Nuclear Activation Enhanced MHD and MPD Thruster

IEPC-2007-357

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Abstract

Radiation induced ionization enhances electric conductivity of the working fluid in Magnetohydrodynamic (MHD) generators and increases the electron temperature in the Magnetoplasmadynamic (MPD) thruster. The enhancement of the partially ionized plasma properties is well above what is obtained under equilibrium condition, which is dictated by pressure and temperature of the gas. The nonequilibrium enhancement of the conductivity is the key factor in achieving performance characteristics that are well above the state-of-the-art MHD generators or MPD thrusters. A fully integrated nuclear MHD-MPD electric propulsion system is proposed with potential to provide quantum improvement in the thrust level, specific impulse (I_{SP}) and efficiency of MHD power system as well as the MPD thruster. The proposed MHD-MPD electric propulsion system is intended to be used as an orbital transfer vehicle for multiple uses with a single propellant tank and potential for in-orbit replacement of the spent propellant tank. Due to similarity in design, the power generated by the MHD generator could be conditioned to directly drive the MPD thruster. This would eliminate or at least significantly reduce the need for the power management and conditioning system that is a major weight and size burden for all conventional high power electric propulsion systems. The coupled MHD-MPD system could also share the high field magnet and some other auxiliary systems to further reduce the overall weight, size, and complexity of the new reusable orbital transfer vehicle. The key innovation in the proposed idea is the coupling between nuclear powered MHD and radiation enhanced MPD thruster. The coupled MHD-MPD system function as a transformer with high mass flow rate and relatively low velocity on the primary (MHD) side and low mass flow rate and extremely high velocity on the secondary (MPD) side.

I. Introduction

The paper describes the basic design and performance characteristics of nuclear enhanced magnetohydrodynamic (MHD) electric power generation and magnetoplasmadynamic (MPD) thruster systems. Due to similarity between the physical processes governing the operation of these devices, the primary focus of discussion in this paper is on the nuclear powered MHD design that will produce results that are directly applicable to MPD thrusters. The priority given to nuclear powered MHD is due to higher complexity of the power generation system without it, the operation of Kilo Newton level thruster system is a moot point.

The nuclear powered magnetohydrodynamic (MHD) generator system is designed to achieve overall cycle conversion efficiencies in excess of 50% (~ 30% efficiency of the stand alone MHD conversion cycle) at temperatures well within the limits of existing materials. The quantum leap in performance characteristics of the nuclear MHD system is achieved by fully utilizing the thermal, ionizing, and the activating power of the fission energy. A review of the nuclear properties of rubidium has revealed unique characteristics that would allow for MHD power conversion at temperatures that have not been possible in the past. A naturally abundant (27.83%) isotope of Rubidium, ^{87}Rb, absorb neutrons with reasonable cross-section (σ_{th} = 0.12 b, and resonance integral = 1.9 b) and is transmuted into a radioactive β^- emitter ^{88}Rb. The half-life of ^{88}Rb is 17.8 minutes and the average β^- particle energy per disintegration is 2.06 MeV. This average β^- particle energy is at least four times larger than the average β^- emission energy of any other activated liquid metals. The high rate and energy of β^- emission provides an increase of several orders of magnitude in the electron mobility and overall electric conductivity of the rubidium vapor. Furthermore, the relatively high activity and short half-life of ^{88}Rb would perfectly match the β^- emission rate and the reactor core-to-MHD duct transport time that are needed for achieving very high enthalpy extraction and conversion efficiency, enabling MHD conversion even at uncharacteristically low temperatures of less than 1000 K.

Due to very high electron mobility in ^{88}Rb vapor, the proposed Nuclear activated MHD system could be operated using natural rubidium (~ 28% ^{87}Rb and 72% ^{85}Rb) or 100% enriched ^{87}Rb. Activation of ^{85}Rb generates ^{86}Rb, a radioisotope, emitting β particles with average of 1.23 MeV per disintegration and half-life of 18.63 days. Though the added electron mobility due to activation of ^{85}Rb is significant by itself, it is still very insignificant compare with the activation of ^{87}Rb. Preliminary calculations have shown that even with concentration of only 10% ^{87}Rb, the nuclear activated MHD could be operated at temperatures as low as 700 K at low backend pressure of the MHD generator. This would allow operating the nuclear activated system with natural rubidium, enriched rubidium, or with a mixture of about 10% ^{87}Rb and another alkali metal such as sodium, potassium, or cesium. Obviously, the absolute maximum performance (high power density,

low weight, compactness, low working flow rate per KWe, and high conversion efficiency) is achieved when 100% enriched ^{87}Rb is used.

II. Nuclear Enhanced MHD System

As space reactor coolant and MHD working fluid, rubidium possesses excellent thermodynamics and electrodynamics properties. The density of liquid-phase rubidium is very low (~ 1.15 g/cm^3), it melts at close to room temperature (312 K) and boils at fairly low temperature (640K at .01 bar and 959 K at 1 bar). The ionization energy of rubidium is 4.18 eV, which, after cesium, is the second lowest among all elements in the nature. The unique nuclear activation and radiation emission characteristics of rubidium enhance the MHD conversion properties of this element.

The key characteristic of nuclear activated rubidium that is pivotal to efficient and compact nuclear MHD power conversion can be summarized as follows: At about 50% of the equilibrium activity condition that is achieved about 18 minutes (one half-life), the ratio of activated rubidium (^{88}Rb) to non-activated rubidium is more than 10^{-7}. Decay of the ^{88}Rb nucleus yields more than 2 MeV of β^- particles (corresponding to electron temperature of about 2.3×10^{10} K – 230 trillion Kelvin). With this quantum jump in the average energy of electrons, the non-equilibrium electric conductivity of the rubidium vapor is estimated to be in excess of 10 mho/m at 800 K and 0.1 bar. This would allow for efficient and compact enthalpy extraction in the MHD channel at temperatures in the range of 1000 – 2000 K.

In a self field MPD thruster, the arc current created between a central cathode and an annular peripheral anode ionizes the propellant and induces an azimuthal magnetic field. In a manner somewhat reminiscent of dense plasma focus devices, the generated J × B Lorentz body force compresses and accelerates partially ionized plasma along the central axis. Because the self-induced magnetic field is only significant at very high power, low power MPD thrusters often resort to an externally applied magnetic field in order to enhance the acceleration process. MPD thrusters may operate in steady state mode or in pulsed, quasi-steady mode. The latter strategy is aimed at improving their efficiency via an increase of the instantaneous operating power, while keeping an average power requirement consistent with conventional spacecraft capabilities.

The great scalability of MPD thrusters allows them to cover an impressive range of operating parameters: from a few kW to several MW of power, from a few mN to several hundred N of thrust and from 1000 s to 10000 s of specific impulse. MPD thrusters, in particular self-field thrusters, are most efficient at high power and have been demonstrated to perform at up to 65% efficiency. The nonequilibrium ionization induced by the nuclear field from the primary MHD power system is expected to enhance the electron temperature in the MPD plasma. Preliminary analysis has shown that the nonequilibrium increase of the

electron temperature in the MPD system could reduce nonisentropic losses, thereby increasing the thruster efficiency by 10 to 20%.

Nuclear-based MHD energy conversion and MPD propulsion has been pursued in various forms since the 1950's. The majority of this work focussed on the compatibility of MHD generators and MPD thrusters with the high temperatures achievable with nuclear reactors and the related potential for very high cycle efficiency. From this perspective traditional thermal ionization processes, often referred to as equilibrium ionization, were typically employed for electrical conductivity enhancement. However, thermal conductivity enhancement has several significant drawbacks including the need for an ionizing seed, typically an alkali metal, and a thermally imposed limit on power density. To avoid these potential limitations, various non-thermal, or non-equilibrium, ionization sources have been considered.

One promising technique is the utilization of energy released in nuclear interactions to enhance the electric conductivity of the working fluid. Specifically, the kinetic energy liberated in interactions between reactor neutrons and isotopes with a large neutron interaction cross-section is used to ionize the surrounding gas via collisions. Some examples of potentially promising interactions include ^{3}He(n,p)^{3}H (760 keV), ^{10}B(n,α)^{7}Li (2.3 MeV), ^{6}Li(n,α)^{3}He (4.78 MeV), and the fissioning of ^{235}U (~200 MeV). The most promising interaction among this group of neutron induced reactions is the fissioning of ^{235}U that produces the maximum energy and additional neutrons that would be needed to maintain the chain reaction. A number of gas and vapor fueled reactors have been proposed to take the advantage of fission enhancement of electric conductivity that is a prerequisite for MHD conversion at low enough temperature for which containment materials are available. Though there is no question about the great potential of gas and vapor core reactors with MHD generator for low specific mass space power production, there are some technology challenges that could not be surmounted for near term space power needs. The ^{87}Rb based nuclear MHD concept possesses the right characteristics and design features that are needed to make the space nuclear MHD a realizable technology for very near term space missions with power needs in the range of 30-200 kWe and for multiMWe-unit size for the fra out future applications

The activated rubidium MHD power conversion cycle is coupled to a cermet fuel nuclear reactor. Preliminary analysis indicates that the activated rubidium nuclear powered MHD could be used as a stand alone power cycle with efficiencies of 30% or higher and heat rejection temperatures above 1000 K. This is the simplest design option for any power level, granted light radiator materials could be found for heat rejection at such high temperatures. In a more efficient cycle, the rejected heat from the direct MHD power cycle is then used to drive a Brayton gas turbine cycle that uses a mixture of helium and a heavy inert gas (xenon) as the working fluid to generate electricity in a cycle that operates between 1000 and 500 K. The overall ideal efficiency of this combined cycle is

over 50% and the heat rejection temperature is about half of the direct MHD cycle. This value for the efficiency is based upon the fact that significant enhancement of the electrical conductivity of rubidium vapor can be engineered by utilizing the non-equilibrium ionization by [88]Rb decay products. The schematic of the combined MHD-Brayton power cycle is shown in Figure 1.
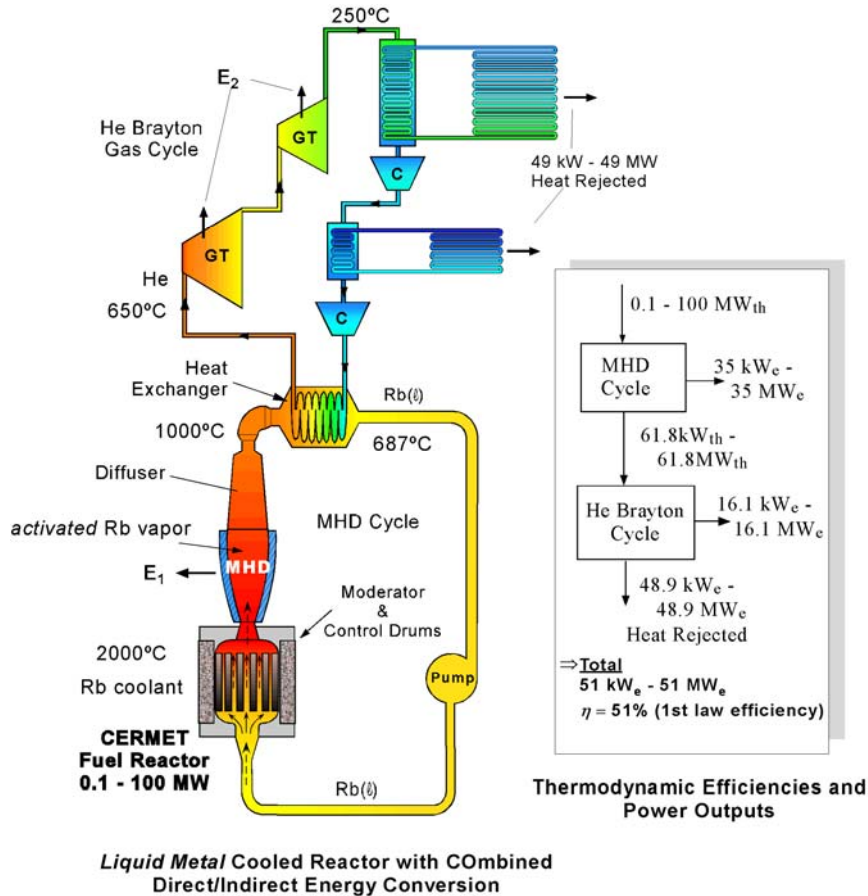

Figure 1. Combined Activated Rubidium MHD and Brayton Power Cycle

III. MHD Power Conversion and MPD Thruster

A nuclear-driven MHD generator operates on the principle that energy released in the reactor can be directly converted into electricity by applying a strong magnetic field transversely across a channel fast flowing ionized gas. The basic principle is illustrated pictorially in Figure 2. In a self field MPD thruster, the arc current created between a central cathode and an annular peripheral anode ionizes the propellant and induces an azimuthal magnetic field. In a manner somewhat reminiscent of dense plasma focus devices, the generated J × B Lorentz body force compresses and accelerates the partially ionized plasma along the central axis. In both nuclear enhanced MHD and MPD, the ionization

induced by the radiation field increases the electron temperature by releasing very large number of high energy electrons.
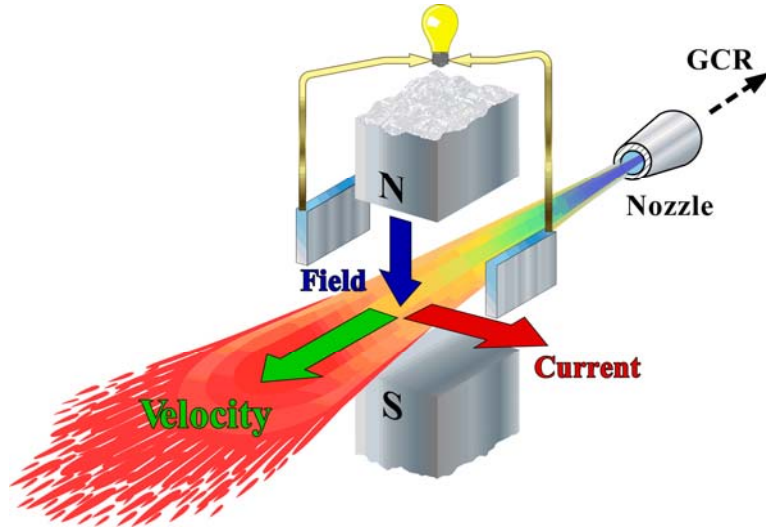

Figure 2. Schematics of MHD power conversion process.

The flow with scalar conductivity σ, consists of a population of free electrons, ions and neutral species with a bulk velocity, **u**. As the flow passes through a magnetic induction field **B**, the components of the field perpendicular to the velocity vector induce a Lorentz force acting on the free charges. This force acts perpendicularly to both the velocity vector and the magnetic field. The negative ions and electrons move in the opposite direction of the positive ions, producing an electric field **E**, and associated current **j**, parallel to the Lorentz force. This electric field induces a potential on the electrode plates and drives a current through a load. From the generalized form of Ohm's Law, the power density of the ideal generator can be expressed as:

$$P = K(1 - K)\sigma u^2 B^2 \qquad\qquad (1)$$

where the velocity and magnetic induction vectors are assumed perpendicular. The term K is a non-dimensional parameter called the loading parameter defined as the ratio of the load resistance to the sum of the load resistance and the internal resistance. For the case of the ideal generator, the loading parameter is $K=uB/E$.

The magnetic field interacts with the current induced in the channel to produce a **j**×**B** force in the opposite direction of the flow. This opposing **j**×**B** force only acts directly on the charges in the flow. This interaction is called the Hall effect and its significance is measured by the Hall parameter defined as the product of the cyclotron frequency, ω, and the mean time between collisions, τ. The Hall parameter in real MHD generators is typically 0.2 to 5.0. The Hall parameter is

also a measure of the strength of the MHD interaction where $\omega\tau < 1$ is generally considered a weak interaction and $\omega\tau > 1$ is considered a strong interaction. It should also be noted that for most MHD flows, the magnetic Reynolds number, a measure of the relative effect of the motion of the ionized flow on the applied field, is not greater than unity. Hence, the magnetic field induced by the gas motion can usually be neglected.

The energy of the bulk flow is only accessible to the MHD generator by the interaction of the charge carriers with the neutral background molecules via collisions. The bulk flow is retarded by the Hall effect via collisions of the neutral molecules with the charged particles. Or another way of considering the interaction is to say that the energy of the bulk neutral flow is made available to the generator via collisions with the charge carriers. In order to maximize the accessibility of the energy of the flow, the ion-neutral collisions must be sufficient to prevent the ions from slipping relative to the flow. In real fluid MHD flows, there is always some degree of ion slip that reduces the overall generator efficiency. In principle, the magnetic field strength could be increased to the point that the charges are brought to rest. Any further increase in the magnetic field would have no effect on the power output of the channel for a given set of flow conditions.

For the case of the ideal generator, the ion slip is neglected which corresponds to the maximum power extraction possible for given flow conditions and magnetic field. In all cases, a fraction of the power in the flow, called the "push power," must be used to overcome the retarding force due to the Hall effect. The local electrical efficiency, η_e, of the generator is defined as the ratio of the output power density to the push power density and, for the ideal generator can be shown to be equivalent to the loading parameter K,

$$\eta_e \equiv \frac{P}{P_{push}} = K \qquad (2)$$

As can be seen from these governing equations, the electrical conductivity, flow velocity, and applied magnetic field strength are very significant. Typically, the energy in the flow originates as thermal energy from a heat source such as fossil fuel combustion or a nuclear reactor. Most concepts for MHD power generation follow either a Brayton or Rankine cycle. For space applications, the Rankine cycle is preferred if the right working fluid could be identified. The thermal energy is converted to kinetic energy as the flow accelerates through the nozzle. The flow kinetic energy is then converted to electrical energy in the MHD channel via the Lorentz force while the $\mathbf{j}\times\mathbf{B}$ force decelerates the flow via collisions. The energy extracted per unit flow is equal to the difference in enthalpy at the entrance and exit of the channel. Although not explicit in the expression for power density, the flow fluid dynamics and thermodynamics are implicit in the flow velocity.

IV. Nuclear Enhanced Conductivity

The electrical conductivity of the flow is very important for the effectiveness of the MHD conversion process. In particular, for space power applications, the power density in the MHD channel is directly proportional to the value of electric conductivity. The conductivity is physically the ability of the free electrons and ions to move within a medium. In most cases, the motion of electrons dominates the conductivity and the ion motion can be neglected. The units of conductivity are the inverse of resistivity and usually expressed as 1/ m or mho/m although the SI unit siemens is also used in place of the mho (1 mho = $1/\Omega$ =1 siemens). As a rule of thumb, the electrical conductivity must be greater than10 mho/m to be useful for MHD energy conversion with exceptions to this rule easily found in the literature. In a weakly ionized gas such as the case for most MHD generator concepts, the neutral population far outnumbers the electron and ion population, usually by a factor of 10^4 to 10^8. Therefore neutral-ion collision processes dominate the physics of the gas.

In the majority of MHD systems considered to date, the conductivity of the MHD fluid is dependent upon thermal ionization processes governed by Saha's equation. Saha's equation describes the equilibrium population of free electrons and ions in a gas originating from thermal ionization processes as a function of temperature. Following Saha's equation, there is a continuous generation and recombination of free charges in a gas in thermal equilibrium. Under standard temperature and pressure conditions, argon with an ionization potential of 15.7 eV has an equilibrium ionization fraction on the order of 10^{-132} according to Saha's equation, which is effectively zero. However, if the temperature is increased to 9000 K, the equilibrium ionization fraction is 3×10^{-5} and the conductivity is 100 mho/m, which is ideal for MHD flows. However, even if the MHD system could be operated at such extreme temperatures, the conductivity of the argon gas drops below 1 mho/m at temperatures less 6000 K. To achieve the desired mass and size, low values of electrical conductivity must be compensated by high applied magnetic field or gas velocity. In order to reduce the operating temperature to a more practical level, a seed species with a lower ionization potential must be added to the flow to make use of thermal ionization processes. Examples of common seeds and their respective ionization potentials are cesium (3.89 eV), rubidium (4.18 eV), potassium (4.34 eV), and sodium (5.14 eV).

In seeded flows, the ionization fraction of the bulk gas species can be assumed negligible and the conductivity is attributed entirely to the seed species ionization. Adding 0.1% cesium to argon at 1 atm reduces the temperature necessary to achieve 1 mho/m to less than 2500 K. Though still high, 2500 K is much more practical so MHD generators using thermal ionization processes almost universally consider alkali metal seeded flow. For space power applications, there are two other major issues with the thermal ionization MHD. First, even a conductivity of 1 mho/m is at least one order of magnitude less than what is

needed to meet the size and weight requirements for these systems. Second, due to high flow velocity requirement, MHD is a high-pressure ratio power conversion device. For space applications, a closed gas turbine (Brayton) cycle with MHD would yield very low work ratio and low overall efficiency due to high power demand by compressor.

A detailed Monte Carlo model is developed to predict the activation level of rubidium-87 in the neutron field of the fast spectrum fission power system. Results of analysis indicate that for a 50 megawatt class propulsion system, the activity of the rubidium working fluid could reach asymptotic value of 7×10^9 energetic electron (β particles) emissions per gram. The average energy of emitted electrons is 2,072 KeV. This non-equilibrium release of super-energetic electrons results in enhancement of the electrical conductivity of the rubidium vapor by several order of magnitude at temperatures between 700 – 2500K and pressures up to 1 MPa.

A 50 MW fission system is used to calculate the activity of the rubidium working fluid. The average neutron flux in the system is 2.5×10^{14} per cm^2.sec. The average resident time for the working fluid in the fission systems and in the MHD power conversion system is 5 and 60 seconds, respectively. Figure 3 shows the growth of highly active rubidium-88 ($T_{1/2}$ = 17.8 minutes) and the β particles emission rate as a function of working fluid (rubidium-87) recirculation in the power system side.
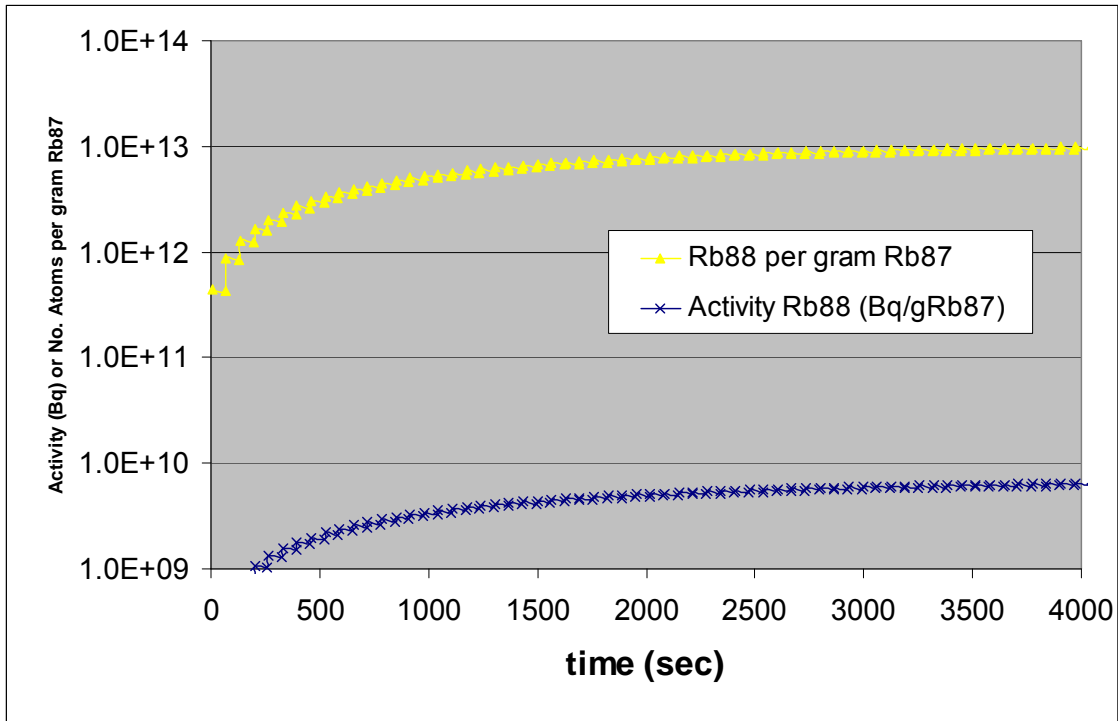

Figure 3. Equilibrium activity and concentration of β emitting rubidium-88 per gram of circulating rubidium-87.coolant/working fluid.

By eliminating the dependence of the electrical conductivity on rubidium vapor temperature, the range of application for nuclear activated MHD cycles is dramatically increased. Due to the temperature-independent nature of the electrical conductivity in this concept, much higher power density, and hence smaller scale, is achievable. Also, cycles operating at lower ultimate temperature are feasible, making low power MHD cycles more practical. With the same technology, very high temperature, highly efficient cycles are also possible for large-scale power production. The nuclear activated MHD cycle could be used as a stand-alone cycle or as a topping cycle in addition to indirect conventional Brayton or Rankine cycles. Previous investigations of MHD topping cycles suggest total system efficiency as high as 70% is achievable, about twice as large as those of conventional nuclear power plant systems. At this level of performance, in addition to space power potential applications of nuclear activated MHD include high-capacity commercial power production, compact power sources for remote locations including Mars and Moon surface, and naval ship power.

Variations also exist for the MHD generator. Although Figure 2 illustrates the basic idea of MHD power conversion, the normal Faraday current perpendicular to both the bulk gas velocity and the applied magnetic field is dominant only for subsonic fluid flow or moderate magnetic induction field. When the Hall parameter $\omega_e \tau_e$, the product of the cyclotron frequency ($\omega_e = eB/m_e$) and the collision mean free time ($\tau_e = 1/nQ\,v_e$), becomes much larger than unity then a Hall current dominates, in the conventional sense exactly opposite to the bulk gas velocity, and in this case it is then more favorable to short circuit the Faraday current and draw off the voltage by placing the load across the ends (outlet and inlet) of the MHD generator duct. This is effectively how a disk MHD generator operates. Figure 4 shows a conceptualized rubidium cooled cermet fuel reactor with disk MHD generator.

Though the linear MHD generator is simpler in design and implementation, there may be advantages in disk-type generators, particularly where gas conductivity depends sensitively upon the length of the channel. The longer the channel the more dramatic is the loss in conductivity near the exit, and the lower the overall power density. It may be that a disk MHD vortex flow can achieve high power density while taking advantage of the reactor radiation field in addition to neutron activation of the rubidium working fluid, to a greater extent than the linear MHD ducts (for the latter the flow directs the gas entirely away from the high radiation field region of the reactor, whereas the former disk vortex flow remains longer in the central region).

In Figure 5, the local electrical energy conversion efficiency is plotted as a function of disk MHD swirl number and Hall parameter; we can see how effectively the ideal MHD generator can perform when driven with a fairly strong magnetic field. The local electrical efficiency is defined as the ratio of the electrical power output from the working gas = |**j·B**|, to the electromotive power
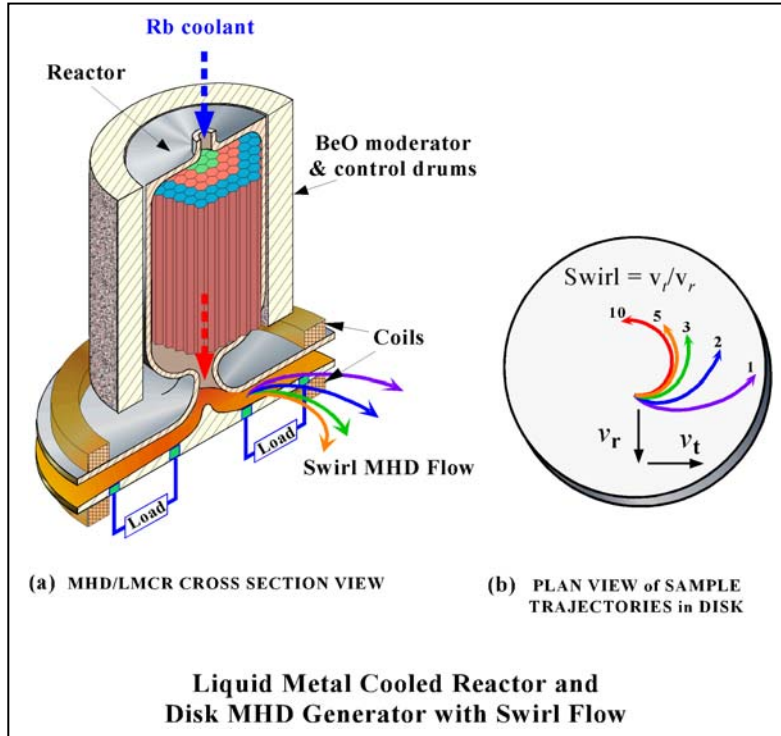
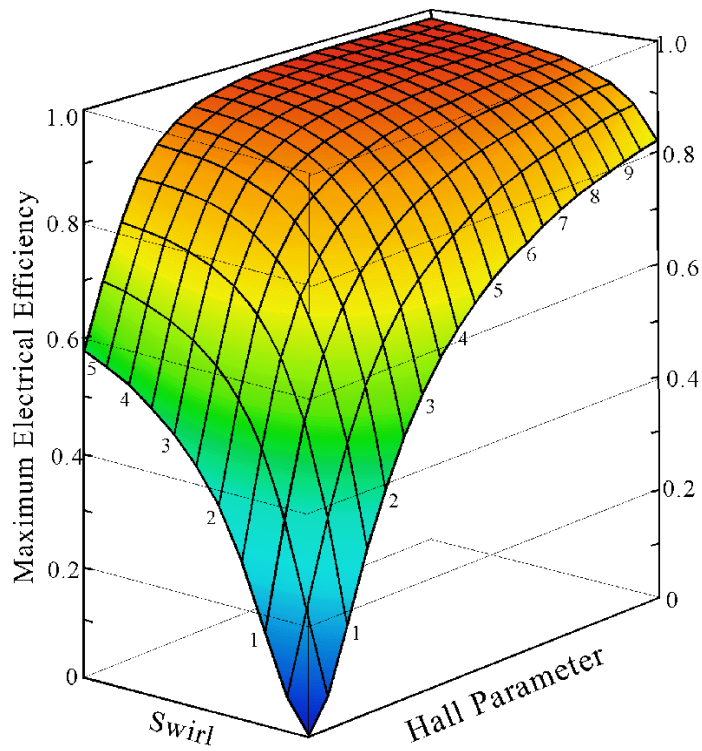Figure 4. Activated Rubidium Cooled Reactor and Disk MHD with swirl flow

Figure 5. A 3-D plot showing the maximum electrical efficiency as a function of swirl and the Hall parameter.

that is required by the gas to "push" through the magnetic field $= |\mathbf{u \cdot jxB}|$. It thus expresses the fraction of work converted into useful electrical power done by the gas in pushing through the electromagnetic fields across the duct.

V. Materials Selection

A key design issue is materials selection for the reactor and MHD generator. A survey of possible materials for use in the reactor and MHD power conversion system was conducted. Ceramics have found application in MHD for electrodes in the MHD channel including graphite, ZrB_2, SiC and others. These have been preferred over metal electrodes due to need for electrode cooling and problems encountered with discharge and arcing. Problems with the ceramics appear to be an increase in Joule losses in the electrodes due to temperature gradients that develop away from the channel (Libowitz, 1979).

The lower temperatures enabled by the rubidium enhanced system means that metals for structural materials in the reactor and MHD channel as well as perhaps electrodes may be considered. A number of higher alloy ferritic-martensitic steels some of which are under consideration or active research and development for advanced gas-cooled reactors (GCR) are promising candidates (Corwin, 2004). These materials under consideration for the GCR reactor pressure vessel are required to withstand temperatures as high as 1100°C in transient conditions. It is acknowledged that in some cases insulating materials may be required where considered where the temperatures clearly exceed the service temperature of these advanced alloys. However, their potential for improved creep strength at high temperature places them in the running for consideration in the reactor and MHD channel applications for the space reactor system under investigation.

The more well characterized of these alloys such as HT9 (12Cr-1MoWV) generally have poorer properties and might only be considered for the lowest temperature range below 850°C. Those with more potential for very high temperature applications include 9Cr-1MoVNb class of alloys however the database is less well developed. Like its terrestrial counterpart in advanced nuclear reactors, the long lead time for implementation with these materials makes the consideration of these advanced alloys tenable and points to the need for additional research into these advanced materials.

Further, an unknown for most of these advanced alloys is their behavior under irradiation. The better characterized class of 2 1/4Cr-1Mo steels has been ruled out due to low tolerance under irradiation. Its use is only considered in gas-cooled reactors if shielding materials are added such as tungsten.

Still if refractory alloys must be considered because of issues of high temperature creep strength or as a requirement for shielding of the advanced alloys mentioned earlier, a number of tungsten and molybdenum based alloys have

been proposed for vapor core nuclear reactors. These include molybdenum and tungsten and alloys such as TZM (Mo with 0.5% Ti, 0.08% Zr, 0.01 – 0.04% C). While molybdenum has a melting point of just under 2900 K, it undergoes excessive grain growth above about 1900 K resulting in a marked decrease in strength. This grain growth can be inhibited by the addition of obstacles such as finely dispersed particles. This method is used in the TZM alloy, which is the preferred material up to 1700 K. Above this temperature, molybdenum doped with potassium silicate is preferred. Doped molybdenum is cold worked in a single direction to produce a material that has a much lower creep rate but retains most of its ductility. However, because of the large degree of cold working that is necessary, parts only up to 0.2 cm in thickness can be produced at present. Because of its improved properties it is preferred for applications up to 2100 K. Tungsten, because of its high melting point and the fact that it retains much of its strength at high temperature, is preferred for temperatures exceeding 2100 K (Plansee, 1994). The tensile strength of several molybdenum and tungsten alloys is shown in Figure 6.
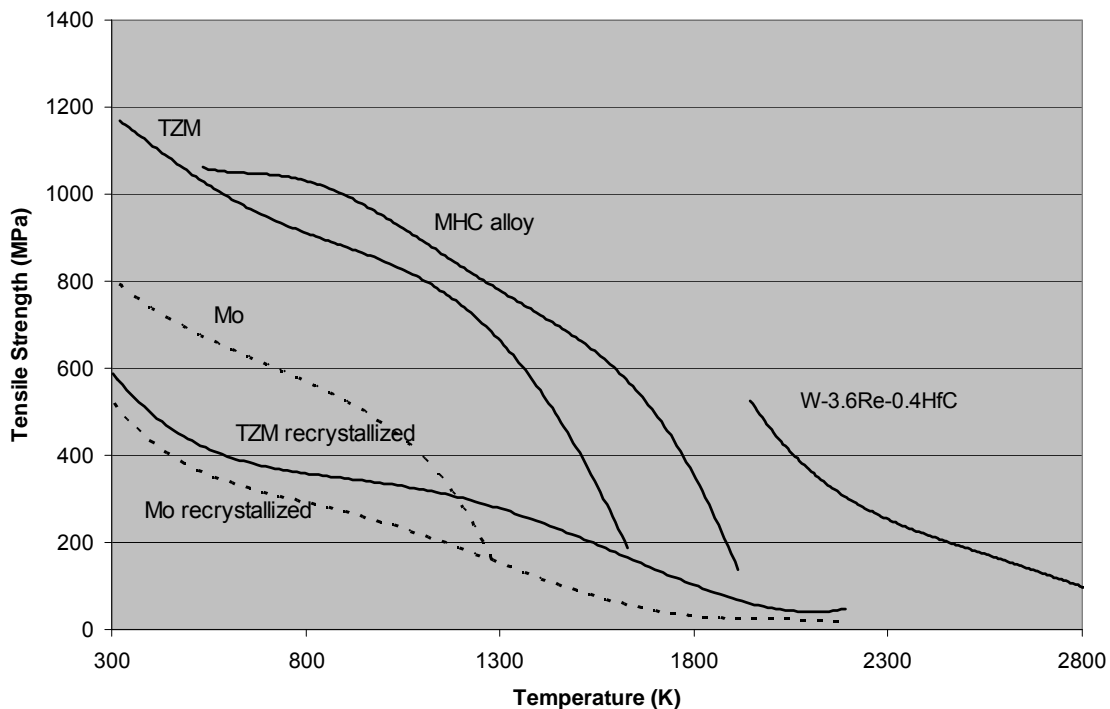

FIGURE 6. Tensile strength of several molybdenum and tungsten based alloys. MHC alloy after Shields (1999), W-3.6Re-0.4HfC after Chen (1989), remainder after Plansee (1994).

Based on neutronics criteria, molybdenum and its alloys are preferred over tungsten because of their lower thermal neutron cross section. Still, a maximum thickness of about 0.25 cm can be tolerated for molybdenum-based alloys in order to maintain the reactor in a critical condition as shown in Figure 7. As

noted above the thickness of these advanced alloys is limited in manufacture to approximately this same thickness. Therefore these advanced refractory alloys are most likely useful as a liner to be used along with other high temperature materials such as the advanced steel alloys discussed above along with any requisite wall cooling.
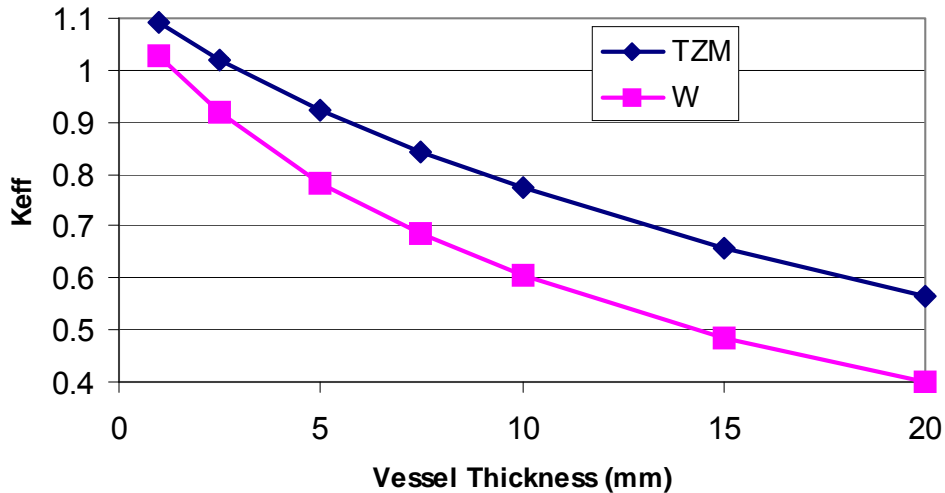

FIGURE 7. Variation of vapor core reactor keff with W or TZM pressure vessel thickness. Reactor core L/D=1, 8m^3, 8 MPa

VI. Chemical Compatibility with Rubidium

Stainless steels have long been studied for their compatibility with alkali metals particularly sodium and potassium for application in liquid metal reactors (Draley, 1970). These have been limited to temperatures around 873 K (Borgstedt, 1973). Higher temperatures up to 973 K of sodium with advanced Ti stabilized stainless steel have been studied recently with good results (Borgstedt, 2003). Studies involving mechanically alloyed (MA)-oxide dispersion strengthened (ODS) steels have been evaluated as a possible alternative to refractory metal alloys. Still these evaluations have been limited to temperatures up to 1100 K (El-Genk, 2005).

While rubidium is more reactive than either sodium or potassium its compatibility with many of the aforementioned alloys is worth testing to evaluate their chemical compatibility as well as resistance to creep at high temperatures. Some lower temperature studies with rubidium have been conducted on stainless steel (Borgstedt, 1983).

Other studies involving alkali metals and their chemical compatibility have included studies for space reactor fuel claddings (Adamson, 1984). Higher

temperatures using refractory metals have been investigated for heat pipe systems with some studies at temperatures as high as 1800 K (Tower, 1978; Razzaque, 1990). Of the studies with low alloy ferritic steels, these have been limited to temperatures typically less than 873 K (Tu, 1999).

Finally it is worth noting that limited studies have been carried out on the compatibility of certain plastics and elastomers with rubidium (Rosenblum, 1962). These were conducted at low temperatures generally less than 450 K. This and similar data on compatibility with a broader array of materials could prove useful in the design of the backend systems required in handling the working fluid and the seed material.

VII.   Conclusions

A new concept is presented for compact space power using activated rubidium MHD power conversion cycle coupled to a cermet fuel nuclear reactor. Nuclear activation of rubidium working fluid enhances the electric conductivity enabling power conversion at significantly lower temperatures that what is achieved at conventional MHD systems. Cermet fuels envisioned for the reactor include uranium dioxide, uranium nitride, or uranium carbo-nitride particles coated and dispersed in a refractory alloy matrix. The choice of refractory alloy is dictated by the maximum operational temperature of the rubidium activated MHD generator. The baseline fuel design is uranium dioxide coated with Nb-Zr alloy that would allow operation at the maximum cycle temperature of about $1,700^0$C. temperatures in influenced by the ma and in refractory al Preliminary analysis indicates that the activated rubidium nuclear powered MHD could be used as a stand alone power cycle with efficiencies of 30% or higher and heat rejection temperatures above 1000 K. This is the simplest design option for any power level, granted light weight and durable radiator materials could be found for heat rejection at temperatures above 1000 K.

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