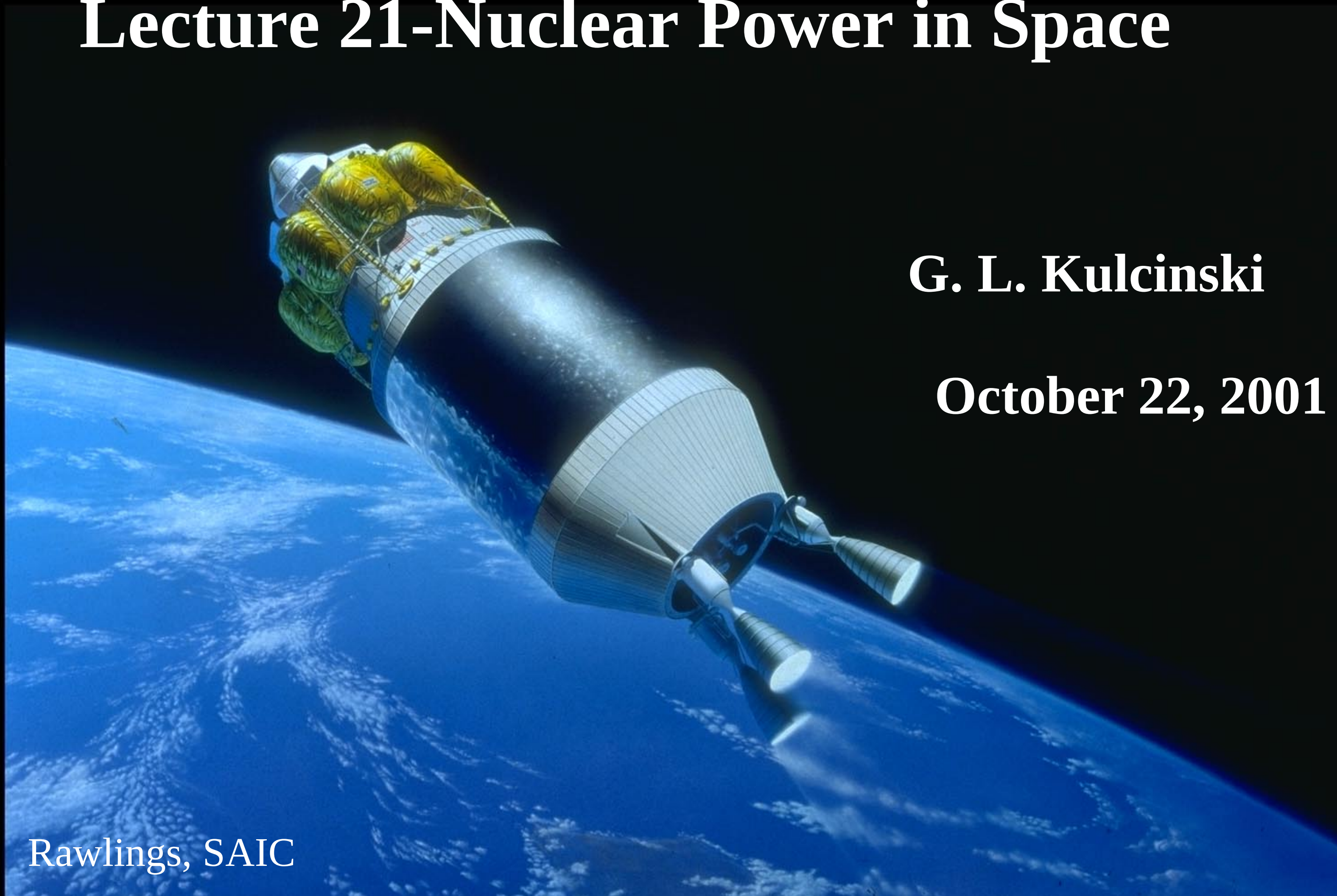
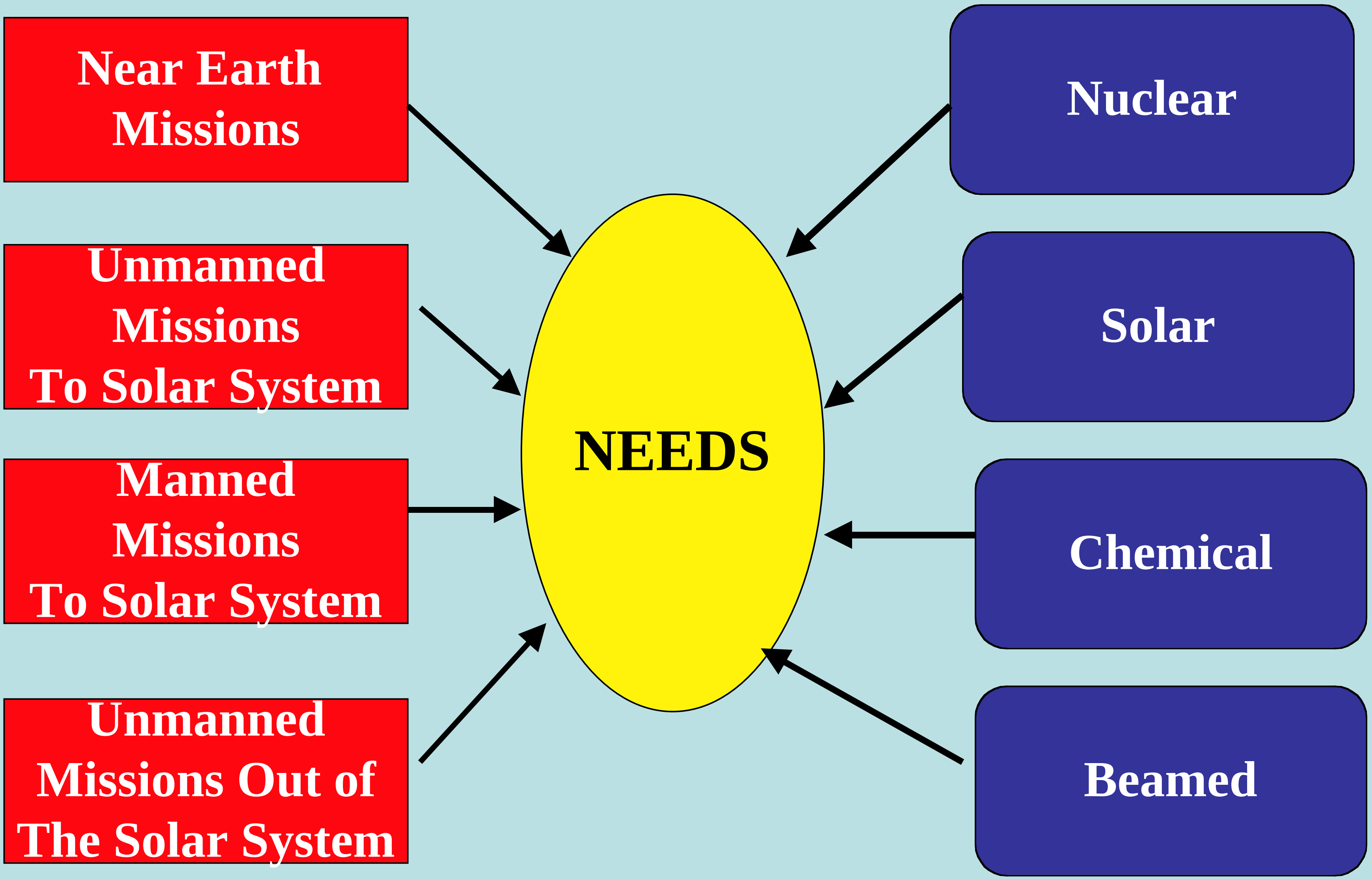
Lecture 21-Nuclear Power in Space

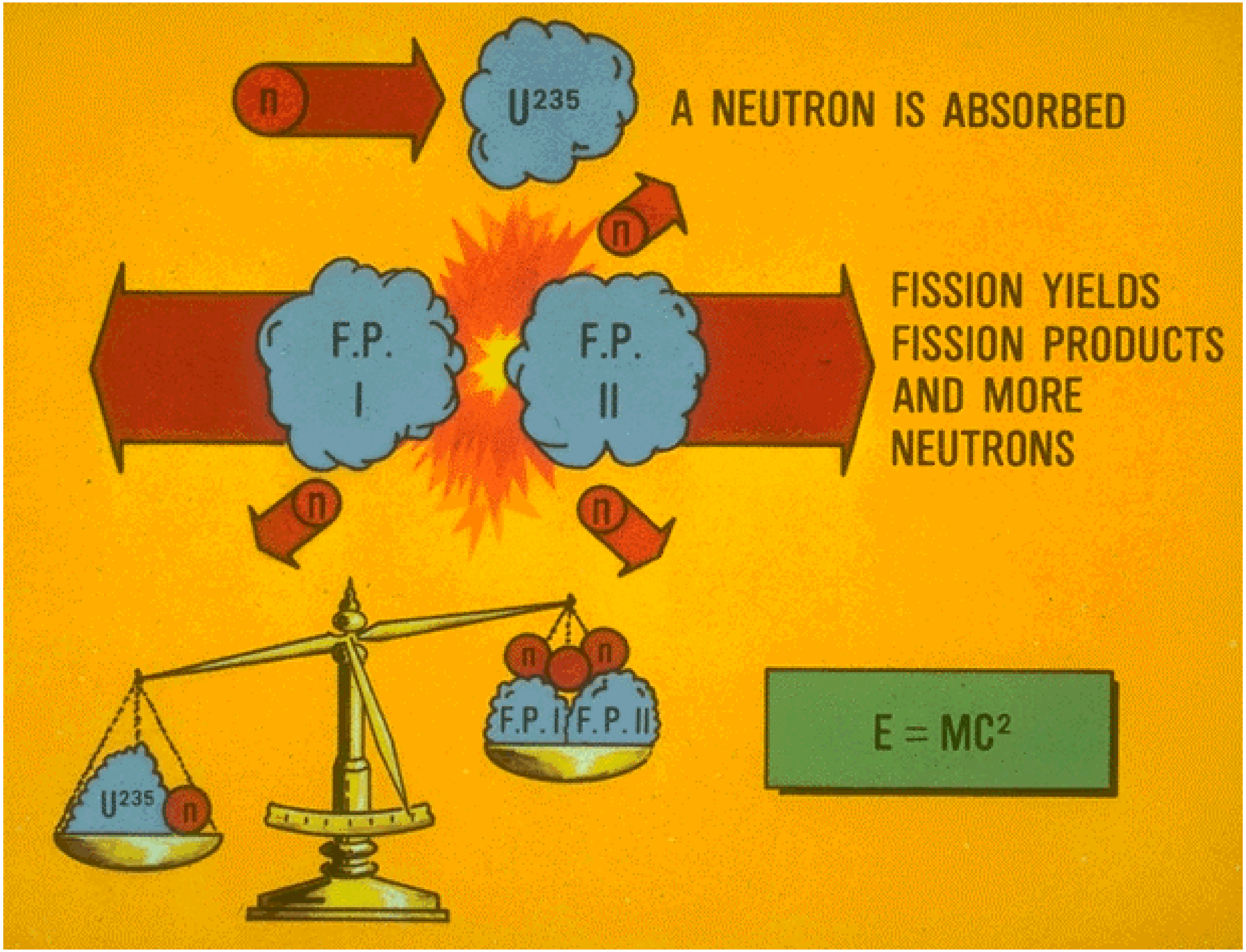


G. L. Kulcinski

October 22, 2001

There are Many Requirements and Solutions to the Power Needs in Space




n
U235
A NEUTRON IS ABSORBED
n
F.P. I
F.P. II
FISSION YIELDS FISSION PRODUCTS AND MORE NEUTRONS
n
n
n
n
F.P. I
F.P. II
U235
n
E = MC2

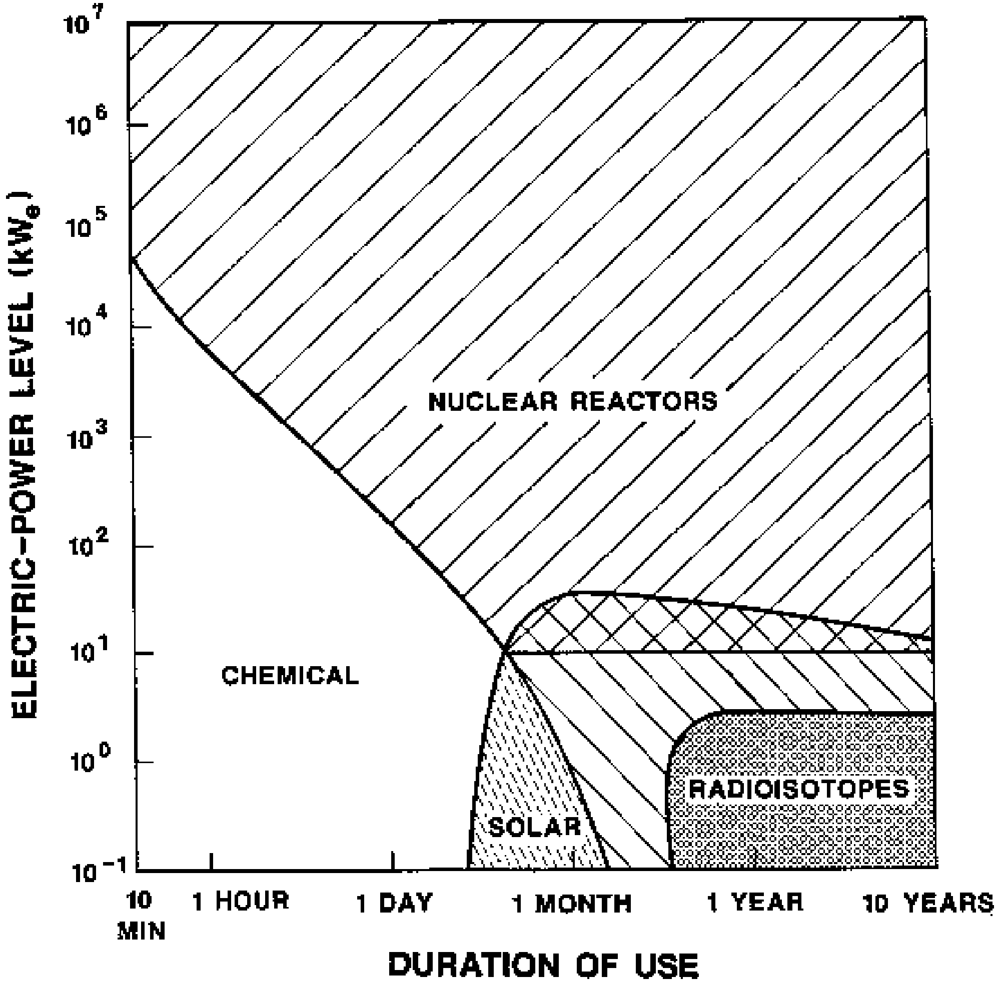
Why Use Nuclear Energy in Space?

1 kg of nuclear fuel contains

10,000,000

times the energy in 1 kg of chemicals

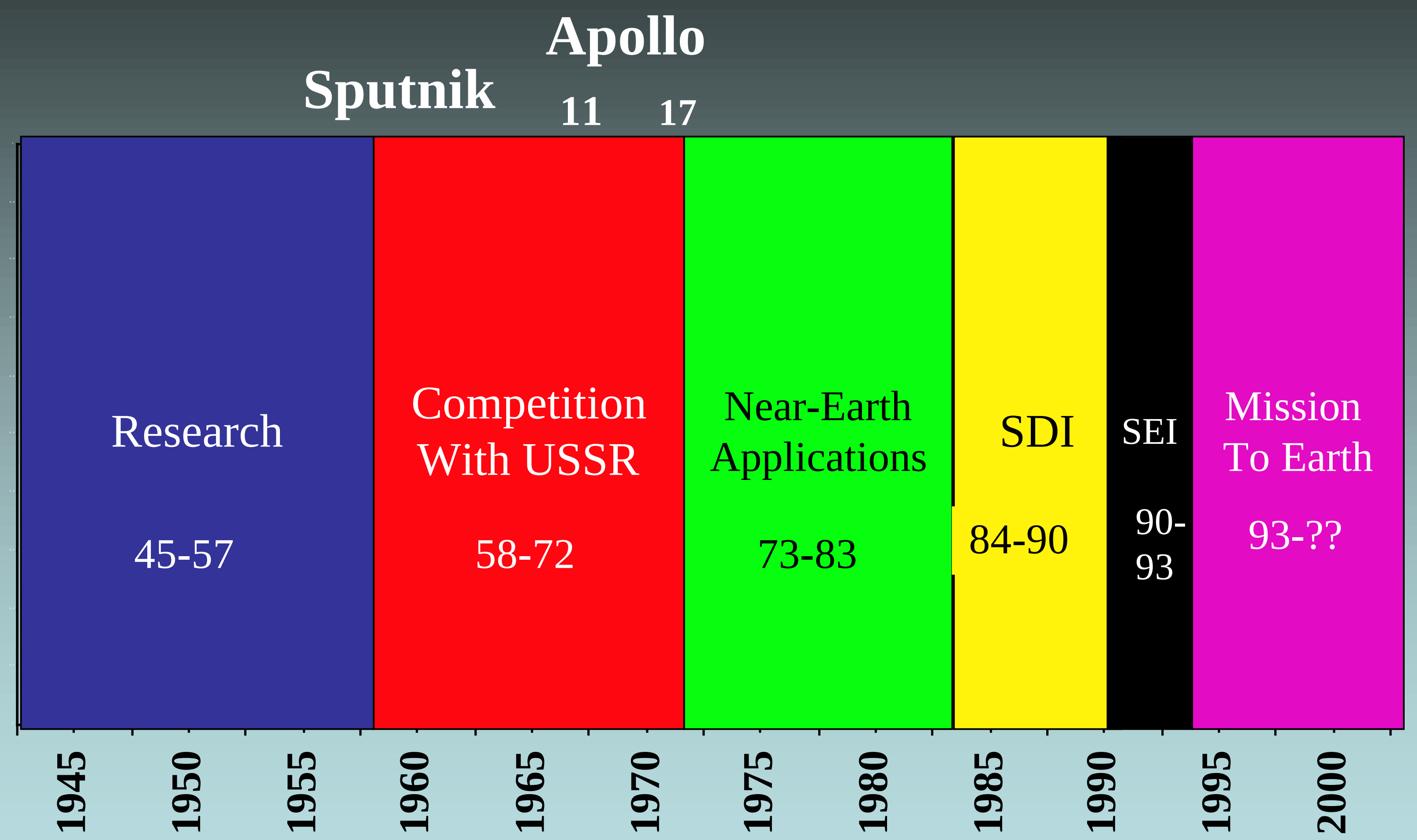
Nuclear Power is Necessary for Human Exploration of Space



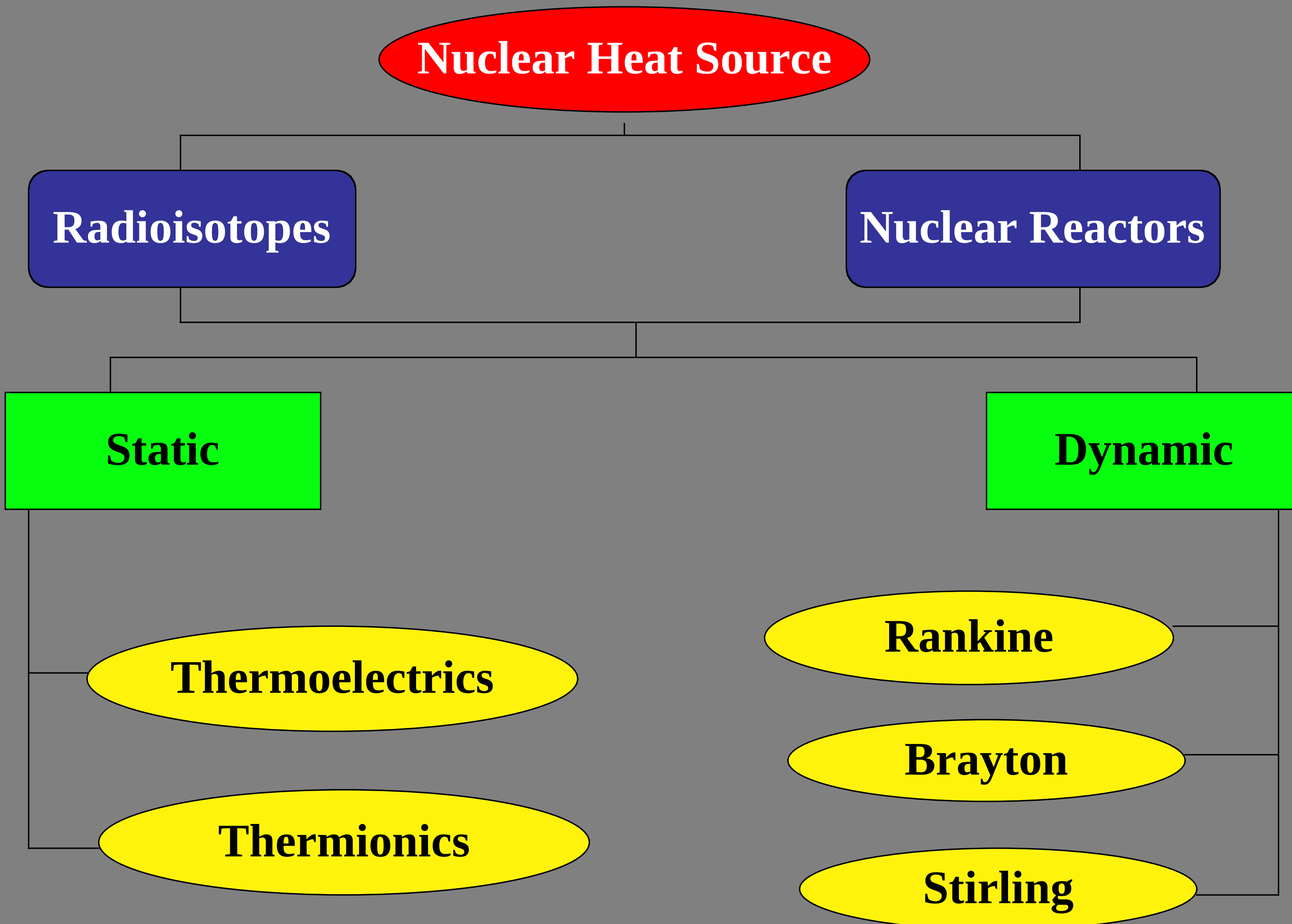
International Space Station Power Requirements

- Total continuous needs->105 kW_e (MIR≈ 30kW_e)
- Two independent PV supplies (US=79 kW_e, Russian=29 kW_e)
- 120 VDC for US, 28 VDC for Russian system
- US array-108.6 by 240 ft (54% of football field)
- Mass ≈ 0.64 lb/ft^2, 7.56 tonnes
- Power density ≈ 100 kg/kW_e
- US system-24 NiH batteries (eclipse, 168 kg, 6.5 y)
- Plus coolant to keep batteries @ 0-10 °C

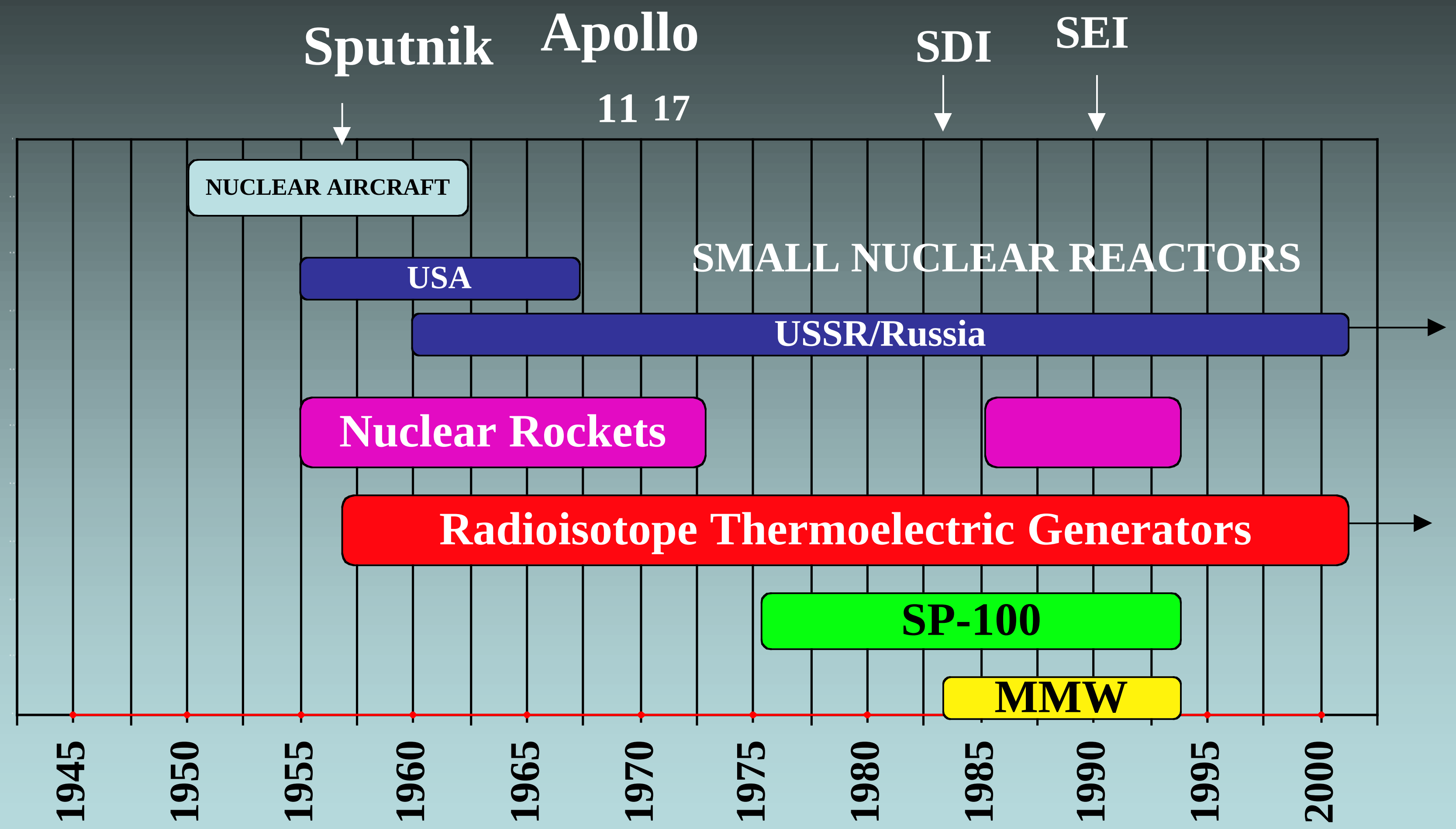
There Have Been Many Driving Forces Behind the Development of Nuclear Power in Space



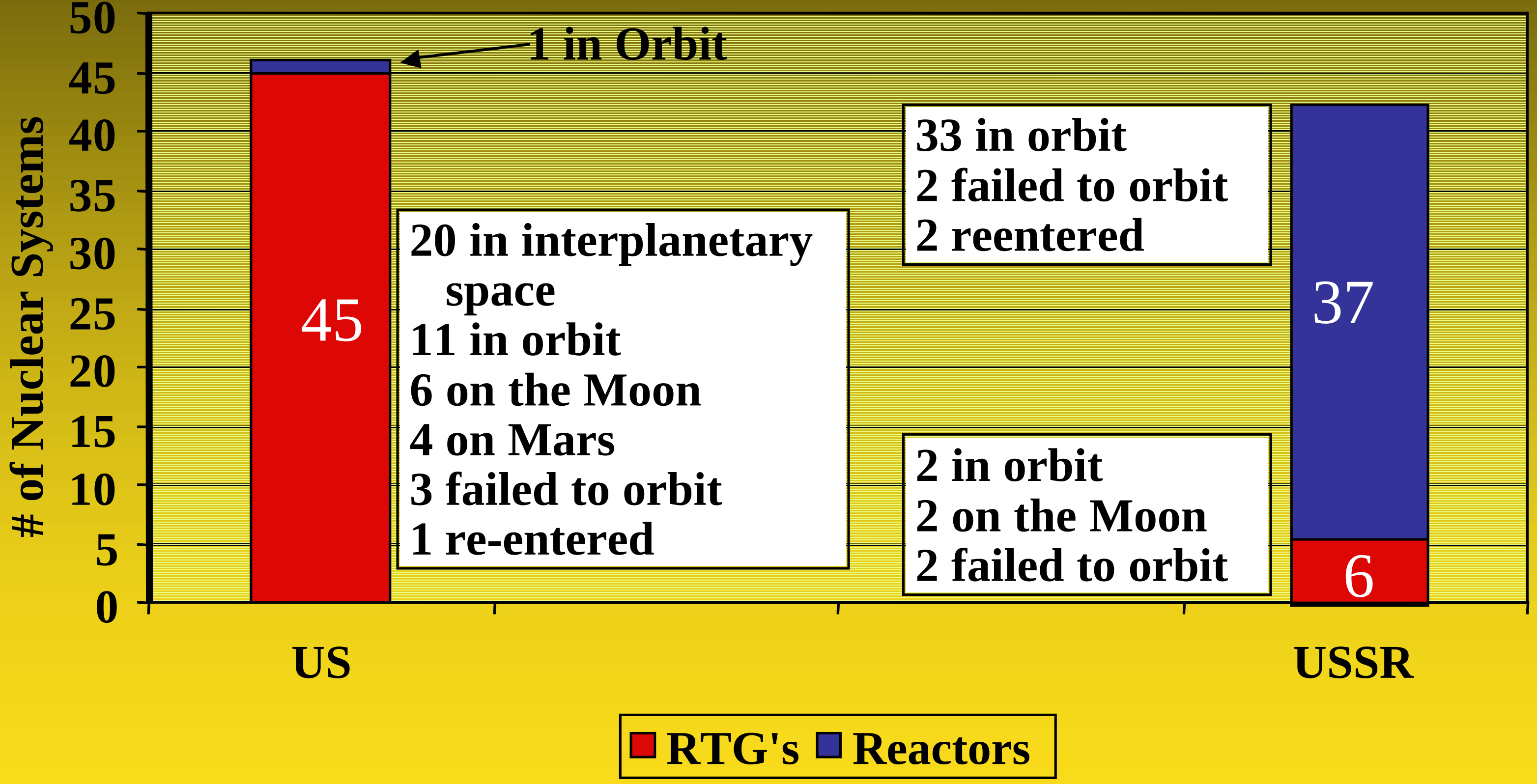
Nuclear Energy Can Be Converted to Electricity in a Variety of Ways



CHRONOLOGY OF SPACE NUCLEAR POWER DEVELOPMENT



The U. S. and USSR Took Different Approaches to Nuclear Power Units in Space



RTG's Produce Power by Radioactive Decay

- Half life of radioactive species:
  - Law of Radioactive Decay $dN/dt = - \lambda N$
  - Integrating, $N(t) = N_o \exp(-\lambda t)$
    - Where the decay constant $\lambda = \ln 2/t_{1/2} = 0.693/t_{1/2}$

- Units of radioactive decay rate:
  - 1 Curie = 3.7×10^{10} disintegrations/s (dps)
  - 1 Becqeral = 1 dps

The Energy Released Depends on the Mass Difference Between Isotopes

- **Maximum energy released in the decay of parent isotope $^{a}X_{z}$ to daughter's $\sum_i {}^{a_i}Y_{z_i}$**

$E = \Delta m \bullet c^2$

$E = (\text{mass } {}^{a}X_{z} - \text{mass } \sum_i {}^{a_i}Y_{z_i}) \bullet c^2$

- **Example:**

$^{238}Pu_{94} \rightarrow {}^{234}U_{92} + {}^{4}He_{2}$ 1 amu=931.5 MeV

Mass $^{238}Pu_{94}$ =238.049555 amu
Mass $^{234}U_{92}$ = 234.040947 amu
Mass $^{4}He_{2}$ =4.002603 amu
Dm = 0.006005 amu or E = 5.59 MeV

Power Generated by Radioisotopic Heat Sources

Power (t) =

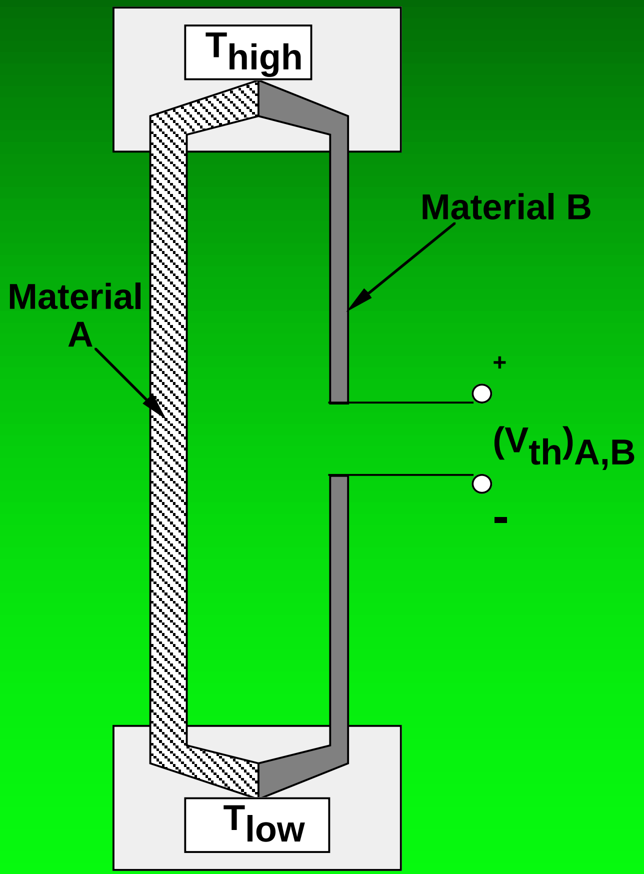
Initial # of Radioisotopes	N_o
Decay Rate, s-1	$\lambda = \frac{\ln 2}{t_{1/2}}$
Energy Released Per Decay MeV	E
Number of Radioisotopes Left After t Years	$\exp -\left(\frac{t * \ln 2}{t_{1/2}}\right)$

$$\text{Power}(t) = \frac{N_o * E * \ln 2}{t_{1/2}} \exp -\left(\frac{t * \ln 2}{t_{1/2}}\right)$$

^{238}Pu-The Radioisotope of Choice for Long Term Space Missions

- Half life-87.4 years
- Decay energy-5.6 MeV
- Specific activity-17 Ci/g
- Specific power density-30 Ci/W
- Power density-0.56 W/g
- Energy content for 10y mission-47 kWh/g
- Useful form-PuO_2 (MP = 2,250 °C)
- Production rate in fission reactor-15 kg/1,000 $Mw_e y$
- Cost of ^{238}Pu-$300/g

Thermoelectricity-A Reliable Way to Convert Heat Energy Directly into Electricity



efficiency = $\eta_{carnot} \cdot \eta_{mat}$

$\eta_{carnot} = (T_H - T_L)/ T_H \approx 50\%$

$\eta_{mat} \approx 10\text{–}20\ \%$

Typical Efficiencies ≈ 5–10%

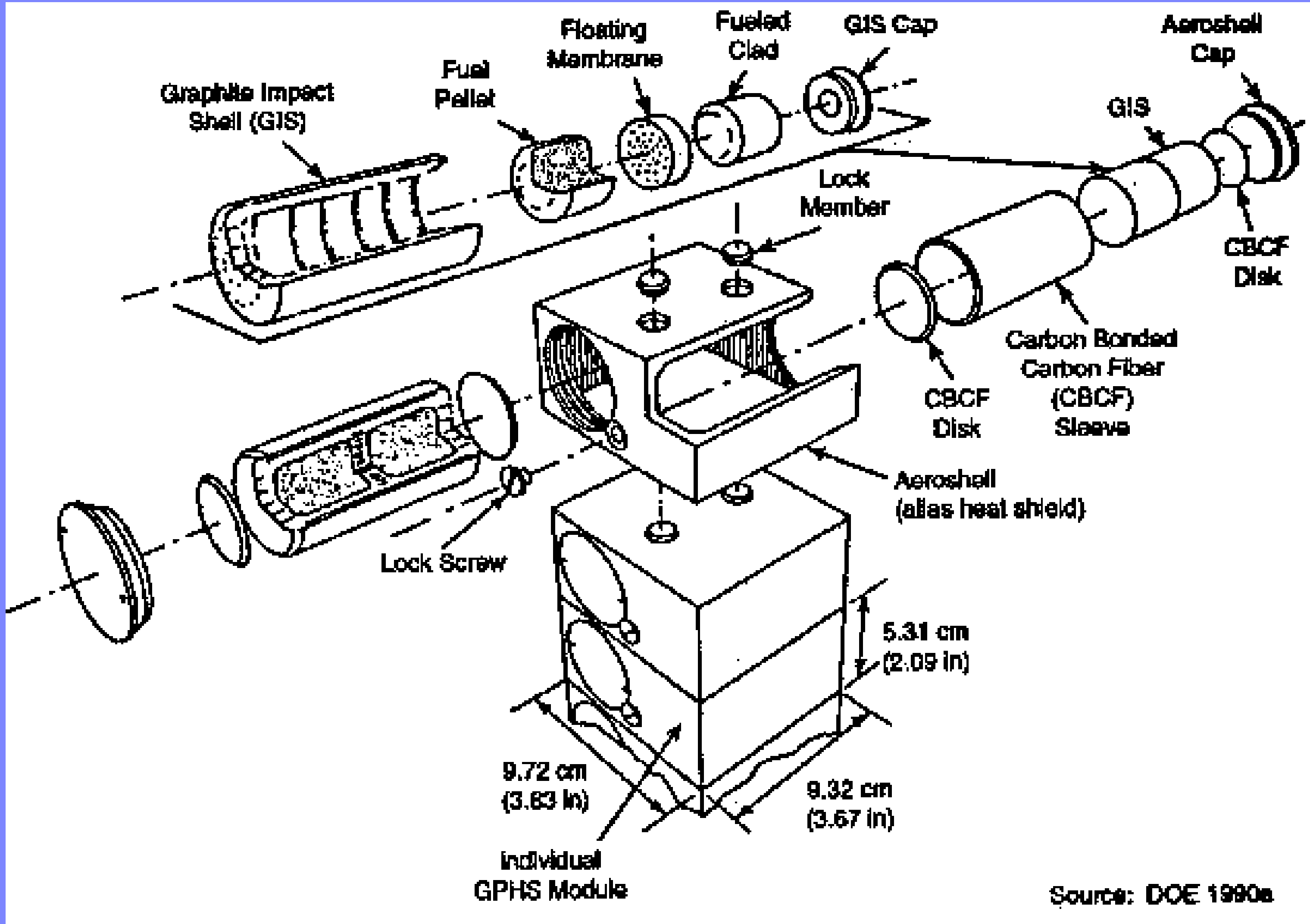
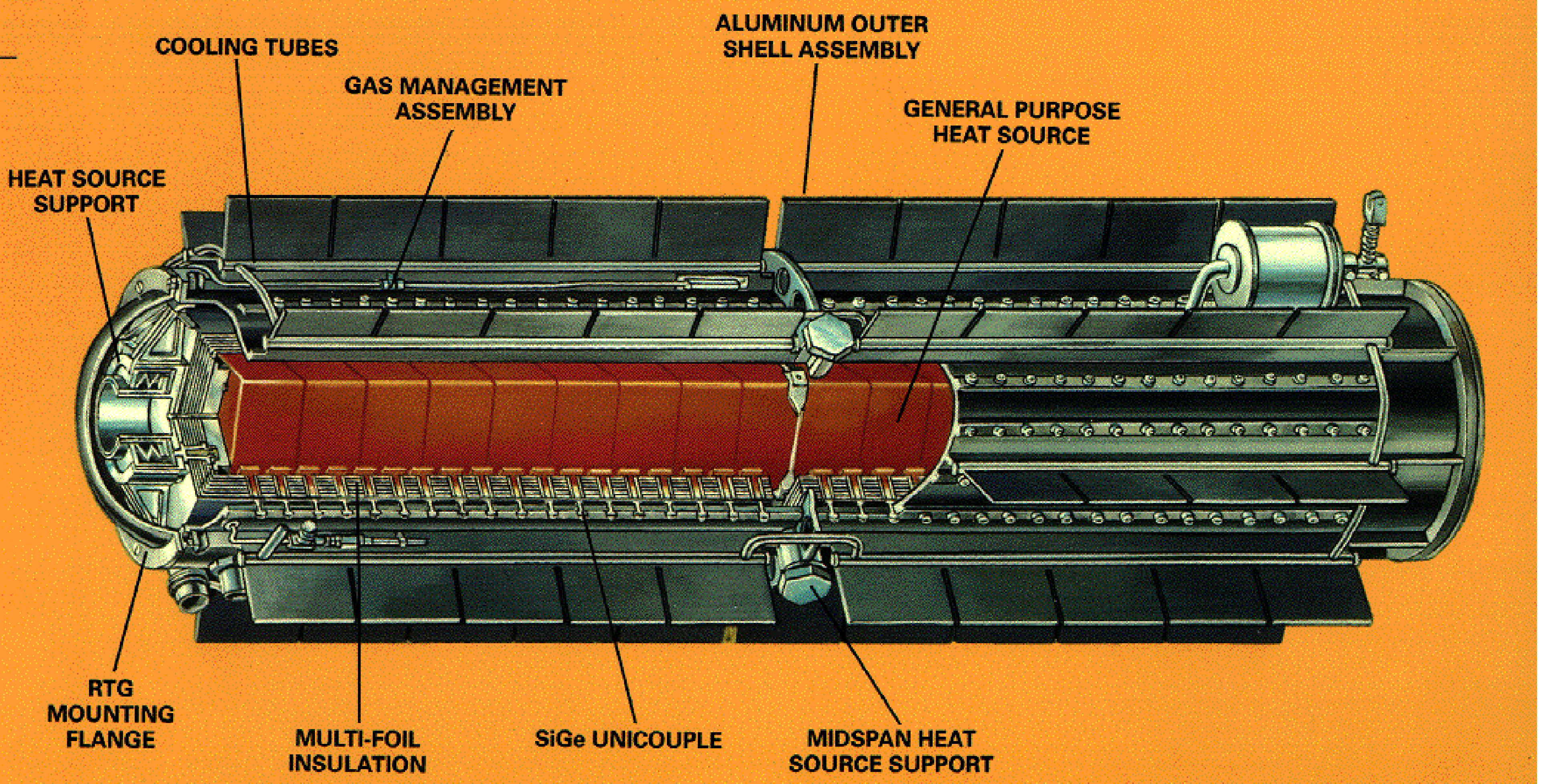


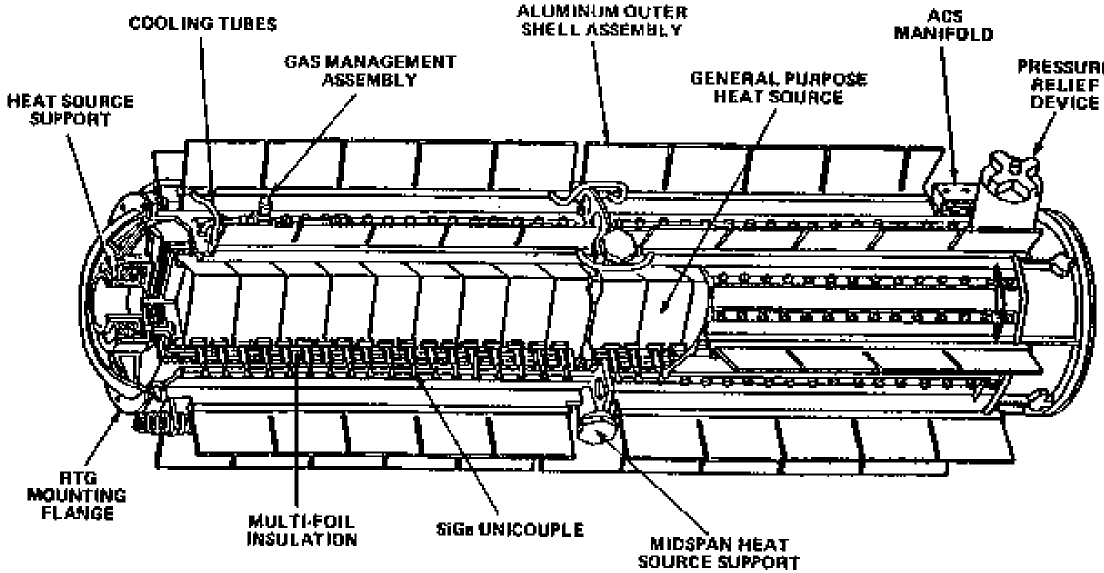
FIGURE 2-6. DIAGRAM OF GENERAL PURPOSE HEAT SOURCE MODULE



Courtesy General Electric

General Purpose Heat Source – RTG

The Galileo RTG Operated Perfectly



- **Power Out BOL/EOL = 290/250 W_e**
- **Mass =55 kg**
- **Dimensions = 114 cm long/42 cm diam.**
- **Hot/Cold Junction T °C- 1000/300**
- **Mass ^{238}Pu - 7.561 kg**
- **Thermal Power = 4,234 W_t**

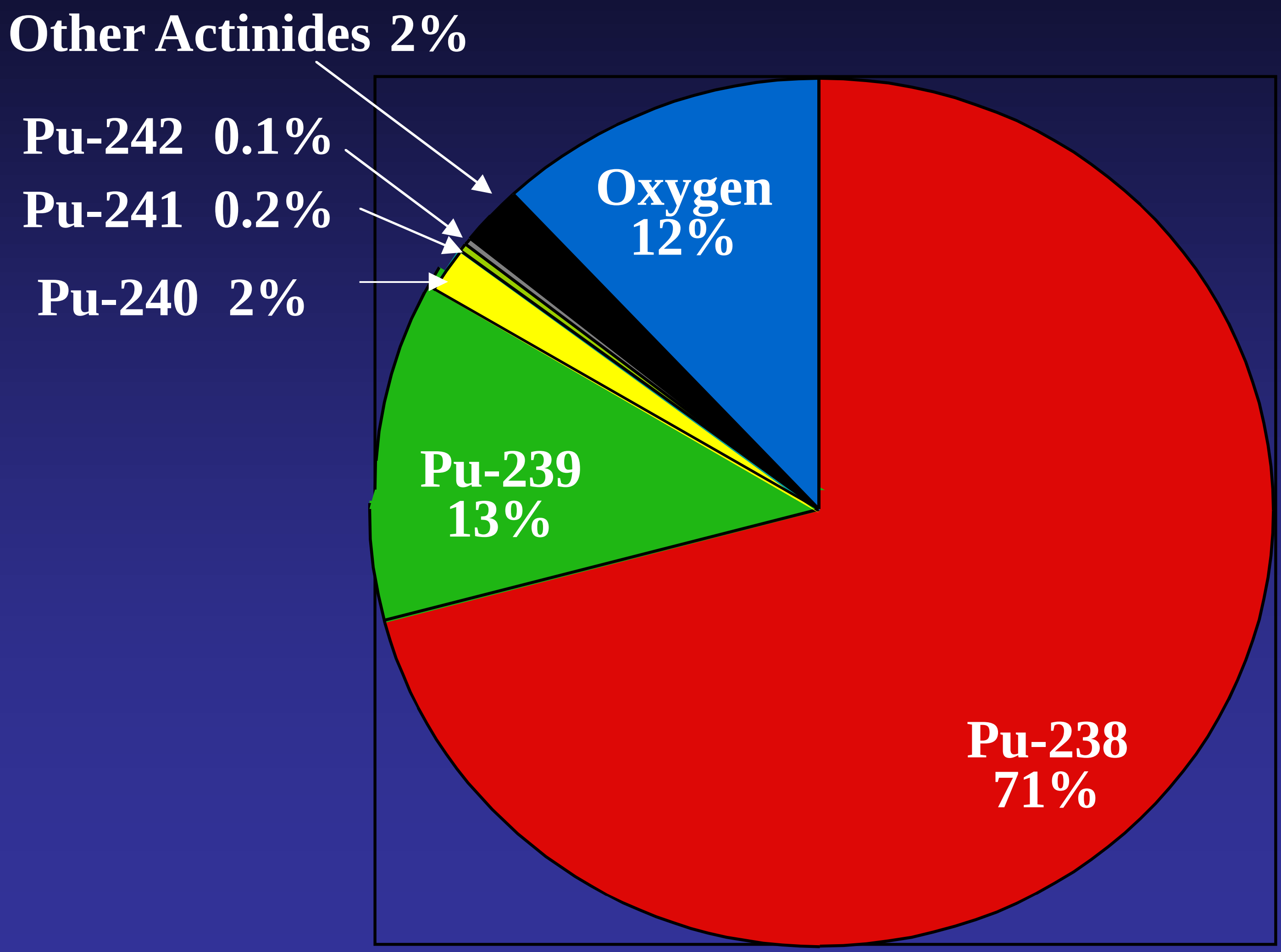
The Cassini Space Craft

RTG's (3)

Cassini RTG Performance Characterisitics

# of RTG's	3
Mass/RTG	56 kg (168 kg total)
Total Power @BOL	888 Watts (electric)
Total Power @ EOL	628 Watts (electric)
BOL Thermal Power	13, 182 Watts
Conversion Efficiency	6.7%
Mass PuO_2/RTG	10.9 kg (32.7 kg total)
Mass Pu/RTG	9.71 kg (28.8 kg total)
Mass of ^{238}Pu/RTG	7.72 kg (23.2 kg total) (21% of all ^{238}Pu already launched)

Cassini Fuel Composition at Launch

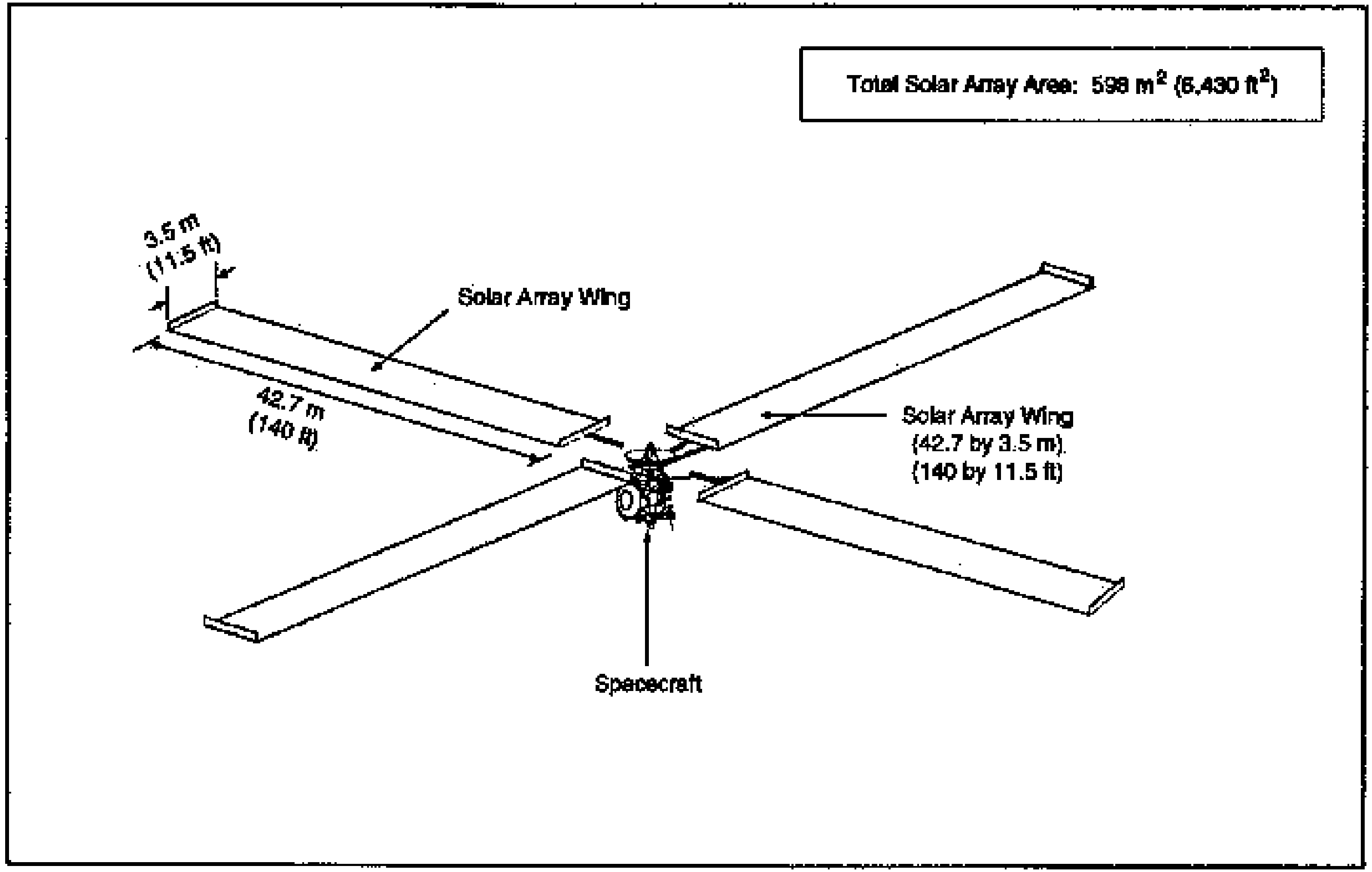


Cassini Electrical Power Requirements

"600-700 W at Saturn (1.6 billion km from sun) for 11 years"

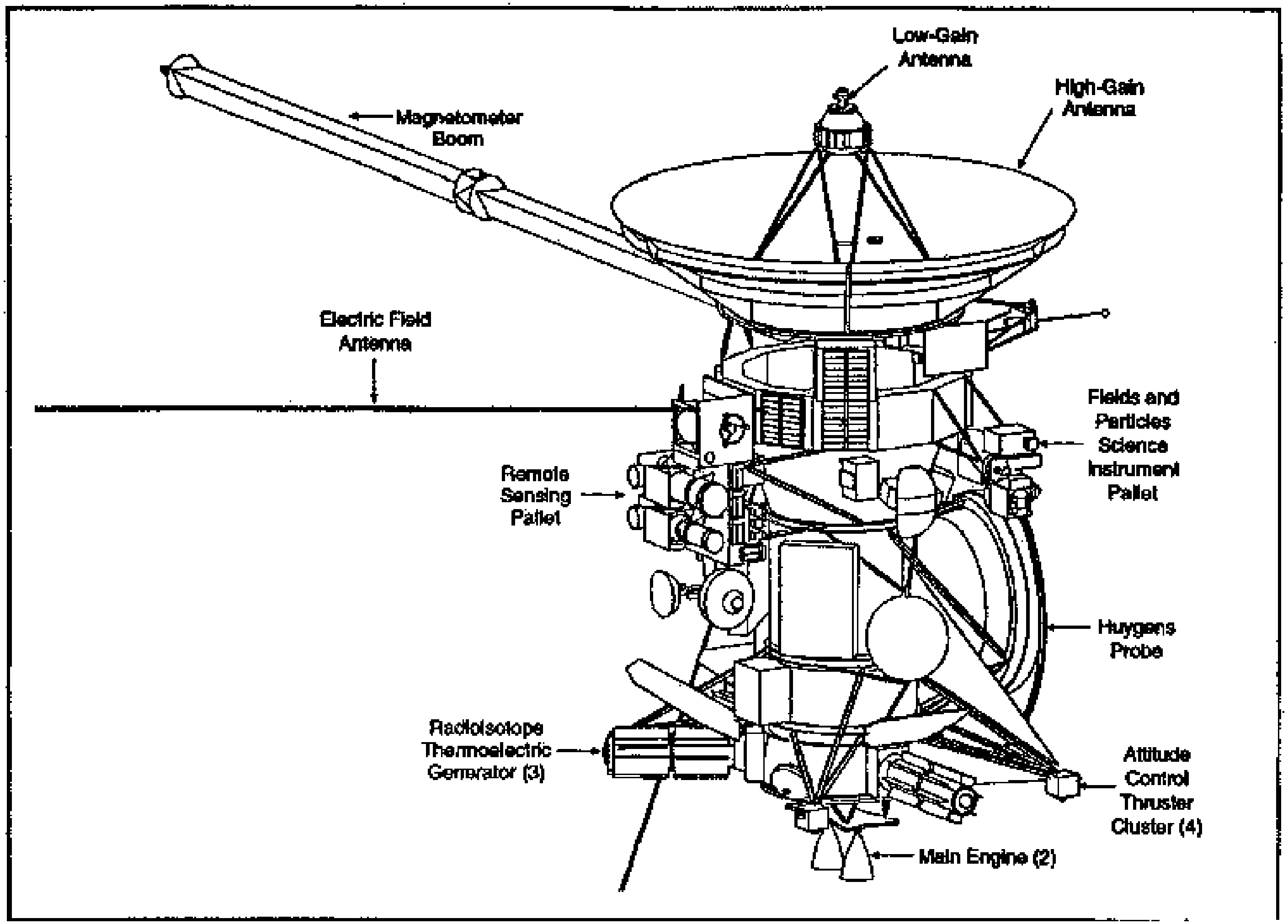
- RTG's
- Mass 168 kg
- Advantages
  - Small size 1.13m x0.43 m dia.
  - No moving parts
  - Easy maneuverability
- Disadvantages
  - Public fear of nuclear

- Solar panels
- Mass 1,337 kg
- Advantages
  - No nuclear material
- Disadvantages
  - No rocket available
  - Slow maneuverability
  - Higher risk of failure



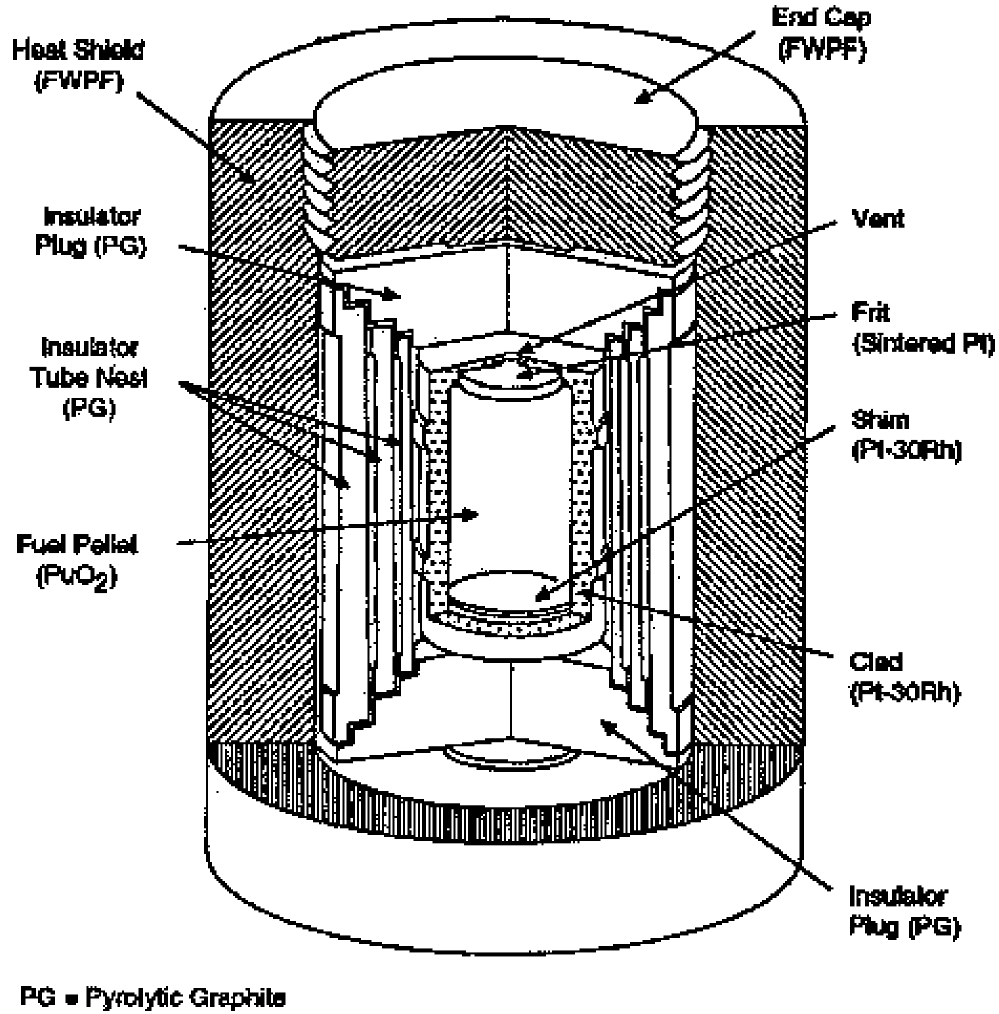
Source: JPL 1994a

FIGURE 2-15. ALL-SOLAR (GaAs APSA) CONFIGURATION FOR THE CASSINI SPACECRAFT



Source: JPL 1993a

FIGURE 2-4. DIAGRAM OF THE CASSINI SPACECRAFT



Source: DOE 1988a

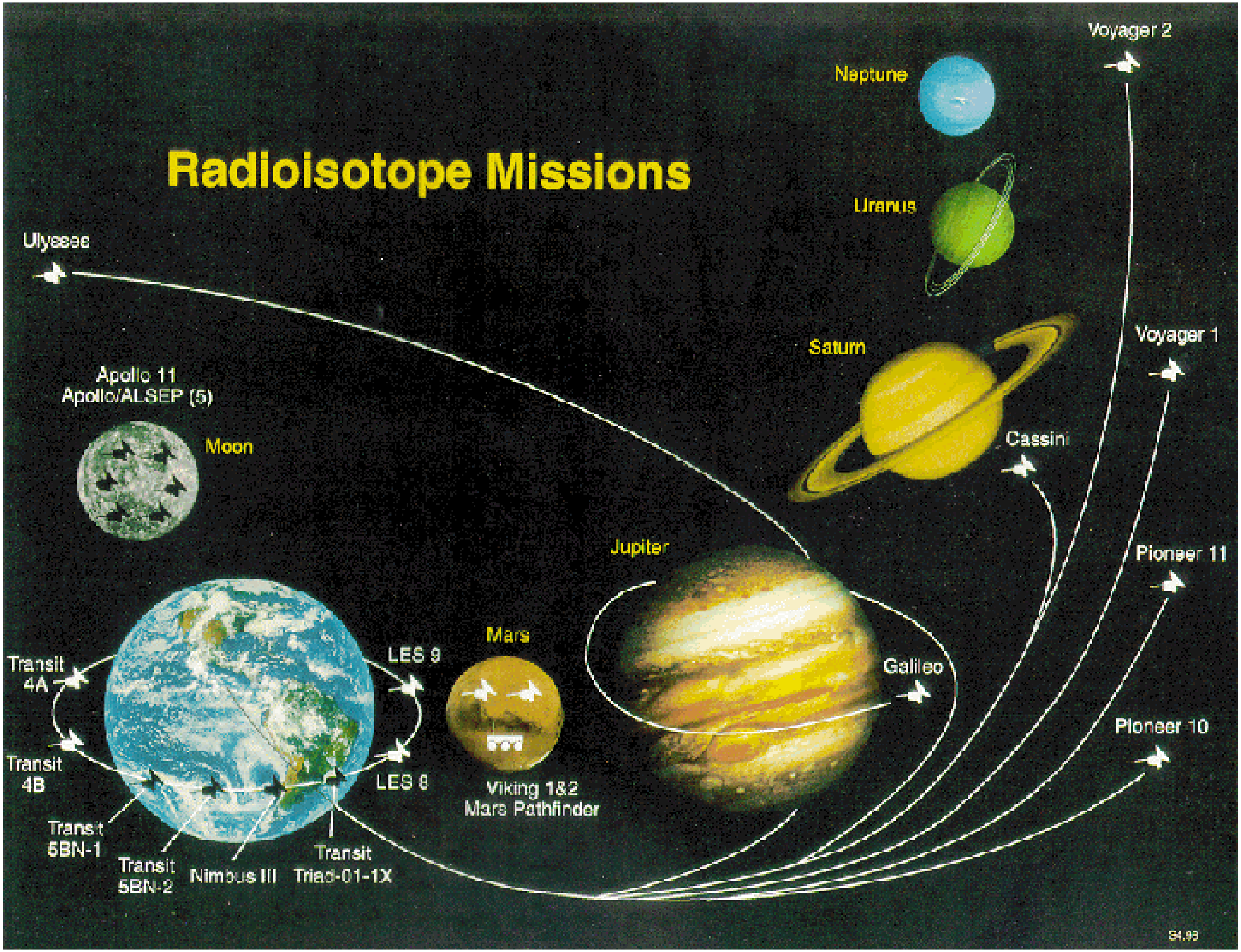
FIGURE 2-7. THE PRINCIPAL FEATURES OF THE RADIOISOTOPE HEATER UNIT

Cassini RHU Performance Characterisitics

# of RHU's	157
Mass/RHU	40 g (6.28 kg total)
Thermal Power @BOL	≈ 1 Watt
Mass PuO_2/RHU	2.7 g (424 g total)
Mass Pu/RHU	2.38 g (374 g total)
Mass of ^{238}Pu/RHU	1.91 g (300 g total)

RTG's Have Had a Remarkable Performance Record

# of Launches	# of RTG's	Power /unit, W_e	Mission	Launch Dates
4	4	2.7, 25,25, 30	TRANSIT (navigation)	1961-4, 72
1	2	40	NIBUS (meteorology)	1969
6	6	70	APOLLO(Lunar Exp., 11 ht 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	4160 tot.		
			Mission failures	
1	1	25	TRANSIT (failed to reach orbit)	1964
1	2	40	NIMBUS (destroyed during launch)	1968
1	1	70	APOLLO-13 (mission aborted)	1970
3	4	135 (tot.)		


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
Pioneer 10
Transit
4B
LES 8
Viking 1&2
Mars Pathfinder
Transit
5BN-1
Transit
5BN-2
Nimbus III
Transit
Triad-01-1X
94.93