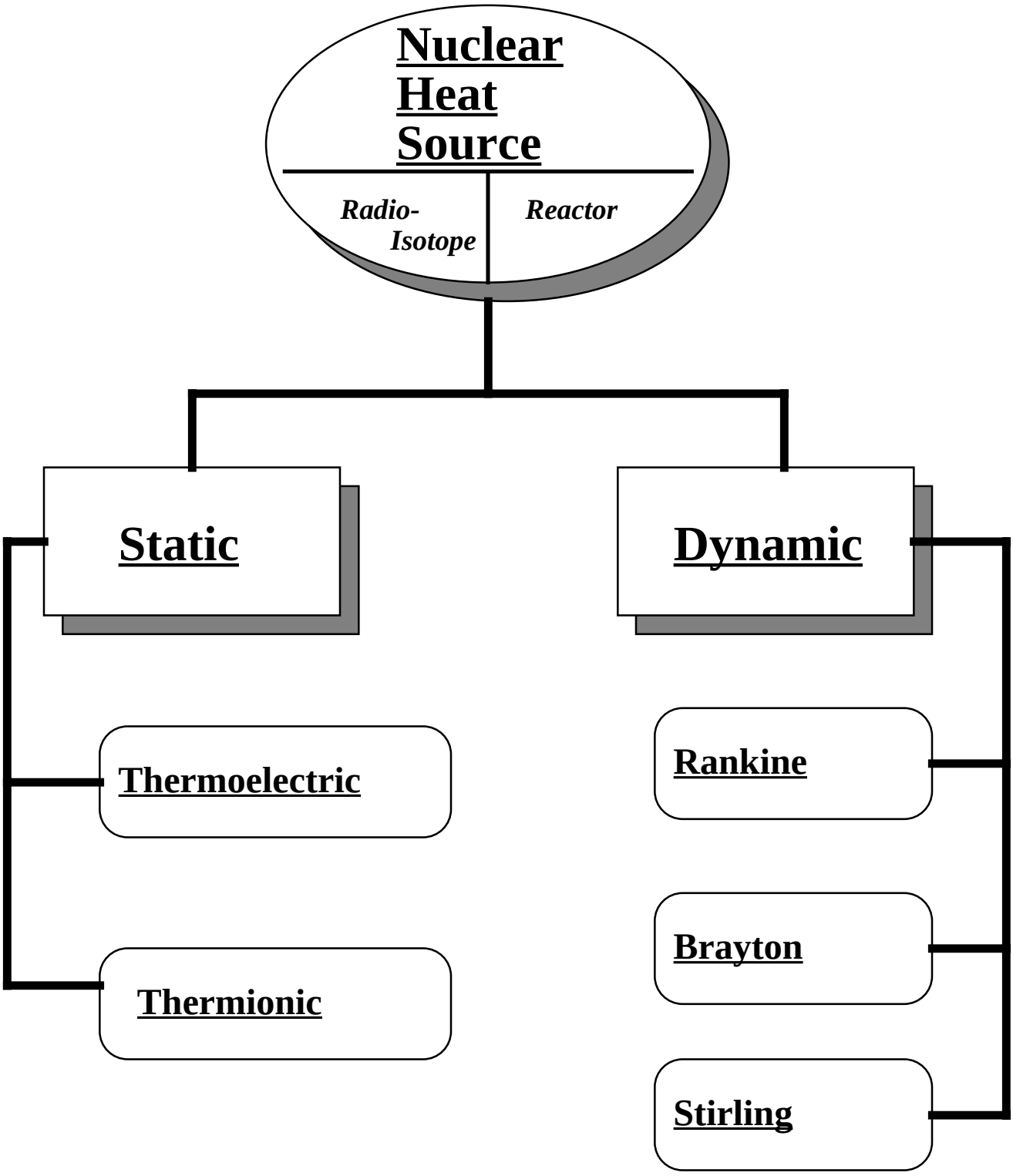
Major Power Conversion Techniques in Space



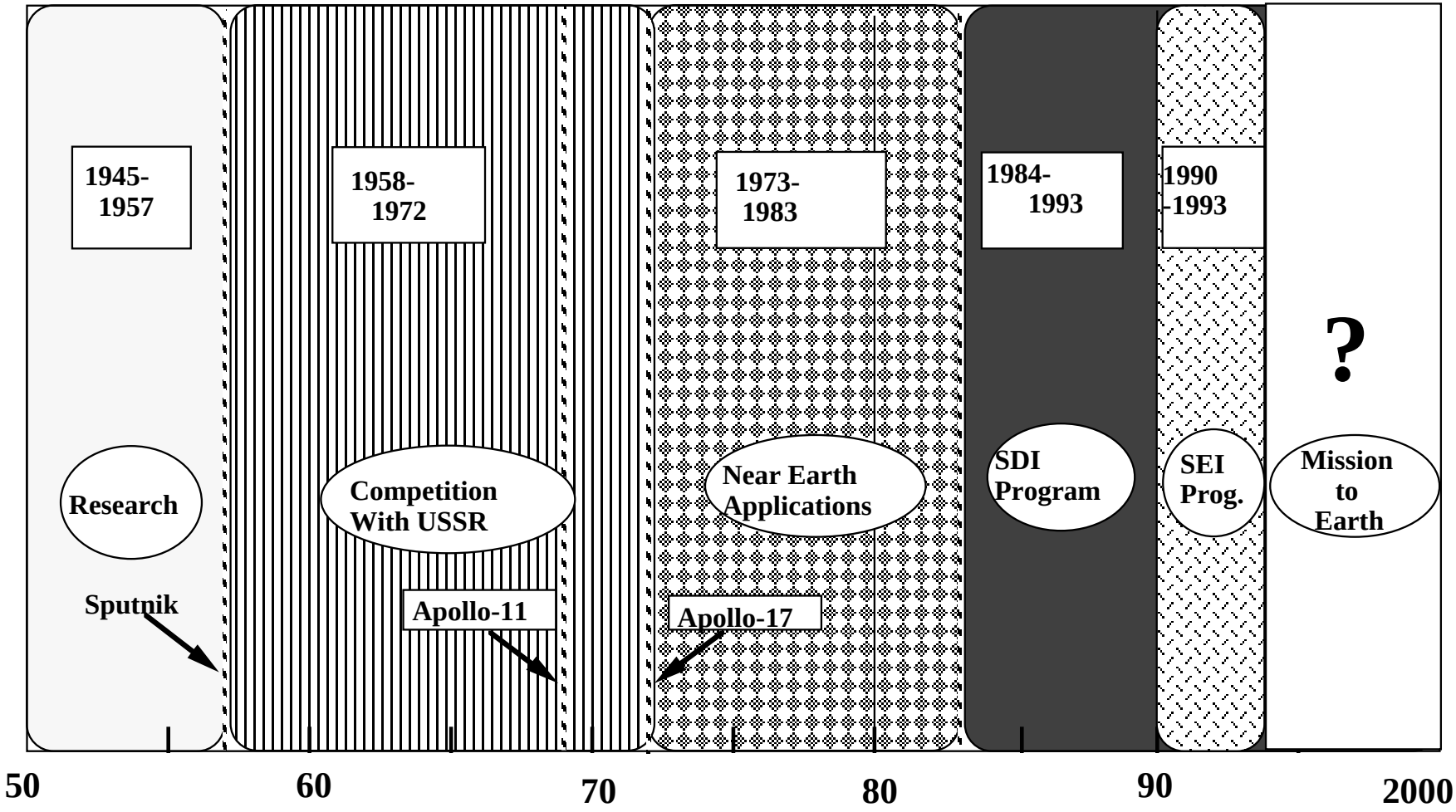
Why Use Fission Reactors In Space?

1 kg of ^{235}U Contains

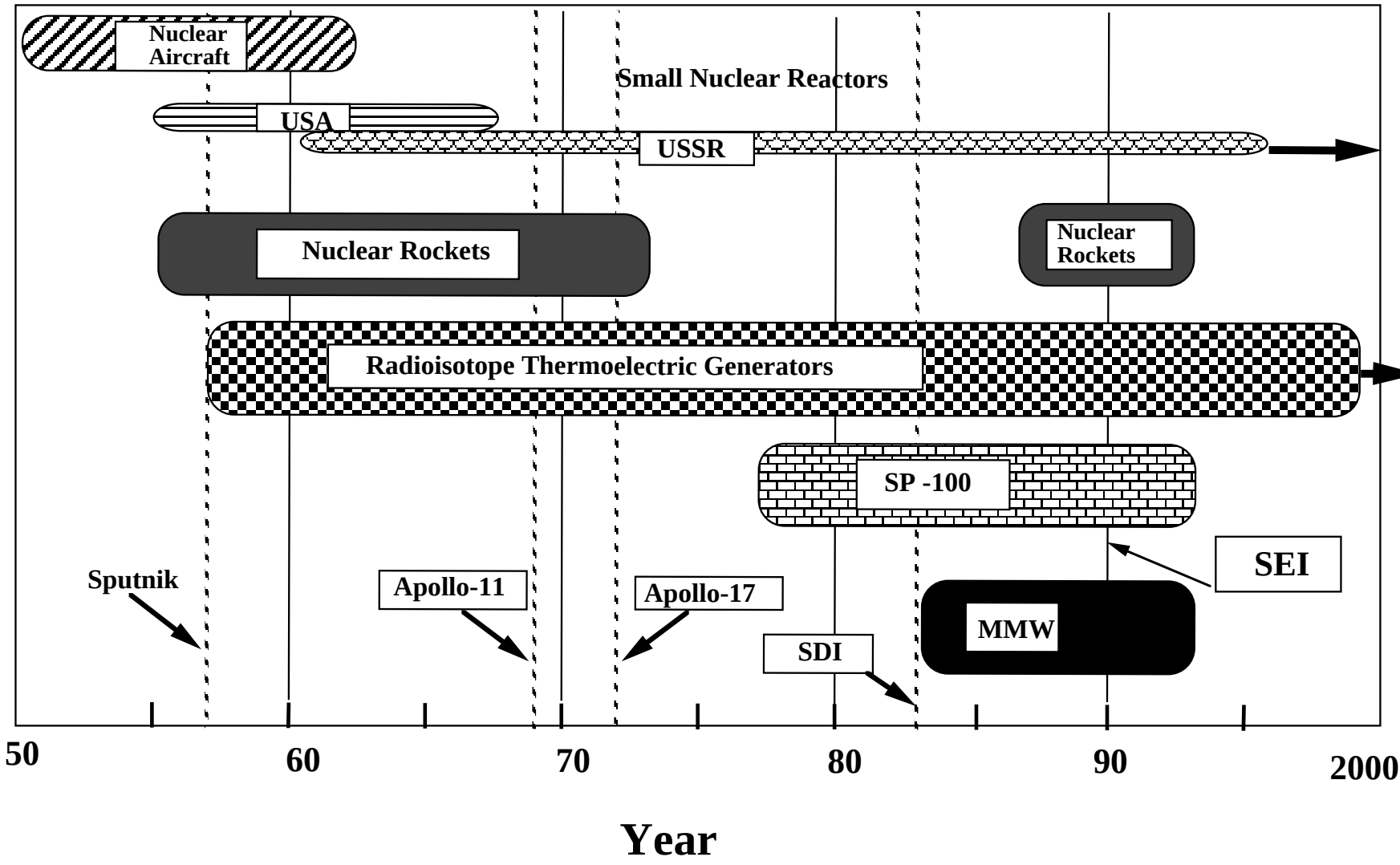
500,000

times the energy released by the decay of 1 kg of ^{238}Pu over 10 years

Chronology of Space Nuclear Power Development



Chronology of Space Nuclear Power Development



History of Nuclear Power in Space

Date	Event
1946 (May)	Contract-Army Air Force/Fairchild to study Nuclear Energy for Propulsion of Aircraft (NEPA) To be conducted at ORNL
1948	• AEC/MIT-Lexington Project -Big Feasibility. Recommend 15 year/1 $B development program
	• AEC/North American Aviation(NAA)--Feasibility study of nuclear rockets and ramjets...C. Starr et. al.
1950	AEC/USAF-Aircraft Nuclear Propulsion (ANP) Prog. Obj.-Est feasibility in 3-5 y of mat'ls, shielding, power plant, airframe design.
1951	• ANP -Increased obj. to incl. nuclear powered flights.
	• AEC/AF/GE- Direct cycle turbo jet, compressor, reactor, turbine.
	• AEC/AF/Pratt Whitney- Indirect cycle turbojet, compressor,[Li -air heat exchanger], turbine.
1953	LANL, Nuclear rocket study recommend nuclear rocket ICBM, R. Bussard, R. Shrieber.
1954	• USAF Rand Corp.-Pied Piper Satellite Feasibility Study -Salter
	• AF/Rand/NAA Pied Piper Reactor Study. R. Balent H_2O-$U(SO_4)_2$ reactor & reciprocating steam engine.
	•AF/AEC/GE Nuclear Ram Jet Study, Austin Corbett

History of Nuclear Power in Space

Date	Event
1955	• LANL, Nuclear Rocket Rover Program, R. Shrieber
	• AF/AEC/NAA ,PLUTO SLAM (nuclear ram jet), use BeO-UO_2 , N. Rasor
1956	• AF/AEC/NAA Contract Pied Piper-Nuclear power for satellites based on $UZrH_{1.84}$ thermal reactor and Hg Rankine turboalternator.
	• ANP dir. cycle HTRE -1, H_2O mod. air cooled,150 h
1957	• Sputnik launched by USSR
	• NAA Pied Piper critical, name changed to Systems for Nuclear Auxiliary Power, [SNAP].
	• SNAP -1 Isotope [Hg Rankine] 100 Watts, program start, (Martin Marietta)
	• ANP, Li -air concept downgraded to "adv. res. prog."

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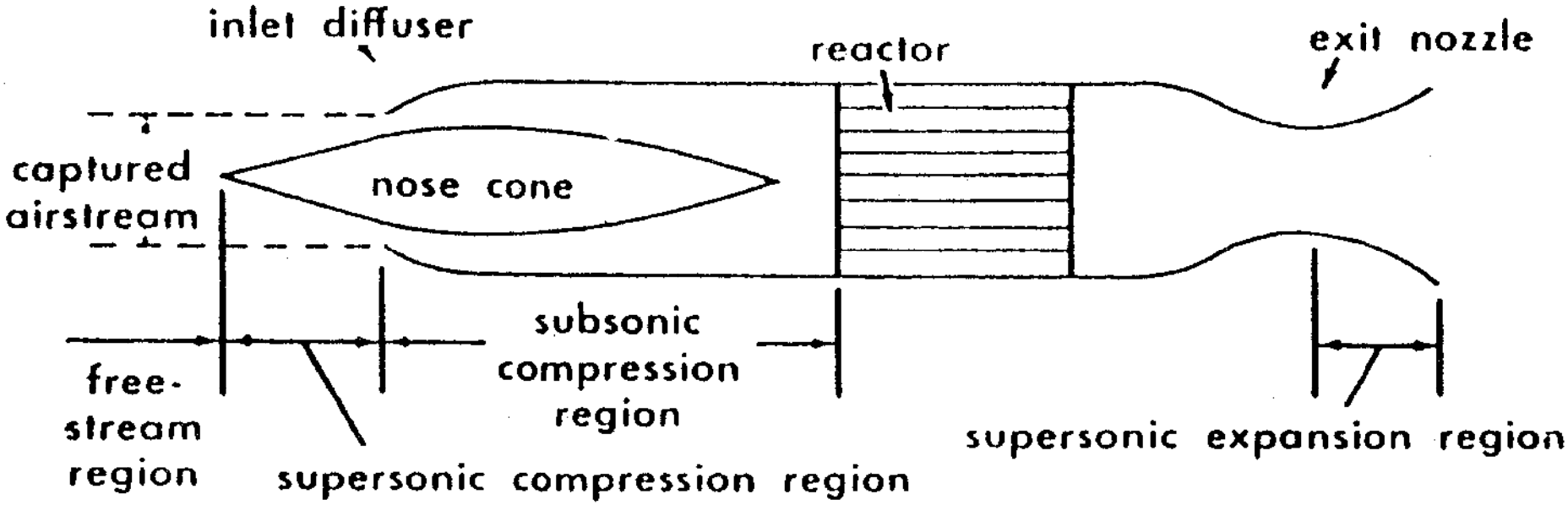
History of Nuclear Power in Space

Date	Event
1958	• ANP/HTRE -3 operates, (GE -INEL) with solid mod. • AEC/ANP--GE invents Thermionic ignited mode
1959	• AEC/AF -SNAP Advanced reactor program[NAA]
	• Inv.of multicell (flashlight) thermionic fuel element (TFE), N Rasor.
	• AEC/AF, SNAP Advance Reactor Prog. Invention of Boiling Rb reactor -Wetch NAA
	• Rover Rocket test, KIWI-A, reactor test (LANL-Nev)
	• SNAP operates at 50 kWt for > 6000 hrs.(NAA)
	• SNAP -3,Pb -Te radioisotope demo. (M^2)
	• AF/AEC/LLNL/Marquardt, Pluto nucl, ramjet start
	• NASA -Aerojet, AEC -NAA, Snap -8, 600 kWt Hydride reactor with 30 kW_e Hg turbine, conv. program start-H Finger/J. Wetch.
	• AF/AEC Rover Program -KIWI A, A1 &3
1960	•SNAP –10 (100-200 W_e) solid conduction, prog. start
	• AF/AEC, Tory -2, Nuclear ramjet tests- Jackass Flat Nevada, LLNL

History of Nuclear Power in Space

Date	Event
1961	• NASA/AEC, Rover -KIWI B Tests, LLNL, Nev.
	• AF/AEC, SNAP -2 runs at 50 kW_t /1200 °F, 11000 h
	• DOD/AEC, SNAP -3B, 9A RTG's launched in Transit Navigational National Satellites.
	• NASA-Manned Lunar Landing given top priority.
	• AF/AEC, ANP program discontinued.
	• AF/AEC, SNAP -10(200 W_e) -> SNAP -10a (500 W_e)
	• AEC Thermionic Tech. Dev., GE vs GA -TECO

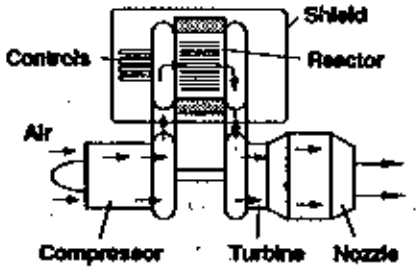
SIMPLIFIED SCHEMATIC OF A NUCLEAR-RAMJET ENGINE



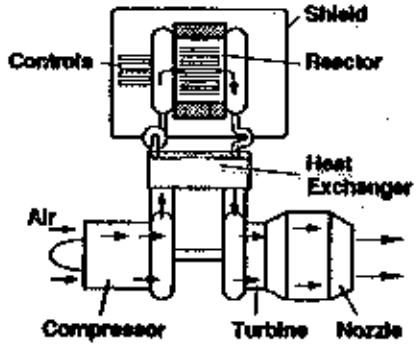
NUCLEAR PROPULSION

SPI

Manned Aircraft



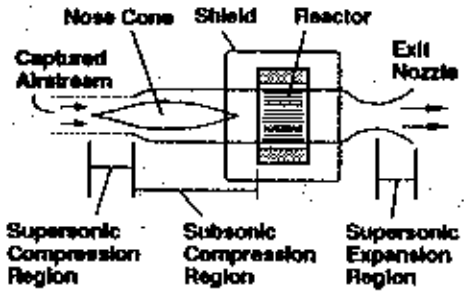
Direct Open Brayton Cycle



Indirect Open Brayton Cycle

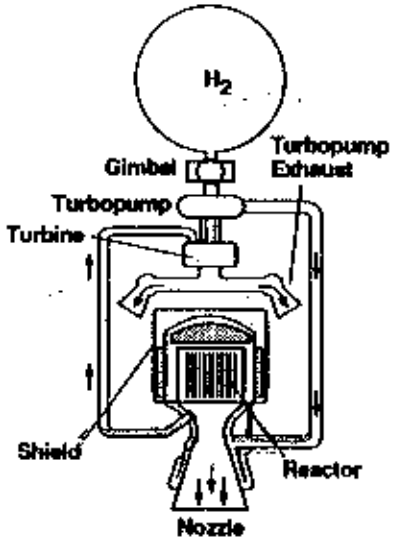
Turbo Jet

Unmanned Missle



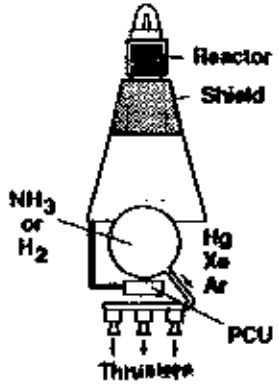
Ram Jet

Unmanned Missle

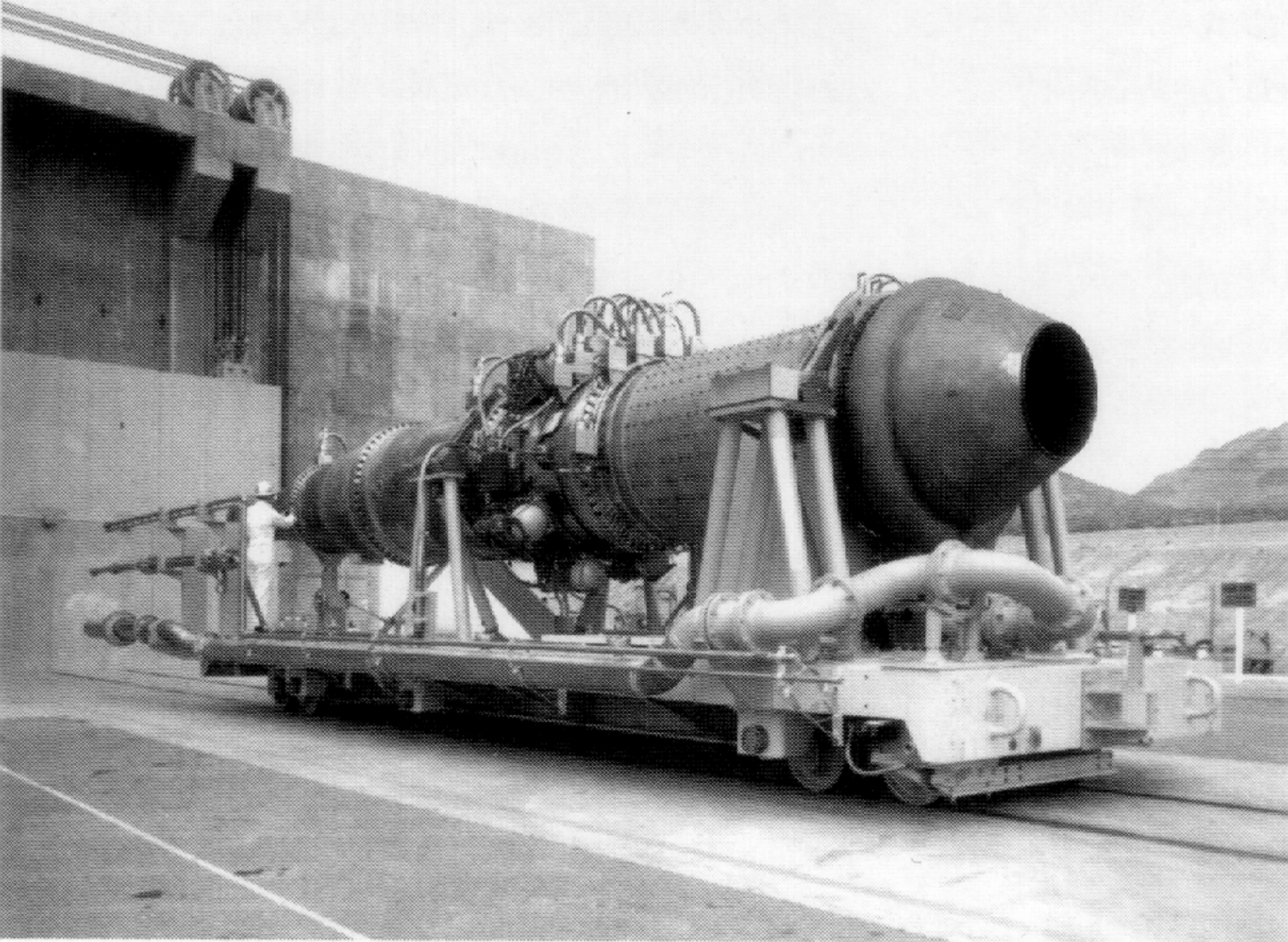


Rocket

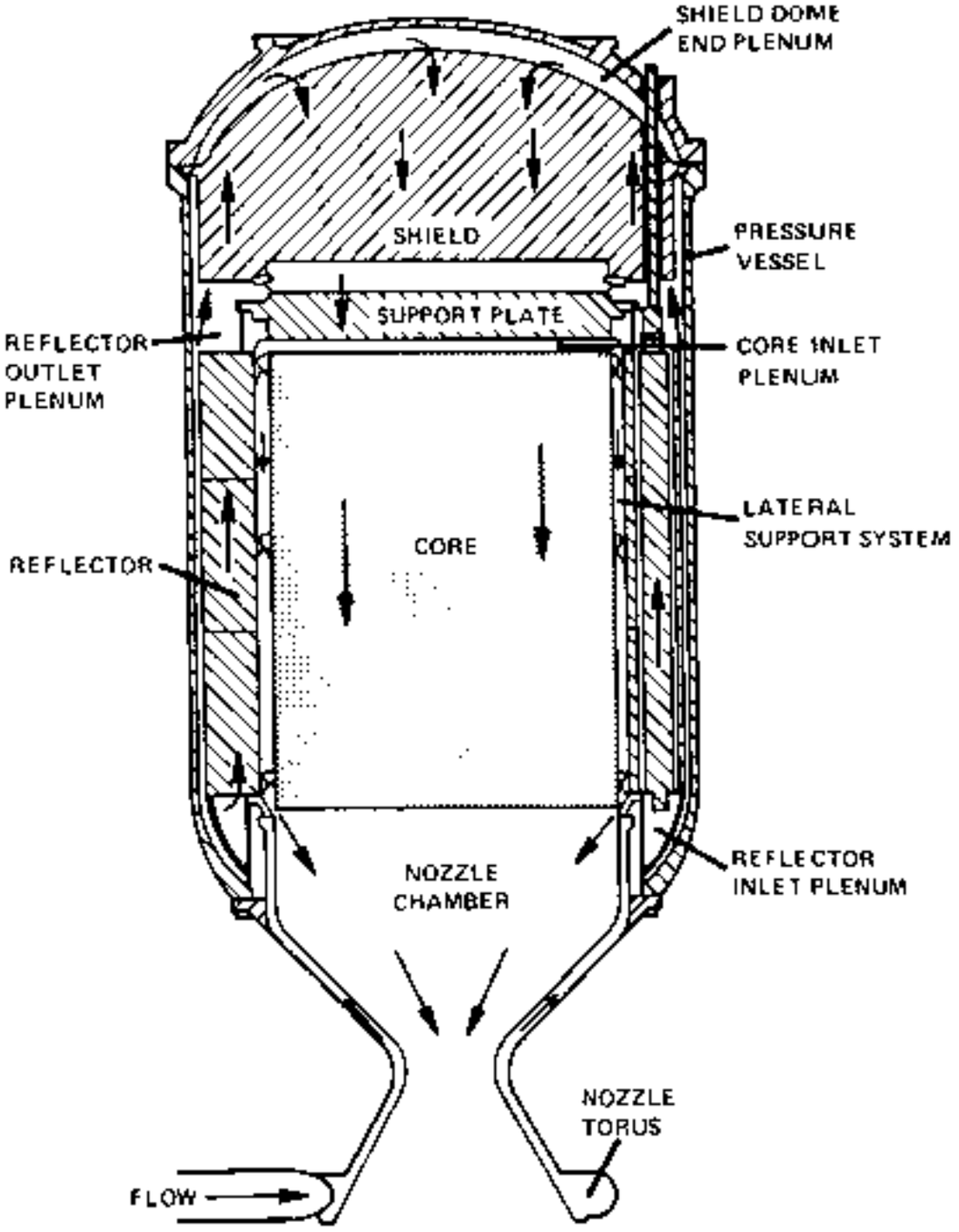
Spacecraft



Electric Thrusters

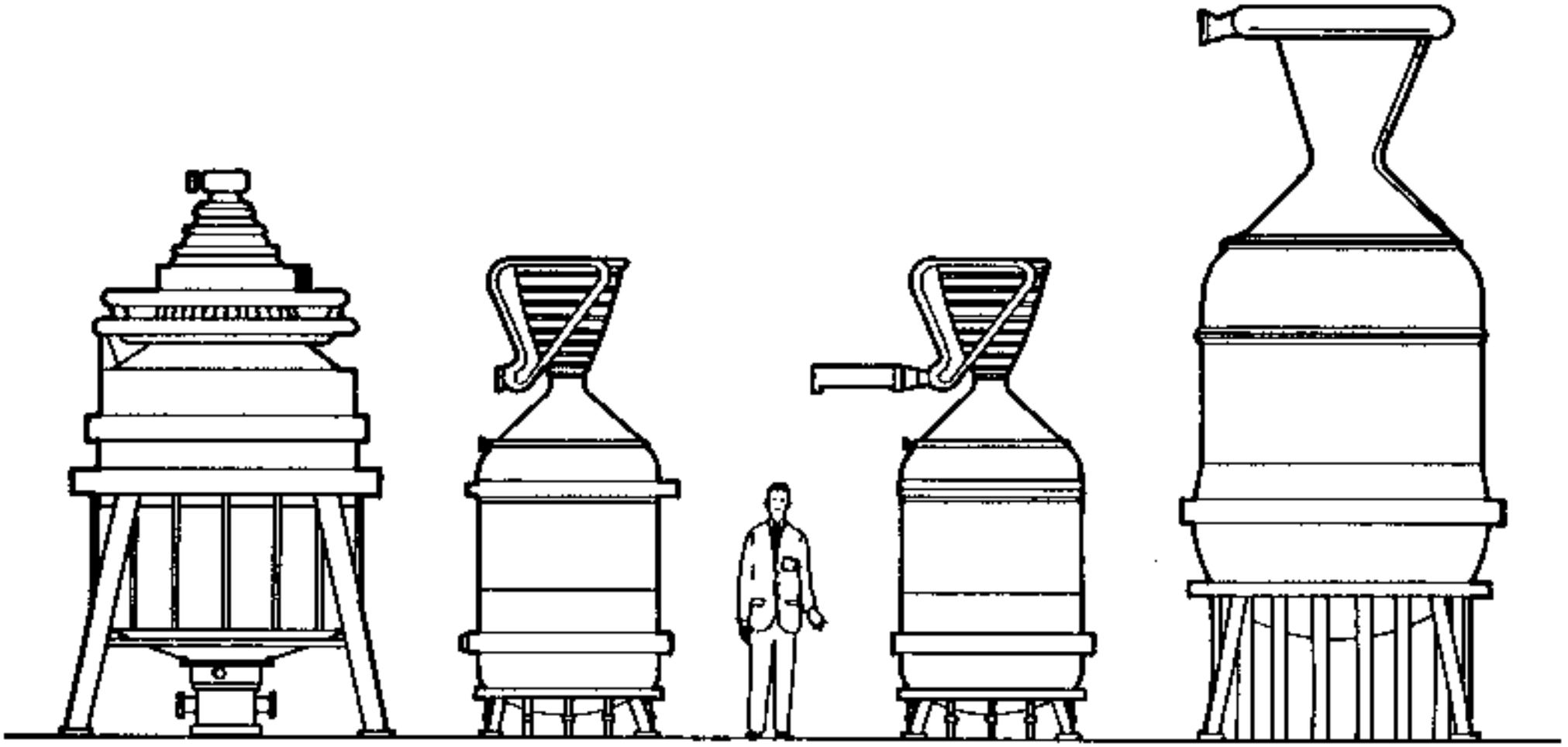


Nuclear Rockets Simply Provide a Heat Source to Heat Hydrogen to Very High Temperatures



Source: Westinghouse , (1967) "NRX-A6 Test Predictions", WANL-TME-1613

Nuclear Rockets Were Developed to a High State of Readiness in the 1960's



KIWI A	KIWI B	PHOEBUS 1/NRX	PHOEBUS 2
1958–60	1961–64	1965–66	1967
100 MEGAWATTS	1000 MEGAWATTS	1000 and 1500 MEGAWATTS	5000 MEGAWATTS
5000 lb THRUST	50,000 lb THRUST	50,000 lb THRUST	250,000 lb THRUST

Source: S. V. Gunn, (1989) "Development of Nuclear Rocket Technology", AIAA paper 89-2386

Achievements of the ROVER/NERVA Program

* **Biggest** ****Phoebus 2, 4086 elements, 4100 MW
* **Highest Thrust****Phoebus 2A-930 kN
* **Highest H_2 Flow Rate****Phoebus 2A, 120 kg/s
* **Highest Specific Impulse***Pewee ≈ 838 s
* **Minimum Reactor Specific Mass***Phoebus 2A, 2.3 kg/MW
* **Smallest** **** Nuclear Furnace, 49 elements (44 MW)
* **Hottest**** Pewee, 2,550° K exit gas, 2,750°K fuel
* **Longest Lived** ****Nuclear Furnace, 109 min
* **Highest Power Density** **** Pewee-1.3 MW/ fuel element
  5,200 MW/m^3 *(fuel)*
* **Greatest Number of Restarts***XE, 28

See Bennett 1994, for further information

HISTORY (CONT.)

1962

- **NASA/AEC NERVA program reorganized. Design smaller reactors for orbital startup, transfer and Lunar missions (LANL,WEST, Aerojet, & Rocketdyne)**

- **AEC SNAP 14 Boiling Rb and K Reactor studies/Aerojet**

1963

- **AEC SNAP -8 Experimental Reactor Test -500 kW_t or 11,000 hrs at 750 °C (NAA).**

- **AEC - Liquid Li cooled fast reactor/ K Rankine Cycle development studies, SNAP -50, (ORNL & PW).**

1964

- **NASA/AEC Rover/NERVA - KIWI -B4E, operates 10.5 min. at 890 MW_t and 2220 ° K exhaust. (West – Nev.)**

- **DOD/AEC, SNAP -9A, isotope RTG, abort and burnup**

- **AF loss of space nuclear power req'ts & loss of AF $$$**

- **Congress support of SNAPSHOT test of SNAP -10A**

HISTORY (CONT.)

1965

- **Jan 1, SNAP -10A, 10FS -3 start (operate 1 y in vacuum & no active control. After 10,000 hr post mortem reveals at least 5 y life.**

- **April; SNAP -10A, 10FS -4 launched into 750 mile, 3,700 y orbit. System started in orbit at 500 W_e(NAA). At last minute, AF added exp to test ion engine. After 43 days of operation, identical to 10FS -3, the AF exp was started up. Faulty voltage regulator commanded reactor to eject reflectors and permanently shut reactor down (Lockheed).**

- **AEC/NASA Rover/NERVA Phoebus 1A & 1B ran 30 min at 1460 MWt and 2440 °K exhaust.**

1966 **AEC de-emphasized SNAP program.**

1967

- **AEC/AF SNAP hardware research program ended.**

- **AEC, Thermionics research down selected to GA.**

- **AEC, K Rankine research downselected to incore boiling K, Midpower Reactor Expt. -MPRE (ORNL)**

1968

- **AEC SNAP -19B2, Isotope RTG Nimbus -B-1 abort and retrieval.**

- **NASA/AEC , Rover/NERVA Phoebus 2 ran 32 min; 12 min at 4,000 MW_t (LANL,West., Aerojet).**

- **NASA/AEC , Pewee 1, ZrH moderator ran for 2 (20 min) runs at 500 MWt and 2550 ° K exit.**

- **Thermionics Fuel Element (TFE) begin.**

HISTORY (CONT.)

1969	**• NASA/AEC, SNAP -19B3 Nimbus III orbit success.**
1969-72	**• NASA/AEC, SNAP -27 successful lunar landings on Apollo 12, 14, 15, 16, 17.**
1972	**• Thermionic 2E2 series demonstrate 1 y in core life.**
	• NASA/AEC NERVA - Nuclear Furnace test; 54 MWt, for 108 min., 2200- 2400 °K (LANL, West.)
	• NASA/AEC , SNAP -19 isotope RTG pioneer -10 probe to Jupiter.
	• Entire Aerospace Nuclear Reactor program stopped.
1973-1980	**• NASA/DOE successful SNAP RTG's, Pioneer and Voyager probes, and Viking Mars landers.**
1978-1982	**• NASA/LANL Space Reactor studies (SPAR). Heat pipe cooled fast reactor thermoelectric conversion.**
1982	**• DARPA/NASA, RFP for Tech. Adv. Space Power Studies**
1983	**• Mar., Pres. Reagan, Strategic Defense Initiative Speech**
	• Mar., DARPA/DOE/NASA 4 Major awards (GE, West., GA, Razor Inc.)
	• May, NASA/DARPA, assessment of Multi Megawatt Class Nuclear Space Power Systems.

HISTORY (CONT.)

1984

- **SDI authorized.**
- **SDI/AF Integrated Total Energy Space Power System Assessment. (TRW, West.)**

1985

- **DOE/NASA/SDI down-selected SP -100 to Li cooled fast reactor -1450 ° K - SiGe thermoelectrics (GE).**
- **SDI/DOE, Evaluation of Effluent Effects on Spacecraft.**

1986

- **SDI/DOE, TFE Verification program, (consolation),**
- **SDI/DOE Multi-megawatt Concept Studies(W,GE,B&W)**
- **AF, Survivability of Space Nuclear Power**
- **SDI/AF Space Power Assessment study (SPAS), SDI Burst and steady state Power Requirements, GE , Martin Marietta. TRW.**

1987

- **AF/Lockheed/GA; "Star C" (Thermionic Ramashka)**
- **SDI/DOE Phase I MMW Nuclear Power Awards, (West, GE,Razor Inc. GA, Grumman, B&W) .**
- **Advanced Radiator Design Phase I and 2,**

HISTORY (CONT.)

1988

- **SDI/AF Strong Thermionic Emitter Study.**
- **AF, Nuclear Power Integration Requirements, (Lockheed, TRW) .**
- **SDI/DOE, Low Cost, Low Power, Survivable**

1989

- **SDI/DOE Multi-megawatt (Phase II Awards)**
  Cat I-West- Open cyl. H_2, Burst, NERVA Concepts
  Cat II-Rocketdyne, Li cooled - K Rankine + Bat.
  Cat III-B&W, Grumman Open cycle H_2, Part. Bed
- **Jan. USSR delegation attends US space power reactor conference, offers to sell TOPAZ reactor.**
- **SDI/DOE, SNAP - Topaz reactor and moderator development program.**
- **SDI/AF Survivable Advanced radiator developed**

1990

- **President Bush announces that the US is going to Moon "this time to stay" and to Mars by 2019. (SEI)**
- **Space Nuclear Propulsion prog. revived for SEI.**
- **Ground component test for SP -100 delayed.**
- **Galileo Launched**

1991

- **US purchases USSR Topaz reactor.**
- **U.S. Nuclear Particle Bed Fission Rocket Prog. Declas. "Timberwind"**
- **Russian Nuclear Rocket Program Declassified.**
- **Stafford Report Calls for Nuclear Propulsion Devel.**

HISTORY (CONT.)

1992 • **U.S. Purchases 4 More TOPAZ-II Russian Reactor.**

• **U. S. Purchases 40 kg of ^{38}Pu from Russia**

1993 • **Nuclear Rocket Program Stopped Again**

• **SP-100 Program Discontinued**

• **MMW Program Stopped (for SEI)**

• **More Tests of Topaz**

• **Timberwind (Classified) nuclear rocket project canceled**

1994 • **More Tests of Topaz**

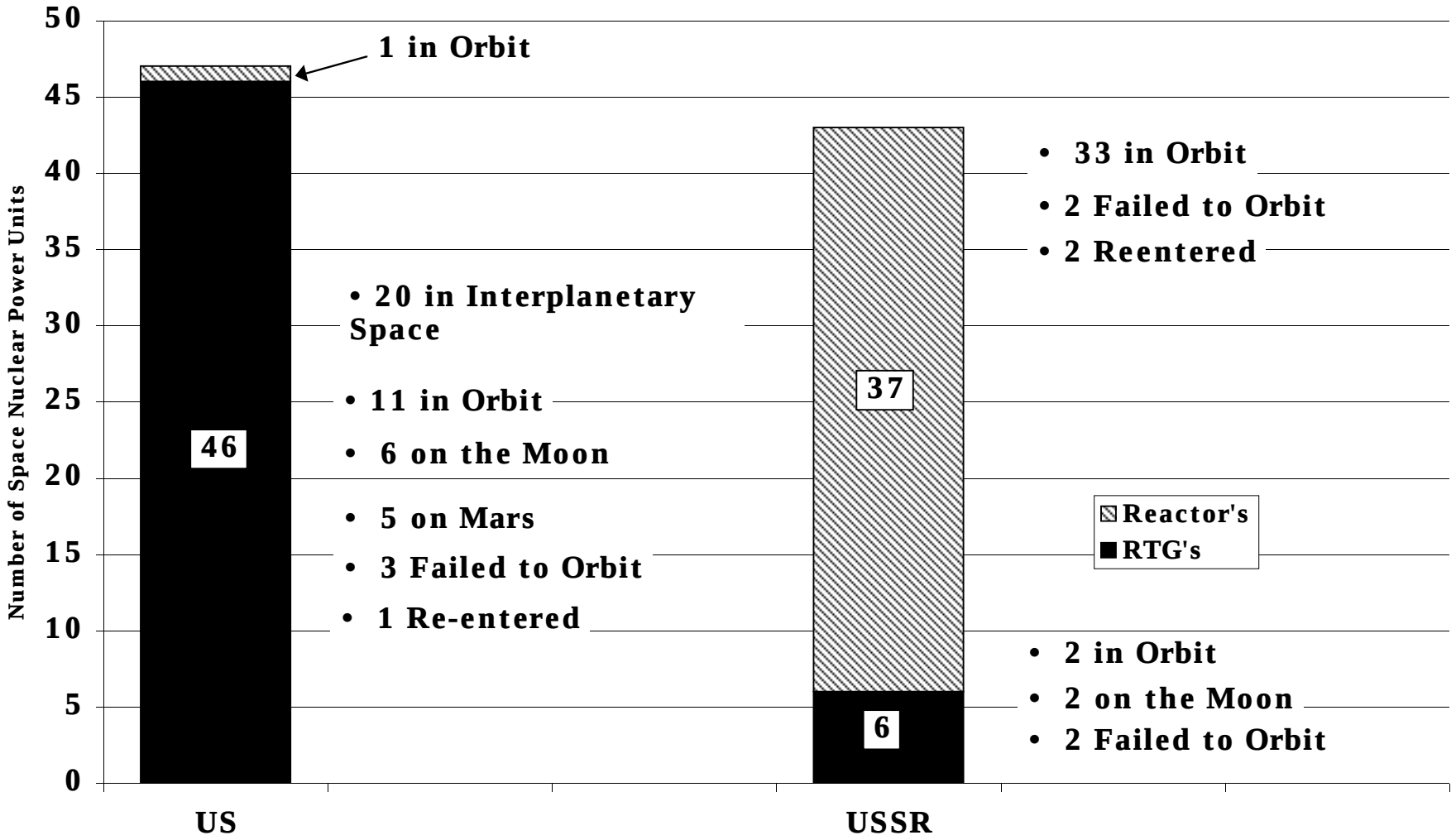
1995 • **Galileo, powered by an RTG arrives at Jupiter**

1996 • **Topaz program canceled**

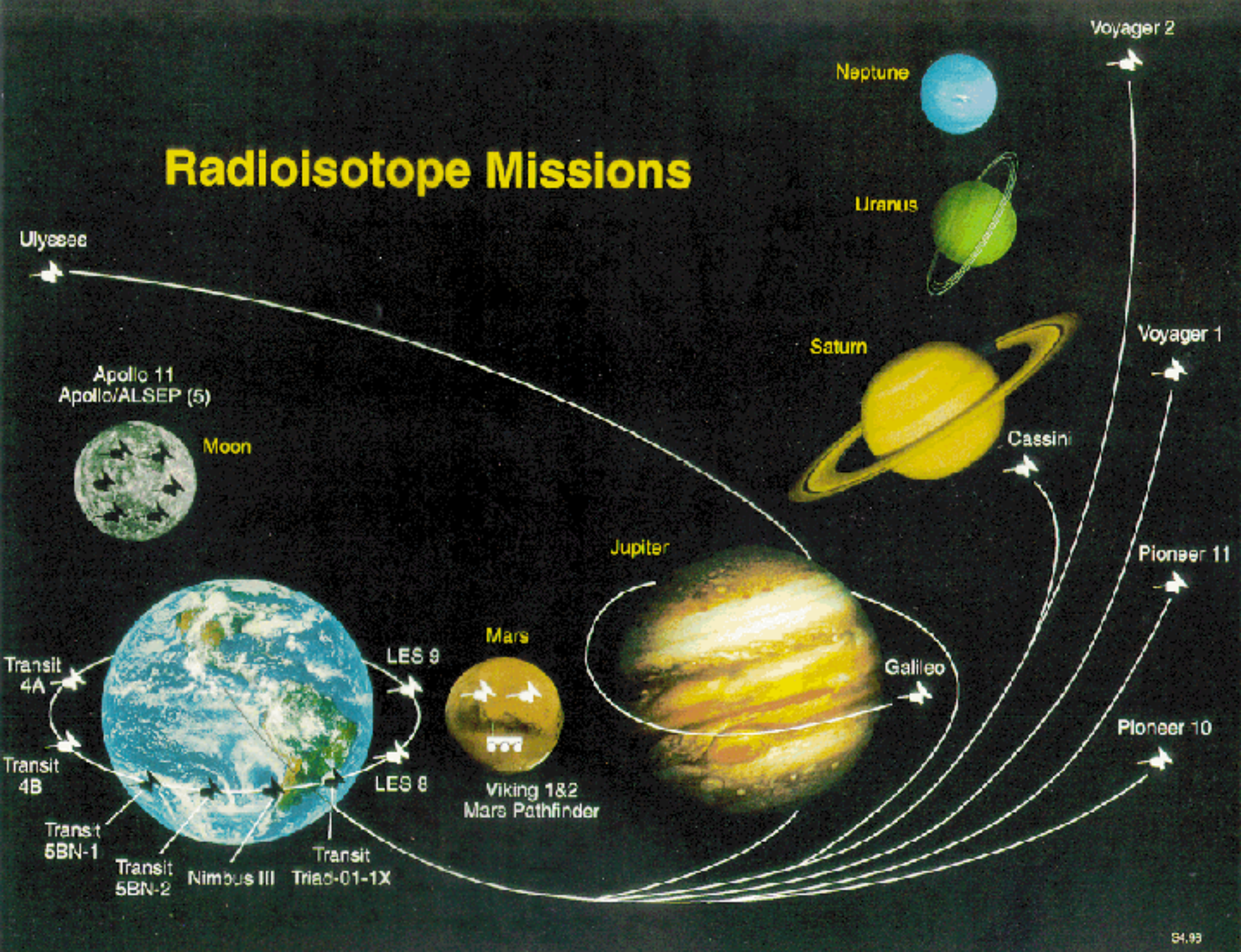
1997 • **Cassini launched (2 RTG's)**

• **Mars Pathfinder lands (RHU's)**

The U. S. and the Soviet Union Took Different Approaches to Nuclear Power Units in Space



Partial reference: G. L. Bennett, (1995), p.515 in CRC Handbook of Thermoelectrics, ed. D. M. Rowe, CRC Press


Radioisotope Missions
Voyager 2
Neptune
Uranus
Ulysses
Saturn
Voyager 1
Apollo 11
Apollo/ALSEP (5)
Moon
Cassini
Jupiter
Pioneer 11
Mars
LES 9
Transit
4A
Galileo
Transit
4B
LES 8
Viking 1&2
Mars Pathfinder
Pioneer 10
Transit
5BN-1
Transit
5BN-2
Nimbus III
Transit
Triad-01-1X
84.93

RTG's Have Had A Remarkable Performance Record

# of Launches	*# of RTG's*	*Power Level/Unit W_e*	*Mission*	*Launch Date/Time Period*
4	**4**	**2.7 (1), 25 (2)**	**TRANSIT (Navigation)**	**1961-4, 72**
1	**2**	**30 (1) 40**	**NIMBUS (Meteorology)**	**1969**
6	**6**	**70**	**APOLLO (Lunar Exploration) [Apollo-11 Heat Source only]**	**1969-72**
2	**8**	**40**	**PIONEER-10,11 (Interplanetary)**	**1972-3**
2	**4**	**40**	**VIKING-1,2 (Mars)**	**1975**
2	**4**	**150**	**LES (Communication)**	**1976**
2	**6**	**150**	**VOYAGER-1,2 (Interplanetary)**	**1977**
1	**2**	**275**	**GALILEO (Jupiter)**	**1989**
1	**1**	**275**	**ULYSSES (Sun)**	**1990**
1	**3**	**296**	**Cassini (Saturn)**	**1997**
22	**40**	**4,160 (Tot)**	**Total**	**1961-1997**
Mission Failures With RTG's				
1	**1**	**25**	**TRANSIT (Satellite Failed to Achieve Orbit)**	**1964**
1	**2**	**40**	**NIMBUS (Vehicle Destroyed During Launch)**	**1968**
1	**1**	**70**	**APOLLO-13 (Mission Aborted En-route to Moon)**	**1970**
3	**3**	**135 (Tot.)**	**Total**	**1964-1970**

After G. L. Bennett (1995), p. 515 in CRC Handbook of Thermoelectrics, ed. D. M. Rowe, CRC Press and www.jpl.nasa.gov/cassini/