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NERVA Technology Reactor Integrated with NASA Lewis Brayton Cycle Space Power Systems

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A conceptual design of this 2.2 Mw reactor has been performed to permit integration with power conversion units which are in an advanced state of development. The reactor has flexibility for application with 25 to 600 kwe space power systems. Design concepts and methods utilized were developed in the NERVA program. Uranium bearing graphite fuel elements, utilizing fuel particles developed for commercial power reactors, form a cylindrical core, reflected radially, and at the inlet end by beryllium. It is controlled by rotating control drums located in the radial reflector. A manned space-base system design concept, including shielding analysis, is also discussed.

Introduction

Westinghouse Astronuclear Laboratory has engaged in a design study of a high-temperature space power reactor for application in a Brayton cycle space electric power system. A 1-Mw version of this reactor has been reported.[1] The reactor has been designated "The NERVA Technology Reactor" (NTR) because it utilizes the proven design concepts and design methods developed in the NERVA (Nuclear Engine for Rocket Vehicle Application) program. This report presents the conceptual design of the 2.2 Mwt reactor integrated with Brayton cycle power conversion systems under development at the NASA Lewis Research Center. This reactor has the flexibility for application over a range of thermal power providing electric power requirements from 25 kwe to 600 kwe. Two applications are considered: one for the 100-kwe power requirement of the manned space base,[2] and one to provide 506 kwe at the reactor design point of 2.2 Mwt for 50,000 hr at 1600°F exit gas temperature.

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Since 1963, The NASA Lewis Research Center has carried on a closed Brayton-cycle component and power system development program. Favorable long-duration test experience has been accumulated on a 15-kwe power system, and on individual components of this system, while a 160-kwe system is in the initial hardware design phase. For this application, these power conversion units are in a direct gas loop with the reactor.

The NERVA technology is a broad-base highly-developed technology covering all reactor engineering and systems technology. This nuclear rocket program started by the Los Alamos Scientific Laboratory in 1955 has been marked since 1964 by ground tests of 12 reactors at unprecedented power density and temperature levels. Reference 3 presents a summary of the NERVA program. The use of an inert gas in the direct reactor Brayton cycle space power system permits the NTR to operate for the extended duration required. Both the NERVA reactor and the NTR are gas-cooled beryllium reflected reactors utilizing graphite dispersion uranium carbide fuel and controlled by rotating control drums in the radial reflector.

Several operating and planned central station gas-cooled power reactors utilize fuel similar to that required for this space power application. Some of these, or their prototypes, have been built (HTGR, AVR, DRAGON, and UHTREX), while others are still under construction (Ft. St. Vrain and THTR).[4] The requirements for fuel performance in these graphite dispersion fueled reactors are nearly identical to those of the reactor-Brayton system application. The fuel has the required excellent fission product retention at the temperatures, burnup, power rating, irradiation levels, and lifetime needed for this space electric power system.[5]

Operating temperature levels in the Brayton system are limited by the turbine capability, rather than the fuel capability.

General System Description

A concept of the space power plant adapted to the 100-kwe space-base application is pictured in Fig. 1. This depicts the NERVA Technology Reactor in a direct gas cycle with eight NASA Lewis power conversion units. The system illustrated accommodates the 15-kwe power conversion units arranged in a line along the gallery axis to minimize the size of the shadow shielding required. Seven of the units would be operating with a redundant unit on standby. The modules illustrated were extracted directly from NASA Lewis work and are 69 in. × 55 in. × 33 in.

The flexibility of the reactor combined with various combinations of the NASA Lewis 15-kwe and 160-kwe power conversion units is illustrated in Fig. 2. At a conservatively low 23% efficiency, power outputs of from 25-kwe to 506-kwe can be obtained for the 50,000 hr (approximately 5 yr) design lifetime with a turbine inlet temperature of 1600°F.

A minimal 4 π shield system is employed with a primary and secondary shadow shield in the preferential direction of the manned station. Protection from the coolant and fission product activity in the power units is provided by the secondary shield. The reactor is oriented with the axial reflector in the direction of the crew to exploit the inherent neutron shielding capability of this reflector.

An inert gas mixture of helium and xenon is heated in the reactor and delivered to the power conversion units through the center of a coaxial piping arrangement. The power conversion units are independent, each containing the turbine-compressor-alternator combined rotating unit, a recuperator, a gas management system, electric control system, and a gas to liquid heat exchanger for heat rejection. The liquid radiator loop is not shown in Fig. 1. A valve in each conversion unit provides the capability for operation with a redundant unit to be used in case of failure of one unit.

NASA Lewis Brayton Cycle Power Units

This section is drawn primarily from a NASA Lewis Research Center Report[6] which describes two Brayton cycle power systems which are under development. The first of these systems, currently under test in the Space Power Facility of the NASA Lewis Research Center, has an electric power generation capability of from 2 to 15 kwe. A schematic for this system is shown in Fig. 3. In this reactor application the NTR reactor would be in the loop replacing the heat source heat exchanger. This system utilizes a gas-to-liquid heat rejection loop which has the distinct advantage of confining the fission products that escape from the reactor to the primary loop only. The use of gas bearings in the rotating unit of this system is a key accomplishment in its development.

Table 1 NASA Lewis 15 kwe Brayton cycle power system experience summary as of October 1969

Component	No. tests	Total hours	Max. time-single units, hr
Brayton rotating unit	1	1197 (2000)[a]	1012
Brayton heat exchange unit	2	280	235
Pump motor assemblies	7	2827	1716
Inverter	7	3452	1606
d.c. power supply	4	5419	2670
Electric control package			
Speed control	2	1206	1186
Voltage regulator exciter	2	1103	1032
Parasitic load resistor	1	315	267
Complete package	1	195	195
Engine control system	1	285	285
Gas management system	1	216	216
Brayton system	1	185	185
Full system test at space power facility		(700)[a]	

[a] Numbers in parentheses are total hours as of March 1970, Ref. 2.

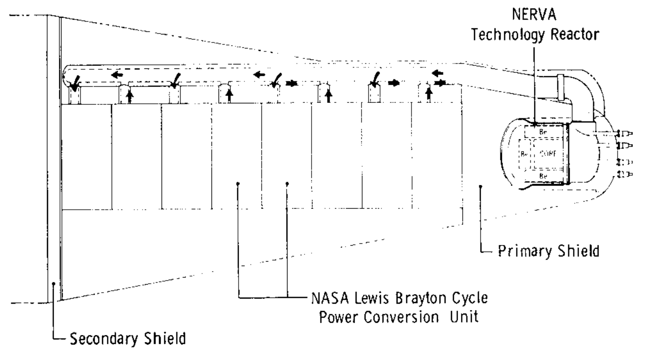


Fig. 1 Space base system design concept.

The development status of the 2–15 kwe Brayton cycle unit is evidenced by the fact that all of the major components and subsystems and the assembled system have been tested at Lewis Research Center.[7] Table 1 is a summary of the testing as of October 1969. The test results on the complete power conversion system indicate that all the components have been close to their design performance and the system as a whole has exceeded its design goal. The Brayton rotating unit (turbine, alternator, and compressor on a single shaft supported by gas bearings) has to date accumulated about 2000 hr of testing over a range of temperatures, pressures, and electric powers up to 15 kwe. The data indicate that this system can operate up to 15 kwe at a system efficiency approaching 30%. Analysis indicated that good performance can be obtained over a range of turbine inlet temperatures from 1600°F design down to about 1000°F. These temperatures are very conservative for todays technology. As Lewis indicates, although the system has not accumulated full lifetime duration, the tremendous technology base existing in gas turbines for aircraft applications and the trouble-free operation to date indicate that there should be no difficulty in meeting the lifetime objective of 5 yr. A similar Brayton cycle system has been operated successfully at the Houston Manned Space Flight Center.

Dimension data on the 15 kwe unit is given in Fig. 4. For the system layout and shielding analysis described in this report these dimensions were used as well as dimensions of a postulated more compact package (56 in. × 47 in. × 22.5 in.).

Lewis Research Center performance data on this system for a range of temperatures and cycle conditions show that for applications where the thermal power required is not important, compromising the conversion efficiency will result

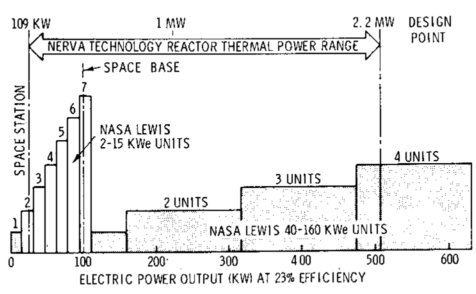


Fig. 2 Brayton cycle power output range with 15 kwe and 160 kwe power conversion units.

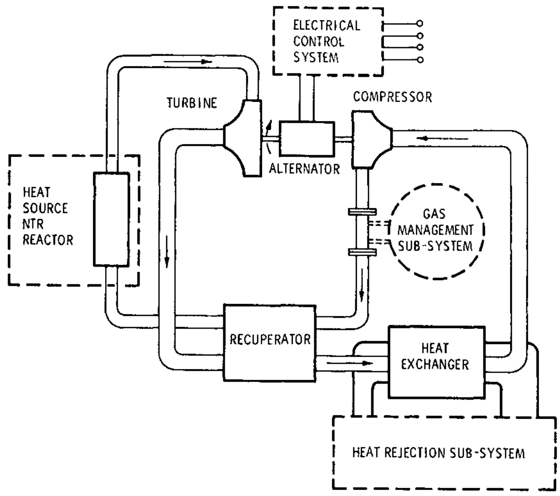


Fig. 3 Schematic of the NASA Lewis Brayton cycle power conversion system.

in reduced total radiator size. Such is certainly the case for the NTR reactor since power level restrictions are virtually non-existent. The cycle design conditions selected for the power system utilizing these 15 kwe units are given in the first column of Table 2. The estimated flight weight of a complete power conversion unit is 1376 pounds.

NASA Lewis now has under development a Brayton cycle power conversion system capable of electric outputs from 40 to 160 kwe. This unit will be capable of operation from 1050°F turbine inlet temperature to its design temperature of 1600°F. It is expected that turbomachinery development will lead to a capability in the future at a turbine inlet temperature of 2100°F. The NTR reactor can operate over this full range of turbine inlet temperature with an inert gas. Conceptual design of the turbine-alternator-compressor package is now underway with identical contracts at General Electric and AiResearch, while heat exchanger design is underway with AiResearch as the contractor. It is expected that this effort will lead to the eventual development of a high temperature lithium cooled reactor with a thermal output of 2.2 Mw for use with a Brayton Cycle power conversion system. For this reason, the NERVA Technology Reactor described in this report was sized for 2.2 Mwt to be integrated into a system utilizing the Lewis developed power system. This system with four 160 kwe units can cover most presently projected space power requirements. Selected system operating conditions for this application are listed in the second column of Table 2.

Design conditions for the NERVA Technology Reactor to meet the requirements of this system are 2.2 Mwt, 1161°F inlet gas temperature, 1600°F exit gas temperature, 228 psi inlet gas pressure, 50,000 hr operation, a maximum pressure loss ratio (reactor pressure drop/inlet pressure) less than

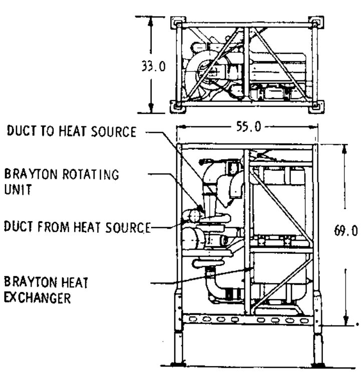


Fig. 4 NASA Lewis 15 kwe Brayton cycle module.

Table 2 System parameters of 100 kwe and 506 kwe NTR Brayton System

	Space base	Design point
Reactor power, kwt	435	2200
Conversion efficiency[a]	23%	23%
Gross electrical power, kwe	100	506
Power conversion unit size, kwe	2–15	40–160
Number of operating units	7	4
Design lifetime, hr	50,000	50,000
Compressor inlet temperature, °R	700	700
Turbine inlet temperature, °R	2060	2060
Cycle temperature ratio[b]	0.34	0.34
Average radiator temperature, °R	820	820
Specific radiator area, ft^2/kwe	27.5	27.5
Radiator area, ft^2	2750	13,900
Gas and molecular weight	He-Xe, 83.8	He-Xe, 39.9
Reactor inlet pressure, psia	110	228
Reactor pressure drop, psid	1.2	7.2
Reactor flow rate, lb/sec	16.	38.

[a] Conversion efficiency has been deliberately compromised in order to minimize radiator area.
[b] Ratio of compressor inlet to reactor outlet temperature.

4% with a 39.94 molecular weight helium-xenon gas mixture. The reactor will meet the operating requirements for either the 100 kwe or 506 kwe system.

NERVA Technology Reactor Design

General Description

An isometric drawing of the reactor is given in Fig. 5. The design employs basic structural and mechanical concepts which were successfully developed in the technology phase of the NERVA reactor program. The core of the reactor consists of an array of enriched graphite fuel elements of hexagonal cross section and length equal to that of the core. The across-flats dimension of the hexagonal section of the element is approximately 0.75 in. These fuel elements are bundled together and supported in the radial direction by the lateral support system. Thermal insulation is provided at the core periphery, with the insulating pieces together with filler strips of various shapes making up a regular cylindrical geometry. Gas leakage around the periphery is minimized and a radial bundling force provided by a system of spring loaded seal segments which are supported in a graphite cylinder or barrel. The graphite barrel also serves to reduce the neutron flux peak at the inner diameter of the beryllium reflector. A graphite barrel, lateral support system, and

Table 3 Key mechanical features of the 2.2 Mw NTR reactor

Equivalent core diameter, in.	20.5
Core length, in.	20.5
Number of fuel elements	673
Number of coated fuel particles	2×10^8
Beryllium reflector thickness, in.	
Radial reflector	7.7
Axial reflector	7.0
Number of control drums	8
Control drum diameter, in.	7
Support plate thickness, in.	3.5
Pressure vessel o.d., in.	41
Pressure vessel length, in.	63
Pressure vessel thickness, in.	0.18
Fuel element material—graphite containing dispersed UC_2 fuel particles	
Reflector material—inner barrel	Graphite
outer segments	Beryllium
Material for lateral support spring, support plate, and ducting	René 41
Actuators—permanent magnet stepping motor with planetary reduction gear	
Reactor total weight—excluding shield, lb	2705

Table 4 Nuclear design characteristics of NTR reactor at design point

Core uranium weight, kg	56.4
Core carbon weight, kg	144.3
Core volume, liters	110.9
Fuel volume, liters	82.1
Average fuel loading, mg/cm^3	687.
Core void fraction	0.26
Reflector volume, liters	256.
Core life, hr	50,000
Average total core flux, n/cm^2 sec	1×10^{14}
U-235 atoms fissioned, %	8.2
Fuel power density, w/cm^3	26.8
Fluence at core exit, n/cm^2	
$E > 1$ Mev	0.12×10^{22}
1 Mev $> E > 0.4$ ev	0.35×10^{22}
0.4 ev $> E$	0.98×10^{19}
Fluence at core inlet (max.), n/cm^2	
$E > 1$ Mev	0.7×10^{22}
1 Mev $> E > 0.4$ ev	2.8×10^{22}
0.4 ev $> E$	0.14×10^{22}

beryllium reflector of this type was utilized and tested in five reactors of the NERVA program (NRX-A2, -A3, -EST, -A5, and XE).

Axial core support is provided by a series of tie rods which are bolted to the core support plate. These rods also provide support for the beryllium inlet end reflector which is built up of 0.75 in. hexagonal elements in a similar manner to the core. The core support plate is bolted to the reflector structure which is supported from the pressure vessel. An assembly of compression springs between the support plate and the graphite barrel is used to apply an axial load to the barrel and force it into intimate contact with a seal ring on the flange of the outlet duct.

The reflector structure is composed of eight beryllium segments, each of which contains a control drum. The segments are bolted to René 41 rings at each end and the complete assembly is supported from the pressure vessel flange through an extension of one of the rings. Each control drum contains a poison plate made of copper-boron material. The drums are driven from electric actuators of the NERVA type which are mounted on extension tubes welded to the pressure vessel.

The outlet duct is supported, together with the reflector assembly, by trapping a flanged extension of this component between the flanges of the pressure vessel. The concentric arrangement of the inlet and outlet pipes preferentially exposes the hotter and therefore weaker pipe to the lower pressure forces.

Key mechanical features of the reactor are given in Table 3. The diameter of the pressure vessel is 41 in. and the length is 63 in., while the weight of the entire assembly is 2705 lb.

Nuclear and Thermal Design

Nuclear design of this small graphite-uranium reactor is based on NERVA nuclear technology, and a variety of small,

Table 5 Comparison of fuel requirements for the NTR space power reactor and fuel development requirements for central station HTGR power reactors

	NTR reactor		HTGR
	Space base	Design point	reactors[13]
Burnup, %	1.6 (average)	8.2 (average)	20
Temperature, °C	915	920	1250
Fast fluence,[a] 10^{22} n/cm^2	0.7	3.6	0.8

[a] Neutron energy greater than 0.18 Mev.

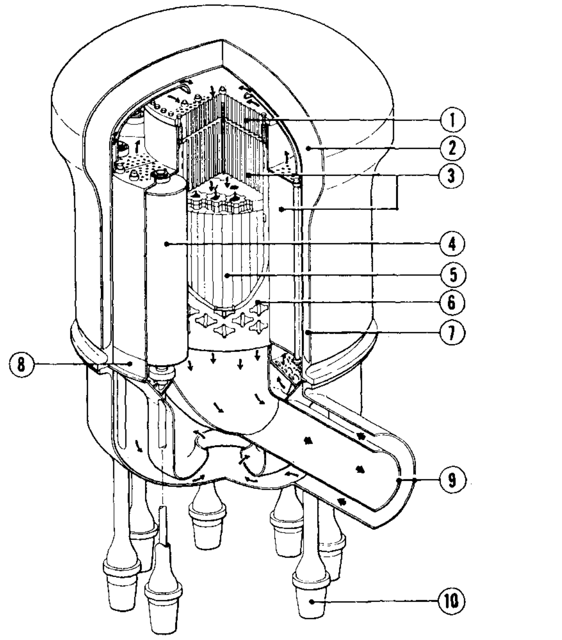


Fig. 5 The NERVA technology reactor. (1) core support plate; (2) Pb shield; (3) Be reflector; (4) control drum; (5) core; (6) graphite barrel and lateral support system; (7) pressure vessel; (8) support ring; (9) ducting; (10) electric actuator.

reflected graphite-uranium critical assembly experiments conducted at LASL and at the University of California Radiation Laboratory. The results of work in these programs were reviewed and a series of nuclear parametric studies conducted. The nuclear design procedure was demonstrated to be adequate by comparing the analytical results to experimental results. Critical reactor sizes were calculated as a function of void fraction, uranium content of the fuel, and core length to diameter ratio. The initial multiplication factor of 1.05 used in the calculation was derived from the following values: 1) Initial multiplication factor for cold, clean, dry core, 1.05; 2) Thermal effects (Doppler coefficient and thermal expansion), -0.01; 3) Fuel burnup and fission product poisoning for 110,000 Mw-hr, -0.02; 4) Reactivity allowance for detail design changes, -0.02; 5) Final multiplication factor for hot, end-of-life core, 1.00.

Selection of the reactor dimensions were based on the results of a parametric study of critical core sizes and void fractions as well as core pressure loss at design conditions. A maximum fuel loading was selected and critical core sizes determined for acceptably low-core pressure drop. The

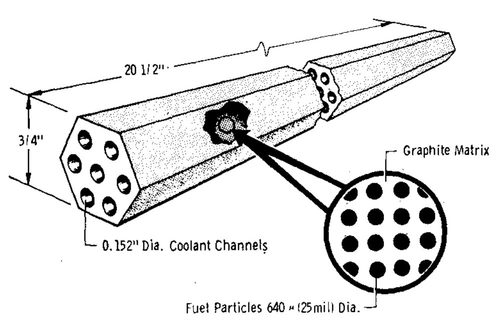


Fig. 6 NTR reactor fuel element.

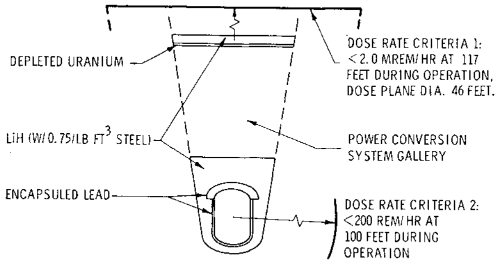


Fig. 7 Nuclear shielding configuration and radiation dose criteria used in shielding analysis.

optimum core length to diameter ratio for minimum weight was found to equal 1.0 or slightly higher. For this length to diameter ratio the core diameter (and length) was selected to be 20.5 in. with a void fraction of 0.26 and average loading of 687 mg U-235/cc. This parametric evaluation to select the core size was based on a $\frac{3}{4}$-in. hexagonal element with 7 axial coolant channels. Reactor pressure drop was limited to less than 4% of the reactor inlet pressure. A reduction in reactor length and diameter to 19.7 in. would have been possible if the reactor were designed only for the space base power requirement; however, this limits to some extent upgrading for future higher power requirements. Nuclear design characteristics at the 2.2 Mw design point are in Table 4.

An evaluation of decay heat removal was performed as part of this study. It appears feasible to remove decay heat from the reactor by continuing to operate the radiator loop and a single power conversion unit in the primary loop. Operation would continue in this mode until the power decays to a level which could be conducted from the reactor and radiated to space without excessive temperatures in any reactor components. A better definition of the low-pressure operational limit of the turbine-compressor due to insufficient bearing pressure for self-acting operating is needed for final assessment of this decay power removal method.

Fuel Element Design

A schematic of the fuel element for the NERVA Technology Reactor is shown in Fig. 6. The fully enriched uranium fuel contains pyrocarbon coated UC_2 particles dispersed in a graphite matrix. This graphite fuel design utilizes graphite fuel technology primarily developed for central station power application. Some of these gas cooled power reactors, or their prototypes, have been built (HTGR, AVR, DRAGON, UHTREX), while others are under construction (Ft. St. Vrain, and THTR[4]). Requirements for fuel performance in these graphite dispersion fueled reactors[8] is shown to be similar to that of the NTR reactor in Table 5. A detailed evaluation of graphite dispersion fuel for this space power reactor application is given in Ref. 5.

Rapid development of this coated particle has occurred over the last 12 yr as a result of the extensive effort in both development and evaluation testing. Fuel particles with multiple coating layers of porous carbon, high density isotropic pyrolytic carbon, and SiC have demonstrated excellent irradiation stability for burnups as high as 13% and temperatures up to 1300°C.[9,10] The release of fission products from these particles come from three sources. These are 1) from fissions in uranium contamination in the outer coating, 2) fission product leakage through defective coating, and 3) diffusion of fission products through the coating of intact, perfect fuel particles. The intrinsic release is so low that defective or contaminated particles comprise the major source of release. Irradiation testing of the multiple coating particles indicate fission product release fractions of 10^{-6} to 10^{-8}. Considering the possibility of fractured particles a fuel element release fraction of 10^{-5} can be met with confidence.

Table 6 Comparison of alternate fuel elements at design point

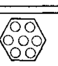
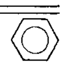
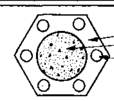
			
Coolant channel diameter, in.	0.152	0.233	0.403
Relative core ΔP	1.0	0.7	0.4
Maximum matrix temperature, °C	920	985	1137
Matrix radial ΔT, °C	2	4	16
Void fraction	0.26	0.26	0.26
Loading, mg/cc	687	687	687

Table 7 Bonded bed fuel element concept at design point



Fuel element length, in.	20.5
Fuel particles	Coated UC_2
Void fraction	0.19
Average U235 loading, mg/cc	631
Relative core pressure loss compared to 7 hole element	2
Axial peak matrix temperature, °C	1120
Internal matrix radial temperature difference, °C	255

Fabrication techniques for the NTR fuel element with the fuel particles uniformly dispersed in the matrix could be by extrusion or molding. Alternate fuel element configurations with one and three axial coolant channels are compared to the 7 channel design in Table 6. The simpler single hole element would require less development effort but would operate at higher matrix and fuel particle temperatures.

A bonded bed fabrication technique is being developed in the ORNL Gas-cooled Reactor Program[11] as well as at Gulf General Atomics[12] for commercial power reactor application. A fuel element concept utilizing the cylindrical bonded bed elements combined with an unloaded graphite section is shown in Table 7. The volume fraction of fully enriched fuel particles in the bed is 52% based on average uranium loading requirements. A volume fraction of 64% can be obtained[13] and will provide for zone loading, with a maximum uranium loading 23% higher than the average loading. This fuel element concept is of interest because it utilizes fuel of the type that have demonstrated good irradiation stability in the gas cooled reactor program.

Nuclear Shield

The shield concept for the 100 kwe manned space base application of the NTR reactor is shown schematically in Fig. 7. The reactor and power conversion system shield configuration is similar to current SNAP system shield studies in that a minimal 4 π shield system is employed in conjunction with a shadow shield system for protection of the crew. The radiation dose rate criteria specified on the figure were taken from SNAP shield system studies.[14] A conceptual shield design was developed using SNAP shield system dimensions as an initial estimate and then adjusting

Table 8 Unshielded radiation levels at power conversion equipment gallery after shutdown from 435 kwt

	Unshielded dose rate one foot from surface of gallery, MRem/hr	
Time after shutdown, days	Neutron induced coolant activity	Fission product contamination
0.0	200.	490.
0.05	3.	80.
0.5	1.3	34.
5.0	Negligible	16.

Table 9 Principle shield dimensions for space base application

Shield Location	Lead	Shield Thickness, in. LiH[a]	Depleted uranium
Forward	1.0	8.6	0
Side	0.57	8.6	0
Shadow	7.0	22.4	0
Gallery	0	12.1	0.76

[a] Includes 0.75 lb/ft² of steel.

the shield configuration and dimensions based on detailed neutron and photon transport analyses. Radial and axial 29 group coupled neutron and gamma calculations were performed.

An assessment of the radiation levels in the vicinity of the power conversion units during operation and after shutdown was made considering the coolant activation and fission products in the coolant loop. It was assumed that a 10^{-5} fraction of the fission products in the core is released and deposited in the power conversion system. Dose rates due to these sources in the gallery are well below the secondary dose rate criteria of 200 rem/hr at 100 ft. With the short half-lives of the induced coolant activity, the dose rate in the vicinity of the power conversion system is at acceptable levels for personnel maintenance operations in less than one half day (see Table 8).

To define the gallery shield thickness, the dose rates from fission products and gas coolant activities were calculated as a function of the gallery shield thickness. Gallery shield attenuation calculations were performed using a disk source-slab shield model and calculation procedures, with the disk source placed centrally in the gallery. The assessment of shield weights is based on the shielding calculations described above and a simplified geometric model in Fig. 7. The principle shield dimensions for the 100 kwe manned space base system as pictured in Fig. 1 are shown on Table 9. The more compact packaging of the conversion unit was assumed (56 in. × 47 in. × 22.5 in.). Total shield weight is 25,690 lb for this case. Assuming the dimensions of the NASA Lewis unit in Fig. 4, total shield weight is 26,390 lb.

System Weight Estimates

Total weight of the 100 kwe space base application utilizing the NTR reactor with eight Brayton power conversion units (seven units operating) has been estimated to be 46,065 lb, as given in Table 10. Reactor weight, primary loop duct weight, and shield weights were calculated. Conversion unit weight was taken from the NASA Lewis work and the space radiator weight was estimated. A radiator weight of 2 lb/ft² of radiating area was estimated to include the radiator and structure weight.

The 506 kwe system reactor weight would also be 2705 lb. Nuclear shield weights were not calculated for this system and weights are not available for the 40–160 kwe conversion units.

Conclusions

A small 2.2 Mwt graphite reactor based on NERVA technology provides an attractive space electric power system when integrated with the NASA Lewis Research Center Brayton cycle power conversion systems.

The NERVA Technology Reactor utilizes design concepts developed in the NERVA program and fuel of the type developed for gas cooled commercial power reactors. The Brayton power conversion systems are in an advanced state of development with long duration test experience on the 2–15 kwe unit. Reactor design conditions are 2.2 Mwt for 50,000 hr at 1600°F exit gas temperature. However, the reactor has the flexibility to operate in the 100 kwe manned space base with eight 15 kwe power conversion units, and in a 506 kwe system with four 160 kwe power conversion units. The diameter of the reactor pressure vessel is 41 in. and the length is 63 in., while the weight of the reactor without nuclear shielding is 2705 lb. Total weight of the 100 kwe manned Brayton cycle space base system is 46,065 lb. Additional details of this conceptual design study are given in Ref. 15.

Table 10 Weight estimates of 100 kwe power system

NTR reactor	2,705 lb
Eight 15 kwe power conversion units	11,000 lb
Primary loop duct	470 lb
Nuclear shield	26,390 lb
Space radiator	5,500 lb
Total	46,065 lb

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