Power Production With Direct Energy Conversion*

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Introduction

The United States Department of Energy, Nuclear Research Initiative (NERI) Direct Energy Conversion (DEC) project has as its goal the development of a direct energy conversion process suitable for commercial development. We define direct energy conversion as any fission process that returns usable energy without using an intermediate thermal process. Enough of the project, one third, has been done to indicate that a viable direct energy device is possible.

This paper reports on the progress of the DEC project. It includes a short project description, an abbreviated summary of the work completed to date, a description of ongoing and future project activities, and a discussion of the potential for future research and development. Readers interested in technical details are referred to references [1] and [2].

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Project Overview

Experiments conducted during the late 1950s and early 1960s demonstrated the scientific viability of direct energy conversion. However, technical challenges and material constraints limited efficiencies that were attained to values below 10% [1]. Since then, dramatic improvements have occurred in such disciplines as computational mechanics and in technologies such as reactor-pumped lasers, pulsed power, and space nuclear power that directly apply to this problem. These developments may make it possible to refine the initial attempts to define an efficient and economical fission power conversion scheme.

A project team consisting of scientists and engineers from Sandia National Laboratories, General Atomics, Los Alamos National Laboratory, Texas A&M University, and the University of Florida obtained funding from NERI to investigate this potentially innovative energy source. The project consists of three phases:

- Phase 1 (complete) involved an extensive literature review to familiarize participants with previous activities in this area, the creation of nine concepts, and the down selection to three options. This activity is summarized in the Phase 1 report
- Phase 2 (ongoing) has as its goal the selection of one final option for detailed concept definition in Phase 3. The activity of this phase centers on the development of the information necessary to carry this process forward. This phase receives more detailed discussion below.
- Phase 3 (future) activities include final concept definition of the most promising concept, design and conduct of proof of concept experiments and completion of a final report that could serve as the technical basis for further commercial development.

Concepts Considered (Phase 1)

During the first phase of study, nine different concepts were investigated. These concepts were analyzed and ranked to select the top three concepts. Efficiency was given the most weight with feasibility, academic interest, operability, and proliferation resistance also being considered. Based on this review, the three concepts discussed above were chosen for further study. As always, safety was a necessary condition before the concepts were considered.

All the selected proposals use a magnetic field in various configurations to form a fission electric cell. In its simplest form, the cell's cathode, a fissioning material, emits charged fragments for collection by the anode. The fission process emits both positively charged heavy ions and negatively charged electrons. If the electrons can be separated from the positive charges, a usable voltage develops between the two electrodes.

Quasi-Spherical Magnetically Insulated Fission Electrode Cell. Early designs place a fine grid of negatively charged wire between the cathode and the anode. This grid forms a barrier to electron flow, but is inefficient. Advances in complex magnetic-field modeling and superconductor technology make it possible today to replace the wire grid with a more efficient magnetic field. Magnetic insulation was developed at Sandia for inertial confinement of fusion. This concept (Figure 1) uses spherical cells with the fissioning cathode placed at the center. High-intensity shaped magnetic fields trap the electrons near the cathode allowing the more massive fission fragments to reach the anode and deposit their charge.

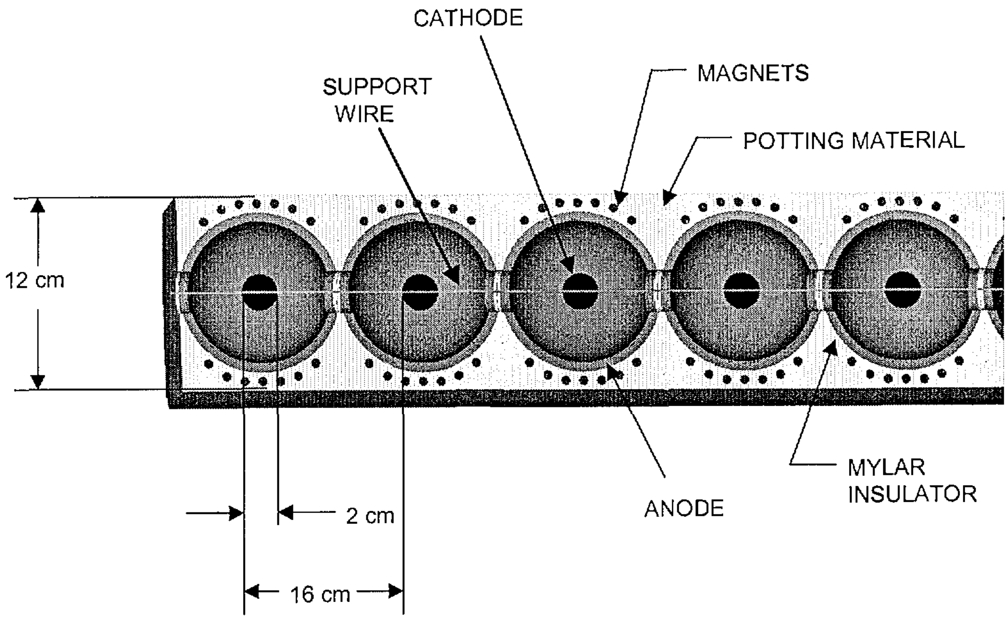

Figure 1. Stack of Quasi-Spherical Magnetically Insulated Fission Electrode Cells. Each cell produces 0.4 Watts of electrical power.

Because a spherical geometry maximizes the recovery of fission particles, this scheme could theoretically achieve efficiencies as high as 60%. Overall, this device would be very compact and would be stacked, like batteries, to produce the desired voltage and current. The concept allows for the creation of devices with remarkable efficiency and power-generation potentials.

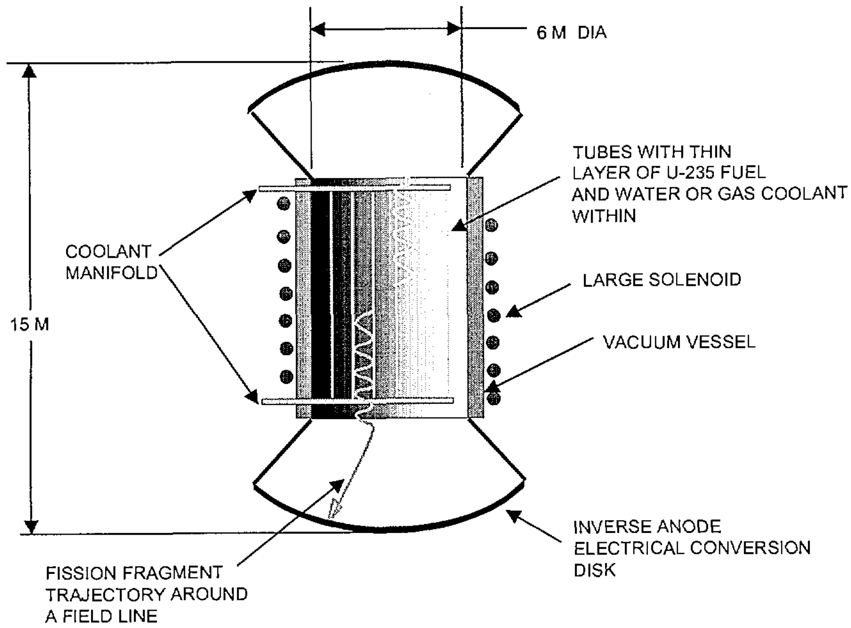

Figure 2. Fission Fragment Magnetic Collimator

Another use of magnetic fields is to separate the charged particles and fragments and direct them to the ends of a cylinder.

Fission Fragment Magnetic Collimator. This theoretical device (Figure 2) uses magnetic fields to direct positive and negative charges to common collectors. Fissionable material in thin wires is placed in a parallel magnetic field inside a cylindrical vacuum chamber. As the fuel fissions, the electrons and positive fission fragments remain separated and drift to the ends of the cylinder. At the ends, the particle energy is collected in an electric-field insulated collector. Efficiencies could reach 35%. These devices can be large and have the potential for generating large quantities of power.

Mathematical modeling indicates that efficiency for both the quasi-spherical magnetically insulated fission electrode cell and the fission fragment magnetic collimator depends upon having very thin assemblies of the fissionable material in the cathode. For these devices to succeed, fragments must leave the cathode with enough kinetic energy to reach the anode. That is, fission must occur close to the surface of the cathode.

Gaseous Core Reactor with MHD Generator. The next approach to direct conversion uses magnetohydrodynamics to generate electricity. A charged material moving through a magnetic field causes electrons to flow in electrodes. There are no moving parts. The higher the charge and the faster the fluid flow, the higher the electrical output. Such fluid devices are called magnetohydrodynamic (MHD) generators (Figure 3). One device, the gaseous vapor core reactor utilizes this principle. This direct scheme uses a high-temperature gaseous core reactor to generate partially ionized fissioning plasma that passes through an MHD channel to generate electricity. The unprocessed heat in the MHD cycle is transferred to a superheated Brayton cycle (gas turbine) and/or Rankine power cycle (steam turbine) to achieve combined efficiencies on the order of 60 to 70%.

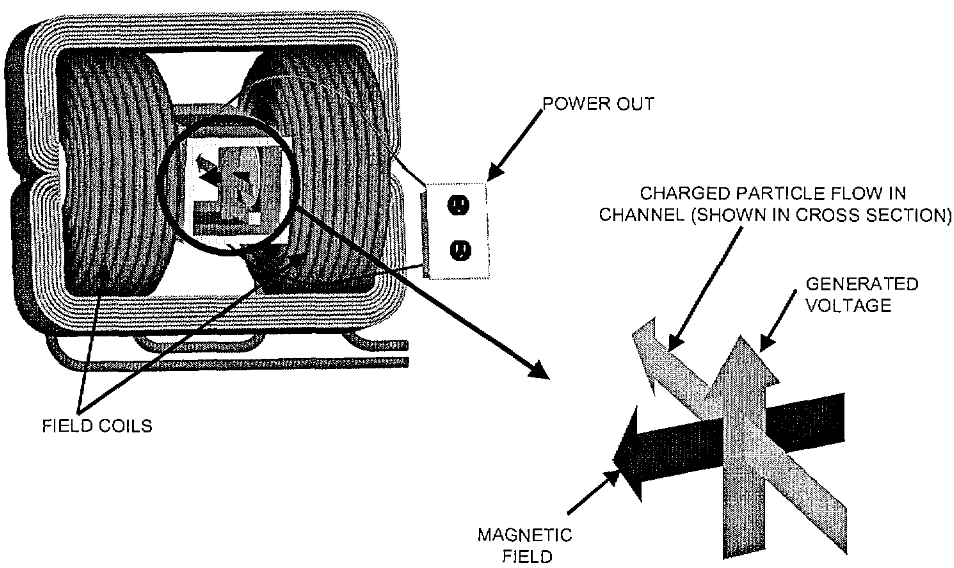

Figure 3. MHD Power Conversion Concept

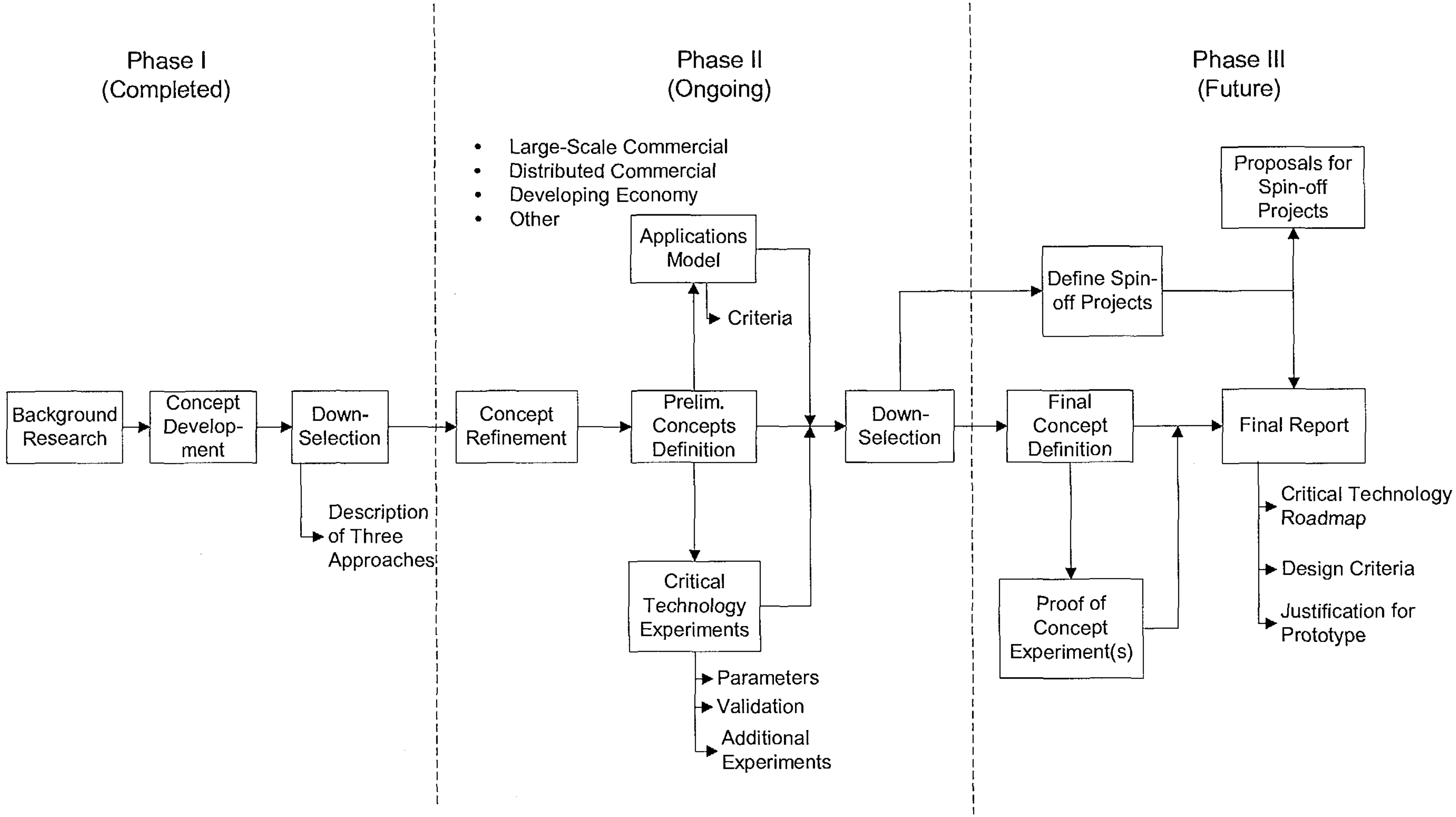

Figure 4. DEC Project Flowchart

The Path Forward (Phases II and III)

Figure 4 shows a flowchart of the project's plan to completion. The plan is subdivided into three phases, each lasting approximately a year. The central line of the flow chart shows basic method of the project – iteration and refinement of direct conversion concepts with down-selection after each refinement. Activities off the axis of the plan relate specifically to that phase and function to further refine the activity.

Given the project goal of commercial applicability, it is important that each of the concepts be measured against viable economic criteria. However, an issue that comes out of Phase 1 is the diversity of the concepts developed. This diversity makes economic evaluation difficult because each concept may fit a different market. The gaseous core reactor with MHD generator and the fission fragment magnetic collimator, for example, appear to fit a large-scale commercial economic environment, while the quasi-spherical magnetically insulated fission electrode cell appears better suited for distributed commercial use or possibly for use in a developing third-world economy. One activity of Phase 2 will be the development of applications models that describe the various economic environments and prescribe criteria against which the preliminary concept definitions may be measured.

The project identified four economic environments in which the concepts can compete:

- Large-scale commercial. This category would compete with current nuclear, coal-fired, or hydrocarbon-fired power plants. In this market, energy density, plant capacity, thermodynamic efficiency and capital efficiency are important criteria.
- Distributed commercial. This category would compete with such distributed applications as wind energy or hydroelectricity. While this is a small market now, trends in electricity deregulation may allow it to grow. For this market, flexibility, initial cost, and operating simplicity will matter.
- Developing economy. This category would support power development activities in remote areas and third-world countries. Important parameters will include size/weight, initial cost, inherent proliferation resistance and simplicity of operation.
- Other. This category covers such specialized and noncommercial applications as military or space applications. If a concept fits this category, it will be spun off for consideration by the appropriate funding organization (Phase 3).

The criteria included above do not constitute a complete list. The project team will work in Phase 2 building the list of criteria and associating them with each of the above environments. Upon completion of the high-level applications models, the team will determine the degree to which the preliminary concepts fit the criteria of each environment. The model will include a conceptual economic analysis for information only. It will use consensus techniques to establish degree of fit.

The second phase also involves a suite of critical technology experiments. These experiments validate physics models of the concepts and provide new or extend existing constitutive relationships that further the refinement process. Experiments fall into three possible classes:

1. Establishing and maintaining steady-state magnetically insulated gaps capable of holding tens of millions of volts per cm. This has been done to date only in the pulsed regime.
2. Demonstrating the efficiency of magnetically directing fission fragments.
3. Establishing the degree of ionization of fission gaseous vapor.

The increased knowledge will serve as the springboard for additional questions leading to further experiments in Phase 3.

The final activity of Phase 2 is to select one of the three concepts from Phase 1 for further refinement in the last phase of the project. By the end of the second phase, the team will have some experimental results and economic comparisons on which to base this decision.

For each of the three options, three possible outcomes exist. The primary option would be selected for additional study within the outline of this project. Alternatively, although unlikely, the results of Phase 2 analyses may dictate that the concept is dropped as unattractive. Finally, the team may choose to spin off a concept for one of two reasons. The idea may fit best in a military or space application. In the third case, the concept, while still viable, would not be allowed to divert resources away from the primary option.

By the time the project enters the final phase, the team will possess baseline information about the selected concept. The team will have not only the organized data from the critical technology experiments and the applications-model comparison, but also the additional ideas, synergy, and iterations associated with the down-selection discussion. Consequently, the first activity of Phase 3, "Final Concept Definition," (as shown in Figure 4) must integrate the information into a consolidated concept definition suitable for refinement and publication.

Equally important to the final project is the definition and conduct of experiments to provide preliminary proof of the chosen concept. While only one laboratory-sized rough prototype may be necessary, current planning must allow for the possibility that several parallel experiments are necessary to illustrate various aspects of the overall design.

Phase 3 experiments will fall into three classes:

1. Measurement of overall systems energy balance,
2. Preliminary systems integration, and
3. Reduced scale.

The philosophy of these experiments will be to sketch a roadmap for long-term research and development.

In order to avoid losing valuable information about spin-off possibilities, Phase 3 includes activities to define spin-off projects and prepare the technical data for use by others. These technical sections will be included in the final report.

Throughout the entire process, the intent of the project has been to provide the technical basis for an alternative commercial energy source. We expect the final report to provide continuity between this effort and any future design development and commercialization efforts.

Resulting Opportunities

In addition to the usual components of a project final report and the proposals for spin-off projects already discussed, this report must also contain:

- A project design criteria with the theoretical mathematical basis.
- Justification for continuation to the prototype phase.
- A preliminary roadmap of critical technological and commercial developments necessary for successful implementation.

The design criteria and justification will be discussed in a future paper. However, the roadmap provides an interesting subject for current discussion. The following table summarizes projected research opportunities. The table will change as the project matures and is presented here to provide insight into the project needs as a whole.

Research Opportunities

Technical	**Commercial**

1. Thin fuel technology
• Mechanical properties of Uranium compounds
• Criticality of cathode films
• Manufacturing processes with Uranium compounds
2. Magnetic insulation
• Field stability
• Superconducting materials
3. Materials characterization
4. Magnetic forces on high voltage electrodes
• Mechanical stability of electrode arrays
5. Reactor design
• Fuel cycle
• Core design
• Waste heat utilization system
6. Reactor control and possibilities of autonomous operation
7. Reactor safety design
	1. Scaling
	2. Infrastructure
	• Interface with commercial grid
	  • Frequency control
	  • Microwave transmission
	• Refueling and burn-up
	• Waste management
	3. Customer definition
	• Commercial
	  • Large scale
	  • Distributed
	  • Developing economies
	• Other
	4. Proliferation characterization

The table illustrates the need to balance technical development with commercial applications in this new technology

<u>**Technical Opportunities.**</u> As discussed previously, fission cells require very thin fuel structures to allow the fission products to escape to the anode. Design and

manufacture of these fuel structures will require a new discipline of thin fuel technology. While bulk properties of uranium and some uranium compounds are known, we know little about such details as response to work hardening or heat treatment, Poisson's ratios, or even details of the stress/strain responses. Similarly, little is known about our ability to maintain criticality in very thin films.

These unknowns bring up basic issues of manufacturability and industrial safety in the manufacturing environment. Given the size, geometry, dimensions and industrial-hygiene requirements of these devices, a requirement may exist for new designs for robotic fabrication technology.

Fission cells are inherently high voltage (~2 to 4 million volts) direct-current devices [1]. Perhaps high-voltage dc transmission is the best way to utilize this characteristic. On the other hand, it may be possible to use the magnetic field to create an oscillating current. Taken further, these oscillations may be shortened to the point that the cell output is in the form of microwaves, an easily transported energy form that can be used without alteration.

The magnetic field needed to control fission cells must be very strong. This raises the question of magnetic-field stability, particularly with transient conditions. Magnetic fields of this power need superconductor materials to achieve the field strengths required. The prospect of large-scale manufacture brings up again questions regarding material properties and manufacturing technique.

The intensity of the magnetic fields also gives rise to increased pressure on the electrode materials. Maintaining the required geometric tolerances may require high-strength materials.

Current reactor safety systems are designed to control large concentrated structures of potentially supercritical fissionable material in configurations that are not inherently safe. Given the diffuse nature of the thin films used in direct energy conversion systems, we can expect them to behave in ways that are completely different. This imposes new safety criteria and probably new safety system designs. In fact it probably means a rethinking of the analytic tools used in safety systems design.

Commercial Opportunities. The term "commercial" includes all those issues that arise with the development of large electrical energy markets. The growth of an industrial base to support a new energy source will happen via capitalistic processes. Entrepreneurs will need economic and social models and the data to feed these models to manage their risks. In addition, governments will need similar information in order to provide proper oversight and support. While the issues discussed below would appear to be of concern late in the development cycle, early decision makers will also need conceptual information and structure.

A most important issue will be analysis and control of the proliferation potential for these new nuclear fuel configurations. Is it possible to configure these new devices to virtually eliminate their attractiveness as sources of nuclear material for proliferation? If not, what level of protection is required? How does this affect commercial viability of the device? Risk managers will need modeling tools based on the material forms and flows of the new structures discussed above.

Developers will be interested in the optimum size for one of these new power plants. Are they best scaled for distributed implementation? The term "distributed" could mean something analogous to batteries for the individual user, a local generator, or possibly small plants feeding a massive grid. Perhaps these plants are best designed as massive centralized investments.

The kind of development under discussion here could mean the growth of a new utility form. The more likely effect will be significant alterations to existing forms. An interesting study, for example, might look at the impact of high voltage dc systems on the existing ac transmission/distribution network, and the regulations required to ensure compatibility.

Best refueling methods will depend on scale, and waste management depends on the refueling method. A small fission electric cell, for example, might be used up completely, then either discarded or rebuilt. The economics of this decision deserve investigation. On the other hand, a larger plant might use the existing nuclear power plant as a model. However, a new design would probably approach burn-up and waste management in entirely different manner.

Many of the issues discussed above depend on scale. The best scale, in turn, often depends on the characterization of the market size and demographics. We have used the terms large scale, distributed, and developing economy to categorize commercial markets. More study is needed to refine these descriptions and redefine them.

Conclusion

Technological advances of the last century, when applied to the old idea of direct energy conversion, may provide economic energy sources for the future. The DEC project identified three viable candidates for this new source. However, realization of their potential requires an investment in both technically and commercially oriented research. The direct-energy conversion project has a process in place to take one of these concepts forward and to outline the roadmap for further development. Future research and development should address a balance of technical and commercial issues.

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