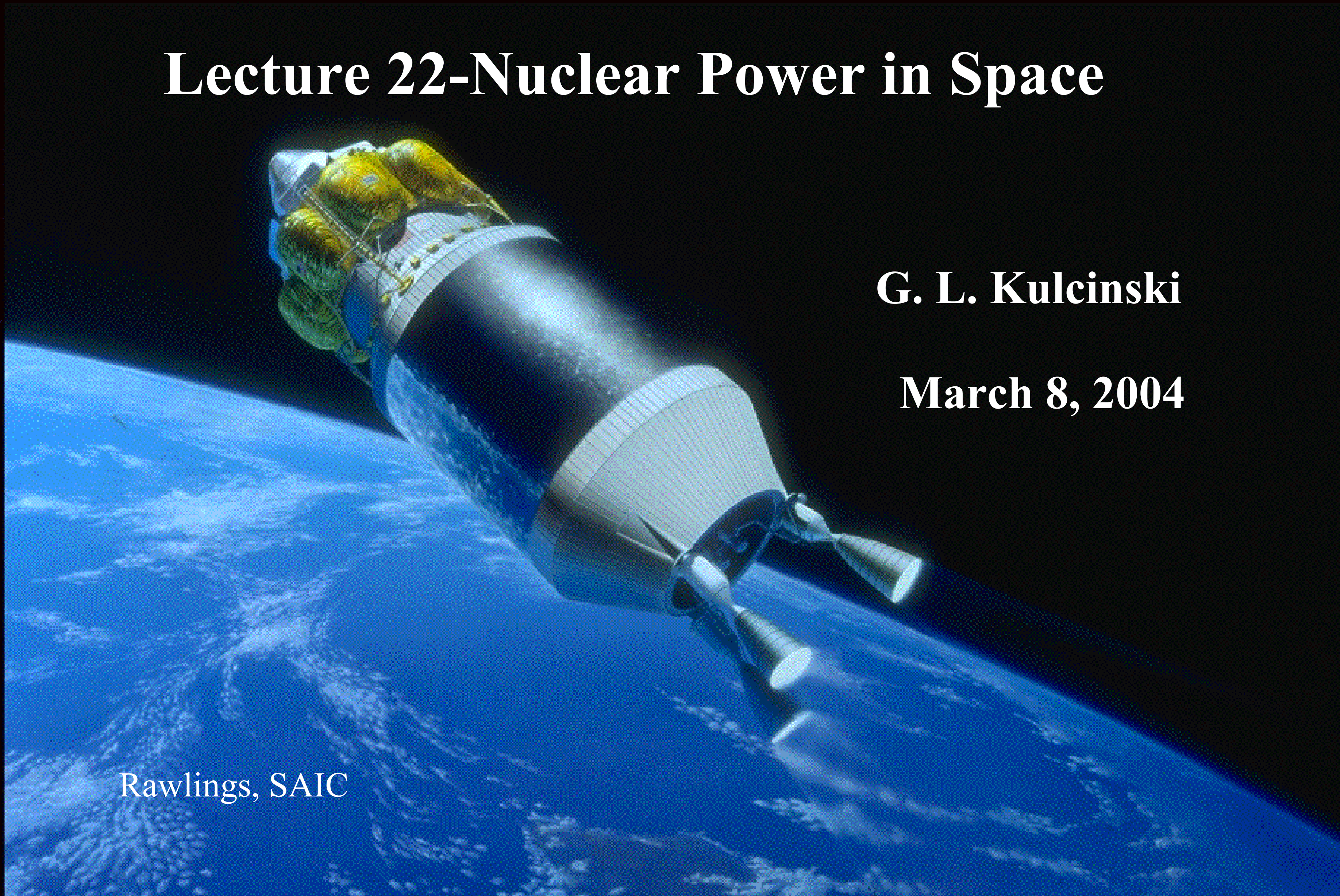
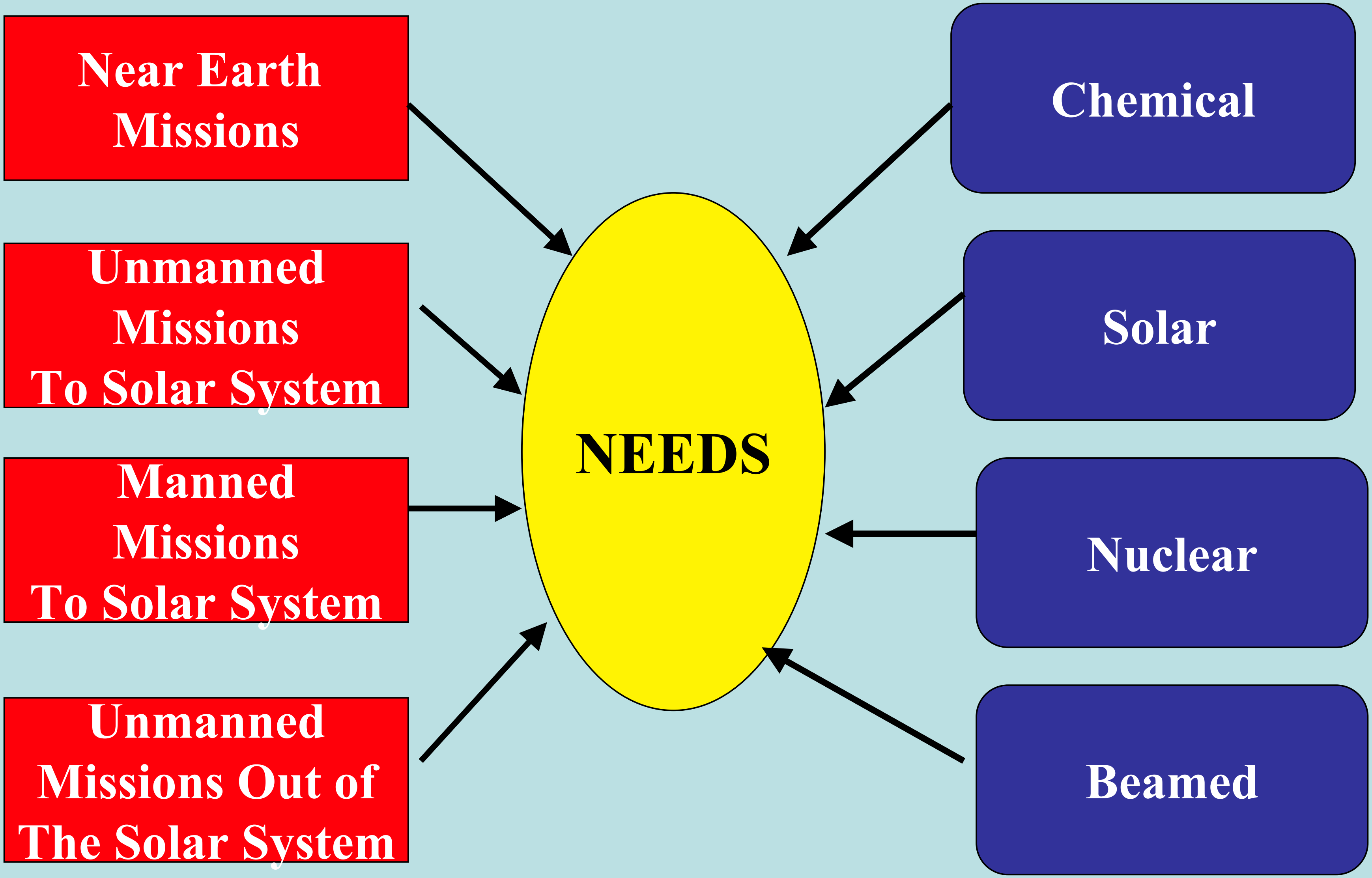
Lecture 22-Nuclear Power in Space

G. L. Kulcinski

March 8, 2004



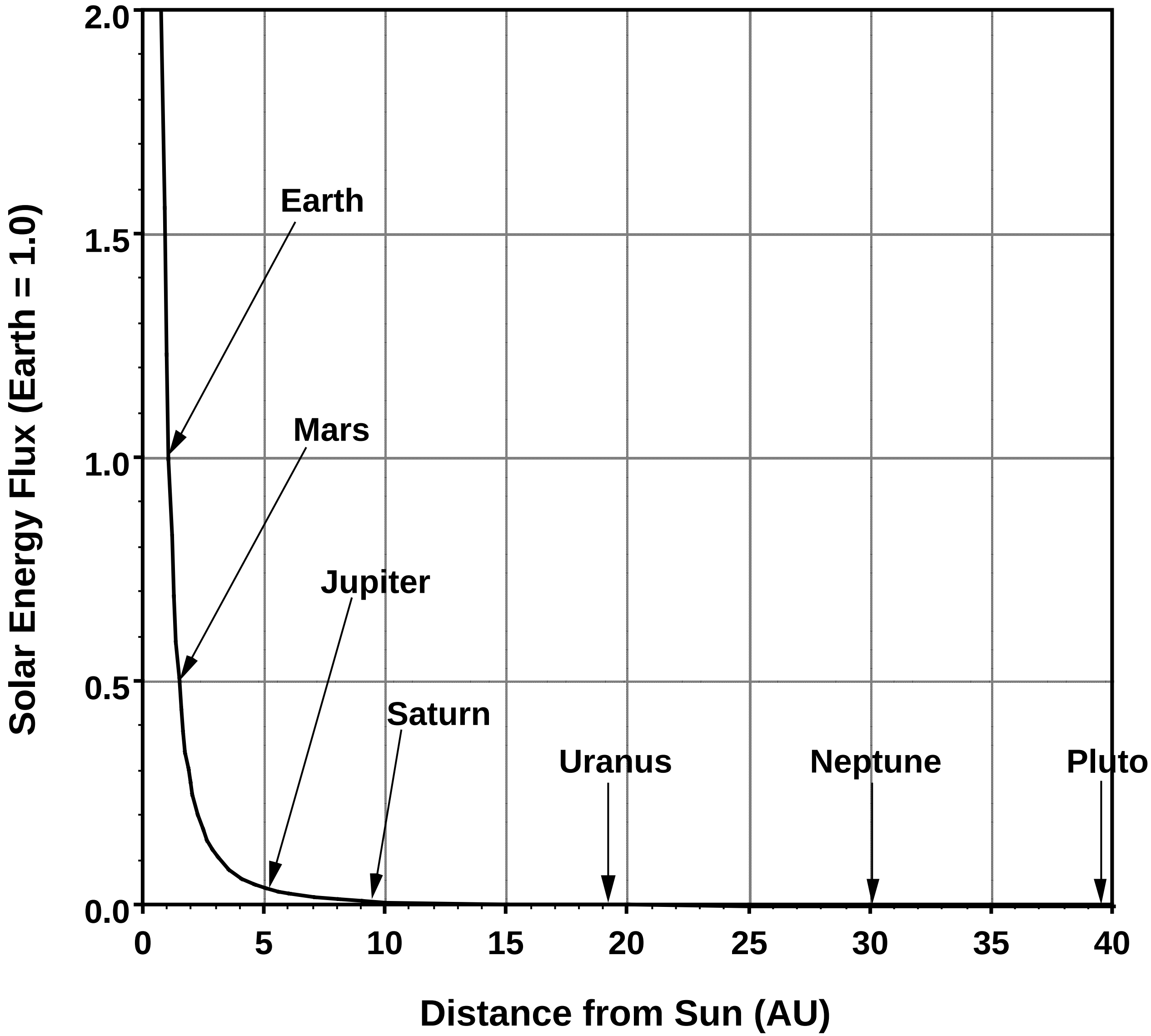
There are Many Requirements and Solutions to the Power Needs in Space



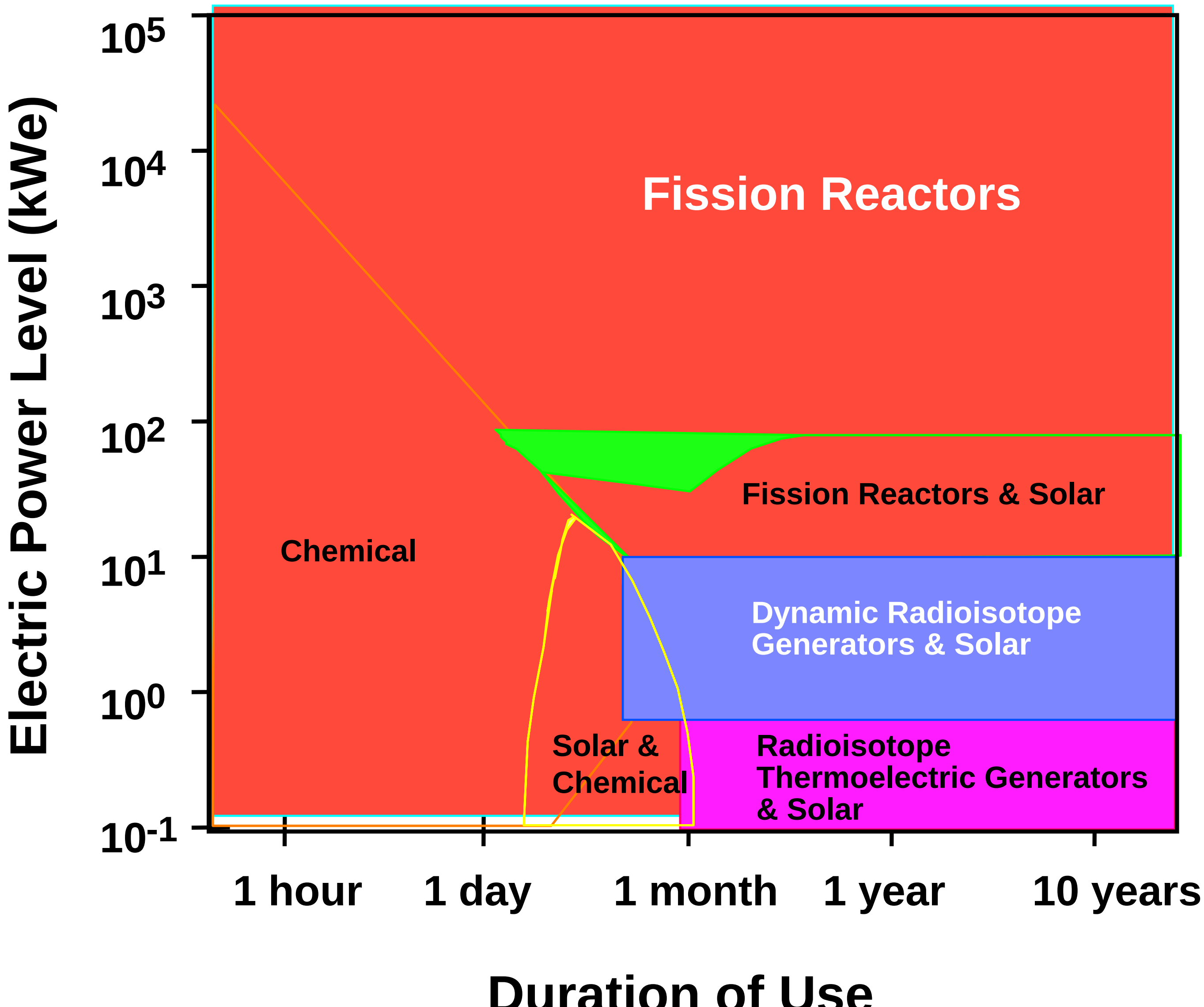
International Space Station Power Requirements -Full Station Envisioned-

- 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-33.1 by 73.2 meters (54% of football field)
- Mass ≈ 3.1 kg/m^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

Solar Power is Impractical Beyond Mars



The Use of Nuclear Power in Space is Absolutely Necessary for High Power and Long Time Operations

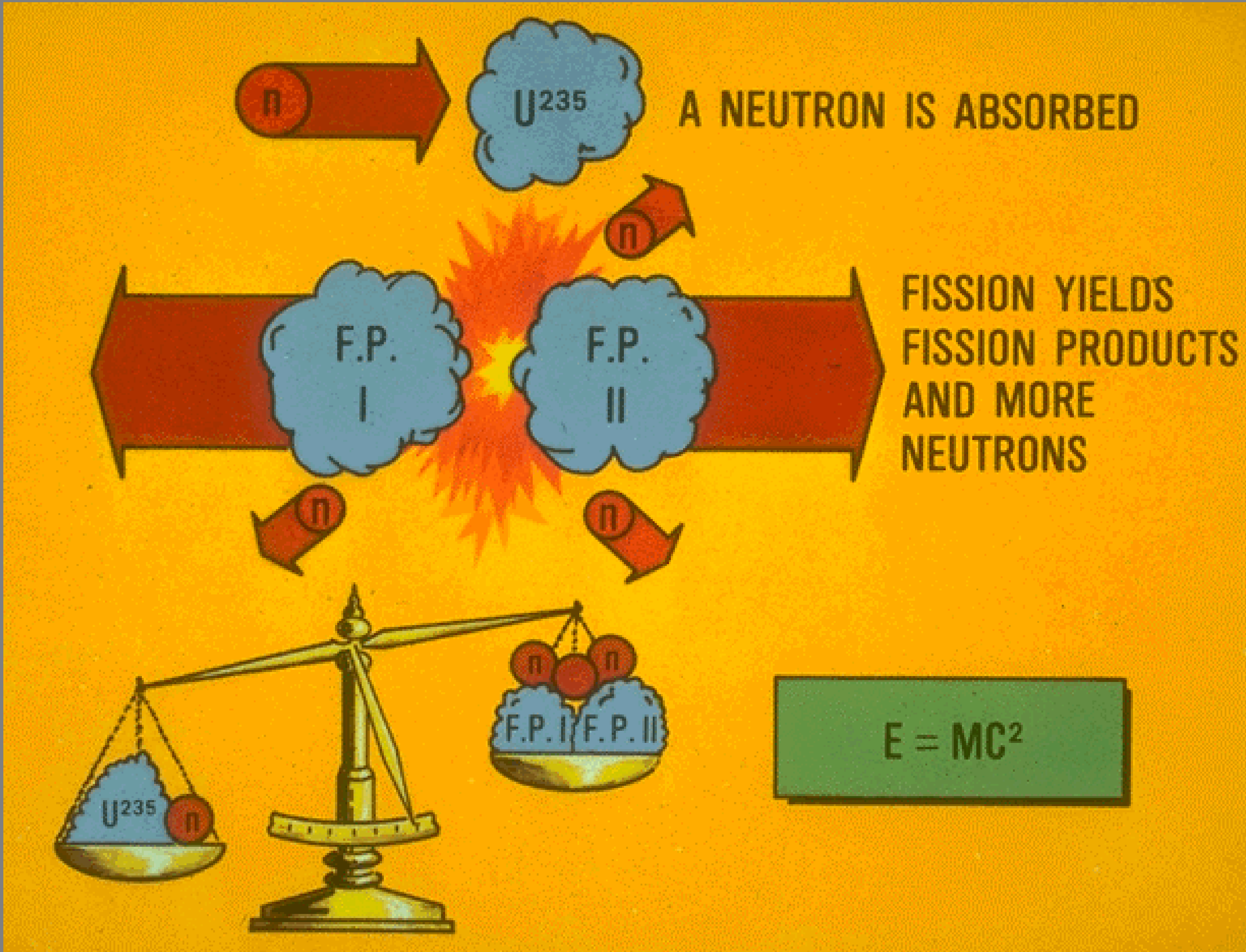


What is the Advantage of Using Nuclear Energy in Space?

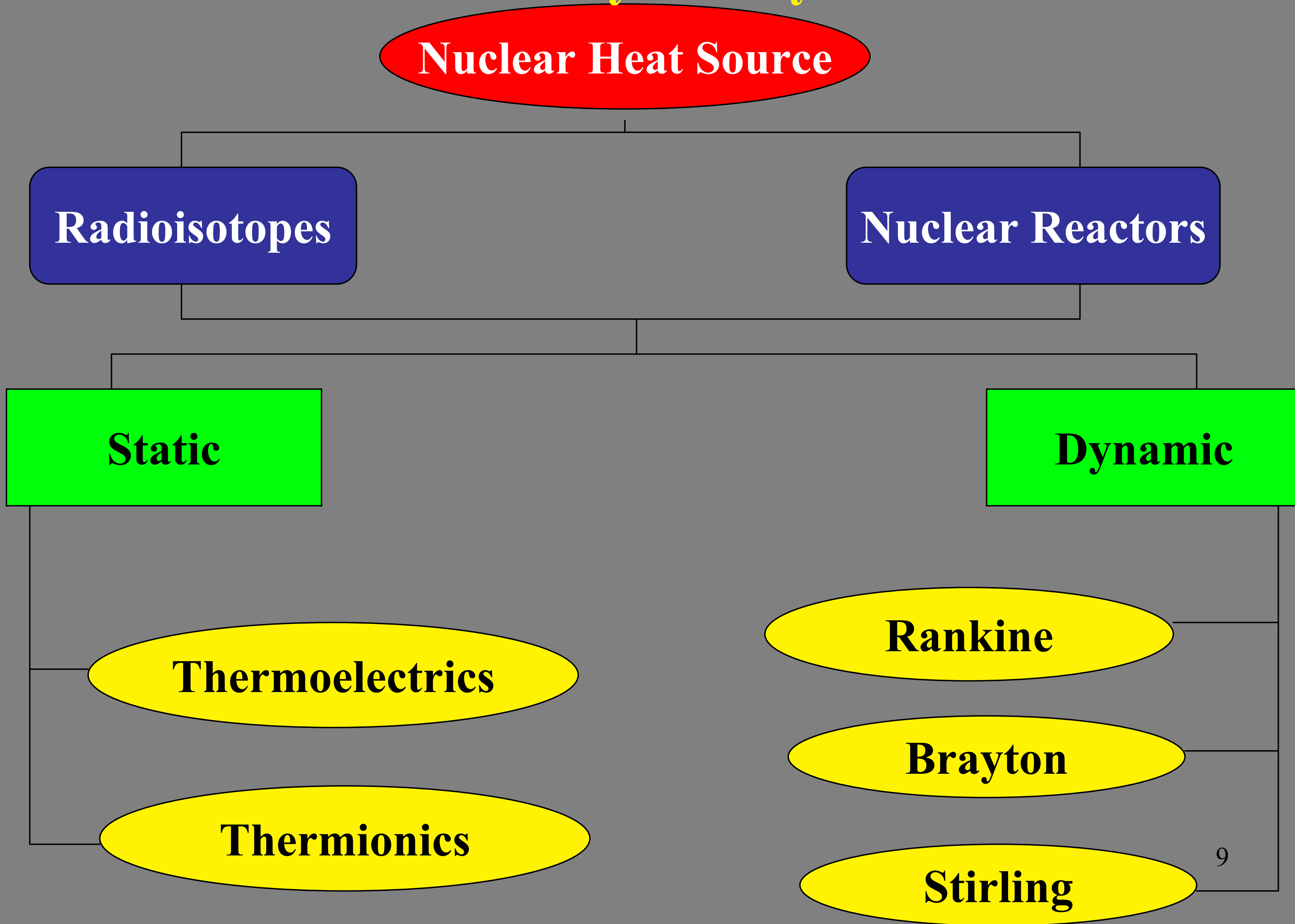
1 kg of nuclear fuel contains

10,000,000

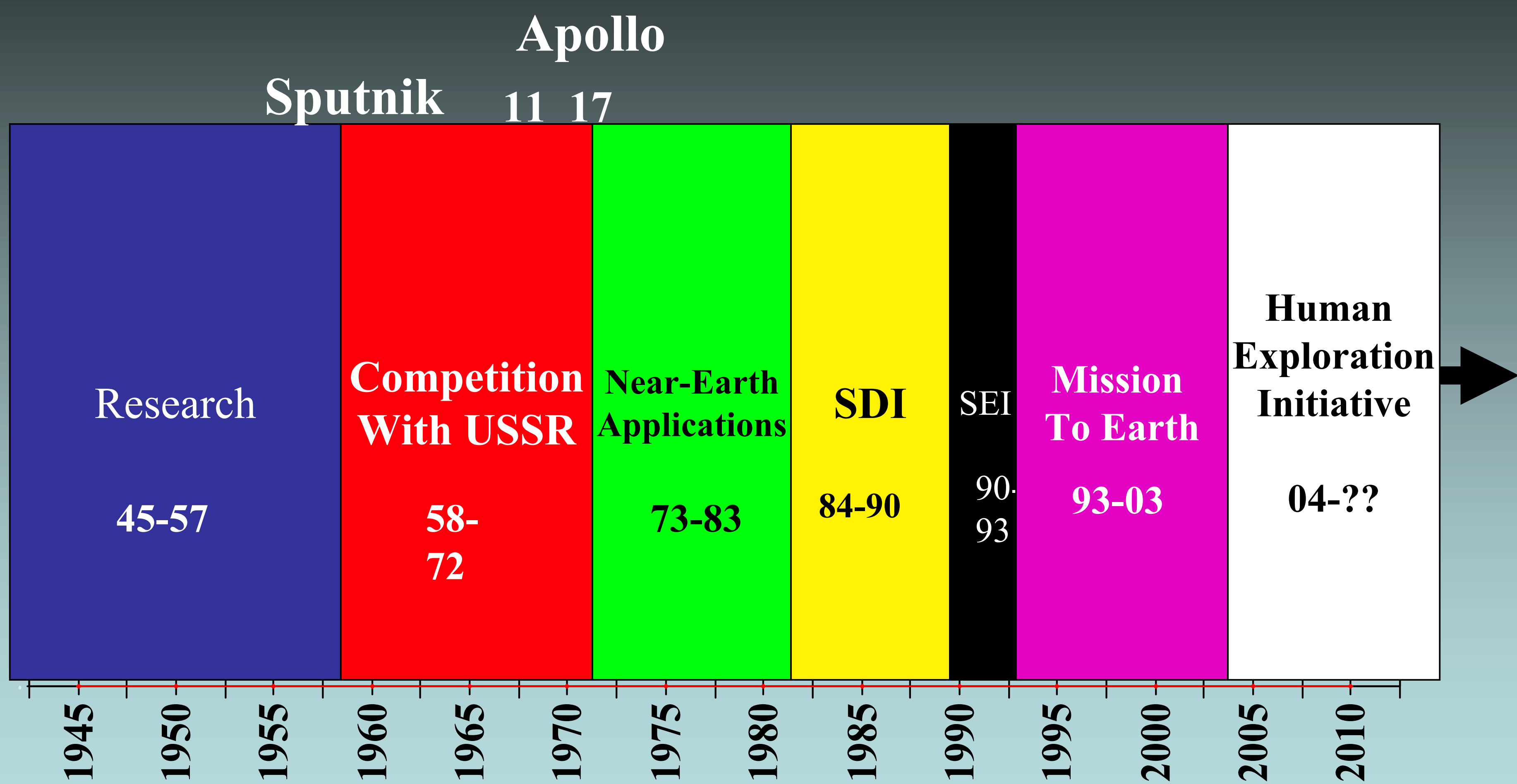
times the energy in 1 kg of chemicals


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

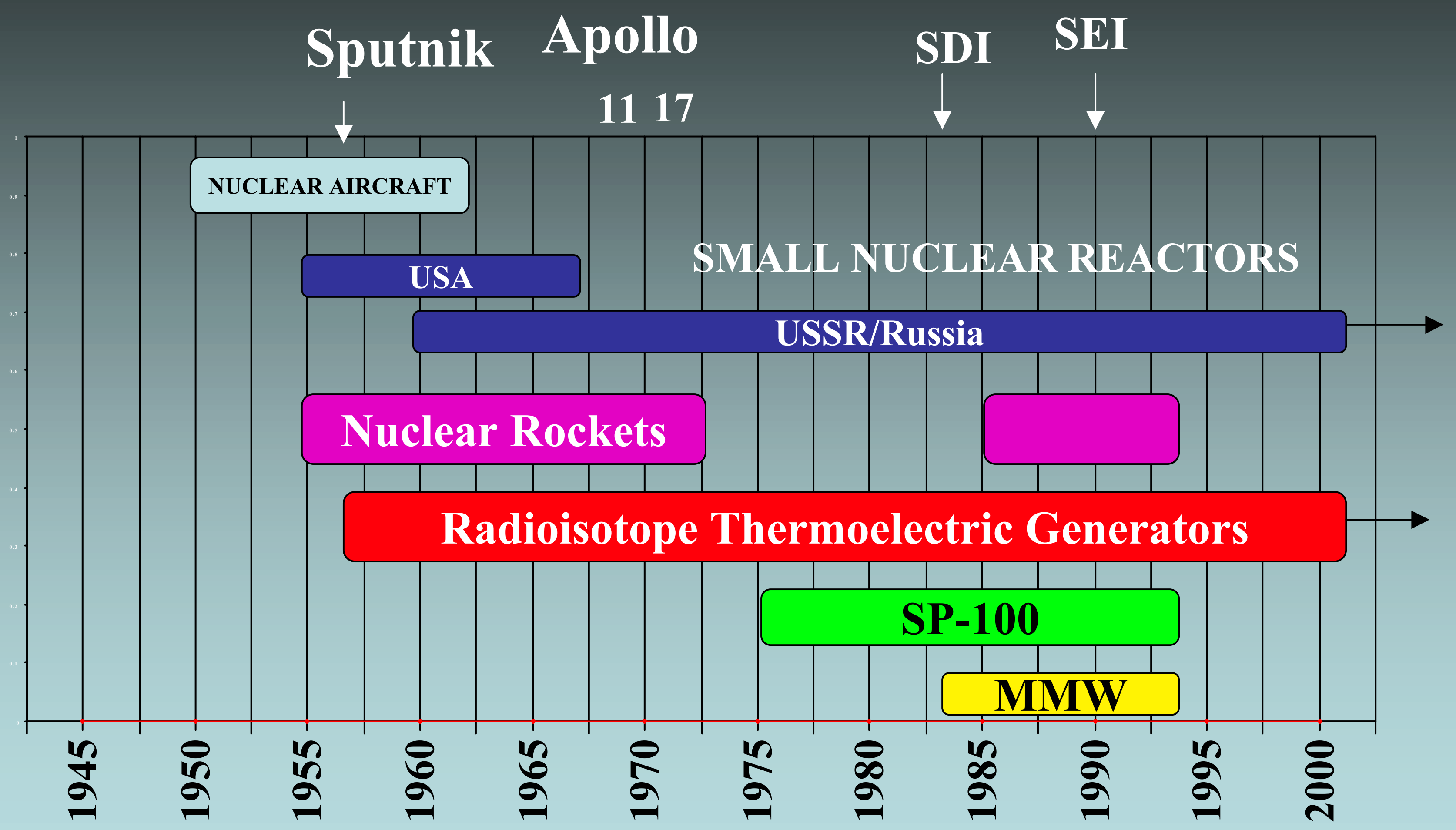
Nuclear Energy Can Be Converted to Electricity in a Variety of Ways



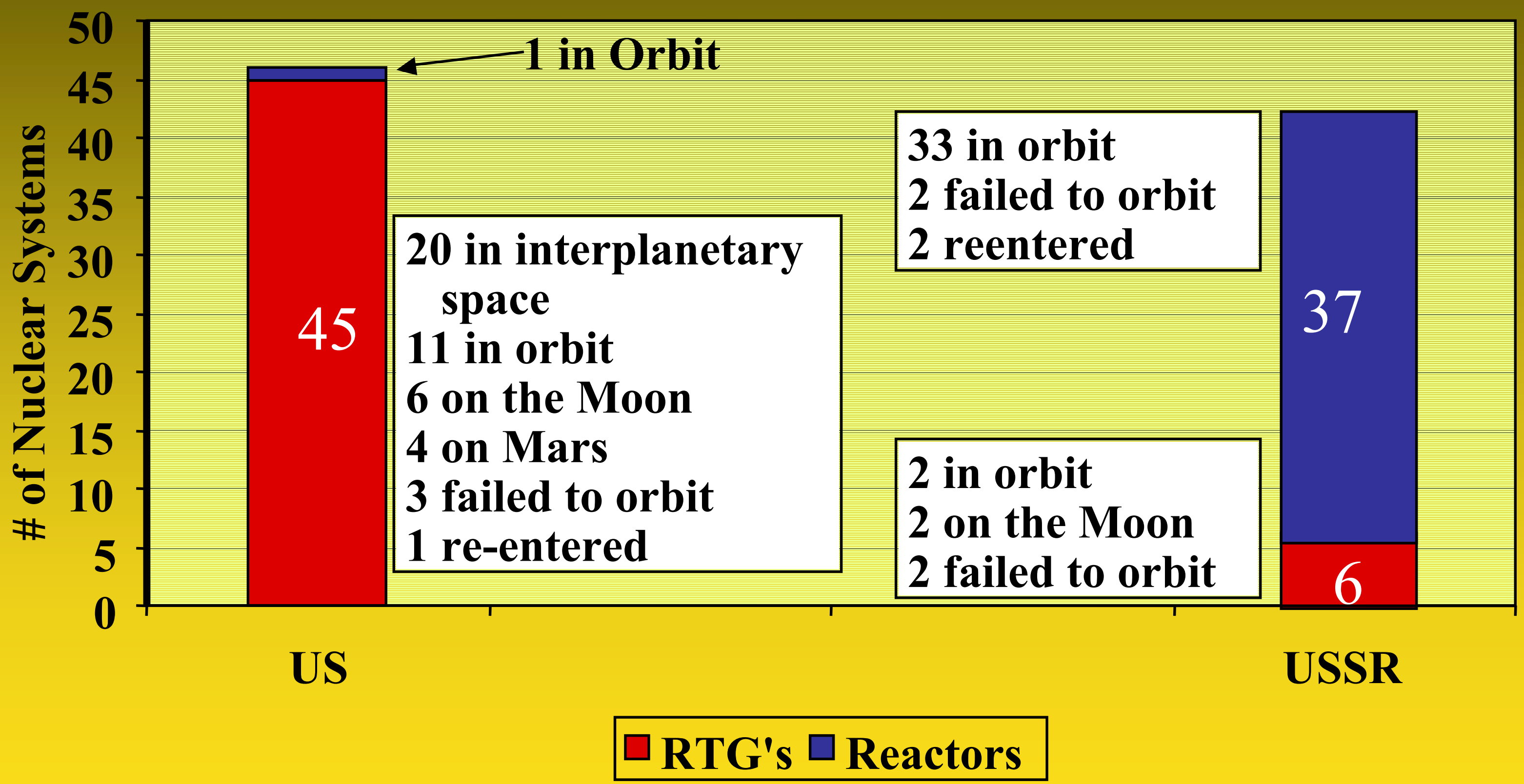
There Have Been Many Driving Forces Behind the Development of Nuclear Power in Space



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** $\sum {}^{A_i}Y_{Z_i}$

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

$$E = (\text{mass } {}^{A}X_{z} - \text{mass } \sum {}^{A_i}Y_{Z_i}) \cdot c^2$$

- **Example:**

$^{238}Pu_{94} \dashrightarrow {}^{234}U_{92} + {}^{4}He_{2}$ **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**
Δm **= 0.006005 amu or E = 5.59 MeV**

Power Generated by Radioisotopic Heat Sources

Power (t) =

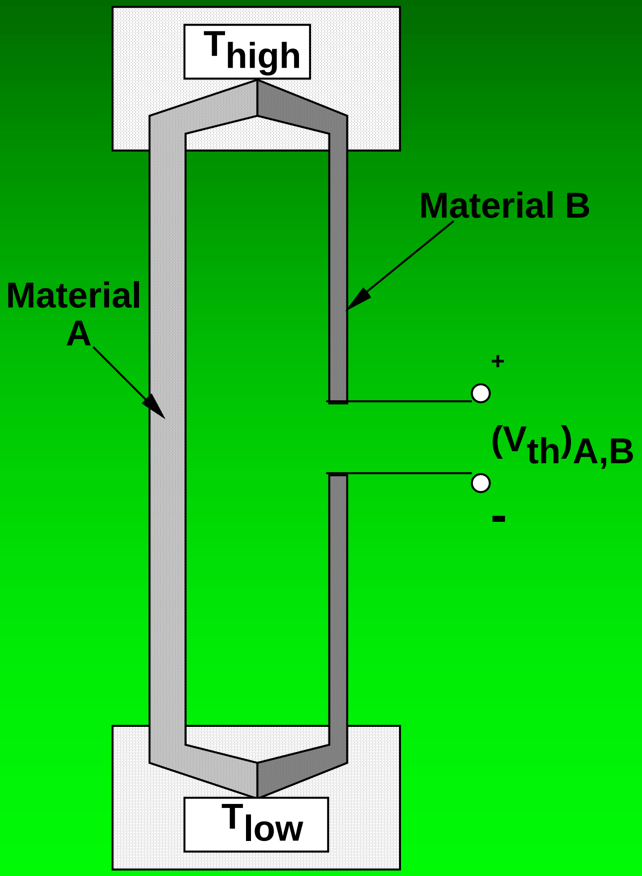
Initial # of Radioisotopes	N_o
Decay Rate, s-1	$\lambda = \frac{\ln 2}{t_{1/2}}$
Energy Released Per Decay MeV	E
Number of Radioisotopes Left After t Years	$\exp -\left(\frac{t * \ln 2}{t_{1/2}}\right)$

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

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

- Half life-87.4 years
- Energy released per decay-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_ey
- Cost of ^{238}Pu-$300/g

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

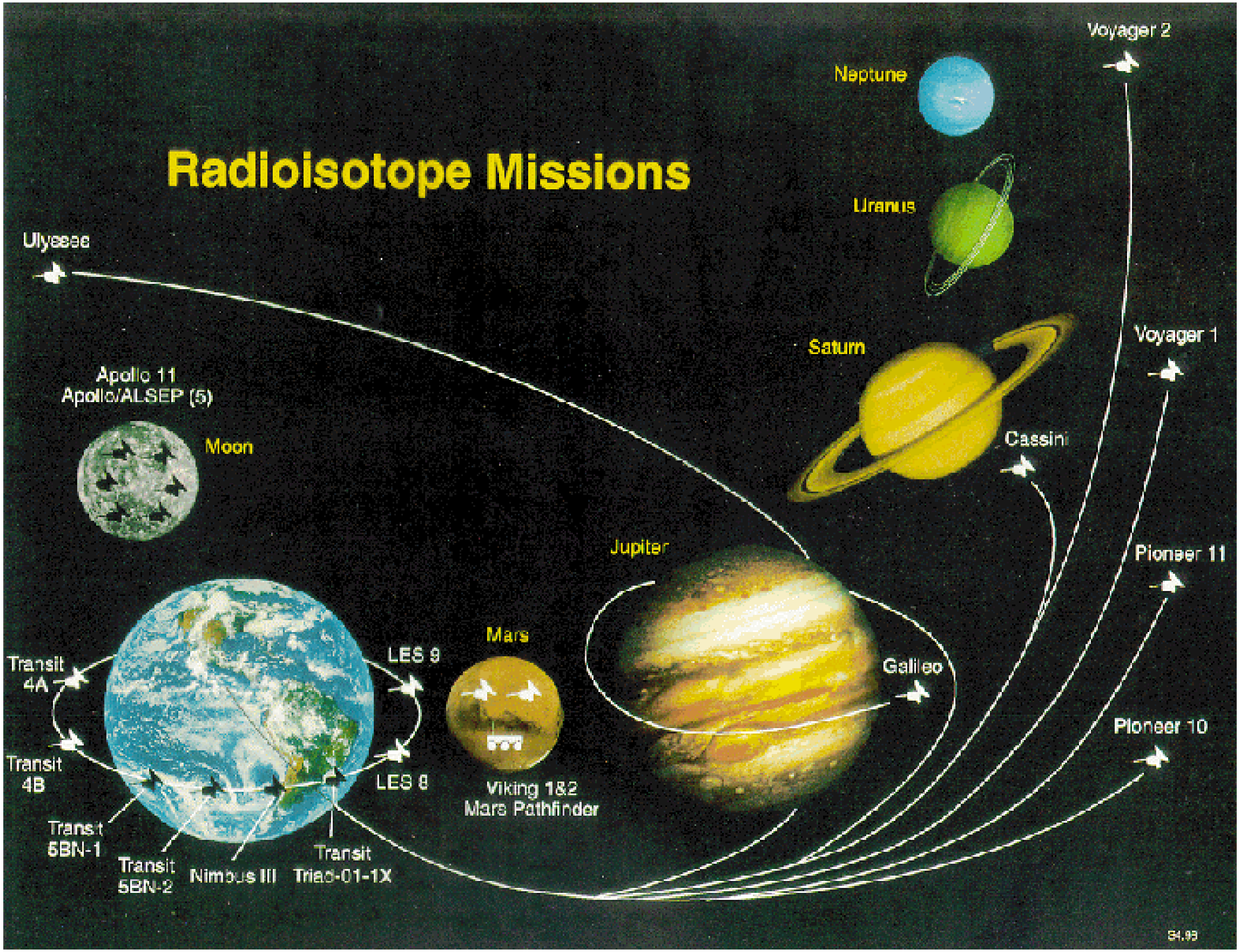


efficiency = $\eta_{carnot} \cdot \eta_{mat}$

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

$\eta_{mat} \approx 10\text{-}20\ \%$

Typical Efficiencies ≈ 5-10%


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

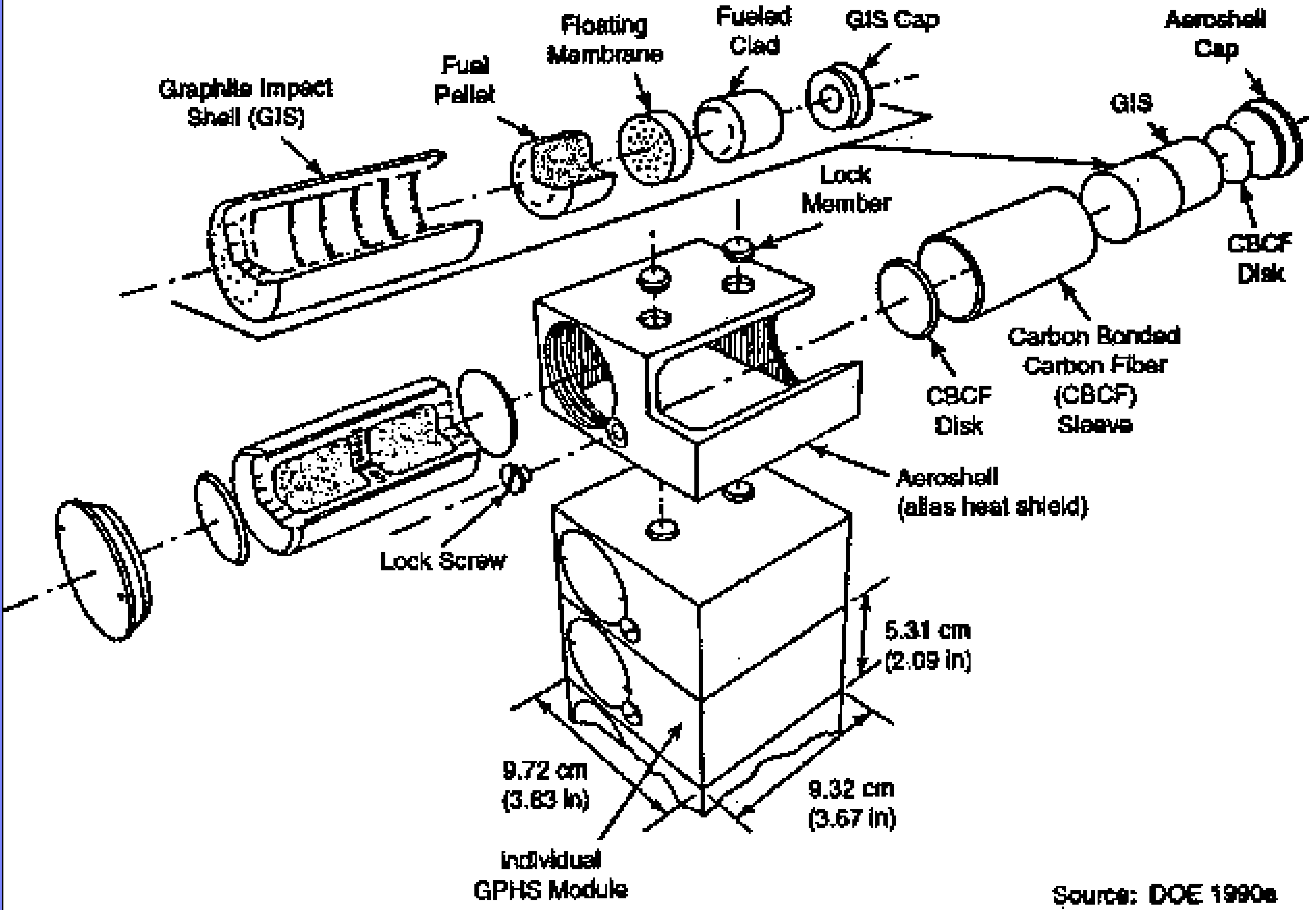
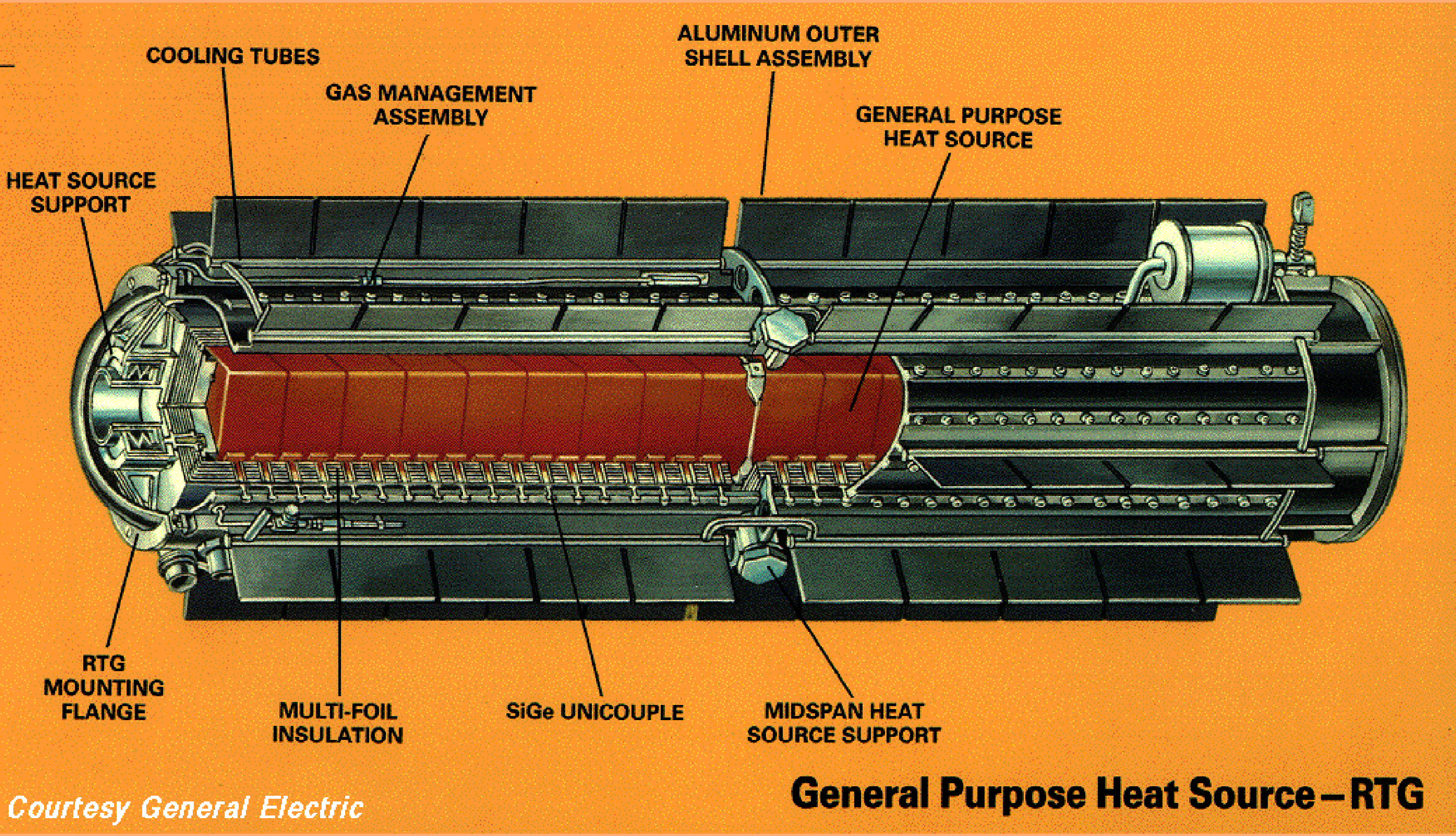
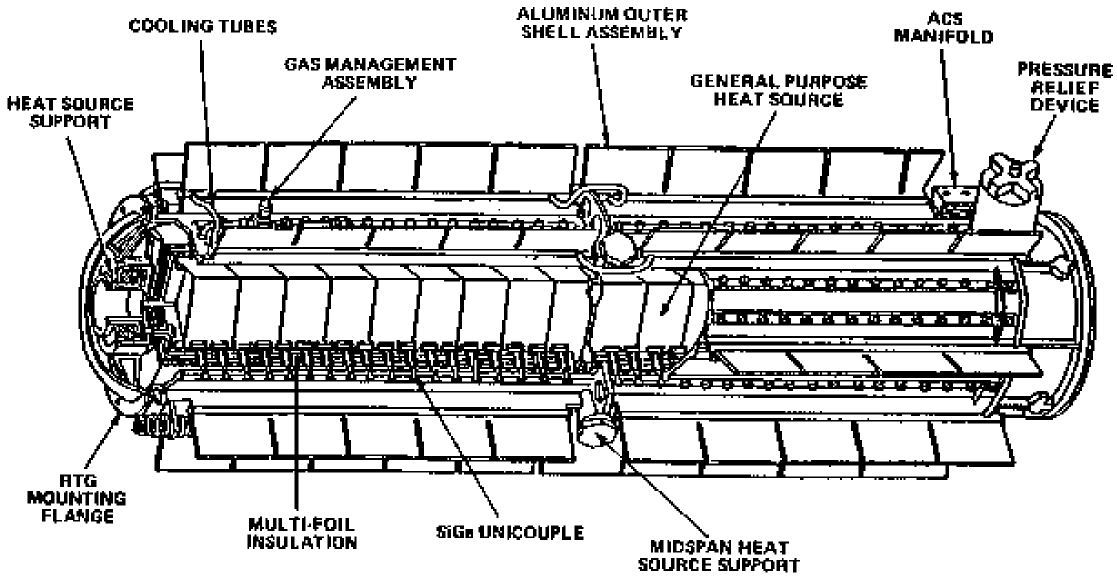


FIGURE 2-6. DIAGRAM OF GENERAL PURPOSE HEAT SOURCE MODULE


COOLING TUBES
GAS MANAGEMENT ASSEMBLY
ALUMINUM OUTER SHELL ASSEMBLY
GENERAL PURPOSE HEAT SOURCE
HEAT SOURCE SUPPORT
RTG MOUNTING FLANGE
MULTI-FOIL INSULATION
SiGe UNICOUPLE
MIDSPAN HEAT SOURCE SUPPORT
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**

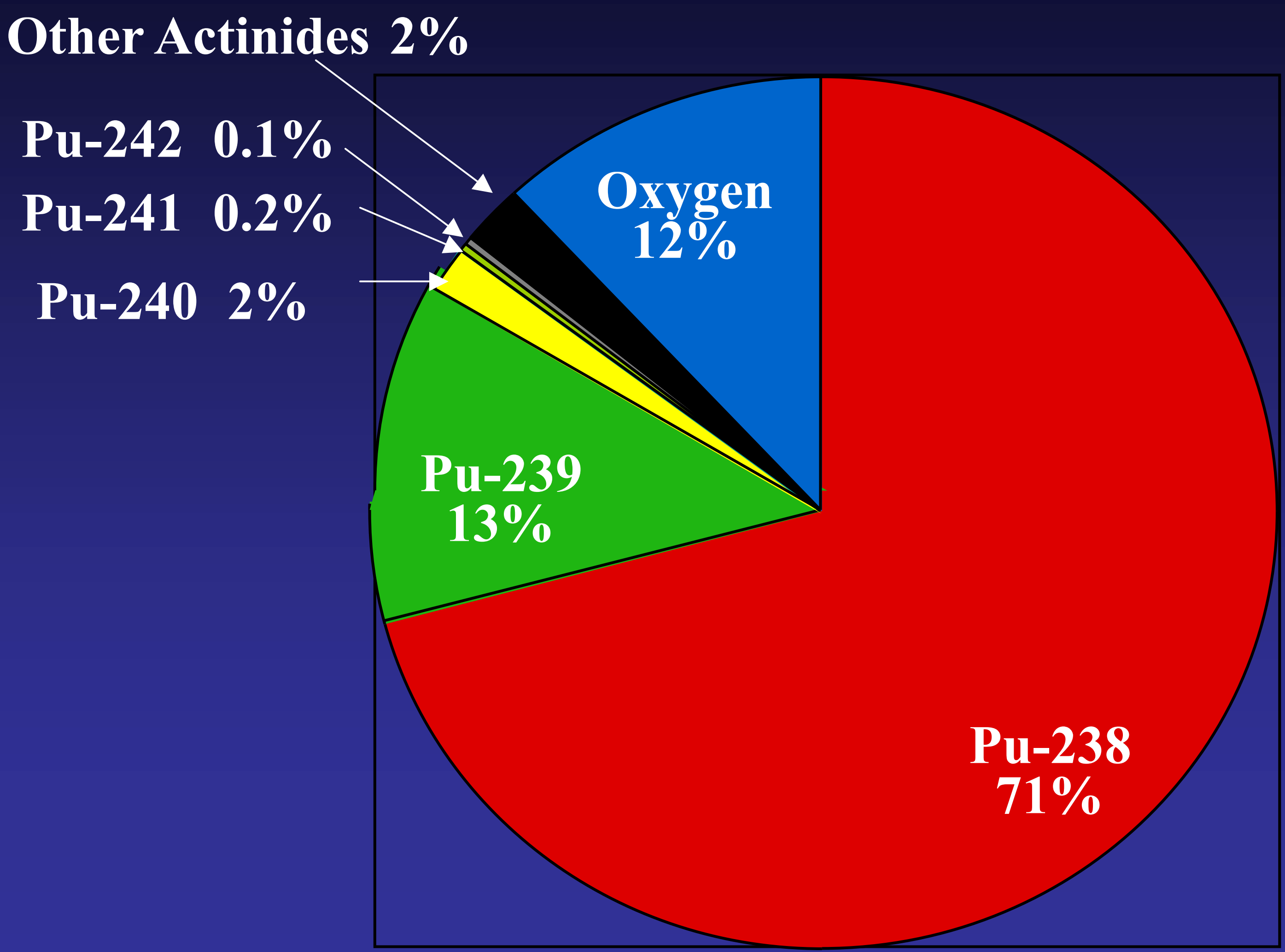
The Cassini Space Craft

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

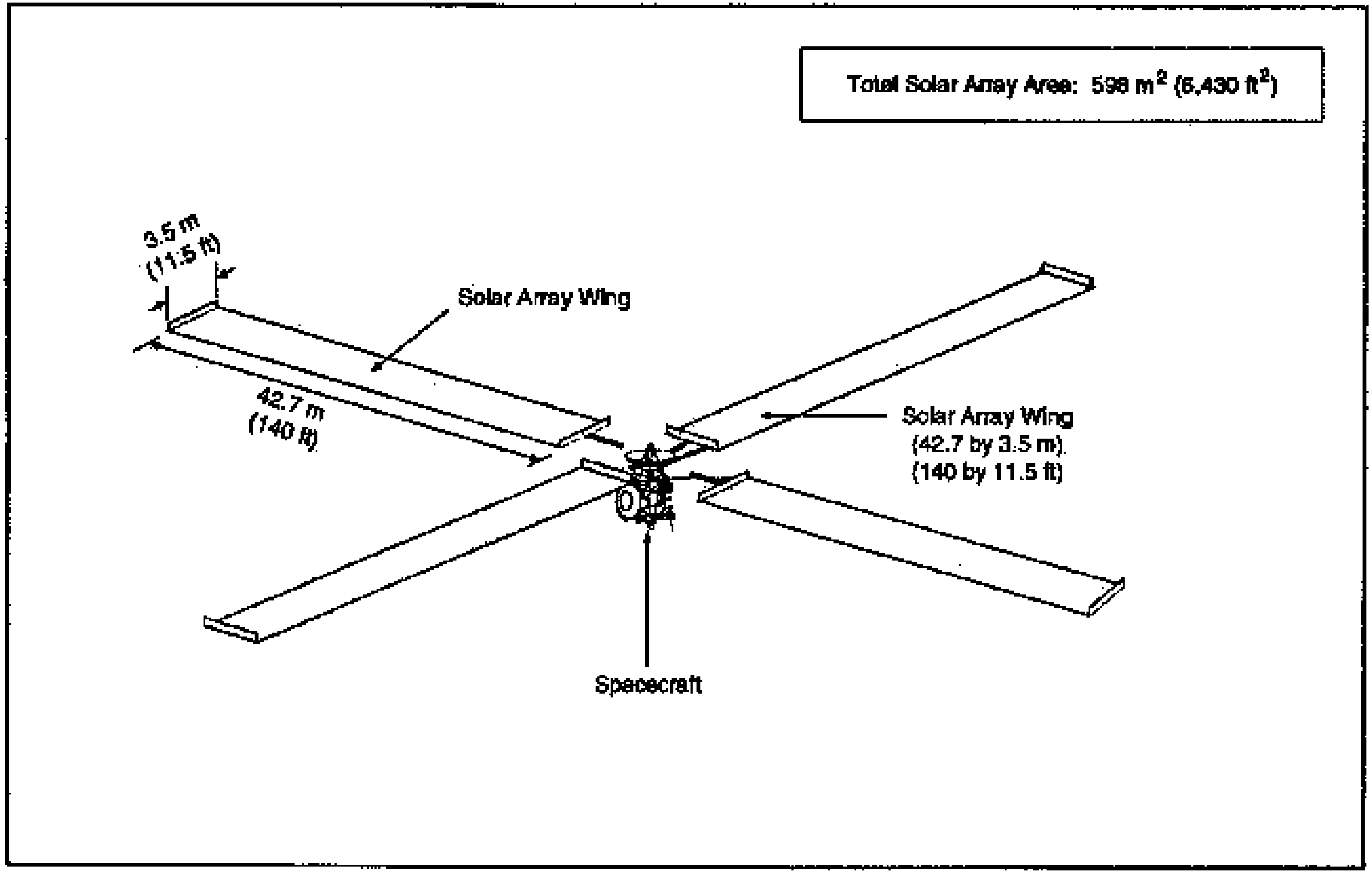


Cassini Electrical Power Requirements

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

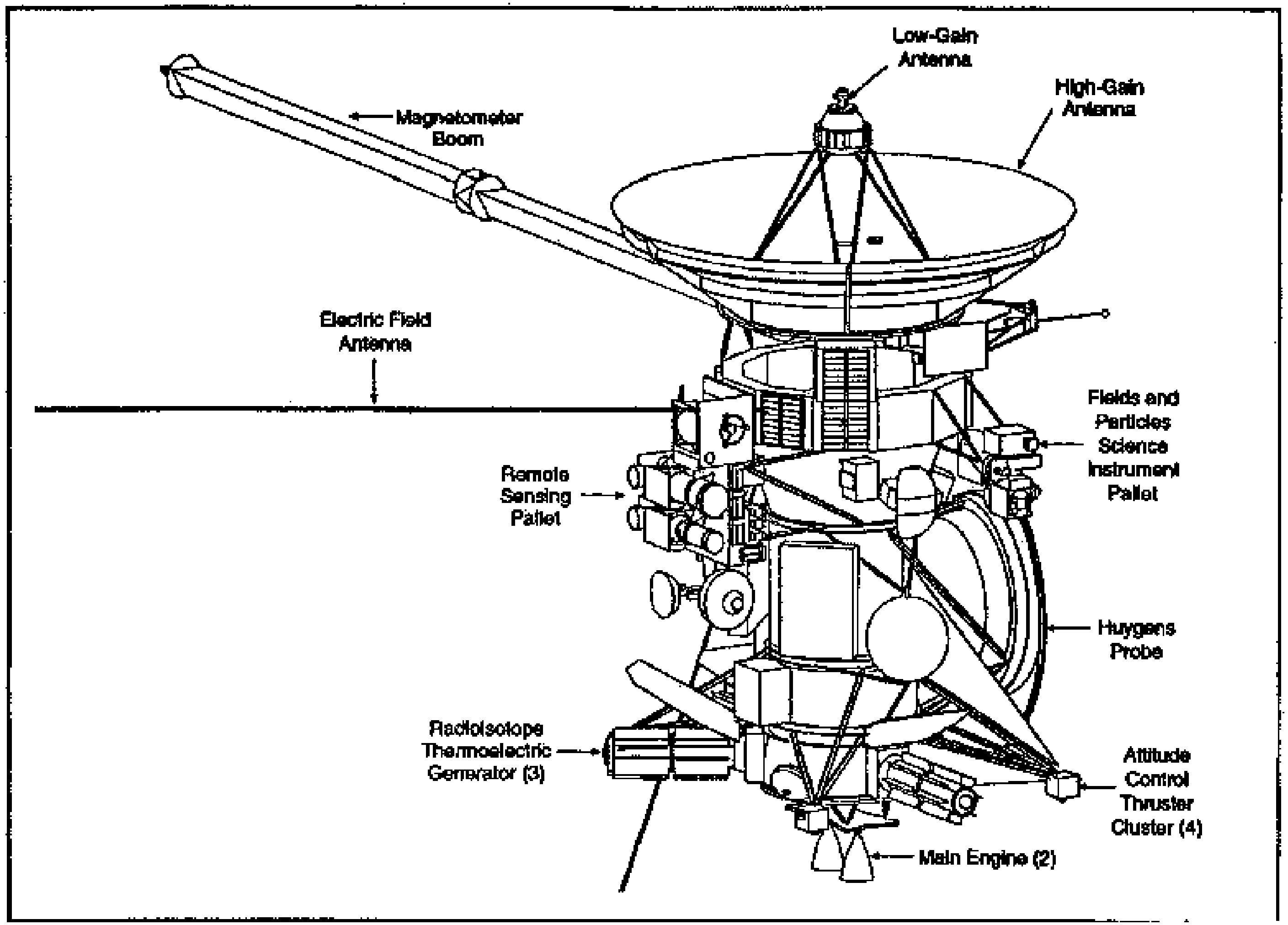
- RTG's
- Mass 168 kg
- Advantages
  - Small size 1.13m x0.43 m dia.
  - No moving parts
  - Easy maneuverability
- Disadvantages
  - Public fear of nuclear

- 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

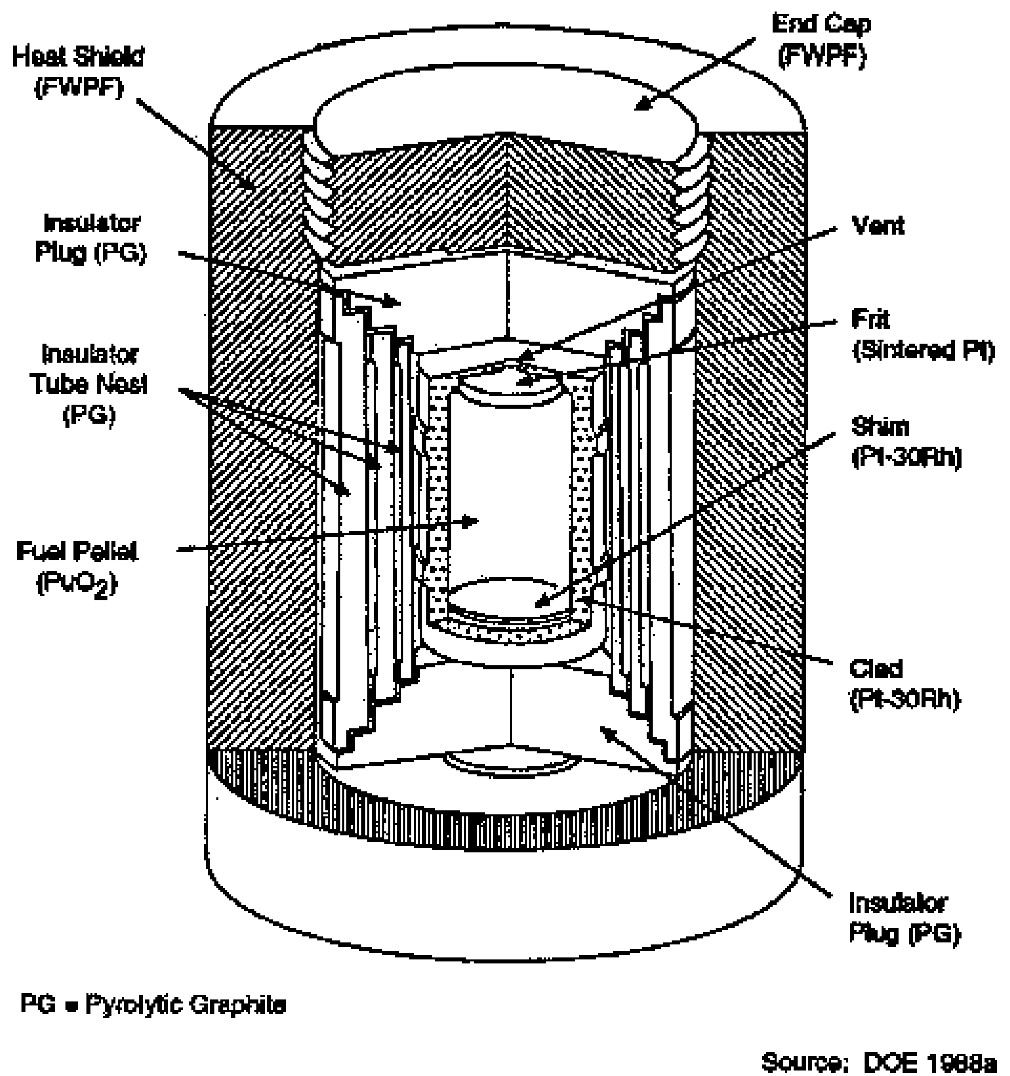


FIGURE 2-7. THE PRINCIPAL FEATURES OF THE RADIOISOTOPE HEATER UNIT

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.)		