PLASMA CORE REACTOR APPLICATIONS*

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Abstract

Analytical and experimental investigations are being conducted to demonstrate the feasibility of fissioning uranium plasma core reactors and to characterize space and terrestrial applications for such reactors. Uranium hexafluoride (UF_6) fuel is injected into core cavities and confined away from the surface by argon buffer gas injected tangentially from the peripheral walls. Power, in the form of thermal radiation emitted from the high-temperature nuclear fuel, is transmitted through fused-silica transparent walls to working fluids which flow in axial channels embedded in segments of the cavity walls.

Radiant heat transfer calculations were performed for a six-cavity reactor configuration; each cavity is approximately 1 m in diameter by 4.35 m in length. Axial working fluid channels are located along a fraction of each cavity peripheral wall. The remainder of the cavity wall is constructed of highly reflective aluminum which focuses radiant energy onto the working fluid channels. Results of calculations for outward-directed radiant energy fluxes corresponding to radiating temperatures of 2000 to 5000 K indicate total operating pressures from 80 to 650 atm, centerline temperatures from 6900 to 30,000 K, and total radiated powers from 25 to 2500 MW, respectively.

Applications are described for this type of reactor such as (1) high-thrust, high-specific-impulse space propulsion, (2) highly efficient systems for generation of electricity, and (3) hydrogen or synthetic fuel production systems using the intense radiant energy fluxes.

Introduction

Since 1955, various researchers have considered the prospects for utilizing nuclear energy with fissile fuel in the gaseous state. Most of this work was concentrated on the gaseous nuclear reactor technology required for high-performance space propulsion systems. The current research program on gaseous nuclear reactors includes continued consideration of high-thrust, high-specific-impulse space propulsion applications and, in addition, plasma core reactor (PCR) applications for meeting terrestrial energy needs.

Extraction of energy from the fission process with the nuclear fuel in gaseous form allows operation at much higher temperatures than those of conventional nuclear reactors with solid fuel elements. Higher operating temperatures, in general, lead to more efficient thermodynamic cycles and, in the case of fissioning uranium plasma core reactors, result in many possible applications employing direct transfer of energy in the form of electromagnetic radiation. The applications for PCR's require significant research and technology development, but the benefits in potential increases of domestic energy resources and utilization, reductions in environmental impact, and the development of new highly-efficient techniques for extracting energy from the fission process with nuclear fuel in the gaseous or plasma state justify an investment to establish the feasibility of fissioning uranium PCR's as a prime energy source.

Possible applications for plasma core reactors are:

(1) High-thrust, high-specific-impulse space propulsion.

(2) Advanced closed-cycle gas turbine driven electrical generators.

(3) MHD power conversion systems for generating electricity.

(4) Photochemical or thermochemical processes such as dissociation of hydrogenous materials to produce hydrogen.

(5) Thorium--Uranium-233 thermal breeder reactor with gas turbine driven electrical generators.

(6) Direct nuclear pumping of lasers by fission fragment energy deposition in lasing gas mixtures.

(7) Optical pumping of lasers by thermal and non-equilibrium electromagnetic radiation from fissioning UF_6 gas and/or fissioning uranium plasmas.

Cavity reactor experiments have been conducted to measure critical masses in cavity reactors to obtain data for comparison with theoretical

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calculations at both Los Alamos Scientific Laboratory (LASL) and the National Reactor Testing Station (NRTS) in Idaho Falls. Critical mass measurements have been made on both single cavity and multiple cavity configurations. In general, nucleonics calculations have corresponded to within a few percent of the experimental measurements. A review of these experiments is contained in Ref. 1. These studies provide the basis for selecting additional experiments to demonstrate the feasibility of the plasma core nuclear reactors.

A program plan for establishing the feasibility of fissioning UF_6 gas and uranium plasma reactors has been formulated by NASA and is described in Refs. 2 and 3. Briefly, the series of reactor tests consists of gaseous nuclear reactor experiments of increasing performance, culminating in an approximately 5 MW fissioning uranium plasma reactor experiment. Each reactor experiment in the series will yield basic physical data on gaseous fissioning uranium and basic engineering data required for design of the next experiment. Initial reactor experiments will consist of low-power, self-critical cavity reactor configurations employing undissociated, nonionized UF_6 fuel at near minimum temperatures required to maintain the fuel in gaseous form. Power level, operating temperatures, and pressures will be systematically increased in subsequent experiments to approximately 100 kW, 1800 K, and 20 atm, respectively. The final 5 MW reactor experiment will operate with a fissioning uranium plasma at conditions for which the injected UF_6 will be dissociated and ionized in the active reactor core. A review of the initial UF_6 reactor experiments in the planned series conducted at LASL is given in the Proceedings of this conference and in Ref. 4. Discussions of experimentally realized nuclear pumped lasers are also given in the Proceedings of this conference (Session III) and in Ref. 5.

The analytical investigations reported herein were performed to examine potentially attractive applications for gaseous nuclear reactors fueled by UF_6 and its decomposition products at operating temperatures of 2000 to 6000 K and pressures of approximately 100 to 650 atm. Emphasis was placed on predictions of performance of this class of gaseous nuclear reactors (1) as the primary energy source for high-thrust, high-specific-impulse space propulsion applications, (2) as the energy source for highly efficient systems for generation of electricity, (3) as the source of high intensity photon flux for heating seeded working fluid gases for applications such as hydrogen production and MHD power extraction, and (4) in a Thorium--Uranium-233 nuclear breeding fuel cycle. Configurations to permit the coupling of the intense radiant energy fluxes to working fluids are presented. Energy conversion systems using the gaseous nuclear reactor as the prime energy source were analyzed to determine system performance and thermodynamic efficiencies. Conceptual designs are presented which indicate the overall features of the application systems and the method of integration of the principal components with the gaseous nuclear reactor energy source.

Plasma Core Reactor Configurations

In the plasma core reactor (PCR) concept a high-temperature, high-pressure plasma is sustained via the fission process in a uranium gas injected as UF_6 or other uranium compounds. Containment of the plasma is accomplished fluid-mechanically by means of an argon-driven vortex which also serves to thermally isolate the hot fissioning gases from the surrounding wall. For applications which employ thermal radiation emitted from the plasma, an internally-cooled transparent wall can be employed to isolate the nuclear fuel, fission fragments, and argon in a closed-cycle flow loop and permit transfer of the radiant energy from the plasma to an external working fluid. For applications which employ fission-fragment-induced, short wavelength, nonequilibrium radiation emitted from the plasma, the working fluid such as lasing gases can be either mixed with fissioning gas or injected into the peripheral buffer gas region such that there is no blockage of radiation due to the intrinsic absorption characteristics of transparent materials at short wavelengths. The PCR configurations discussed below are for applications based on use of intense thermal radiation transmitted through transparent walls to working fluids; closed-loop circulation of gaseous nuclear fuel and buffer gas is an intrinsic feature of the configurations.

Geometry of Unit Cells and Reactor

Concepts for coupling radiant energy from a fissioning plasma to working fluids are shown in Fig. 1. The unit cell shown at the top of Fig. 1 is from the nuclear light bulb space propulsion concept described in Ref. 6. Energy is transferred by thermal radiation from gaseous uranium fuel through an internally-cooled transparent wall to seeded hydrogen propellant. The fuel is kept away from the transparent wall by a vortex flow field created by the tangential injection of buffer gas near the inside surface of the transparent wall. The buffer gas and the entrained gaseous nuclear fuel pass out through ports located on the centerline of the endwall of the cavity.

An alternate unit cell configuration is shown at the lower left of Fig. 1. The fuel and buffer gas zone is surrounded by a reflective aluminum liner with axial working fluid channels along portions of the periphery of the fuel cell surface. The reflective liner would be made of aluminum, for example, which has a reflectivity of approximately 0.9 for the spectral distribution of thermal radiation emitted from the nuclear fuel. The liner materials which are highly reflective to thermal radiation reduce heating of the cavity surfaces and concentrate the thermal radiation onto the working fluid channels. The working fluid could be heated by being passed over graphite fins which are not surrounded by fused-silica tubes. Or, the graphite fins could be replaced by micron-sized particles or opaque gases to absorb the thermal radiation from the fissioning plasma.

A working fluid assembly which consists of a series of uncooled U-tube-shaped fused-silica coolant passages is shown in the lower right of Fig. 1. The tubes have walls sufficiently thick to withstand compressive pressure loads should it be desirable to operate the working fluid at a pressure significantly lower than that in the fissioning uranium plasma region. Interstitial zones surrounding the U-tubes are filled with inert gas (argon or helium) at the same pressure as the plasma region. Working fluid such as helium passes through the fused-silica tubes and is heated by convection from high temperature graphite fins inside the fused-silica tubes which absorb thermal radiation emitted from the plasma. The upper limit on working fluid outlet temperature imposed by a limit on the fused silica operating temperature would be approximately 1200 K.

A sketch of a conceptual design of a plasma core reactor for use in generating electricity is shown in Fig. 2. The reactor consists of six unit cells which are imbedded in a beryllium oxide reflector-moderator and surrounded by a pressure vessel. Each of the six unit cells is a separate cylindrical unit consisting of a fuel region assembly and an outer working fluid assembly. The two assemblies can be withdrawn from opposite ends of the reactor configuration for periodic maintenance and inspection. The fuel assembly consists of a plasma fuel zone with nuclear fuel injected in the form of UF_6. The uranium used in the UF_6 can be either highly enriched U-235 or U-233. Gaseous nuclear fuel is confined in the central region of the fuel zone by argon buffer gas. The mixture of nuclear fuel and argon buffer gas is withdrawn from one or both endwalls at the axial centerline for separation and recirculation.

A cross section of a breeder reactor version of a plasma core reactor is shown on the bottom of Fig. 2. Results of calculations of breeding ratios and doubling times for a plasma core breeder reactor are described in a subsequent section.

Plasma core reactors which have been discussed thus far have working fluid channels closely coupled neutronically to the reactor. Applications for plasma core reactors are under consideration for which it would be more advantageous to locate the working fluid channels at positions other than those adjacent to the fuel cavity, so that the neutron absorbing characteristics of material in the working fluid channels will be unimportant. Thus, a transmission cell must be provided so that thermal radiant energy fluxes can be transmitted from the nuclear fuel cavity, through the moderator and perhaps through the pressure vessel, to the working fluid channels.

A schematic diagram of two possible plasma core reactor configurations which make use of transmission cells is shown in Fig. 3. The configuration on the left shows an arrangement in which transmission cells are connected to working fluid channels within the pressure vessel, but outside of the beryllium oxide reflector-moderator, thus minimizing the neutronic coupling between the fuel cavity and working fluid channel. Potential applications for this configuration are principally terrestrial. The configuration shown on the right in Fig. 3 has a single centralized working fluid channel which receives thermal radiant energy from each of the surrounding six nuclear fuel cavities, and which is outside of the inner pressure vessel wall structure. This particular configuration can be employed in providing a high temperature gaseous propellant stream for space propulsion applications or for terrestrial power conversion applications. Further, radiant energy deposited in the reflective liner as well as neutron and gamma energy deposited in the moderator can be extracted to provide onboard power for the space vehicle.

The transmission cell employs series of fused-silica transparent walls with intermediate regions of gaseous hydrogen and/or deuterium gas to balance pressure between the fuel cavity region and the transmission cell. The hydrogen and/or deuterium gas provide a transparent light path for the thermal radiation emitted from the plasma. The gas also scatters neutrons effectively and, therefore, reduces leakage of fast and thermal neutrons from the system. The transmission cell supporting structure is cylindrical in shape and the inner cylindrical wall is lined with a highly reflective material such as aluminum. The reflective liner minimizes the loss of radiant energy to the walls of the transmission cell as it is transmitted from the fuel cavity to the working fluid channel. The fused-silica walls which are components of the transmission cells are not completely transparent to thermal radiant energy and absorption must be included in evaluating the transmission cell efficiency.

A summary of transmission cell performance is given in Table I. These results are calculated for an outward-directed thermal radiant energy flux corresponding to a black-body temperature of 4000 K. One component of transmissivity is related to the radiant energy absorbed by the fused silica and is a function of the wall thickness. This component varies from 0.941 to 0.85 for wall thicknesses of 0.25 and 3.5 cm, respectively. A second component of transmissivity is related to losses from the incident beam resulting from multiple wall reflections within the transmission cell along the path to the external working fluid channel. The transmissivity of a right circular, cylindrical transmission cell with aluminum reflecting walls was calculated as a function of the cell length-to-diameter ratio. Based on the Monte Carlo technique developed in Ref. 7 in which the transmission of radiation from the diffuse source was calculated along a specular reflecting cylinder, the transmissivity at the exit of the cell varied from 0.92 to 0.56 as the length-to-diameter ratio varied from 0.5 to 4.0. The total transmissivity can be estimated, to a first approximation, by multiplying the two independent transmissivity components.

Fresnel reflection losses for fused silica and gas interfaces were not considered. The transmission cell must have a minimum of two fused-silica walls and thus four potentially reflecting surfaces. However, not all of the reflected energy is lost. Some of the energy will be reflected back into the fuel region to be reabsorbed and, subsequently, re-radiated by the plasma; some will be re-reflected within the transmission cell and find its way to the working fluid channel. Furthermore, reflection losses occurring at the interfaces of the fused silica can be reduced within given wavelength bands by depositing anti-reflection coatings on the surfaces. Further analyses or measurements are required to quantify the effects of interface reflections on overall transmission cell performance.

Criticality and Radiant Heat Transfer

Calculations of critical mass were performed using the one-dimensional neutron transport theory computer program, ANISN (Ref. 8), for the nonbreeder reactor configuration shown in Fig. 2. The volume of each region was transformed into equivalent-volume spherical zones. A twenty group neutron energy structure was used in the calculation for which neutron cross sections were obtained from the HRG (Ref. 9), TEMPEST-II (Ref. 10), and SOPHIST-I (Ref. 11) computer programs. A critical mass of 86.4 kg of U-235 was calculated; 14.4 kg is in each of the six unit cells.

Nuclear fuel will be injected into the fuel region of plasma core reactors in the form of gaseous UF_6. Upon entering the plasma zone, the UF_6 will dissociate such that at high temperatures ($\sim$8000 K) the total pressure of the mixture will consist primarily of contributions from uranium atoms and ions, free fluorine atoms and ions, the corresponding electrons from ionized species, and some argon buffer gas which will mix into the plasma zone. The composition of UF_6 as a function of temperature and pressure were calculated using a UTRC computer code described in Ref. 12. The following species were included in the analyses: UF_6, UF_5, UF_4, UF_3, F, F^-, F_2, U^o, U^+, U^{+2}, U^{+3}, and electrons. A composite plot of the variation of the ratio of fluorine to uranium and uranium fluoride species is shown as a function of temperature for several total pressures in Fig. 4. The abrupt increase in fluorine partial pressure with temperature occurs with the onset of the dissociation of UF_6. A plasma core reactor must by definition be an ionized gas. If fueled by UF_6, the six fluorines and electron partial pressures add to those of the uranium species, resulting in operating pressures of several hundred atmospheres.

In calculating the temperature distribution for the fissioning plasma region for a given radiant heat flux at the plasma edge, the containment characteristics in the fuel and buffer-gas region must be considered. A reasonable constraint for containment is to require that from the edge-of-fuel location inward, the local density at any station be less than or equal to the density of the buffer gas at the edge-of-fuel location. With this constraint, and for constant total pressure, there exists an upper limit on the amount of uranium (which has a higher mass number) that can be confined with the fluorine and argon at a given local temperature. Calculations were performed to determine the ratios of uranium to fluorine and argon at local temperatures in the fuel region such that the total pressure is preserved and the total density of uranium, fluorine, and argon is equal to or less than that of the argon at the edge-of-fuel location. The compositions of fluorine, argon, and uranium as functions of temperature and pressure, including the effects of ionization at high temperatures, were taken from Refs. 13 and 14, and from the UF_6 decomposition calculations. By using UF_6 decomposition products and argon decomposition products in conjunction with the estimated spectral absorption cross sections, Rosseland mean opacities were calculated for the mixture of argon and UF_6 decomposition species in the fuel region. The estimates of the spectral characteristics of UF_6 and its dominant decomposition products over the range of pressure, temperature, and wavelength important to the plasma core reactor concept, were reported in Ref. 15. Results of current research on the experimental measurement of spectral emission and absorption characteristics by UF_6 and its decomposition products is reported in Ref. 16.

These mixture opacities were used in a radiation diffusion analysis to determine the temperature distribution required to deliver a net heat flux at radial boundaries, which are located at 110 cm intervals from the centerline of the fuel zone, equal to the total energy release due to the fissioning of the nuclear fuel within each boundary (local argon, fluorine, and uranium densities and partial pressures were calculated using the program discussed above). The calculation converges when the heat flux at the outer boundary corresponds to the net heat flux at the edge-of-fuel location and the contained uranium, based on the imposed density and total pressure constraints, equals the critical mass.

Radiant heat transfer calculations were performed for the unit cells in the reactor configuration shown in Fig. 2. Temperature distributions were calculated for edge-of-fuel temperatures of 2000 K, 3000 K, 4000 K, and 5000 K, and working channel duct to total cavity surface area ratios of 0.0, 0.1, 0.2, 0.3, and 1.0. The centerline temperatures and total cavity pressures which include the resulting UF_6 and argon decomposition product partial pressures are given in Table II. The critical mass was held constant for the different operating conditions, so that the characteristic of the pressure increasing as the centerline temperature increases is indicative of the degree of UF_6 dissociation.

The reflective aluminum liner tends to trap photons in the fuel region. A portion of the reflected thermal radiation is reabsorbed by the nuclear fuel in the edge-of-fuel region which causes the local temperature to rise. The spectral heat flux incident on the aluminum liner was used to calculate an aluminum spectrum-weighted average reflectivity which at the liner surface was 0.909. The effective reflectivity is different from the spectrum-weighted average reflectivity of the aluminum liner because of geometrical factors. Diffusely reflected radiation from the liner would have a cosine distribution about the inward normal. Some of the reflected radiation, therefore, would not intercept the fuel cloud but would pass by the cloud and reflect off another portion of the liner.

The equations which describe the effective reflectivity for a given fuel region and reflective liner geometry are derived in Ref. 17. A given steady-state outward-directed heat flux and the reflected component of the thermal radiation which is absorbed by the fuel cloud, are related uniquely when the fuel cloud is assumed to be a cylindrical, optically-thick radiating fuel cloud. The radiant energy which is not reabsorbed by the fuel cloud is either absorbed by the reflective liner or is incident on the working channel duct where it represents energy available for an energy extraction cycle. The distribution of radiant energy absorbed by the working fluid channel and the reflective liner as a function of ratio of the area of the working fluid channel to the total cavity surface area is shown in Fig. 5. These energy deposition distributions were used to determine the radiant thermal powers deposited in the line[illegible] duct for the parametric series of calculati[illegible] Calculations were also performed to estimate [illegible] convective removal of energy from the fuel cavity by the flowing gases as well as the energy deposited in the moderator by fission neutrons and gammas. The model used for the convective energy removal is similar to that described in Ref. 18. Using the temperature distributions calculated for each thermal heat flux condition and with a buffer gas residence time of 30 s and a ful residence time of 60 s, the total convective energy removal, Q_{CONV}, was calculated. In addition, the power deposited in the moderator, Q_{MOD}, was calculated to be equal to 0.125 times the total reactor power. The resulting energy balances for the cases calculated are given in Table III.

For the conditions at which the edge-of-fuel temperature is 4000 K and the working channel duct-to-cavity surface area ratio is 0.2, the calculated radial density distributions of the fuel, fluorine, and argon within the unit cell is shown in Fig. 6. The temperature variation was assumed to be linear with radius through the argon buffer region. This buffer gas region temperature variation and corresponding density variation was matched to the temperature and density radial distributions obtained from the radiation diffusion analysis of the fuel region. The actual temperature and density distributions in the buffer gas region are not as linear as shown in Fig. 6, but this approximation does indicate the expected steep density gradient which should result in a strong stable vortex flow for containing the hot fuel gas within an outer cool buffer gas layer.

Plasma Core Reactor Applications

The salient feature of the plasma core reactor applications investigated is the coupling of power to working fluids by radiant heat transfer. The applications studied include high-thrust, high-specific-impulse, space propulsion systems, electric power generators using closed-cycle helium gas turbines, an MHD power conversion concept, and photochemical/thermochemical processes for the production of hydrogen. In addition, Thorium-U-233 breeder configurations of plasma core reactors were analyzed to determine possible ranges of breeding ratios and doubling times.

High-Thrust, High-Specific-Impulse Space Propulsion

Historically, research on gaseous nuclear reactors was focused on high-performance space propulsion systems. Research was conducted on two major concepts of gaseous nuclear rockets: the open-cycle, coaxial flow concept and the closed-cycle nuclear light bulb concept. Comprehensive surveys of the ranges of performance of the open-cycle and nuclear light bulb rocket engines are discussed in Refs. 19 and 20, respectively. In addition, a version of the nuclear light bulb engine with size and critical mass reduced by use of cold beryllium reflector-moderators (less than 300 K) backed by cold deuterium-compound moderator materials and by use of axial propellant channels is described in Ref. 21. Table IV summarizes the performance characteristics of these propulsion systems.

The performance studies described below were done for closed-cycle gaseous nuclear rocket engines which employ gaseous UF_6 nuclear fuel and its decomposition products with radiating temperatures of 6000 K and lower and total pressures of a few hundred atmospheres. The resulting systems should be considered "first generation" plasma core reactor thrusters; the higher performance systems which should follow with technological improvements and growth having been thoroughly modeled and analyzed in earlier studies.

Engine performance characteristics were calculated for a derivative of the reference nuclear light bulb engine. Dimensional characteristics and component weights for this engine are given in Ref. 6. The assumptions employed to determine the performance of the engines over a range of fuel radiating temperatures from 4000 to 6000 K were as follows:

(1) Propellant exit temperature assumed to be 80% of fuel radiating temperature.

(2) Heat loads were assumed to be the same fraction of total power as those calculated for the reference nuclear light bulb engine in Ref. 6. Operating pressure and fuel and buffer gas heating were based on the calculations described in the preceding section.

(3) Specific impulse was reduced to 84% of the ideal value to allow for incomplete expansion, friction and recombination losses, nozzle transpiration coolant flow, and for the flow of tungsten seeds in the propellant to absorb thermal radiation.

(4) The total flow passing through the nozzle exit was increased by approximately 16% to include tungsten seed flow and transpiration coolant flow.

(5) Engine weight was determined by adding the reference nuclear light bulb moderator weight to the pressure vessel weight calculated using a weight factor given by $Z = W_{PV}/PV = 1.125$ kg/atm-m^3.

Performance characteristics for the cases considered are given in Table V. For the derivative of the nuclear light bulb reference engine with radiating temperatures from 4000 to 6000 K, the performance characteristics are: engine mass 32,700 to 42,900 kg; operating pressure 540 to 900 atm; Isp 880 to 1220 s; thrust-to-weight, 0.14 to 0.47.

For comparison purposes, preliminary analyses based on the techniques described in Ref. 22 were conducted of the performance of the engines described in Tables VI and V for a mission requiring a total V of approximately 853 m/s (i.e., low circular orbit to escape velocity, applicable to supply missions to synchronous orbit, for example). Comparisons were made in terms of initial mass required in earth orbit (IMEO) to a chemical rocket employing H_2/O_2 propellant with a specific impulse of 450 s, a weight of 1135 kg, and a thrust level of 890,000 N.

The missions comprised minimum energy Hohmann transfers from low circular earth orbit (100 nautical miles) to synchronous orbit and back using two rocket burns per transfer. Due to relatively low accelerations, gravity loss correction factors were included. The payload was assumed to be four space shuttle payloads, approximately 90,000 kg. Comparisons were made for two plasma core reactor rocket engines; a derivative of the nuclear light bulb reference engine with UF_6 fuel with an Isp of 1220 s and a thrust-to-weight ratio of 0.47 (see column 3 of Table V) and a small nuclear light bulb engine with an Isp of 1150 s and a thrust-to-weight ratio of 0.14.

For the cases calculated, the IMEO's for the plasma core rocket engines were about 40 to 60 percent of those for the chemical system. The performance advantage increases with increased payload also. These results indicate that the plasma core reactor engine with UF_6 nuclear fuel with "first generation" performance characteristics could be a desirable system for ferrying space shuttle payloads to selected earth orbits and possibly for other operations in cis-lunar space. The benefits of performance extension by technology growth and improvements to the high-thrust, high-specific-impulse systems described by the performance ranges quoted in Table V from earlier work are clear.

Closed-Cycle Helium Gas Turbine Electrical Generators

Basic performance analyses of closed-cycle gas turbine systems which could effectively utilize the high temperature capability of plasma core reactors were performed. The closed-cycle system uses a helium-driven gas turbine coupled to an electrical generator with a nominal output of 1000 MWe. Heat from the reactor can be transferred directly to the closed-cycle helium working fluid or can be transmitted through a secondary heat exchanger. The cycle under consideration would employ a multistage turbine connected to compressor spools. The working fluid leaving the main turbine would enter a second multistage turbine directly connected to the electric generator. Several heat exchangers would be incorporated in the system (i.e., a regenerator, precooler, intercooler) to increase the system performance. A schematic diagram of the closed cycle gas turbine system is shown in Fig. 7. Additional power generation is also possible by utilizing some of the heat from the working fluid at the regenerator and intercooler exhaust temperatures to operate supplementary steam or organic working fluid power systems to increasing the system overall efficiency. These additional systems were not investigated in this study.

The reactor configuration for electrical power generation was described in the preceding section. Sketches of the configuration and unit cells for power extraction are shown in Figs. 1 and 2. The mechanisms for extracting heat from the reactor can be either the system employing fused-silica U-tubes with graphite fins within the tubes to absorb thermal radiation, or the system with axial working fluid channels in which graphite fins absorb the thermal radiation without surrounding them with fused silica. The fused-silica U-tubes permit a pressure differential between the operating pressure of the reactor and the operating pressure of the helium gas turbine loop. For example, fused-silica tubes under a compressive loading of 500 atm would require a ratio of OD to ID of 1.19 for a design point compressive stress of 1.38×10^8 N/m^2 (20,000 psi). Due to the temperature limitation on fused silica, the helium outlet temperature for the U-tube system is limited to approximately 1200 K. The alternate unit cell configuration with axial graphite fins would operate at working fluid pressures equal to those in the reactor fuel region. The working fluid would be conducted through a secondary heat exchanger across which a pressure drop could be sustained such that the helium gas turbine system could be operated at a desired cycle pressure. Helium outlet temperatures would be limited only by material limits in other system components. The latter unit cell would use less fused silica and structure in the reactor core and would be more adaptable to breeder reactor configurations where it is necessary to minimize parasitic neutron absorbers to maintain a desirable breeding ratio.

Performance was optimized by determining the system's overall efficiency, electrical power output divided by the total reactor thermal power, for a range of pressure ratios across the helium compressors and for three turbine inlet temperatures of 1098, 1506, and 1922 K. Efficiencies of the compressors, turbines and regenerator were assumed to be 0.9. The generator efficiency was assumed to be 0.98. Fractional pressure drops of $\Delta P/P = 0.02$ were assumed across all heat exchangers and through the reactor core. A compressor inlet temperature of 322 K was selected to permit use of a dry cooling tower for heat rejection (selection and evaluation of specific heat rejection systems was not included in the study, however). Based on the calculated results, a compressor pressure ratio of 1.75 was selected for cases with turbine inlet temperatures of 1089 and 1505 K and a compressor pressure ratio of 2.0 was selected for t[illegible] case with a turbine inlet temperature of 19[illegible] Three operating pressures were considered, 20, [illegible], and 153 atm. The overall cycle efficiency was found to be relatively insensitive to cycle pressure over the range from 20 to 150 atm. Thus, the principal impact of pressure selection would be on eq[illegible]ment size and cost.

The variation of overall cycle efficiency with turbine inlet temperature is shown in Fig. 8 with inlet temperatures noted for various blade materials and turbine blade cooling schemes. The progression of gas turbine technology into the 1980's is discussed in Ref. 23. With the use of cooled molybdenum alloy (TZM) blades and vanes, operation with turbine inlet temperatures of about 1900 K might be feasible by the mid 1980's. The cross-hatched region on the plot at working fluid temperatures of the order of 2500 K is indicated with an MHD label. The description of possible concepts which could be used for MHD system is given in the following section.

MHD Power Conversion Concepts

The high working fluid temperatures available from plasma core reactors make the use of MHD power extraction concepts attractive options. A comprehensive review of MHD power conversion systems based on gaseous nuclear reactor technology is given in Ref. 24. Plasma core reactors with fuel region radiating temperatures sufficiently high (4000 to 5000 K) to heat MHD working fluids to desired temperatures of 2000 to 2500 K have operating pressures on the order of 500 atm. Conductivity of MHD working fluid with alkali metal seeds decreases rapidly with increasing pressure ($\alpha P^{-\frac{1}{2}}$ for thermal ionization, αP^{-4} for nonequilibrium ionization). Therefore, MHD cycle performance for a given working fluid temperature tends to favor operation at a few atmospheres pressure. In the process of conceiving and evaluating configurations which might be used to couple MHD power extraction systems to plasma core reactors, two principal considerations are dominant; (1) the MHD duct operating pressure should be a few atmospheres while the reactor operating pressure is of the order of 500 atm; and (2) space occupied by MHD duct magnets and electrodes and parasitic neutron absorptions by the MHD duct materials should be small to minimize their impact on reactor criticality. The transmission cell concepts described in the preceding section provide a means to satisfy both constraints.

The configurations shown in Fig. 3 are both adaptable for use as MHD systems. In both cases, the MHD ducts would be located outside the nuclear fuel and moderator zones and essentially neutronically isolated. The transmission cells with series of fused-silica ports under compressive load would permit operation with the appropriate pressure differential between the PCR fuel region and the MHD duct. Two modes of operation would be possible. The MHD duct could be attached at the ends of the working fluid channels [illegible]wn in Fig. 3. Power would be extracted after the fluid was heated as in most MHD concepts. A second option could be to install the MHD ducts with magnets and electrodes in the working fluid channels. Power would be extracted as the working fluid was heated, resulting in a very efficient cycle since the working fluid temperature and conductivity would be constant in the MHD duct. The latter constant temperature MHD power conversion system was first suggested in Ref. 25.

Preliminary investigations were made of possible MHD seeding materials. The most attractive working fluid and seeding materials identified for a PCR-MHD system were suspensions of thermionically emitting particles of barium oxide or mixed oxides of barium, calcium, and strontium in argon gas. The main theoretical advantages of an emitter suspension over an alkali metal seeded gas are its higher conductivity at temperatures up to about 2000 K (especially at pressures of 10 atm and above) and its relatively small variation in conductivity with changes in pressure ($\alpha P^{-0.13}$). The latter property permits conceptual designs of MHD systems with operating pressures up to 50 atm with the resulting savings in component size. Discussions of theoretical and experimental investigations of the conductivities of gas borne suspensions of thermionic emitters are given in Refs. 26 and 27. Particle suspensions also tend to be broadband absorbers of radiant energy, making them ideally suited as PCR working fluids.

Related analyses of a closed-cycle nuclear MHD system using dust suspension described in Ref. 28 indicate that overall cycle efficiencies up to ~ 60 percent are theoretically possible with conventional nuclear reactors. Overall cycle analyses and identification of system components should be performed for a reference PCR-MHD power plant to evaluate its potential as an efficient power generation system.

Photodissociation of Halogens to Produce Hydrogen

Plasma core reactors have been proposed as a high power source of radiant energy for which efficient use of high intensity photon fluxes emitted from the radiating ionized fuel cloud can be employed in thermochemical and photochemical employing hydrogen as a fuel is attractive because it is nonpolluting. Hydrogen may be produced from energy sources such as nuclear reactors or solar radiation to the exclusion of production from fossil fuel sources. However, for hydrogen to become a viable fuel, satisfying significant future energy requirements, a means of producing vast quantities in an economic process must be identified and demonstrated.

Studies were conducted to evaluate methods for producing hydrogen using the intense photon fluxes emitted from plasma core reactors. A relatively simple concept proposed here for the photolytic decomposition of water in which the unique radiation emission characteristics of the plasma core reactor are utilized is shown in Fig. 9. Three successive working fluid channels are employed in the process. The first two channels provide a reaction site for the two-step, closed-cycle photolytic decomposition of water and the third channel is provided to absorb the residual thermal radiation either by flowing particle laden gases or by graphite finned rods which transfer the absorbed energy to a flowing gas stream by convection. The concept utilizes radiation and the chemical properties of halogens and hydrogen halides and the unique radiation characteristics of the plasma core reactor to circumvent the problems associated with the direct thermal or photolytic decomposition of water. The key to the concept depends upon the ability of halogens to react with water to form the corresponding hydrogen halide and oxygen species.

In the concept a series of relatively low temperature thermal or photolytic reactions are used to effect decomposition of water and to permit easy separation of reaction products. The combined overall reaction describing the process may be expressed as

$$Br_2(G) + 2I_2(G) + H_2O(G) \overset{h\nu}{\rightleftarrows} H_2(G) + Br_2(G) + 2I_2(G) + \tfrac{1}{2}O_2(G) \qquad (1)$$

Results of composition calculations indicate that molecular bromine (Br_2) does not appreciably react with water. However, similar composition calculations with atomic bromine (Br) and water yield hydrogen bromide (HBr) and oxygen (O_2) as the principal products. Thermal dissociation of the halogens occurs to an appreciable degree (~ 50 percent) only at temperatures greater than 1500 K. In the concept, the radiant flux is used to induce photodissociation of the bromine and iodine molecular species and thermal dissociation is used for the hydrogen iodide and iodine monobromide species. Gaseous molecular bromine (Br_2) and water (H_2O) are allowed to react at approximately 450 K in the presence of radiation ($365 \leq \lambda \leq 535$ nm) to yield gaseous hydrogen bromide and oxygen. Since HBr is not appreciably dissociated at temperatures below approximately 1500 K, HBr is then allowed to react with iodine (I_2) at 456 K in the presence of radiation ($430 \leq \lambda \leq 740$ nm) to yield gaseous hydrogen iodine (HI) and iodine monobromide (IBr). Cooling the reaction mixture below the boiling point of IBr permits separation of liquid IBr from gaseous HI and HBr. Iodine (I_2) and bromine (Br_2) are regenerated from IBr at a temperature of about 700 K. The HI-HBr mixture is heated to about 700 K to thermally decompose HI to hydrogen (H_2) and I_2. Upon quenching to a temperature below 456 K, I_2 is liquefied and separated from the H_2 and HBr. Finally, the solubility of HBr in H_2O is utilized to separate H_2 from HBr.

For plasma core reactors with radiating temperatures between 4000 K and 6000 K, iodine absorbs over a larger fraction of the available spectra than bromine and overlaps portions of the spectra in which bromine also absorbs. To maximize bromine photodissociation to atomic bromine, the bromine region is positioned to intercept the incident thermal radiation first and is of sufficient thickness to reduce the spectral flux to less than one percent of its incident value. The iodine region is located behind the bromine region in the thermal radiation path and is also of sufficient thickness to absorb all but one percent of the spectral flux in its photodissociation wavelength range.

The fractions of radiant energy available to induce photodissociation of bromine and iodine are 0.25, 0.353, and 0.438 for black-body radiating temperatures of 4000 K, 5000 K, and 6000 K, respectively. The concept process also requires