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Nuclear Materials & Propulsion Operation

SELECTION OF 710 REFERENCE REACTOR

May 1967

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SELECTION OF 710 REFERENCE REACTOR

R. E. Reid
E. L. Semple
J. D. Simpson

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ABSTRACT

A reactor configuration and operating conditions are selected for a 200 kwe Brayton cycle space power system as a reference point for the 710 reactor fuel systems development program and for studies of the effects of the reactor and space power system designs on the 710 reactor fuel system.*

*This report partially fulfills Milestone No. 1 of the Design and Analysis task of the 710 Program.

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1. INTRODUCTION

A study of Brayton cycle nuclear space power systems was performed jointly by General Electric's Missile and Space Division,¹ under a contract from the NASA Lewis Research Center, and by General Electric's Nuclear Materials and Propulsion Operation,² under AEC Contract AT(40-1)-2847. The purpose of the study was to determine the influence of Brayton cycle system requirements on the design of the 710 fast spectrum, refractory-metal reactor, and to optimize a 200 kwe Brayton cycle space power system for a specific manned space station application. A study³ also was performed by GE-NMPO to determine the effects of various Brayton cycle system and configuration options, such as recuperative or non-recuperative cycle and redundant or non-redundant power conversion systems, on the design of the 710 reactor. The results of this latter study were used in conjunction with the MSD-NMPO study to define the configurations of the system and reactor which were used in optimizing the operating conditions for a minimum weight, 200 kwe system for a manned space station application.

The purpose of the work summarized in this report was to re-evaluate the reactor configuration and operating conditions selected under the MSD-NMPO study to determine if they could be used as a general reference point for development of the 710 fuel system and for studies of the effects of reactor and space power system designs on the 710 fuel system. This re-evaluation consisted of determining if this reactor was applicable for mission constraints other than those imposed by the manned space station application and also if it met the following two criteria established by 710 Program guidance:

1. The reference reactor selected should be capable of covering a power range corresponding to a range of electrical output from 50 to 300 kwe by varying coolant pressure and flow rate.
2. The feasibility of extending the reactor lifetime to 20,000 hours should be established.

¹"Nuclear Electric Brayton Powerplant Characteristics Study," GE-MSD, ANSO 6300-200 (To be published).

²"710 Reactor-Shield Study Support for Manned Spacecraft Applications," GE-NMPO, GEMP-485 (To be published).

³"Designs "A" Study," GE-NMPO (To be published).

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The results of this re-evaluation indicate that the previously selected reactor appears to be applicable for other mission restraints and can meet the above criteria. In order to provide insight into the basis for the selection of the reactor for a minimum weight system, the primary ground rules for the MSD-NMPO study and the resulting reactor configuration and operating conditions are reviewed. Preliminary results of studies of the applicability of this reactor for other mission constraints and its power extensibility and operating life potential then are described.

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2. MSD-NMPO STUDY

The MSD-NMPO study involved a manned, three-spoke space station using a 200 kwe space power unit. Station stabilization considerations dictated that the powerplant be close-coupled to the station, i.e. 23 feet from its hub. The angle from the reactor to the payload dose plane was 133 degrees. Dose rates were specified to be 2 mrem/hr at the payload and 5 rem/hr at 50 feet from the reactor in all other directions. An integrated fast neutron dose at the generator of 10^{11} nvt (> 0.1 Mev) also was specified. The primary result arising from these assumptions was that the shield weight was the dominant factor in the weight of the overall system.

The power system's radiator was designed for packaging on presently projected boosters. At a power level of 200 kwe, the physical radiator area limit could not be met without utilizing non-optimum radiator design parameters which markedly increased the weight of the radiator. As a result, the system optimum-weight solution was forced toward operating conditions, such as low system pressure drops, which reduce radiator area.

The turbomachinery design parameters for the study were furnished by NASA. These parameters specified the use of gases with molecular weights of 40 or greater for the turbine inlet temperature of 2140°F that was finally selected.

With these primary assumptions, calculations were made to determine the cycle operating conditions and reactor configuration which would yield the minimum system weight. For these calculations, GE-NMPO constructed a model of the reactor-shield assembly and generated parametric weight data for this assembly as a function of the primary system operating conditions. MSD then constructed an overall system weight optimization program. The calculated operating conditions for a minimum-weight recuperative Brayton cycle system, the resulting reactor configuration, and system weights are listed in Tables 1, 2, and 3. Also listed in Tables 1 and 2 for comparison are the 710 interim reference reactor conditions previously used for guidance in the fuel systems development and as a basis for the reactor design work. The significant differences are that the reactor for the minimum-weight system has a lower fuel element surface temperature, lower reactor thermal power, and lower reactor core pressure drop. The lower fuel element surface temperature is due to the use of He-Xe 40⁴ which has

⁴ A helium-xenon gas mixture with an average molecular weight of 40.

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TABLE 1

DESIGN POINT OPERATING CONDITIONS

	Interim Reference Reactor	MSD-NMPO Study Reactor
<u>General</u>		
Total electrical power, kwe	200	200
Total thermal power, M_{th}	1.05	0.872
Thermal efficiency, %	19.0	22.9
Primary coolant	Neon	He-Xe 40
Reactor coolant flow rate, lb/sec	5.19	10.7
Reactor inlet gas temperature, °F	1464	1519
Reactor outlet gas temperature, °F	2240	2140
Reactor inlet pressure, psia	172	397
Reactor core pressure drop, %	3.00	0.83
<u>Core Thermodynamic and Nuclear Characteristics</u>		
Channel inlet Reynolds number	7370	14,900
Channel outlet Reynolds number	5900	12,410
Average heat flux, watts/cm ²	13.3	12.9
Maximum average surface temperature, °F	2450	2250
Maximum fuel burnup, fissions/cc of matrix	$6.1 \times 10^{19} \text{ }^a$	$5.3 \times 10^{19} \text{ }^a$
Average core fuel burnup, fissions/cc of matrix	$3.23 \times 10^{19} \text{ }^a$	$2.76 \times 10^{19} \text{ }^a$
Maximum average element burnup, fissions/cc of matrix	$4.58 \times 10^{19} \text{ }^a$	$3.55 \times 10^{19} \text{ }^a$
Maximum fuel element fast neutron dose, nvt > 1.0 Mev	9.10×10^{20}	7.90×10^{20}
Maximum matrix power density, watts/cm ³	51.5 ^a	46.1 ^a

^aVolumes are computed with cold dimensions.

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TABLE 2
DESIGN POINT REACTOR GEOMETRY AND DIMENSIONS

	Interim Reference Reactor	MSD-NMPO Study Reactor
<u>Active Core</u>		
Core diameter, in.	15.41	16.03
Core length, in.	17.62	14.27
Core volume, ft ³	1.90	1.67
Core L/D	1.143	0.890
Number of fuel elements	85	85
Free flow area, in. ²	23.5	25.9
Void area, in. ²	37.1	34.0
Void VF	0.199	0.169
Structure VF	0.055	0.062
Tungsten VF	0.298	0.307 ^a
UO ₂ VF	0.448	0.462 ^a
<u>Fuel Element</u>		
Shape	Hexagonal	Hexagonal
Cladding and tube material	T-111	W-30Mo-30Re
Cladding thickness	0.015	0.010
Matrix, vol. %	W-60UO ₂	W-60UO ₂
Length, in.	17.62	14.27
Across-flats dimension, in.	1.531	1.622
Number of channels per fuel element	19	19
Hydraulic diameter, in.	0.136	0.143
Channel pitch, in.	0.349	0.370
Channel spacing, in.	0.196	0.207
Fuel element natural frequency, cps	80	125

^aDensity of tungsten and UO₂ is 95% of theoretical.

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TABLE 3
DESIGN POINT SYSTEM WEIGHTS

Reactor Assembly		2,810 lbs
Shield		70,460 lbs
	Payload shield	50,540
	Radial shield	14,340
	Generator shield	3,130
	Shield structure	2,450
Radiator		13,410 lbs
Turbomachinery, Heat Exchanger, Recuperator, and Ducting		5,230 lbs
Total System Weight		91,910 lbs

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better heat transfer properties than neon. The reduced thermal power requirements are due to the lower pressure drop in the core and the other system components. These lower pressure drop requirements are due in turn to the limited radiator area assumptions.

The resulting operating conditions are less stringent than those established for the present fuel system development program. Currently, maximum surface temperatures of 3000°F are maintained in all static and dynamic out-of-pile tests and 2800°F in the in-pile static tests. The reduction in thermal power level and changes in reactor size and fuel loading indicated in Table 2 decrease by 15 percent both the maximum fuel burnup and fast neutron dose requirements presently assumed.

The changes in fuel element geometry between those for the reactor of the MSD-NMPO study and those presently being used in the fuel element fabrication program can be seen in Table 4. The significant difference is an increase in the matrix-to-void area ratio which reduces the stresses in the matrix due to temperature cycling.

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TABLE 4
FUEL ELEMENT GEOMETRIES AND DIMENSIONS

	710 Fuel Development Program	Joint MSD-NMPO Study Reactor
Shape	Hexagonal	Hexagonal
Cladding and tube material	W-30Mo-30Re(at.%) ^a	W-30Mo-30Re(at.%)
Cladding thickness, in.	0.010	0.010
Matrix, vol. %	W-60UO ₂	W-60UO ₂
Length, in.	14.77	14.27
Across-flats dimension, in.	1.426	1.622
Number of tubes per fuel element	19	19
Hydraulic diameter, in.	0.140 ^b	0.143
Channel pitch, in.	0.329	0.370

^aFuel elements clad with 0.015 inch of T-111 also are being developed.

^bDimension after autoclaving cycle.

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3. OTHER MISSION APPLICATION

The use of a single reactor for missions involving different power levels and different radiation restraints will cause weight penalties at these conditions because the reactor will not be of an optimum size. However, the maximum possible variation in the size of the reactor over the range of power levels considered is not large, i.e., a minimum size reactor with no void volume and no cladding would have a diameter of approximately 13 inches compared to about 16 inches for the 200 kwe unit. A variation of 3 inches causes a variation of approximately 9 percent in reactor-shield assembly weight and 7 percent in total system weight for the 200 kwe unit and for the radiation restraints assumed in the MSD-NMPO study. For systems with less stringent radiation restraints where the reactor-shield assembly is a smaller percentage of the weight of the overall system the effect on the total system weight would be less.

System weight and efficiency can also be affected if the reactor does not meet the optimum operating conditions required by the overall system for particular mission restraints. As a result, exploratory optimization calculations were made at other power levels and for less stringent radiation restraints to determine if the optimum operating conditions vary significantly with these different assumptions. This work utilized the MSD optimization program previously constructed for the 200 kwe system.

Variations in power level and radiation restraints can cause variations in the following reactor operating conditions which have a direct influence on the system: inlet and outlet temperatures, inlet pressure, pressure drop, coolant weight flow, and coolant gas species. The outlet temperature of 2140°F selected from the results of the MSD-NMPO study appears to be realistic based on current technology and is the temperature assumed for this study.

The optimization calculations were performed for power levels of 50 kwe to 300 kwe, for less stringent radiation restraints which reduce the shield weights determined in the MSD-NMPO study by as much as a factor of 10, and for the following coolant gases: neon, argon, xenon, and various He - Xe gas mixtures with molecular weights ranging from 20 to 100. In performing the optimization calculations, the same radiator area restraints were assumed as in the previous calculations since larger boosters than presently envisioned, assembly in space, or new techniques in radiator packaging would be required to raise this limit.

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These calculations indicated that cycle pressure level does not have a significant effect on the system weight for different mission restraints. Inlet temperatures of the reactor varied from approximately 1350°F to 1650°F. Core pressure drop varied appreciably. Even lower pressure drop requirements than for the design point of the MSD-NMPO study were indicated at higher power levels, while at lower power levels, where the radiator area is below the area limit, higher pressure drops resulted, i.e., 2 to 3 percent. When the radiation limits were raised, the pressure drop decreased at any given power level since the radiator weight then becomes more dominant in the overall weight of the system.

The principal conclusion from the above calculations is that low pressure drop requirements will be characteristic for most high-power applications where the area of the radiator is limited by present booster requirements. In a low-pressure-drop core, the primary design consideration is the uniformity of flow distribution into the reactor. Exploratory calculations indicate that if the pressure drop in the core is maintained at a relatively high value in relation to that in the nose piece and tube sheet (at least 8 to 1, the value for the MSD-NMPO design point reactor) variations in the flow resistance of the nose piece and tube sheet or fuel element flow channels will not appreciably affect the flow distribution in the fuel elements. The Mach number in the plenum ahead of the core is relatively low (approximately 0.01). However, this flow is turned as it enters the plenum. Further study is necessary to determine if this affects the flow distribution into the core. Until this can be studied, it is believed that a pressure drop below that obtained for the reactor at the MSD-NMPO design point should not be considered. Therefore, for the studies of the extensibility of this reactor over a range of power levels, a constant pressure drop of 0.83 percent was assumed, realizing that it would be slightly high in some cases and slightly low in other cases with respect to the optimum value. The inlet temperature for the MSD-NMPO design point reactor also was assumed since it appeared to be approximately midway between the possible lowest and highest temperatures.

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4. POWER EXTENSIBILITY AND OPERATING LIFE CONSIDERATIONS

For the previously selected configuration, calculations were made to determine the variations in both fuel element maximum surface temperature and system pressure level caused by varying the thermal power level and gas species used as the system coolant gas while holding the core pressure drop, inlet, and outlet temperature constant. The results of these calculations are shown in Figure 1.

Lines for two additional parameters are drawn on Figure 1. One is for a Reynolds number of 6000 in the fuel element coolant channels which is above conditions where flow transition normally occurs. The second line indicates the conditions under which a 1.0 percent dimensional growth of the fuel element is calculated to occur in 20,000 hours of operation.

As can be seen from the extensibility curves, the reactor selected can be utilized for power levels from 50 kwe (approximately 200 Kw_{th}) to 300 kwe (approximately 1.4 Mw_{th}) by varying gas pressure and species. This can be accomplished without exceeding a calculated dimensional growth of 1.0 percent in 20,000 hours of operation or operating below a Reynolds number of 6000.

He-Xe 40 was selected for the 200 kwe optimization study design point because it produces the lowest system weight for a given fuel element surface temperature within the restraints of a gas with a molecular weight of at least 40. However, no data are available on the use of this type of gas for a closed loop system, and therefore, it cannot be recommended until development work is performed to assess the following factors:

1. Method of purification.
2. Method of measuring impurities.
3. Determination of possible selective leakage in a system.
4. Determination of methods to control molecular weight.

Thus, with the preclusion of gas mixtures pending further development work and with the assumption that gases having molecular weights of 40 or greater may be preferable, the most suitable coolant gas for the 200 kwe design point appears to be argon. All dynamic testing of fuel elements under the 710 Program has been performed with neon but, with the exception of fuel element temperature requirements, there is no reason to believe that the behavior of the fuel element will be different using either of these gases. Therefore, it is recommended that neon continue to be used for fuel element testing, but at the higher temperature level dictated by argon. It also is recommended that the systems and reactor design work should be based on the use

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Fig. 1 - Reactor power extensibility

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of argon and the reactor configuration selected for the joint MSD-NMPO study design point. Table 5 shows the applicable operating conditions for the three gases (He-Xe 40, neon, and argon) at the 200 kwe power level.

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TABLE 5

REFERENCE REACTOR OPERATING CONDITIONS

	Coolant		
	He-Xe 40	Neon	Argon
<u>General</u>			
Total electrical power, kwe	200	200	200
Total power thermal, Mw_{th}	.872	.872	.872
Reactor coolant flow rate, lb/sec	10.7	5.42	10.7
Reactor inlet gas temperature, °F	1519	1519	1519
Reactor outlet gas temperature, °F	2140	2140	2140
Reactor inlet pressure, psia	397	294	392
Reactor core pressure drop, %	0.83	0.83	0.83
<u>Core Thermodynamic and Nuclear Characteristics</u>			
Channel inlet Reynolds number	14,900	7170	18,260
Channel outlet Reynolds number	12,410	6010	15,190
Average heat flux, watts/cm ²	12.9	12.9	12.9
Maximum average surface temperature, °F	2250	2387	2476
Maximum fuel burnup, fissions/cc of matrix	5.3×10^{19}	5.3×10^{19}	5.3×10^{19}
Average core fuel burnup, fissions/cc of matrix	2.76×10^{19}	2.76×10^{19}	2.76×10^{19}
Maximum average element burnup, fissions/cc of matrix	3.55×10^{19}	3.55×10^{19}	3.55×10^{19}
Maximum fuel element, nvt > 1.0 Mev	7.90×10^{20}	7.90×10^{20}	7.90×10^{20}
Maximum matrix power density, watts/cm ³	46.1	46.1	46.1

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