A Review of Previous Research in Direct Energy Conversion Fission Reactors

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Introduction

From the earliest days of power reactor development, direct energy conversion was an obvious choice to produce high efficiency electric power generation. Directly capturing the energy of the fission fragments produced during nuclear fission avoids the intermediate conversion to thermal energy and the efficiency limitations of classical thermodynamics. Efficiencies of more than 80% are possible, independent of operational temperature. Direct energy conversion fission reactors would possess a number of unique characteristics that would make them very attractive for commercial power generation. These reactors would be modular in design with integral power conversion and operate at low pressures and temperatures. They would operate at high efficiency and produce power well suited for long distance transmission. They would feature large safety margins and passively safe design. Ideally suited to production by advanced manufacturing techniques, direct energy conversion fission reactors could be produced far more economically than conventional reactor designs.

The history of direct energy conversion can be considered as dating back to 1913 when Moseley[1] demonstrated that charged particle emission could be used to build up a voltage. Soon after the successful operation of a nuclear reactor, E.P. Wigner suggested the use of fission fragments for direct energy conversion. Over a decade after Wigner's suggestion, the first theoretical treatment of the conversion of fission fragment kinetic energy into electrical potential appeared in the literature[2]. Over the ten years that followed, a number of researchers investigated various aspects of fission fragment direct energy conversion. Experiments were performed that validated the basic physics of the concept, but a variety of technical challenges limited the efficiencies that were achieved. Most research in direct energy conversion ceased in the United States by the late 1960s. Sporadic interest in the concept appears in the literature until this day, but there have been no recent significant programs to develop the technology.

Technical Approach

In nuclear fission, more than 80% of the total energy release is the kinetic energy of the two, positively charged, major fission fragments. These fission fragments are born moving randomly in all directions and possess a very high positive charge. There are two major challenges to directly capturing the energy of these fission fragments. First, as the fission fragments have a relatively short range in solid materials, the fission must occur in a solid layer that is thin enough to ensure that there is a high probability that the fission

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fragment will be released from the solid layer. There are significant material science and reactor engineering issues for such systems. Second, in order to capture the energy of this charged particle directly, it must be decelerated across a 2 to 4 million-volt potential. The challenges associated with maintaining such charge differentials in an intense radiation field and capturing the charged particles efficiently are significant.

In previous efforts to develop fission fragment direct energy conversion, a number of reactor concepts were proposed. Most of these reactor concepts were based on some form of a fission electric cell known as a triode[3], illustrated in Figure 1. The central cathode is coated with a thin layer of fuel to permit the fission fragments to escape. The anode is held at a potential of several million volts. The space between the electrodes is evacuated to serve as an electrical insulator. When a fission fragment leaves the cathode it has a high kinetic energy and a large positive charge. It is decelerated by the charge differential and arrives at the anode with its kinetic energy exhausted and deposits its charge. Large numbers (100-400) of electrons leave the cathode with each fission fragment. Fortunately, most of these electrons are at low energies, less than 100 eV, and can be returned to the cathode by maintaining a relatively small negative bias (20-30KV) on a series of grid wires surrounding the cathode.

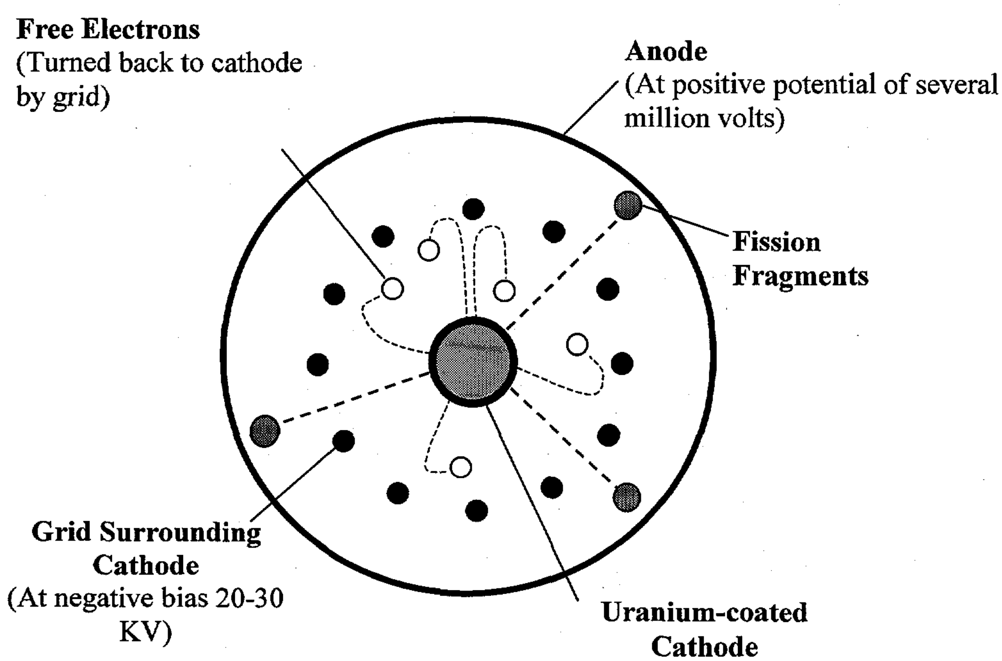

Figure 1 – Illustration of Triode concept for a fission electric cell.

Although hundreds of experiments[3,4] were performed to test the performance of these early triode fission cells, most of the work was devoted to understanding the nature of the charged particles and their control in the triode. These experiments were adequate to verify the fundamental physics of the process of fission fragment direct energy conversion, but the performance of these cells was too low to be considered for practical applications. A number of specific problem areas were identified[3,4] in these early research efforts, including:

- the understanding electron and ion behavior in complex electric and magnetic fields
- the development of insulators for high radiation environments
- the stability of high voltage differentials in radiation environments, and
- the fabrication and performance of thin film reactor fuels.

The poor performance of these early fission cells should not be too discouraging to those interested in the concept. These early designs were based on a "cut and try" approach to design of a complex system. Early attempts to model the performance of the fission cells[5] were limited to a relatively simple analysis of only a few systems parameters. A more comprehensive systems model[6] was developed towards the end of the research effort and, even though it was limited to relatively simple geometries it provided new insights into the design of fission cells. It appears that no additional experiments were performed in the United States after the development of this model.

More recent research on fission cells in Romania[7], has employed catastrophe theory to predict the critical neutron flux for maximum cell efficiency. Experiments by this same group[8], shows promising results for fission cells tested near these predicted critical neutron fluxes. These results are especially encouraging as the cell performance was improved significantly by only optimizing a single cell parameter.

Related Technology Developments

Although there has been little work in recent years in the field of direct energy conversion, many other research programs have made developments that could find application in advancing the technology. Specific advances that could find application in direct energy conversion include:

- Maintaining high voltage differentials in radiation environments – Research in pulse power inertial confinement fusion[9] and accelerator development programs has dramatically improved our capabilities in maintaining high voltage differentials in radiation environments. One obvious opportunity to improve the design of the triode cell is by eliminating the grid wires and employing a magnetic field to suppress electron flow. This concept was understood at the time of previous experiments in direct energy conversion but never tested. The magnetically insulated diode has been studied extensively since its invention in the middle 1970s in the ion beam fusion program. A magnetically insulated fission cell is essentially the reverse of a magnetically insulated diode. The improved understanding of the behavior of these high voltage devices resulting from fusion research could have a dramatic impact on fission cell design..

- Insulators and other material developments – Developments in space nuclear power for in-core conversion techniques such as thermionics[10] have advanced the state of the art in insulators and related technologies, such as metal to ceramic seals, for high radiation environments. In many ways, the environment in a direct energy conversion fission cell is less hostile than that encountered in in-core thermionic power conversion. These technologies should address many of the material issues that challenged previous researchers in direct energy conversion.

- Reactor pumped laser technology – Research in reactor pumped laser technology[11] has dramatically improved our understanding of fission fragment release from solids. Related developments in fuels technology has produced thin film fuels with long lifetimes and good manufacturability. Like reactor pumped lasers, direct energy conversion fission reactors will also have highly dilute reactor cores. Research in reactor pumped lasers has improved our understanding of the design issues in such systems and has application to direct energy conversion reactors.

- Advanced simulation technology – The greatest opportunity to improve the performance of direct energy conversion fission reactors is through the use of advanced simulation. The ability to accurately predict the behavior of the fission fragments in three-dimensional electric and magnetic fields is key to developing efficient concepts. Dramatic breakthroughs in this type of modeling[12], combined with the performance of modern supercomputers, provide tools to fully optimize the performance of such devices.

- Utilization of high voltage direct current power – The power form produced by fission fragment direct energy conversion, high voltage direct current, was a major barrier to commercial utilization 30 years ago as it was incompatible with the power generation and transmission infrastructure. Today, the conversion between high voltage direct current and alternating current can be performed with losses of only about 0.6% of total power and high voltage direct current power transmission is recognized as being more economical for long distance (over 600-800 kilometers) power transmission. This advantage exists even when the power conversion must be performed at both ends. High voltage direct current power generation would eliminate one of these conversion steps.

Even these many technological advances hardly make direct energy conversion fission reactors an "off the shelf" technology. Instead they provide confidence that a systematic and focused research effort could determine in a relatively short period if this technology should now be developed for commercial application.

Future Research

Even though the technical challenges associated with direct energy conversion fission reactors remain formidable, the payoff for success is a revolutionary method of electrical power production. A team consisting of Sandia National Laboratories, Los Alamos National Laboratory, General Atomics, the University of Florida, and Texas A&M University has recently been awarded a grant to study direct energy conversion. This three year research project will apply modern technologies to the development of direct energy conversion fission reactors. A preliminary design will be developed and assessed in terms of performance, technology development needs, manufacturability, and economics. At the end of this research program, potential customers will be able to make an informed decision as to whether direct energy conversion fission reactors are now ready to enter engineering development. Early nuclear researchers realized the unique potential of direct energy conversion fission reactors, but were unable to overcome the technical challenges associated with their development. The question today is whether we know have the knowledge to succeed where these pioneers of our field could not.

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