Vapor-Gas Core Nuclear Power Systems with Superconducting Magnets

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These notes and graphics summarize present concepts investigated at the Innovative Nuclear Space Power and Propulsion Institute with a focus on advanced gaseous or vapor core nuclear reactor power systems using magnetohydrodynamic(MHD) power generators. Gas or vapor core nuclear MHD systems could potentially provide multimegawatt space power at less than 1 Kg/KWe, which would enable many space missions including manned exploration of Mars in less than 6 months time period. These systems require two key advanced technologies, (i) materials capable of withstanding greater than 2000K temperatures and chemically compatible with uranium tetrafluoride vapor, and (ii) light-weight, high-field superconducting magnets with good radiation hardness properties.

In recent years research conducted at Innovative Nuclear Space Power and Propulsion Institute (INSPI) at the University of Florida has led to promising nuclear space power system designs that use gaseous or vapor fuel in very compact and low mass configurations ideal for nuclear powered space flight vehicles. A number of technologies required to realize these designs in actual space exploration applications are discussed and the technology needs are illustrated with design schematics and critical system diagrams. Gas/Vapor fuel reactors (G/VCR) are well understood systems, but they face technology challenges before they could be tested and used in NASA missions. G/VCRs use a fissioning gas fueled with uranium tetrafluoride (UF_4) and a vapor working fluid, such as KF or NaF molten salt vapor, and operating at above 2000K these reactors burn up the fissile fuel in a steady state cycle, employing some means of power extraction and radiative cooling for waste heat removal at temperatures just on the vapor point of UF_4 (about 1500K), which allows higher efficiency radiative cooling than any other type of nuclear reactor proposed for NASA missions. Radiators are normally the most massive component of any space power system, and so a concept (such as the VCR) that can reduce radiator area offers potential for much improved space vehicle performance and safety margins. An even more advanced and untested, but promising, concept is that of a subcritical shockwave driven pulsed reactor, for which electromagnetic shock tubes would be used to drive two MHD shock waves together, these shocks would be launched into a fissioning gas (highly enriched UF_4 vapor) and made to collide together in an intense collision which could release a short burst of fission energy. A cummulative flux compression magnetic power generator could be then used to extract any outgoing shock created by the initial shock-on-shock collision. In theory a net power gain could result because the outgoing shocks would be highly energetic and carry an extra burst of fission energy. The magnetic flux compression generator would extract power by slowing the outgoing shocks to a stop, thereby inducing a burst of current in sets of magnet coils surrounding the expanding shock waves. This concept has been named the Pulsed Magnetic Induction Gas Core Reactor, or PMI-GCR. But there are other modes of pulsed gas core operation that could also conceivably be used to supply low specific mass power for a space vehicle or space applications in general.

Steady-State Gas and Vapor Core Reactor Technology

Fissioning plasmas, such as are proposed in the aforementioned concepts, are much less dense and much lower temperature than fusion plasmas, therefore gaseous fuel systems (GCRs or VCRs) employing fission power have an immediate technological advantage over fusion power systems for stringent space exploration requirements. This is true of all fission reactors at present, but vapor-fueled reactors are the most advanced fission power sources for at least two reasons. First, they allow *direct energy conversion* of the heat energy released into the fuel *at the highest possible quality*. This is possible for example by using magnetohydrodynamic (MHD) generators through which the activated ionized fission plasma can flow. For this effect to generate hundreds of kilowatts up to many megawatts of power in a compact low mass system requires high field magnets of up to 4 to 10 Tesla or more. Secondly, vapor core reactors can be constructed at almost half the mass and scale of conventional solid fuel reactors, this is because many subcomponents of conventional nuclear reactors are simplified or entirely removed from gas or vapor core reactors. The main distinguishing feature in this regard is that a vapor core reactor combines fuel and coolant as one. The fuel mixture includes the fissioning UF_4 as well as the working fluid vapor (normally an alkali metal-halide fluid) necessary for the thermal hydraulics requirements.

The two critical technologies that will need to be developed for space applications of these advanced reactor concepts are, (1) materials that are compatible with the radiation environment in space and that are chemically non-reactive with uranium tetrafluoride vapor (and hence fluorine radicals that would form in the plasma) a high temperatures, and (2) superconducting magnets with sufficient field strength and radiation tolerance for the MHD power requirements in the space environment. Sizeable 10 to 30 bore superconducting magnets are needed to generate the 4 to 10 Tesla applied fields necessary for efficient disk-MHD operation. Development of such magnets would constitute a major enabling technology for space-based gas/vapor core nuclear reactors. If materials for UF4 vapor fuel reactors can also be developed then both manned exploration for the solar systems and large payload missions to the outer planets, or long duration missions to other planets would be possible using G/VCR-MHD power in combination with high specific impulse plasma thruster technologies, such as the VASIMR rocket engine being developed at NASA Johnson Space Flight Center.

Space nuclear power systems must be light-weight, and must provide better power to weight than terrestrial power plants, but space reactors need not be as efficient as terrestrial reactors, because any improvement in efficiency is generally at the cost of size, which in space applications is the higher premium, so lower size and mass generally always trump energy efficiency (within good reason).

One design favored in INSPI analyses is the disk MHD configuration (see Figure 1). Usign a helical nozzle a fissioning partial plasma can be induced into a swirl flow, and the tangential velocity of the conducting gas can be decelerated by MHD magnets, with the consequent induction of a high voltage in the MHD electrodes placed in contact with the gas and MDH duct walls. For this system to be viable the gas needs to have an electrical conductivity of about 10 to 100 Siemans, and the MHD duct must be surrounded by a magnetic field of 4 to 10 Tesla or more. Even higher fields would be advantageous due to the Hall effect mode that the disk generator operates by (see Figure 2 and Figure 3).

An alternative G/VCR-MHD configuration is to place smaller linear MHD ducts radially outward from a gas fuel nuclear reactor outlet, as illustrated in Figure 4. In the accompanying this is illustrated with a sharp 90° bend at the outlet, but if sufficient plasma activation could be maintained further away from the reactor then the linear ducts could be arranged in a cone to give a less severe flow disruption. Intense magnetic fields are still required in this arrangement to keep the whole system to as small as possible geometrically. A more compact geometry also helps reduce radiation shielding material.

Pulsed Reactor Technology

Analysis of the aforementioned PMI-GCR pulsed reactor concept has been conducted at INSPI. Efforts have shown that a fissile gas can be sent into a critical state after initially being kept at subcritical (hence safe) densities. There is a great deal of R&D work that needs to be performed to explore the possibilities of this concept for viable net power extraction. Currently the shock formation and collision process is under investigation. A coupled MHD-MCNP (Monte Carlo Neutron transport) code has been used to numerically simulate the generation of thermal power from colliding shock waves in a UF_4 gas-filled electromagnetically driven shock tube. A point design for the Pulsed Magnetic Induction Shock-Driven Gas Core reactor (PMI-GCR) has been investigated and sets of planned experiments have been devised, including demonstrating generation of intense shock waves using a pulsed magnetic field, and demonstrate conversion of kinetic energy of the shock into electrical energy. These are yet to be funded. The proposed concept is understood to be a *subcritical* system that is driven to criticality when two colliding shock waves interact and briefly result in fast neutron fission energy release. It is an open question whether any realistic configuration will achieve net gain in power sufficient for useful space power applications. The reliability of conversion of the fission power to electric power, or direct propulsion, induced by shock waves, is also an open question, although the feasibility is not an issue, the reliability and efficiency (and practicality) are major issues. As with steady-state gas core reactors, a pulsed type of reactor will require light-weight and high field magnets for efficient operation. Superconducting magnets would be used for the pulse drive and θ-pinch of the plasma during power input. A schematic of the conceptual design for one type of PMI-GCR is shown in Figure 5.

The concept is termed the PMI-GCR (pulsed magnetic induction gas core reactor), it utilizes the physics of electromagnetic shock generation, magnetic compaction and prompt fission criticality, and magnetocumulative flux compression power generation (MFC/FCG or MCFG). The main innovation in the proposed fission based propulsion system is the use of established fusion plasma confinement and compression methods to achieve supercritical condition in a highly sub-critical fissile gas (the so-called θ-pinch effect). In particular, electromagnetic induced shock wave compaction and gas dynamic trap techniques are merged to bring a relatively small volume (~ 1 m^3) of a fissile (^{235}U, ^{233}U, or ^{239}Pu) compound gas to prompt supercritical condition, thereby, releasing an intense pulse fission power. A magnetic field compaction scheme is designed to directly convert the fission energy to electricity. The specific energy of the proposed nuclear electric system for megawatt level power operation is estimated to be well above 1 kWe/kg.

Other Power and Propulsion Systems Based on G/VCR

A further spin-off from the space technology applications of gas core reactors and magnetohydrodynamic power generation using fissioning plasmas is in terrestrial large-scale power plants. A gas core reactor coupled to a disk MHD unit with superconducting magnets is the basis for a high performance topping cycle in a proposed MHD-GT (Brayton)-ST (Rankine) heat recovery combined cycle for a future Generation IV nuclear power plant Optimized studies show that such a power plant could reach nearly 70% energy efficiency. This design would be a high fuel burn-up system with online extraction of fission products and most importantly for environmental and long-term economic viability this proposed concept would enable a completely closed fuel cycle (the only unspent nuclear fuel would result from the minimal amount of fuel in the reactor loop at shut-down when the plant would be decommissioned, this poses no long term storage problem whatsoever).

There is also a need for a new generation of navy propulsion systems. Seawater is highly conducting and a suitable fluid for MHD power or propulsion effect. Both in space power systems and on-board nuclear power for navy applications, the power conditioning sub-system delivering power to thrusters can comprise a considerable extra mass and complexity. If a G/VCR reactor was used to provide the gas flow for an MHD power generator, then this could be fairly simply and naturally coupled to a reversed MHD unit that injects energy (directly by ion acceleration) into seawater for navy vehicle propulsion. This is a potentially very efficient and compact way to provide ship propulsion. Both for space and navy propulsion a solid fuel reactor could also be used if the coolant could be activated enough by fission products and radiation to become electrically conducting, then MHD generators could again be employed for direct power conversion (see Figure 7).

NASA Support History of G/VCR-MHD Technology

Over the past few years NASA has fundeded four research projects with primary objective to explore and assess the viability of steady and pulse gas/vapor core reactors with MHD power conversion. These projects include:

1. NASA-MSFC Phase I Contract NAS9—01075, “A Fissioning Plasma Core Reactor Powered MHD-MPD Propulsion Sustem,” 2001

2. NASA-MSFC Phase II Contract NAS8-01075-II, ““A Fissioning Plasma Core Reactor Powered MHD-MPD Propulsion Sustem,” 2001- 2003

3. NASA-MSFC Phase I Contract NAS8-02103, “Ultrahigh Energy Propulsion by Pulsed Magnetic Field Compression of Fissile Plasma,” 2002

4. NASA-MSFC Phase II Contract NAS8-02103-II, “Ultrahigh Energy Propulsion by Pulsed Magnetic Field Compression of Fissile Plasma,” 2003-2005

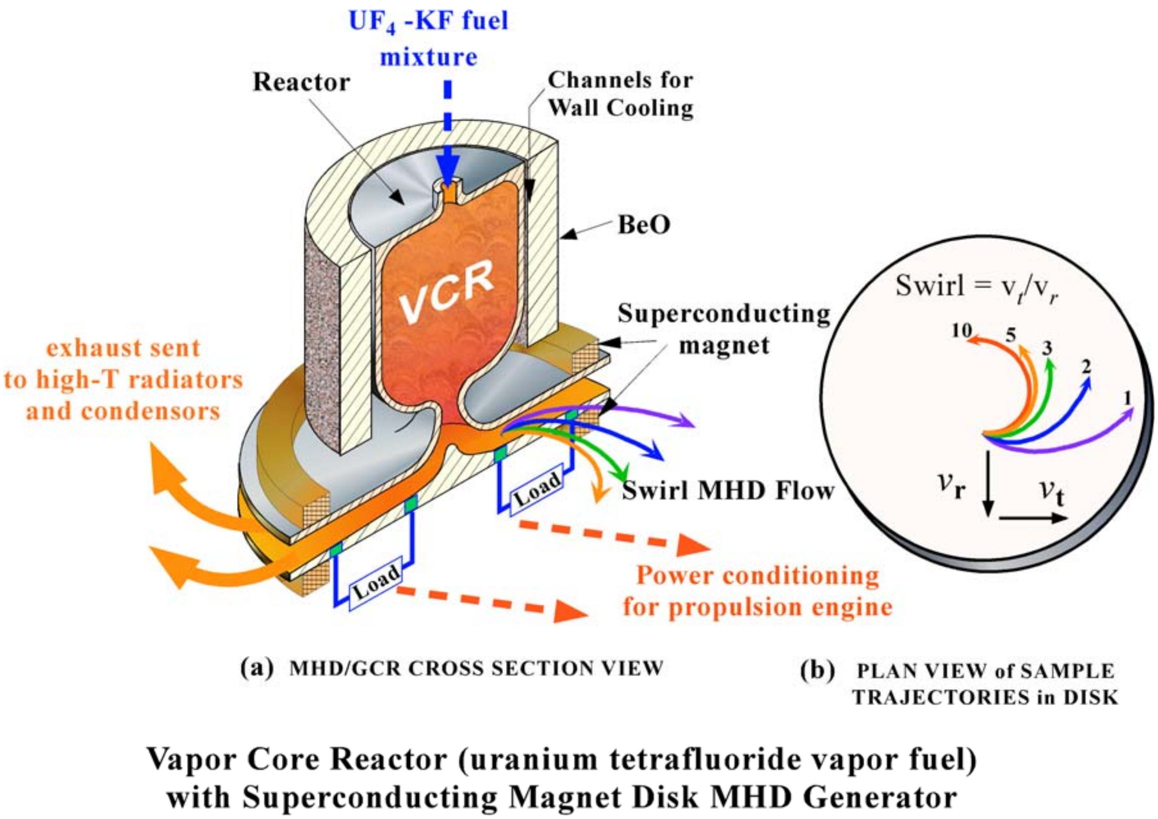
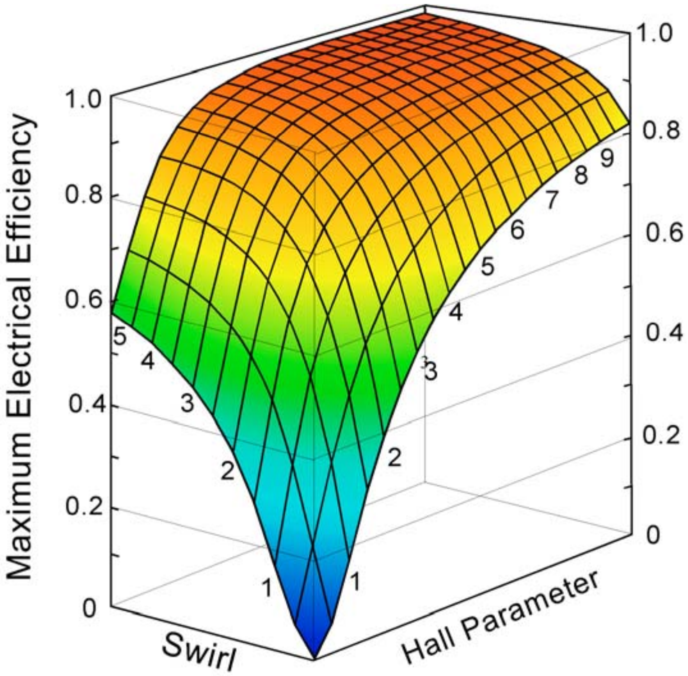


Figure 1. Schematic of vapor core reactor coupled to disk MHD unit for compact multi-megamatt space power and nuclear electric propulsion system. This single stage power cycle would be low in efficiency but extremely good specific mass with $\alpha < 1.0$ kWe/kg. If combined with a VASIMR engine plasma thruster it could comprise the basis of a very low specific mass nuclear electric propulsion vehicle.



$$\text{Swirl} = \frac{\text{tangential velocity}}{\text{radial velocity}}$$

$$\text{Hall parameter, } \beta = \omega\tau = (\text{e}^{-}\text{ cyclotron freq.}) \times (\text{e}^{-}\text{ mean free time})$$

$$\text{also, } \beta = \mu B = (\text{e}^{-}\text{ mobility}) \times (\text{applied magnetic field})$$

Figure 2. Parametric plot showing the increase in magnetohydrodynamic power generation efficiency of a superconducting magnet disk MHD generator operating using the Hall EMF with a swirling partially ionized gas flow. The electron mobility μ, is related to the plasma electrical conductivity σ and the electron number density n_e by $\sigma = n_e e \mu$., where e is the electron charge. When the Hall parameter exceeds unity the electron drift velocity can exceed the gas velocity and a significant "back" Hall EMF is generated that implies an MHD generator can extract more power by altering it's configuration. A disk-MHD device by design is fixed at always operating in the "Hall mode", so a large Hall parameter is required.

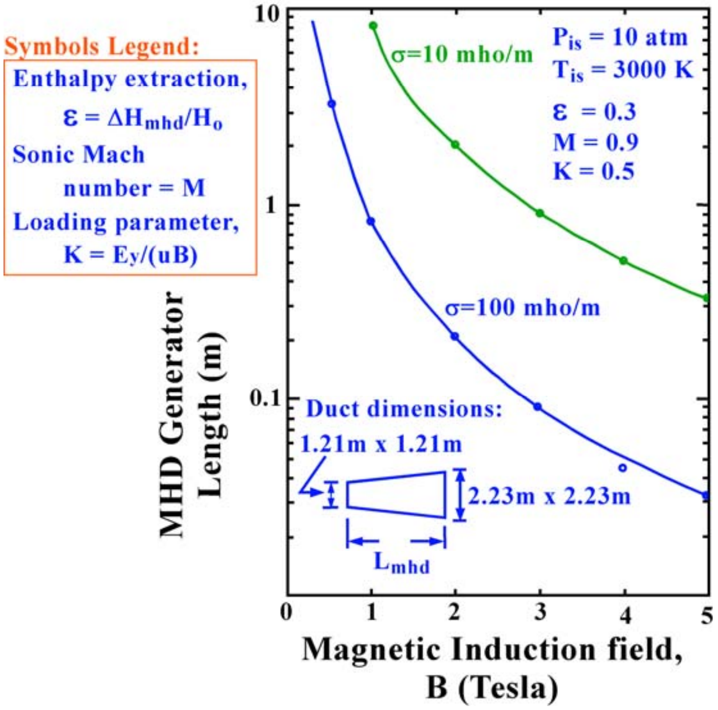
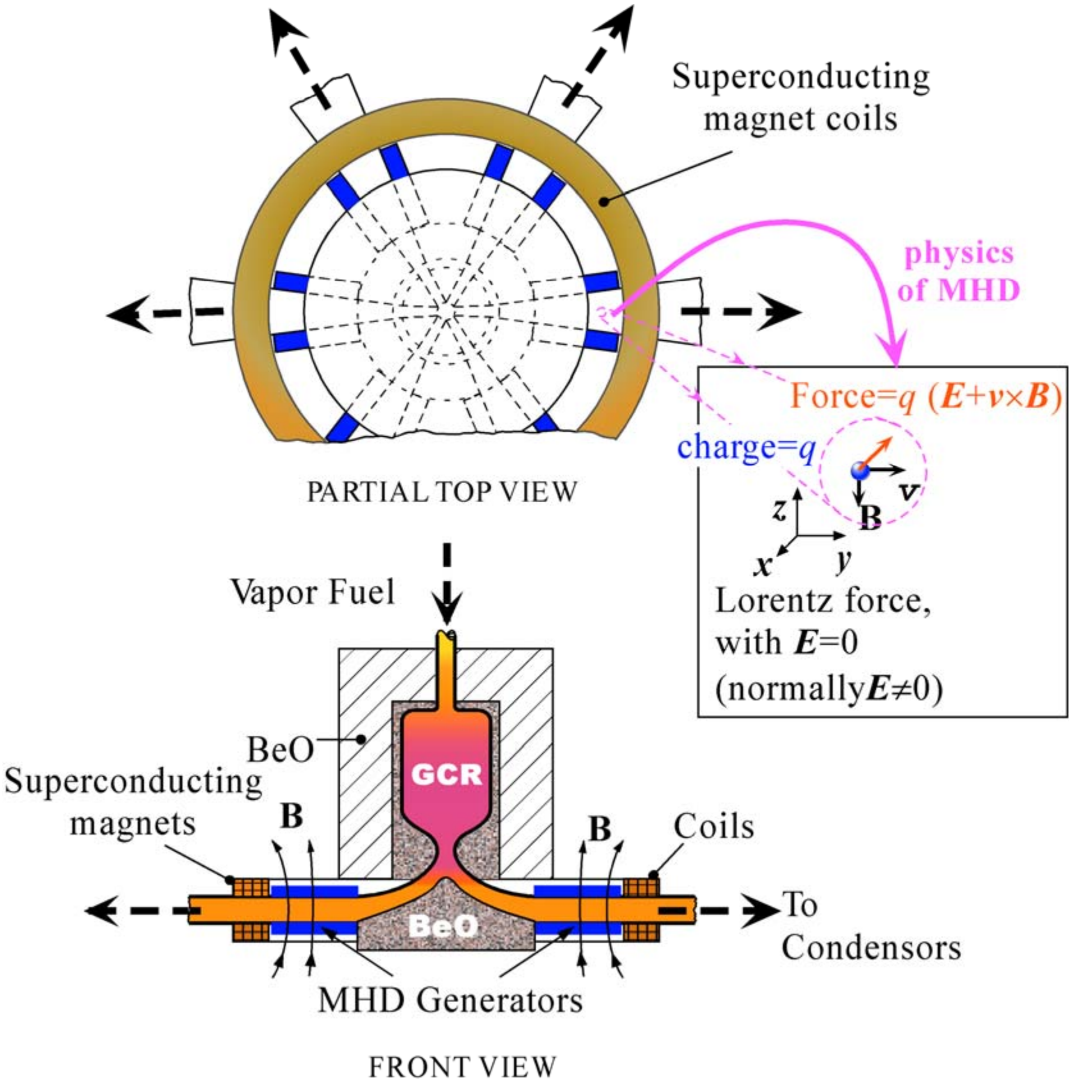


Figure 3. Plot of data showing the influence of magnet field strength and gas electrical conductivity on MHD power generator duct length. Maintaining a compact sized MHD generator is important in space power applications for both reducing the specific mass and maintaining strong gas conductivity (and hence power extraction) along the length of the MHD duct region. The plot illustrates the importance of both high gas conductivity and high magnetic field strength for compact MDH power generation.



Vapor Core Reactor with Radial Array of Superconducting Magnet Line MHD Generators

Figure 4. Alternative scheme to disk MHD coupled gas-core reactor. This concept uses simpler linear duct MHD generators arranged in a radial configuration. The system has good safety features due to redundant MHD generators, the simple linear duct design is more fail-safe than the single disk-MHD generator, so the additional MHD units contribute only marginally to increased probability of a single unit failure, leading to dramatic overall lowering of the risk of total system failure.

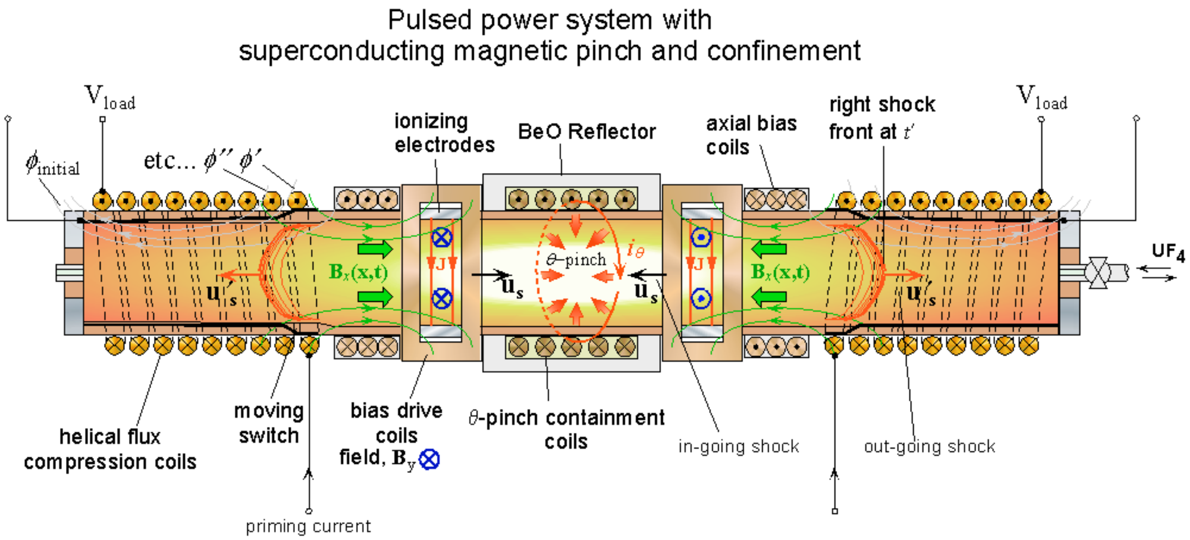
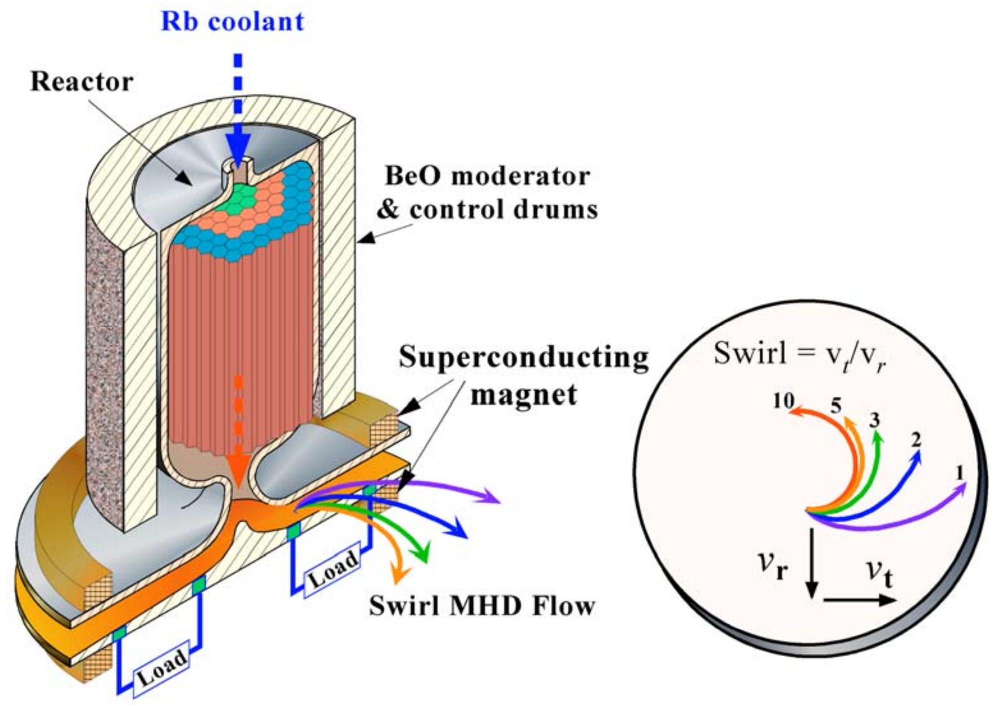


Figure 5. Shock-wave driven pulsed power concept for nuclear electric propulsion power generation. High field strength superconducting magnets are used for confinement but do not need to control the plasma for more than a few milliseconds, so plasma stability is not an issue, power is generated by moderate temperature fission in a highly enriched UF$_4$ gas mixture.



(a) MHD/LMCR CROSS SECTION VIEW

(b) PLAN VIEW of SAMPLE TRAJECTORIES in DISK

Liquid Metal Cooled Reactor with Superconducting Magnet Disk MHD Generator

Figure 2. Another nuclear driven MHD power generator concept using a CERMET fuel reactor with activated rubidium coolant for beta decay enhanced gas conductivity for high quality MHD power extraction. This system could be used for Generation IV nuclear power plants or for a new generation of nuclear powered navy vehicles.

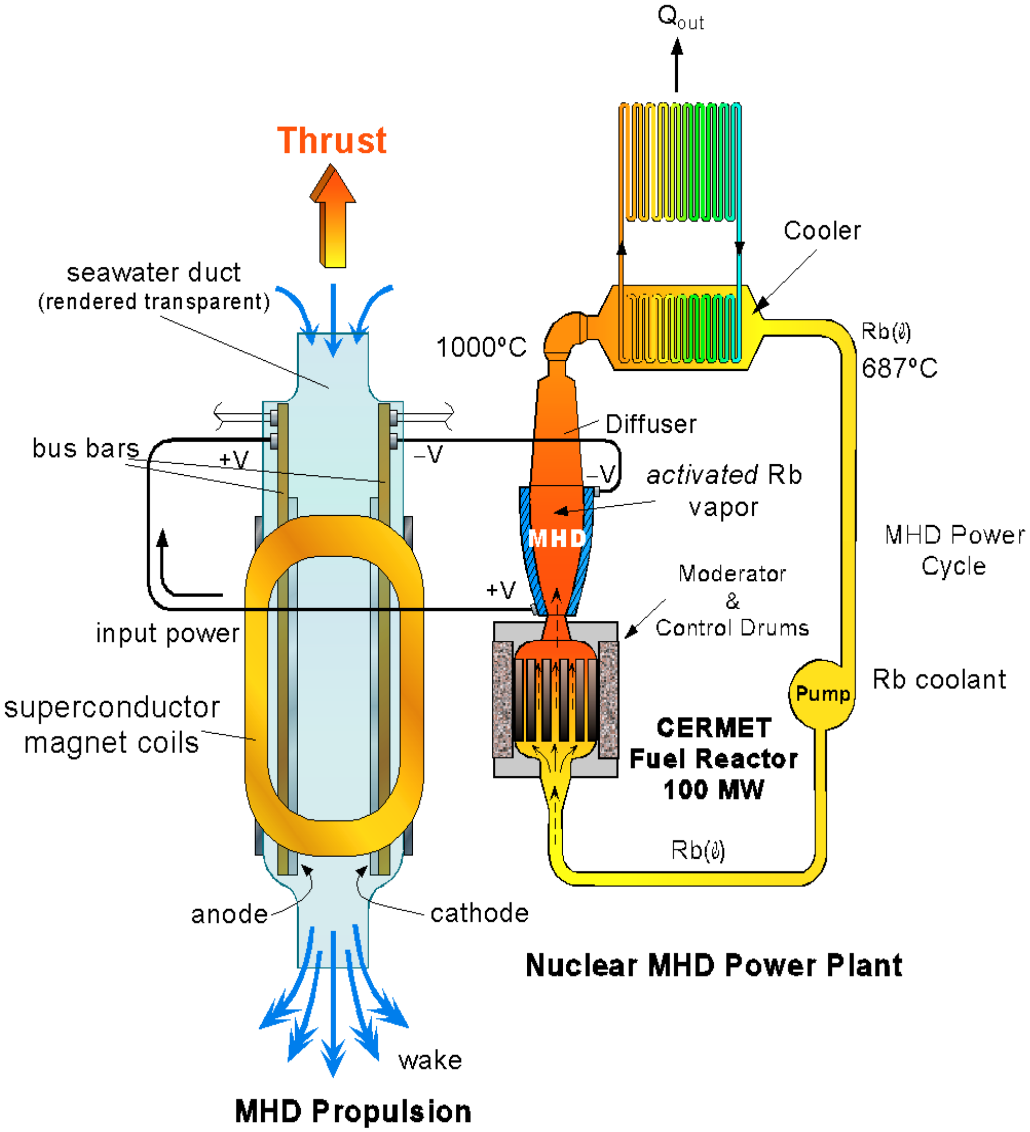


Figure 7. Cycle design and coupling of nuclear-MHD power unit to sea-water MHD propulsion system for naval propulsion.