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Title: DIRECT ENERGY CONVERSION (DEC) FISSION REACTORS--A U.S. NERI PROJECT

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DIRECT ENERGY CONVERSION (DEC) FISSION REACTORS
A U.S. NERI PROJECT

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Abstract

The direct conversion of the electrical energy of charged fission fragments was examined early in the nuclear reactor era, and the first theoretical treatment appeared in the literature in 1957. Most of the experiments conducted during the next ten years to investigate fission fragment direct energy conversion (DEC) were for understanding the nature and control of the charged particles. These experiments verified fundamental physics and identified a number of specific problem areas, but also demonstrated a number of technical challenges that limited DEC performance. Because DEC was insufficient for practical applications, by the late 1960s most R&D ceased in the U.S.A.. Sporadic interest in the concept appears in the literature until this day, but there have been no recent programs to develop the technology. This has changed with the Nuclear Energy Research Initiative that was funded by the U.S. Congress in 1999.

Most of the previous concepts were based on a fission electric cell known as a triode, where a central cathode is coated with a thin layer of nuclear fuel. A fission fragment that leaves the cathode with high kinetic energy and a large positive charge is decelerated as it approaches the anode by a charge differential of several million volts, it then deposits its charge in the anode after its kinetic energy is exhausted. Large numbers of low energy electrons leave the cathode with each fission fragment; they are suppressed by negatively biased on grid wires or by magnetic fields. Other concepts include magnetic collimators and quasi-direct magnetohydrodynamic generation (steady flow or pulsed).

We present the basic principles of DEC fission reactors, review the previous research, discuss problem areas in detail and identify technological developments of the last 30 years relevant to overcoming these obstacles. A prognosis for future development of direct energy conversion fission reactors will be presented.

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 could possess a number of unique characteristics that would make them very attractive for commercial power generation. These reactors could be modular in design with integral power conversion and operate at low pressures and temperatures. They could operate at high efficiency and produce power well suited for long distance transmission. They could feature large safety margins and passively safe designs. 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. More than 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] During 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. That remained true until the U.S. Congress passed new legislation to fund nuclear research and development, the Department of Energy then initiated the Nuclear Energy Research Initiative (NERI), and researchers at Sandia National Laboratories and several other institutions became interested in once again pursuing this intriguing technology. We report herein the background for this NERI DEC project, recent progress, and future plans. Technical details of many of the concepts that are being examined in this project, including efficiency calculations, are reported in another recent paper.[3]

Technical Approach

In a 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 move randomly in all directions and possess a very high positive charge. Two major challenges limit the direct capture of the energy of these fission fragments. First, the fission fragments have a relatively short range in solid materials, so the fission reaction must occur in a solid layer that is thin enough to ensure a high probability that the fission fragment will be released from the solid layer. Significant material science and reactor engineering issues face such systems. Second, to capture the energy of this charged particle directly, it must be decelerated through a potential of 2 to 4 megavolts (MV). The challenges associated with maintaining such charge differentials in an intense radiation field and capturing the charged particles efficiently are significant. To calculate the efficiency of a direct energy conversion scheme that involves absorbing the kinetic energy of fission fragments in an opposing electrostatic field, the distribution in fragment energy and charge state must be known, so an analysis of the available information was made.[4] Information from that analysis is summarized below:

Charge, Mass, and Energy Distribution of Fission Fragments

Fission is a stochastic process, but it does have fairly well known average values of energy and fragments released, as well as distributions about those averages. Table I summarizes the average quantities that are familiar to most nuclear scientists and engineers. Each fissionable isotope has its own set of these values, and fission with fast neutrons produces a different distribution than fission with slow ("thermal") neutrons. The table below is for thermal neutron fission of ^{235}U only.

Table I. Average values for thermal neutron fission of ^{235}U.[5]

Item	Average Value	Approx. FWHM of spread
Total energy	202 MeV	
Fission fragments	166 MeV	15 MeV
Prompt gamma rays	7 MeV	
Neutrons	5 MeV	
Delayed beta particles	7 MeV	
Delayed gamma rays	6 MeV	
Neutrinos	11 MeV	
Number of neutrons	2.47	
Light fragment energy	91.1 MeV	12.6 MeV
Heavy fragment energy	58.8 MeV	20.3 MeV
Light fragment mass	95 amu	
Heavy fragment mass	138 amu	

Though the average kinetic energy carried from the reaction by the fission fragments is 166 MeV, there is fission fragment energy is spread between about 120 MeV to 180 MeV. An approximate full width at half maximum (FWHM) in the spread is 15 MeV. The energy of fission is shared between the two fission fragments and 1 to 3 neutrons; and the energy of a given fragment is approximately:

$$E = (166\,\mathrm{MeV})\left(1 - \frac{\mathrm{m}}{233\,\mathrm{amu}}\right) \quad (1)$$

where m is the mass of the fission fragment and 233 amu is the approximate mass of the two fission fragments combined. Table 2 also shows the average energy in each fragment, as derived by equation 1.

The fractional yields of a fission fragment of a given mass (A) and atomic number (Z) have also been tabulated.[6,7] Figure 1 shows a plot of the mass yield; the shape defined by the mass yield dots may be approximated by the sum of two Gaussian distributions, which facilitates modeling in computational analysis for the NERI DEC project. The yields are expressed as percent per amu--when the yields are summed they add up to 200%.

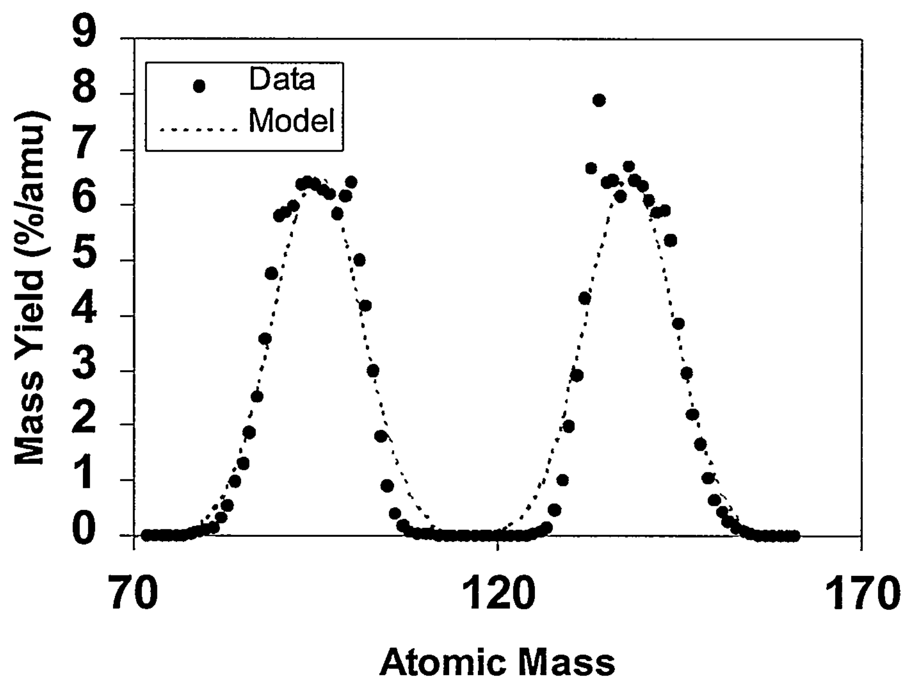

Figure 1. Mass yields vs atomic mass number of fission fragments for thermal fission of ^{235}U.

The energy-to-charge (E/q) ratio is the most important quantity for calculating the stopping of a fission fragment with an electrostatic field. The charge on a fission fragment depends on the atomic number, the thickness of material it has just passed through, and its velocity during passage. For a given velocity, the charge reaches an equilibrium value (balancing loss and gain of electrons) which is dependent primarily on velocity and atomic number.

Bretz[8] reviewed the literature on fission fragment charge and concluded that the following is a good formula for charge:

$$q = Z\left(1 + \left(\frac{v_0 Z^{\alpha}}{v}\right)^{1/k}\right)^{-k} \quad (2)$$

where Z is the atomic number, $v_0 = 3.6 \times 10^8$ cm/s, v is the fragment velocity, $\alpha = 0.45$, and $k = 0.6$. If the fuel is in a layer that is very thin compared to the range, then v is close to the initial velocity of the fission fragment. The resulting charge for a given fission fragment mass and atomic number is determined by equation 2, and the ratio E/q determines the voltage required to stop that fission fragment.

The range of gross fission fragments in U_3O_8 is 10 mg/cm^2, which corresponds to about 12 microns.[5] So the yields in Figure 2 are valid for uranium or uranium oxide layers much less than 12 microns. Deposition of uniform layers less than 2 microns has been demonstrated in past programs. Knowledge of this detailed information about the properties of fission fragments (energy, atomic number and mass distributions, energy to charge ratios, and stopping powers) will permit the NERI DEC team to use computational tools to investigate DEC concepts and their application to future reactors.

DEC Reactor Concepts

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,[9] which is illustrated in Figure 2. 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 of electrons (100 to 400) leave the cathode with each fission fragment. Most of these electrons are at low energies, less than 100 eV, so they can be returned to the cathode by maintaining a relatively small negative bias (20-30 kV) on a series of grid wires surrounding the cathode.

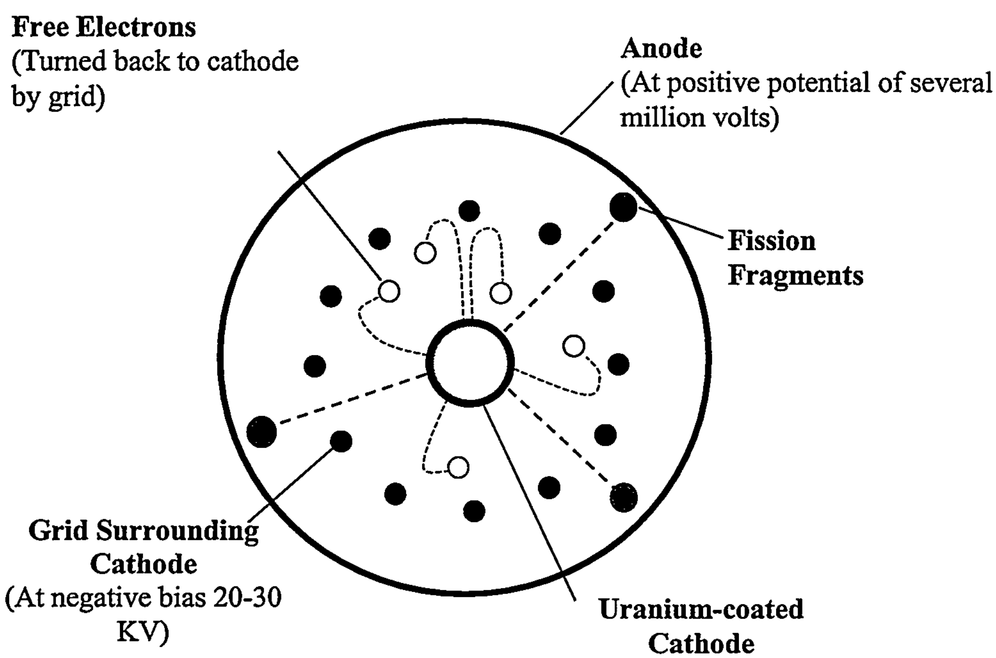

Figure 2 – Illustration of the Triode concept for a fission electric cell.

Although hundreds of experiments[9, 10] 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 these cells did not perform well enough for them to be considered for practical applications. A number of specific problem areas were identified in these early research efforts, including:

- the understanding of 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 an exceedingly complex system. Early attempts to model the performance of the fission cells[11] were limited to a relatively simple analysis of only a few systems parameters. A more comprehensive systems model[12] 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 has employed catastrophe theory to predict the critical neutron flux for maximum cell efficiency.[13] Results of experiments conducted by this same group show promising results for fission cells tested near these predicted critical neutron fluxes.[14] 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[15] and accelerator development programs have 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 entire design of the fission cell must be re-examined based on this improved understanding.
- Insulators and other material developments – Developments in space nuclear power for in-core conversion techniques such as thermionics have advanced the state of the art in insulators and related technologies, such as metal to ceramic seals, for high radiation environments.[16] 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 issues that challenged previous researchers in direct energy conversion.
- Reactor pumped laser technology – Research in reactor pumped laser technology has dramatically improved our understanding of fission fragment release from solids.[17] Related developments in fuels technology has produced thin film fuels that have long lifetimes and are readily manufactured. 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.
- 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.[18] Dramatic breakthroughs in this type of modeling 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 power transmission (more than 600-800 km). 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 will not 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 or other applications.

Recent 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 researchers at Sandia National Laboratories, Los Alamos National Laboratory, General Atomics, the University of Florida, and Texas A&M University is now conducting research on these concepts funded by a grant from the NERI program. This three year research project will apply modern technologies to the development of direct energy conversion fission reactors. A thorough literature search has already been completed, and more than a thousand pages of reports have been reviewed. After a down-selection process, a preliminary design will be developed and assessed in terms of performance, technology development needs, ease if manufacture, 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 now have the knowledge to succeed where these pioneers of our field could not.

To begin evaluation of alternate concepts for this research program, a number of potential "direct" conversion technologies were presented for consideration by members of the research teams. Although some of these concepts would not directly convert fission-fragment energy into electricity, they do take advantage of fission fragments or their ionized state, and they offer much higher conversion efficiency than thermal (steam or gas) cycles. The concepts that are being examined, listed in Table II, are discussed here only briefly. The Quasi-spherical Magnetically Insulated Cell is an attempt to overcome deficiencies of previous work that were caused by poor performance of electric grid suppression, while simultaneously taking advantage of advanced understanding of magnetic field analysis and superconducting materials. The Fission Fragment Magnetic Collimator is a concept similar to direct conversion for fusion reactors, with a different mass, energy, and charge distribution than fusion fuel and ash. The Knock-off Electron Collector would attempt to collect electrical energy from electrons that are knocked free from materials as high-energy fission fragments and electrons pass through them. Concepts that are less direct, or quasi-direct, include the Pulsed MHD Generator and the MHD Generator. Several other alternate concepts include Reactor Pumped Laser or Maser, Solid State Converters, Hybrid Converters, and Radioactive Isotope Direct Converter Spin-offs (The U.S. DOE has awarded a grant to the University of Missouri for a multi-year project to examine this isotope direct converter concept under second-year NERI funding).

Table II. Direct Energy Conversion concepts.

Name/description	Primary Responsibility
Quasi-spherical Magnetically Insulated Cell	Sandia
Fission Fragment Magnetic Collimator	Sandia
Knock-off Electron Collector	Sandia
Pulsed MHD Generator	General Atomics
MHD Generator	University of Florida
Reactor Pumped Laser or Maser	Sandia
Solid State Converters	Sandia
Hybrid Converters	Sandia
Radioactive Isotope Direct Converter Spin-offs	

During Phase 1 of the NERI DEC Project, these concepts are examined from several different perspectives, and a decision will be made to screen out those that are less promising, and to select two or three concepts for concentrated research and analysis. During Phase 2 of the NERI DEC teams will develop conceptual designs of components, systems, and reactors; will identify critical technologies; and will identify the most promising concept for further design work. Finally, in Phase 3 we will develop a detailed design of the most promising technology, perform detailed design analyses focussed on the key issues, and perform selected experiments. To facilitate our decision making, a framework for rating or scoring these concepts was developed based on a decision matrix. The metrics used in this matrix are based on properties of the concepts. Some of the metrics are listed in Table III.

Table III. Metrics for the determination of primary concepts for further NERI DEC research.

Feasibility	• Scientific Reasonability • Engineering/Technical Reasonability • If not feasible, document reasons • Identify spin-offs where ever possible.
Energy Conversion Efficiency	• Measured as a % of fission energy converted to electrical energy or system efficiency • Not the same scale as 30% thermal to electrical conversion for LWR since fission energy losses are not considered
Technical/Operational Specifications	• Operating Temperature • Material issues • Fuel Burn-Up • Utilization • Refueling • Waste Output • Control and Kinetics
Proliferation Resistance	
Safety	
Critical Path to Design	• Technology Road Map • Rough estimate of cost to develop

Although evaluations of these concepts for Direct Energy Conversion are not yet complete, Principle Investigators and others on the DEC research team have completed an initial comparison based on a preliminary decision matrix. Other than those in Table III, metrics included the following: 1) Is it DEC? and 2) Is there a potential for R&D at academic institutions? All metrics except efficiency were given scores from -1 to 1 (-1--not applicable or negative impact, 0--not certain, 1-- very applicable or high potential). Efficiency was given a score based on an initial assessment of potential gross or net efficiency for generating electricity. By using this method with weights assigned to each parameter or quality (see the last row of Table IV for weights), we determined that the primary candidates for future research are the Quasi-spherical Magnetically Insulated Cell, the Fission Fragment Magnetic Collimator, the MHD Generator, and Thermophotovoltaic (TPV) Hybrid Converters.

Table IV

Title	Is it DEC?	Feasi-bility	Effic-iency	Opera-bility	Aca-demic	Prolife-ration	Safety	Score 1	Prio-rity	Tech-nology
Quasi-spherical Magnetically Insulated Cell	1	0	0.5	0	1	-1	1	27	1A	Elect-romag.
Fission Fragment Magnetic Collimator	1	0	0.5	0	1	-1	1	27	1B	Elect-romag.
MHD Generator	0	1	0.7	0	1	-1	-1	25	2	FFAM HD
Thermo-photovoltaic (TPV) Hybrid Converters	-1	1	0.6	1	0	1	1	26	3	Photo-nic
Pulsed MHD Generator	-1	1	0.3	0	1	0	-1	4		MHD
Radiovoltaic Converters	1	0	0.2	-1	1	-1	0	2		Solid State
Reactor Pumped Laser or Maser	-1	1	0.02	0	-1	-1	1	-20		Photo-nic
Knock-Off Electron Collector	1	-1	0.01	-1	-1	-1	1	-26		Electro-static
weights	10	10	40	5	8	5	4			

Summary

This paper reports on an ongoing project to re-examine the science and technology for direct conversion of the electrical energy of charged fission fragments. Experiments were conducted during the 1950s and 1960s to investigate fission fragment direct energy conversion (DEC) to understand the nature and control of the charged particles. These experiments verified fundamental physics and identified a number of specific problem areas, but also demonstrated a number of technical challenges that limited DEC performance. Sporadic interest in the concept continued between the late 1960s and the 1990s, but there were no recent programs to develop the technology until Nuclear Energy Research Initiative was funded by the U.S. Congress in 1999. The U.S. Department of Energy then initiated a competitive, peer-reviewed NERI Project, and researchers at Sandia National Laboratories and several other institutions became interested in once again pursuing this intriguing technology. We summarized the background for this NERI DEC project, recent progress during Phase 1 of the project, and future plans.

Most of the previous concepts were based on a fission electric cell known as a triode, where a central cathode is coated with a thin layer of nuclear fuel. A fission fragment that leaves the cathode with high kinetic energy and a large positive charge is decelerated as it approaches the anode by a charge differential of several million volts, it then deposits its charge in the anode after its kinetic energy is exhausted. Large numbers of low energy electrons leave the cathode with each fission fragment; they are suppressed by negatively biased on grid wires or by magnetic fields. Other concepts include magnetic collimators and quasi-direct magnetohydrodynamic generation (steady flow or pulsed).

We presented the basic principles of DEC fission reactors, briefly reviewed the previous research, discussed problem areas, and identified a few technological developments of the last 30 years relevant to overcoming obstacles. A prognosis for future development of direct energy conversion fission reactors and plans for Phases 2 and 3 were discussed.

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