Lecture 22-Nuclear Power in Space

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

- Near Earth Missions
- Unmanned Missions To Solar System
- Manned Missions To Solar System
- Unmanned Missions Out of The Solar System
- Chemical
- Solar
- Nuclear
- Beamed
International Space Station Power Requirements
-Full Station Envisioned-

- Total continuous needs -> 105 kWₑ (MIR ≈ 30 kWₑ)
- Two independent PV supplies (US = 79 kWₑ, Russian = 29 kWₑ)
- 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/m², 7.56 tonnes
- Power density ≈ 100 kg/kWₑ
- 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 graph illustrates the decrease in solar energy flux as distance from the Sun increases. Solar energy flux is normalized to 1.0 at Earth. The distances are measured in Astronomical Units (AU), with Earth at 1.0 AU, Mars at 1.52 AU, Jupiter at 5.2 AU, Saturn at 9.58 AU, Uranus at 19.18 AU, Neptune at 30.07 AU, and Pluto at 39.53 AU. The energy flux decreases dramatically with increasing distance, making solar power impractical beyond Mars.
The Use of Nuclear Power in Space is Absolutely Necessary for High Power and Long Time Operations

![Graph showing electric power level (kWe) against duration of use.]

- **Fission Reactors** dominate in high power and long duration scenarios.
- **Chemical** sources are limited to very short durations.
- **Dynamic Radioisotope Generators & Solar** offer a mix that is effective for medium durations.
- **Radioisotope Thermoelectric Generators & Solar** are good for medium to long durations.
- **Solar & Chemical** are suitable for very short durations.

The graph illustrates that fission reactors are essential for high power and long duration missions.
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.
A neutron is absorbed by U^{235}.

Fission yields fission products and more neutrons.

E = MC^2
Nuclear Energy Can Be Converted to Electricity in a Variety of Ways

Nuclear Heat Source

Radioisotopes

Nuclear Reactors

Static

Thermoelectrics

Thermionics

Dynamic

Rankine

Brayton

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

- **Research**: 1945-1957
- **Competition With USSR**: 1958-1972
- **Near-Earth Applications**: 1973-1983
- **SDI**: 1984-1990
- **SEI**: 1990-1993
- **Mission To Earth**: 1993-2003
- **Human Exploration Initiative**: 2004-2010

- **Sputnik**: 1957
- **Apollo**: 1969

Timeline:
- 1945
- 1950
- 1955
- 1960
- 1965
- 1970
- 1975
- 1980
- 1985
- 1990
- 1995
- 2000
- 2005
- 2010
CHRONOLOGY OF SPACE NUCLEAR POWER DEVELOPMENT

- Sputnik
- Apollo 11 17
- SDI
- SEI

NUCLEAR AIRCRAFT

USA

SMALL NUCLEAR REACTORS

USSR/Russia

Nuclear Rockets

Radioisotope Thermoelectric Generators

SP-100

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

- **US**: 45 systems
  - 20 in interplanetary space
  - 11 in orbit
  - 6 on the Moon
  - 4 on Mars
  - 3 failed to orbit
  - 1 re-entered

- **USSR**: 37 systems
  - 33 in orbit
  - 2 failed to orbit
  - 2 reentered
  - 2 on the Moon
  - 2 failed to orbit

- **USSR**
  - 6 systems

**Legend**: Red = RTG's, Blue = Reactors
RTG’s Produce Power by Radioactive Decay

• Half life of radioactive species:
  – Law of Radioactive Decay  \( \frac{dN}{dt} = -\lambda N \)
  – Integrating,  \( N(t) = N_0 \exp(-\lambda t) \)
  • Where the decay constant \( \lambda = \ln 2 / t^{1/2} = 0.693 / t^{1/2} \)

• Units of radioactive decay rate:
  – 1 Curie = 3.7 x \( 10^{10} \) 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 $^{A_X}_{Z_x}$ to daughter’s $\sum^{A_i}_{Y_{Z_i}}$

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

  $E = (mass^{A_X}_{Z_x} - mass \sum^{A_i}_{Y_{Z_i}}) \cdot c^2$

- Example:

  $^{238}{Pu}_{94} \rightarrow ^{234}{U}_{92} + ^4{He}_2 \quad 1 \text{ amu} = 931.5 \text{ MeV}$

  Mass $^{238}{Pu}_{94} = 238.049555 \text{ amu}$

  Mass $^{234}{U}_{92} = 234.040947 \text{ amu}$

  Mass $^4{He}_2 = 4.002603 \text{ amu}$

  $\Delta m = 0.006005 \text{ amu} \quad \text{or} \quad E = 5.59 \text{ MeV}$
Power Generated by Radioisotopic Heat Sources

\[
\text{Power (t)} = \frac{N_0 \cdot E \cdot \ln 2}{t^{1/2}} \cdot \exp\left(-\frac{t \ln 2}{t^{1/2}}\right)
\]

- Initial # of Radioisotopes: \( N_0 \)
- Decay Rate, s\(^{-1} \): \( \lambda = \frac{\ln 2}{t^{1/2}} \)
- Energy Released Per Decay MeV: \( E \)
- Number of Radioisotopes Left After t Years: \( \exp\left(-\frac{t \ln 2}{t^{1/2}}\right) \)
$^{238}$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$_{e}y$
- Cost of $^{238}$Pu - $300/g
Thermoelectricity-A Reliable Way to Convert Heat Energy Directly into Electricity

**Efficiency** = \( \eta_{\text{carnot}} \cdot \eta_{\text{mat}} \)

\[ \eta_{\text{carnot}} = \frac{T_H - T_L}{T_H} \approx 50\% \]

\[ \eta_{\text{mat}} \approx 10-20\% \]

Typical Efficiencies \( \approx 5-10\% \)
FIGURE 2-6. DIAGRAM OF GENERAL PURPOSE HEAT SOURCE MODULE
General Purpose Heat Source – RTG

Courtesy General Electric
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 $^{238}\text{Pu} - 7.561$ kg
- Thermal Power = 4,234 W_t
The Cassini Space Craft

RTG’s (3)
Cassini RTG Performance Characteristics

<table>
<thead>
<tr>
<th># of RTG’s</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass/RTG</td>
<td>56 kg (168 kg total)</td>
</tr>
<tr>
<td>Total Power @BOL</td>
<td>888 Watts (electric)</td>
</tr>
<tr>
<td>Total Power @ EOL</td>
<td>628 Watts (electric)</td>
</tr>
<tr>
<td>BOL Thermal Power</td>
<td>13,182 Watts</td>
</tr>
<tr>
<td>Conversion Efficiency</td>
<td>6.7%</td>
</tr>
<tr>
<td>Mass PuO₂/RTG</td>
<td>10.9 kg (32.7 kg total)</td>
</tr>
<tr>
<td>Mass Pu/RTG</td>
<td>9.71 kg (28.8 kg total)</td>
</tr>
<tr>
<td>Mass of (^{238})Pu/RTG</td>
<td>7.72 kg (23.2 kg total)</td>
</tr>
</tbody>
</table>
Cassini Fuel Composition at Launch

- Pu-238 71%
- Oxygen 12%
- Pu-239 13%
- Other Actinides 2%
- Pu-240 2%
- Pu-241 0.2%
- Pu-242 0.1%
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
FIGURE 2-15. ALL-SOLAR (GaAs APSA) CONFIGURATION FOR THE CASSINI SPACECRAFT

Source: JPL 1994a

Total Solar Array Area: 598 m² (6,430 ft²)
FIGURE 2-4. DIAGRAM OF THE CASSINI SPACECRAFT
FIGURE 2-7. THE PRINCIPAL FEATURES OF THE RADIOISOTOPE HEATER UNIT
## Cassini RHU Performance Characteristics

<table>
<thead>
<tr>
<th># of RHU’s</th>
<th>157</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass/RHU</td>
<td>40 g (6.28 kg total)</td>
</tr>
<tr>
<td>Thermal Power @BOL</td>
<td>≈ 1 Watt</td>
</tr>
<tr>
<td>Mass PuO$_2$/RHU</td>
<td>2.7 g (424 g total)</td>
</tr>
<tr>
<td>Mass Pu/RHU</td>
<td>2.38 g (374 g total)</td>
</tr>
<tr>
<td>Mass of $^{238}$Pu/RHU</td>
<td>1.91 g (300 g total)</td>
</tr>
</tbody>
</table>
RTG’s Have Had a Remarkable Performance Record

<table>
<thead>
<tr>
<th># of Launches</th>
<th># of RTG’s</th>
<th>Power/unit, $W_e$</th>
<th>Mission</th>
<th>Launch Dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>4</td>
<td>2.7, 25, 25, 30</td>
<td>TRANSIT (navigation)</td>
<td>1961-4, 72</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>40</td>
<td>NIBUS (meteorology)</td>
<td>1969</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>70</td>
<td>APOLLO (Lunar Exp., 11 ht only)</td>
<td>1969-72</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>40</td>
<td>PIONEER-10, 11 (interplanetary)</td>
<td>1972-3</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>40</td>
<td>VIKING-1,2 (Mars)</td>
<td>1975</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>150</td>
<td>LES (communication)</td>
<td>1976</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>150</td>
<td>Voyager-1,2 (Interplanetary)</td>
<td>1977</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>275</td>
<td>Galileo (Jupiter)</td>
<td>1989</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>275</td>
<td>ULYSSES (Sun)</td>
<td>1990</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>296</td>
<td>CASSINI (Saturn)</td>
<td>1997</td>
</tr>
<tr>
<td>22</td>
<td>40</td>
<td>4160 tot.</td>
<td></td>
<td></td>
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Mission failures

<table>
<thead>
<tr>
<th># of Launches</th>
<th># of RTG’s</th>
<th>Power/unit, $W_e$</th>
<th>Mission</th>
<th>Launch Dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>25</td>
<td>TRANSIT (failed to reach orbit)</td>
<td>1964</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>40</td>
<td>NIMBUS (destroyed during launch)</td>
<td>1968</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>70</td>
<td>APOLLO-13 (mission aborted)</td>
<td>1970</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>135 (tot.)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>