899551

CONCEPTUAL DESIGN OF A CATEGORY III MULTIMEGAWATT SPACE NUCLEAR POWER SYSTEM

Ronald E. Feddersen
Grumman
Space Systems Division
Bethpage, N.Y. 11714-3588

John R. Coiner, Jr.
Babcock & Wilcox
Nuclear Power Division
Space Power & Propulsion
Lynchburg, VA 24506-0935

ABSTRACT

As part of the Strategic Defense Initiative Office's Space Power Programs, the Department of Energy (DOE) is directing a multi-year, multi-phase effort known as the Multimegawatt Space Reactor Project (MMW). Six companies were winners of Phase I contracts. In the Phase I effort, completed in February 1989, the six prime contractors conducted the trade-off studies and analyses required to arrive at MMW conceptual designs in three categories. The Category I concept is capable of delivering 10's of megawatts of electric power (MW_e) for 100's of seconds with effluents permitted. Category II has the same basic requirements as Category I, but no effluents are permitted. Category III is the same as Category I, but must produce 100's of MW_e.

This paper presents a summary of some of the results of the Category III conceptual design studies. Design requirements are reviewed, an overall system description is presented with major components identified and primary state points quantified, followed by a discussion of our concept's unique particle bed reactor (PBR).

INTRODUCTION

The overall purpose of the Multimegawatt Program is to provide for the development of a space-based nuclear power system to meet the needs of the Strategic Defense Initiative Office (SDIO) and some future civilian space missions. The Phase I study of a Category III Open Brayton Cycle System was conducted by a Grumman Space Systems team with Babcock & Wilcox, Allied-Signal Fluid Systems Division, Aerojet TechSystems Co., Maxwell Laboratories, Inc. and S-CUBED as subcontractors and the Brookhaven National Laboratory as a safety and reactor consultant. It was performed for the U.S. Department of Energy, Idaho Operations Office, under Contract No. DE-AC07-88ID12753. Contract effective date was 1 May 1988 and Phase I tasks covered a period of ten (10) months.

In order to permit the obvious synergism resulting from integration of potential weapons with the MMW, while at the same time separating weapon design from the MMW effort, DOE established a firm set of requirements and initial conditions for each of the three MMW categories. This has the additional advantage of having a common requirements base for comparison of the resulting design concepts.

The Category III objective was to provide a conceptual design of a safe, space-based nuclear power system capable of providing 100's of MW_e for 100's of seconds. The design is to be less than 55,000 Kg mass and be smaller than a cylinder 30 m long and 10 m in diameter. Safety must be built into the design from the outset and integrated from start-to-finish so that the safety of the public, the workers and the environment will not be compromised in any phase of the Multimegawatt Program.

Hydrogen is supplied by the weapon to the MMW at given conditions with the flow rate determined by the weapon cooling requirements (see Table 1). The design and mass of the hydrogen feed subsystem are not considered part of the MMW effort, but are to be considered in system optimization.

SYSTEM DESCRIPTION

Figure 1 is a system block diagram showing the major system components. The crosshatched areas indicate the parts of the system that are considered to be part of the weapon and not part of the MMW prime power system. Indicated in the figure are the turbopump (T-P), turbocompressor (T-C), alternator drive turbine (T), super-cooled alternator (ALT) and power conditioning subsystem (P/C).

Liquid hydrogen is pumped by the turbopump from the storage tank into the linear accelerator heat exchanger (LINAC), where it cools the LINAC. After it exits the LINAC, some of the hydrogen is used to cool the alternator, power conditioning, turbine bearings, and any valves, tanks, and control system components which might require cooling due to radiation heating. The bulk of the hydrogen flows through the compressor. The hydrogen then splits into two streams - one passes through the weapon heat exchanger and cools the weapon, and the other enters the decay heat tanks. Hydrogen will accumulate in the decay heat tanks until they reach system pressure, after which it will flow through the tanks, maintaining them in the charged state with high pressure, cold (66 K) hydrogen. Hydrogen that flows through the tanks mixes with hydrogen from the weapon outlet in the reactor plenum, and continues through the reactor. During the early stages of operation (until the start tanks are at system pressure), some of the hydrogen flows

CH2781-3/89/0000-1121 $1.00 © 1989 IEEE

Table 1 – State Points & Normalized Flow Rates at Various System Locations During Steady-State Operation

POINT DESCRIPTION	POINT	NORMALIZED PRESSURES	TEMPERATURE (K)	NORMALIZED FLOW RATE
HYDROGEN TANK OUTLET	0	1.00	20.0[1]	1.00
TURBOPUMP OUTLET	1	10.50	21.4	1.00
COMPONENT COOLING STREAM	2	7.00[2]	30.0[3]	0.05-0.10
TURBOCOMPRESSOR OUTLET	3	42.15	69.0	0.45-0.55
WEAPON OUTLET/REACTOR INLET	4	39.20	224.0[4]	0.45-0.55
REACTOR OUTLET	5	34.95	1050.0	0.45-0.55

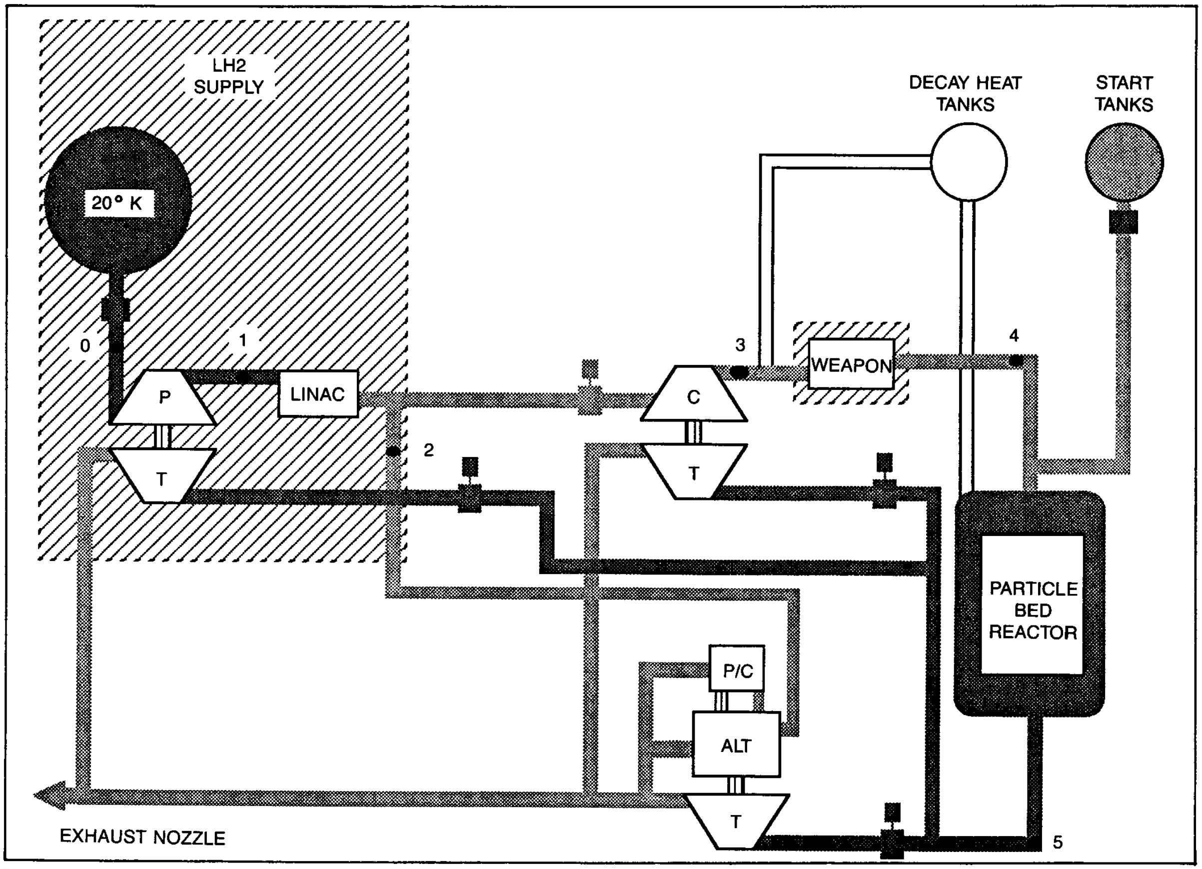
[1] LIQUID HYDROGEN STORAGE TEMEPRATURE GIVEN

[2] HYDROGEN PRESSURE AT LINAC OUTLET MUST BE SUPERCRITICAL

[3] LINAC OUTLET TEMPERATURE LIMIT GIVEN = 35°K

[4] WEAPON OUTLET TEMPERATURE LIMIT GIVEN = 400°K

R89-0694-004



R89-0694-001

Figure 1 System Block Diagram

from the weapon outlet into the start tanks, refilling them for the next start-up. The hydrogen that exits the reactor is used to power the alternator turbine, the turbocompressor, and the turbopump.

Note that the decay heat tanks operate passively. After reactor shutdown, the hydrogen in these tanks will automatically blow down through the reactor for decay heat removal.

The turbopump outlet pressure assures that the hydrogen in the LINAC will be at super-critical pressure, including allowance for the pressure drop across the LINAC. This minimum pump outlet pressure generates a minimum enthalpy rise across the pump and maximum heat capacity of the hydrogen in the LINAC. Both of these factors result in the minimum flow rate required to maintain the LINAC at 35 K.

The compressor outlet pressure was selected as the result of a trade-off between the size, mass and required work of the compressor, and the size, mass, and efficiency of the reactor turbines. Higher pressure would result in a smaller required flow area and smaller reactor vessel, as well as smaller and lighter turbines. However, achieving higher system pressure would require a larger and heavier compressor and more compressor work, especially since the compressor efficiency tends to decrease as the outlet pressure increases. Thus, the compressor drive turbine would require additional hydrogen mass flow. Additionally, a higher pressure system would require heavier piping and would operate with smaller safety margins. The optimum compressor outlet pressure, accounting for pressure losses in piping and components, was determined.

PBR DESCRIPTION

The PBR for MMW Category III was designed with strict attention to integrating safety without sacrificing performance. The development risk was minimized by selecting operating temperatures that allow the use of well characterized materials.

The MMW PBR design consists of fuel elements arranged on a triangular pitch forming a hexagonal lattice. Figure 2 (PBR Radial Section) and Figure 3 (PBR Longitudinal Section) depict the core arrangement and identify the major reactor components and materials.

The MMW Category III PBR is a thermal reactor utilizing circulating water for both the moderator and the reflector. The water is drained from the reactor except while on-station, thereby assuring criticality safety for assembly, transport, handling, launch, and disposal. For accidents, such as water flooding, criticality is prevented by safety rods and the reactor control drums. Other than fuel, no toxic materials are employed.

The selection of a water moderator/reflector simplified the reactor design and resulted in a lighter reactor. Some of the advantages are

- High hydrogen density, therefore a small core
- Eliminates the use of Be in the reactor
- Improves safety during handling, launch, and transport through removal of the moderator and reflector ($k_{eff} > 0.5$)
- Provides assured shutdown at end of life
- Improves reactor control and operation by providing a large negative moderator coefficient
- Easily cooled during operation, thereby reducing design complexity.

The PBR is unique in that most of the reactor operates at low temperatures, with only a fraction of the fuel bed, the hot frits, and the outlet nozzle seeing the outlet temperature of 1050 K. The remaining reactor components operate at temperatures ranging from 220 K to approximately 500 K.

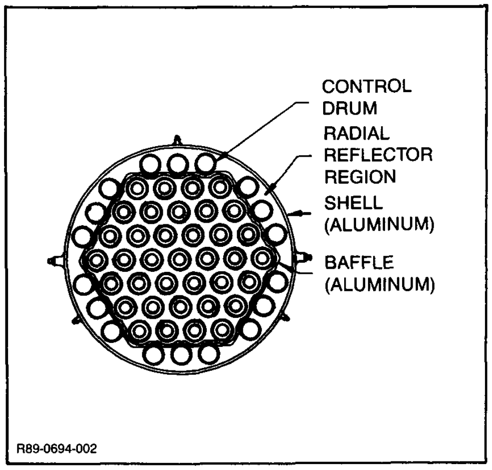


Figure 2 PBR Radial Section

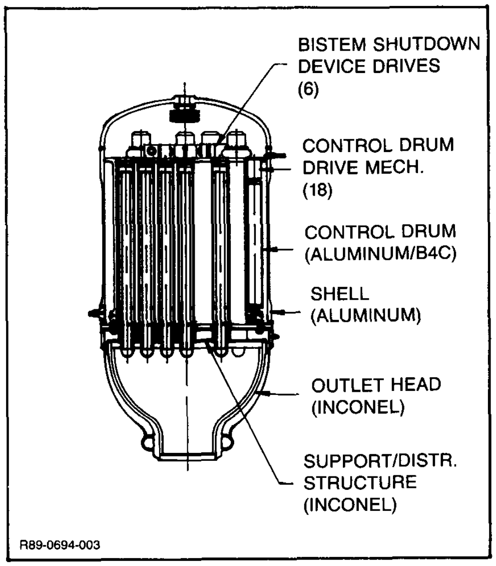


Figure 3 PBR Longitudinal Section

The large heat transfer surface area of the fuel bed, up to 65 cm^2 per cm^3, allows high power densities without thermally stressing the fuel particles. The kernel center temperature for the highest power particle is less than 200 K hotter than the coolant gas. Table 2 provides design functions and operating conditions of selected key reactor components.

Table 2 – PBR Component Function and Operating Temperature Range

COMPONENT	FUNCTION	TEMPERATURE
FUEL PARTICLE	FP, F, C, P	450 K – 1250 K
COLD FRIT	S, F, P, R	250 K – 600 K
HOT FRIT	F, P, R	1000 K – 1200 K
CALANDRIA	S, F	250 K – 600 K
VESSEL	S, F	220 K – 500 K

WHERE:
FP – FISSION PRODUCT CONTAINMENT
C – NUCLEAR CRITICALITY
R – PARTICLE RETENTION
F – FLOW CONTROL
P – POWER SHAPING
S – STRUCTURAL SUPPORT

R89-0694-005

CONCLUSIONS

Advances in technology in the fields of power generation, power condition and reactor design have significantly improved the mass and volume characteristics of these components. These improvements were instrumental in producing a Category III MMW prime power system conceptual design that meets all performance requirements and betters the mass and volume goals by more than 20 percent.

ACKNOWLEDGMENT

The work described in this paper was supported by the U.S. Department of Energy, Idaho Operations Office, under DOE Contract No. DE-AC07-88ID12753.