Final Report – Part I

Direct Energy Conversion Fission Reactor

Gaseous Core Reactor with Magnetohydrodynamic (MHD) Generator

University of Florida NERI-DEC Project

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I. Introduction

This report focuses on the power conversion cycle and efficiency. The technical issues involving the ionization mechanisms, the power management and distribution and radiation shielding and safety will be discussed in future reports.

1.1. Design Options—The Reactor System

The reactor system that preliminary investigation has shown to be highly promising in terms of fuel utilization and fission energy conversion efficiency is of the type illustrated in Figure 1. This shows a disk MHD generator coupled to a vapor or gas core reactor. Most variations of the MHD channel are fully compatible with the modeling results and analysis of MHD generator-based power cycles discussed in this report.

Fission fragment interactions in the gas core and MHD duct region are expected to produce significant ionization, including about 10^5 electrons per fragment. The high pressure in the core is then released through a nozzle in order to accelerate the fissioning gas to high velocity at the MHD generator inlet. Thus the gas core functions as heat generator, ionizing radiation source and accelerant all in one.

Figure 1. Schematic view of a section of a generic gas core/vapor core reactor with a disk MHD generator outflow.

1.2. MHD Power Conversion

A nuclear-driven MHD generator has been chosen as the preferred device for direct energy conversion in concert with the GCR heat source. The MHD generator operates on the principle that energy released in a fissioning gas can be directly converted into

electricity by applying a strong magnetic field transversely across a channel fast flowing ionized gas.

Variations exist for the MHD generator although the design of the MHD generator is an important aspect of the proposed power cycle that has not been optimized yet. This is due in part to the absence of sufficient data that would enable a confident assessment of the relative merits of the various MHD generator device options. Of particular concern is the detail of the gas kinetics and ionization, since this feeds into the calculation of the electrical conductivity and hence the power conversion efficiency. In 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 $b = \omega t$, the product of the cyclotron frequency ($\omega = eB/m_e$) and the collision mean free time ($t = 1/nQ v_e$), 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 favourable 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, and a linear duct generator can be configured to operate as a Hall device. The models described in this report assume a Hall MHD generator configuration unless otherwise indicated.

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 neutron radiation field of the gas core to a greater extent than the linear MHD ducts (for the latter the flow directs the gas entirely away from the high neutron flux region, whereas the former disk vortex flow remains longer in the central region).

Referring to Figure 2 where 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 $= |\mathbf{j} \cdot \mathbf{B}|$, to the electromotive power that is required by the gas to “push” through the magnetic field $= |\mathbf{u} \cdot \mathbf{j} \times \mathbf{B}|$. 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.

Figure 2. 3-D plot showing the maximum electrical efficiency as a function of swirl, where the swirl number = (tangential velocity)/(radial velocity), and the Hall parameter.

1.3. Design Optimization

So far it has been possible to model a combined power cycle, consisting of an MHD topping cycle, rejecting heat to a Gas Brayton Cycle, which in turn supplies heat that can be recovered to drive a bottoming superheated Rankine cycle.

One of the key problems in the cascading power cycle model is the MHD topping cycle low thermal efficiency. It is frustrating to analyze a conceptually appealing direct energy conversion technology that only manages less than 19% first law efficiency. In the present design case studies the main crippling factor comes from the high power input demand from the MHD leg helium compressor. In order to purify the fuel, the uranium tetrafluoride needs to be separated from the helium working fluid, and the best method is to condense the UF_4 , to allow the cyclone separator to function. But that means that the helium is compressed as a separate stream, and places a huge power demand upon the cycle balance. One option to alleviate this is to lower the MHD leg minimum temperature at the helium compressor inlet. But the Brayton cycle is almost optimized and cannot accept unlimited waste heat at low temperature. However, supposing only that some extra heat is dumped before the helium compressor, then the following combined cycle outputs could typically be obtained, tabulated in Table 1.

Table 1. Output Sample for GCR-MHD Combined Cycle with extra waste heat rejection.

1.3.1.1 MHD Subcycle				
Thermal Power	1340 MWth		Mass Flow	313 kg s ⁻¹
MHD Power	-522 MWe		UF4 mole fraction	0.05
He-Compressor	185 MWe		Work ratio	0.63
UF4 Pump	40 KWe		h Carnot	0.6
MHD Subcycle Power	333 MWe		Efficiency ₁	0.11
1.3.1.2 Brayton Gas Subcycle				
Heat In	546 MWth		Mass Flow	137 kg s ⁻¹
Gas Turbine Power	378 MWe		Work ratio	0.48
Compressor Power	195 MWe		h Carnot	0.6
Brayton Net Power	184 MWe		Efficiency ₁	0.33
1.3.1.3 Superheat Rankine Subcycle				
Heat In	362 MWth		Mass Flow	114 kg s ⁻¹
ST Turbine Power	132 MWe		Work ratio	0.61
Pump Power	1.1 MWe		h Carnot	0.58
Rankine Net Power	131 MWe		Efficiency ₁	0.36
Net Combined Power		648 MWe	Efficiency	
			0.48	

So we can see that with extra waste heat rejection the overall cycle efficiency is reduced to 48%, significantly below the previously thought highest benchmark possible of 70%.

The above outputs were obtained with input parameters similar to those quoted in Table 2 below. In addition, a fraction of just under half the GCR thermal power is used to preheat the re-entry helium stream, which also doubles as a wall-cooling stream for the gas core. There are design improvements in the wall cooling and such like that may lead to better use of the reactor power. There may also be ways to alter the heat exchanger configurations or balances to achieve greater overall efficiency, but the calculations require some care because of the sensitivities and feedbacks at various parts of the connected components of the three subcycles.

Further modifications to the combined cycle are being considered. Options include running some of the heat from the MHD cycle to the Rankine cycle, possibly to preheat a greater water mass flow, or to drive a low pressure steam turbine. Other things requiring attention are the details of the MHD channel geometry. The optimum MHD parameters have not yet been determined. It is also possible that a realistic MHD generator will result in further reduced overall efficiency, but we need to wait for more data to confirm. The hope is that a detailed modeling of the reactor neutronics and the MHD gas kinetics will result in closer to 70% overall efficiency for a 1000 MWe plant.

The remainder of this report is an appendix that describes some of the modeling processes in brief. Most of this was set out in a previous project report, and is reproduced here for completeness.

2. II. Appendix: The Coupled GCR-MHD Model

The single most distinguishing feature of gas/vapor core class reactors is that the reactor outlet temperature is not constrained by solid fuel-cladding temperature limitations. It combines the functions of fuel and coolant into one. Therefore, VCRs can potentially provide the highest reactor and cycle temperatures among all existing or currently proposed fission reactor power plant designs. With MHD power conversion replacing conventional gas turbine power generation the GCR-MHD concept inherits these three very powerful features, volumetric energy conversion, fission enhanced conductivity, and high Carnot efficiency.

In a uranium tetrafluoride (UF_4) fueled system with He working fluid a closed MHD power generation cycle is used to directly process and convert the fission power between temperatures of 1800-3000 K (the upper limit depending upon materials available for containment and reactor wall lifetime requirements). The rejected heat from the direct VCR-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 1500 and 700 K. The gas turbine cycle rejects heat at 700K to drive a superheated Rankine steam cycle. Neglecting non-isentropic losses due to flow and component cooling, the overall efficiency of the combined VCR-MHD/Brayton/Rankine system is estimated to be in excess of 70%. This value for the efficiency is based upon the assumption that significant enhancement of the gas conductivity can be engineered by utilizing the non-equilibrium ionization of the gas by fission products. Figure 3 illustrates the concept under consideration.

Figure 3. Schematic design for a VCR-MHD power generator with combined Brayton/Rankine heat recovery cycles.

Prior reports have also outlined the rationale behind the selection of suitable fuel materials for a coupled GCR-MHD system. Metallic uranium boils at around 5000 K at the 10 to 20 atmospheres of core pressure required for criticality, a temperature beyond presently envisaged material limitations. Uranium metal vapor fuel could be considered if introduced as micron size droplets dispersed in a vapor working fluid, but only if the droplets can be separated from the working fluid as it exits the core. UF_6 is less stable than UF_4 at the current design temperatures, however the UF_n species present will be temperature dependent, for the present model UF_4 is assumed as the fissioning gas. The thermodynamic and chemical stability of UF_4 recommends a UF_4 -He mixture of around 0.05% mole fraction of UF_4 as the most suitable choice for the main MHD power loop at present.

2.1. Power Cycle Modeling

The following overview of the GCR-MHD power cycle modeling is provisional. There remain many features that need optimization or inclusion of more realistic physical modeling. Some of these will be touched upon briefly in the descriptions of the modeling presented in the next few paragraphs.

The analysis is further limited to strictly thermodynamic cycle analysis. There is no need at this level of detail to go through the full electrodynamic-quasi-1-dimensional hydrodynamic model. It should also be noted that Rankine cycles are sometimes considered for MHD power generation when a suitable vapor constituent is found to be appropriate for use. Generally the complexity of a Brayton gas cycle is preferred for MHD direct energy conversion for most applications because MHD generator length and plasma conductivity are severely limited by pressure and temperature, making a wide range of temperatures and pressure inappropriate for MHD conversion, whereas Rankine cycles perform best with large pressure and temperature ratios. Also, a Brayton cycle can employ relatively inert working fluids like helium or argon, whereas Rankine cycle fluids tend to be more corrosive. A steam cycle can be considered as a bottoming cycle for a high temperature Brayton cycle, but when the top temperature gets really large, as is possible with nuclear reactor heat generation, then a simple Brayton cycle again becomes favourable.

Experience shows that state-of-the-art MHD power generators can be approximately modeled as turbines with isentropic efficiency in the range 50-60% and enthalpy extraction ratio between 30-40%.

The thermodynamic analysis then proceeds straight forward as if the MHD generator were a turbine with isentropic efficiency η_s . To provide a model for η_s and to obtain technologically feasible η_{en} while extrapolating towards future advanced technology requires examining the detailed electrodynamics and fluid mechanics.

An empirical equation of state is used for the UF₄ constituent gas, and a perfect gas model for helium. For rapid analysis an ideal gas model can be used for the mixture when exactness is not required. The GCR component is modeled based upon existing neutronics data. The MHD generator can be modeled with 2D or quasi-1D ideal fluid equations, or alternatively, for rapid analysis, the MHD component can be modeled as a simple adiabatic turbine with nominal isentropic efficiency and enthalpy extraction ratio. A thermodynamic model is used for all other components.

Solving the model equations begins with a generic gas core reactor consisting of a core region under 40 to 60 atm pressure and 3000 to 4000 K and an outer reflector of BeO material. It is assumed that the reflector temperature is held constant and a nominal value in the range 2100 K to 2200 K is used. From the equation of state the ²³⁵U atom density is calculated and then the neutron multiplication factor, k_{eff} , is obtained by looking up data tables. The effect of the non-fissile working fluid (He) on k_{eff} is neglected. This value is then corrected for the presence of structural materials and moderator temperature. The desired core pressure and temperature are then chosen or adjusted so

that the corrected k_{eff} is close to 1.0 as required for reactor criticality. The core power density is then calculated using standard nuclear reactor engineering handbook formulae, where the fission energy released per fragment is taken as 185 MeV, and the fission cross section is calculated from the thermal neutron fission cross section (577 barns) and the average neutron temperature in the reactor together with a Wescott correction factor. The neutron temperature is based on existing data for BeO reflector/moderators that give the neutron temperature corresponding to various BeO moderator temperatures. The data exists only for $T_M=1200$ K, above which linear extrapolation is used.

The MHD generator is modeled as an ideal flow of a conducting gas either through a duct or swirling out of a vortex flow created between two disks, one of which has a central aperture through which the gas enters from the gas core nozzle exit as in Figure 1. Depending upon modeling requirements either a simple turbine model with a specified isentropic efficiency (actual change in enthalpy/isentropic enthalpy change) and a specified enthalpy extraction ratio (actual enthalpy change/inlet enthalpy) can be used, otherwise various approximations to the governing MHD hydrodynamical flow equations can be used to obtain varying details of the MHD channel variables. Constant pressure or constant temperature flows are two unrealistic approximations that are nevertheless useful if analytic results are sought. Otherwise simplified quasi-1 dimensional steady state governing equations can be solved for a suitable set of specified MHD generator parameters. For an adequate and reasonably complete analysis the quasi-1D flow equations (perhaps with wall heat transfer and friction effects) suffices, together with an entry convergent-divergent nozzle (for supersonic flow operation) and an exit diffuser section are also added to calculate more realistic thermodynamic variables.

A simple ideal gas approximation suffices for most modeling purposes. The nozzle is usually choked and the diffuser shock wave discontinuity is calculated when the flow is supersonic. A nominal value for the isentropic efficiencies of the nozzle and diffuser is set so that the actual state variables can be determined from the isentropic flow equations. A simplified electrodynamics model suffices for initial modeling purposes, a constant magnetic field across the MHD disk or duct is assumed, provided the magnetic Reynolds number $R_m = \mu_0 \sigma_g u L$ is less than unity. Here μ_0 is the magnetic permeability, σ_g is the gas conductivity, u is the gas velocity and L is the duct length or radius.

An intermediate heat exchangers then used, either to reheat the working fluid as it reenters the reactor core, or to provide thermal heat generation for a bottoming heat recovery cycle. In a complete thermodynamic cycle model the moderator/reflector surrounding the gas core will have boiler columns to reheat the fuel and vaporize the UF₄, which also serves to cool the moderator walls to the desired temperature.

A bank of compressors and coolers that can also supply reasonable heat for a low temperature steam turbine bottoming cycle closes the cycle. This is in fact a fundamental feature of the GCR-MHD concept, namely the availability of excess heat even after the primary power loop has extracted the high quality energy from the fissioning gas.

Figure 4. Sample T-s diagram for helium Brayton gas cycle with reheat and single stage compression.

A single stage compressor helium Brayton cycle temperature-entropy diagram is shown in Figure 4 to compare against a sample UF₄-He Brayton cycle of very similar form. The main UF₄-He Brayton cycle T-s diagram is plotted in Figure 5. Typical starting parameters for this cycle were taken from Table 2.

Figure 5. UF₄-He fuel Brayton cycle T-s diagram. This is drawn with a reheat stage and three stage cooler-compressor section (between points 5 and 7). The fuel mix is 0.95 moles He for 0.05 moles UF₄. Core pressure=40 atm, cycle minimum temperature=500 K, MHD generator isentropic efficiency =0.60, and reactor duty = 100 MW_{th}.

Table 2. Initial Parameters for Brayton Cycle VCR-MHD.

Input Parameters:	
Heat exchanger:	
ϵ_{reg}	0.9
MHD Generator:	
η_s	0.7
η_{en}	0.4
He-Compressor:	
η_c	0.87
Number of stages	3
Cycle Limits	
T_{max} (UF ₄ -He)	4000 K
T_{min} (steam)	320 K
VCR:	
Power in	1400 MW _{th}

This can be considered a basic “baseline” ideal power cycle. Analyzing the cycle now by varying the pressure drop across the MHD generator as well as T_{max} we get the variation of net cycle efficiency versus MHD turbine pressure ratio as in Figure 6. Note that the MHD acting as an ideal “magnetic-turbine” here has a significantly higher temperature limit than available with conventional gas turbines. Although the lifetime of such an MHD generator is not known the advantages of the higher Carnot efficiency become evident, particularly when a heat exchanger could be added to power a steam bottoming cycle.

Figure 6. Net Brayton cycle efficiency as a function of MHD turbine pressure ratio for $T_{\text{max}}=3500$ K to 2000 K. The minimum temperature here is fixed at $T_{\text{min}}=500$ K. Core pressure=40 atm, cycle minimum temperature=500 K, MHD generator isentropic efficiency=0.60, and reactor duty = 100 MW_{th}. Fuel mix, 0.95 moles He : 0.05 moles UF₄.

For comparison a similar set of plots is shown in Figure 7, where for the two selected temperatures an extra curve has been plotted to show the effect of multiple stage cooler-

compressors. The work done by the compressor is a major contributing factor to loss in efficiency, by utilizing a series of compressors with inter-staged coolers a small gain in efficiency can be accomplished as can be seen in the curves of Figure 7. The solid curves have three stages; the dashed curves only a single compressor and cooler. For more than three stages the gain in efficiency is usually only slight.

Figure 7. The effect of multiple compressor-intercooled stages on the cycle efficiency. The finely dotted line and the solid curve are the multiple stage compressor curves, the dashed curves are for single compressors.

These relatively simplistic models really show the payoff in going to high temperature where only a static turbine like an MHD device can work.

In Figure 8 a set of cycle minimum temperatures are shown for their effect upon the efficiency as a function MHD duct pressure ratio.

Figure 8. Variation of UF₄-He Brayton cycle first law efficiency as a function of the MHD generator pressure ratio for fixed cycle maximum temperature ($T_{max}=2500$ K) and for four different cycle minimum temperatures.

Figure 9 plots the work ratio (net work/ positive work) for various cycle minimum and maximum temperatures. Overlaid is the cycle first law efficiency at for a range of temperatures. For the given MHD isentropic efficiency in Table 2 and other fixed parameters this would indicate an optimum MHD enthalpy extraction ratio of between 0.2 and 0.4, operating between about 3000 K and 500 K, a higher enthalpy extraction ratio would be appropriate for higher maximum temperatures. For reference, the enthalpy extraction ratio follows a power law with the pressure ratio, with an exponent equal to $(1-\gamma)/\gamma$ for an ideal gas. For a 0.05 mole fraction mixture of UF_4 in helium then the MHD pressure ratio is unity $h_{en}=0$, and a pressure ratio of 40 corresponds roughly to an enthalpy extraction ratio of $h_{en}=0.495$.

Figure 9. Plot of the work ratio for the primary Brayton cycle. Contours are cycle maximum temperatures. The dashed line shows the work ratio W_R for $T_{max}=3500\text{K}$ (upper dashed curve), and W_R for $T_{max}=2000\text{K}$ (lower dashed curve).

A further indication of the performance of a coupled GCR-MHD power cycle, as for all the previous plots it is for a $\text{UF}_4\text{-He}$ working fluid, nominal $60 \text{ mho}\cdot\text{m}^{-1}$ conductivity, and a reheat Brayton-MHD gas cycle is shown in Figure 10. For the same cycle, the net power produced peaks at about $h_{en}=0.2$ to 0.3 , corresponding to $T_{max}=200\text{K}$ and 3500K respectively. However, perhaps the specific work as shown in Figure 10 is a better performance indicator bearing in mind the value of reducing the amount of ^{235}U in the cycle inventory. In that case the figure would indicate that a higher enthalpy extraction ratio, or higher MHD pressure drop could be tolerated, perhaps upwards of 0.5 in a very high temperature gas core reactor. This is for a 100 MWth reactor duty. With the other specified parameters the mass flow rate comes out to about 45 to $95 \text{ kg}\cdot\text{s}^{-1}$. A lower reactor duty could of course give the same performance as previously if the mass flow rate were to be allowed to increase proportionately. The main point to bear in mind is that these cycle thermal efficiencies are only indicative of what the primary $\text{UF}_4\text{-He}$ MHD loop can achieve under relatively conservative estimates. With up to 20% or 25% efficient steam bottoming cycles, or a two stage Xe-He Brayton bottoming cycle driving a third steam Rankine cycle, then a combined cycle efficiency of up to 70% is not unrealistic.

Figure 10. UF4-He Brayton-MHD cycle specific work versus MHD generator enthalpy extraction ratio. Plotted for core pressure=40 atm, cycle minimum temperature=500 K, MHD generator isentropic efficiency =0.60, and reactor duty = 100 MW_{th}.

This serves to illustrate the potential performance of energy extraction within the MHD generator itself, independent of the other power cycle components. Once again the virtues of nuclear MHD power conversion systems is impressed, particularly when compared to conventional gas turbine and steam turbine plants based on fossil fuel cycles, or conventional light water reactors.

2.2. Addendum

This report is not definitive and gives only a brief survey of work in progress. There are many aspects of MHD modeling that have not been covered and there remain many unexplored options and design optimization goals that have yet to be fully exploited, as well as potential problems that cannot be estimated without detailed research and development that is an objective of the University of Florida Phase III project.

Cost Performance:

The estimated University of Florida total cost in the second quarter of Phase III project is \$42,000. This will bring the total expenditure of the University of Florida during the first and second quarters of Phase III project to \$82,000. At the current expenditure rate, the cost of the third quarter performance is expected to be \$48,000.

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3. Introduction

A gas core reactor (GCR) with magnetohydrodynamic (MHD) power converter and cascading power cycle forms the basis for a Generation IV concept that is expected to set the upper performance limits in sustainability and power conversion efficiency among all existing and proposed fission powered systems. The GCR-MHD system described in this report is not constrained by solid fuel-cladding temperature limitations, and is only constrained by the less restrictive vessel limits. It combines the functions of fuel and coolant into one. It can potentially provide the highest reactor and cycle temperature among all existing or proposed fission reactor designs. The system also features a low inventory and fully integrated fuel cycle with exceptional sustainability and safety characteristics. A cascading power cycle furthermore allows very high first law efficiency. Preliminary power cycle optimization design studies are presented and options for future research are outlined.

This report still focuses on the power conversion cycle efficiency as explored in previous NERI reports, however significant effort has also been put into evaluating the burnup characteristics of the GCR reactor. This is important for the proposed concept because sustainable closed fuel cycles with minimum waste and minimum source terms in the radioactive fission product waste are key elements of much needed Generation IV nuclear power systems. Thus the sections of this report are as follows,

- Fuel cycle and sustainability issues.
- Nuclear design and power conversion.
- Power cycle efficiency analysis and inventory characteristics.

We begin with a summary description of the system.

3.1. Description of the GCR-MHD System Concept

The system is a fissioning gaseous core reactor (GCR) with a direct energy conversion disk or line magnetohydrodynamic electricity generator (MHD). The reactor is fueled with uranium tetrafluoride (UF_4) with 10% enriched uranium and with 95% mole fraction He gas working fluid to enhance heat transport properties. A closed-cycle MHD power generator is used to directly process and convert the fission power between temperatures of 1800-3000 K (the upper limit depending upon materials available for containment and reactor wall lifetime requirements). The rejected heat from the direct GCR-MHD loop 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 1500 and 700 K. The gas turbine cycle rejects heat at 700K to drive a superheated Rankine steam cycle. Neglecting non-isentropic losses due to flow and component cooling, the overall efficiency of the combined GCR-MHD/Brayton/Rankine system is estimated to be in excess of 70% when fully optimized. This value for the efficiency is based upon the assumption of minimum pressure losses in pipes and fittings and that significant enhancement of the gas conductivity can be engineered by utilizing the non-equilibrium ionization of the gas by fission products in the MHD duct section.

4. Fuel Cycle and Design Characteristics

Gas and vapor fuel reactors feature a low inventory and fully integrated fuel cycle with exceptional sustainability and safety characteristics. With respect to fuel utilization, there is no fuel burn-up limit for gas core reactors due to continuous recycling of the fuel. Owing to the flexibility in nuclear design characteristics of cavity reactors, a wide range of conversion ratio from completely burner to breeder is achievable. The continuous recycling of fuel in G/VCR systems allow for complete burning of actinides without removing and reprocessing of the fuel. The only waste product at the backend of the gas core reactors' fuel cycle is fission fragments that are continuously separated from the fuel. As a result the G/VCR systems do not require spent fuel storage or reprocessing. Due to very low fuel inventory and continuous burning and transmutation of actinides, gas core reactors minimize the environmental impact and stewardship burden.

G/VCR systems also feature outstanding proliferation resistance characteristics and minimum vulnerability to external threats. Even for comparable spectral characteristic, gas core reactor production of fissile plutonium is two orders of magnitude less than Light Water Reactors (LWRs). In addition, the continuous recycling and burning of actinides further reduces the quality of the fissile plutonium inventory. The low fuel inventory (about two orders of magnitude lower than LWRs for the same power generation level) combined with continuous burning of actinides significantly reduces the need for emergency planning and vulnerability to external threats. Low fuel inventory, low fuel heat content, and online separation of fission fragments are among robust features that improve the safety performance and reliability of G/VCR systems under normal operation and abnormal operational transients in compare with other fission power systems.

Due to circulation of fuel in gas core reactors, the entire operation is remote and robotically controlled. Continuous separation of fission products from fuel reduces the delayed source of radiation (after reactor shut down) to a bare minimum. These factors result in significant reduction in the probability of worker radiation overdose during normal operation. Any loss of system pressure, core damage, or fuel leakage result in loss of reactivity that is needed to keep the reactor critical. Because the fuel is in gaseous phase the core damage would be limited to pressure vessel and reflector damage that are not at the same level of severity with any other solid fuel reactor.

Radionuclide generation and burn-up analysis was performed recently on a gaseous uranium-tetrafluoride fueled reactor using the ORIGEN-S code in the SCALE 4.4 licensing code package. Data for the major actinides is shown in Figure 11 and Figure 12. The core was modeled using MCNP, with mass concentrations corresponding to that filled by a 3m right circular cylinder operating under a pressure of 2 MPa with He and UF₄ gas in a 9:1 molar ratio. At an enrichment of 10% this corresponds to ~60kg of ²³⁵U.

The relative amount of thermal expansion in the reactor is determined by parameters in the ORIGEN-S code, default LWR values were used. Figure 11 shows uranium and plutonium concentrations in the 10% enriched GCR (600 kg ²³⁵U). Figure 12 shows the main radioisotope source terms (⁹⁰Sr, ^{99m}Tc, ¹³¹I, and ¹³⁸Cs) also in 10% enriched GCR fuel. The radioisotope sources generally build up rapidly then level off to between 0.1g (¹³⁸Cs) to 10³g (⁹⁰Sr).

Figure 11. Masses of actinide radioisotopes in fuel versus burnup for 10% enriched fuel in a gaseous core reactor with UF₄ (10% mole fraction)-He(90% mole fraction) fuel.

Figure 12. Masses of major source term radioisotopes versus burnup for 10% enriched fuel in a gaseous core reactor UF₄(10% mole fraction)-He(90% mole fraction) fuel.

5. GCR Nuclear Design and Power Conversion

An advanced GCR-MHD concept utilizes closed magnetohydrodynamic (MHD) power generation cycle to directly process and convert fission power at temperatures of 1800-2500 K. The rejected heat from the MHD power cycle is used to power single or multiple gas turbine employing a high temperature gas turbine, developed by Siemens-Westinghouse, in a Brayton cycle, with a bottoming superheated steam Rankine heat recovery cycle and/or superheated steam cycles. The magnetohydrodynamic generator extracts energy directly from the gas core fluid at the highest possible quality, with sufficient heat left over to drive two heat recovery cycles and delivering close to 70% over all energy conversion efficiency. The schematic for this advanced system is shown in Figure 14 on page 24. Several different working fluids such as He, KF, LiF, or BeF₂ could be used in a GCR-MHD system.

5.1. GCR Design and Neutronics

Conventional solid core reactors have limited applicability to MHD power generation compared to gas core and vapor core reactors. A gas core reactor (GCR) can send fissioning gas directly to an MHD generator, with a low molecular weight working fluid such as helium, argon or an alkali metal fluoride, added to enhance heat transfer properties. Neutronics analyses, dynamics and control studies have been performed for a few G/VCR systems that reveal desirable stability characteristics [1], [2] and of particular interest for a Brayton cycle gas core reactor system [3], [4]. Studies have also shown that for intermediate values of the fuel mass reactivity coefficient α_{fm} (the fractional change in reactivity $\Delta k/k$ per kg of fuel, nominally set at 0.035 per kg) there is a natural stabilization of the core power in response to positive reactivity insertions. For $\alpha_{fm} < 0.0005$ a positive insertion leads to an unstable increase in power and for $\alpha_{fm} > 0.2$ undamped oscillations in power occur [5]. This is a feature of the GCR-MHD type systems analyzed by INSPI. Because the fuel-mass reactivity feedback is negative these systems require methods other than positive reactivity insertions into the core to get power output variability. At INSPI ultra-high temperature VCR-MHD based Rankine cycles, burst-mode GCR-MHD Brayton cycles, multiple-cavity GCR-disk MHD Rankine cycles, and bimodal GCR-MHD systems, all employing either UF₄, UF₆-He or KF working fuels, have been analyzed. Most designs use a UF₆ or UF₄ fissioning gas with a 90 to 97% mole fraction helium working fuel. In most designs there is some kind of wall-cooling mechanism included, using the circulating fluid from the condenser to cool the walls.

Compatible materials with high temperature gaseous and liquid fuel have been developed and demonstrated [6–10], and thermal fluid design analysis models have been developed and used to assess the heat transport and energy conversion characteristics of these systems [11–15].

Gas core reactors also have better inherent safety features compared to LWRs, and have neutron reflectors, that also function as external moderators to provide criticality in the gas core reactor. Any loss of system pressure, core damage, or fuel leak result in loss of reactivity that is needed to keep the reactor critical. Because the fuel is in gaseous

phase the core damage would be limited to pressure vessel and reflector damage that are not at the same level of severity with any other solid fuel reactor. Low thermal conductance of the vapor fuel/working fluid allows for very high average bulk fluid temperatures greater than 3000 K, while maintaining wall temperatures significantly cooler. However, gas core reactors are at an early stage of development and the system model uncertainty is very high.

5.2. MHD Generator Specifications

Disk MHD units can reach higher power densities, but linear MHD units have fewer costs associated with gas recycling apparatus, which is a huge factor when mass reductions for space missions have to be considered. On the other hand, the magnet design for disk MHD units is simpler, consisting of a simple split solenoid pair.

The geometry of an MHD duct has been described in previous NERI reports and documented in papers that discuss the space power vapor core reactor concept of the same pedigree [16].

The key to MHD power efficiency is electron mobility. High conductivity is needed for satisfactory power output in a MHD unit, this can be achieved with high electron densities, but this also increases recapture, so this leaves electron mobility as the only other way to leverage higher power densities [17]. Recent studies, with ^3He [18], suggest a range of thermodynamic and neutron flux conditions may exist that can produce the required conductivity (up to 10 mho m^{-1} with a flux of $>10^{12} \text{ cm}^{-2} \text{ s}^{-1}$). An advantage of fission fragment ionization and non-equilibrium ionization in general, according to these models, is that ionization wave instabilities are suppressed which would otherwise develop due to localized Joule heating of the electron gas if only thermal ionization predominated [19].

One-dimensional ideal gas calculations are used to set up inlet nozzle conditions and exit supersonic-to-subsonic diffuser thermodynamic variables. The MHD channel itself is suitably modeled for scooping purposes by quasi-1-dimensional MHD equations. Compressible, steady state, ideal gas, inviscid Navier-Stokes equations are combined with Maxell equations, with the usual “MHD approximations” including a simplified Ohm’s law, negligible electrical force term $\mathbf{r}^c \mathbf{E}$, negligible induced magnetic field (low magnetic Reynolds number $R_m = \mathbf{m}_0 \mathbf{s}_g u L$). These are used to model disk or linear duct MHD generators. As an example, for a disk MHD generator, with radial variable r , tangentially symmetric flow approximated ($\partial/\partial\theta$ terms $\rightarrow 0$), zero heat transfer but with significant neutron flux fission power input, the governing equations simplify to the following.

$$\text{Mass continuity: } \frac{d}{dr}(\dot{m}) = 0$$

$$\text{r-momentum: } \frac{d}{dr}(\dot{m}u) = -A \frac{dp}{dr} + \mathbf{b} J_r A B - \mathbf{s}_g u A B^2 + \frac{\mathbf{r} v^2 r}{r}$$

$$\theta\text{-momentum: } \frac{d}{dr}(\dot{m}vr) = -J_r E_r B \cdot r$$

$$\text{Energy: } \frac{d}{dr}(\dot{m}h) = -J_r E_r A + \frac{\mathbf{r} \cdot \mathbf{q}'''}{\mathbf{r}_i} A$$

$$\text{Enthalpy: } h^0 = h + \frac{u^2 + v^2}{2}$$

$$\text{Current: } \frac{d}{dr}(J_r A) = 0$$

$$\text{Electric Field: } E_r = \frac{1 + \mathbf{b}^2}{\mathbf{s}_g} J_r - (\mathbf{b} \cdot \mathbf{u} + v) \cdot B$$

$$\text{Gas Equation of State: } p = \mathbf{r} R_M T$$

Here $q'''_{MHD} = q'''_{core} \mathbf{f}_{MHD} / \mathbf{f}_{core}$ is the fission power density term for the MHD channel, which is computed from the same equations used to calculate the fission power density in the core but with the multiplicative flux ratio factor to account for the lower neutron flux through the MHD channel. It is the neutron flux that allows the gas conductivity to be assumed higher than the thermally ionized conductivity predicted by the Saha equation (and the latter would be too low for power production in the current design). The variable A is the MHD channel cross sectional flow area, and $\mathbf{r}_i$ is the gas density at the MHD channel inlet. The radial u , tangential v , velocities, the area A , the current J_r , the field E_r , the enthalpy h , density $\mathbf{r}$, and the pressure p are all functions of the radial coordinate that ranges from the duct inlet $r=R_i$ to the outlet $r=R_f$. The equation of state uses a gas constant determined by the UF_4 mole fraction and the working gas (helium) mole fraction. Other symbols are defined in the appendix. In addition a swirl number is useful to define, $s=u/v$, the higher the swirl of the flow the greater the electrical efficiency as illustrated parametrically. To calculate the MHD generator exit thermodynamic state, as well as the electrical power output, the mass-continuity, $\mathbf{q}$ -momentum, and current equations can be immediately integrated to yield constants of the flow. The velocity and electric field remaining equations are then integrated using standard numerical methods.

Figure 13. A 3-D plot showing the maximum electrical efficiency as a function of swirl and the Hall parameter.

An alternative to integrating the approximate MHD equations is to use look-ups of data tables of known experimental MHD generator performance parameters. For example, considered as a “blackbox” turbo-generator an MHD duct has a relatively low isentropic efficiency, typically $\eta \sim 0.6$, and an enthalpy extraction ratio of between 0.4 to 0.7.

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6. Power Cycle Analysis

In the present calculations the gas core reactor component of the power plant is modeled using tables of neutronics data compiled for generic gas core reactors at the University of Florida [20], [21]. The uranium tetrafluoride thermal properties are taken from JANAF data tables and proprietary INSPI data [14] for high temperatures. There are unresolved fuel property issues that cannot be detailed here, but would need new experimental data, high temperature fission cross-section data and the like. The fuel mixture is taken to be an ideal gas, and at the UF_4 condensing heat exchanger the liquid properties of UF_4 are used. Typical gas core operating conditions are 3500 to 4000 K peak average temperature, and 40 to 60 atm core average pressure. The nuclear design

characteristics are flexible, owing to the fact that the fissile fuel is in fluid form. This allows, among other things, control of the spectral characteristics, and online fission product removal.

Turning now to the integrated power cycle, standard cycle analysis tools are used to input design point parameters, such as the GCR maximum average temperature and pressure, the MHD inlet and exit Mach numbers, the turbine and compressor maximum inlet temperatures and pressure ratios, the Rankine cycle maximum and minimum temperatures, and all the heat exchanger effectiveness values. The unknown thermodynamic variables at each of the computational nodes can then be stepped through or iterated when necessary to find a solution to the steady state cycle problem. Compressor, gas turbine and liquid pump components are modeled as adiabatic components with certain isentropic efficiencies. The heat exchangers are approximated as isobaric. Multistage compressor banks can be employed when the compressor exit temperature for a single stage is demanding too high.

Analysis has been performed for a combined cycle consisting of a UF_4 -He MHD topping cycle, an intermediate high temperature Brayton gas turbine cycle (He-Xe) and a superheated Rankine steam bottoming cycle.

Figure 14. Schematic design for a GCR-MHD power generation system with combined heat recovery cycles.

Table 3. Typical disk MHD generator characteristics

$\eta_{\text{isentropic}}$	0.6	Hall parameter	2.6
Pressure ratio	50–70	B field	6 Tesla
Radius	1 to 2 m	Conductivity	60 $\text{ohm}^{-1}\text{m}^{-1}$
Inlet Mach No.	3.0	Exit Mach No.	1.1
Inlet swirl	2.0^{-3}	Exit swirl	0.4
Inlet T	2000–3000 K	Exit T	1900–2200 K
Power density (electric)	200 MW m^{-3}	Load E /Open-circuit $E=K$	0.5

It should be pointed out that not all of the possible design variations here represent viable systems. To determine a viable system the power plant efficiency needs to be

considered at least, as well as other performance parameters such as the work ratio, w_{net}/w_{out} , and efficient ratio h_{net}/h_{carnot} .

Figure 14 shows the basic power cycle layout for a G/VCR-MHD nuclear power generation system. Table 4 lists a few of the key design parameters for a multi-megawatt power plant scheme.

Table 4. Design characteristics of a 1900 MWe GCR-MHD system, high temperature for an advanced materials design $T_{max}=4000\text{K}$, $T_{inlet}=3500\text{K}$.

Net Power	1900 MWe	Total fuel inventory	165 kg (UF ₄ +He)
Thermal efficiency	71%	UF ₄ inventory	132 kg
Core volume	5.0 m ³	²³⁵ U	95 kg
Vessel pressure	51 bar	Enrichment	95%
Average power density	186 MW m ⁻³	Total Mass flow rate	1441 kg s ⁻¹
Be Reflector mass	52 MT	UF ₄ mass flow rate	1160 kg s ⁻¹

The ²³⁵U mass inventory for the GCR-MHD system is plotted in Figure 15 for various permutations of the key GCR-MHD control variables. In particular the power level is controlled via the GCR core volume, which in Figure 15 varies from 5m³ to a very high power rating 25m³. The enrichment fraction is also varied in accordance with the requirement that the k_{eff} remain between 0.95 to 1.05 for core pressure of around 40 to 60atm.

Figure 15. Mass inventory of ²³⁵U in primary loop for various net power levels of a GCR-MHD-Brayton-Rankine combined cycle: (a) upper estimate with enrichment ~0.95 to 0.7, (b) lower estimate for enrichment ~0.6 to 0.3.

To illustrate some of the performance capabilities of the GCR-MHD system it is instructive to plot variations of the net cycle efficiency with key control variables. Although one cannot get a full indication of the potential of the system a rough idea can be gained from the following figures that display efficiency variations with the MHD enthalpy extraction ratio, $h_{en}=\Delta h_{MHD}/h_{in}$. The perturbations in the accompanying Figure 16 are partly due to automated procedures employed to facilitate the power cycle analysis. Smother variation could be expected by using fixed power plant parameters

throughout the study, however, to avoid excessive input routines the cycle analysis model used for this study had a number of local component routines to set things like the heat exchanger effectiveness values, the number of compressor bank stages for the helium loops, and the GCR wall cooling effectiveness and UF₄ boiler column fission power fraction.

Figure 16. Efficiency of the GCR-MHD combined cycle versus MHD generator enthalpy extraction ratio η_{en} . The curves are constant GCR exit temperatures = T_{max} .

It is not clear in this figure whether the net cycle efficiency bottoms out at ~60% or whether a region of operation of higher efficiency is possible. Certainly by going to higher temperatures (including higher GCR inlet temperatures) the efficiency can be improved. Significant improvements also follow if the MHD generator performance can be improved, but this would entail technology enhancements beyond what is currently predictable, so here the investigation is limited to exploring high temperatures and incremental improvements associated with turbine and compressor advancements (high turbine inlet, and compressor outlet temperatures are assumed). A contour plot of the net cycle efficiency in Figure 17 shows that regions in the cycle thermodynamic phase space do exist where the efficiency can be close to 70%. Again the perturbations are apparent that arise from the dependence of the global variables upon the local power plant component input settings. In this figure the GCR is taken to be a 25m³ core volume with core pressure around 50atm, and roughly constant core temperature rise of 1000K (not necessarily the optimum), the fuel enrichment was taken to be 60%.

6.1. Flexible Design Options and Optimization Issues

A number of built-in automated procedures were used to conduct the power cycle analysis discussed above. However, the global combined cycle characteristics were found to vary sometimes contrary to isolated component optimums. Therefore much work remains to be done to investigate global optimums for the cascading GCR-MHD-Brayton-Rankine combined cycle. Other fuel options can be explored. The core containment material and reflector are critical issues with direct impact to the safe operation and long life of the GCR system. Beryllium, beryllium oxide, and graphite are primary reflector materials for these systems. Due to chemical compatibility of the gas

and liquid phases of UF_4 with all forms of carbon, it is also possible to use graphite or pyrocarbon as internal moderator.

Figure 17. Isoefficiency curves for maximum cycle temperature and MHD pressure ratio variations. See text for discussion of the perturbations in the contour lines.

For the balance of plant design many optimization choices have to be worked out. In future work various configurations of turbine stages, reheaters and cogeneration will be considered. Reheating could be achieved either by taking a portion of fluid from the reactor exit or by recirculating the fluid from the high-pressure turbine exhaust back through the reactor. An option of providing nuclear reheat is attractive because it could increase the overall efficiency of the cycle by 5 to 10%.

The development of an effective method to separate all fission products that contribute to the radiotoxicity and neutronic poisoning of the fuel is another aspect that has not been treated. Most fission products form fluorides that could be separated from the fuel based on their volatility. There are other emerging techniques such as plasma mass spectroscopy that could be used to separate fission products based on their atomic mass that is significantly different than fuel.

7. Summary

An advanced high-performance, high-temperature gas or vapor core reactor concept has been described that has the potential to provide safe, highly efficient and sustainable nuclear power. This gas core reactor system can employ either advanced gas turbine power conversion in a secondary cycle, or utilize future MHD generator designs to provide direct energy conversion at the highest possible quality and Carnot efficiencies conceivable within known material temperature limitations. The MHD cycle design can supply heat to run a combined bottoming cycle that could be a Brayton gas cycle as in the first option. Both designs operate at high enough temperatures to enable a further cascade down to a bottoming superheated steam Rankine cycle. In this way the overall first law efficiency of the combined power plant can be as high as 55% for a GCR-GT option and 70% for the GCR-MHD nuclear energy system.

Known challenges for the development of a deployable GCR-MHD nuclear energy system include high-pressure containment, fine-tuning the nuclear design, the requirement of high gas conductivity (hence ionization) in the MHD channel, possible use of high neutron flux to achieve non-equilibrium ionization. Although several theoretical design studies have been mentioned there remain many tests that need to be performed to gather crucial experimental data needed to prove the commercial viability of the proposed systems. Fuel and vapor chemistry issues remain to be fully understood. For the balance of plant design many optimization choices have to be worked out and economic development issues remain to be addressed.

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