Status of the Nuclear-Induced Conductivity Experiment (NICE) Project

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Nuclear-based magnetohydrodynamic (MHD) energy conversion has been pursued in various forms since the 1950's. The majority of this work was motivated by the compatibility of MHD generators with the high temperature achievable with a nuclear reactor and the associated potential for very high cycle efficiency. As a result of this perspective, methods for enhancing the electrical conductivity of the MHD flow have primarily focussed on traditional thermal ionization processes, especially those utilizing alkali metal seeds. However, electrical conductivity enhancement via thermal interactions imposes significant limitations on the flow expansion through the generator, and hence on the ultimate power density. Furthermore, the introduction of an alkali metal seed into the flow significantly complicates the engineering design and increases the potential for system failures due to plating of the evaporated metal on cold surfaces.

In order to avoid these limitations and difficulties inherent to most practical thermal ionization techniques, various non-thermal, non-equilibrium ionization processes have been considered over the past 50 years. The ability to achieve sufficient electrical conductivity, typically greater than 1 mho/m, independent of flow bulk temperature and the associated implications for enhanced flow expansion through the generator has motivated numerous investigations. Concepts for non-thermal ionization sources have included charged particle beams, lasers, rf energy, and electrical arcs, among others. The effectiveness of these concepts has been limited in large part by the necessity to utilize some fraction of the generator output power to drive the ionization source. Difficulties associated with introducing the ionizing energy to the flow have also limited the success and interest in these alternatives to thermal ionization.

One concept that has shown great promise in recent years is the utilization of energy released in nuclear interactions to enhance conductivity. Specifically, the kinetic energy liberated in interactions between reactor neutrons and isotopes with a large neutron absorption cross-section is used to ionize the surrounding gas via collisions. Some examples of promising interactions and the associated kinetic energy liberated per interaction include $^{3}He(n,p)^{3}H$ (760 keV), $^{10}B(n,\alpha)^{7}Li$ (2.3 MeV), $^{6}Li(n,\alpha)^{3}He$ (4.78 MeV), and the fissioning of heavy elements such as uranium (~200 MeV). Conceptually, either the reactor coolant gas or a parallel working fluid flowing through the region of high neutron flux is thermodynamically driven through a MHD generator. The neutron interaction energy can be introduced to the flow either by utilizing a flow composed of the interacting isotope (^{3}He, $^{235}UF_6$), seeding a bulk flow with the isotope (10% ^{3}He + 90% ^{4}He), or lining the flow channels with a solid form of the isotope (^{10}B, ^{235}U). By utilizing the reactor neutrons to enhance the electrical conductivity, none of the generated power is needed to drive the ionization source, resulting in higher overall cycle efficiency. Furthermore, the nuclear-induced ionization is volumetric in nature resulting

in a more uniform ionization than is possible with various beam or surface ionization processes.

By eliminating the dependence of the electrical conductivity on gas temperature, the range of application for nuclear-based MHD cycles is dramatically increased. Due to the temperature independent nature of the nuclear-induced electrical conductivity, the flow can be expanded to lower temperature and higher velocity through the generator resulting in higher power density and hence, a more compact generator for a given power output. Also, cycles operating at lower ultimate temperature become 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 expanded range of operation of MHD cycles utilizing nuclear-enhanced electrical conductivity may have application in high-capacity commercial power production, compact power for remote locations, space-based power and propulsion, and naval power. In an earlier report[1], the potential benefit and requirements for application to space power and propulsion was considered. In particular, this report showed that nuclear-MHD energy conversion is a feasible option for achieving a system mass to power ratio on the order of 1 kg/kW. A mass-to-power ratio equal to or less than 1 kg/kW is essential for fulfilling many of the envisioned NASA missions to the outer Solar System as well as manned exploration of the planets.

In order to evaluate the concept of nuclear-induced conductivity enhancement, the fundamental physics of the weakly ionized gas must be understood. Computational studies of nuclear-induced ^{3}He plasma indicate that useful levels of conductivity enhancement may be attainable independent of temperature. The computational model, CSOLVE, and predicted results for a static gas have been described in detail in past publications[2]. In brief, CSOLVE uses a two-temperature kinetic model of ^{3}He/^{4}He mixtures in a neutron field to calculate electrical conductivity. The model calculates the number density of atomic and molecular helium ions, atomic and molecular metastable helium neutrals, and free electrons as well as electron temperature from a set of kinetic rate equations that includes 22 different interactions. The conductivity model uses a standard series resistance model that combines the effects of electron-neutral, electron-ion, and electron-electron collisions allowing reasonable application over a wide range of charge and neutral densities.

The results of these computations are summarized in Figure 1 for the steady-state case of pure ^{3}He over a range of temperature, density and neutron flux in an infinite volume. This data indicates that at thermal neutron fluxes greater than ~10^{12} /cm^{2}s and density less than standard density, conductivity greater than 1 mho/m is achievable. This data also shows that the bulk temperature has a secondary effect on conductivity while the density is of primary influence. In this paper, the predicted behavior of ^{3}He plasma will be further discussed. This discussion will include brief descriptions of the behavior of the plasma species, transition from electron-neutral to electron-charge collision dominance, and decay of the conductivity in absence of the source.

In order to confirm these computational results, NASA Marshall Space Flight Center's Nuclear-Induced Conductivity Experiment (NICE) project is performing a series of experiments to measure the electrical conductivity and related plasma parameters in pure helium in both static and MHD flow conditions. There are three phases of experiments in various states of progress. In the first phase, the diagnostic tools needed to accurately characterize the nuclear-induced plasma are being developed and tested. For these experiments, a non-equilibrium helium plasma is created by means of a flood of energetic electrons. Up to 1 mA of electrons spread over a 10 cm diameter window are introduced into the helium gas at a nominal energy of 50 keV. Collisions between electrons and helium atoms produces an approximately volumetric ionization very similar to that caused by neutron interaction. For comparison, the energy deposited in the gas by the electrons is equivalent to the predicted effect of a thermal neutron flux of order 10^{12} /cm^{2}s. The second phase of these experiments uses the same diagnostic tools to fully characterize the nuclear-induced helium plasma for comparison to the computational results. These nuclear experiments are designed to cover the full range of density and neutron flux included in Figure 1. Finally, in the third phase of experiments, a sub-scale MHD flow utilizing non-thermal ionization is characterized to examine the effect of flow, magnetic field, and related parameters on the plasma kinetics. The MHD flow will make use of a 3 Tesla split coil superconducting magnet currently being fabricated. This paper primarily describes the objectives, design, and current results of these experiments.
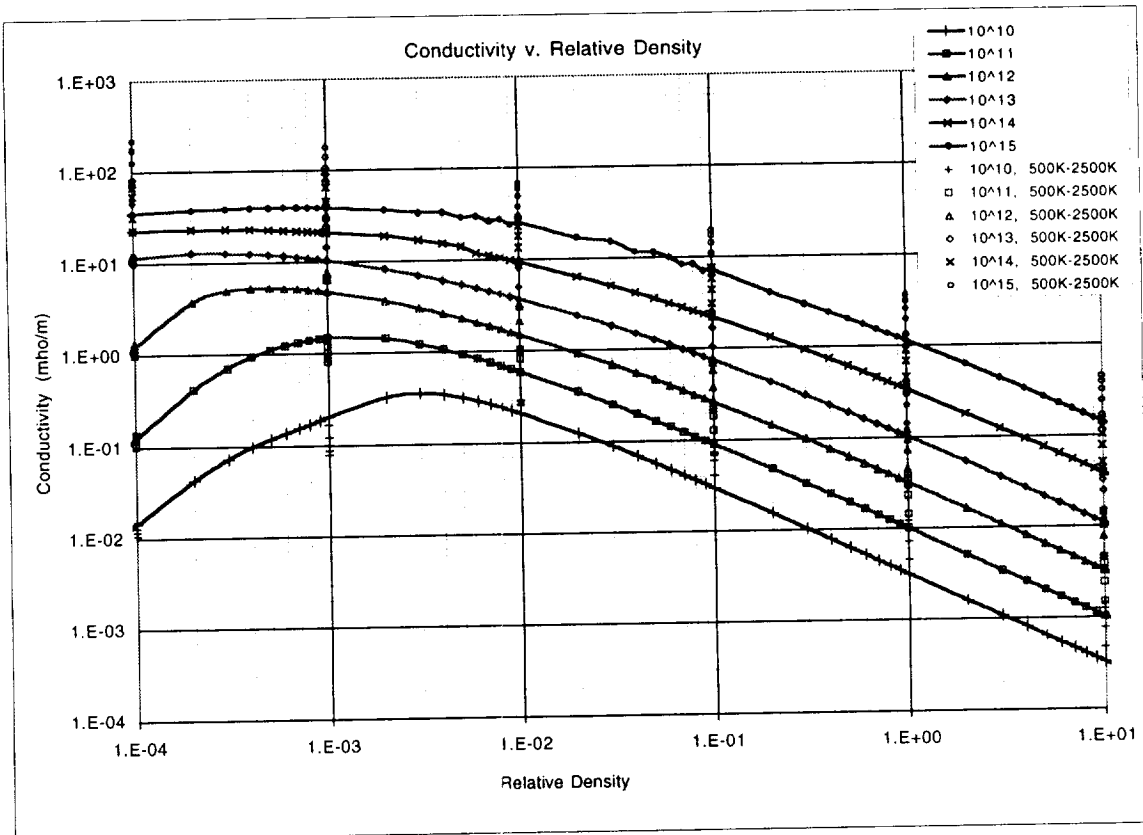
Figure 1: Electrical conductivity versus relative density in pure ^{3}He as a function of neutron flux (/cm^{2}s) and bulk temperature (K) as calculated by the CSOLVE computational model. Continuous line corresponds to 300 K, symbols plotted at each decade cover the range from 500 K to 2500 K.

References

1 - R. J. Litchford, L. Bitteker, J. Jones, "Prospects for Nuclear Electric Propulsion using Closed-Cycle Magnetohydrodynamic Energy Conversion," AIAA Paper No. 2001-0961, 39th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Jan. 2001.

2 – L. Bitteker, "Nuclear induced electrical conductivity in ^{3}He," *J. App. Phys.*, Vol. 83, No. 8, 1998, pp. 4018-4023.