JOURNAL OF PROPULSION AND POWER
Vol. 9, No. 1, Jan.–Feb. 1993

Ultrahigh Temperature Vapor-Core Reactor—Magnetohydrodynamic System for Space Nuclear Electric Power

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This article presents the conceptual design of a nuclear space power system based on the ultrahigh temperature vapor-core reactor (UTVR) with magnetohydrodynamic (MHD) energy conversion. This UF_4-fueled gas-core cavity reactor operates at a maximum core temperature of 4000 K and 40 atm. Potassium fluoride working fluid cools the reactor cavity wall and mixes with the fissioning fuel in the core. Neutron transport calculations with specialized high temperature gas-core cross-sectional libraries indicate criticality at core radii of 60–80 cm, with BeO reflector thicknesses of ~50 cm. The heated core exhaust mixture is directed through a regeneratively cooled nozzle into a disk MHD channel to generate electrical power. The MHD generator operates at fluid conditions below 2300 K and 1 atm. Fission fragment ionization enhances the electrical conductivity in the channel significantly, allowing an overall conversion efficiency of 20%. The mixture is condensed in heat exchangers, and pumped back to the core in a MHD-Rankine thermodynamic cycle. Heat rejection temperatures of 1500–2100 K lead to compact heat exchangers and an overall specific weight of ~1 kg/kWe for 200 MWe. Material experiments, performed with UF_4 up to 2200 K (to date), show acceptable compatibility with tungsten-, molybdenum-, and carbon-based materials. This article discusses the supporting nuclear, fluid flow, heat transfer and MHD analysis, materials experiments, and fissioning plasma physics.

Introduction

SOLID-CORE reactors provide the path for minimum risk in generating nuclear space power in the coming decade. These reactors can be expected to achieve evolutionary improvements in their performance based on modest extrapolations of current fuel technology. In contrast, gas- and vapor-core reactors offer a path for extraordinary improvements in performance, and have the highest potential for reducing overall system specific mass.[1,2]

Gaseous-core reactors impose minimum geometrical constraints on the fuel configuration while providing a high-temperature heat source plus a powerful ionization source. These features lead to the inherent technical advantages of energy conversion temperatures that are not limited by fuel integrity limits, and working-fluid properties that are enhanced by the ionization processes.

These technical features lead to design advantages that include high working-fluid and heat-rejection temperatures, high fuel utilization [burn-ups up to 200,000 megawatt-days per metric tonne (MWd/MT)], elimination of fuel fabrication, testing, and verification, simplified fuel management, inherent hot-spot compensation, and flat-power density profiles.

Operationally, these design advantages lead to planetary mission benefits and improved safety. These include lower trip times and initial mass in orbit, reduced radiator mass, the potential for reactor refueling and reuse due to the fluid nature of the fuel, and a zero (0) probability of accidental criticality on launch since the reactor is launched unfueled.

The performance limitations of gas-core reactors have traditionally been set by energy transfer from the hot fissioning fuel to the working fluid, cavity wall and structure cooling, and fuel confinement and separation.[1] As described in the sections below, these limitations are addressed in the current design by maintaining intimate mixing of the fuel and working fluid in the core and energy conversion system, using liquid metal film and/or regenerative cooling of metal structures, operating in a closed-loop power cycle, and separating the fuel and working fluid integrally with heat rejection.

System Description

A schematic diagram of a gas-core reactor for generating megawatt-level electrical power based on the ultrahigh temperature vapor-core reactor (UTVR) with magnetohydrodynamic (MHD) energy conversion[3–5] is shown in Fig. 1. The schematic diagram of a 200 MWe UTVR-MHD power system state-point design is shown in Fig. 2. The rationale that led to the selection of many of the key aspects of the design is summarized in Ref. 6. Vaporized UF_4 fuel is mixed with potassium fluoride working fluid in the gas-core chamber at 40 atm. Fission energy heats the mixture to an outlet temperature of 4000 K. The mixture is exhausted through a nozzle, where it expands to Mach 3 at 2000 K and 0.65 atm, and into a disk MHD generator duct for electrical power generation.

A key feature of the UTVR-MHD system is that the disk MHD generator is an integral part of the reactor assembly. The working fluid mixture in the channel is exposed to a neutron flux of 10^{16} n/cm^{2}s so that significant fissioning occurs in the MHD channel by design. The generator therefore operates with electrical conductivity enhanced by fission fragment ionization; this is much higher than that attributable alone to thermal ionization of this mixture at 2000–2300 K and less than 1 atm. The result is a net cycle conversion efficiency of 22%.

Following the MHD generator and a diffuser section, the mixture enters the main condensing radiator; here the potassium fluoride is condensed out and predominantly separated

Presented as Paper 91-3632 at the AIAA/NASA/OAI Conference on Advanced SEI Technologies, Cleveland, OH, Sept. 4–6, 1991; received Nov. 12, 1991; revision received May 1, 1992; accepted for publication May 5, 1992.

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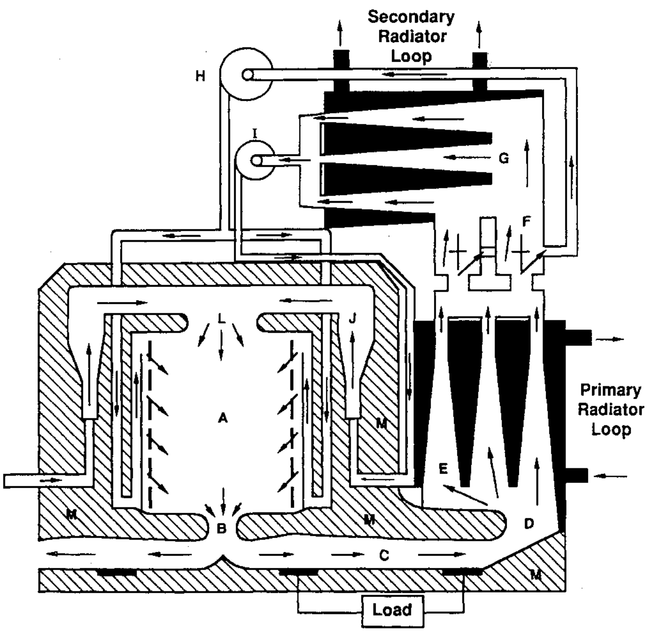

Fig. 1 Schematic diagram of an ultrahigh temperature vapor-core reactor-disk MHD generator system.

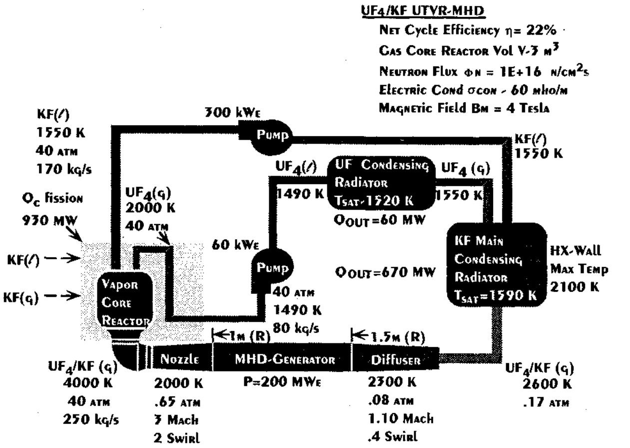

Fig. 2 Schematic diagram of a 200-mwe UTVR-MHD conceptual design with a specific mass of ~1 kg/kWe.

from the UF_4. The UF_4 and any KF carryover is further cooled and condensed in a second radiator. Condensing fluid temperatures are in the range of 1500–2600 K. Material temperatures achieve a maximum of 2100 K, resulting in very compact heat exchanger/radiator configurations.

The UF_4 is pumped to the reactor operating pressure and enters the moderator/reflector, where it is boiled/superheated in boiler columns. The superheated UF_4 is injected into the core as a vapor. The KF is pumped back to the reactor at 1550 K, where a portion is used to cool the BeO moderator before entering the core and mixing with the UF_4. The balance of the KF is pumped directly to the cavity wall and nozzle for film and regenerative cooling respectively, of these components before joining the main fuel/working fluid stream.

Fuel and Working Fluid

Early studies of gas-core reactor concepts used gaseous UF_6 or metallic uranium vapor as the fissionable fuel.[1] However,

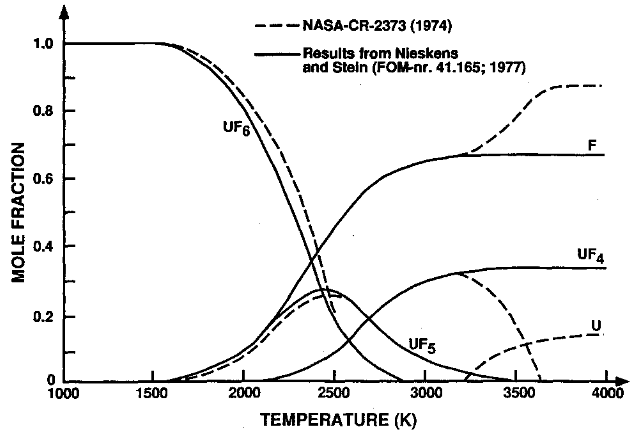

Fig. 3 Mole fractions of constituent species of uranium-fluorine system vs temperature at 1 atm.

UF_6 is chemically unstable as the temperature increases above 2000 K, as shown in Fig. 3 (from Refs. 7 and 8). UF_4 is thermodynamically stable, more chemically stable than UF_6, and its 1700 K boiling point at 1 atm is close to the present maximum achievable temperature in space radiators. This feature can be used to minimize the size/mass of the radiator system of systems using UF_4.

A comparison of the UF_4 and U metal saturation vapor curves also reveals the advantage of UF_4. The 5000 K boiling point of uranium at the 10–20 atm of core pressure required for criticality presents challenging material issues. At these pressures, the boiling point of UF_4 is 2000 K. Considering also the difficulties of addressing criticality during handling and recirculation of vapor or liquid uranium, UF_4 appears to be a more suitable fuel for vapor-core systems. Reference 9 addresses the issues of uranium-based reactors by investigating a uranium-droplet concept. Though research into chemical, thermodynamic, and compatibility of the use of UF_4 are still needed, it presents the minimum research path to vapor-core reactors. It is noted that UF_4 in liquid form was used as reactor fuel in the 1960s in the 2.6 MWe aircraft reactor experiment (ARE), and later in the molten salt reactor experiment (MSRE). The ARE used a mixture of UF_4-ZrF_4-NaF exiting at 1170 K; the MSRE used UF_4-LiF-BeF_2 at 1100 K.[10]

To maximize the heat-rejection temperature and therefore minimize the radiator size and mass, the UTVR-MHD uses a Rankine thermodynamic cycle. The working fluid candidates are thus the alkali metals, Li, K, Na, and their fluorides. System designs with the various candidates offer similar performance, with K and KF providing the optimum combination of neutronic, thermodynamic, and conductivity performance.

Neutronic Analysis and Design

Static and dynamic analysis of the UTVR-MHD were carried out to characterize the neutronic performance of the system.[3–5,11,12] These analyses revealed a number of attractive features, including some unique and very effective negative reactivity control mechanisms, such as the vapor-fuel density power coefficient of reactivity, the direct neutronic coupling among the fissioning core regions, and the mass flow coupling feedback between the fissioning cores.

One- and two-dimensional static neutronic calculations were performed with the S_n transport theory codes XSDRNPM and DOT4. Three-dimensional static calculations were performed using the Monte Carlo neutron transport code MCNP. Parameters needed for the dynamic studies were obtained from the three-dimensional analysis.

The UTVR has three radial reflector zones: 1) the outer, 2) boiler, and 3) inner BeO regions (OBEO, BBEO, and IBEO) separating the core (UTVC) from the UF_4 boiler columns, and top/lower BeO (TBEO and LBEO) regions. Figure

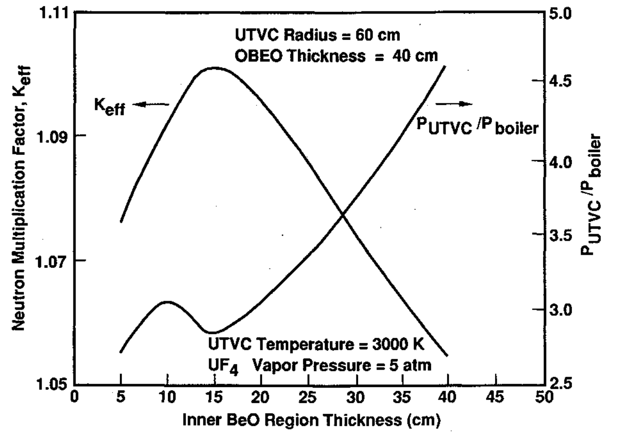

Fig. 4 k_{eff} **and** P_{UTVC}/P_{boiler} **vs inner BeO moderator-reflector region thickness.**

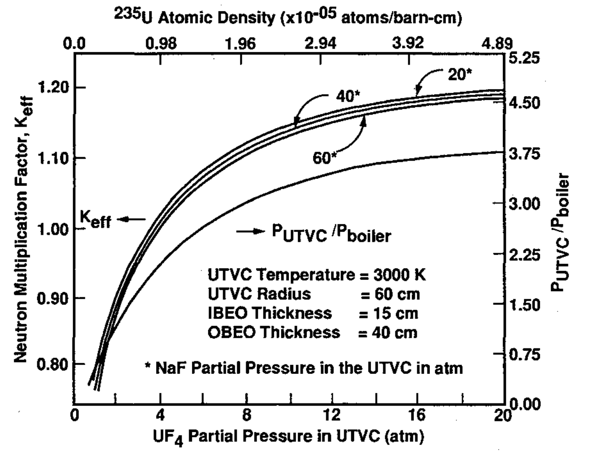

Fig. 5 k_{eff} **and** P_{UTVC}/P_{boiler} **vs** UF_4 **partial pressure in the UTVC.**

Table 1 Optimum BeO thickness in the UTVR

BeO Region	Optimum thickness, cm
IBEO	15
MBEO	7.5
OBEO	40
TBEO	50
LBEO	55

Table 2 k_{eff} **and** P_{UTVC}/P_{boiler} **vs number of** UF_4 **boiler columns**

Number of boiler columns	k_{eff}	P_{UTVC}/P_{BCOL}
2	1.032	4.32
4	1.048	3.11
6	1.068	2.32
8	1.087	1.90

4 shows the neutron multiplication factor, k_{eff}, and the power split in the core and boilers, P_{UTVC}/P_{boiler}, as a function of the IBEO region thickness. Similar optimization studies were performed for the other BeO zone thicknesses. The results are presented in Table 1. With the optimum thicknesses shown in the table, the maximum k_{eff} was obtained for a UTVC radius of approximately 80 cm. With the UF_4 partial pressure as a controllable parameter, criticality can be achieved with radii of 60–80 cm.

Figure 5 shows the variation of k_{eff} and P_{UTVC}/P_{boiler} with the UF_4 partial pressure in the core at different working fluid partial pressures (NaF in this calculation). The figure shows that the working fluid partial pressure does not appreciably affect the system k_{eff} in comparison to the UF_4 partial pressure. The actual choice of metal fluoride also has little effect on k_{eff}. Thus, the fuel/working fluid mixture ratio can be selected to enhance MHD generator performance and efficiency.

Figure 5 illustrates an important feature of externally-moderated reactors. This feature is a saturation effect by which beyond a certain UF_4 partial pressure, additional increases in the partial pressure yield diminishingly smaller increases in k_{eff}. This point is reached when the neutron mean-free path for absorption is small compared to the core dimensions, and neutrons are therefore absorbed in the outer regions of the fuel. From a control standpoint, it is desirable to operate well below this saturation point.

The variation of k_{eff} and P_{UTVC}/P_{boiler} as a function of the number of boiler columns, with the total volume of the boiler column region remaining fixed, is shown in Table 2. The results show that as the number of boiler columns increase, k_{eff} increases while P_{UTVC}/P_{boiler} decreases. This is due primarily to an increased fission rate in the smaller columns as the neutron flux self-shielding decreases, and also to enhanced boiler-to-boiler and UTVC-to-boiler neutronic coupling.

Selected UTVR configurations were analyzed using the MCNP code on the Cray X-MP/48 at the San Diego Supercomputer Center. The results were used to benchmark the k_{eff} and P_{UTVC}/P_{boiler} values obtained in Sn transport theory calculations, and to obtain reactivity worths and neutronic coupling coefficients among the various core regions. The results confirmed a system k_{eff} of 1.046 and a P_{UTVC}/P_{boiler} of 3.68. Summary discussions of the neutronics results are contained in Refs. 11 and 12.

Fluid Flow and Heat Transfer

For analysis of the thermal hydraulics of the fissioning gas in the reactor core, a single-phase, three-dimensional, compressible, turbulent computer code was developed, COMMIX-GCR,[4,5] based on a code originally developed at Argonne National Laboratory.[13] The flow of the fuel gas/working fluid mixture is treated as a viscous, turbulent compressible flow with variable thermodynamics and transport properties. The computational model is designed to solve the unsteady, axisymmetric partial differential equations for conservation of mass, momentum, and energy, along with the two-equation (k-epsilon) turbulent model.

For the axisymmetric geometry of the UTVR and disk MHD, the numerical model is simplified to be two-dimensional axisymmetric (see Fig. 6). The model is solved by assuming a constant core-exit pressure, while the applied inlet pressure is time dependent. At the outlet, the velocity is determined from the continuity equation. Along the solid walls the usual nonslip boundary condition is assumed, while along the symmetry the gradient of the velocity and other scalar quantities normal to the symmetry line are assumed zero.

Numerical calculations of thermal and flowfields in the UTVR-MHD with internal heat generation revealed interesting results for test cases. The results for an inlet flow assumed constant at 1500 K and 20 atm, a conducting wall temperature maintained at 1000 K, and a static pressure at the core exit fixed at 1 atm, are shown in Fig. 6. This figure shows the computed flow patterns, temperature, and density contours of superheated UF_6 vapor with a uniformly distributed heat source of 200,000 W/m^3. These results show a distinctive turbulent pattern, with higher temperatures in the central regions due to the heat source and turbulence, while higher density appears near the conducting wall due to the lower temperatures. Additional examples are presented in Ref. 14.

The COMMIX-GCR code is being utilized as a preliminary computational tool for predicting the thermohydraulic features of the UTVR core and converging-diverging disk MHD generator. The numerical grid generation code was designed to improve the solution efficiency and accuracy, and plotting

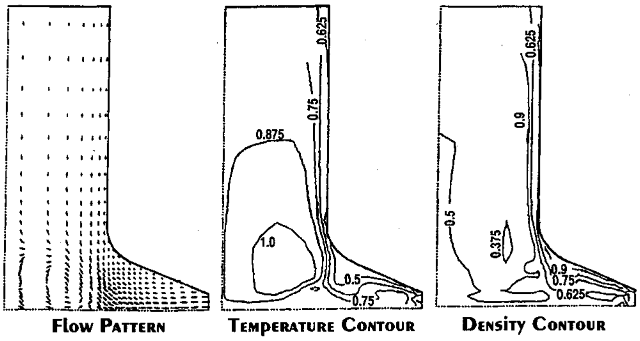

Fig. 6 COMMIX-GCR Simulation and prediction of flow, temperature, and density fields in UTVR (Q = 200,000 W/m^3, v_{in} = 50 m/s).

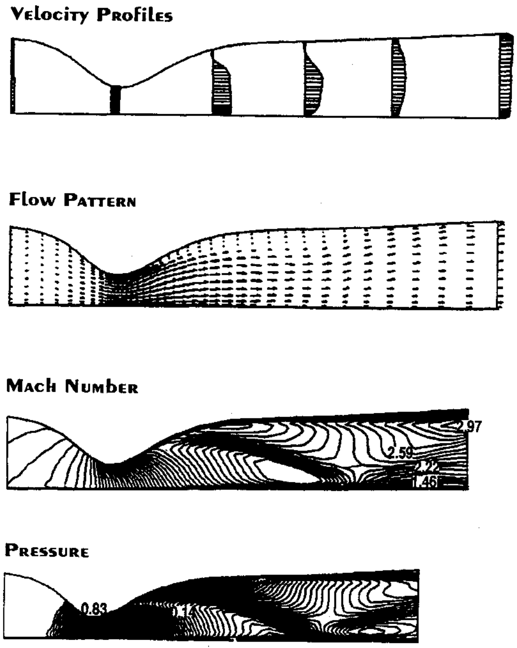

Fig. 7 SMATH-2D Predictions of steady-state flow and pressure fields in a case study UTVR nozzle and MHD channel design.

programs were added. Since the fluid flow and nuclear characteristics are interdependent, it is intended to fully couple these aspects in future improvements of the code.

In the MHD generator, modeling requires coupling of the flow conservation equations with Maxwell's equations. A new code was written, SMATH-2D,[3,4] in which the governing Navier-Stokes equations were modified to include the Lorentz force, Joulean energy dissipation, and MHD working source terms. The solution method uses a flux-splitting hybrid explicit-implicit numerical scheme enhanced by the turbulent model of Baldwin and Lomax.[15]

The code has been executed with the magnetic Reynolds number (the ratio of induced magnetic field to the background magnetic field) maintained below 0.3. This allows for neglecting of the induced field. Both MHD and nonMHD flows have been simulated, including very high-temperature supersonic gas flow through a two-dimensional converging-diverging nozzle and a long MHD channel. The results indicate adequate performance and high resolution in simulating complex flow phenomena.[16] An example is shown in Fig. 7 where the lower wall is a flat plate, the inlet conditions are 50 atm and 2500 K, the back pressure is 1 atm, and the wall temperature is maintained at 1000 K. Figure 7 shows a specific time in the development of the flow and demonstrates flow separation and an oblique shock and its reflection. Other cases show the development of vortex formation, normal shocks, etc. The code has been used to compute the current and electric potentials between electrodes and MHD power output for different load factors and electrical conductivities.

Materials Selection

The preferred fuel form in the UTVR is vapor UF_4. However, UF_6 is a gas close to room temperature, and it was initially selected for the early material experiments to determine its compatibility with candidate materials.[4,5] Prior to 1987, no materials had been identified to be compatible with UF_6 above 800 K. As part of this program, a series of materials were analyzed, tested, and proven compatible (no weight loss) up to nearly 1300 K for service times of 1 h.[17]

A flowing UF_6 test-loop was used to expose materials in an alumina reaction tube housed in a 1500 K electrically heated furnace. The reaction rates were measured by a discontinuous gravimetric method. Posttest analysis of the morphology of the exposed surface was conducted with a variety of techniques, e.g., scanning electron microscopy (SEM), x-ray diffraction and energy dispersive spectroscopy (XRD and EDS), and electron microprobe analysis (EMP). The results of weight-gain experiments are shown in Fig. 8 for alumina and sapphire. These were determined to have a service temperature up to 1300 K. Other potential candidates and their service temperatures are thoria (ThO_2) to 1200 K, and yttria (Y_2O_3) to 1100 K.

Since UF_4 is the fuel of choice for gas/vapor-core reactors above 1100 K, as discussed above, its compatibility with various materials was studied by thermodynamic analysis and experimental corrosion testing. The thermodynamic analysis was conducted with the FACT computer program[18] up to 3000 K. Corrosion tests have been performed with liquid and vapor phases of UF_4 to 2200 K to date. For liquid compatibility tests, a candidate material sample was immersed in molten UF_4 in a graphite or molybdenum crucible held in a vacuum chamber within an alumina tube and heated in an induction furnace. For vapor compatibility tests, the material sample was exposed to UF_4 vapor in a reflux loop within an alumina reaction chamber.

The computational thermodynamic analyses were performed at 1 atm in a temperature range of 1400–3000 K. The analysis results indicate carbon will be stable to 2400 K. Above 2400 K, a small amount of carbon fluorides form. With Mo, W, Re, and Ta, no reactions were found to occur. However, the UF_4 may start to decompose and release U and F atoms, as shown in Fig. 3.

The UF_4 compatibility experiments established that W, Mo, and glassy carbon gain weight slightly at 2200 K after 2 h. This was the maximum temperature achievable with the equipment. The weight gain was attributed to side reactions with the alumina housing, rather than direct reactions of the candidate materials with the UF_4. Control of oxygen concentration was therefore found to be critical in suppressing the oxygen-fluorine exchange mechanism which leads to material

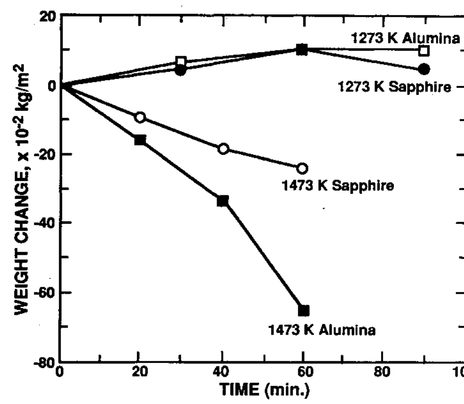

Fig. 8 Weight change vs time for alumina and sapphire in a flowing UF_6 loop.

transport. Additional tests with detailed analyses and discussion of the results are in progress.

MHD Energy Conversion

This section provides an overview of the disk MHD generator component magnetofluidynamic (MFD) modeling, and results from the parametric design analysis, following the presentation in Ref. 19. The high-temperature gaseous-UF_4/metal-fluoride mixture enters the active region of the generator with a radial Mach number greater than one and with some positive swirl factor; the swirl factor is defined as the ratio of tangential-to-radial velocity components induced by turning vane.

The high-temperature fissioning plasma working fluid is a weakly ionized plasma with finite electrical conductivity and Hall parameter. The supersonic plasma working fluid interacts with the applied magnetic field and establishes an electric current density with a short tangential (Faraday) component J_θ, and a radial (Hall) component J_r, and a radial (Hall) electric field E_r; the magnitude of E_r and J_r depend in part on the impedance of the load connected between the anode and cathode. The current density in turn interacts with the applied B-field and gives rise to large radial and tangential body-force components. These body-force components each act against the direction of the flow and tend to diffuse the flow towards Mach one. The electric power is extracted from the MHD generator over the channel volume where $|\mathbf{J}\cdot\mathbf{E}|$ is nonzero. The local electrical conversion efficiency, the local electric power density, and the generator isentropic efficiency are all enhanced by high inlet swirl flows.

The disk MHD generator analysis is based on the governing equations of quasi-one-dimensional, tangentially-symmetric, steady state, inviscid, perfect gas flow of a fissioning plasma. Heat transfer and induced magnetic field effects are neglected. The applied magnetic field and neutron flux profiles are specified. The working fluid is modeled as a single-component background gas with a superimposed electron fluid characterized by a Maxwell-Boltzman distribution with electron temperature T_e. The electron source term includes the contribution of fission fragment-induced ionization.

A parametric analysis of the disk MHD generator was conducted over a wide range of generator inlet conditions and fluid mixtures. With reactor exhaust stagnation conditions of 4000 K and 50 atm, optimum inlet total Mach numbers are found between 3–3.5, with inlet swirl factors near 2. With MHD duct neutron flux levels of 10^{16} n/cm^{2}s and applied magnetic fields near 4 T, electrical conductivity between 50–100 mho/m and electron mobilities near 1 T^{-1} are anticipated. At these conditions, the disk MHD generator exhibits enthalpy extraction between 20–30% with overall isentropic efficiencies between 50–60%. Additional results and discussion are contained in Ref. 19.

Fissioning Plasma Physics

Fissioning plasmas have transport and optical properties that can allow revolutionary improvements in the efficiency and conditions of energy conversion. The working fluid in the UTVR-MHD system is a fissioning, partially ionized plasma mixture of vaporized UF_4 and a metal/fluoride such as K/KF. Significant enhancement of the efficiency of the direct energy conversion comes from nuclear-driven nonequilibrium ionization of the fissioning fluid. Earlier studies of nonequilibrium ionization of MHD were oriented to the development of a combustion generator using applied or MHD-induced electric fields, rapid expansion of a plasma flow, using electron beams and photoionization, etc. The resultant ionization was very nonuniform and the recombination rates were high. The result was a lack of success for nonequilibrium combustion-driven MHD. However, in the present situation, the nonequilibrium ionization is generated volumetrically and in situ to the channel, thus avoiding some of the difficulties experienced earlier.

The fission process creates two high-energy fragments, each averaging ~67 and 90 MeV. In a solid fuel, this high-quality energy is converted predominantly to heat. In a gas/vapor fuel, the opportunity exists to use this energy in higher forms than heat, e.g., increased ionization and electrical conductivity. The key issue in obtaining the necessary performance in the MHD channel is the electrical conductivity of the mixture. This idea was proposed for the current program, and a simplified analysis was performed in Refs. 20 and 21. The results were very encouraging, predicting conductivities of close to 100 mho/m at 2500 K. Therefore, an experimental program was initiated to demonstrate and measure nuclear-enhanced electrical conductivities and MHD energy conversion at fluid temperatures less than 2500 K. A theoretical task was also initiated to develop physics models for the transport properties of fissioning plasmas at reactor conditions.

Nuclear experiments were performed at the Los Alamos National Laboratory's Godiva reactor. The experimental setup described in Ref. 22 was used to measure the conductivity of flowing helium at 2500 K with and without a neutron flux. To simulate fission fragments, ^{3}HE was substituted for ^{4}He during neutron irradiation. The ^{3}He(n,p)T reaction has a very large reaction cross section and produces charged particles with a total of 765 keV of kinetic energy. The resultant ionization characteristics approximate those expected in fission.

The key results of the experiments are shown in Figs. 9 and 10, from Ref. 22. Without the nuclear reactions, helium has a very low conductivity. Therefore, no voltage is expected to be measured across a test section. The lower trace in Fig. 9 shows that after an initial transient during which the plasma is being established using an electrical discharge arc, the measured voltage returns to its initial dc-offset value. During neutron irradiation, however, the upper trace shows that significant voltages are measured in the test section. The voltage

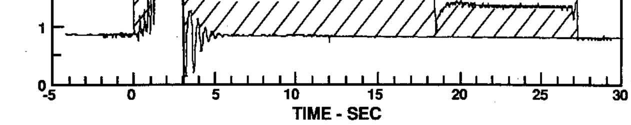

Fig. 9 Voltage measured across flowing helium (^{3}He + ^{4}He) plasmas at 2500 K with and without a neutron flux, demonstrating nuclear-enhanced electrical conductivity.

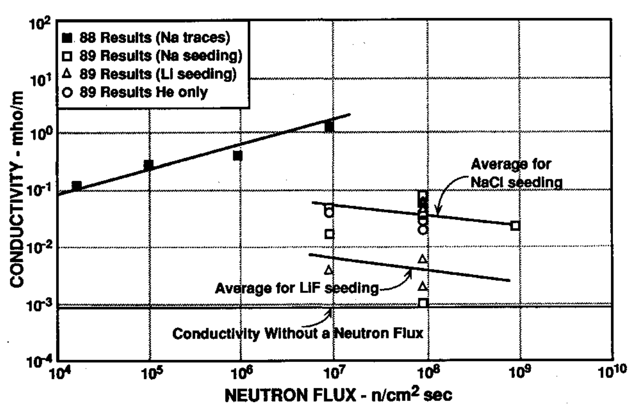

Fig. 10 Electrical conductivity of flowing helium (^{3}He + ^{4}He) plasmas at 2500 K measured as a function of neutron flux.

is measured because nuclear-enhanced ionization increased the plasma conductivity sufficiently to allow a current to flow through the plasma. The measured voltage corresponds to a conductivity of 0.1–1 mho/m for a helium plasma at 2500 K.

The dependence of the conductivity on neutron flux was measured in a series of experiments,[22] and is shown in Fig. 10. The figure shows that conductivities up to 1 mho/m can be obtained by way of nuclear ionization. The measured conductivity of a 2500 K helium plasma with nuclear-enhanced ionization is up to three orders of magnitude higher than without a neutron flux. Additional experiments are currently in progress at the University of Florida's Plasma Irradiation Facility to further quantify and characterize this effect.

To compute the electrical conductivity of UF_4/K/KF mixtures, theoretical physical and chemical models were developed, solving the rate equations for the 26 species (neutrals, positive and negative ions, and electrons) in such mixtures.[23] To bench mark the calculational procedure, a two-temperature model was developed for the conductivity of flowing ^{3}He plasmas seeded with Na and Cl atoms under neutron irradiation.[24] The latter chemical reaction model includes He, Na, Cl, He^+, He_2^+, Na^+, Cl^-, and metastable helium atoms and molecules. The model was applied in the analysis of past experiments which have used neutron irradiation to produce nonequilibrium ionization. The computational results are in good agreement with experimental results,[24] validating the approach. The full UF_4/K/KF model was then used to calculate the expected conductivity at reactor conditions. The results indicate that such mixtures could achieve a conductivity of 25–50 mho/m at 2500 K with the neutron flux of 10^{16} n/cm^{2}s expected in the MHD channel.

The models were also used to identify the mechanism for the enhanced conductivity. A group of nonMaxwellian subexcitation electrons were identified as the source of nonequilibrium effects in fissioning plasmas. These are electrons that have slowed below the excitation threshold of the bulk material, e.g., K/KF, but still possess sufficient energy to ionize the fuel material, i.e., the uranium atom. The result is that fissioning plasmas are "supercool." This refers to a lower temperature fissioning plasma which has the ionization equivalent of an equilibrium, thermally ionized plasma at a much higher temperature. This effect could provide a mechanism for lowering the required power input to thrusters, since the electrical energy previously required to ionize the plasma may now be provided by a fissioning source.

System Code Analysis

A system analysis code UTVRMHD, was developed for this power cycle.[25,26] This PC-based code calculates the system power output, specific mass, T-s diagram and thermodynamic state points, core neutronics performance, and other parameters of interest.

The user interface in the UTVRMHD code reflects the latest developments in interactive analysis. The code's calculations results are presented graphically on the screen, superimposed on a schematic of the system. This presents an immediate visual representation of the physical system. The code is highly flexible in allowing the user to change the values of many of the system parameters right on the screen with simple mouse or cursor movements. This allows the immediate evaluation of the effect of changes on all other system parameters. A screen display of the T-s diagram is included. Output can also be directed to disk or printers and plotters, including fluid properties, individual component masses, constants used in the models, etc., as text or parametric *x-y-p* curves. The *x, y,* and *p* are the independent, dependent, and parametric variables chosen on-screen from a large array containing most variables of interest.

The code contains detailed engineering and physics models for all the major components of the system as described in the preceding sections. These include 1) vapor-core criticality and neutronics based on one- and two-dimensional S_n transport calculations, including structural material penalties and temperature reactivity effects; 2) disk MHD performance based on analytical representations of the quasi-one-dimensional calculational model discussed above; 3) nozzle, diffuser, heat exchanger, and pump equations; 4) fluid properties based on curve-fits to JANAF-format data for the fuel and working fluids; and 5) mass estimates based on calculated and estimated component sizes and proposed materials.

The models were developed specifically for this code based on reports, published literature on the UTVR-MHD system, and classical derivations as applicable. The code construction is modular and allows substitution of alternate models for any component (source is available on request). The code will autoconfigure to most IBM-compatible personal computers (XT, AT, 386) with most monitors (B/W, CGA, EGA, VGA).

Conclusions

This article summarizes the conceptual design of a high-performance nuclear space power system based on the UTVR with MHD energy conversion. The point-design presented attempts to self-consistently satisfy the often conflicting requirements of nuclear, thermohydraulic, MHD, thermodynamic, material, and plasma physics requirements. The resultant design offers the potential for a low-specific mass (~1 kg/kWe) nuclear electric power system of 200 MWe, with downscaling to the hundred MWe range. Additionally, mission, design, and safety benefits derive from the use of vapor fuel, including shortened trip times, lower mass in orbit, high burn-ups, reactor reuse and refueling, and zero (0) criticality on launch.

In the present design, direct fission fragment ionization was seen to increase the electrical conductivity of a plasma by factors of 10–1000, allowing lower fluid temperatures in the MHD channel and thus relieving material demands, leading to a more attractive channel design. This use of energy in its highest form (i.e., without first converting it to heat) has the potential for significant payoffs in other applications, such as for direct ionization in MPD thrusters or ion engines.

Acknowledgments

This work was performed for the Strategic Defense Initiative Organization, Innovative Science and Technology Office under Contract NAS3-26314, managed by NASA's Lewis Research Center through INSPI, and the Frederick A. Hauck Fund at the University of Florida. Neutronics calculations were performed in part with the support of the National Science Foundation and the San Diego Supercomputer Center. The authors thank their colleagues in the Innovative Nuclear Space Power and Propulsion Institute (INSPI) for the supporting calculations and fruitful discussions.

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