Four Major Fission Reactor Concepts Which Have Survived the Screening for the Multi Megawatt Program

**MMW Power Needs in Space (10-500 MWe)**

- **Gas Cooled**
  - Particle Fuel
    - Particle Bed
    - Pellet Bed
    - NERVA
    - Cermet
  - Prismatic Fuel
    - Pluto
    - NERVA/Pluto
    - UB2
    - Foam Fuel
    - Wire Core

- **In-Core Thermionic**
- **Liquid Metal Cooled**
Figure 2.1 Schematic of Space Reactor Closed Cycle System Showing Possible Choices of Components (Open Cycle Systems Do Not Need a Mass Storage Sub-System)
Figure 3.2 Generic Classes of Space Nuclear Power Systems
General Comments on Space Power Reactor Designs

A.) Fast Vs Thermal

1.) Reactor Mass

- Thermal reactors require moderator
- Moderator/ Fuel molecular ratios \( \approx 500:1 \)
- Generally thermal reactors are bigger (size) and heavier than fast reactors

2.) Fissile Material Requirements

- \( \sigma_{\text{fiss}}/\sigma_{\text{capt}} \) for fast reactors is less than for thermal reactors, \( \implies \) more \( ^{35}\text{U} \) is required for fast reactors
- Control of thermal reactors is easier and less complicated;
  - \( \sigma_{\text{absorption}} \) larger for thermal neutrons
  - delayed neutrons help control thermal reactors

3.) Fission Product Poisoning

- Because of higher \( \sigma_{\text{absorption}} \) for fission products in thermal reactors, more attention must be paid to FP buildup and decay (i.e., \( \text{Xe} \))
B.) Direct vs Indirect Cycles

1.) In-Core Heat Transfer

- Liquid metal boiling in a micro-g environment has not been adequately explored (e.g., critical heat flux, flow instabilities, etc.)

2.) Enhanced Erosion and Corrosion

- Due to In-core boiling and 2-phase flow

3.) Contamination of Power Conversion System

- Occurs through coolant activation, FP release, and activated corrosion products
  - Indirect confines activation to primary loop
  - Direct cycle requires shielding to protect electronics from contamination

4.) Working Fluid Optimization

- Indirect- both fluids can be, independently optimized for reactor and turbine
• Direct-Same working fluid used for all power system components

5.) Number of Components

• Indirect cycle requires at least a heat exchanger and an extra pump

C.) Liquid Metal vs Gas Cooling

1.) Heat Transfer Surface Area

• Because the heat transfer of liquid metals is much better than gases, the surface area required is much less ==> smaller size and less complicated fuel design

2.) Pump Requirements

• Electromagnetic pumps, with no moving parts can be used for liquid metals, not gases

3.) Coolant Freezing

• Thawing, space for expansion .

4.) High Temperature Material Compatibility
• More severe at MMW operating T

• Trace impurities in gas (e.g., O₂, N₂, or hydrocarbons in He) may make these coolants incompatible with refractory alloys.

5.) Safety

• Gases better than liquid metals with regard to fire, explosions, and void coefficients.

6.) Neutron Activation

• Liquid metals present shielding problems (both from activation of the coolant and because of activated corrosion product.)

7.) Two Phase Thermal/Hydraulics

• Boiling and 2 phase flow can be avoided with gases
## Related Technologies for Lead MMW Fission Power Plants

<table>
<thead>
<tr>
<th>Generic Concepts</th>
<th>Gas Cooled</th>
<th>In-Core Thermionic</th>
<th>Liquid Metal System</th>
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<tbody>
<tr>
<td>Technology</td>
<td>Particle Fuel</td>
<td>Prismatic Fuel</td>
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<td>Fuels</td>
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<td>UZrC</td>
<td>UN</td>
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<td></td>
<td>W-emitter C-emitter Refractory Alloys</td>
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<td>Refractory Alloys Ceramic Composite Metal Composite</td>
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<td>Operating Temp/ Coolant</td>
<td>1500-200 0 °K He/²He</td>
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<td></td>
<td>1000-150 0 °K NaK or Li</td>
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<td>1400-170 0 °K Li</td>
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Comparison of System masses for Steady State Multimegawatt Power in Space

Remember that these systems may have to generate a few MW’s for a year or so.

This Means They will Be Closed!

See table of masses for MMWSS

General Comments

• Even though the Rankine system is the lightest, the uncertainty with 2 phase flow in zero g is an inhibiting feature

• If the efficiency of Thermionic systems approaches 15-20%, then they can compete with Rankine cycles

• Closed cycle Brayton cycles avoids the flow problems and the need for more ‘breakthrus’

1.) Rankine Cycle

• Used a single fluid system, K.

• Because of the difficulty in predicting the amount of fluid which will be entrained in K vapor, the turbine must be designed to handle significant erosion.

• Fires on the pad a potential problem
• Could go to an indirect cycle, but the heat exchanger mass would be equivalent to a vapor separator

2.) Brayton System

• Use He/Ne mixture, non-corrosive and inert

• Heavy, but simple and developed

3.) Thermionic System

• Heavy but has no moving parts

• Assumed technology is modest, and 1800 °K emitter give 10-12% efficiency. General Atomics has laboratory devices that exhibit much higher efficiencies ($\approx 20\%$)
Comparison of 10 MW<sub>e</sub> Steady State Mode Space Power Systems

<table>
<thead>
<tr>
<th>Component</th>
<th>Metric Tonnes for 1 Year</th>
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<tbody>
<tr>
<td></td>
<td>Therm-ionic</td>
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<tr>
<td>Reactor &amp; Shield</td>
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<tr>
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<td>Turbine</td>
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<td>Generator</td>
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<tr>
<td>Mise</td>
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<tr>
<td><strong>TOTAL</strong></td>
<td><strong>70.4</strong></td>
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</table>
Figure 4-1. Comparison of Specific Weights of Multimegawatt Space Power Systems for the MMWSS Mode Assuming 10-MWe Power for 1 Year of Operation
Mass of Steady State 10 MWe Space Power System

1 Year Operating Time

1500 K Brayton

1350 K Rankine

Thermionic

Mass-Tonnes

Legend:
- Reactor & Shield
- Turbine
- Compressor
- Generator
- Vapor Separator
- Power Cond.
- PC & Gen Rad
- Radiator and condensor
- Mise
Comparison of Specific Masses for Multi Megawatt Space Power Sources

A. ) Burst Mode

• Within the range of 100-1000 MWe, the specific power density (kg/kWe) does not depend on the power level.

• General Assumptions:
  1.) The H\textsubscript{2} coolant from the weapon is used as a working fluid in the power source.

  2.) The weapons put out more H\textsubscript{2} than the power supply needs, therefore the H\textsubscript{2} is not included in the power supply mass.

\begin{center}
\textbf{Compare}
\end{center}

\begin{tabular}{lll}
Reactors & Batteries & O\textsubscript{2}-H\textsubscript{2} Combustion \\
\hline
• Open Gas & • 100 Wh/kg & • Open System \\
• Brayton & • 500 Wh/kg & \\
• Rankine & & \\
• Thermionic & & \\
\end{tabular}

See Figure
In general, open systems are lighter than closed systems, but the H₂ and H₂0 effluent can interfere with the weapon system

*Note: There is no advantage to a closed system if the cooling system of the weapon is open!*

Table of Power System Weights

General Observations
1. Reactor mass is < 2 % of system mass in open gas cooled systems (< 4 % if the load specific power conditioning system is subtracted)

2. Power conditioning represents a significant portion of the total mass, and that system depends strongly on the load (weapon)

3. Electromagnetic Launch weapons require almost no power conditioning (can use power directly from the power system)

4. Free Electron Laser and Neutral Particle Beam weapons use substantial power conditioning to provide 1MV DC power for RF generation

5. Closed Brayton and Rankine cycles dominated by radiator mass
FIGURE 2. H₂-O₂ Combustion,
Power System
The diagram depicts a system flow from left to right:

1. Reactor
2. Turbine
3. Flywheel
4. Generator
5. Power Condenser
6. Weapon

There is an alternative bypass route from the power condenser to a pump labeled \( \text{LH}_2 \), which is connected to a refrigeration system.
Weight Depends on Whether the System is Open or Closed and on Run Time

No Power Conditioning Weight
Weights Include Hydrogen

Closed Thermodynamic Cycle Systems

Closed Power Systems

Open Power Systems
Figure A-1. Comparison of Specific Weights of Burst-Mode Space Power Systems