Comments on the Mass of the Burst Mode Power Reactors

1) **Open Gas Cooled Reactor System**

- Lightest system

- Hydrogen cooled (exits the weapon at 300 °K and 13.6 MPa)

- H₂ first cools the power conditioning unit and the generator, then it enters the reactor where it is heated to 1200 °K.

- The 1200 °K H₂ runs the turbine to make electricity, and then it is exhausted into space.

- Although the H₂ was not included in the total mass, it was calculated and the tank, insulation, refrigeration, and meteorite protection was calculated and added.
2) **Open Hydrogen-Oxygen Combustion System**

- Similar to the reactor system except oxygen is used to obtain the energy to turn the turbine.

- Exhaust is a mixture of hydrogen and steam at 1200 °K

- Mass of combustion system (including O₂ cryo system) is more than 10 times a fission reactor, but overall mass is only 15% more.

- Water is not expected to be significantly different than hydrogen for contamination.

- Main advantage of combustion is safety and environment as well as probably lowers development and fabrication costs.

3) **Closed Rankine and Brayton Cycles**

- Prime advantage is no effluent (However, this may be moot if weapon has to exhaust coolant.)

- Both systems operate at high temperatures requiring superalloys, and in the case of the Rankine cycle, an understanding of two-phase flow in microgravity.
4) **Energy Storage Systems**

- Present batteries, fuel cells and flywheels have power densities of 50 Wh/kg, so to get to 500 Wh/kg will be difficult.

- Need a 1000 °K radiator to dissipate 20% of the energy of the power supply.

- Major advantage is that they have no effluent and they are relatively light when only a short-time operation is required.

5) **Thermionic with Energy Storage**

- Uses LiH as a moderator and as a thermal energy storage medium

- Advantage — No moving parts and no effluent.

- Disadvantage — Heavy mass during long engagements.
## Comparison of 500 MW<sub>e</sub> Burst Mode Space Power Systems

<table>
<thead>
<tr>
<th>Component</th>
<th>Open Gas Cooled Reactor</th>
<th>Open H&lt;sub&gt;2&lt;/sub&gt;-O&lt;sub&gt;2&lt;/sub&gt; Comb.</th>
<th>500 Wh Energy Store</th>
<th>Thermionic Energy Store</th>
<th>1350 °K Rankine</th>
<th>1500 °K Brayton</th>
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<tbody>
<tr>
<td>Power Source</td>
<td>3</td>
<td>42</td>
<td>166</td>
<td>214</td>
<td>21</td>
<td>47</td>
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<tr>
<td>Turbine &amp; Generator</td>
<td>63</td>
<td>64</td>
<td>0</td>
<td>0</td>
<td>143</td>
<td>131</td>
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<tr>
<td>Compressor</td>
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<td>0</td>
<td>0</td>
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<tr>
<td>Radiator</td>
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<td>0</td>
<td>24</td>
<td>0</td>
<td>585</td>
<td>2452</td>
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<td>Vapor Separ.</td>
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<td>0</td>
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<tr>
<td>Power Conditioning</td>
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<td>100</td>
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<td>100</td>
<td>100</td>
<td>100</td>
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<tr>
<td>PC &amp; Gen Radiator</td>
<td>0</td>
<td>0</td>
<td>53</td>
<td>53</td>
<td>115</td>
<td>115</td>
</tr>
<tr>
<td>Mise</td>
<td>17</td>
<td>21</td>
<td>34</td>
<td>37</td>
<td>108</td>
<td>308</td>
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<td><strong>TOTAL</strong></td>
<td><strong>183</strong></td>
<td><strong>277</strong></td>
<td><strong>377</strong></td>
<td><strong>405</strong></td>
<td><strong>1187</strong></td>
<td><strong>3309</strong></td>
</tr>
</tbody>
</table>
Mass of 500 MWe Burst Mode Power Systems

1500 K Brayton

1350 K Rankine

Thermionic

500 kWh Store

H2-O2 Comb

Open -Gas Cooled

Mass -Tonnes

600 second operating time
Gas Cooled Reactor Mass Studies

A.) Burst Mode Mass Estimates

1.) Pellet Bed Reactor (see explanation)
   • Used 500 μ diameter UC₂ particles imbedded in 1.5 cm spheres. A 5.4 tonne mass was obtained with 900 kg U/m³

2.) Pluto Derivative (see explanation)
   • Used UO₂-BeO hex fuel rods, 6.83 mm across.
     • Found that minimum reactor mass occurs at only 19 kg U/m³

3.) NERVA/Pluto Hybrid (see explanation)
   • Pluto geometry with NERVA fuel (UC₂)
   • Minimum reactor mass occurs at 900 kg U/m³

4.) UB₂ Reactor (see explanation)
   • Minimum reactor mass of 34.9 tonnes occurred at 500 kg U/m³
   • Not as crucial to get rid of B-10 as originally thought (UB₂ in B₄C)
Pellet Bed Reactor

• Uses fuel in the form of spherical pellets 0.5 to 2 cm in diameter

• Fuel contains 93 % enriched UC$_2$ coated fuel, particles embedded in a graphite matrix

• Fuel pellets are loaded into a cylindrical, refractory metal containment cylinder with perforated end plates for coolant flow (figure)

• A BeO reflector surrounds the core

• Control is by rotatable BeO drums with B$_4$C strips attached

• See;
  a.) Noncirculating fuel design
  b.) Once through then out
  c.) Circulating fuel

• Proposed by SAIC

• References
Figure B-3. Particle-Bed Reactor
Pluto Derivative Reactor

- Geometry (see figure)

- Fuel elements are hexagonal with a single coolant channel running down the center.

- Flat to flat dimension is 6.83 mm with a 4 mm diameter coolant channel running the length of the fuel rod, 10 cm

- the fuel rods are stacked lengthwise

- Fuel element is BeO moderator with 93% enriched UO₂ mixed homogeneously throughout

- A 10 cm thick BeO reflector is used

- Reactivity is controlled in 2 ways;
  a.) Variable leakage reflector
  b.) Burnable poisons

- Flux profile is flattened by;
  a.) Variations in the fuel concentration
  b.) Internal absorber rods placed throughout the core

- Tory II-C reactor came from the PLUTO concept in the early 1960’s for nuclear ramjets

- Tory II-C operated at 500 MWt with coolant outlet of 1450 °K
- Proposed by LLNL, see references
References for Pellet Bed Reactor


References for Pluto Reactor


38. C. E. Walter, Privileged Information, April 1985.


NERVA/PLUTO Hybrid Reactor

- Uses PLUTO geometry
- NERVA fuel type (UC$_2$ in graphite matrix)
- Proposed by LLNL and Westinghouse (see references)

--------------------------------

UB$_2$ Reactor

- Uses PLUTO geometry
- Uses UB$_2$ fuel in B$_4$C matrix
- Fuel enriched in B$^{11}$ to reduce parasitic B$^{10}$ absorption
- If hard spectrum used, minimal enrichment required


---

**References for Foam Fuel Reactor**


Gas Cooled Reactor Mass Studies

A.) Burst Mode Mass Estimates (cont.)

5.) Cermet Reactor (see explanation)
   • Uses no moderator
   • Used full loading of 2000 to 6000 kg U/m³

6.) Nerva Derivative (see explanation)
   • Reactor mass of 3.3 metric tonnes at 900 kg/m³

7.) Particle Bed Reactor (see explanation)
   • The small (500 Microns diameter) $UC_2$ particles contained between concentric circles gave a 4.07 tonne reactor

   • May Substitute LiH for $B_4C$

8.) Wire core reactor (see explanation)

   • Spacer wires are 13 mm apart
   • makes a big difference whether the coolant flow is axially or radially
   • we have the 2,200kg system mass for a simple design

9.) Foam Fuel Reactor (see explanation)

   • Randomly oriented 0.55mm UC2 'wires' with a 0.1 mm thick coating
   • Fuel density $\approx 20\%$
   • Reactor mass $\approx 2.5$ tonnes
Cermet Reactor

- Based on the 710 High Temperature Gas Reactor system of the 1960’s
- Uses a fast spectrum
- Refractory metal, hexagonal cermet fuel elements with multiple tubular flow channels (see figure)
- BeO side and bottom reflectors
- Control by B strips embedded in radial BeO reflector
- Coolants are:
  a.) Hydrogen for open cycle burst mode
  b.) Ne for closed loop (Brayton cycle) MMWSS mode
- A UO2/W cermet fuel was chosen because of high strength and high thermal conductivity
- Proposed by GE
- See references
Longitudinal and cross-sectional views of 710 Reactor

INITIAL DEVELOPMENT FUEL ELEMENT GEOMETRY

<table>
<thead>
<tr>
<th>FEATURE</th>
<th>MEASURED VALUE</th>
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<tbody>
<tr>
<td>MATRIX ACROSS-PLATES DIMENSION, IN.</td>
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<tr>
<td>OUTER CLADDING THICKNESS, IN.</td>
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<tr>
<td>NO. OF COOLANT CHANNELS</td>
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<tr>
<td>COOLANT CHANNEL HYDRAULIC DIAMETER, IN.</td>
<td>0.030</td>
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<tr>
<td>COOLANT CHANNEL PITCH, IN.</td>
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<tr>
<td>COOLANT CHANNEL CLADDING THICKNESS, IN.</td>
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<td>MATRIX LENGTH, IN.</td>
<td>12</td>
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</tbody>
</table>

Cermet fuel element

Figure B-5. Cermet Reactor
References for NERVA/Pluto Hybrid Reactor

See references 29 and 36

References for UB₂ Reactor

See References 35-40

References for Cermet Reactor


44. J. A. Angelo Jr., and D. Buden, Space Nuclear Power, (Orbit Book Co, 1985).


NERVA Derivative Reactor

• Based on ROVER nuclear rocket program in which 20 reactors were built and tested in the 1960’s and early 70’s

• Two types of fuel were considered; (figure)

• Each fuel module consists of 6 hexagonal graphite fuel rods surrounding a central support element (tie tube)

• Basic NERVA fuel is UC₂ in a graphite matrix

• the ZrC coating replaces the graphite coating of HTGR’s

• Typical fuel element is 1.91 cm across the flats with 19 (2.5 mm diameter) coolant holes

• Proposed by Westinghouse

• See references
NERVA FUEL MODULE

NERVA FUEL TYPES

CUT-AWAY AND SCHEMATIC FLOW DESCRIPTION OF THE NERVA REACTOR

Figure B-2. NERVA Reactor (Used With Permission of Los Alamos National Laboratory)
References for NERVA Reactor


22. Pewee I. Reactor Test Report, Los Alamos Scientific Laboratory of the University of California, LA-4217-MS, August 1969.

23. A Design of Low Power Light Weight Rover Reactors, Los Alamos Scientific Laboratory of the University of California, LA-3642-MS, June 1968.

References for NERVA Reactor


Particle Bed Reactor

- Based on extensive experience from the High Temperature Gas Cooled Reactor (HTGR) program

- Figure

- Fuel is TRISO -like particles (see figure) contained between two porous cylinder frits (screens)

- Both moderated and unmoderated systems have been designed

- For moderated systems, the fuel elements are inserted into a monolithic solid moderator

- Coolant flow is axial in moderator, radially inward through the frit into the central fuel element channel and finally to exit

- The outer layers of the TRISO are different from the HTGR; SiC is replaced with ZrC.

- Typical reactor would consist of 37 fuel elements in a moderator of ZrH$_2$ or Li$^7$H.

- Outer diameter would be 5.8 cm and inner diameter 2.7 cm.

- Outer frit -Stainless Steel, inner (exit) frit - Re

- Proposed by BNL and B&W (references)
Figure B-1. Particle-Bed Reactor
References for Particle Bed Reactor


Major Declassification after Jan 1992 Meeting.
Wire Core Reactor

• Reactor core made up of annular fuel assemblies of continuous clad fuel wires

• Between layers of fuel wires, unfueled spacer wires maintain spacing and allows coolant flow throughout the void spaces (see figure)

• Reactor uses fast spectrum

• Coolant flows into the reactor axially and then radially through the fuel

• Central void region is occupied by single rod with 2 sections
  a.) Be
  b.) Poison

Axial motion controls the reactor power

• Fuel rods have UN core, clad with W -5Re and outer diameter of 0.5 to 2.5 mm

• Spacer wires are of W -5Re and thinner to keep the temperature down

• At lower temperatures (1400 °K) can use UO₂ clad with Nichrome -V

• Proposed by Rockwell, see references
Figure B-6. Wire-Core Reactor (Used with permission of Rockwell International)
Foam Fuel Reactor

- Not particularly well defined

- Fuel consists of UC$_2$ in the form of porous foam coated with graphite and ZrC

- Assumes that the porous foam fuel element occupies the same position as the particle-bed concept

- The coolant passe from the outside of the fuel element into the central cavity (see Figure)

- Proposed by B&W, see references
CONCEPTUAL CORE CONFIGURATION
(NUMBER OF FUEL ELEMENTS VARIES WITH DESIGN REQUIREMENTS)

POROUS FUEL ELEMENT

INLET COOLANT CHANNEL

COOLANT PLENUM

PRESSURE VESSEL

MODERATOR

END REFLECTOR

EXIT COOLANT CHANNEL

REFRACTORY FOAM FUEL ELEMENT CONCEPT

COLD GAS RADIAL THROUGHFLOW

HOT GAS AXIAL OUTFLOW

NESTED RIGID POROUS CARBIDE FUEL CYLINDERS

Figure B-7. Foam-Fuel Reactor Concept
Rating of Gas Cooled Concepts for Space Power

- Burst Mode:
  - NERVA (1st Choice)
    - Cermet
    - NERVA/Pluto
    - Particle Bed
    - Pellet Bed
    - Pluto
    - Wire Core
  - Not Recommended

- Steady State:
  - NERVA/Pluto (1st Choice)
    - Particle Bed
    - Pellet Bed
    - Pluto
  - Cermet
  - Wire Core

- Foam Fuel UB2 Reactor