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)**

- **H_2 first cools the power conditioning unit and the generator, then it enters the reactor where it is heated to 1200 °K.**

- **The 1200 °K H_2 runs the turbine to make electricity, and then it is exhausted into space.**

- **Although the H_2 was not included in the total mass, it was calculated and the tank, insulation, refrigeration, and meteorite protection was calculated and added.**

2) <u>Open Hydrogen-Oxygen Combustion System</u>

- **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 O_2 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) <u>Closed Rankine and Brayton Cycles</u>

- **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) <u>Energy Storage Systems</u>

- **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) <u>Thermionic with Energy Storage</u>

- **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.**

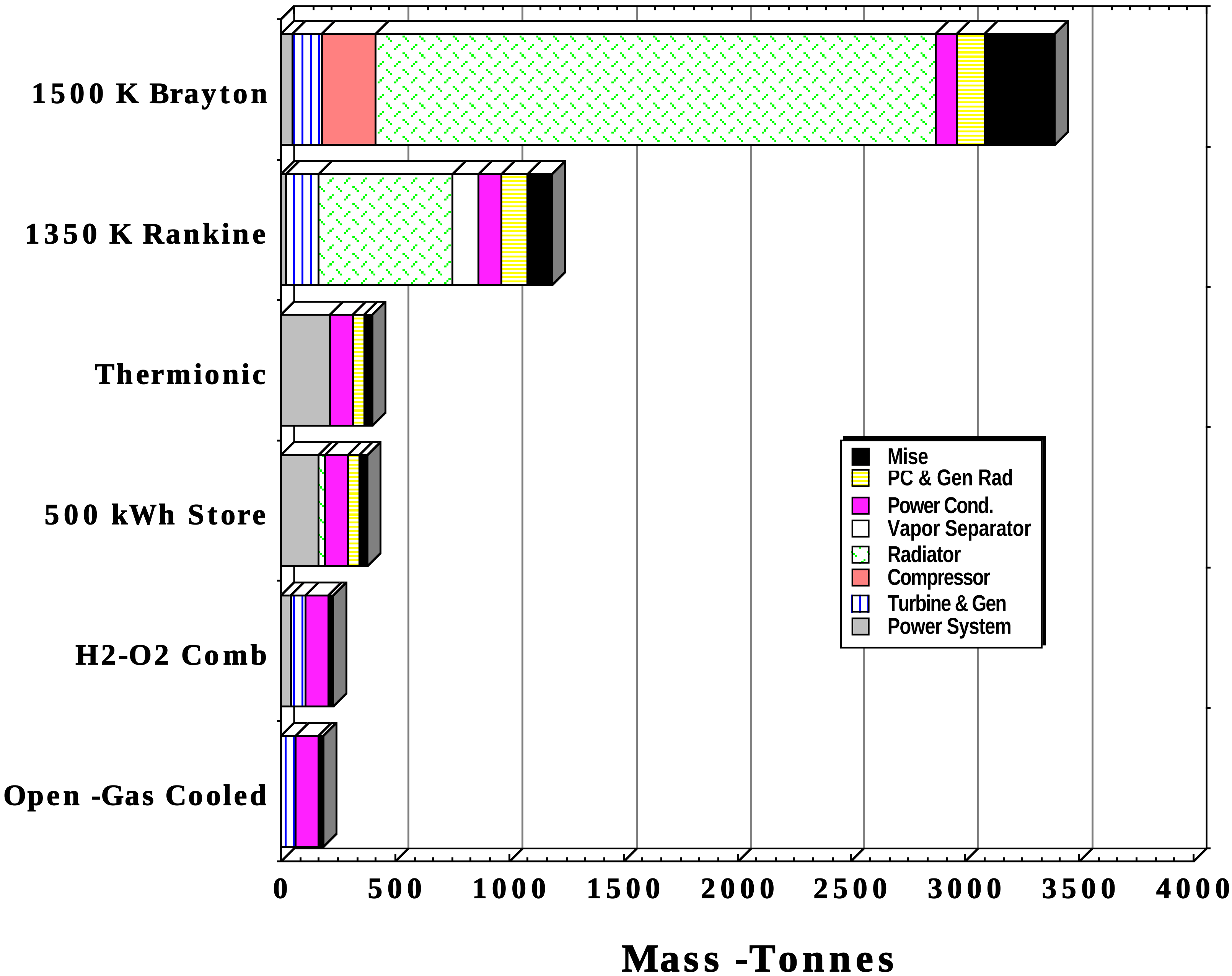
Comparison of 500 MW_e Burst Mode Space Power Systems

Metric Tonnes

Component	Open Gas Cooled Reactor	Open H2-O2 Comb.	500 MWh Energy Store	Therm-ionic Energy Store	1350 °K Rankine	1500 °K Brayton
Power Source	3	42	166	214	21	47
Turbine & Generator	63	64	0	0	143	131
Compressor	0	0	0	0	0	236
Radiator	0	0	24	0	585	2452
Vapor Separ.	0	0	0	0	115	0
Power Conditioning	100	100	100	100	100	100
PC & Gen Radiator	0	0	53	53	115	115
Misc	17	21	34	37	108	308
TOTAL	183	277	377	405	1187	3309

Mass of 500 MWe Burst Mode Power Systems

600 second operating time



Gas Cooled Reactor Mass Studies

A.) Burst Mode Mass Estimates

1.) **Pellet Bed Reactor (see explanation)**

• Used 500 μ diameter UC_2 particles imbedded in 1.5 cm spheres. A 5.4 tonne mass was obtained with 900 kg U/m^3

2.) **Pluto Derivative (see explanation)**

• Used UO_2-BeO hex fuel rods, 6.83 mm across.

• Found that minimum reactor mass occurs at only 19 kg U/m^3

3.) **NERVA/Pluto Hybrid (see explanation)**

• Pluto geometry with NERVA fuel (UC_2)

• Minimum reactor mass occurs at 900 kg U/m^3

4.) **UB_2 Reactor (see explanation)**

• Minimum reactor mass of 34.9 tonnes occurred at 500 kg U/m^3

• Not as crucial to get rid of B-10 as originally thought (UB_2 in B_4C)

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_4C strips attached

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

- Proposed by SAIC

- References

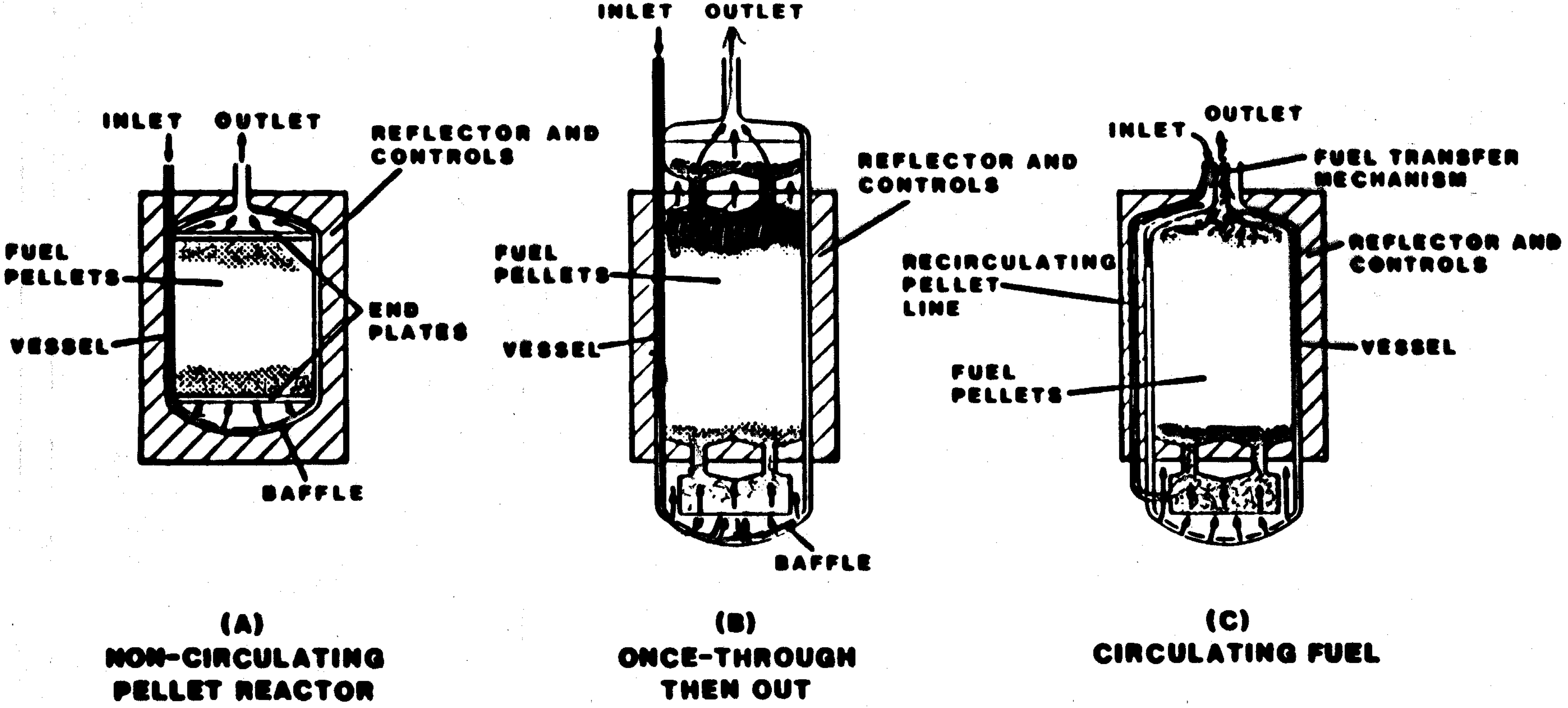


Figure B-3. Particle-Bed Reactor

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 UO_2 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

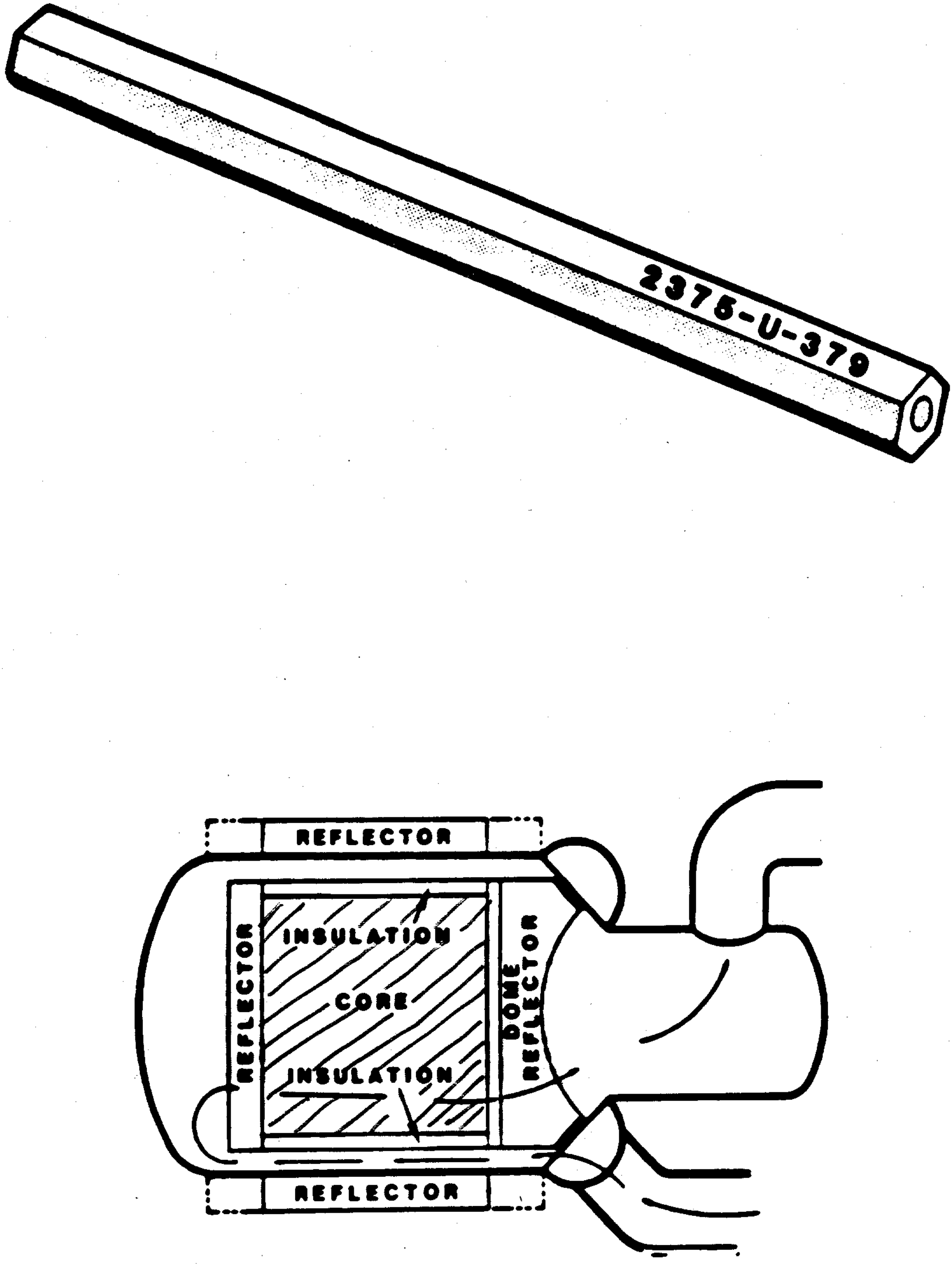


Figure B-4. PLUTO Reactor

References for Pellet Bed Reactor

33. D. Buden, <u>Pellet Bed Reactor Concept</u>, Science Applications International Corporation, White Paper Submitted to the Air Force Space Technology Center for the SDI Multi-megawatt Power Program, May 30, 1985.

34. D. Buden, et al., <u>Pellet Bed Reactor Concept</u>, Science Applications International Corporation and the University of New Mexico, March 1987.

References for Pluto Reactor

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Pluto Hybrid

* 36. C. E. Walter, <u>SPR-9 Concept Definition Study, FY 1986 Summary</u>, Lawrence Livermore National Laboratory, UCID-20883, October 1986.

37. C. E. Walter, <u>Technology Development Plan for Multi-Megawatt Space Power Systems</u>, COMS84-8/Rev 2, Unclassified, May 1984.

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

39. C. E. Walter, Privileged Information, October 28, 1985.

40. Carl Walter, personal communication, October 1986.

41. C. E. Walter, et al., <u>Gas-Cooled Reactor Power Systems for Space--Concept Definition Study Final Report</u>, Lawrence Livermore National Laboratory, March 27, 1987.

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_4C matrix**
- **Fuel enriched in B^{11} to reduce parasitic B^{10} absorption**
- **If hard spectrum used, minimal enrichment required**

References for Wire Core Reactor

47. Advanced High-Temperature Nuclear Reactor Power System, Rockwell International, White Paper Submitted to the Air Force Space Technology Center for the SDI Multimegawatt Power Program, RI/RD85-227, July 11, 1985.

48. Advanced High-Temperature Nuclear Reactor Power System Volume II, Rockwell International, RI/RD85-189P, May 30, 1985.

49. D. J. Arnold, et al., Metallic Annular Rocket Reactor System (MARRS) Design Study, Atomics International, AI-65-34, May 1, 1965.

50. R. Hansen et al., Rockwell International, personal communication, October 1986.

References for Foam Fuel Reactor

51. L. G. Weatherford, B&W Proposed R&D 86-048, "Ultra-High Temperature Gas-Cooled Reactor with Porous Refractory Foam Fuel," Babcock and Wilcox letter to US DOE, San Francisco Operations Office, April 1986.

52. B. J. Short, Babcock and Wilcox, personal communication, October 1986.

53. B. J. Short, Ultra High Temperature Gas Cooled Reactor with Porous Refractory Foam Fuel (Preliminary Feasibility Assessment Report, Phase I), Babcock and Wilcox, February 1987.

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/m^3**

6.) Nerva Derivative (see explanation)

- **Reactor mass of 3.3 metric tonnes at 900 kg/m^3**

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 UC_2 'wires' with a 0.1 mm thick coating**
- **Fuel density ≈ 20%**
- **Reactor mass ≈ 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

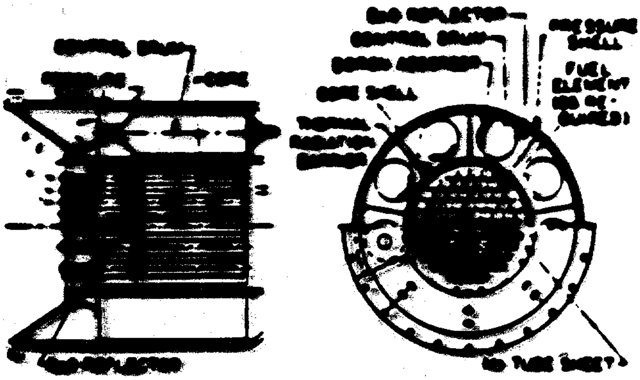
- Coolants are;
  a.) Hydrogen for open cycle burst mode
  b.) Ne for closed loop (Brayton cycle) MMWSS mode

- A UO2/W cermet fuel was chosen because of high strength and high thermal conductivity

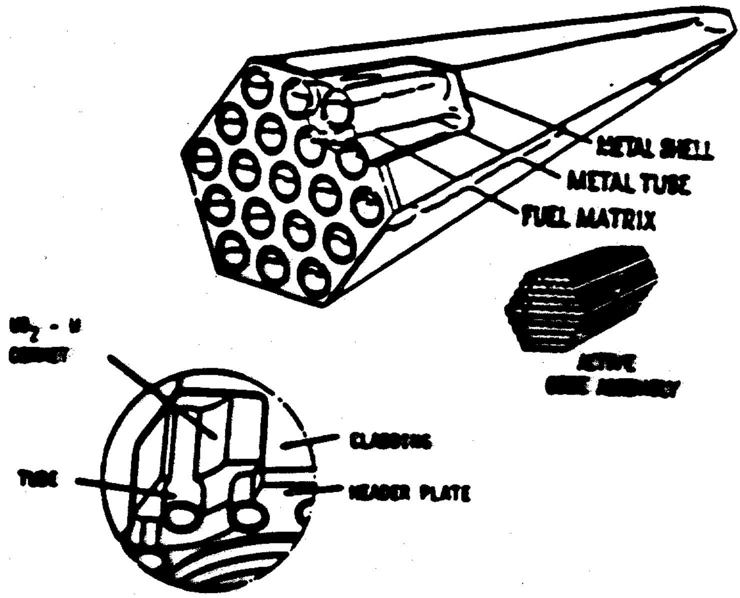
- Proposed by GE

- See references

710 REACTOR ASSEMBLY



Longitudinal and cross-sectional views of 710 Reactor



INITIAL DEVELOPMENT FUEL ELEMENT GEOMETRY

SHAPE	HEXAGONAL PRISM
MATRIX ACROSS-FLATS DIMENSION, IN.	[illegible]
OUTER CLADDING THICKNESS, IN.	0.015
NO. OF COOLANT CHANNELS	91
COOLANT CHANNEL HYDRAULIC DIAMETER, IN.	0.036
COOLANT CHANNEL PITCH, IN.	[illegible]
COOLANT CHANNEL CLADDING THICKNESS, IN.	0.006
MATRIX LENGTH, IN.	12

Cermet fuel element

Figure B-5. Cermet Reactor

References for NERVA/Pluto Hybrid Reactor

See references 29 and 36

References for UB_2 Reactor

See References 35-40

References for Cermet Reactor

42. A Bimodal Cermet Fueled Refractory Metal Reactor for MMW Applications, General Electric Corporation, October 15, 1986.

43. 710 High Temperature Gas Reactor Program Summary Report, Volume I through V Summary, General Electric, GEMP-600.

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

45. W. Ranken, Los Alamos National Laboratories, personal communication, October 1986.

46. C. L. Cowan, et al., A Bimodal, Cermet Fueled, Nuclear Power System for Strategic Defense Applications--Final Report; Vol. 1 - Executive Summary, Vol. 2 - Technical Presentation, General Electric Company, GEFR-00803, March 1987.

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)**

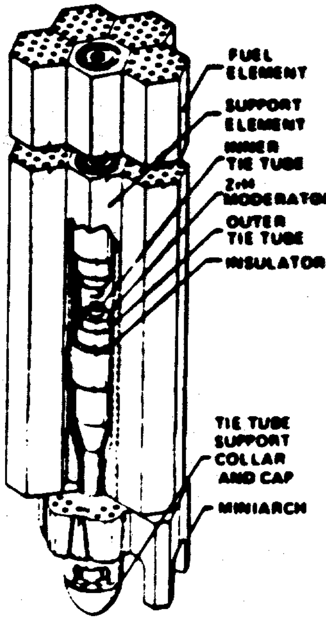
- **Basic NERVA fuel is UC_2 in a graphite matrix**

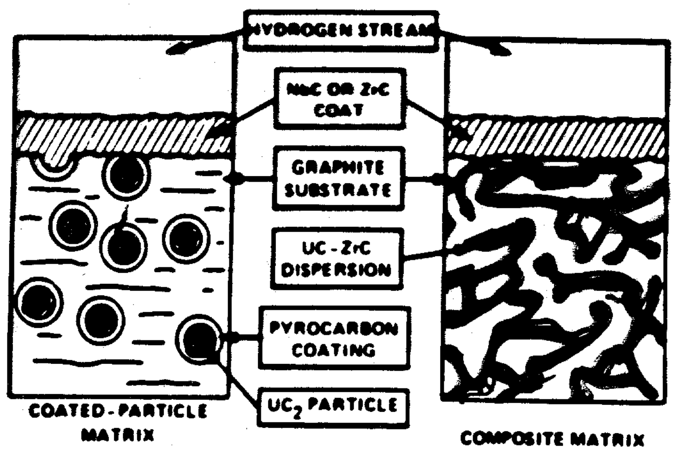
- **the ZrC coating replaces the graphite coating of HTGR's**

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

- **Proposed by Westinghouse**

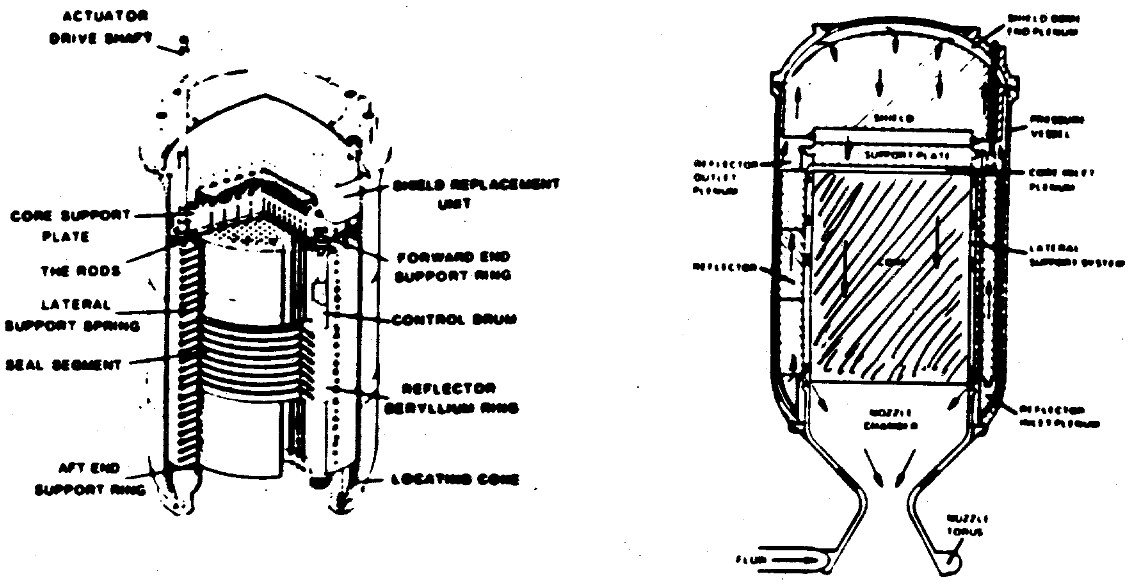
- **See references**





NERVA FUEL TYPES

NERVA FUEL MODULE



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

13. D. R. Koenig, Experience Gained from the Space Nuclear Rocket Program (Rover), LA-10062-H, UC-33, May 1986.

14. Technical Summary Report of NERVA Program, Phase I, NRX & XE, Volume IV, Technology Utilization Survey, Westinghouse Astronuclear Laboratory, TNR-230, July 31, 1972.

15. Technical Summary Report of NERVA Program, Phase I, NRX & XE Volume III, Full Scale Program, TNR-230, July 15, 1972.

16. Technical Summary Report of NERVA Program, Phase I, Volume V, Abstracts of Significant NERVA Documentation, Westinghouse Astronuclear Laboratory, TNR-230, September 1972.

17. Technical Summary Report of NERVA Program, Phase I, NRX & XE Addendum to Volume II, NERVA Fuel Development, Westinghouse Astronuclear Laboratory, TNR-230, July 15, 1972.

18. Rover Program Reactor Tests Performance Summary, NRX-A1 Through NRX-AG, Westinghouse Astronuclear Laboratory, WANL-TME-1788, July 1968.

19. Technical Summary Report of NERVA Program, Phase I, NRX & XE, Volume II, NERVA Component Development and Testing, Westinghouse Astronuclear Laboratory, TNR-230.

20. F. P. Durham, Nuclear Engine Definition Study Preliminary Report Volume I - Engine Description, LA5044-MS, Vol. I, September 1972.

21. F. P. Durham, Nuclear Engine Definition Study Preliminary Report Volume II - Supporting Studies, LA5044-MS, Vol. II, September 1972.

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.

24. W. L. Kirk, Nuclear Furnace-1 Test Report, Los Alamos Scientific Laboratory, LA-5189-MS, March 1973.

References for NERVA Reactor

25. Use of the NERVA Reactor as the Heat Source for a Space Propulsion/Electrical Power System, Westinghouse Astronuclear Laboratories, WANL-TME-2714, August 1970.

26. Technology Development for the NERVA Derivative Gas Cooled Reactor, Westinghouse Electric Corporation, White Paper Submitted to the Air Force Space Technology Center for the SDI Multimegawatt Power Program, July 1985.

27. F. A. Snipe, Corrosion Rate of Pyrolytic Graphite, Westinghouse Astronuclear Laboratories, WANL-TMI-1429, March 30, 1965.

28. The NERVA Technology Reactor Integrated with NASA Lewis Brayton Cycle Space Power Systems, Westinghouse Astronuclear Laboratories, Handout with TNR-LL5, May 1970.

Pluto hybrid

29. B. Holman, G. Farbman, Westinghouse Electric Corporation, personal communication, November 1986.

30. I. Helms, Department of Energy, personal communication, December 1986.

31. R. Bohl, Los Alamos National Laboratory, personal communication, November 1986.

32. T. Carlson, et al., NERVA Derivative Reactor Brayton Space Power System Concepts for Multimegawatt Applications Final Report, Westinghouse, March 1987.

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^7H.

- 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)

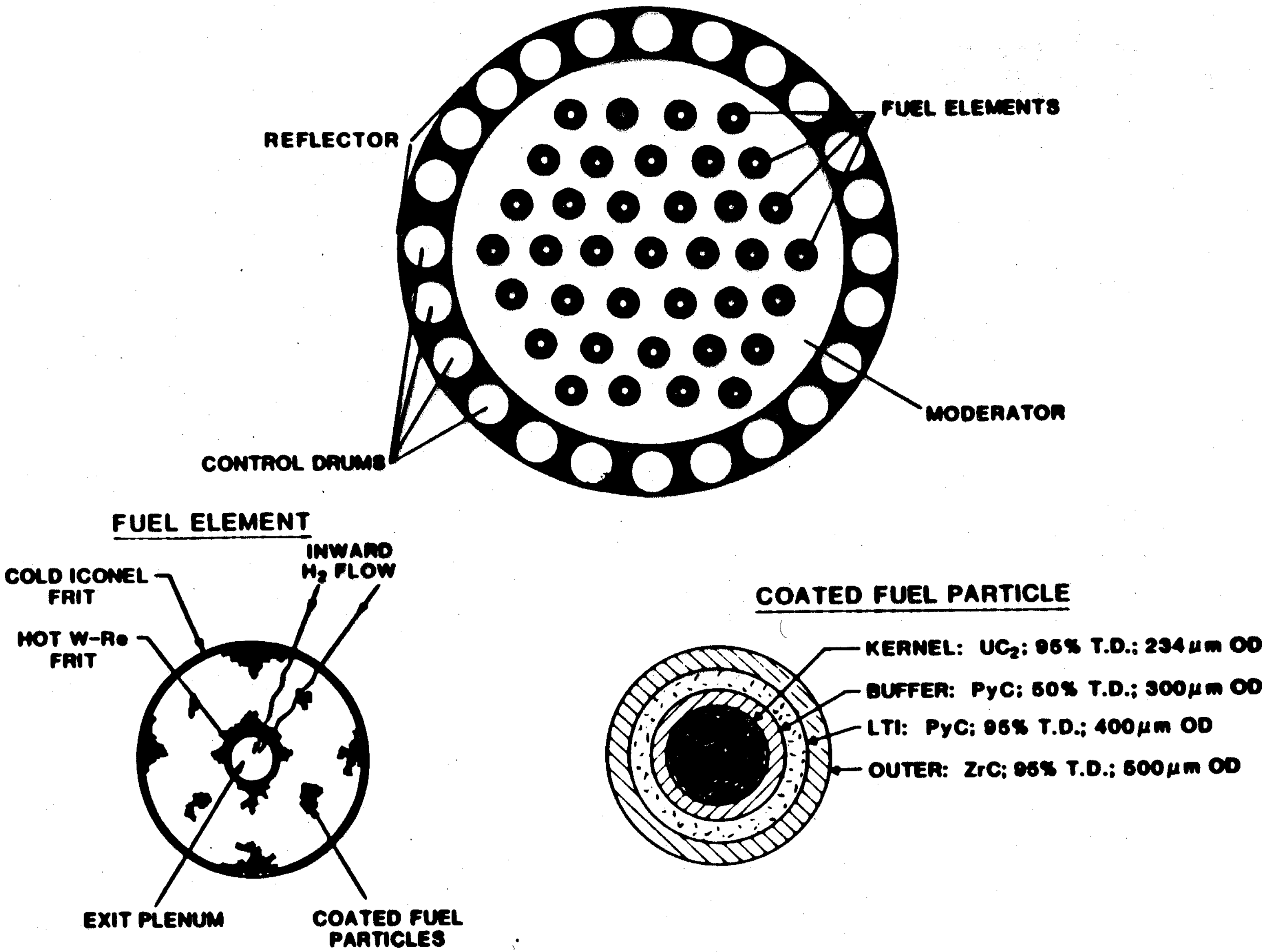


Figure B-1. Particle-Bed Reactor

References for Particle Bed Reactor

1. B. J. Short et al., Multi-Megawatt Space Power Reactor for Providing 1 to 15 MWe Power for the Strategic Defense Initiative, Babcock and Wilcox Company, White Paper Submitted to the SDI Innovative Science and Technology Office, White Paper Number 85-141-B, July 1985.

2. J. Powell et al., Multi-Megawatt Power Systems Based on the Particle Bed Reactor, White Paper Submitted to the SDI Innovative Science and Technology Office, 1985.

3. J. A. Belisle, Near Term Nuclear Space Power for SDI Applications, Grumman Aerospace Corp., White Paper Submitted to the SDI Innovative Science and Technology Office, July 1985.

4. R. V. DeMars, Babcock and Wilcox, Sandia National Laboratories, "MMW PBR Fuel Element Radiation Test," letter to P. McDaniel, July 1986.

5. J. Powell and H. Ludwig, Brookhaven National Laboratories, personal communication, October 1986.

6. P. McDaniel, Sandia National Laboratories, personal communication, October 1986.

7. B. J. Short, et al., Burst Space Power Reactor: An Innovative Nuclear Reactor for Providing 100 to 600 MWe Power for the Strategic Defense Initiative, White Paper submitted to the SDI Innovative Science and Technology Office, White Paper No. 85-141-C, July 1985.

8. J. Powell, Privileged Information, April 17, 1984.

9. J. Powell, Privileged Information, April 30, 1985.

10. J. Powell, Privileged Information, May 22, 1985.

11. J. Powell, Strategic Defense Applications of Particle Bed Reactors, April 30, 1985.

12. J. R. Powell, et al., Privileged Information, March 1987.

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**

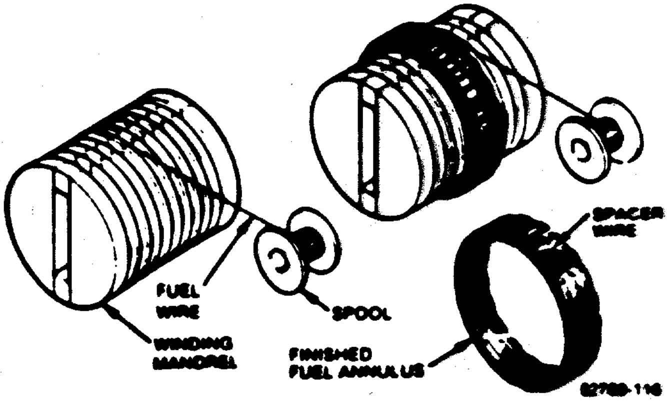
Axial motion controls the reactor power

- **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 UO_2 clad with Nichrome -V**

- **Proposed by Rockwell, see references**



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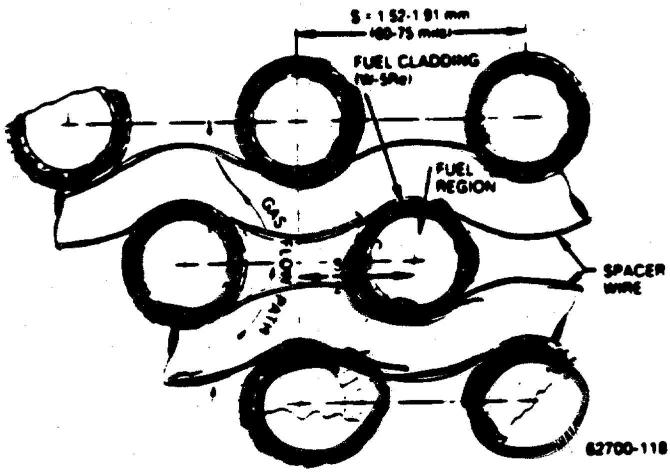
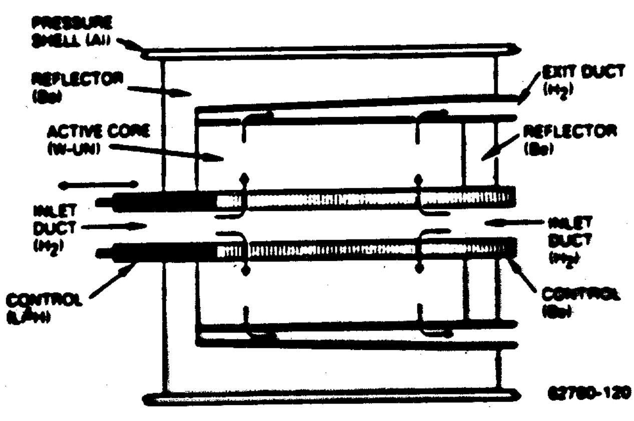


REACTOR WIRE FUEL ELEMENTS



REACTOR SIDE VIEW - SCHEMATIC

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

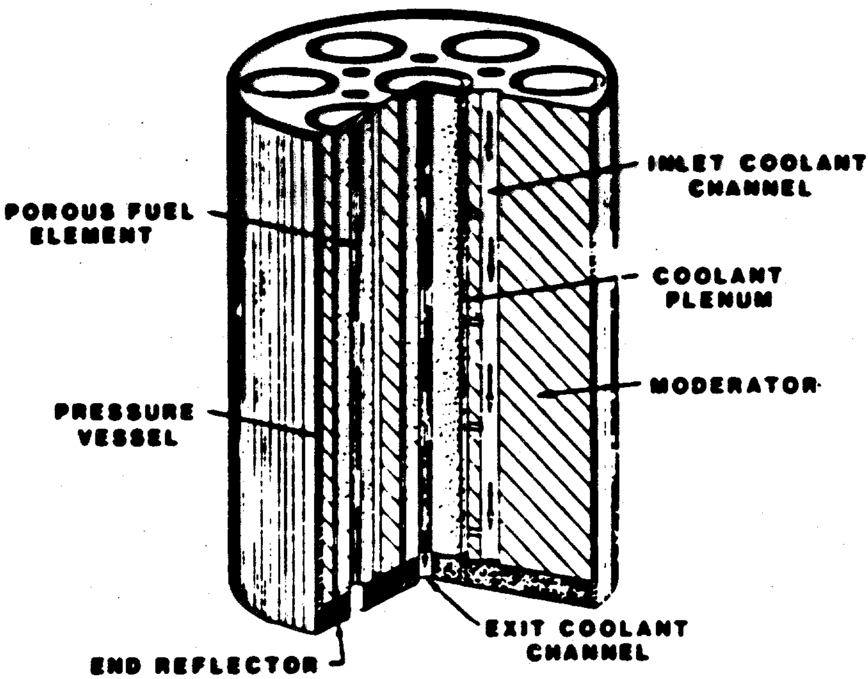
- Assumes that the porous foam fuel element occupies the same position as the particle -bed concept

- 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)



REFRACTORY FOAM FUEL ELEMENT CONCEPT

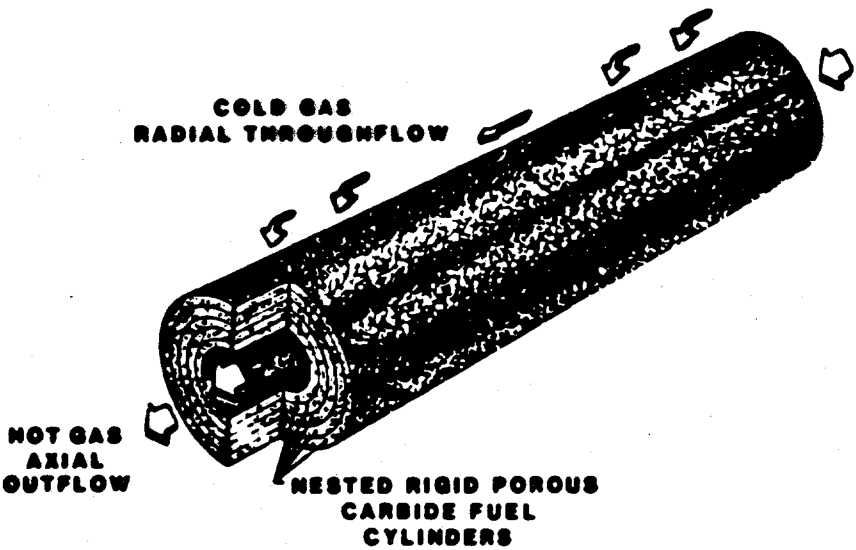


Figure B-7. Foam-Fuel Reactor Concept

Rating of Gas Cooled Concepts for Space Power