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Civilian Applications of Particle-Beam-Initiated Inertial Confinement Fusion Technology

Samuel G. Varnado, John L. Mitchiner, Gerold Yonas

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CIVILIAN APPLICATIONS OF PARTICLE-BEAM-INITIATED
INERTIAL CONFINEMENT FUSION TECHNOLOGY

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ABSTRACT

Electrical power generation by controlled fusion may provide a partial solution to the world's long-term energy supply problem. Achievement of a fusion reaction requires the confinement of an extremely hot plasma for a time long enough to allow fuel burnup. Inertial confinement of the plasma may be possible through the use of tightly focused, relativistic electron or ion beams to compress a fuel pellet. The Sandia Particle Beam Fusion program is developing the particle-beam accelerators necessary to achieve fuel ignition. In this report we review the status of the particle-beam fusion technology development program and identify several potential civilian applications for this technology. We describe program objectives, discuss the specific accelerators presently under development, and briefly review the results of beam-focusing and target-irradiation experiments. Then we identify and discuss applications for the beam technology and for the fusion neutrons. The applications are grouped into near-term, intermediate-term, and long-term categories. Near-term applications for the beam technology include electron-beam (e-beam) pumping of gas lasers and several commercial applications. Intermediate-term applications (pellet gain < 50) include hybrid reactors for electrical power production and fissile fuel breeding, pure fusion reactors for electrical power production, and medical therapy using ion accelerators. In the long term, complex, high-gain pellets may be used in pure fusion reactors.

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CIVILIAN APPLICATIONS OF PARTICLE-BEAM-INITIATED INERTIAL CONFINEMENT FUSION TECHNOLOGY

I. Executive Summary

A. Introduction

Electrical power generation by controlled thermonuclear fusion may provide a partial solution to the world's long-range energy needs. Achievement of a fusion reaction requires the confinement of an extremely hot plasma for a time long enough to allow fuel burnup. Research on this problem has for many years concentrated in the area of magnetic confinement, and achieving the required confinement time has been a most difficult task.

The application of super-focused, relativistic electron beams (REBs) to the compression and subsequent heating of DT to fusion conditions by classical energy deposition in a high-density shell surrounding the DT was first proposed at Sandia Laboratories and separately at the Kurchatov Institute in the Soviet Union less than 4 years ago. After making substantial experimental progress in beam focusing and completing theoretical studies that indicated the scalability of these early results, an expanded program was initiated at Sandia to investigate the feasibility of the REB approach to pellet fusion. This effort has made substantial progress since its inception. The approach was broadened to include the use of ions, and a major ERDA commitment was subsequently made to pursue a comprehensive particle beam research program that could lead by 1985 to a net energy gain experiment.

The ultimate goal of the Sandia Particle Beam Inertial Confinement Fusion Program is to design and build an operational experimental power reactor by 1990. This reactor will provide the basis for the design of a commercial inertial confinement fusion reactor to be operable by 2000. In order for fusion-produced power to be a workable energy option for the United States, the reactors used must be reliable, efficient, safe, and economically competitive. Therefore, the technical goal of achieving a controlled fusion reaction must be balanced against the applications goal of achieving a practical power plant. Conceptual designs for fusion reactors are currently being developed within each fusion research program; however, there are technical uncertainties and impracticalities in many of these designs. For example, some authors believe that the 5000-MWe power capacity postulated for certain Tokamak reactor concepts is too large to be useful for most utilities. This asymmetry between technical and applications goals can worsen as progress is made toward achieving the controlled fusion reaction and the technical goals are focused more sharply at the expense of the practical aspects. Accordingly, Sandia has structured its Particle Beam Fusion Program to allow the aggressive pursuit of technical goals, while at the same time directing this activity toward developing a viable energy option.

At its inception in 1973, the Sandia Particle Beam Fusion Program was based on a fundamentally different approach to inertial confinement fusion from that found within the rest of the

AEC program. This approach was to use electron beams generated as efficiently and inexpensively as possible for direct pellet ignition and to arrive at a practical reactor concept with the fewest technical risks. Essential features of this program concept are the use of an efficient driver and reliance on the extensive pulsed-power technology base that is continually evolving to achieve scientific breakeven and net energy gain. Since 1973, several new discoveries have occurred that have led to a broader range of alternatives. Specifically, the use of ions as well as electrons for pellet ignition is being investigated as a natural extension of pulsed power technology since the accelerators developed for e-beam applications can also be used to accelerate ions. There are potential advantages to using ions rather than electrons and these advantages should be explored. The program can now be represented by a triad with pulsed power central to each approach.

Figure 1. Representation of the particle beam fusion program as a triad with pulsed power central to each approach

The Sandia Inertial Confinement Fusion Program is therefore best described as following a primary direction, the use of electron beams, but with alternate paths considered through the scientific feasibility stage in the early 1980s. At that point the scope of the program will narrow to a single approach (i.e., electrons, light ions, or heavy ions) to reach the goals of net energy gain and assured survivability of the accelerator components in the reactor environment.

Central to the research effort is the development of the pulsed power technology required to achieve pellet ignition. The goal of this program is to develop relatively small, simple, and thus inexpensive drivers for this application. This goal has been met for single pulse accelerators used in weapons effects studies and more recently in advanced e-beam accelerators for fusion studies. These accelerators are presently operating in the peak power range of $>10^{12}$ W. Operation at 4×10^{13} W, 500 kJ, is expected in 1980 with the electron-beam fusion accelerator (EBFA) at Sandia.

Since high average power (i.e., repetitively pulsed) driver systems are needed for any particle beam or gas laser fusion approach, we have initiated a pulsed power development program aimed at achieving megawatt average power levels by the early 1980s. The projected cost of these high repetition rate systems is estimated at \$20 - \$30/J, a cost significantly lower than that for

any other proposed fusion igniter. Based on Sandia's extensive experience in pulsed power technology development and the fact that a low-cost, efficient igniter will be required for a commercial power reactor, we are pursuing a vigorous program of accelerator development and subsequent application to particle beam fusion reactors.

B. Particle Beam Fusion Concepts

At the outset, we felt that particle beam initiators would be more efficient and less costly than laser beam initiators; our feelings have not changed. Present estimates are that efficiencies (e-beam energy/electrical energy input) as high as 50 percent are achievable with e-beam accelerators. Nd-glass lasers have efficiencies of 0.2 percent and are not being considered for reactor applications. Estimated efficiency for the CO₂ gas lasers is 7 percent. The product of igniter efficiency and pellet gain is the most important parameter in determining the recirculating power fraction for a power plant and, therefore, the cost of electricity produced by the plant. If similar pellet gains are achieved in laser-driven and particle beam-driven reactions, then the more efficient system will produce power at a lower cost, assuming the plant costs are approximately equal.

The immediate task, then, is to evaluate the relative usefulness of the three media (lasers, electrons, and ions) for driving inertially confined thermonuclear fuel and to determine the various efficiencies involved in the process.

Figure 2. Approaches to inertial confinement fusion illustrating conversion efficiencies at each point in the process

The direct e-beam approach has fewer steps than the laser approach if a hot electron gas can be produced directly. Because of the greater penetration depth of these relativistic electrons, targets must employ either massive ablaters and deal with the attendant increased energy requirements ($>10^6$ J), or the deposition characteristics of the electron must be modified in order to scale down the target mass.

The ion beam approach employs particles that have more suitable deposition characteristics than do electrons, and this approach leads to required beam currents for breakeven almost two orders of magnitude lower than that for electrons. This implies a lower diode impedance for the same beam power. The limited emphasis thus far on ion beam technology has provided an inadequate base to predict the practicality of efficient ion beam generation and focusing. Fortunately, recent discoveries in ultrahigh-current diodes may make it possible to convert the existing pulsed power technology to the ion option.

While particle beam fusion offers compelling advantages, there are also practical problems that demand attention. First, the peak power required on the target for ignition is approximately 10^{14} W. Generation of this high peak power requires advances in switching technology and pulse-forming techniques to provide the extremely short pulses (~ 20 ns) demanded. In addition, the beam must be focused to a small diameter at the target. Second, the beam must be transported to the target from the diode; or, alternatively, the microexplosion must take place within the diode. This second option creates a hostile environment for the diode that requires it to be made of durable or replaceable materials. We are presently investigating the possibility of using beam transport to increase the diode-target distance, thereby ensuring diode survivability even with high gain pellets. Finally, research is needed to optimize the beam energy deposition in the pellet for achievement of maximum pellet gain. In simplified terms, the thrust of the Sandia particle beam program is to find optimum methods for: power concentration and energy delivery to vacuum diodes, beam generation and focusing, symmetric and efficient energy absorption, compression of matter through stable implosions, and fusion ignition.

Our approach to these problems is subdivided organizationally into three major efforts--pulsed power research, theoretical research, and experimental research.

TABLE I
Electron Beam Fusion Program Outline

	Program Elements	Objectives
Pulsed Power	Energy storage; energy transfer and switching; power flow	Low cost; high reliability; high power density
Experimental and Theoretical Research	Beam generation and focusing; deposition physics; implosion physics and target concepts	Efficient beam concentration; Modified energy deposition; stable implosions

C. Program Status

The Sandia program has been underway for almost 4 years. Key previous milestones and future milestones in the program are illustrated on the following page.

A major immediate element in the program is the construction of a new facility to house the e-beam fusion accelerator. This facility is presently scheduled as an FY 77 line item. The accelerator will provide the capability to carry out a critical test of the REB fusion concept, in that sufficient power levels will be available to produce enough neutrons to carry out significant measurements. The accelerator will, in addition, test important elements of accelerator technology, beam generation, energy deposition, and pellet implosion physics.

The fundamental technology basis for EBFA is to be provided by the pulsed power program at Sandia. This program is geared to provide the technical basis for developing short-pulse REB accelerators that can be employed in pellet-implosion experiments. In order to test the elements of the proposed EBFA, two prototype devices (Proto I, 2×10^{12} W, and Proto II, 8×10^{12} W) are being developed that will incorporate relevant pulse forming lines, switching, and diode configurations. During the prototype development phase, operational experience will be obtained on both accelerators, and additional supporting studies are planned in industry and universities in order to ensure that an optimal approach to EBFA is taken.

A conceptual design of EBFA was completed in May 1975 that employed annular, water-insulated pulse forming lines and a dual-disk transmission line coupled to two face-to-face diodes. This accelerator is being designed to deliver 500 kJ at a peak power of 4×10^{13} W, a fivefold increase in power over that from the Proto II device presently under initial testing. Based on the experimental programs now underway on Proto I and Proto II, the final EBFA design completion and start of component procurement will take place in July 1977.

TABLE II

Electron Beam Fusion Program Key Milestones

1972	Low impedance superpinch beam experiments at 200 J on Nereus and then 800 J on SLIM.
1973	Theoretical models showing role of anode plasma and demonstration of plasma injection methods. Demonstration of 5-kJ superpinched beam on Hydra.
1974	Hemispherical target implosion experiments. Two-beam irradiation using Hydra. Flash radiographic technique developed for implosion studies.
1975	Operation of Proto I in untriggered mode. Demonstration of low-jitter, multichannel water switching. Symmetric single-beam irradiation of spherical targets. Theoretical discovery of enhanced ion flows in self-pinched diodes. Design of ion beam targets and ion beam fusion reactor concepts. Plasma-enhanced pinch collapse velocity on Proto I. Experimental confirmation of enhanced ion currents. New pellet concepts predicting breakeven with $< 10^{14}$ W using 1-MeV electrons. Shock response studies showing pusher breakup phenomenon.
1976	High resolution and multiple pulse holography and radiography studies of target implosions. Completion of development of Proto I. Initial operation of Proto II. Ion beam generation and focusing experiments on Hydra. Development of improved beam focusing and energy deposition codes.
1977	Measurement of neutron production using D-filled targets on Hydra. Complete the detailed design of EBFA. Complete development of Proto II and begin diode and target experiments. Carry out e-beam target experiments on Proto I. Advanced target studies on Hydra and Proto I. Begin beam focusing studies on Proto II.
<u>Projected</u> 1978-1979	Complete construction of e-beam fusion facility (EBFF). Detailed stability, symmetry, and target concepts on Proto II. Complete assembly of EBFA and initiate pulsed power testing. Advanced target experiments on Proto II at 8×10^{12} W. Begin Construction Planning and Design study for EBFA II.

TABLE II (contd)
Electron Beam Fusion Program Key Milestones

1980-1982	Beam focusing, electron and ion target experiments at $\leq 4 \times 10^{13}$ W. Initiate EBFA II construction.
1984	Net energy gain experiments on EBFA II. High repetition rate experiments.
1990	Operation of experimental power reactor.

As described above, the basic orientation of the e-beam program is the application of advanced pulsed power technology to ignition of e-beam driven targets, but developments have permitted broadening of the activity to include ion beam generation. Usefulness of the basic e-beam technology base for these other applications has become apparent in the last 2 years, and this other option is likely to play a significant role in the future. Several years ago we recognized that electron beams could be viewed as competitors to lasers for applications to inertial confinement fusion. We now feel that it may be possible to include in this consideration ion beams generated by the same accelerators.

The program plan for reaching power levels of $\sim 10^{14}$ W shows three steps prior to EBFA II, which has as its goal to reach net energy gain. If the proposed schedule can be met, ERDA will have a definitive basis in the early 1980s from which to decide the fate of the various methods of reaching inertial confinement goals. Protos I and II as essential parts of this program plan will provide the design information and operational experience required to define the EBFA-I characteristics and design details.

D. Experimental Results

Beam focusing is one of the most critical questions to be answered in applying particle beams to ICF. Proto I has been used for focusing experiments. Several diodes have been investigated, and focusing has been demonstrated. For example, 70 percent of the beam energy from a 56-cm-diameter cathode has been deposited in a 3.8-cm-diameter area at the center of the anode. Favorable conditions for fusion target exposures have already been obtained in experiments using 2.5-cm-diameter cathodes. Here, focusing to a 2-mm-diameter spot has been achieved.

Particle beam fusion experiments eventually will require that megajoules of beam energy be incident on a fusion target in 10 to 20 ns. To achieve this goal, speed and simultaneity of high-current switching, and high power flow through the interface separating the transmission-line dielectric from the vacuum diode region must be achieved. These concerns are significantly influenced by the dielectric fluid chosen for the accelerator insulation. Two investigative approaches were explored in laboratory tests. One approach used on Proto I followed a more conservative extrapolation from existing technology by using an oil dielectric and triggered multi-channel switches. The other more advanced but more risky approach employed a water dielectric

Figure 3. Program plan for reaching power levels of $\sim 10^{14}$ watts

and untriggered multichannel switches. The first of the water dielectric accelerators using this new technology, the 8 TW Proto II, is now under construction, and the second, EBFA, will begin operation in 1979 and produce about five times more power than Proto II.

In addition to experiments directed toward the development of pulsed power technology, target irradiation experiments have also been conducted. The first experiments to study target response used a 4-mm-diameter gold hemisphere placed on the anode at the diode axis. The configuration modeled one-half of a proposed dual-beam experiment in which both lines of the Hydra accelerator were to be used with a two-sided diode to obtain symmetric irradiation of an entire sphere. These initial experiments resulted in much greater damage to the anode than had been observed previously. The extensive damage was explained by computer simulations that showed that a dense gold jet, formed because of the momentum imbalance, pierced the flat copper anode.

Subsequently, we performed a more quantitative experiment to measure the hemisphere implosion time and the jet velocity with a laser reflection technique similar to that used for the simple flat anode target experiments. Computer calculations indicated that these measurements could provide an estimate of both the amount of beam energy deposited and the symmetry of the deposition. Additional information concerning plasma blowoff velocities and symmetry of irradiation was obtained with holographic and X-ray pinhole camera techniques. The combined

experimental and computational results indicated that from 17 to 50 percent of the beam energy could be deposited in the hemispheres, and that irradiation uniformity as good as ± 20 percent could be obtained.

A separate series of Hydra experiments was performed in which a 4-mm sphere was placed on a stalk at the focus of the electron beam. X-ray pinhole photographs from these experiments demonstrated that it was possible to obtain excellent uniformity (~ 10 percent) using only a single beam of the accelerator. This surprising result is thought to be due to the "hot fluid" nature of the focused electron beam, which tends to immerse the target in a gaslike cloud of electrons.

E. Theoretical Research

Design studies for e-beam pellet targets have continued since the first simple gold ablator-pusher target was first presented in 1973. These first target concepts required a peak power for breakeven of 8×10^{14} W using 1-MeV electrons. Work has since concentrated on lowering these requirements for electrons and also for the first time has considered the use of ions.

The most important recent development in e-beam target design was the consideration of fuel preheat and electron thermal conduction suppression. These ideas, which are very similar to those being considered at LLL, permitted calculations that showed breakeven for 1-MeV electrons at a peak power of 5×10^{13} W. This is more than an order of magnitude reduction below that first thought necessary. Other improvements in power requirements were considered using various ablator materials in order to minimize the effect of bremsstrahlung preheat of the inner wall, and it was found that these changes in themselves could reduce the power requirements by about a factor of four.

In 1975, ion beam target design studies began by following the design philosophy first adopted for electrons. These studies showed that breakeven could be achieved at 10^{14} W using 10-MeV protons, which means a diode impedance of 1Ω as compared to the impedances in the $0.01\text{-}\Omega$ range required for electrons. Further improvements were also predicted for ions using more complex targets, such as multiple shells leading to breakeven power predictions as low as 10^{13} W with 10-MeV protons. Clearly the design improvements using ions instead of electrons are substantial. The beneficial ion deposition characteristics yield an optimum voltage level roughly 10 times higher for protons than for electrons.

We have also recently initiated analyses of the important question of ablator stability using both analytical and numerical methods. Our results indicate that more stable implosions should be possible for electrons, in comparison to implosions driven by lasers, with ion-driven implosions falling in between.

2

In addition to our pellet design studies oriented toward reducing necessary breakeven levels, other work emphasized the design of targets for initial neutron production experiments. These initial experiments are being carried out using two basic methods: (1) multiple shells and (2) exploding pushers. The multiple-shell targets have been designed in conjunction with LASL and LLL, and the exploding pusher targets are being carried out in parallel with a similar design approach at LLL. A critical difference exists, however, between the Sandia and LLL exploding pusher target concepts. Sandia has postulated that self-field effects could play a dominant role in enhancing the energy deposition in thin-walled targets, and has designed its targets accordingly. These target calculations predict that measurable neutron yields can be achieved with an absorbed power of 0.2 TW.

One of the most important recent developments in our theoretical program was the discovery that ion emission from a region of plasma near the anode of a diode was required to obtain agreement with our measurements of e-beam current density. In 1976, using our two-dimensional particle code, we found that the treatment of ion flow was essential to explain beam pinching, and methods were devised to limit the ion current in electron applications.

As our knowledge of beam focusing capabilities, deposition physics, and target response advances along with the technology of complex target fabrication, a concrete evaluation of the feasibility of particle beam fusion will be made.

F. Near-Term Applications of Particle Beam ICF Technology

Particle beam accelerators being developed for the ICF program have potential civilian applications apart from fusion. Near-term applications for this beam technology include gas laser pumping and several commercial applications. The commercial applications include sludge purification, e-beam welding, hard-rock drilling and tunneling, radiography, and materials processing.

1. E-Beam Excitation of Gas Lasers

Gas-laser excitation with intense relativistic electron beams has gained popularity through many successful demonstrations of efficient conversion of e-beam energy to laser energy. In some instances, e-beam excitation of gas lasers has resulted in record laser energy and/or power, in higher efficiencies than have ever been obtained with any other excitation scheme, and in the discovery of lasers that have not been produced by any other excitation schemes. The feature of electron beams that makes this laser excitation scheme so promising for use in high-power lasers is the high-power capability of electron beams. Recent developments in untriggered oil and water switching at Sandia now permit one to construct compact, high-energy density, pulsed-power sources for laser excitation.

Recently, Sandia and Physics International combined to supply an e-beam generator to Los Alamos Scientific Laboratory for use in pumping KrF lasers for isotope separation experiments. This device delivers 300 J/pulse at a rate of 1 pulse/s in a 470-keV, 27-kA beam. Pulse duration is 50 ns. The high-repetition rate technology developed for this device is directly applicable to that required for inertial confinement fusion reactors. Higher pulse rates are possible with present switching technology at low beam power levels. For example, another accelerator designed to operate at a pulse rate of 100 Hz is under development. This device will have a beam voltage of 350 keV and should deliver 300 J/pulse in a 20-40-ns pulse. Experience gained during this development will enable extrapolation of switching techniques to the higher beam powers required for ICF.

In addition to the present use of low-energy, high-repetition-rate systems for laser pumping, there is also a requirement for high-energy laser pumping. For example, the existing relativistic e-beam accelerator (REBA) at Sandia has been used to ignite an HF chemical laser. This experiment utilized axial injection of the beam into the laser cavity. The machine was operated at a voltage of 2 MV with 50 kA delivered in a 70-ns FWHM pulse. This type of excitation is used for low-pressure gases or when the ratio of laser length to diameter is large. This geometry has been used to excite many lasers, and 2 kJ of laser output have been obtained from an HF chemical laser with an e-beam igniter.

The higher e-beam power levels that will be available with Proto I, Proto II, and EBFA may be effectively utilized to pump lasers for laser fusion. Lasers in the 10^5 to 10^6 -J range, operating at efficiencies of 1 percent, require pumping energies of 10^7 to 10^8 J. These levels will require multiple accelerators and multiple laser beams.

The main alternative to e-beam pumping of gas lasers is electric discharge excitation. There are several advantages of an electron beam over an electric discharge for high-power gas laser systems. (1) There are e-beam accelerators available that have both high power and high-energy capability. High-power excitation limits the degradation of laser performance by collisional and radiative deexcitation of the excited molecules that comprise the upper-energy level of the laser transition. (2) The energy source is decoupled from the excited medium. Consequently, nonlinear phenomena such as arc formation are less important. It is possible with electron beams to uniformly excite large gas volumes operating at high pressures. Also, since the energy deposition is not seriously affected by the electrical characteristics of the medium, gases that are electronegative can be used. (3) The electron energy distribution function may be more suitable for a specific application than that produced in an electric discharge.

There are, of course, disadvantages to e-beam excitation, such as unwanted X-ray production and low repetition rates. However, for many lasers, e-beam excitation is the most efficient, and developments in beam accelerators are extending the range of applications.

2. Commercial Applications

Sludge Purification -- Pulsed-power e-beam technology is applicable to municipal sludge sterilization in the near term. Sludge is the sediment resulting from the preliminary and primary treatment of sewage. An increased national awareness of water pollution problems and stricter governmental control on wastewater treatment have resulted in larger quantities of sludge that require processing to higher standards. As an indication of the magnitude of the problem, the average person in the United States generates 50 lbs of sludge yearly. The final disposition of this sludge requires significant expenditures in land and money. If the bacterial, viral, and infestation content of the sludge can be reduced enough to be considered harmless by health officials, the sludge may become salable as fertilizer, thus transforming a waste product into an asset.

The pulsed-power and e-beam technology required for sludge treatment is similar to that being developed as a first step toward inertial confinement fusion. The electron energies must be high in order to penetrate a reasonable thickness of sludge. Studies indicate that 3-MeV electrons are required for penetration of 1 cm of sludge. The beam energy requirements are on the order of 10 kJ distributed uniformly over an area of 400 cm^2 . The pulse rate requirement is approximately 10 Hz.

The degree of sludge disinfection and disinfestation is determined by the radiation dose. The electron accelerator system described above is capable of supply a 1-Mrad dose to approximately 100,000 gal of sludge per day assuming a 40-percent beam/sludge coupling efficiency. A 1-Mrad dose is sufficient to sterilize the sludge by reducing bacterial, infestation and viral contamination to insignificant levels. At these levels, there should be no health questions related to using the processed sludge as fertilizer.

A continuous, hot-filament electron beam is currently being operated by MIT at the Deere Island Waste Treatment Plant. The 50-kW accelerator uses a 750-keV electron beam to irradiate a 2-mm thickness of sludge with a 0.4-Mrad dose. The plant processes approximately 100,000 gal of sludge per day. The accelerator costs are \$6000/kW. The principal advantages cited for e-beam irradiation are (1) the controllability and availability of the beam, (2) the necessity for shielding only when the machine is in operation (3) the fact that no radiation is introduced into the sludge, and (4) the favorableness of economic studies. On the negative side, electron penetration is low at 750 keV, and the 2-mm thickness of sludge currently being used is marginal.

The sterilization of sludge is an increasingly important process in the United States for health and environmental reasons. Current practice does not appear to be particularly desirable; thus alternatives are being sought. Pulsed power e-beam accelerators developed for the inertial confinement fusion program will be potentially competitive. The desirable physical characteristics are the same as those being developed in the fusion program. The economics are currently soft, but favorable.

E-Beam Welding -- Welding with electron beams has become a common technique in many industries. Advantages of the technique are a high depth-to-width ratio in the weld zone, a small heat-affected zone, and the ability to join dissimilar metals. Many of the existing e-beam welders employ low-voltage beams (~125 kV) and require a vacuum region surrounding the weld zone. High-voltage, pulsed beams similar to those being developed in the ICF program offer additional advantages in welding applications. First, welding may be accomplished at atmospheric pressure because of the propagation characteristics of the high-voltage beam. Second, if a large amount of energy is delivered in a short pulse, the heat conduction loss is minimized, and a more efficient process is the result. Third, it may be possible to use the self-focusing characteristics of the beam to obtain a small weld dimension. The high-repetition-rate accelerators being developed under the ICF program may be directly applicable to the welding application.

Hard-Rock Drilling and Tunneling -- Present techniques for drilling and tunneling are slow and may require blasting. The use of electron beams for this application has been under study at Lawrence Berkeley Laboratories for several years. The objective of these studies is to increase the penetration rate in hard rock. Present drill/blast techniques proceed at a rate of approximately 5 mm/s. Spalling of rock with 1-to 10-MV electron beams has been demonstrated. The depth of spall is proportional to the beam voltage, and the amount of material removed per pulse is proportional to the energy of the beam. The conceptual design of an e-beam tunneling system that would bore a 7-m-diameter tunnel at a rate ten times faster than the conventional method has been completed. The device would use a high repetition rate e-beam accelerator similar to those being developed for the ICF program.

Radiography -- Intense X-ray sources are presently being used to perform radiography on thick samples. These intense sources are generated from intense electron beams. Many applications require repetitively pulsed sources. One example of this is the study of the motion of fuel rods within a reactor core as part of the Reactor Safety Research Program. The intense, repetitively pulsed electron accelerators being developed under the ICF program are directly usable in this application.

Materials Processing -- Another application for high-voltage electron beams is in curing inks and coatings and in initiating the cross-linking of polymers. In comparison to thermal curing, radiation curing offers lower fuel costs, faster production, less air pollution, reduced safety hazards, and increased design flexibility with heat-sensitive products. Ultraviolet sources can also be used in these applications. Electron beams may offer some advantages over these sources in terms of energy efficiency.

G. Intermediate-Term Applications of Particle Beam ICF Technology

Intermediate-term applications of ICF technology are loosely defined as those that can be realized from the present time until achievement of pellet gains of 50 or higher. There are applications both for the beam technology and for the fusion neutrons that can be produced with pellet gains of this magnitude.

1. Electrical Power Generation

The ultimate goal of the particle beam fusion program is commercial electrical power production. A number of reactor concepts have been proposed that would utilize electrons or ions to ignite a fusion reaction and convert the resulting 14-MeV neutrons into electricity. This conversion can be accomplished by using a lithium blanket (the pure fusion concept) or by using a fissioning blanket (the hybrid concept.) If the lithium blanket is chosen, electricity is the primary product of the power plant. If, on the other hand, the hybrid option is chosen, fissile fuel can be produced as well as electricity. An e-beam fusion reactor concept for low gain pellets is shown in Fig. 4, and cathode construction is detailed in Fig. 5.

The concept can be visualized by first considering a large metal "transmission disk" with an aperture in the center. An electromagnetic pulse from large energy storage and pulse-forming capacitors is released to the outside edge of the disk. The energy sweeps inward along both surfaces of the disk at the speed of light and emerges into the central aperture or diode as a radially flowing dual electron beam that converges onto the focal point of the diode.

The transmission disk is enclosed in a water jacket with the water acting as the high-energy-density dielectric to transfer the electromagnetic pulse to the diode. The diode is contained within a spherical vacuum chamber in which a solid insulator separates the water from the diode vacuum.

After the electromagnetic wave passes through the insulator at the perimeter of the diode, it is converted to a dual electron beam that flows in radially as a result of complex, self-generated electric and magnetic fields. Computer simulation of the particle flow provides an understanding of the resultant beam behavior, and a fairly simple picture has evolved. The magnetic fields near the common anode tend to counteract the effect of the electric fields farther away from the anode. As a result, the electrons move over the anode much as a flat stone skips over the surface of a lake. The pellet and plasma anode are replaced automatically after every firing.

The reaction region is surrounded by a blanket that converts neutronic energy from the fusion reaction into thermal energy for use in a conventional steam turbine power generation cycle. The minimum pellet gain that can be utilized effectively in this concept is determined by the beam generation efficiency, the blanket gain, and the steam cycle efficiency. This reactor concept lends itself to modular design and can result in small reactors.

Figure 4. Proposed configuration for an e-beam fusion reactor vessel

Figure 5. Detail of cathode construction

Energy gain is inherent in the neutronic conversion. For the lithium blanket, a gain of ~ 1.3 is realized, while hybrid blankets can be designed with gains as high as 75. The pure fusion option then requires a higher gain pellet than does the hybrid option. Power balance analyses of e-beam fusion reactors have indicated that pellet gains of approximately 10 can be utilized with a hybrid blanket to produce a viable reactor. In fact, breakeven pellets can conceivably be used if sufficient blanket gain is provided.

Since the diode is in close proximity to the microexplosion, it must be designed to withstand the blast and radiation environment that results from the fusion reaction. X-ray damage appears to be the most severe problem. Techniques for protecting the cathode; e.g., covering it with carbon cloth, are under investigation; however, diode vulnerability will limit the maximum pellet yield that can be used. Another approach receiving increased emphasis involves drifting of the beams to a distant target using a preformed plasma channel. This technique has been demonstrated recently and holds promise for use in high-gain scenarios.

Ion-beam initiated ICF can to a large extent alleviate the power flow problem since higher voltages are usable. One ion concept is to use geometric focusing to focus ion beams from ion diodes. This involves accurately shaping the electrode surfaces to produce a converging ion beam. Alternatively, heavy ion beams may be generated by collective ion accelerators or multi-stage accelerators. Heavy ions can be focused using magnetic optics. These concepts are under investigation; however, we will concentrate here on e-beam initiation of the fusion reaction. Whether electrons or ions are used, beam transport is a necessary ingredient for any high-gain pellet application.

In order for any fusion generator to be economically practical, the circulating power fraction (CPF) must be small, and this requirement places stringent demands on energy conversion efficiency and pellet energy multiplication. The CPF is the ratio of power required to operate the plant to the total power produced by the plant. To determine this quantity, the conceptual REB fusion power plant was structured into major subsystems as shown in Fig. 6.

Figure 6. Power balance diagram for a conceptual e-beam fusion power plant

In evaluating the CPF, two sets of subsystem efficiencies were used. While experimental data are needed in almost all areas, estimates of the efficiencies thought to be obtainable in a first generation system are listed in the second column in Table III. Further subsystem research and development should allow these values to be increased to those listed in the third column of this table.

TABLE III
Estimated Subsystem Efficiencies

Parameter	Projected Efficiency	Maximum Efficiency
Marx generator efficiency (η_M)	0.9	0.95
Beam-energy transfer efficiency (η_T)	0.65	0.85
Pellet absorption efficiency (η_A)	0.7	0.9
Blanket gain (η_L)	Variable	Variable
Thermodynamic cycle efficiency (η_E)	0.4	0.56

2. Relativistic E-Beam Hybrid Fusion Reactors

Many challenging problems remain to be solved before pure fusion reactors become a reality. An extremely significant milestone on this path will be achieved in the early 1980s when EBFA II is used to produce a scientific breakeven reaction; i.e., $Q = 1$. It is of interest to ask whether breakeven or low gain pellets are useful for commercial power generation.

In the hybrid concept, fusion-produced neutrons are used to cause fission in a subcritical heavy-element blanket surrounding the fusion plasma. The synergistic combination of fusion and fission enhances the ability of each technology to produce energy. The fast neutrons characteristic of fusion are capable of fissioning all isotopes of uranium and thorium. The fusion neutrons also convert fissionable blanket material into fissile material that can be used in light-water reactors (LWRs). In the fissioning blanket, the 200-MeV fission reaction improves the plant power production significantly and provides neutron multiplication. The fission neutrons, although of lower energy, improve the marginal tritium breeding characteristics of pure fusion. The hybrid system can be configured to emphasize electrical power production or fissile fuel production. The model shown in Fig. 6 is used to study the effect of a fissioning blanket.

Figure 7 is a plot of the CPF of an REB fusion reactor as a function of blanket gain, assuming a breakeven pellet ($Q = 1$). Breakeven plant operation ($CPF = 1$) occurs at blanket gains of 6 and 1.6 for the two cases. A CPF of 0.33 (a value thought to be necessary) occurs for blanket gains of 23 and 9. Therefore, a breakeven fuel pellet can be used in the power generation mode if sufficient gain is provided in the blanket.

It is anticipated that breakeven pellet gain can be obtained for e-beam energies of the order of 1 MJ. Use of such generators in 100-MWe modular power plants may be an attractive option. To produce this power level, the system must be repetitively pulsed.

Figure 8 illustrates the pulse repetition rate required for a 100-MWe hybrid reactor as a function of blanket gain when a breakeven pellet is assumed. An absorbed e-beam energy of 1 MJ is assumed. Blanket gains in excess of 20 are required to reduce the repetition rate to < 10 Hz. If a pellet with increased gain is used in conjunction with a hybrid blanket, considerable relaxation of subsystem requirements is allowed. With a gain-10 pellet and gain-50 blanket, the required repetition rate drops below 1 Hz.

Figure 7. Circulating power fraction as a function of blanket gain for a hybrid reactor with unit pellet gain

Figure 8. Pulse rate as a function of blanket gain for a 100-MWe hybrid reactor operating at unit pellet gain

A systems simulation model has been developed that optimizes the design of an e-beam fusion hybrid power plant. The following table summarizes the results for two different pellet designs using a hybrid blanket with a gain 7 designed by LLL. One pellet has a high-density ablator-pusher. The other uses a low-density ablator and a high-density pusher. Revenue is assumed for both electricity and fissile fuel. The calculation indicates that such a system would permit pellet costs as high as \$0.45 at a capital cost of \$2100/kW. Because of the high efficiency of the e-beam generator, pellet gains of approximately 10 can be utilized.

TABLE IV
REB Hybrid Reactor Plant Parameters for Alternative Pellet Designs

<u>System Characteristics</u>	<u>Low-Density Ablator Pellet</u>	<u>High-Density Ablator Pellet</u>
Pellet gain	12.0	7.7
E-beam energy	21 MJ	16 MJ
Vessel pulse rate	3.4 Hz	7.2 Hz
Number of vessels	1	1
Chamber radius	6.1 m	6.2 m
Plant capacity	1230 MWe	1220 MWe
Allowable pellet fabrication cost	\$0.46/pellet	\$0.44/pellet
Price of fissile fuel	\$30/g fissile	\$30/g fissile
Capital cost per kW capacity	\$2100	\$2150

3. E-Beam Fusion Reactors

Pure fusion reactors are usually envisioned as employing a lithium blanket for neutronic energy conversion and tritium breeding. The conversion gain for such a blanket is $\eta_L \cong 1.3$. Using a pure fusion blanket requires higher pellet gains than are needed with the hybrid system. However, because of the higher efficiencies associated with particle beam accelerators, it appears possible to achieve pure fusion electrical power generation with intermediate-term ($Q < 50$) pellets. To illustrate this point, we again utilize the model depicted in Fig. 6.

Figure 9 is a plot of the CPF of a hypothetical e-beam fusion power plant as a function of pellet gain for the two sets of efficiencies. Breakeven power generation occurs at unity CPF. Note that pellet breakeven ($Q = 1$) does not imply breakeven power generation for the subsystem efficiencies assumed here.

Figure 9. Circulating power fraction as a function of pellet gain for a conceptual e-beam fusion power plant

Earlier economic estimates of laser fusion power plants indicated that a circulating power fraction (CPF) less than 0.33 would be required for economic feasibility. However, the precise value required will be determined by system costs and by the revenue-producing capability of the system; i. e., the worth of the product. To achieve this value of CPF in a pure fusion reactor would require a pellet gain of approximately 100 with a low efficiency igniter. Therefore, in light of the definition of "intermediate term" used here, pure fusion reactors would not be achievable in this time frame with low-efficiency igniters. On the other hand, an e-beam fusion reactor should be able to achieve $CPF = 0.33$ at a pellet gain of 16 with a lithium blanket. Of course, higher gains are desirable; but because the generation of electron beams is efficient, it appears to be possible to achieve pure fusion electrical power generation in the intermediate term with e-beam-driven fusion reactors.

A value for CPF of 0.33 is obtained with pellet gains of 16 and 5.5 for the projected and maximum efficiencies, respectively. The gain of 5.5 required with the maximum efficiencies appears obtainable based on theoretical predictions of pellet performance.

Pulse repetition rate for a reactor supplying 100 MW_e to the electrical grid and employing a 1 MJ e-beam is shown in Fig. 10 as a function of pellet gain. This rate is important in determining fuel requirements, e-beam switching configuration, and wall loading. At a nominal pellet gain of 10, pulse repetition rates of 35 and 17 Hz are required for the projected and maximum cases, respectively. Pulse rates of < 10 Hz require pellet gains in excess of 20. Techniques for operating pulsed power systems at these rates are being developed. It may be that inductive energy storage with resonant charging and discharging must be used ultimately. In addition, new, higher-gain pellets that would relax these requirements are being investigated.

Figure 10. Pulse repetition rate as a function of pellet gain for a 100-MWe reactor (energy absorbed by pellet = 1 MJ)

In summary, the high efficiency with which particle beams can be generated may permit achievement of a pure fusion ICF reactor with intermediate term pellets. Problems to be solved include diode protection, optimization of pellet design, and development of high-repetition-rate accelerators.

4. Medical Therapy

High energy ions that may be useful for the initiation of fusion reactions may also have medical applications. The development of GeV collective ion accelerators such as that using the ionization front approach may result in compact accelerators and subsequent application to cancer therapy and radiography.

For radiography, an energetic beam of ions (protons, or heavy ions) may be employed to produce high-contrast radiographs. The deposition profile of ions can be utilized so that small variations in tissue density create large variations in the final radiograph. The advantages of ion beam radiography (which include substantially lower doses) over conventional X-ray radiography are presently being assessed in several active research programs that use conventional accelerators. The energy levels and total fluxes required for radiography (for protons, these are ~ 200 MeV and 10^8 , respectively) should eventually be easily attainable by a collective accelerator.

For cancer therapy, energetic particle beams (protons, heavy ions or negative pions) can be used to irradiate and destroy cancerous tissue. These particles have a higher relative biological effectiveness (RBE) than do gamma rays. This means that a smaller radiation dose can be used to produce the same effect as a larger dose of gamma rays. They also have a smaller oxygen enhancement ratio (OER), which means that damage to healthy tissues is minimized. Further, because of the deposition characteristics of the ions, deep-seated tissues can be radiated effectively.

The relative advantages of various particles for cancer therapy are being assessed in several ongoing research programs using conventional accelerators, but it may be some time before the best particle for cancer therapy is clinically established. In any event, the energies and current levels required for protons, heavy ions, or negative pions are within the range of those projected for ion-beam ICF.

H. Long-Term Applications for Particle Beam ICF Technology

For the purposes of this report, long-term applications are those for which pellet gains of greater than 50 are utilized. The ultimate, long-term goal of the particle beam fusion program is to produce electrical power. Other applications are secondary. Although the low-yield pellet approach should permit pellet ignition within a hollow diode structure, systems studies have indicated that this approach would be of economic benefit only if high repetition rates and inexpensive pellets were used, or one employed a fissioning blanket for breeding and power production (the hybrid concept). The obvious, and by now well-known, advantages of hybrids are often countered by the equally well-known drawbacks, and our attention has also been directed to the solution of the "standoff" problem that would permit the use of high-gain pellets in a particle-beam-initiated reactor. Standoff can be obtained by transport in the case of focused electron beams or through the use of ions that can be focused at a distance.

At least two advantages accrue when high-gain pellets are used in a pure fusion reactor. The CPF and pulse rate are reduced. This should result in a lower price for the electricity produced by the reactor. However, higher yield pellets may be complex and thus, more expensive. In addition, if the pellet yields are high, the reactor will have to be designed to withstand and contain a large explosion on a repetitive basis. The upper limit for pellet yield will be set by the containment capability of the reactor and by the vulnerability of the igniter components that may be inside the cavity. Careful studies of these tradeoffs, both physical and economic, need to be made. It should be emphasized, however, that extremely high gains are not required for particle beam fusion reactors because of the high efficiency of the igniter. The optimal pellet gain will be determined by reactor design tradeoffs.

II. Purpose

The purpose of this study is to identify and quantify, when possible, the potential civilian applications of particle beam ICF technology.

III. Review of Particle Beam ICF Technology

A. Introduction

The application of super-focused, relativistic electron beams (REBs) to the compression and subsequent heating of DT to fusion conditions by classical energy deposition in a high-density shell surrounding the DT was first proposed at Sandia Laboratories and separately at the Kurchatov Institute in the Soviet Union less than 4 years ago.¹⁻⁸ Although the use of REBs in pellet fusion had been discussed widely prior to that,⁹⁻¹¹ fundamental problems in beam focusing, REB technology and energy deposition prevented the development of serious interest. After making substantial experimental progress in beam focusing in 1972¹²⁻¹⁴ and completing theoretical studies at Sandia¹⁵⁻¹⁷ that indicated the scalability of these early results, an expanded program was initiated at Sandia to investigate the feasibility of the REB approach to pellet fusion. Target designs employing a high-density ablator-pusher concept¹ were proposed to permit efficient classical absorption of megavolt electron beams, and these ideas were first publicly presented in 1974.¹⁸ This effort has made substantial progress since its inception. The approach was broadened to include the use of ions as well as laser excitation aspects, and a major ERDA commitment was subsequently made to pursue a program that could lead by 1985 to a net energy gain experiment based on REB technology.

The ultimate goal of the Sandia Particle Beam Inertial Confinement Fusion Program is to design and build an operational experimental power reactor by 1990. This reactor will provide the basis for the design of a commercial inertial confinement fusion reactor to be operable by 2000. In order for fusion-produced power to be a workable energy option for the United States, the reactors used must be reliable, efficient, safe, and economically competitive. Therefore, the technical goal of achieving a controlled fusion reaction must be balanced against the applications goal of achieving a practical power plant. Conceptual designs for fusion reactors are currently being developed within each fusion research program; however, there are technical uncertainties and impracticalities in many of these designs. For example, some authors¹⁹⁻²⁰ believe that the 5000-MWe power capacity postulated for some Tokamak reactor concepts is too large to be useful for most utilities. This asymmetry between technical goals and applications goals can worsen as progress is made toward achieving the controlled fusion reaction and the technical goals are focused more sharply at the expense of the practical aspects. Accordingly, Sandia has structured its Particle Beam Fusion Program to allow the aggressive pursuit of technical goals, while at the same time directing this activity toward developing a viable energy option.

At its inception in 1973, the Sandia Particle Beam Fusion Program was based on a fundamentally different approach to inertial confinement fusion from that found within the rest of the AEC program. This approach was to use electron beams generated as efficiently and inexpensively as possible for direct pellet ignition in order to avoid the counterpart of the "discovery of laser X" and to arrive at a practical reactor concept with the fewest technical risks.

Essential features of this program concept are the use of an efficient driver and reliance on the extensive pulsed-power technology base that is continually evolving through ERDA support at Sandia and DNA support of its contractors to achieve scientific breakeven and net energy gain. Since 1973, several new discoveries have occurred that have led to a broader range of alternatives. Specifically, the use of ions as well as electrons for pellet ignition is being investigated as a natural extension of pulsed power technology since the accelerators developed for e-beam applications can also be used to accelerate ions. There are potential advantages to using ions rather than electrons and these advantages must be explored. The program can now be described as a triad with pulsed power central to each approach.

The Sandia Inertial Confinement Fusion Program is therefore following a primary direction, the use of electron beams, but with alternate paths considered through the scientific feasibility stage in the early 1980s. At that point the scope of the program will narrow to a single approach (i.e., electrons, light ions, or heavy ions) to reach the goals of net energy gain and assured survivability of the accelerator components in the reactor environment.

Central to the research effort is the development of the pulsed power technology required to achieve pellet ignition. The goal of this program is to develop relatively small, simple, and thus inexpensive drivers for this application. This goal has been met for single pulse accelerators used in weapons effects studies and more recently in advanced e-beam accelerators for fusion studies. These accelerators are presently operating in the peak power range of 10^{13} W. Operation at 4×10^{13} W, 500 kJ, is expected in 1980 with the electron-beam fusion accelerator (EBFA) at Sandia.

Since high average power (i.e., repetitively pulsed) driver systems are needed for any particle beam or gas laser fusion approach, we have initiated a pulsed power development program aimed at achieving megawatt average power levels by the early 1980s. In 1976 a 300-W accelerator was developed by Sandia and Physics International for laser excitation studies at LASL, and Sandia is presently developing a 3×10^4 -W accelerator. The projected cost of these high repetition rate systems is estimated at \$20 - \$30/J, a cost significantly lower than that for any other proposed fusion igniter. Based on Sandia's extensive experience in pulsed power technology development and the fact that a low-cost, efficient igniter will be required for any ICF commercial power reactor, we are pursuing a vigorous program of accelerator development and subsequent application to particle beam fusion reactors.

B. Particle Beam Fusion Concepts

At the outset, we felt that particle beam initiators would be more efficient and less costly than laser beam initiators; our feelings have not changed. Present estimates are that efficiencies (e-beam energy/electrical energy input) of approximately 50 percent are achievable with e-beam accelerators. Estimated efficiencies for Nd-glass lasers and CO_2 gas lasers are 0.2 percent and

7 percent respectively.²¹ The product of igniter efficiency and pellet gain is the most important parameter in determining the recirculating power fraction for a power plant and, therefore, the cost of electricity produced by the plant. If similar pellet gains are achieved in laser-driven and particle beam-driven reactions, then the more efficient system will produce power at a lower cost assuming that plant costs are approximately equal.

The immediate task, then, is to evaluate the relative usefulness of the three media (lasers, electrons, and ions), for driving inertially confined thermonuclear fuel and to determine the various efficiencies.

Both the laser and e-beam approaches seek to bathe the pellet in a "hot electron cloud." In the laser approach the goal is to reduce the effect of superthermal electrons by minimizing or entirely avoiding nonclassical absorption, and to optimize the conduction of energy from the corona to the dense ablation layer. If these goals are met, and a stable implosion is achieved (giving fuel densities of several thousand g/cm^3), then the critical remaining questions governing the economic feasibility of laser fusion are: (1) the efficiency of conversion of the pulsed power source into a focused photon beam, and (2) the fusion gain available from the pellet.

The direct e-beam approach has fewer steps than the laser approach if a hot electron gas can be produced directly, but here, all the electrons are "superthermals." Because of the greater penetration depth of these relativistic electrons, as well as the even more penetrating bremsstrahlung radiation produced by these electrons, targets must employ either massive ablators and deal with the attendant increased energy requirements ($> 10^6$ J), or the deposition characteristics of the electron must be modified in order to scale down the target mass.

The ion beam approach employs particles that have more suitable deposition characteristics than do electrons, and this approach leads to required beam currents for breakeven almost two orders of magnitude lower than that for electrons. The limited emphasis thus far on ion beam technology has provided an inadequate base to predict the practicality of efficient ion beam generation and focusing. Fortunately, recent discoveries at Sandia and other U.S. laboratories, principally NRL, in ultrahigh-current diodes may make it possible to convert the existing pulsed power technology to the ion option. Intense ion beams can be produced in several ways. For ion diodes, the positively charged anode serves as an ion source, and ions are accelerated from the anode toward a grounded transparent cathode. A series of such diodes can also be fired sequentially to reach the high ion energies needed for use of heavy ions.

Another approach is to use the collective ion accelerator. Here, a conventional diode produces an intense relativistic electron beam (IREB). Downstream, the IREB is used to collectively accelerate ions to energies much higher than that possible with only the applied gap potential in a single diode. It is anticipated that the particle beam approach will be significantly more efficient than the laser approach.

In addition to efficiency considerations, igniter cost and complexity are also important considerations in power-plant economics. Advanced laser costs are estimated at approximately \$200/J, while particle-beam accelerators are estimated at approximately one-tenth this amount. Conceptual designs for laser fusion reactors usually show at least eight laser beams impinging upon the target²¹ to achieve symmetry. Such an arrangement adds complexity in reactor chamber design and in synchronization of time of arrival of the laser beams at the target. Nd-glass lasers require multiple beams to achieve the power levels needed on target while remaining below the allowable flux limit of the amplifier chain. Added cost is the result.

While particle beam fusion offers compelling advantages there are also practical problems that demand attention. First, the peak power required on the target for ignition is approximately 10^{14} W. Generation of this high peak power requires advances in switching technology and pulse-forming techniques to provide the extremely short pulses (~20 ns) demanded. In addition, the beam must be focused to a small diameter at the target. Second, the beam must be transported to the target from the diode; or, alternatively, the microexplosion must take place within the diode. This second option creates a hostile environment for the diode that requires it to be made of durable materials. The possibility of using beam transport to increase the diode-target distance, thereby ensuring diode survivability even with high gain pellets, is presently being investigated. Finally, research is needed to optimize the beam energy deposition in the pellet for achievement of maximum pellet gain. In simplified terms, the thrust of the Sandia particle beam program is to find optimum methods for: power concentration and energy delivery to vacuum diodes, beam generation and focusing, symmetric and efficient energy absorption, compression of matter through stable implosions, and fusion ignition.

Our approach to these problems is subdivided organizationally into three major efforts, pulsed power research, theoretical research, and experimental research. The status of efforts in these three research areas is summarized in the next section.

C. Program Status

The Sandia program has been underway for almost 4 years. A major immediate element in the program is the construction of a new facility to house the e-beam fusion accelerator. This facility is presently scheduled as an FY 77 line item at a cost of \$13.5 M. The accelerator will provide a capability to carry out a critical test of the REB fusion concept, in that sufficient power levels will be available to produce enough neutrons to carry out significant measurements. The accelerator will, in addition, test important elements of accelerator technology, beam generation, energy deposition, and pellet implosion physics.

The fundamental technology basis for EBFA is to be provided by the pulsed power program at Sandia. This program is geared to provide the technical basis for developing short-pulse REB accelerators that can be employed in pellet-implosion experiments. In order to test the elements of the proposed EBFA, two prototype devices (Proto I, 2×10^{12} W, and Proto II, 8×10^{12} W) are being developed that will incorporate relevant pulse forming lines, switching, and diode configurations. During the prototype development phase, operational experience will be obtained on both accelerators, and additional supporting studies are planned in industry and universities in order to ensure that an optimal approach to EBFA is taken.

A conceptual design of EBFA was completed in May 1975 that employed annular, water-insulated pulse forming lines and a dual-disk transmission line coupled to two face-to-face diodes. This accelerator is being designed to deliver 500 kJ at a peak power of 4×10^{13} W, a five-fold increase in power over that from the Proto II device presently under construction. Based on the experimental programs now underway on Proto I and planned for Proto II, the final EBFA design completion and start of component procurement will take place in late 1977.

The projected power output of EBFA (4×10^{13} W) should provide a neutron output from a DT target that will permit high-quality neutron diagnostics. This theoretically projected achievement is based on experimental studies of target concepts, beam focusing analysis, target response, and pulse-forming technology at power levels that are presently below 10^{12} W. Before implementing this ambitious scaling step, many questions remain to be answered and will be addressed through the prototype program at power levels up to $\sim 10^{13}$ W. EBFA can thus be looked upon as the first of the next generation of devices beyond 10^{13} with enough energy on target to produce sufficient neutrons to allow for adequate diagnosis of implosion and thermonuclear reaction physics. An essential feature of these predictions is the projected ability to focus the energy efficiently on the target. The present pellet and beam behavior calculations treat focusing and target dynamics incompletely, and fully self-consistent treatment requires further guidance from experiments as well as extensive model development.

As described above, the basic orientation of the e-beam program is the application of advanced pulsed power technology to ignition of e-beam driven targets, but developments have permitted broadening of the activity to include ion beam generation. Usefulness of the basic e-beam technology base for these other applications has become apparent in the last 1-2 years, and this other option is likely to play a significant role in the future. Several years ago we recognized that electron beams could be viewed as competitors to lasers for applications to inertial confinement fusion. It is now felt that it may be possible to include in this consideration ion beams generated by using the same accelerators.

1. Pulsed Power Research

The program plan for reaching power levels of $\sim 10^{14}$ W shows three steps prior to EBFA II, which has its goal to reach net energy gain. If the proposed schedule can be met, ERDA will have a definitive basis in the early 1980s from which to decide the fate of the various methods of reaching inertial confinement goals. Protos I and II as essential parts of this program plan will provide the design information and operational experience required to define the EBFA-I characteristics and design details.

Proto I

Proto I is the first step in an accelerator development program that will eventually lead to a 100-TW accelerator. As our first accelerator designed and built for particle beam fusion research, Proto I extends our capabilities and includes features not found on previous accelerators. With a design power level of 2 TW, this accelerator is the most powerful we have ever built; it will produce two 400-kiloampere beams of 3-MeV electrons in a 24-ns pulse. A new high-voltage switching technique (the rail switch using an oil dielectric), a novel modular pulse-forming transmission line, and a dual diode especially suited for target interaction studies had to be developed before Proto I could become a reality. The modular construction can be readily adapted to the development of much higher energy systems of this type.

Although the power level of Proto I is still a factor of 50 below that thought to be required for energy gain experiments, the accelerator enables us to explore a number of questions that must be answered before such experiments are undertaken. The accelerator is particularly useful for studying the generation and focusing of electron beams from large-diameter cathodes and for investigating e-beam energy deposition in solids that will be used in fusion targets. Target compression experiments can also be advanced to new levels with this accelerator. Finally, Proto I is a useful tool for studying the generation and focusing of ion beams. If protons are used for the fusion ignition, then 10-MeV ions are more desirable than the 3-MeV ions Proto I will produce, but the pulsed power technology that has been developed for Proto I is applicable to 10-million-volt accelerators as well.

Description of Proto I -- Proto I is constructed with two Marx generators located in one oil-filled tank and connected to trigger circuits, transmission lines, and diodes in an adjacent oil-filled tank (Fig. 11). One of the Marx generators is used to charge the transmission lines, and the second is used to provide precision triggering to the rail switches. Six stacks of transmission lines with four lines in each stack are contained in a 9.1-m diameter, 2.4-m deep tank that is filled with 30,000 gallons of transformer oil during operation. The two vacuum diodes (Fig. 12) have a common anode supported by a 1.2-m-diameter stack of plastic insulators that separate the vacuum from the oil insulation of the transmission lines. The pulse from the trigger Marx generator is transmitted to the 12 rail switches through a system of coaxial, oil-dielectric transmission lines that appear as a network of ducts in Fig. 11.

Figure 11. Proto I electron beam accelerator

Figure 12. Dual vacuum diode being installed in Proto I

Operation -- The Marx generator can be used to directly charge the pulse-forming transmission lines to 2 MV in 760 ns. The dielectric strength of liquids is higher for shorter voltage pulses, so the peak operating voltage can be raised to 3 MV, provided that the transmission lines can be charged in less than 250 ns. Such voltage increase will double the energy available to the diode. The more rapid charging can be accomplished by inserting three intermediate storage capacitors between the Marx generator and the transmission lines. (One such capacitor is shown in Fig. 11.) After the Marx generator charges these capacitors, each of the three is discharged at precisely the same time (within nanoseconds) through a gas spark-gap switch into two stacks of transmission lines. In all, 24 transmission lines, in six stacks, are connected in a configuration of 12 Blumleins, six providing energy to each diode.

The discharge of the pulse-forming lines is initiated with the closure of the 12 rail switches. The voltage pulse has a duration of 24 ns, and pulse risetimes of 8 to 10 ns are typical. To achieve this fast risetime, the individual switches must not only have very low inductance but must also exhibit very small variation in their time to closure. Since switches that could satisfy these requirements did not exist at the beginning of this program, we began a research effort on switches. As a result we developed an oil-dielectric rail switch† having a jitter‡ of 2 ns and a low inductance that is achieved by the simultaneous formation of an average of ten current-carrying channels in the switch. This low-jitter, multichannel operation requires that a 1-to 2-MV trigger pulse be applied to the trigger electrode. The trigger pulse is produced by using one of the Marx generators to charge a special water-dielectric, pulse-forming transmission line that transmits a pulse to all 12 rail switches through a system of coaxial, oil-dielectric, transmission lines. The Blumlein transmission lines then simultaneously supply high-voltage pulses to the diodes to complete a charge-discharge sequence of power compression that results in 1 to 2 TW at the diodes.

Electron beams are generated from the surfaces of cathodes that are between 25 and 300 times larger in diameter than the fusion targets. For compression experiments, the fusion target is attached to the common anode. Experiments have shown that spherical targets can be uniformly irradiated with only two beams.

Results and Plans -- Two principal objectives of our Proto I experiments are to investigate (1) beam focusing from large-diameter cathodes and (2) energy deposition in fusion targets.

The low-impedance accelerators that are required to generate the high currents necessary for inertial confinement fusion will need to focus beams from large-diameter (low-inductance) cathodes. Proto I, which provides our first opportunity to generate beams from large cathodes,

† This development extended the earlier work of J. C. Martin, Atomic Weapons Research Establishment, Aldermaston, Berkshire, UK.

‡ Jitter is the standard deviation of the variation in closure time.

is serving as a research tool for developing focusing techniques. We have now generated beams in vacuum diodes from cathodes of various shapes and with diameters ranging from 2.5 cm to 60 cm; but beams from large-diameter cathodes have not yet been focused to fusion target dimensions.

Our first attempts to focus beams from large cathodes, using techniques we had previously employed, were not successful. A succession of experiments with cathodes of decreasing diameters eventually yielded a focused beam with a cathode of 12-cm-diameter. A beam spot ~ 1 cm in diameter was obtained, but only a small fraction of the beam energy was deposited in the spot. Interpretation of the experiment, based on computer simulations and hydrodynamic calculations, showed that a substantial portion (~ 80 percent) of the beam energy had to be deposited in the anode to create an anode plasma and provide enough ions to allow the remainder of the beam to focus.

In a series of experiments aimed at maintaining the focus but increasing the energy available for deposition in a target, we used a larger-diameter (56 cm) cathode and supplied the diode plasma from an external source. In this case our measurements and analyses showed that at least 70 percent of the energy contained in the beam was deposited in a 3.8-cm-diameter area at the center of the anode.

Even though the beam convergence in these experiments did not produce an adequate focus, a considerable improvement was obtained in the velocity of the collapsing beam as it moves from the edge of the cathode to the center of the anode. While the first experiment, which had no plasma injection, had a collapse velocity of 10^8 cm/s, the velocity for the second experiment exceeded 30×10^8 cm/s. This higher velocity is significant because it approximates the collapse velocity necessary to focus beams from the large-diameter cathodes that will be used in future accelerators.

One reason that the plasma-aided beam did not focus more sharply was that the electron density in the beam, when it had converged to a 3.8-cm diameter, was higher than the background ion density, and electrostatic neutralization no longer existed. Techniques for improving the focus with a dense plasma on axis are being explored. Other beam focusing techniques will also be investigated as we learn how to produce the required current densities.

In late 1976 we began energy deposition experiments using fusion targets rather than the flat-plate anode targets that had been used previously. Favorable conditions for fusion target exposures have already been obtained in experiments using 2.5-cm-diameter cathodes that produced two tightly focused beams of high energy content. In these experiments we achieved deposition of ~ 12 kJ from dual beams in 6-mm-thick flat anodes (Fig. 13). The spot size, ~ 4 mm in diameter, is appropriate for fusion targets. This capability of Proto I--to deposit large amounts of energy in a small target--may enable us to produce our first thermonuclear neutrons by e-beam irradiation of a fusion target and thus take a substantial "first step" in our particle beam fusion program.

Figure 13. Anode damage in the upper plates was produced by single 200,000-ampere electron beams; in the lower plate, by dual 200,000-ampere beams. The diameter of the beam focus was approximately 4 mm.

Proto II and EBFA

Particle beam fusion experiments eventually will require that megajoules of beam energy be incident on a fusion target in 10 to 20 ns. As a consequence of that requirement, two aspects of accelerator development have been identified as primary areas for research; first, the need for speed and simultaneity of high-current switching, and second, the necessity for large power flow through the interface separating the transmission-line dielectric from the evacuated beam-formation region. Since these concerns are significantly influenced by the dielectric fluid chosen for the accelerator insulation, two investigative approaches were explored in laboratory tests. One approach described in the preceding article on Proto I followed a more conservative extrapolation from existing technology by using an oil dielectric and triggered multichannel switches. The other more advanced but more risky approach employed a water dielectric and untriggered multichannel switches. The first of the water dielectric accelerators using this new technology, the 8-TW Proto II, is now under construction (Fig. 14) and the second, EBFA, (Fig. 15), will begin operation in 1979 and produce about five times more power than Proto II.

Water-Dielectric Accelerators -- The questions addressed by Proto II and EBFA are in many cases qualitatively the same but are different enough in scale that new concerns will surface. Both accelerators share the objective of solving the scientific and engineering problems of using high-purity water as an insulator. Water is an excellent insulator for short periods; relatively easily obtained 1-M Ω -cm water will insulate well for 1 to 2 μ s. The high dielectric constant of water (81 times that of vacuum) significantly increases the electrical energy density in a circuit and reduces the dimensions required for pulse forming lines that are to produce a pulse of a given duration; but these benefits are accompanied by problems. For example, the energy storage capability of the dielectric can allow energy to be stored in locations not readily accessible on short time scales; so special care must be taken with line geometries. Furthermore, triggering the discharge of a short transmission line under water presents problems. The pulse-forming lines in Proto II, which create a pulse of only 24-ns duration, are physically so small that a trigger electrode would itself have dimensions (hence capacitance) comparable to those of the pulse-forming element. Thus the energy required to trigger such a configuration would be as great as the energy stored on the line element. Use of a gas switch, triggered or untriggered, is not an alternative because a 3-MV gas switch is too large to fit in the lines.

A new approach for switching was required before a water-insulated accelerator could be considered at the desired power levels. A successful technique for switching* was developed in a series of experiments with Ripple (Fig. 16), a test configuration that modeled the electrical energy storage, switching, and transport concepts being used on Proto II. Accelerators for fusion reactors will require beam currents of the order of 100 MA, with rise times of about 5 ns, or current rise rates of about 2×10^{16} A/s. A single switch channel in a typical circuit will produce current rise rates of about 10^{12} A/s, suggesting that one way to obtain the desired rates for such high currents is to have many switch channels, about 20,000 of them, strike simultaneously.

*First suggested by J. C. Martin of the Atomic Weapons Research Establishment, Aldermaston, Berkshire, UK.

Figure 14. The 8-TW Proto II electron-beam accelerator

Figure 15. Construction of the 40-TW EBFA will begin in 1978

Figure 16. Experiments with Ripple modeled concepts that are used in the Proto II accelerator. The switches (E&F) self-break in multiple current carrying channels to transfer energy from the transfer capacitor system (A) to the pulse forming line (B) and finally to the output line (C) and load resistor (D). Switch performance was photographed through screened cutouts in the upper line and voltages were monitored with resistors (G).

A concept, tested on Ripple and incorporated in Proto II, is to generate voltage rise times so short that multiple breakdowns occur and, in effect, create many switches by producing numerous current-carrying channels between the electrodes of each switch. If sufficiently fast voltage pulses and adequate synchronization can be achieved, the approach can probably be scaled up for use on large fusion accelerators.

Accelerator Descriptions -- Proto II will produce approximately 100 kJ of beam energy in a double diode at a voltage of 1.5 MV and a peak current of about 6 MA in a pulse of 24-ns duration. The power compression process begins with eight Marx generators (voltage multipliers) that charge 16 intermediate storage capacitors. These capacitors then charge the first set of pulse-forming lines in 240 ns (Fig. 17). The new switching technique now comes into play, and the first set of pulse-forming lines self-switches in 16 current-carrying channels to charge the second set of pulse-forming lines in 70 ns. The voltage rise is now so rapid that the second set of lines switches with about 200 channels and launches a wave down the converging transmission-line transformers toward the diodes. The transmission lines can be adjusted to transform the line impedance by up to a factor of 6 over the length of the line and optimize the energy transfer into the 1.80-m-diameter double diode.

The experimental flexibility of Proto II is derived from a low-impedance, variable polarity, short-duration pulse that can be modified by the transformer lines over a range of output impedances for acceleration of electrons or ions.

The 500-kJ EBFA is in many respects a 5-times scaleup of Proto II. Twenty-four Marx generators charge an equal number of intermediate storage capacitors that are synchronously switched to charge the pulse-forming lines. The longer energy transmission lengths in a scaleup could lead to pulse degradation for pulse risetimes of less than 5 ns, but the present design of a 30-m-diameter accelerator and 10-ns pulse risetime should not present degradation problems due to pulse propagation. Details of the design are being kept flexible, but the results of continuing laboratory experimentation together with operational experience gained on Proto I and Proto II should provide sufficient bases for completing the preliminary EBFA design in late 1977.

Research Objectives -- The general goal--to demonstrate the scientific feasibility of particle beam fusion--will be attained as a result of accomplishing a series of intermediate goals. A priority goal of the accelerator research is to develop techniques for managing the flow of electrical power in accelerators operating at power levels of 8, then 40, and eventually 100 TW.

Power flow through these accelerators can be considered as analogous to water flow through a conduit; where the conduit is wide and deep, there is little problem with the water breaching its channel; but if the channel dimensions are reduced or the shape of the channel is changed, the flow may not remain contained. Correspondingly, the flow of electrical energy occurs in the dielectric that fills an electrically conducting channel. In this case the maximum

Figure 17. Schematic of the accelerator elements used in the power compression process

power flow is proportional to the product of the square root of the dielectric constant of the dielectric and the square of the electric field stress at which an electric breakdown would occur.

In Proto II the channel is formed by the conductors and dielectrics of the transmission lines, the vacuum diodes, and the transition regions between the lines and the diodes. Complications arise in the transfer of the electrical energy from the water-filled transmission lines into the vacuum diodes. There, the electromagnetic pulse encounters dielectrics and interfaces that affect both the electric field in the pulse and the magnitude of field required to cause breakdown. It is in this "front end" of the accelerator (near and in the diodes) that we confront the most serious problems with power flow. Present dielectric materials and front-end designs are not capable of accommodating the power flow that is necessary for breakeven operations.

Several methods for treating the problem of power flow are being pursued. In addition to evaluating the possibility of reducing the power flow problem by using higher voltages, we are seeking to improve the conventional technology of pumping a diode with an electromagnetic wave and to find ways to pump a diode with many electron beams. Other effects aim at increasing the maximum allowable fields by use of magnetic insulation schemes or surface coatings on insulators. Since Proto II will operate at the limit of front end power flow capability, it will have considerable value as a facility for testing methods of concentrating power.

Other research to be conducted with Proto II and EBFA will include studies of beam focusing and of beam interaction with fusion targets. The beam focusing experiments with these high-power accelerators provide opportunities for new investigations of diode physics and beam behavior. In addition, Proto II has been designed with interchangeable electrodes so that it can be operated with a negative polarity for ion beam experiments. Beam/target interaction experiments will explore target designs and materials, and will develop the techniques for initiating inertial confinement fusion reactions. Taken together, the advances in our technology and understanding gained with these accelerators will enable us to demonstrate the scientific feasibility of particle beam fusion.

2. Theoretical Research

Design studies for e-beam pellet targets have continued since the first simple gold ablator-pusher target was presented in 1973. These first target concepts required a peak power for breakeven of 8×10^{14} W using 1-MeV electrons. Our work has since concentrated on lowering these requirements for electrons and also for the first time has considered the use of ions.

Recent developments²⁵ in e-beam target design using ideas that are very similar to those being considered elsewhere²⁶ permitted calculations that showed breakeven for 1-MeV electrons at a peak power of 5×10^{13} W. This is more than an order of magnitude reduction below

that first thought necessary. Other improvements in power requirements were considered using various ablator materials in order to minimize the effect of bremsstrahlung preheat of the inner wall, and it was found that these changes in themselves could reduce the power requirements by about a factor of four. Although these reductions are substantial, they still present extremely difficult requirements for power flow in the diode region if voltages in the megavolt region are employed. Clearly, reductions in the energy deposition length would have substantial impact on the optimum beam voltage and current. In addition, although we have previously proposed²⁷ that power and voltage shaping could lead to further improvements, this area remains largely unexplored.^{28,29}

In 1975, ion beam target design studies began by following the design philosophy first adopted for electrons. These studies showed that breakeven could be achieved at 10^{14} W using 10-MeV protons, which means a diode impedance of $1\ \Omega$ as compared to the impedances in the $0.01\text{--}1\ \Omega$ range required for electrons. Further improvements were also predicted for ions using more complex targets, such as multiple shells or conduction suppression, leading to breakeven power predictions as low as 10^{13} W with 10-MeV protons. Clearly, the design improvements using ions instead of electrons are substantial. The beneficial ion deposition characteristics yield an optimum voltage level roughly 10 times higher for protons than for electrons.

We have also recently initiated analyses of the important question of ablator stability using both analytical and numerical methods. Our results indicate that more stable implosions should be possible for electrons, in comparison to implosions driven by lasers, with ion-driven implosions falling in between.³⁰ Similar results have been found at LLL using the 2-D hydro code, LASNEX,³¹ and although these theoretical results point in certain qualitative directions, experimental determination of ablator and fuel pusher interface stability is required.

In addition to our pellet design studies oriented toward reducing necessary breakeven levels, other work emphasized the design of targets for initial neutron production experiments. These initial experiments are being carried out using two basic methods: (1) multiple shells and (2) exploding pushers. The multiple-shell targets have been designed in conjunction with LASL and LLL, and the exploding pusher targets are being carried out in parallel with a similar design approach at LLL. A critical difference exists, however, between the Sandia and LLL exploding pusher target concepts. Sandia has postulated that self-field effects could play a dominant role in enhancing the energy deposition in thin-walled targets, and has designed its targets accordingly.³² These target calculations predict that measurable neutron yields can be achieved with an absorbed power of 0.2 TW. The radial compression ratios for these targets are 10:1 compared to the design of Meeker, et al.³³ which requires radial compression ratios of 100:1 in order to produce measurable neutrons.

One of the most important recent developments in our theoretical program was the discovery that ion emission from a region of plasma near the anode of a diode was required to obtain agreement with our measurements of e-beam current density.²⁷ In 1976, using our two-dimensional

particle code, we found that treatment of ion flow was essential to explain beam pinching.^{34, 35} These calculations also showed that the ion current could be comparable to the electron current. A similar conclusion was found independently at the Naval Research Labs and the University of Maryland³⁶ using an analytical rather than the numerical approach that we followed. Both the numerical and analytical work then led^{38, 39} to the conclusion that if no steps were taken to limit the ion flow, the efficiency of generating the self-focused electron beam would be reduced. Techniques to suppress the ion current are under investigation.

3. Diode Physics

Our first experiments to study e-beam focusing, begun in 1972, used a fine tungsten wire connecting the anode and cathode on the diode axis to strengthen the magnetic field and supply plasma ions to assist the focusing of a 0.02-TW beam from a Nereus accelerator. Repeatable, efficient focusing was obtained; so the experiments were scaled up, first to the 0.1-TW level with the SLIM facility, then to the 0.8-TW level using the Hydra accelerator, culminating in a demonstration that current densities greater than 1 MA/cm^2 could be obtained.

To improve repeatability of focused beams, a diode was developed in which the wire on the axis was replaced by a plasma that reduced the defocusing space charge fields of the electrons. These successful experiments, using a dense plasma localized on the diode axis, were followed by experiments using a low-density plasma to fill the entire diode volume. This plasma formed a virtual anode near the cathode, and tight e-beam focusing was achieved even when the anode and cathode were relatively widely separated.

Our most recent experiments on beam focusing have been conducted with the Proto I accelerator, operating at 1.0 to 1.5 MV and producing beam currents of 240 to 360 kA. These experiments were the first to demonstrate the feasibility of focusing initially large-diameter beams that last for only 24 ns. These initial experiments, using a plasma-filled diode, demonstrated that focusing can be achieved rapidly, and that tightly focused beams can be obtained with small-diameter cathodes. Now under way are experiments designed to extend the focusing to the larger-diameter cathodes required for higher power operation.

If it is to be used in a fusion reactor, a diode must, in addition to providing a focused beam, survive the damaging radiation and target debris released by the fusion reactions. These problems were addressed by a reactor conceived in 1973 that was based on the use of a diode with a hollow cathode and an injected plasma anode.* We also performed experiments in that year to demonstrate that efficient focusing could be achieved in diodes with hollow cathodes, even in the absence of plasmas on axis.

* Awarded U.S. Patent No. 3,892,970.

E-beam accelerators are efficient converters of stored energy into beam energy, but to realize the advantages of high-power beams, we must understand how to efficiently convert beam energy into target heat. The penetrating power of relativistic electrons is such that the electrons would pass through a target of bare DT, even at solid density, depositing only a small fraction of their energy in the target. Consequently, the energy-absorbing region of a target (the ablator) is typically fabricated from a very dense material such as gold. An unexpected physical effect, such as rapid beam energy loss to a low energy plasma surrounding the dense shell, could alter the ability of the beam to efficiently heat and compress a dense target. On the other hand, if such a mechanism were repeatable and symmetric, it might permit the use of higher-energy electrons or lower-density targets. Therefore, considerable effort has been spent on experiments designed to reveal the details of electron energy deposition mechanisms in targets. One such experiment was the e-beam-driven implosion of a 3-mm-diameter, 350 μ m-thick hollow cylindrical shell (Fig. 18). In this particular target, the e-beam energy was deposited uniformly in the shell inward at a velocity of 20 to 40 $\times 10^6$ mm/s.

Our first investigations of energy deposition used flat anode targets of various materials and thicknesses. When these targets were exposed to a focused electron beam, heat and high-pressure shock waves generated by the beam produced extensive damage--usually in the form of a hole through the target and spallation of material from the back of the target. The beam-target interactions were mathematically modeled by a series of two-dimensional computer simulations with a hydrodynamics code. An example of the sort of comparison obtained is shown in Fig. 19. Since the computed crater dimensions are quite sensitive to the amount of deposited energy assumed for the calculations, the calculations provide an independent estimate of the deposited energy.

A second series of experiments, using more refined measurement techniques, was performed to provide detailed data for evaluating theoretical models of deposition mechanisms. A laser reflection method was used to obtain quantitative measurements of the time required for the shock to be transmitted through the anode and of the velocity of the rear surface of the anode as it expanded outward. In two-dimensional computer simulations of the experiments, the range of electron energy deposition was varied to represent the effects of different deposition mechanisms. The best agreement (± 10 percent) between calculated and measured response of thick targets was obtained when conventional electron energy deposition was assumed.*

4. Target Design and Experiments

Optimum design of the fusion targets is a crucial part of the particle beam fusion program. Variations in the design can influence requirements for beam power by orders of magnitude. Furthermore, different designs are appropriate, depending on the objectives of the

*Conventional electron energy deposition is characterized by theories that include multiple scattering and atomic interactions but ignore influences such as the diode electric and magnetic fields.

Figure 18. E-beam-driven implosion of a hollow cylindrical shell.

Figure 19. A two-dimensional hydrodynamic calculation shows the development of damage to a flat plate target at $4.0\mu\text{s}$ after exposure to a focused electron beam. Agreement with damage produced in an actual target is good.

application of a target. For example, simple high-density spherical shells filled with gaseous DT have been designed for investigating the fundamentals of beam-target interactions. Other classes of target designs that we distinguish are (1) those designed for producing measurable thermonuclear neutron output when used in accelerators available in the near future, and (2) those designed to produce energy gain in the very high-power accelerators that will be available in the more-distant future.

To absorb efficiently the energy of a relativistic electron beam, the outer shell of the target must have a high density, but this results in another physical effect that must be taken into account. The interaction of the beam with the dense shell produces a significant amount of bremsstrahlung that is partially absorbed within the target and raises the temperature and pressure at the inner surface of the shell. The pressure increase causes the inner portion to expand slightly, thereby reducing its density and its ability to compress the fuel. The radiative preheat of the inner wall may be reduced by plating the high-density shell with an outer coat of low-density material, such as iron or even carbon, to reduce the bremsstrahlung production. Theoretical studies of such composite targets have shown that power requirements for breakeven are about 3×10^{14} W, a power that is a factor of three lower than that required for homogeneous gold shells.

Another target design is based on the momentum conservation exhibited by colliding billiard balls. A massive outer sphere, imploded by the electron beam, rushes inward and collides with a less massive shell located concentrically inside the outer shell. Because of its smaller mass, the inner shell acquires a velocity greater than the impact velocity of the outer shell. This velocity amplification can in principle continue through further collisions with additional shells. The benefit to be derived is that higher compression velocities produce higher final temperatures in the fuel. A high-pressure buffer gas contained between the shells improves the elasticity and momentum conservation in the collisions. An example of a colliding-shell target assembly, fabricated by the Los Alamos Scientific Laboratory for our experiment is shown in Fig. 20.

A near-term target, designed to produce measurable thermonuclear neutrons with existing accelerators, uses an iron or plastic shell thin enough that electrons under influence of the diode fields can recirculate and pass through the shell many times. If this repeated deposition occurs, the thin shell becomes heated uniformly and explodes inward and outward simultaneously. The design is computed to produce a measurable quantity of neutrons (10^5) when the Hydra accelerator is used as the energy source.

Calculations have also been carried out for targets driven by focused ion beams. Ion beams tend not to scatter as they deposit their energy in the target, and since they produce essentially no bremsstrahlung, they do not generate radiative preheat of the inner surface of targets. Reduced scattering results in more energy being deeply deposited inside the target that in turn, improves the efficiency of the target implosion. Implosion calculations that take account

Figure 20. The assembled target at the top is made up of a small shell (containing fuel), a shell support and a massive outer shell. Higher final fuel temperatures can result from high compression velocities obtained by the implosion of multiple shell configuration.

of these effects show that the power level required to produce breakeven conditions with a 10-MeV proton beam is about 6×10^{13} W or about a factor of 10 less than the level required when a simple homogeneous target is driven with a 1-MeV electron beam.

The calculations used to design all the targets discussed thus far assume that the target material retains a spherical shape and moves only radially inward and outward during the implosion. Real targets, however, do not behave so ideally. During target acceleration, any ripple or irregularity on the target surface could generate unstable growth that could destroy the symmetry of the ablation. Later, when compression of the fuel has slowed the inner surface, unstable growth becomes possible there. Irregularities on the inner surface could grow to the extent of becoming high-velocity metallic jets that penetrate the compressed fuel and quench the fusion reaction. The significance of these potential instabilities is being investigated computationally with a two-dimensional hydrodynamics code. In a systematic study, a variety of irregularities in the target and in the spatial distribution of the beam power is introduced into the problem, and the subsequent growth of the distortion is calculated. The results indicate that target implosions are most stable when driven by electron beams, and, in order of decreasing stability, less stable when driven by ion beams and laser beams.

Making nanosecond measurements of target behavior in the focus of a high-energy, high-current electron beam is a challenging necessity that has led us to employ a variety of experimental approaches and to develop new measurement techniques. To collect the data, techniques ranging from posttest examination of passive samples to time-resolved X-radiography have been employed. Only by measurement can the response of real targets interacting with actual electron beams in the presence of the fields and plasma of an operating diode be discovered.

The first experiments to study target response used a 4-mm-diameter gold hemisphere placed on the anode at the diode axis. The configuration modeled one-half of a proposed dual-beam experiment in which both lines of the Hydra accelerator were to be used with a two-sided diode to obtain symmetric irradiation of an entire sphere. These initial experiments resulted in much greater damage to the anode than had been observed previously. The extensive damage was explained by computer simulations (Fig. 21) that showed that a dense gold jet, formed because of the momentum imbalance, pierced the flat copper anode.

Subsequently, we performed a more quantitative experiment to measure the hemisphere implosion time and the jet velocity with a laser reflection technique similar to that used for the simple flat anode target experiments. Computer calculations indicated that these measurements could provide an estimate of both the amount of beam energy deposited and the symmetry of the deposition. Additional information concerning plasma blowoff velocities and symmetry of irradiation was obtained with holographic and X-ray pinhole camera techniques (Fig. 22). The combined experimental and computational results indicated that from 17 to 50 percent of the beam energy could be deposited in the hemispheres, and that irradiation uniformity as good as ± 20 percent could be obtained.

Figure 21. Computer simulation showing formation of crater in copper target caused by asymmetric jetting of hemispherical gold shell.

Figure 22. X-ray pinhole photograph of the two-beam-irradiated target.

A separate series of Hydra experiments was performed in which a 4-mm sphere was placed on a stalk at the focus of the electron beam. X-ray pinhole photographs from these experiments (Fig. 23) demonstrated that it was possible to obtain excellent uniformity (~10 percent) using only a single beam of the accelerator. This surprising result is thought to be due to the "hot fluid" nature of the focused electron beam, which tends to immerse the target in a gaslike cloud of electrons. A flash X-ray camera was developed to photograph the target at various times during its implosion. Shadowgrams taken with the camera at intervals of 200 to 300 ns, multiple-pulse holograms recorded during about the first 50 ns of implosion, and further computer simulations, indicate that the target behavior is quite symmetric.

As our knowledge of beam focusing capabilities, deposition physics, and target response advances along with the technology of complex target fabrication, a concrete evaluation of the feasibility of particle beam fusion will be made. The overall schedule showing the implementation of EBFA I and II is presented in the next section.

5. Schedule

Sandia's long-range schedule to provide a particle beam fusion program that can satisfy ERDA's short-term weapons-related needs and move forward in a timely manner toward energy applications is shown in Fig. 24. The schedule incorporates capabilities of the national laboratories, private industry, and universities. The critical milestones on the main-line program, with separate supporting activities feeding input data into that line at key dates, are shown. The most obvious features of this plan are the fairly large number of options that are available due to the richness of the technological fallout from pulsed power technology. The same technology base that permits the study of both electron and ion beam-driven fusion while concurrently delivering methods, components, and actual accelerators to the laser fusion program allows us to support present weapons-related needs. Options must be narrowed by 1980 in order to move forward with EBFA-II rapidly enough to carry out breakeven experiments by 1984. At the same time, supporting activities in pulsed power technology, pellet fabrication, and systems studies must be pursued in order to move beyond EBFA-II to a repetitive rate experiment by 1984. The steps beyond 1990 that lead to commercialization are also shown in Fig. 24.

Figure 23. X-ray pinhole photograph of a spherical 4-mm-diameter target mounted on a stalk (at zero degrees). The near uniform optical density indicates the uniformity of target irradiation with a single electron beam.

Figure 24. Summary

IV. Near-Term Applications of ICF Technology

Achievement of significant neutron yield from an ICF reaction is an intermediate goal of the ICF program. Particle beam accelerators that have already been developed in pursuit of this goal have near-term applications, however, in addition to ICF. This section discusses some specific applications for this beam technology.

A. E-Beam Excitation of Gas Lasers

Gas-laser excitation with intense relativistic electron beams has gained popularity through many successful demonstrations of efficient conversion of e-beam energy to laser energy. In some instances, e-beam excitation of gas lasers has resulted in record laser energy and/or power, in higher efficiencies than have ever been obtained with any other excitation scheme, and in the discovery of lasers that have not been produced by any other excitation schemes. The feature of electron beams that makes this laser excitation scheme so promising for use in high-power lasers is the high-power capability of electron beams. Recent developments in untriggered oil and water switching at Sandia now permit one to construct compact, high-energy density, pulsed-power sources for laser excitation.

When an electron beam is injected into a gas, a large fraction of the energy that is deposited in the gas is expended to excite, ionize, or dissociate the gas atoms and molecules. Most of the excitation, ionization, and dissociation of the atoms or molecules is caused by the secondary electrons that are produced when a primary electron undergoes an ionizing collision with an atom or molecule. The secondary electron energy distribution is a function of the atomic and molecular properties of the gas, but it is almost flat from zero to ~ 10 eV and has a width of a few 10^1 's of eV. These electrons can excite atoms or molecules by direct excitation, ionization followed by recombination, or dissociation. An example of direct excitation is $e + A \rightarrow A^* + e$, where A^* represents the excited species. The excited species then radiates via $A^* \rightarrow A + h\nu$, producing laser emission. When ionization is followed by recombination, the reactions are $e + A \rightarrow A^+ + 2e$ followed by $A^+ + e \rightarrow A^*$. Typically about 10 times more energy goes into ionization than into direct excitation. An example of excitation by dissociation is $e + AB \rightarrow A^* \text{ (or A)} + B \text{ (or B}^*) + e$. This process is important in e-beam-initiated HF chemical lasers. In these lasers the electron beam dissociates F_2 to produce F atoms, which, in turn, produce vibrationally excited HF molecules by the reaction $F + H_2 \rightarrow HF^* + H$. Electron beams have also been used to excite lasers by photolysis where an intermediate atom or molecule is excited by the electron beam and the radiation from the excited atom photolyzes another atom or molecule comprising the laser medium.

Recently, Sandia and Physics International combined to supply an e-beam generator to Los Alamos Scientific Laboratory for use in pumping KrF lasers for isotope separation experiments. This device delivers 300 J/pulse at a rate of 1 pulse/s in a 470-keV, 27-kA beam. Pulse duration is 50 ns. The high-repetition rate technology developed for this device is directly applicable to

that required for inertial confinement fusion reactors. Higher pulse rates are possible with present switching technology at low beam power levels. For example, another accelerator designed to operate at a pulse rate of 100 Hz is under development. This device will have a beam voltage of 350 keV and will deliver 300 J/pulse in a 20-40-ns pulse. Experience gained during this development will enable extrapolation of switching techniques to the higher beam powers required for ICF.

In addition to the present use of low-energy, high-rate systems for laser pumping, there is also a requirement for high-energy laser pumping. For example, the existing relativistic e-beam accelerator (REBA) at Sandia has been used to pump an HF chemical laser^{43, 44} shown in Fig. 25.

Figure 25. Drawing of the axial excitation scheme

This experiment utilized axial injection of the beam into the laser cavity. The machine is operated at a voltage of 2 MV with 50 kA delivered in a 70-ns FWHM pulse. After passing through the anode, the electrons are magnetically guided around a 45° bend into the laser cell. A magnetic field is also used along the cell to reduce electron scattering into the cell walls. A transverse magnetic field is used near the end of the cell to prevent the electrons from damaging the laser window. Using this type of excitation, the laser can be operated either as an oscillator or as an amplifier. This type of excitation is used for low-pressure gases or when the ratio of laser length to diameter is large. This geometry has been used to excite many lasers, and 2 kJ of laser output has been obtained from an HF chemical laser.

With axial excitation, one of the main questions that arises is how much magnetic field is required to minimize the scattering of electrons out of the laser chamber. The results of a two-dimensional Monte Carlo calculation⁴⁴ are shown in Fig. 26. This particular calculation was done for 2-MV electrons injected into a typical HF-laser gas mixture of 360-Torr fluorine, 140-Torr oxygen and 100-Torr hydrogen. The initial electron beam had a normalized radius of 1, with the laser cell wall located at a normalized radius of 2. The deposition is calculated within a given radius over the full length of the laser cell. With no magnetic field, only about 10 percent of the electron beam is deposited in the gas. By applying a magnetic field of just a few hundred gauss, the deposition in the gas can be greatly improved. A magnetic field of a few kilogauss is sufficient to eliminate scattering to the cell walls.

Figure 26. Calculations showing the fraction of e-beam energy deposited as a function of normalized radius

Another scheme that has been widely used is the transverse excitation scheme. Here one or more electron beams are injected into a high-pressure laser cell in a direction transverse to the optical axis. Such a geometry has produced many lasers that are typified by Xe_3 and KrF lasers.^{45, 46}

A third configuration for injecting electrons into the laser gas utilizes a radially converging electron beam generated in a cylindrical diode. The thin anode of the diode serves as the cylindrical wall of the laser chamber. Figure 27 is a sketch of one of these diodes located along a laser chamber. The radial disks that separate the diodes and provide the return current path serve to magnetically isolate each of the cathodes. Each diode will be operated below the critical

current so that a uniform current density can be generated on the anode. The symmetry of this diode should inherently produce uniform current density in the azimuthal direction. This arrangement facilitates modular construction and makes it easy to add as many diodes as are necessary to obtain the required e-beam energy.

Figure 27. Cylindrical diode with radially converging electron beams

This modular construction can be particularly useful for those systems in which distinct advantages are gained by pumping the laser in 10-20 ns such as a high-power HF laser. The technology developed for the Proto I accelerator is applicable to the design of a generator capable of depositing 10-20 kJ of e-beam energy in a laser gas in 20 ns. The optimum operating gas pressure depends upon the efficiency of producing laser energy from the electron beam and upon the optical energy or power density at which gas breakdown occurs. These same considerations plus the optical power density at which window damage is initiated will determine the chamber diameter.

The optimum diode voltage can be determined from a consideration of the gas pressure and chamber diameter. Multiple diodes can be used to keep the beam current below the critical current for self-pinching. With the optimum voltage, our calculations indicate that 50-75 percent of the beam energy can be deposited in the gas with this configuration.

The higher e-beam power levels that will be available with Proto I, Proto II, and EBFA may be effectively utilized to pump lasers for laser fusion. Lasers in the 10^5 to 10^6 -J range operating at efficiencies of 1 percent require pumping energies of 10^7 to 10^8 J. These levels will require multiple accelerators and multiple laser beams.

The main alternative to e-beam pumping of gas lasers is electric discharge excitation. There is a definite distinction between excitation of gases by electron beams and by an electric discharge. In electric-discharge excitation there is an abundance of very low-energy electrons, and an electric field is applied to accelerate these electrons to a sufficient energy to excite or ionize the atoms or molecules. In e-beam excitation, the secondary-electron energy distribution is generally higher than the energy required to excite the atom, and excitation and ionization occur as the secondary electrons are losing their energy. There are several advantages of an electron beam over an electric discharge for high-power gas laser systems. (1) There are e-beam accelerators available that have both high power and high-energy capability. High-power excitation limits the degradation of laser performance by collisional and radiative deexcitation of the excited molecules that comprise the upper-energy level of the laser transition. (2) The energy source is decoupled from the excited medium. Consequently, nonlinear phenomena such as arc formation are less important. It is possible with electron beams to uniformly excite large gas volumes operating at high pressures. Also, since the energy deposition is not seriously affected by the electrical characteristics of the medium, gases that are electronegative can be used. (3) The electron-energy distribution function may be more suitable for a specific application than that produced in an electric discharge.

There are, of course, disadvantages to e-beam excitation, such as unwanted X-ray production, and low repetition rates. However, for many lasers, e-beam excitation is the most efficient, and developments in beam accelerators are extending the range of applications.

B. Commerical Applications

1. Sludge Purification

Pulsed-power, e-beam technology is applicable to municipal sludge sterilization in the near term. Sludge is the sediment resulting from the preliminary and primary treatment of sewage. An increased national awareness of water pollution problems and stricter governmental control on wastewater treatment have resulted in larger quantities of sludge that require processing to higher standards. As an indication of the magnitude of the problem, the average person in the United States generates 50 lbs of sludge yearly.⁴⁷ The final disposition of this sludge requires significant expenditures in land and money. If the bacterial, viral, and infestation content of the sludge can be reduced enough to be considered harmless by health officials, the sludge may become salable as fertilizer, thus transforming a waste product into an asset.

The pulsed-power and e-beam technology required for sludge treatment is similar to that being developed as a first step toward inertial confinement fusion. The electron energies must be high in order to penetrate a reasonable thickness of sludge. Studies indicate that 3-MeV electrons are required for penetration of 1 cm of sludge. The beam energy requirements are on the order of 10 kJ distributed uniformly over an area of 400 cm². The pulse rate requirement is approximately 10 Hz.

Finally, the accelerator must be reliable and inexpensive. Reliable machines of this type are expected to be available in 2-3 years. The electron accelerators are projected to cost approximately \$40/J or \$4000/kW for a first, one-of-a-kind machine.

The degree of sludge disinfection and disinfestation is determined by the radiation dose. The electron accelerator system described above is capable of supplying a 1-Mrad dose to approximately 100,000 gal of sludge per day assuming a 40-percent beam/sludge coupling efficiency. A 1-Mrad dose is sufficient to sterilize the sludge by reducing bacterial, infestation and viral contamination to insignificant levels. At these levels, there should be no health questions related to using the processed sludge as fertilizer.⁴⁸

E-beam sterilization of the sludge may be performed at different stages of the process.^{48, 49} Figure 28 illustrates several possible system configurations. Each of these designs may be advantageous under certain circumstances. In the first system the e-beam sterilization is performed after digestion and thickening. This process uses the electron beam most efficiently. More of the solids in the sludge can be treated with each pulse. This configuration is also conducive to adding e-beam sterilization to an existing system. On the negative side, thickening siphons off a significant quantity of nitrogen, and the end product is more similar to a soil conditioner than it is to a fertilizer.

Figure 28. Possible system configurations for sterilization of sludge

In the system where the electron beam is applied before digestion and thickening, enhanced methane production in the anaerobic digester is a valuable by-product. It is projected that the gas production may increase by as much as 60 percent. In Los Angeles surplus gas production is currently being sold to the utilities. In this case, all of sludge must be irradiated and about half the nitrogen content is lost during digestion, thus decreasing its value as fertilizer.

Finally, the sludge may be treated with electron beams and subsurface-injected into the soil. This process avoids digestion and dewatering costs and relies upon composting for stabilization. It is this approach that should provide the highest-quality fertilizer.

Heat treatment, chlorination and composting are currently used for sludge sterilization.⁴⁸ Heat treatment is a relatively expensive and energy-intensive process where the sludge temperature must be held at 300-400°F and 150-200 psi for 30 minutes. The chemical costs for chlorination of sludge are high and the chlorine breaks down the refractory organics (DDT, PCP) into by-products that are equally as toxic. Composting requires high maintenance costs and large land areas and it may in addition cause odor problems.

Irradiation with ^{60}Co , ^{137}Cs and electrons has been suggested for future use.⁵⁰ The principal advantage of Co and Cs is that gamma rays have a much higher penetrating capability than do electrons. Their major disadvantage is that gamma radiation cannot be turned off. The radiation shielding must always remain in place.

A continuous, hot-filament electron beam is currently being operated at the Deere Island Waste Treatment Plant.^{50, 51} The 50-kW accelerator uses a 750-keV electron beam to irradiate a 2-mm thickness of sludge with a 0.4-Mrad dose. The plant processes approximately 100,000 gal of sludge per day. The accelerator costs are \$6000/kW. The principal advantages cited for e-beam irradiation are (1) the controllability and availability of the beam, (2) the necessity for shielding only when the machine is in operation (3) the fact that no radiation is introduced into the sludge, and (4) the favorableness of economic studies. On the negative side, electron penetration is low at 750 keV, and the 2-mm thickness of sludge currently being used is marginal.

A pulsed power system potentially provides economic and physical advantages over the continuous system. The costs of the pulsed system are currently projected at approximately two-thirds the costs of a continuous accelerator. While the pulsed power costs are speculative and the continuous system costs are real, there are physical reasons for expecting pulsed power costs to be substantially lower. The pulsed system uses a cold cathode that provides simpler and cheaper construction than does the hot cathode used by the continuous system. The cold cathode with a large-area, uniform beam eliminates the magnetic beam steering that the hot cathode continuous system requires. Finally, the extremely high voltages applied over micro-second pulses should allow for smaller physical size and thus cheaper costs. All of the advantages listed for electron beams apply equally well to those provided by pulsed power technology. In addition, 3-MeV electrons can suitably penetrate 1 cm of sludge, a thickness that appears to be much more desirable.

The sterilization of sludge is an increasingly important process in the United States for health and environmental reasons. Current practice does not appear to be particularly desirable; thus alternatives are being sought. Pulsed power e-beam accelerators developed for the inertial confinement fusion program will be potentially competitive. The desirable physical characteristics are the same as those being developed in the fusion program. The economics are currently soft but favorable.

2. E-Beam Welding

Electron-beam welding was originally developed by the nuclear and aerospace industries for joining exotic materials and for making welds that would otherwise be impossible. Since that time, e-beam welding has gradually attained commercial acceptance and can no longer be considered a laboratory oddity.⁶¹

E-beam welding has several characteristics that provide advantages over other techniques for certain applications.⁶² E-beam welds can be very deep and narrow, with depth-to-width ratios as high as 30:1. The heat is very localized, and thus the zone affected by the heat is small. This allows welding near heat-sensitive parts and minimizes distortion and shrinkage, so that finish machined parts may be welded. E-beam welds are very strong, and a 10-cm-thick section of steel may be welded in one pass. A final important characteristics is that by focusing the beam at a distance, welds can be made in otherwise inaccessible locations.

E-beam welding can be accomplished in an environment ranging from a hard vacuum (10^{-4} Torr) to atmospheric pressure. With a hard vacuum, less beam scattering occurs, and low-voltage beams may be used. However, e-beam welding has been commercially applied over the complete range of pressures.

Four control parameters are available: (1) accelerating voltage, (2) beam focus (3) beam current, and (4) welding speed. These parameters may vary greatly. Voltages between 20 kV and 175 kV are common; beam current is usually between 50 mA and 1000 mA. Welding speeds range up to 20 cm/s on sheet metal. Power concentrations of 10 MW/cm^2 are routine, and power concentrations of $10,000 \text{ MW/cm}^2$ are possible. Typical costs of an e-beam welding facility are from \$75,000 to \$1,500,000.

3. Hard-Rock Drilling and Tunneling

Present techniques for drilling and tunneling in hard rock are slow and may require blasting. The use of electron beams for this application has been under study at Lawrence Berkeley Laboratories⁶³ for several years. The objective of these studies is to increase the penetration rate in hard rock. Present drill/blast techniques proceed at a rate of approximately 5 mm/s. Electron beams can be used to cause spallation in rock because of their deposition characteristics. Spalling of rock with 1- to 10-MW electron beams has been demonstrated. The depth of spall is proportional to the beam voltage, and the amount of material removed per pulse is proportional to the energy of the beam. The conceptual design of an e-beam tunneling system that would bore a 7-m-diameter tunnel at a rate 10 times faster than the conventional method has been completed. The device would use a high repetition rate e-beam accelerator similar to those being developed for the ICF program.

4. Radiography

Intense X-ray sources are presently being used to perform radiography on thick samples. These intense sources are generated from intense electron beams. Many applications require repetitively pulsed sources. One example of this is the study of the motion of fuel rods within a reactor core as part of the Reactor Safety Research Program.⁶⁴ The intense, repetitively pulsed electron accelerators being developed under the ICF program are directly usable in this application.

5. Materials Processing

The use of electron beams for curing inks, fillers, and coatings and cross-linking polymers is increasing. In comparison to thermal curing, radiation curing offers lower fuel costs, faster production, less air pollution, reduced safety hazards, and increased design flexibility with heat-sensitive products.⁶⁵

The environmental concerns associated with thermal curing are primarily related to the coating material, where as much as 6 gal of solvent is used per gallon of deposited solids. During the drying process, the evaporated solvent must be recovered. The coatings used with radiation curing are 100 percent reactive and do not contain solvents. They are relatively pollution free.

Radiation curing allows faster production; the curing process is almost instantaneous. Also, subsequent handling can begin immediately because the product has not absorbed significant amounts of heat.

Radiation does have limitations. It is difficult to provide uniform irradiation of three-dimensional objects. For this reason, most present applications are for flat, primary production processes, such as beverage cans and automotive interior panels.

Radiation curing can be accomplished with UV energy sources as well as with electron beams. Currently, the UV systems are simpler and require less capital expense. The e-beam systems use less energy and provide higher rates of production.

The penetration depth of e-beam accelerators is also limited. The beam energy required for curing depends upon the required penetration depth. A 200-kV system is sufficient to accelerate electrons through a 10-mil coating. The penetration depth is particularly important for cross-linking polymers. Pulsed power machines similar to those being developed in the ICF program will produce higher energy particles and thus deeper penetration.

V. Intermediate-Term Applications of ICF Technology

Intermediate-term applications of ICF technology are loosely defined as those that can be realized from the present time until achievement of pellet gains of 50 or higher. There are applications both for the beam technology and for the fusion neutrons that can be produced with pellet gains of this magnitude. In this section we discuss ICF hybrid reactors, ICF pure fusion reactors, and one accelerator application.

A. Electrical Power Generation

1. Reactor Concepts

The ultimate goal of the Particle-Beam Fusion ICF Program is to achieve commercial electrical power generation. At Sandia, the use of ions and electrons to initiate the fusion reaction is under consideration, and several reactor concepts have evolved. For e-beam initiation using low gain pellets the reactor concept shown in Fig. 29 has been proposed.⁵²

The concept can be visualized by first considering a large metal "transmission disk" with an aperture in the center. An electromagnetic pulse from large energy storage and pulse-forming capacitors is released to the outside edge of the disk. The energy sweeps inward along both surfaces of the disk at the speed of light and emerges into the central aperture or diode as a radially flowing dual electron beam that converges onto the focal point of the diode.

The transmission disk is enclosed in a water jacket with the water acting as the high-energy-density dielectric to transfer the electromagnetic pulse to the diode. The diode is contained within a spherical vacuum chamber in which a solid insulator separates the water from the diode vacuum.

After the electromagnetic wave passes through the insulator at the perimeter of the diode, it is converted to a dual electron beam that flows in radially as a result of complex, self-generated electric and magnetic fields. Computer simulation of the particle flow provides an understanding of the resultant beam behavior, and a fairly simple picture has evolved. The magnetic fields near the common anode tend to counteract the effect of the electric fields farther away from the anode. As a result, the electrons move over the anode much as a flat stone skips over the surface of a lake. The pellet and plasma anode are replaced automatically after every firing.

The reaction region is surrounded by a blanket that converts neutronic energy from the fusion reaction into thermal energy for use in a conventional steam turbine power generation cycle. The minimum pellet gain that can be utilized effectively in this concept is determined by the beam generation efficiency, the blanket gain, and the steam cycle efficiency.⁵³ This reactor concept lends itself to modular design and can result in small reactors.

Figure 29a. Proposed configuration for an e-beam fusion reactor vessel

Figure 29b. Detail of cathode construction

Since the diode is in close proximity to the microexplosion, it must be designed to withstand the blast and radiation environment that results from the fusion reaction. X-ray damage appears to be the most severe problem. Techniques for protecting the cathode; e.g., covering it with carbon cloth, are under investigation; however, diode vulnerability will probably limit the maximum pellet yield that can be used. Since focusing has been demonstrated with this concept and since low gain pellets are anticipated in the intermediate term, we concentrate here on the reactor concept just described for e-beam fusion.

Alternatively, heavy ion beams may be generated by collective ion accelerators or multi-stage accelerators.⁵⁴ Heavy ions can be focused using magnetic optics. This concept is also under investigation.

The Particle Beam Fusion Program is investigating both electrons and ions as possible sources for ICF fusion. While there will be differences in the details of the reactor concept for the two cases, a general power balance analysis can be applied to determine basic system performance characteristics. We concentrate here on using the e-beam driver.

In order for any fusion generator to be economically practical, the circulating power fraction (CPF) must be small, and this requirement places stringent demands on energy conversion efficiency and pellet energy multiplication. The CPF is the ratio of power required to operate the plant to the total power produced by the plant. To determine this quantity, the conceptual REB fusion power plant was structured into major subsystems as shown in Fig. 30. A Marx generator is the primary energy storage device. Energy from this store is shaped temporally by a pulse-forming network and then transferred to the vacuum diode by a transmission line. The efficiencies accompanying these processes are denoted η_m and η_T , respectively. Of the energy supplied to the diode, a fraction, η_A , is absorbed by the pellet. The absorbed energy is denoted E_A in Fig. 30. The thermonuclear energy, E_{TN} , released by the resulting microexplosion is related to E_A by the pellet gain Q .

$$Q = \frac{E_{TN}}{E_A} \quad (1)$$

Approximately 80 percent of the thermonuclear energy release is in the form of neutrons. The remaining 20 percent, plus the input energy, appears in the form of X rays and ions.

Figure 30. Power balance diagram for a conceptual e-beam fusion power plant

The neutronic energy is converted into heat in the blanket with gain η_L . If ${}^6\text{Li}$ is used in the blanket, an energy release of 18.3 MeV per 14.1-MeV source neutron is obtained,⁵² yielding a value of 1.3 for η_L . At the same time, sufficient tritium can be bred to replenish that burned in the DT reaction. If a breeding blanket is used, η_L can be much higher.

Ions and X rays arising from the microexplosion impact the first wall of the reactor, causing heating of the wall. It is important to overall system performance to recover this non-neutronic energy.

The efficiency of the steam generating plant in Fig. 30 is η_E . The power produced by the steam generating plant is P_0 ; P_I denotes the power used to charge the electron-beam generator, P_P is the auxiliary power required for pumps and associated equipment, and P_L denotes the power supplied to the electrical grid. In general, P_P is taken as 4 percent of the total power produced.

In evaluating the CPF, two sets of subsystem efficiencies were utilized. While experimental data are needed in almost all areas, estimates of the efficiencies thought to be obtainable in a first generation system are listed in the second column in Table V. Further subsystem research and development should allow these values to be increased to those listed in the third column of this table.

TABLE V
Estimated Subsystem Efficiencies

Parameter	Projected Efficiency	Maximum Efficiency
Marx generator efficiency (η_M)	0.9	0.95
Beam-energy transfer efficiency (η_T)	0.65	0.85
Pellet absorption efficiency (η_A)	0.7	0.9
Blanket gain (η_L)	Variable	Variable
Thermodynamic cycle efficiency (η_E)	0.4	0.56

Earlier economic estimates of laser fusion power plants⁵⁵ indicated that a CPF of less than 0.33 is required for economic feasibility. However, the precise value required is determined by system costs and by the revenue-producing capability of the system; i.e., the worth of the product. Nevertheless, CPF is a useful indicator of overall system performance. This parameter is used in the analysis that follows to evaluate alternative concepts for electrical power production by e-beam-initiated fusion.

2. Relativistic E-Beam Hybrid Fusion Reactors

Many challenging problems remain to be solved before pure fusion reactors become a reality. An extremely significant milestone on this path will be achieved in the early 1980s when EBFA II is used to produce a scientific breakeven reaction; i.e., $Q = 1$. It is of interest to ask whether breakeven or low gain pellets are useful for commercial power generation. Previous analyses⁵³ have shown that if a breeding blanket is used (a hybrid system), pellet gains anticipated in the intermediate term ($Q = 1 - 50$) are useful.

In the hybrid concept, fusion-produced neutrons are used to cause fission in a subcritical heavy-element blanket surrounding the fusion plasma. The synergistic combination of fusion and fission enhances the ability of each technology to produce energy. A pure fusion system is inherently fast-neutron rich (14.1 MeV/neutron) and power poor (17.6 MeV/fusion); a fission system is fast-neutron poor and power rich (200 MeV/fission). The fast neutrons characteristic of fusion are capable of fissioning all isotopes of uranium and thorium. Isotopes such as ^{232}Th and ^{238}U are fissionable but not fissile, and fission only when interacting with high-energy neutrons. Fissile isotopes fission with low energy neutrons as well. The fusion neutrons also convert fissionable blanket material into fissile material that can be used in light-water reactors (LWRs).

In the fissioning blanket, the 200-MeV fission reaction improves the plant power production significantly and provides neutron multiplication. The fission neutrons, although of lower energy, improve the marginal tritium breeding characteristics of pure fusion. The hybrid system can be configured to emphasize electrical power production or fissile fuel production.

The addition of a fissioning blanket to a fusion reactor significantly changes the reactor design, its products and the subsystem efficiencies required for economic performance. The degree of change that is desirable is subject to debate. A consensus has been reached on two basic blanket designs, each with almost unlimited variations, and two fuels that may be desirable to breed. These blanket designs are based on existing fission reactor technology. The first is a fast-fission blanket where most of the energy multiplication occurs in fissionable material interacting with fusion neutrons. Fast-fission blankets use depleted or natural uranium or thorium as a fuel and are used primarily to breed fissile fuel rather than for energy multiplication, because the blanket has a relatively low fissile content. Typically, for a depleted uranium fast-fission blanket, the fusion neutron energy is multiplied by a factor of 10, and two plutonium atoms are created per fusion neutron. For a thorium fast-fission blanket, the blanket energy multiplication is approximately 2, and 0.6 of a fissile uranium atom is produced per fusion neutron.

The second type blanket is a thermal fission blanket. Thermal fission blankets substantially increase energy production over that of fast fission blankets but with a substantial loss of fissile fuel production capability. The fusion neutron energy multiplication is approximately 25 in the blanket, and one fissile plutonium atom per source neutron is produced.

As the issue of choosing a desirable design is not resolvable here, the performance characteristics of a REB hybrid reactor will be investigated as a function of the blanket gain. The model shown in Fig. 30 is used to study the effect of a fissioning blanket.

Figure 31 is a plot of the CPF of an REB fusion reactor as a function of blanket gain, assuming a breakeven pellet ($Q = 1$). Breakeven plant operation ($CPF = 1$) occurs at blanket gains of 6 and 1.6 for the two cases. A CPF of 0.33 occurs for blanket gains of 23 and 9. Therefore, a breakeven fuel pellet can be used in the power generation mode if sufficient gain is provided in the blanket.

It is anticipated that breakeven pellet gain can be obtained for e-beam energies of the order of 1 MJ. Use of such generators in 100-MWe modular power plants may be an attractive option. To produce this power level, the system must be repetitively pulsed.

Figure 32 illustrates the pulse repetition rate required for a 100-MWe hybrid reactor as a function of blanket gain when a breakeven pellet is assumed. An absorbed e-beam energy of 1 MJ is assumed. Blanket gains in excess of 20 are required to reduce the repetition rate of < 10 Hz. If a pellet with increased gain is used in conjunction with a hybrid blanket, considerable relaxation of subsystem requirements is allowed, as shown in Fig. 33. Here, the arbitrary

Figure 31. Circulating power fraction as a function of blanket gain for a hybrid reactor with unit pellet gain

Figure 32. Pulse rate as a function of blanket gain for a 100-MWe hybrid reactor operating at unit pellet gain

assumption of a blanket gain of 50 is made, and pulse rate as a function of pellet gain is plotted. Blankets having this gain have been designed.⁵⁶ With a pellet having a gain of 10, the required pulse rate drops below 1 Hz. Therefore, annual pellet demand is significantly lowered, and higher pellet fabrication costs can be tolerated. Similar arguments can be made for increasing the pellet gain while utilizing a lower gain blanket.

Figure 33. Pulse rate as a function of pellet gain for a 100-MWe hybrid reactor operating at a blanket gain of 50

Table VI presents the results of calculations for an optimized, conceptual e-beam hybrid power plant. Revenue is assumed both for the electricity and the fissile fuel produced. The blanket assumed is based on work by Maniscalco.⁵⁷ The allowable pellet cost may be quite high in a hybrid system. Two columns are shown in the table. One assumes a pellet having a high-density ablator, while the other assumes a low-density ablator with a high-density pusher. The systems simulation model was used to compute optimum pulse rate, number of vessels and allowable pellet costs. The high density pellet has a higher percentage X-ray output than does the structured pellet, but the total output from the structured pellet is higher. The net result is that the reactor radius is approximately the same in both bases, but a lower repetition rate is permissible with the structured pellet. Allowable pellet costs are approximately \$0.45/pellet in both cases.

TABLE VI

REB Hybrid Reactor Plant Parameters for Alternative Pellet Designs

System Characteristics	Low-Density Ablator Pellet	High-Density Ablator Pellet
Pellet gain	12.0	7.7
E-beam energy	21 MJ	16 MJ
Vessel pulse rate	3.4 Hz	7.2 Hz
Number of vessels	1	1
Chamber radius	6.1 m	6.2 m
Plant capacity	1230 MWe	1220 MWe
Allowable pellet fabrication cost	\$0.48/pellet	\$0.44/pellet
Price of fissile fuel	\$30/g fissile	\$30/g fissile
Capital cost per KW capacity	\$2100	\$2150

3. Comparison of REB Hybrid Reactor with Alternatives

Several characteristics of a hybrid reactor appear to make it an attractive option during an energy source transition from a fission economy to a fusion economy. First, the breeding characteristics of the blanket are flexible. Before pure fusion becomes available, the hybrid blankets can be designed to produce significant quantities of fissile fuel for LWRs and to produce only enough tritium to remain self sufficient. As fusion becomes available, the blanket configuration can be altered to produce smaller amounts of fissile material and larger amounts of tritium to fuel a fledgling fusion community.

Another important issue is the safety characteristics of the hybrid. The reactor is designed to be subcritical. When the fusion neutron source is terminated, so are the fissions. No active control systems such as control rods are required. The blanket power density can be designed to operate at any desired level. Blankets can be designed with higher breeding rates than are possible with the liquid metal fast breeder reactor. Economic and safety considerations will probably determine the power density. The higher the power density, the more economical the system; the lower the power density, the safer the reactor. Most current thinking is that the power density should be comparable to that of light water reactors where loss of coolant flow is acceptable but loss of coolant is not. There is no apparent reason to make hybrid significantly safer than the light water reactors that they will fuel.

A hybrid uses considerably less fuel resources than does a comparable fission plant. The blanket can be made of depleted uranium that is the waste product of fission enrichment plants and is currently being stored as waste. Whatever the fissile content of the blanket material, the

resource is used more efficiently than in LWRs because the fissionable material as well as the fissile material is consumed. Additionally, fission plant actinide waste can be burned in a hybrid blanket.

A fusion-fission hybrid appears to be an excellent energy source for advancing scientific and engineering knowledge during a fission-to-fusion transition. The hybrid significantly relaxes the scientific requirements for fusion. Using the hybrid would allow the scientific and utility communities to gain valuable practical experience in designing and operating fusion plants. Fusion would become a producing technology much sooner.

For all the positive aspects of a fusion-fission hybrid, the concept still draws much criticism. Part of the fusion community is concerned about its development because they do not want the stigma of fission to be unnecessarily associated with fusion. From a more pragmatic standpoint, the fusion requirements are probably not relaxed enough to make a hybrid feasible today. It is still a "future" energy source. The longer lasting objections are probably those associated with nuclear technology in general. Although hybrid plants are subcritical and thus inherently safer than are comparable fission plants, many similar questions about safety and the fuel cycle will arise. Hybrid plants will probably produce plutonium, an extremely toxic and long-lived radioactive material. Hybrid plants also generate nuclear waste and thus represent a safeguards problem. In other words, the fate of hybrid reactors is closely tied to that of all nuclear power.

4. E-Beam Fusion Reactors

Pure fusion reactors are usually envisioned as employing a lithium blanket for neutronic energy conversion and tritium breeding. The conversion gain for such a blanket is $\eta_L \cong 1.3$. Using a pure fusion blanket requires higher pellet gains than are needed with the hybrid system. However, because of the higher efficiencies associated with particle beam accelerators, it appears possible to achieve pure fusion electrical power generation with intermediate-term ($Q < 50$) pellets. To illustrate this point, we again utilize the model depicted in Figure 30.

Figure 34 is a plot of the CPF of a hypothetical e-beam fusion power plant as a function of pellet gain for the two sets of efficiencies. Breakeven power generation occurs at unity CPF. Note that pellet breakeven ($Q = 1$) does not imply breakeven power generation for the subsystem efficiencies assumed here.

Evaluating the CPF for the two sets of efficiencies yields values of the critical pellet gain, Q_C , of 4.0 and 1.2 for the projected and maximum efficiencies, respectively. The effect of increasing subsystem efficiencies to the maximum level is then to reduce the critical pellet gain by a factor of ~ 3.3 . A plant operating with the maximum subsystem efficiencies will achieve breakeven operation at slightly higher-than-breakeven pellet gain.

Figure 34. Circulating power fraction as a function of pellet gain for a conceptual e-beam fusion power plant

A value of CPF of 0.33 is obtained with pellet gains of 16 and 5.5 for the projected and maximum efficiencies, respectively. The gain of 5.5 required with the maximum efficiencies appears obtainable based on theoretical predictions of pellet performance.⁵⁸

One of the critical problems of power generation by REB fusion is the achievement of a pellet design that maximizes pellet gain. In the intermediate term, it is anticipated that e-beam pulses with energies on the order of 0.1 to 1 MJ can be achieved with the correct temporal characteristics. The question then arises as to whether e-beam generators of this size are suitable for power generation by REB fusion. As a first step to answering this question, calculations of subsystem requirements were made assuming that the fuel pellet is ignited by an electron beam with an energy of 1 MJ. The electrical output of the plant is assumed to be 100 MWe. A 1000-MWe plant would then comprise 10 such reactors.

Pulse repetition rate for a reactor supplying 100 MWe to the electrical grid is shown in Fig. 35 as a function of pellet gain. This rate is important in determining fuel requirements, e-beam switching configuration, and wall loading. At a nominal pellet gain of 10, pulse repetition rates of 35 and 17 Hz are required for the projected and maximum efficiency cases, respectively. Pulse rates of <10 Hz require pellet gains in excess of 20. Techniques for operating pulsed power systems at these rates are being developed. It may be that inductive energy storage with resonant charging and discharging must be used ultimately. In addition, new, higher-gain pellets that would relax these requirements are being investigated.

Figure 35. Pulse repetition rate as a function of pellet gain for a 100-MWe reactor (energy absorbed by pellet = 1 MJ)

Fuel costs contribute substantially to the total power generation costs in any generation scheme. The number of pellets required annually for the reference 100-MWe reactor operating at a pellet gain of 10 is ~ 0.5 billion or 5000 per kW/yr. This implies, first of all, that the pellets must be very inexpensive to manufacture. A major component of the pellet cost is the high-density ablator material. Gold, which is used in present pellet implosion calculations, is certainly too expensive to use in a commercial reactor. Other materials, such as tungsten and lead, are being investigated and may prove to be useful shell materials.

In summary, the high efficiency with which particle beams can be generated may permit achievement of a pure fusion ICF reactor with intermediate term pellets. Problems to be solved include diode protection, optimization of pellet design, and development of high repetition rate accelerators.

5. Comparison of Relativistic E-Beam Fusion with Alternatives

Laser Fusion

The use of lasers to implode DT fuel pellets to thermonuclear burn conditions has been studied for several years. At the present time, high power lasers are being fabricated at several ERDA, university, and commercial laboratories for studying the physics of laser-induced implosions. Particle-beam-induced fusion is potentially more attractive because of higher efficiency, simplicity, and the ability to scale existing technology to higher power levels.

A comparison of the two approaches will be based upon a power balance analysis. The circulating power fraction (CPF) for the REB fusion reactor is plotted in Fig. 39 for pellet gains of up to 150. Also included in Fig. 36 are the calculated values of CPF for two reference laser fusion reactors.^{55, 59} The higher beam generation efficiencies in the REB case permit operation with a lower pellet gain. CPF for the e-beam system at a pellet gain of 20 compares favorably with the laser system CPF at a gain of 100, assuming projected efficiencies. Improvements in REB system efficiency may allow competitive operation at a pellet gain of approximately 10.

Figure 36. Circulating power fraction for the e-beam fusion reactor including predicted points for the laser fusion reactor

There are basic difficulties in drawing conclusions from Fig. 36. CPF is not an ideal figure-of-merit; but if capital, fuel, and maintenance costs are similar in the two systems, CPF should provide a valid indication of relative system performance. In any case, the higher efficiencies associated with the e-beam system make it an attractive option for future consideration.

Magnetic Fusion

The thrust of the magnetically confined fusion reactor program is directed toward Tokamak and mirror reactors. These devices must be large (1000-5000 MWe) to achieve scientific and economic feasibility. Although the utility industry today orders fission reactors of 1000 MWe and greater, they do so only because of the long history of smaller scale demonstrations of LWR technology.

These demonstrations [< 200 MWe] allowed utilities and groups of utilities to become familiar with the technology without major risks of capacity or capital. The concern of the utility industry is, then, not only that fusion power be scientifically viable, economically competitive, reliable, and economically sound, but that it be developable. That is, it must be capable of demonstrating its desirable properties to the utilities and to the public.²⁰

ICF offers the potential for small modular power plants of virtually any size. This modular construction results in several potential benefits to a utility company.⁶⁶ Interest on borrowed fuels during construction is a major cost component for a power plant. With small modular units, the construction time will be shortened. The result is that the credit demands on the utility company are reduced. Further, siting and cooling of the smaller units are easier than, for example, for a 5000-MWe plant. Since the modular plants are less complex, the plant availability is higher, and this results in lower power generation costs. Finally, it is much easier to implement technological changes or new technological advances in a small plant than in a large one. This could be a major advantage for modular reactors since fusion reactor design is in its infancy.

If we are successful in achieving pellet gain in the intermediate term, it should be possible to design, construct, and test a low-cost, simple, experimental ICF power reactor. Such a reactor would be more readily accepted by the utility industry. This acceptance would accelerate the penetration of fusion power into our nation's energy economy. The flexibility afforded by ICF appears to be one of its major advantages over magnetic fusion.

B. Applications of Collective Ion Acceleration to Cancer Therapy and Radiography

In addition to applications for the fusion-produced neutrons, there are independent civilian applications for the pulsed power technology that is being developed in the ICF program. One such application is the use of high-energy ions for medical purposes.

The Ionization Front Accelerator (IFA) currently shows promise of becoming a feasible high-gradient ion accelerator. Projected typical ion energies should be in the GeV range for protons, and in the multiGeV range for heavy ions. Because of the high accelerating gradients (~ 100 MV/m), the length of the accelerator should be relatively small ($\lesssim 10$ m). As compared to existing conventional ion linacs, this means that a reduction in size and cost by about two orders of magnitude may ultimately be realizable. Such a compact collective ion accelerator could find immediate applications in the medical areas of cancer therapy and radiography.

For radiography, an energetic beam of ions (protons, or heavy ions) may be employed to produce high-contrast radiographs. The deposition profile of ions can be utilized so that small variations in tissue density create large variations in the final radiograph. The advantages of ion beam radiography (which include substantially lower doses) over conventional X-ray radiography are presently being assessed in several active research programs that use conventional

accelerators. The energy levels and total fluxes required for radiography (for protons, these are ~200 MeV and 10^8 , respectively) should eventually be easily attainable by a collective accelerator.

For cancer therapy, energetic particle beams (protons, heavy ions, or negative pions) can be used to irradiate and destroy cancerous tissue. All of these particle beams are examples of high-LET (linear energy transfer) radiation, which has several known advantages over the low-LET radiation provided by conventional ^{60}Co gamma-ray sources. High-LET radiation has a higher relative biological effectiveness (RBE), and a smaller oxygen enhancement ratio (OER) than low-LET radiation. High RBE means a smaller radiation dose may be used to produce the same effect as a larger dose of gamma rays. Low OER means that damage to healthy tissue (oxygenated) will be minimized compared to damage to cancerous tissue (anoxic). In addition, the deposition profile of ions and pions is such that a large amount of energy is deposited near the end of the range. This means that deep-seated tumors could be effectively irradiated with minimal damage to intervening tissue. With ^{60}Co gamma rays, the deposition is such that for a given beam, more energy is actually deposited in the healthy tissue than in the tumor.

The relative advantages of various particles for cancer therapy are being assessed in several ongoing research programs using conventional accelerators, but it may be some time before the best particle for cancer therapy is clinically established. In any event, the energies and current levels required for protons, heavy ions, or negative pions are within the range of those projected for collective accelerators such as the IFA.

The development of a compact, working, collective ion accelerator could therefore result in the near-term use of such an accelerator in the medical areas of radiography and cancer therapy.

VI. Long-Term Applications for Particle Beam ICF Technology

For the purposes of this report, "long-term" applications are those for which pellet gains of greater than 50 are utilized. The ultimate, long-term goal of the particle beam fusion program is to produce electrical power. Other applications are secondary. Although the low-yield pellet approach should permit one to ignite reactions within a hollow diode structure in the intermediate term, system studies⁵³ indicate that this approach would be of economic benefit only if high repetition rates and inexpensive pellets were used, or if one employed a fission blanket for breeding or energy production. The obvious, and by now well-known, advantages of hybrids are often countered by the equally well-known drawbacks, and attention has been directed to the solution of the "standoff" problem that would permit the use of high-gain pellets in a particle-beam-initiated reactor. Standoff can be obtained by beam transport in the case of electron beams, or through the use of ions that can be focused at a distance (see Fig. 37).

Figure 37. Heavy Ion Fusion Reactor

As shown earlier in Figs. 34 and 35, at least two advantages accrue when high-gain pellets are used in a pure fusion reactor. The CPF and pulse rate are reduced. This should result in a lower price for the electricity produced by the reactor. However, higher yield pellets may be complex and thus more expensive. In addition, if the pellet yields are high, the reactor will have to be designed to withstand and contain the large explosion on a repetitive basis. The upper limit for pellet yield will be set by the containment capability of the reactor and by the vulnerability of the igniter components that may be inside the cavity. Careful studies of these tradeoffs, both physical and economic, need to be made. In any case, the transport of the particle beam energy over some finite distance will be required.

The first approach to beam transport in an e-beam fusion reactor was proposed by the Kurchatov group in 1975. They proposed an "imploding lithium blanket" to compress a cusp magnetic field in order to provide a magnetic configuration for beam transport, as well as a liquid lithium blanket for energy absorption and conversion. Sandia has considered other approaches to beam transport and in 1976 discovered a possible method for e-beam transport⁶⁰ that requires neither the use of stationary field coils that would be damaged, nor the use of an imploding liquid metal blanket. In this approach, plasma channels are produced in a background gas in order to transport the beams to the target. This would allow the beam-generating diode to be located away from the pellet microexplosion. Background gas in the reactor chamber could also play a significant role in preventing erosion of the first wall by X-radiation.

Development of the e-beam transport technique or the ion beam focusing technique would allow the utilization of high gain pellets. The advantages of using such pellets are that the required repetition rate would be lower, and the allowable pellet cost would be higher. In addition, igniter efficiency would be less critical. On the other hand, the reactor design would have to change to contain such a large explosion. The tradeoffs in utilizing high-gain pellets for commercial power generation are numerous, and a complete study has not yet been accomplished. It should be emphasized, however, that extremely high gains are not required for particle beam fusion reactors because of the high efficiency of the igniter. The optimal pellet gain will be determined by reactor design tradeoffs.

VII. Conclusions and Recommendations

The goal of the Particle Beam Fusion Program is to achieve commercial electrical power production. The high generation efficiencies inherent in particle beams make their use as igniters an attractive option for ICF reactors. In fact, it appears that viable, pure fusion reactor designs are conceivable with intermediate-term ($Q < 50$) pellets. In addition, the beam technology being developed has several other civilian applications. To help achieve programmatic goals for civilian applications in a timely and efficient manner, the following recommendations are offered:

- Theoretical and experimental research in pellet physics should continue to determine the optimal pellet design for particle beam fusion reactors.
- Increased attention should be given to the questions of e-beam transport and standoff to determine whether the diode vulnerability problem can be alleviated and whether high gain pellets can be utilized in a reactor.
- Research directed toward high repetition rate pulsed power technology should continue.
- Systems studies directed at technical and economic tradeoffs should continue in order to allow identification of optimal designs and to provide goals for the research effort.
- Conceptual reactor design studies should be conducted to identify problem areas and to provide input to the systems studies.
- First wall protection and blast containment problems should be addressed in more detail.
- Theoretical and experimental research on ion beam fusion should continue, and supporting systems studies should be initiated.
- Pellet fabrication techniques should be developed, and cost estimates for the pellets should be obtained as inputs for the system studies effort.
- Techniques for debris removal and recovery from the reactor chamber should be investigated.

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