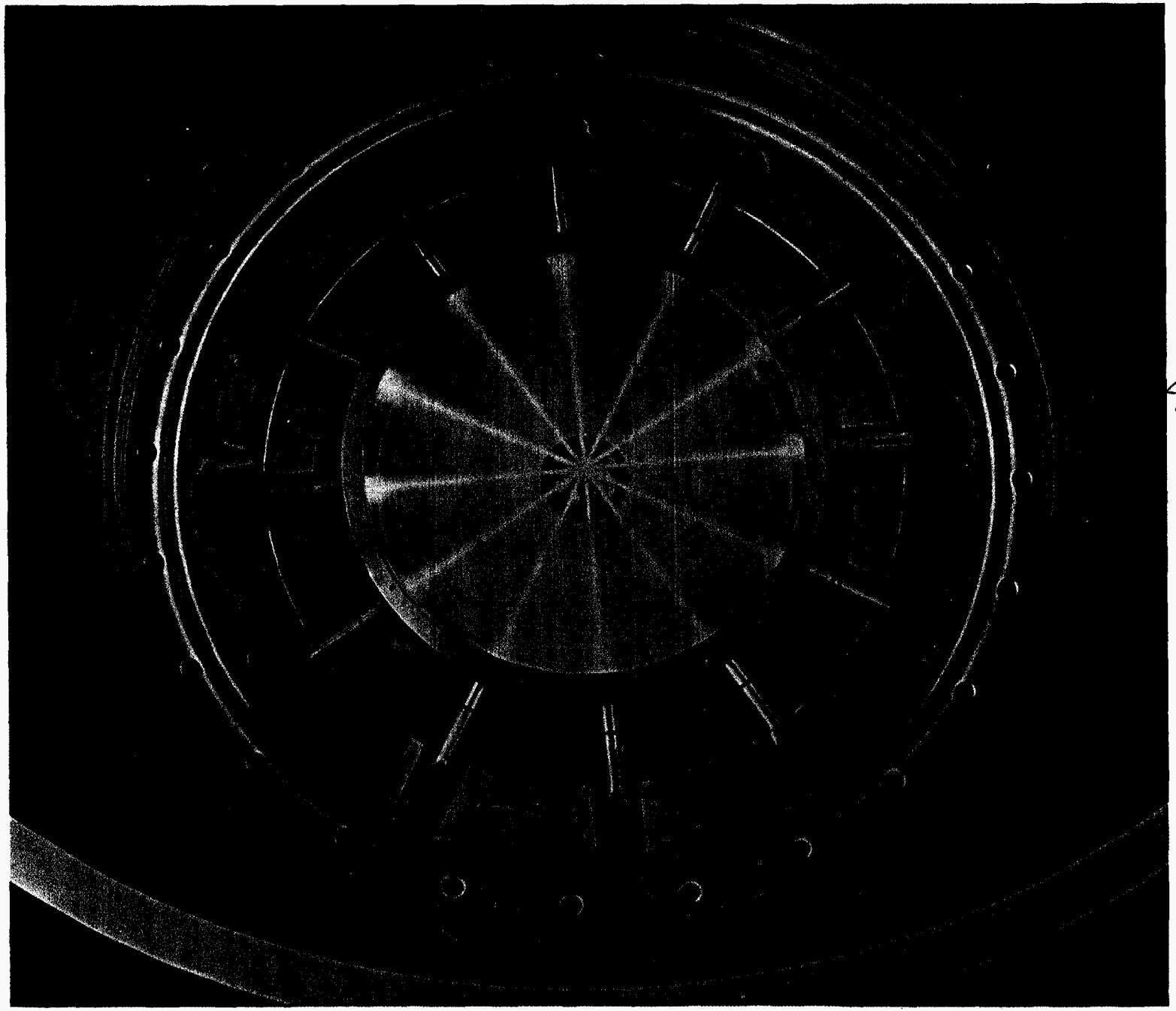

PARTICLE BEAM FUSION

SAND--95-2916

Sandia Laboratories

PULSED ENERGY PROGRAMS

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MASTER

OPON # 103

caption- cover photograph

The cover photograph is a view of the experiment that demonstrated the efficient transport of electron beam energy to a target through multiple discharge channels in air. Fifty kilojoules of electron energy was transported over the 50-cm distance between the source and target with a 90% efficiency. Similar results are expected for ion beams. The 12 cylinders around the edge are electron beam sources in a vacuum. Normally they are hidden from view.

The experimental results from the Proto II accelerator confirmed the theoretical predictions. The demonstration of the "stand off" between particle beam source (diode) and the target, with gas in the intervening space, is significant. In a fusion reactor, this gas would protect the chamber wall from damage by fusion target microexplosions. Before the development of this gas-shielding technique, fusion reactor design concepts were limited to very small low-yield systems that would minimize wall deterioration and the production of debris.

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GOALS OF SANDIA'S PARTICLE BEAM FUSION PROGRAM

Introduction

The quest to harness fusion power — the energy source of the sun — has challenged scientists for 30 years. In the last six years, with the world's energy problems growing increasingly more severe, the pace of research has shown an increase in the commitment of scientific resources.

Today, in keeping with Sandia Laboratories' designation by the Department of Energy as the lead laboratory for the pulsed power approach to fusion, its efforts include major research activities and the construction of new facilities at its Albuquerque site. Additionally, in its capacity as lead laboratory, Sandia coordinates DOE-supported pulsed power fusion work at other government operated laboratories, with industrial contractors, and universities.

Although many complex technical problems remain to be solved, there is reason for optimism about the quest to harness fusion power at Sandia and other laboratories. This nation's investment in its nuclear weapons program may ultimately lead to one of its greatest peacetime benefits.

The beginning of Sandia's involvement in developing fusion power was an outgrowth of its contributions to the nation's nuclear weapon program. The Laboratories' work in the early 1960's emphasized the use of pulsed radiation environments to test the resistance of U. S. nuclear weapons to enemy nuclear bursts. A careful study of options for fusion power indicated that Sandia's expertise in the pulsed power field could provide a powerful "match" to ignite fusion fuel.

Although creating test environments is an achieved goal of Sandia's overall program, this work and other military tasks protected by appropriate security regulations will continue, making full use of the same pulsed power technology and accelerators as the fusion-for-energy program.

Major goals of Sandia's fusion program include the following:

- Complete a particle accelerator to deliver sufficient beam energy for "igniting" fusion targets.
- Obtain "net energy gain." This goal would provide fusion energy output in excess of energy stored in the accelerator.
- Develop a technology base for the repetitive ignition of pellets in a power reactor.

After accomplishing these goals, the technology will be introduced to the nation's commercial sector.

HISTORICAL PERSPECTIVE .... What is Fusion?

Understanding the fission process is helpful in understanding nuclear fusion.

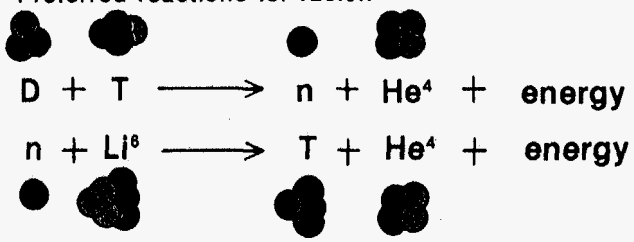
Fission means splitting or breaking up into parts. In this discussion, it means the splitting of heavy atomic nuclei (for instance plutonium or uranium) which releases energy. When a heavy atomic nucleus absorbs a neutron, it becomes unstable. Fission of the nucleus then occurs with the formation of lighter elements and the release of additional neutrons, some of which are used to continue the process. Heat produced from the released energy can be used to make steam and generate electricity.

Fusion is another means of releasing energy from the nucleus, but contrary to the mechanics of fission splitting, fusion is the joining together of the nuclei of light elements. It was recognized in the 1940's that energy could be obtained by fusing together the nuclei of the heavy isotope of hydrogen known as deuterium (D), which is found in ordinary water. It was also discovered that tritium (T), a heavier and much scarcer isotope of hydrogen, fuses even more readily with deuterium nuclei and with a greater release of energy. Further, all the needed tritium can be produced from the interaction of byproducts of the deuterium-tritium (DT) reaction with a relatively abundant element, lithium. The neutron-lithium reaction also produces additional energy.

The fundamental problem in causing light nuclei to fuse is that they are positively charged and repel each other electrically. A fusion reaction requires initial temperatures of at least 300 million degrees centrigrade to give nuclei sufficient energy to fuse. The energy from an explosive fission reaction is used to initiate fusion reaction in a weapon.

The objective of the current program, however, is to use pulsed power technology in place of fission to start and sustain the fusion reaction on a usefully small scale. When methods are developed to "burn" DT fuel on a basis economically competitive with other energy sources, the world will have a plentiful energy supply. Other benefits that make fusion so attractive are that operating fusion systems will not affect the earth's climate (from CO_2, which attends the burning of fossil fuels) and that radioactive waste can be limited to relatively small quantities of short-lived materials that would not present severe handling and disposal problems.

Preferred reactions for fusion



Two Approaches

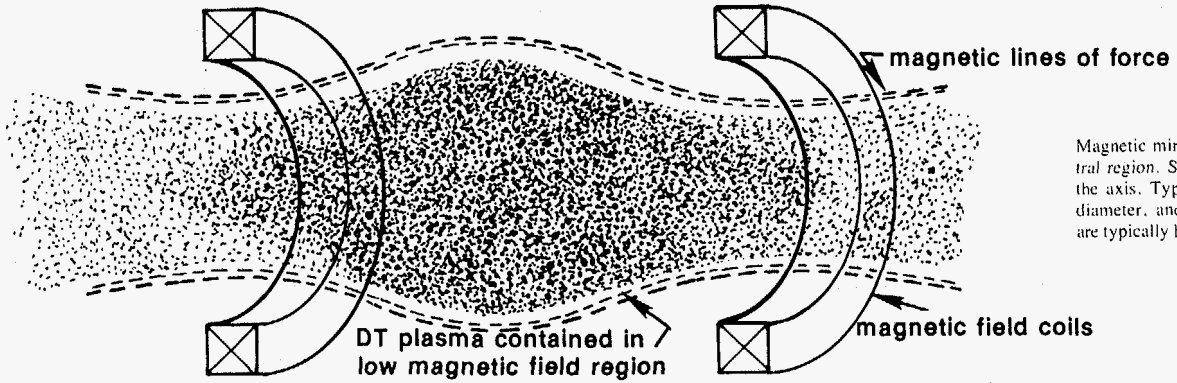
Although there are currently two recognized approaches to harness the DT reaction, each approach requires that the fuel be raised to a temperature of at least 300,000,000°C and that it be contained sufficiently long for the D and T nuclei to combine.

The preferred reactions for a fusion system, as described in the foregoing paragraphs, are

Approximately 5×10^{18} individual reactions will produce one kilowatt hour of electricity. A striking consequence of the energy content in the reactions is that the fusion of deuterium extracted from one gallon of ordinary water has the energy equivalent of about 350 gallons of gasoline. Economy is also a consideration. The cost of the deuterium is less than $1.00 per gram, and would be a negligible contribution to the cost of energy production. It follows that the initial capital investment and plant maintenance costs will determine the cost of power.

Magnetic Confinement Fusion

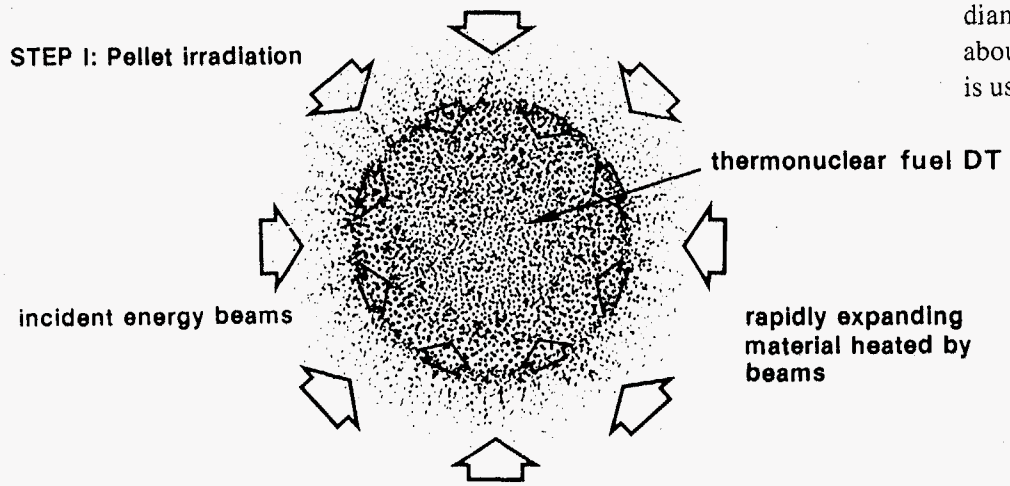
The older of the two approaches to producing fusion energy is to heat the fusion fuel (D and T) inside a container that is surrounded by magnetic field coils. The hot fuel (in the form of a plasma) is completely ionized and consists of ions (bare positively charged nuclei) and electrons moving randomly about at high velocity. The magnetic field forces the moving charges in the plasma away from the comparatively cold reaction chamber walls long enough for the fuel to react. Examples of systems using magnetic confinement include the tokamak, magnetic mirror, theta pinch, and others.



Magnetic mirrors trap plasma in the low field central region. Some plasma tends to squirt out along the axis. Typically such devices are one metre in diameter, and magnetic fusion containment times are typically hundredths of a second.

Inertial Confinement Fusion

Inertial confinement fusion (ICF) utilizes the principle of heating and containment by compression; the pressure is exerted by physical material surrounding the thermonuclear fuel. To accomplish ICF, fuel is contained inside a small spherical pellet composed of one or more layers of material such as metal or glass. During irradiation, an extremely powerful particle beam (or laser light) heats the outer surface of the pellet during a few billionths of a second. The outer heated layer of the pellet rapidly expands outward, and the resulting reaction force causes the remaining material to accelerate inward radially. The fuel is carried inward by the remaining pellet material and compressed, causing a temperature rise. If a temperature of three hundred million degrees centigrade is attained and the fuel is compressed to hundreds of times solid density, a reaction lasting only a billionth of a second releases an intense burst of thermonuclear energy. This energy is in the form of neutrons, ions, and x rays.



Step 1:

Pellet Irradiation

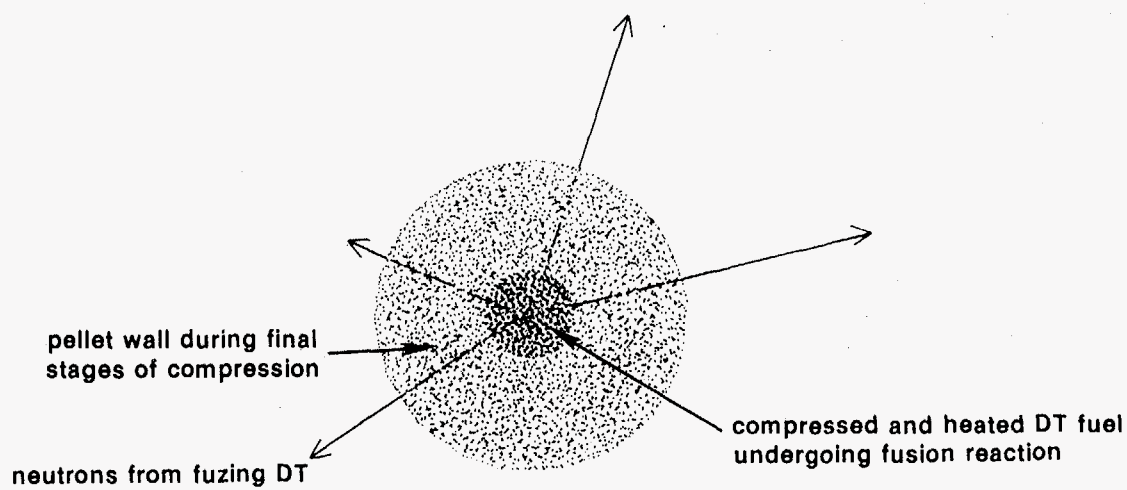
Energy incident on a pellet must be intense enough to rapidly heat and blow off the outer layer of the pellet. The resulting reaction force drives the remaining shell material inward, compressing the fuel. The compression heats the DT mixture, and the pellet wall contains the fuel in a compressed state long enough for ignition and burn to take place. Pellet dimensions typically are a few millimetres in diameter. The energy release takes place in about one billionth of a second. A new pellet is used for each burst of energy.

Step 2:

Fuel Compression and Burn

The neutrons would be trapped in a surrounding lithium blanket where nuclear reactions would result in additional production of tritium needed for fuel. Heat produced by neutrons slowing down in the lithium and by the x-ray and particle energy absorbed in the reaction chamber wall would produce steam for electric generation or industrial process heat.

Step two portrays reaction on a scale ten times larger than step one.



HISTORICAL PERSPECTIVE .... Origin of Sandia Program

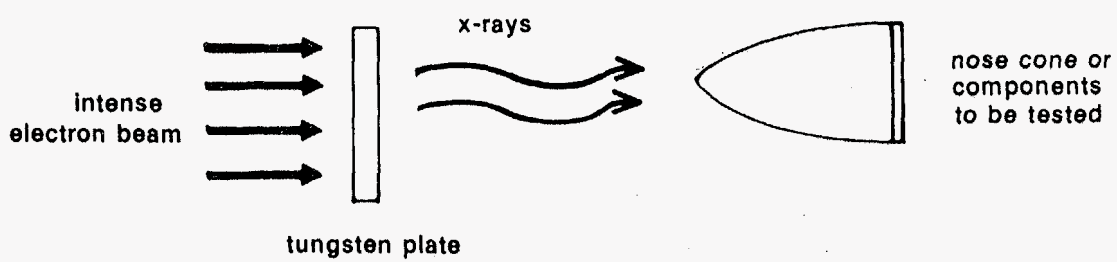
As noted earlier, Sandia's involvement with pulse power fusion grew from military requirements to test weapon components for resistance to nuclear radiation effects. When high-voltage and high-current beams strike a high-atomic-number metal plate, the resulting burst of x rays simulates some aspects of a nuclear burst. During the early 1970's it was recognized that the electron beams used for simulation purposes could be concentrated to high enough intensities for inertial confinement fusion (ICF) research.*

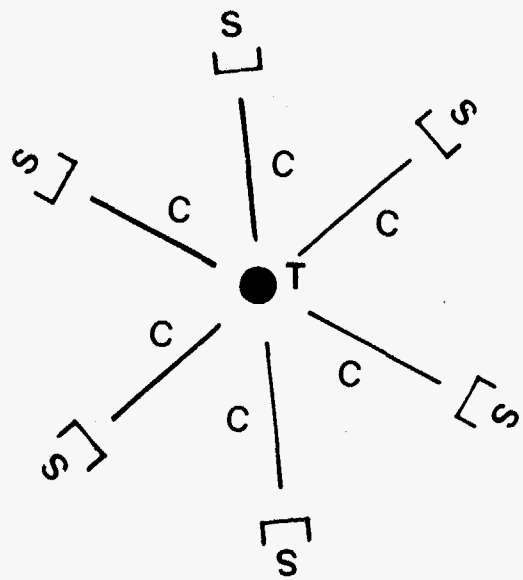
Electrons, however, have a long range in matter. Provision must be made to enhance the interaction of electron beams with the pellet to facilitate the efficient use of energy for compression. Means to enhance electron-beam matter interactions using intense magnetic fields were forecast theoretically and confirmed experimentally during the period 1975 to 1978.

Ion beams have the best properties for igniting pellets. Since the range of ions stopping in matter is shorter than that of electrons having equal energy, ions can more effectively deposit their energy in a small mass of material. No enhancement of energy deposition is required for ions. Another advantage of ion beams is that x-ray emission is comparatively small as ions slow down in matter, unlike the intense radiation that attends the stopping of electrons. Such xrays can heat the pellet walls, severely degrading the quality of the compression needed to ignite the fuel. For ion targets, the designer can choose optimal pellet materials and ion beam properties to maximize use of beam energy in obtaining ignition.

Until the early 1970's, efficient methods for producing intense ion beams had not been sufficiently developed to direct major program resources toward light-ion beam fusion. However, rapid progress made by Sandia, U.S. Naval Research Laboratory, Cornell University, and others made possible a major change in program emphasis during 1979. Proton ion beams with million-volt energy and current density of one million amperes per square centimeter are now produced. Means to extend the power density by the needed factor of 10 to 100 to the fusion regime have been identified. The power sources used for generating beams of either electrons or ions share a common technology — pulsed power. Major facility development underway with the original intent of producing electron beams is equally applicable for ions.

*From the mid-sixties, it was recognized that intense laser beams could be of interest for ICF. Lasers, of course, can be focused onto a pellet using lenses and mirrors, but have limited efficiency and are costly per unit of energy. In addition, the interaction of laser beams with matter is a complex phenomenon which occurs primarily in the low density region of material evaporating from the pellet surface, where coupling of energy may be inefficient.

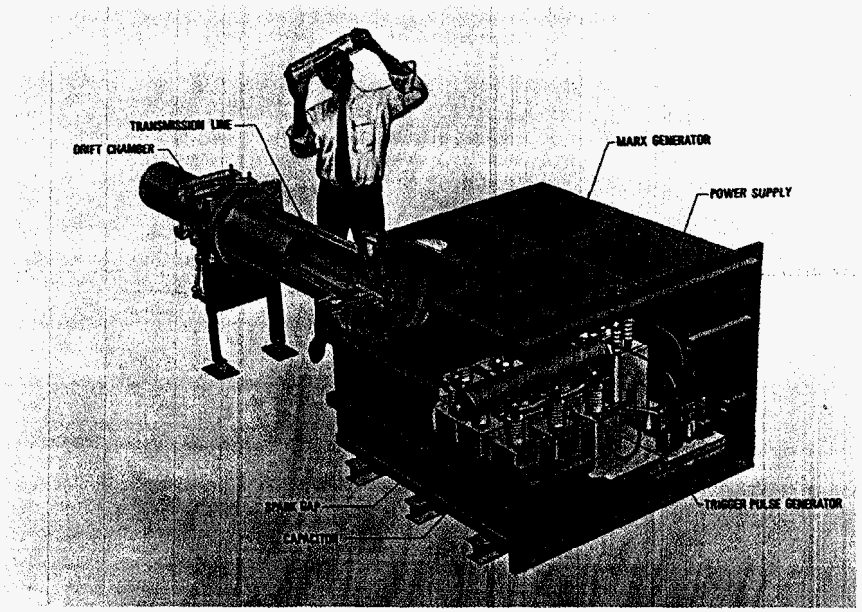


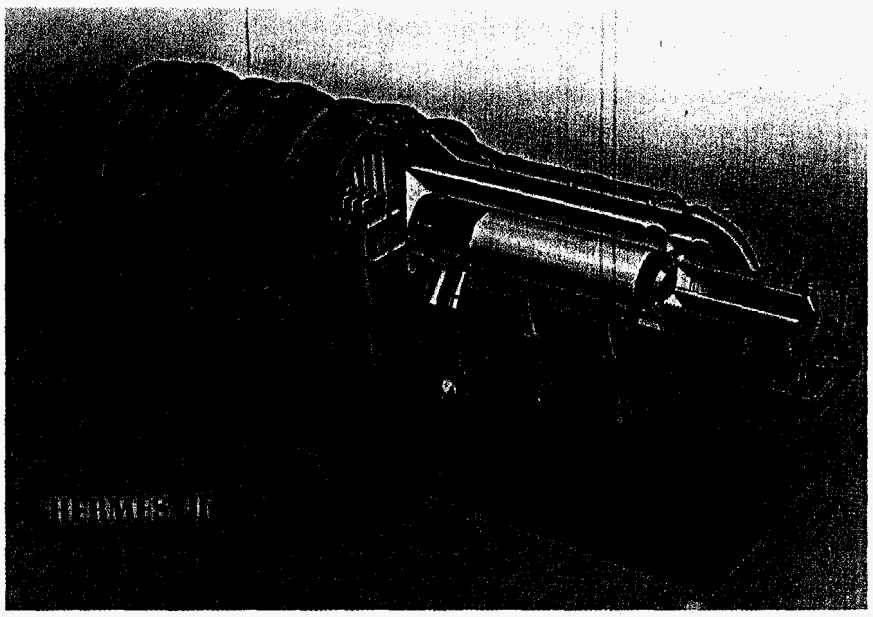


S = beam sources
C = beam channels
T = fusion target

Scenarios were developed for placing sufficient electron beam energy on a target to test proof-of-principle for ICF. The proposed method was to produce a large number of individual electron beams which converge toward a target, as the figure above shows. A photograph of an experiment proving this beam transport principle is shown on the front cover. Although the proof-of-principle for pellet ignition could be obtained using intense electron beams, the superior potential of ion beams for ICF (using the same power source employed for electrons) was recognized.

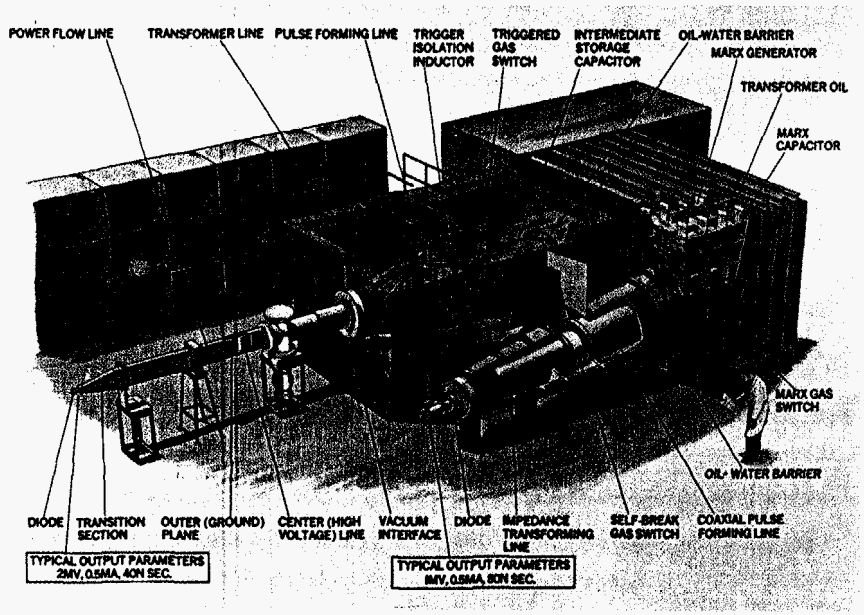
SANDIA FACILITIES



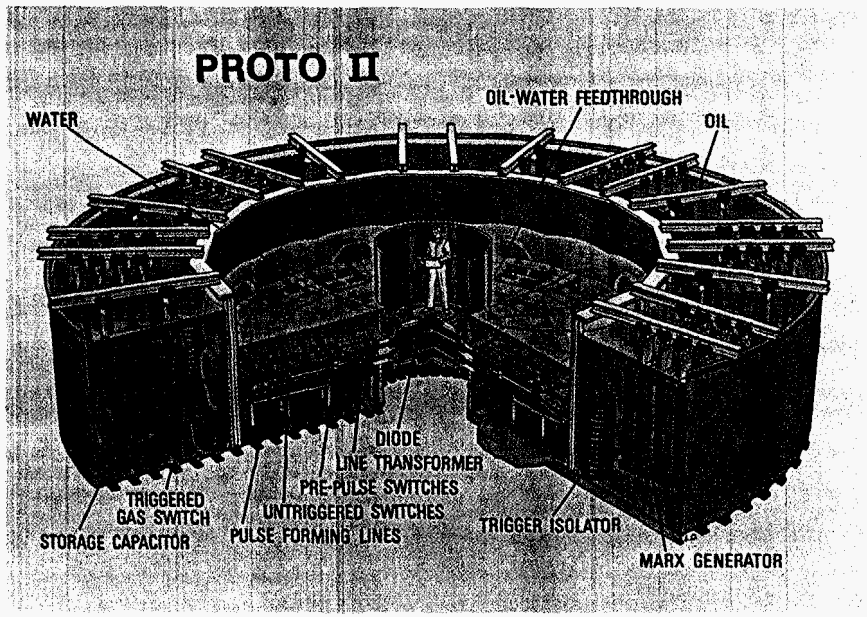


Simulation of radiation effects from nuclear weapons was started in early 1960's, and a series of accelerators ranging in size from the small 300,000-volt Nereus accelerator to the mammoth 12-million-volt Hermes II was developed and in routine use by the late 1960's. Although specific configurations may differ considerably, the major components of all Sandia accelerators are a Marx generator, a pulse-forming line, and a diode. Electrical energy is transferred from the Marx generator to the pulse-forming line where a short-duration, high-power pulse is formed and then applied to the diode through a transmission line. This pulse produces high electric fields in the diode to cause electron emission from the surface of the cathode.

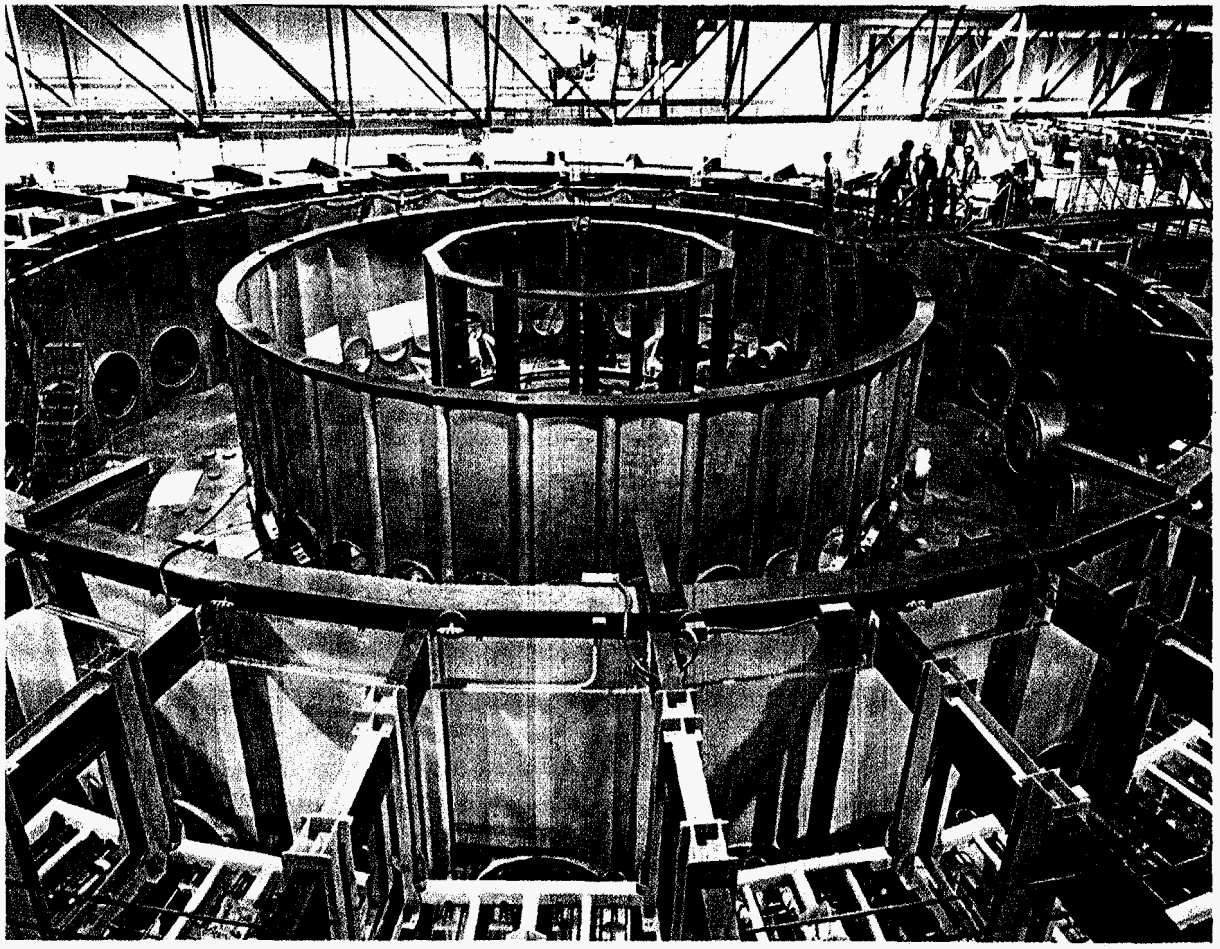
The Hermes II is a high-energy, pulsed, field-emission electron-beam or x-ray source. It was designed and constructed by Sandia Laboratories to provide high-dose-rate radiation effects studies and material response studies of rapid energy deposition.



Hydra, an accelerator that delivers a million-volt, 500,000-ampere pulse of energy 80 billionths of a second in duration, was developed originally for weapons work during 1972 and later became the "workhorse" for performing target interaction experiments for the fusion program. Some of the results of this work are shown here. Hydra Mite, which shares this facility, pre-tested the design of PBFA.



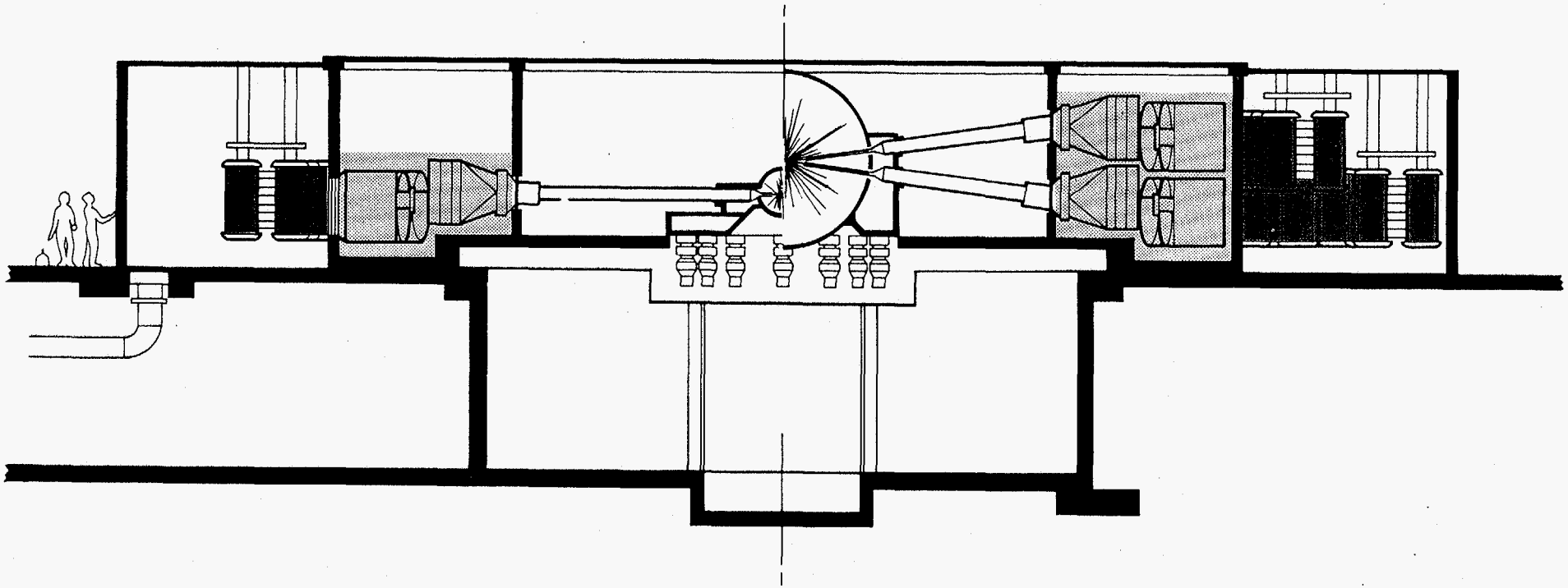
As work progressed, a facility designed specifically for fusion research was needed. Two test-bed accelerators, Proto I (1975) and Proto II (1977), were constructed to test new concepts of high-speed pulse switching in oil and water lines. (Electric pulse energy is stored momentarily in transmission lines that are insulated either by oil or highly purified water.) Both machines were successful and are in daily use in the fusion program. The least costly approach, utilizing flat metal pulse-forming lines with purified water as the insulating medium, was chosen for scale up.



Continuing research led to a request to the Department of Energy and Congress to expend $14 million on a laboratory, a 30-trillion watt accelerator, and an office complex to house scientists and technicians. The accelerator, originally called Electron Beam Fusion Accelerator (EBFA) and recently renamed Particle Beam Fusion Accelerator (PBFA-I), is shown in an artist's concept. Its 36 separate beam lines will be able to deliver 30 trillion watts of power and one million joules of energy to electron or ion sources. PBFA-I is scheduled for first operation during mid-1980.

In the design of PBFA-I, the eventual need to build an upgrade was recognized, so the tank containing the accelerator was designed with sufficient room to contain the modified accelerator as shown. The parameters of this accelerator are to be optimized for ion beam fusion, but the accelerator will also be ideal for radiation effects experiments using electron beams. PBFA-II will have 72 beams, operate at nearly four million joules output energy, and will supply four million volts instead of the two million volts specified for PBFA-I,which itself will be the world's largest pulsed power accelerator. The upgrade of PBFA will begin with the preassembly of components in 1982 with the actual modification taking place over a one-year interval during 1983-84.

PBFA-I PBFA-II



The flexibility of pulse power technology allows us to change the voltage from two to four million volts and to reverse polarity within the volume of the PBFA-I tank. Thus a machine that was designed to supply one million joules to electron sources will be upgraded to supply four million joules to ion sources.

PBFA-II operating in the ion mode is expected to ignite fusion pellets in the mid-1980's and establish ICF proof-of-principle by releasing as much fusion energy as is stored in the accelerator. The success of this experiment will mark "net energy gain."

PBF Plans and Accomplishments

The physics issues involved in Sandia's Particle Beam Fusion Program lie in three basic areas of activity, each of which embraces several subelements of technical skills.*

The first of the basic elements is *source development*. The source is a high voltage pulse generator and the means to convert this energy to particle beams and transport them to the target. The pulse circuit consists of capacitors which are charged from power supplies at relatively low voltage in a parallel arrangement and discharged in series, producing high voltage for one microsecond. This pulse undergoes further intensification by means of subsequent pulse-forming lines, and is delivered to the ion source, or diode, in the form of a pulse only 35 billionths of a second long. The source for PBFA-II must deliver approximately one hundred trillion watts of beam power to the target to initiate the fusion reaction. Among the subelements of this technical field are pulse power technology[1], ion beam formation[2], and transport to target[3].

The second basic element is *target physics*. The target is a multi-layered spherical shell filled with gaseous DT. Of all the fundamental problems that particle beam fusion faces, pellet design is one of the most critical. The subelements of interest in addition to target design[4] are target fabrication and characterization, and measurment of target response.

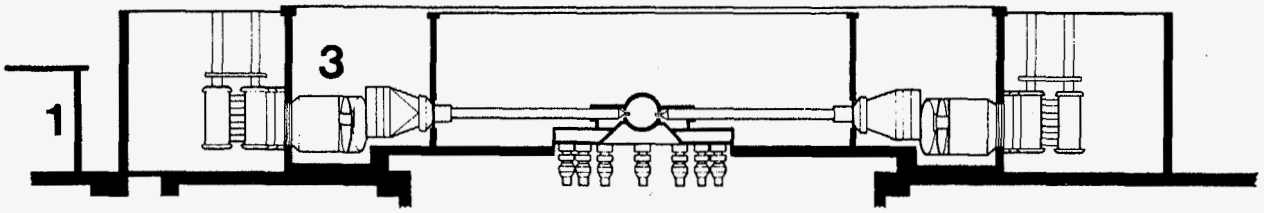
Reactor systems constitute the third segment. Although the accelerator is the laboratory test bed for experimentation in particle beam fusion, the program ultimately will bring the component systems together, when proven, to produce electrical energy. A fusion power plant must contain microexplosions produced about ten times per second. The largest portion of the energy release will be in the form of fast neutrons. The energy of the neutrons will then be converted to heat energy in a moderating region surrounding the central chamber. This moderating region will contain lithium which absorbs neutrons and produces tritium. The heated moderator will produce steam to drive a turbine. In addition, natural uranium may be used to absorb some of the neutrons and thereby be enriched for use in conventional nuclear reactors. Unlike the fission breeder reactor, one unit of a fusion-fission breeder could produce electric power as well as nuclear fuel for *many* ordinary reactors. The subelements include an electrical engineering basis[5], neutronics[6], materials properties for the reaction vessel[7], and environmental impact[8].

*Space here permits coverage of only a small part of these activities; for more details the reader is directed to the citations appearing under "Additional Reading."

Source Development

It is known that ignition of a fusion pellet requires the deposition of approximately one megajoule of energy on the fuel pellet during ten billionths of a second. The energy per unit mass which must be deposited is about 2×10^7 joules per gram. The goal of the source development effort is to develop means for meeting these conditions.

The following sequence of photographs shows the elements in the power flow of PBFA. The photographs illustrate the robust nature of the equipment used. It should be noted that each of the 36 modules composed of these elements can deliver 0.8 trillion watts of power to the terminals of an electron or ion source. In the planned upgrade to PBFA-II, the number of modules will be increased to 72 and the power output of each will be increased to more than one trillion watts.



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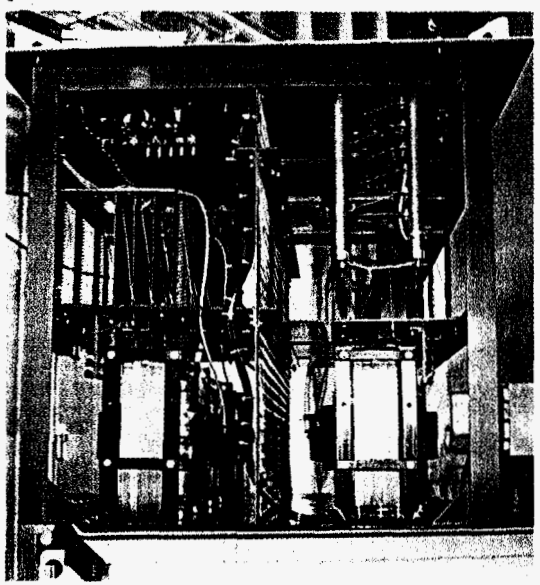
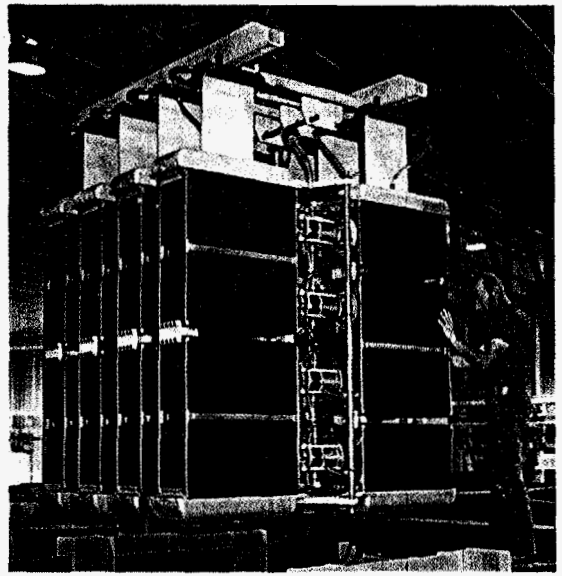


The power supply steps up line power to 100,000 volts DC to charge the Marx generator energy storage system. The peak charging power for each Marx generator is several kilowatts.

The Marx generator contains capacitors submerged in an oil tank; it stores energy for approximately one minute. Each capacitor is charged to 100,000 volts, and at the time of triggering all 32 capacitors discharge their energy in series. During an interval of one microsecond, the 2- to 3-million-volt charge is transferred to the intermediate store. The power flow from each Marx generator is 10^{11} watts.



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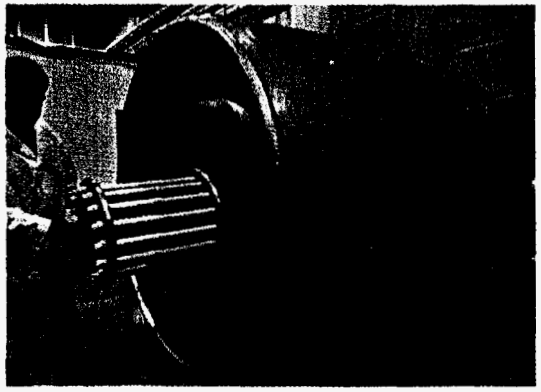
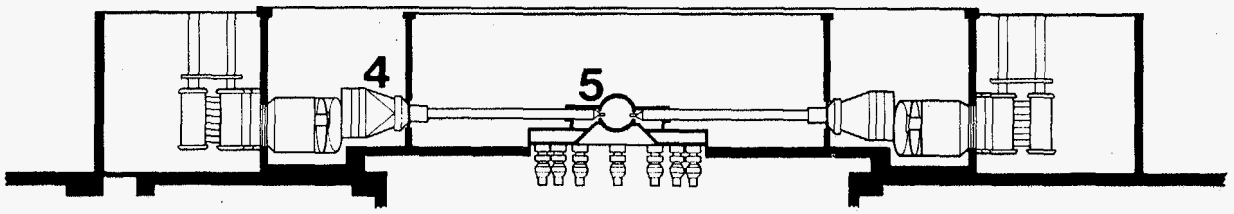
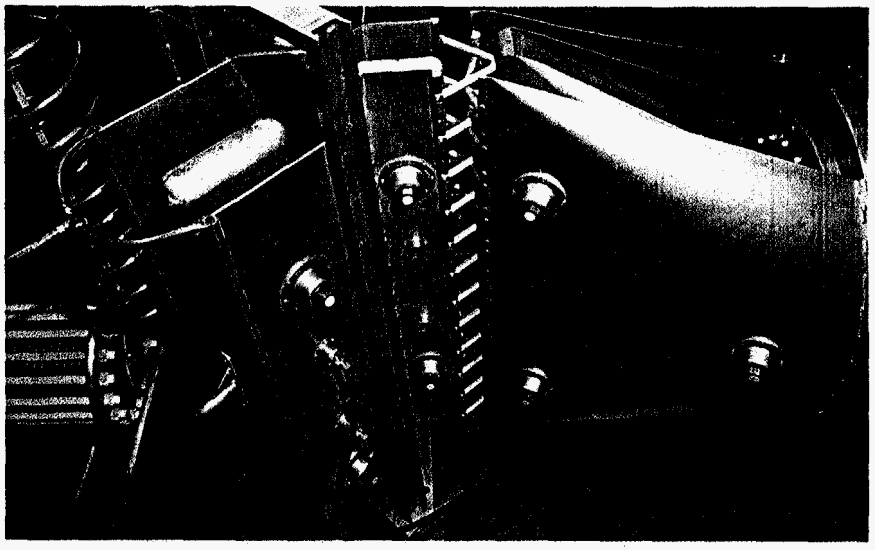


The intermediate storage capacitor is the first section that uses purified water to serve as the energy storing dielectric. The triggered gas switch shown in the center electrode discharges the stored energy into the pulse-forming section during a 1/4-microsecond interval, and is the main time-synchronizing element for the 36 modules. The power level from each intermediate store is approximately 0.25×10^{12} watts.





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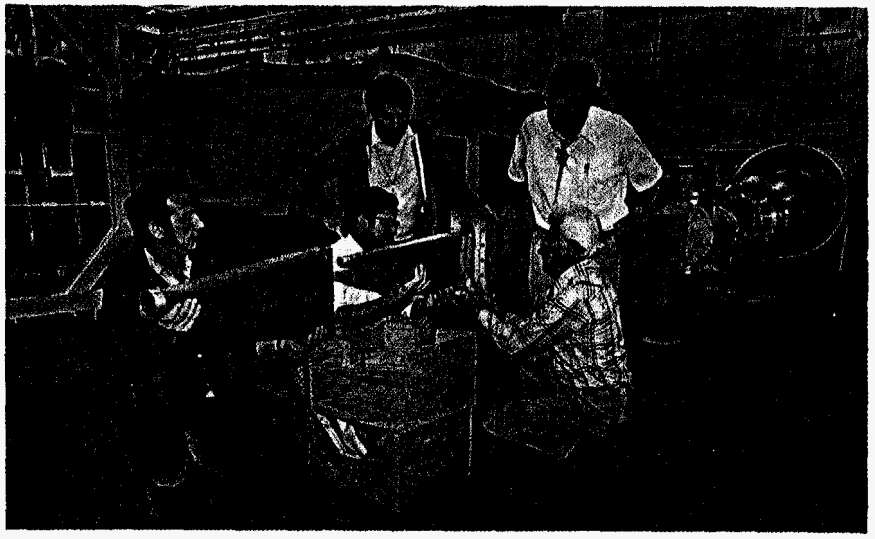
The pulse-forming section, also in water, shortens the pulse from the intermediate store by the self-triggered breakdown of electrodes in water. The output of this section (50 billionths of a second) provides a 1.2-million volt pulse. This pulse enters a tapered transmission line with water dielectric which transforms the pulse to 2 million volts. The criss-cross leads in the lower part of the photo constitute the section for reversing polarity. Nearly 10^{12} watts flows from each module.



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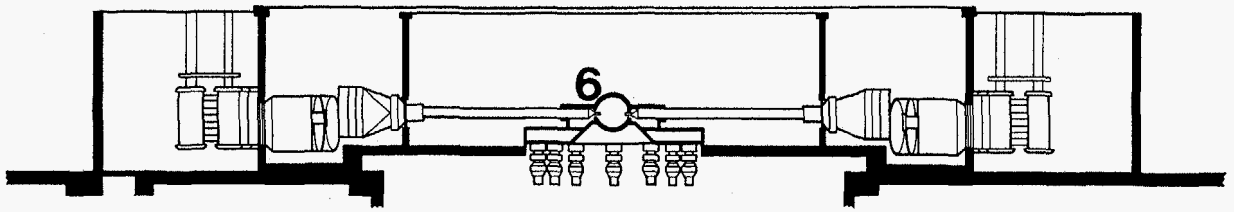
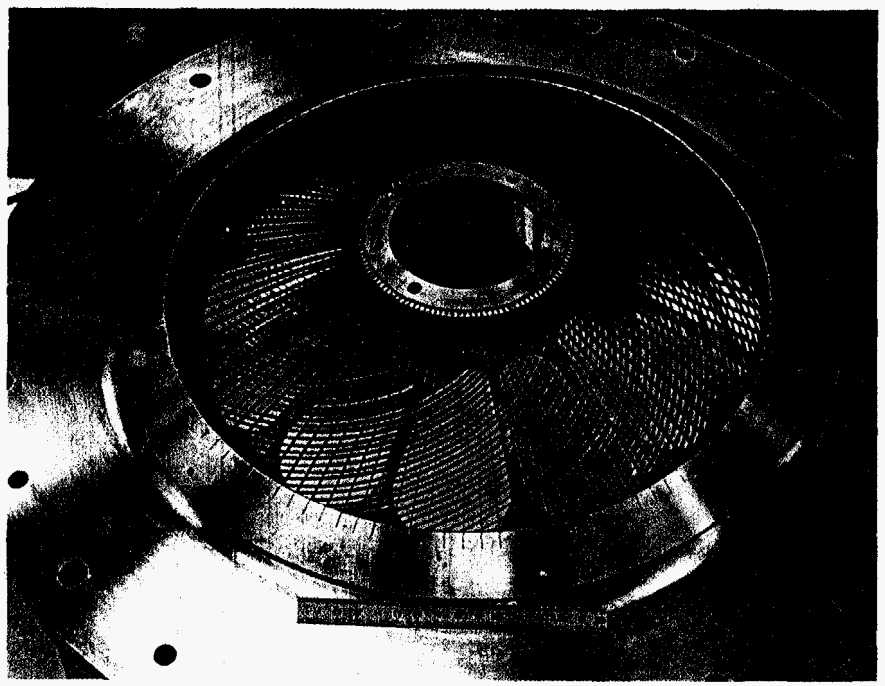
The energy is passed from the water-filled pulse lines, through a water-vacuum barrier, and into a vacuum transmission line which transmits the pulse to the particle beam source 6 metres from the pulse generator. The line is carefully designed so that the magnetic field from current flowing in the line serves to inhibit the loss of electrons. Without this feature, it would be impossible to efficiently deliver energy of many trillions of watts over a distance of several metres. In these transmission lines, 2-million-volt pulses are transported with virtually no loss across a 1-centimetre gap between electrodes.





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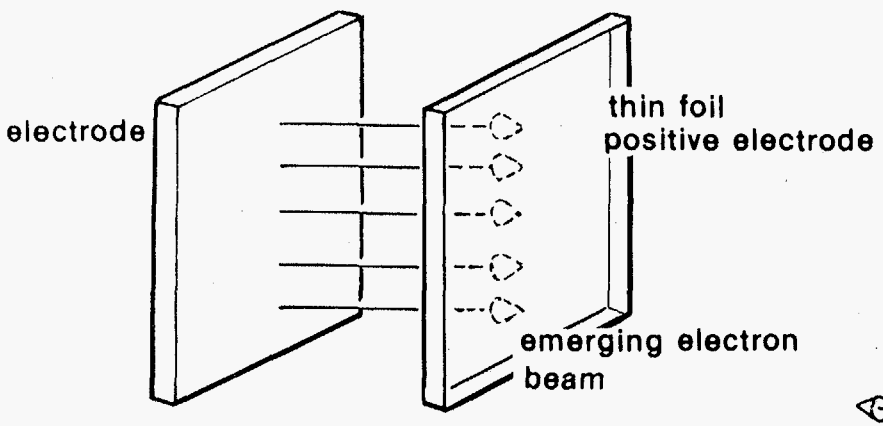
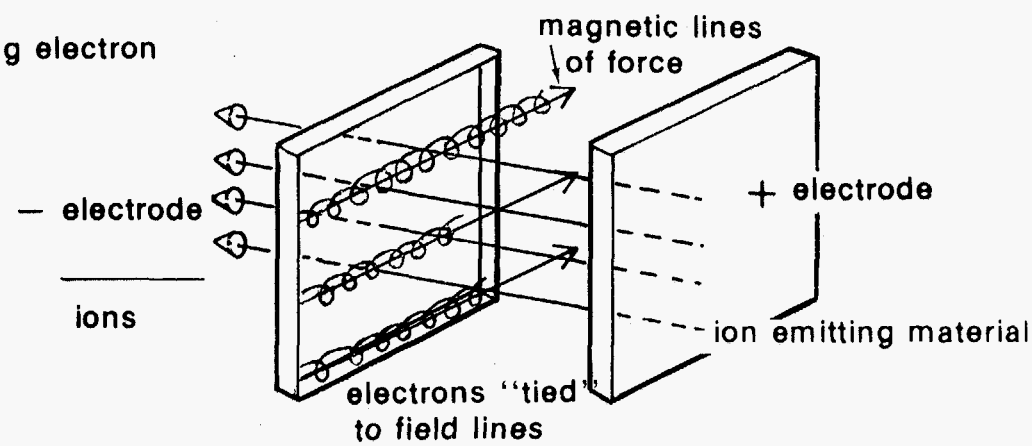
Once the high energy electrical pulse has been formed, it is necessary to transform this energy to an ion beam directed toward the target. The following sequence shows some of the apparatus for accomplishing this transformation.

This photo shows parts of one candidate for ion beam sources for PBFA.

When very high electric stress appears across electrodes in a vacuum, a layer of plasma forms on the negative electrode surface within a few billionths of a second, and electrons are drawn from this plasma to the positive electrode. This is the principle of operation of electron beam sources. When a magnetic field is applied in a direction transverse to the electron flow, the electrons, (being very light charged particles) spiral around the magnetic lines of force and, controlled by proper design, are no longer able to cross the gap. Actual orbits of electrons are complex and include various drift motions. The cloud of circulating electrons has a strong negative charge. If positive ions are introduced in the vicinity of the positive electrode from a plasma layer or from an external injector, the electric field from the negative charge will accelerate intense ion currents. Ions, which are heavier than electrons, can cross the gap nearly undeflected by the magnetic field. Upon this basic principle of ion diodes, several variations are under active study at Sandia and at the Naval Research Laboratory. In experiments at Sandia, ion diodes have produced focused ion beams with 80% efficiency at peak power.



Electron beam source with no magnetic field applied. Electron flow carries most of the energy.



Ion beam source with transverse magnetic field to impede flow of electrons.

Transport of particle beams from the source to the target is a crucial element in fusion for power generation. At least one-metre distance between the pellet and the reactor wall will be required to contain the energy of the microexplosions. While laser beams must be propagated in nearly complete vacuum to avoid gas breakdown and transmission blockage, particle beams can be transported at gas pressure of 0.1 to 1.0 atmosphere. A fortunate consequence of using this gas is that it will moderate intense pulses of x-ray and debris energy from fusion pellets, considerably easing the design of the reactor vessel. Without this moderating effect, bursts of intense power would damage the surface of the reactor wall.

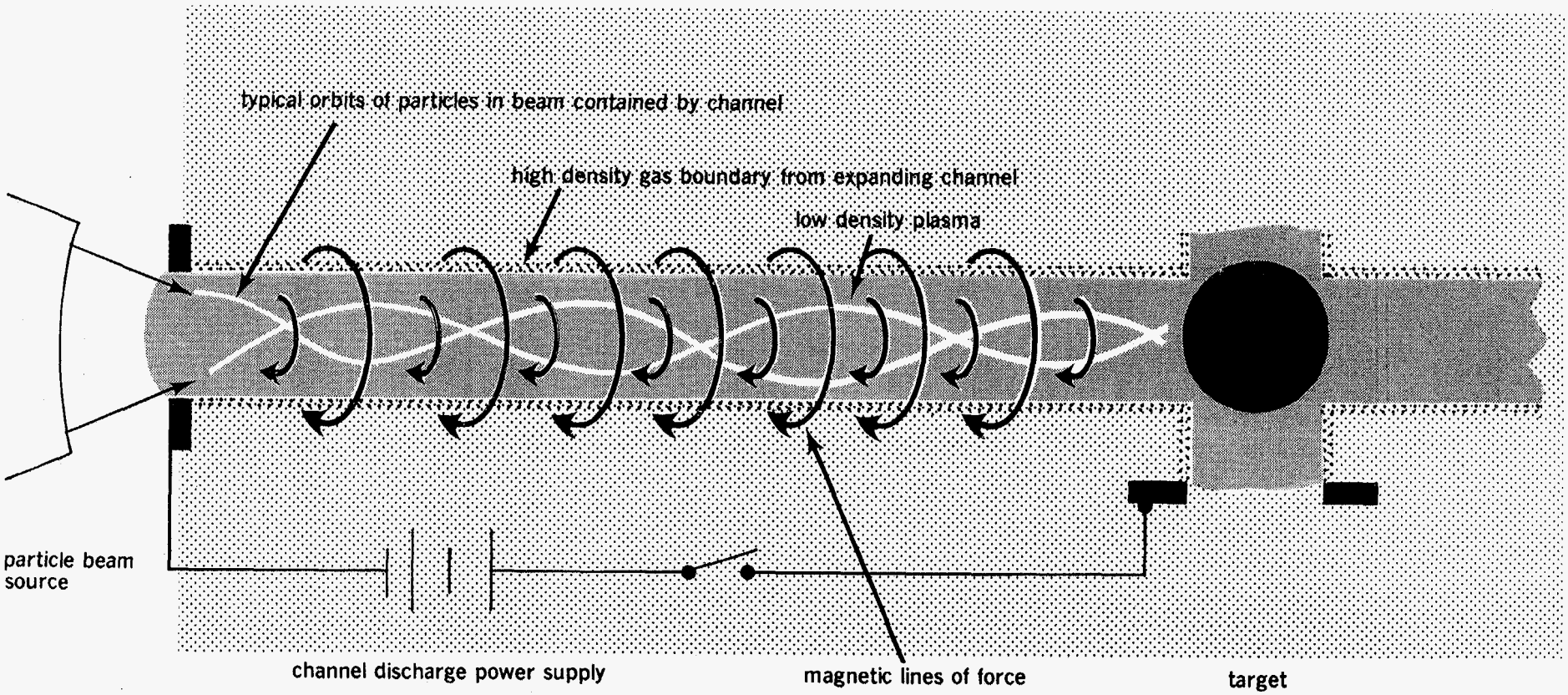
A channel transport experiment is pictured on the front cover. An individual channel is created by passing an intense electric discharge through gas to form a straight man-made "lightning bolt." The discharge path may be initiated by fine wires in laboratory experiments or by low power lasers in a reactor. (Such laser beams would have less than 0.1% the power required for laser ignited fusion.) The "lightning bolt" path works as shown below.

Beam intensity on target may be multiplied by directing a number of channel-guided beams to converge upon a central target. In addition, when ions are transported it is possible to increase the source accelerating voltage (and hence particle velocity) during the pulse in such a way that particles emitted late in the pulse overtake ions emitted early in the pulse. In this manner, a "bunched" beam with shorter pulse and higher intensity than the original source could produce will be focused on the target. It is likely that both bunching and overlap of beams will be used to ignite fusion targets. Transport of the electrons over a 0.5-metre path has proved to be at least 90% efficient, and similar results are expected for ion beams.

Step 1. Lightning bolt is originated, and current flowing in bolt heats gas turning it into a conductor (plasma) which rapidly expands. The flowing current creates a magnetic field in the channel.

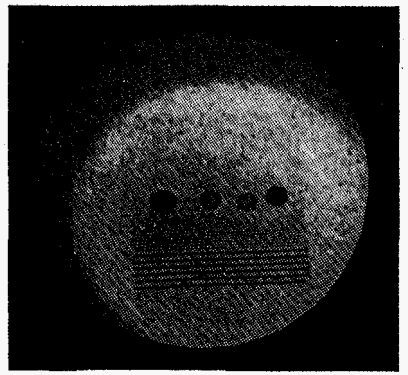
Step 2. After the hot plasma channel expands to a diameter of 0.5 to 1.0 centimetre and the channel current reaches levels of about 50,000 amperes, the particle beam is injected into one end.

Step 3. Repulsive space charge effects as well as current flow of the injected beam are neutralized by the hot conducting plasma in the channel. The magnetic field previously established by the channel-forming discharge confines the beam particles as they travel from the source to the target.

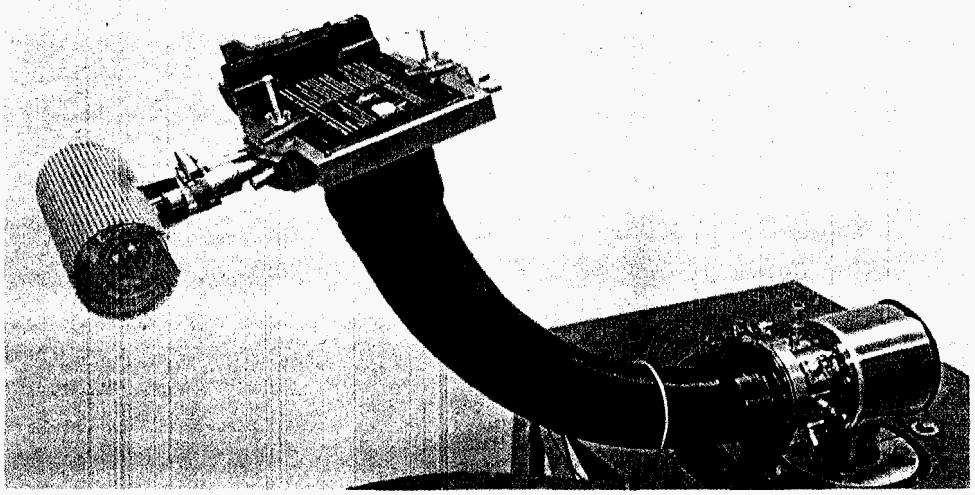


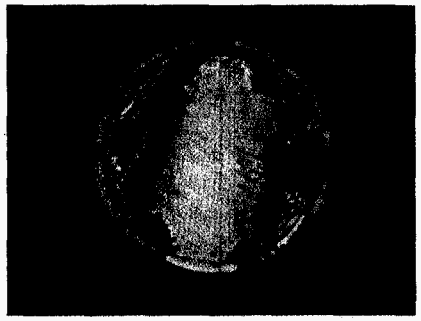
Target Physics

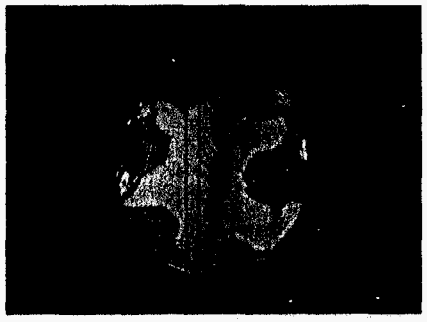
Fusion pellets must be designed to provide very uniform compression of the DT fuel. To examine the inside of imploding spherical pellets for symmetry of implosion or mixing of ejecta of shell material with fuel, a special flash x-ray diagnostic system has been developed. This is but one of many specialized diagnostic techniques employed in the program.



Shown here is an x-ray photograph produced by "backlighting" a series of pellets and recording the image with the special camera shown. The effective exposure time was three billionths of a second. A pattern of gold wires was placed in the same plane as the sample pellets to measure the resolving power of the imaging system. It is possible to resolve details smaller than 0.1 mm.



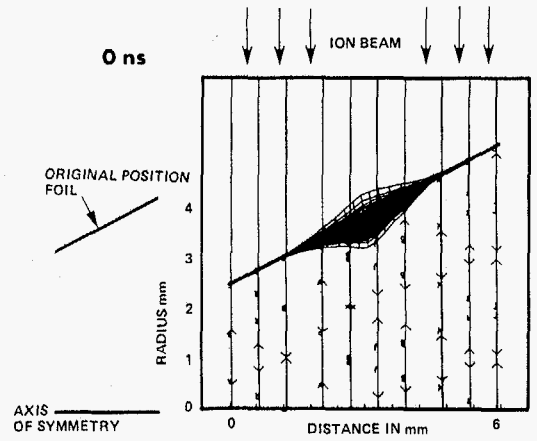


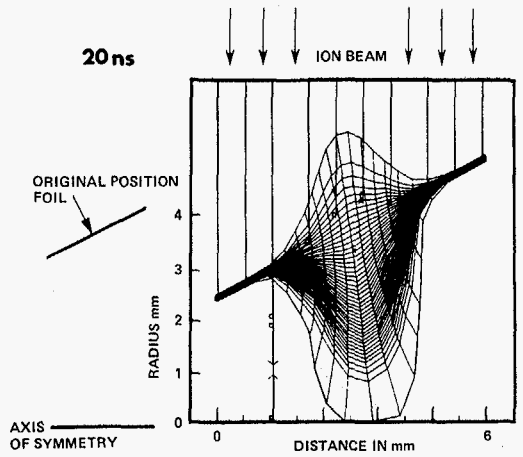


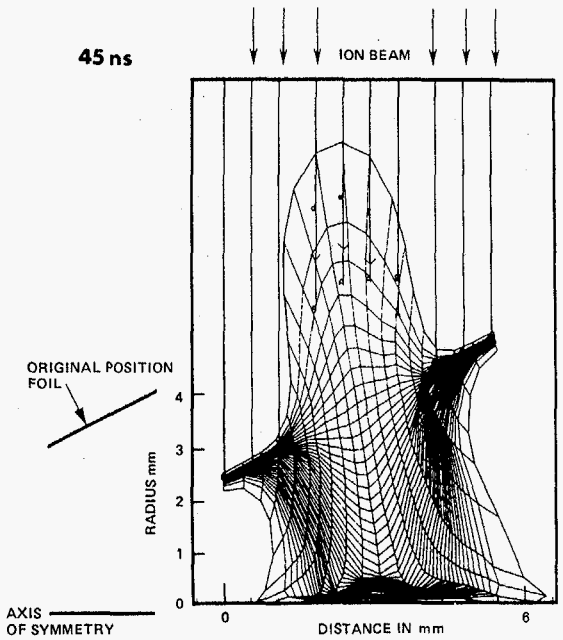
Valuable information can be obtained by examining cylindrical implosions with high speed laser photography (holography). Since 10 to 15 kilojoules of energy on target has been available with electron beams for several years, it has been possible to perform a series of unique experiments with targets large enough to examine details of stability during implosion. An example of data obtained by viewing the collapse of cylindrical targets along the axis is shown. Future target experiments are expected to increasingly emphasize the use of ion sources.

The figures show the time history of an implosion perturbed by six small holes in a 4-mm-diameter cylinder. As the cylinder implodes, the perturbations caused by the holes grow in such a way that shell material would mix with fuel in the center. The case shown is an extreme one used for illustrative purposes. Other results show symmetric implosions.

Such studies in cylindrical geometry help forecast effects that either a small fuel-fill tube attached to a fusion target or an improperly sealed hole would have in a spherical target. Similar techniques are used to measure the effect of shell structure, surface imperfections, and other factors that affect implosions.







A group of scientists with skills in plasma physics, hydrodynamics, atomic physics, and computer technology employs a variety of complex computer programs to predict fusion target performance. A few frames from a sequence showing the implosion of a conical foil irradiated by an intense ion beam are shown. This work models the explosive and implosive motion of the target during and after intense heating by the ion beam. The ions undergo changes in penetrating power as the accelerating voltage varies and as the target temperature changes.

Computations of this nature are used both to predict target performance and to interpret data. Often a dozen or more data collection channels are employed on a single target shot. The photograph below shows a portion of the data-gathering equipment for PBFA. A small on-line computer processes data and helps to interpret results within minutes of accelerator firing.

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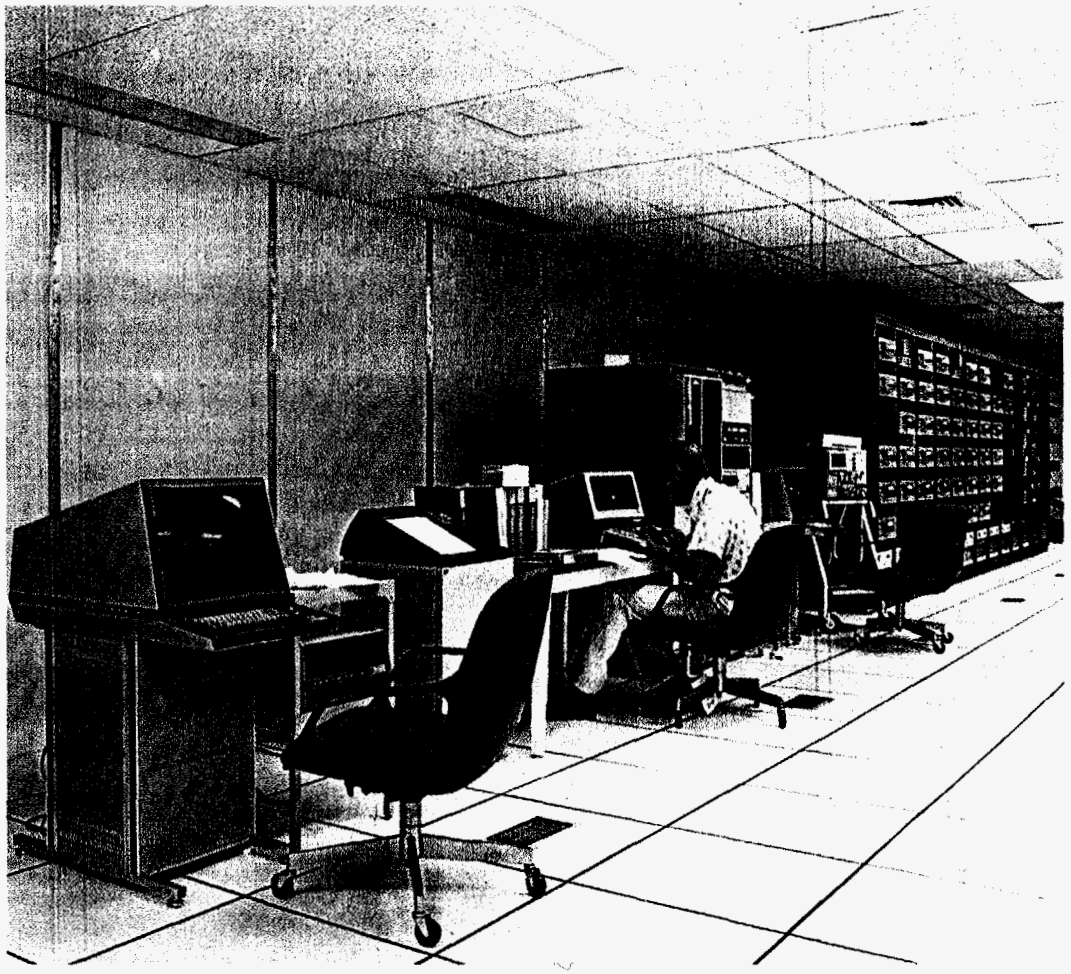


Reactor Systems

In a fusion reactor the fuel is compressed to the conditions of temperature and density required to cause "ignition" and "burn" of the thermonuclear fuel. Energy from the reaction is released in the form of neutrons, xrays, and high velocity ions; when this released energy is deposited in the gas contained in the reactor and in the lithium blanket of the reactor, heat energy is produced. This heat can be used to produce steam to generate electrical energy or for direct use in industrial processes. In a reactor, fusion targets would be injected into a chamber at a rate of one to ten times each second and "ignited" by intense ion beams.

Several possibilities for the design of compact fusion reactor systems have already been investigated. The construction and operation of a prototype particle beam fusion reactor are not foreseen for the immediate future. However, work on possible designs must proceed along with source development and the design of fusion pellets if fusion energy is to become a practical reality as soon as possible.

Although laser-driver systems also offer possibilities for reactor designs, and are being investigated elsewhere, Sandia researchers believe that the higher efficiency particle-beam-driver systems are favored for economic reasons.

It is believed that ion beam reactors offer the best potential for success, because ions offer advantages in target design and ease of transport from the source to the fusion target. A specific advantage of employing ion beams is that power can be intensified as a beam flows from the source to the target. To accomplish this, the accelerating voltage at the source is increased during the interval that the beam is being produced, so that ions near the end of the pulse are moving faster than those early in the pulse. During the transit of the beam to the target, the faster ions overtake the slow ions, and a more intense pulse is available at the target. The cost for accomplishing this is expected to be less than the cost of producing beams without bunching.

Another important consideration is protecting the reactor wall from damage when the pellets are ignited. In the case of ion beam fusion, the gas in the reactor vessel serves a dual function: transport of the beams to the target is facilitated by channels in the gas, and the gas absorbs and slows down the transport of pellet energy that would otherwise damage the reactor wall. By contrast, laser beams would have to be transported through a vacuum, making first wall protection more difficult.

Important factors in sizing a power reactor are determined by the pellet gain (energy released divided by energy needed for ignition) and the efficiency of the ion beam generator. Specifically, the energy released from the pellet must be sufficient to recharge the ion beam source, while allowing a substantial surplus to generate useful power. A large premium must be placed on efficiency of the ion beam source, for several reasons:

1. An efficient ion beam source can be used economically with lower gain and

smaller yield targets. This is expected to ease manufacturing tolerances and increase confidence of success.

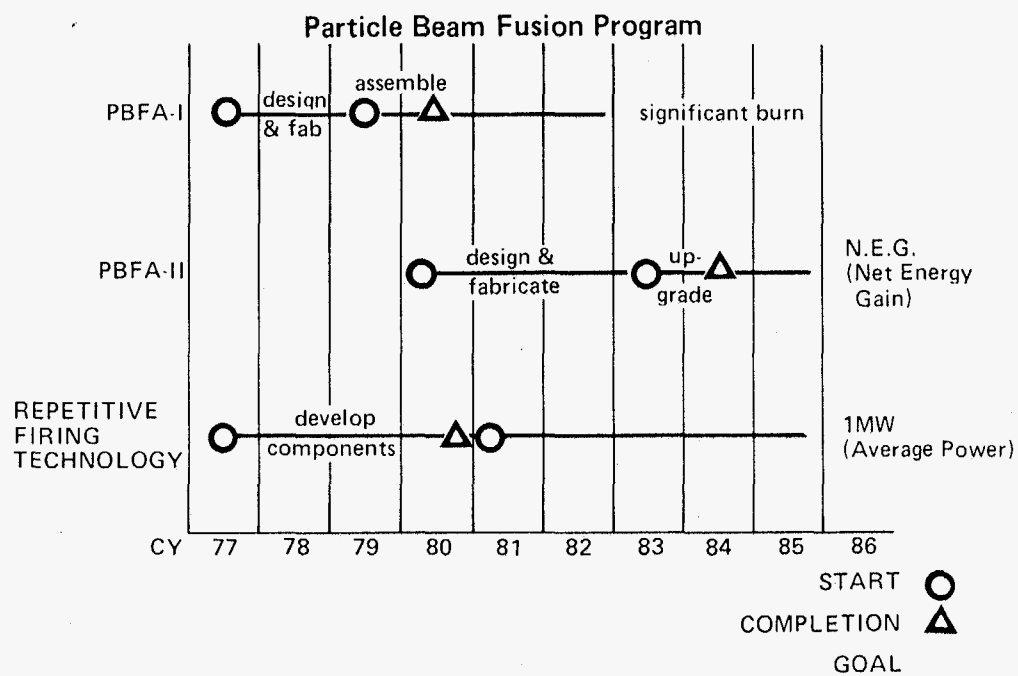
2. An efficient ion source requires less energy storage, reducing capital investment and operating costs.
3. Smaller pellet yields are easier to contain in small reactor systems, which are more easily sited and are more appropriate for introducing fusion commercially.

Based upon present experiments, an overall efficiency of 30 to 40% from the energy accumulated to the ion beam generator is expected. Systems studies show that reactors producing as little as a few 100 MW of electricity may be economically feasible. As the technology becomes more established, larger plants could be constructed. (Typical existing power generating plants range up to about 1000 MW per unit.)

Program Schedule

The Particle Beam Fusion Program is planned to achieve proof-of-principle concurrent with the development of repetitive firing of accelerators. Both developments are expected to be completed in 1986 with the attainment of net energy gain and operation of a repetitive-pulse machine yielding the same output as a module of PBFA-II.

The data from these experiments will provide a basis for the next phase of a program leading to fusion power — an experimental test reactor. Given continued positive results, an experimental reactor will operate during the 1990's, and commercial applications would follow.



A Cross Section of PBF Researcher Disciplines

The complex jobs of research and engineering in the Particle Beam Fusion Program are performed by a group of specialists working at Sandia and elsewhere. As DOE's lead lab for pulse power driven fusion, Sandia directly conducts a broad range of research and coordinates supporting activities in industry, with universities, and other government laboratories. Approximately 30 contracted programs at 16 institutions are contributing to the Sandia particle beam fusion program during the years 1979-1980.

Within Sandia most of the particle beam activity research is centered in the Particle Beam Fusion Research and the Pulsed Power Systems departments.

Scientific disciplines in which advanced degrees are held by direct participants in the Particle Beam Fusion program include plasma, nuclear, low temperature, and atomic physics; and astrophysics and chemistry — as well as electrical, mechanical, aeronautical, nuclear, and computational sciences.

A group of highly trained technicians supports the experimental staff. These men and women have typically from two to four years of formal technical preparation before joining Sandia.

Of approximately 120 individuals associated with the particle beam fusion effort, about one third joined Sandia specifically to work in the fusion area, about one third transferred from other programs, and one third are contractor personnel.

To further augment the broad range of capability permanently assigned to the program, extensive use is made of capabilities in the professional and service organizations that comprise Sandia's 7,600-person work force. A few examples of such organizations are machine-, plastic-, wood-, sheetmetal-, and glass shops, computer sciences, drafting, health physics, photography, and others.

Speakers

Organizations in the Albuquerque area desiring speakers on the Particle Beam Fusion Program may call Sandia Laboratories Information Department, 264-1253.

Additional Reading*

1. **Pulse power technology**
   John A. Nation, "High-Power Electron and Ion Beam Generation," *Particle Accelerators*, 10:1-30, (1979).
2. **Ion beam formation**
   P. A. Miller et al, "Light Ion and Electron Beams for Inertial Fusion," *Comments on Plasma Physics and Controlled Fusion*, Vol 5, (1979).

   D. J. Johnson et al, "Production of 0.5TW Proton Pulses with a Spherical Focusing, Magnetically Insulated Diode," *Phys Rev Lett*, 42(9):610, February 26, 1979.
3. **Transport to target**
   P. A. Miller et al, "Propagation of Pinched Electron Beams for Pellet Fusion," *Phys Rev Lett*, 39(2): 92-95 (July 11, 1977).
4. **Target design**
   R. O. Bangerter and D. J. Meeker, "Charged Particle Fusion Targets," in *Proceedings of the Second International Topical Conference on High Power Electron and Ion Beam Research and Technology*, Cornell University, October 3-5, 1977, p 183.
5. **Electrical engineering basis**
   M. T. Buttram, "Repetitively Pulsed Electron Beam Diode Lifetime Stability," in *Digest of Technical Papers 2nd IEEE International Pulsed Power Conference*, Lubbock, Texas, June 12-14, 1979, p 61. IEEE Catalog Number 79CH1505-7.

   ————, "Operation of a Repetitively Pulsed 300 kV, 10 kA Electron Beam Diode," in *IEEE Trans Nucl Sci*, NS-26(3):4183 (June 1979).

   D. L. Cook and M. A. Sweeney, "Design of Compact Particle-Beam-Driven Inertial-Confinement Fusion Reactors," in *Proceedings of the ANS Third Topical Meeting on the Technology of Controlled Nuclear Fusion*, Santa Fe, New Mexico, May 9-11, 1978, Vol 2, p 1178.

   K. R. Prestwich, D. L. Cook and G. Yonas, "Pulsed Power Technology for Inertial Confinement," in *Proceedings of the ANS Third Topical Meeting on the Technology of Controlled Nuclear Fusion*, Santa Fe, New Mexico, May 9-11, 1978, Vol 1, p 643. CONF-780508.

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   ————, "A Three Megavolt Transformer for PFL Pulse Charging," in *IEEE Trans Nucl Sci*, NS-26 (3):4211 (June 1979).
6. **Neutronics**
   M. A. Abdou and Y. Gohar, "Computations of Nuclear Response Functions with MACK-IV," in *Proceedings of the ANS Third Topical Meeting on the Technology of Controlled Nuclear Fusion*, Santa Fe, New Mexico, May 9-11, 1978, p 402.

   N. Ghoniem and G. L. Kulcinski, "Swelling of Metals During Pulsed Irradiation," *J Nucl Mat* 69 and 70:816-820 (1978).

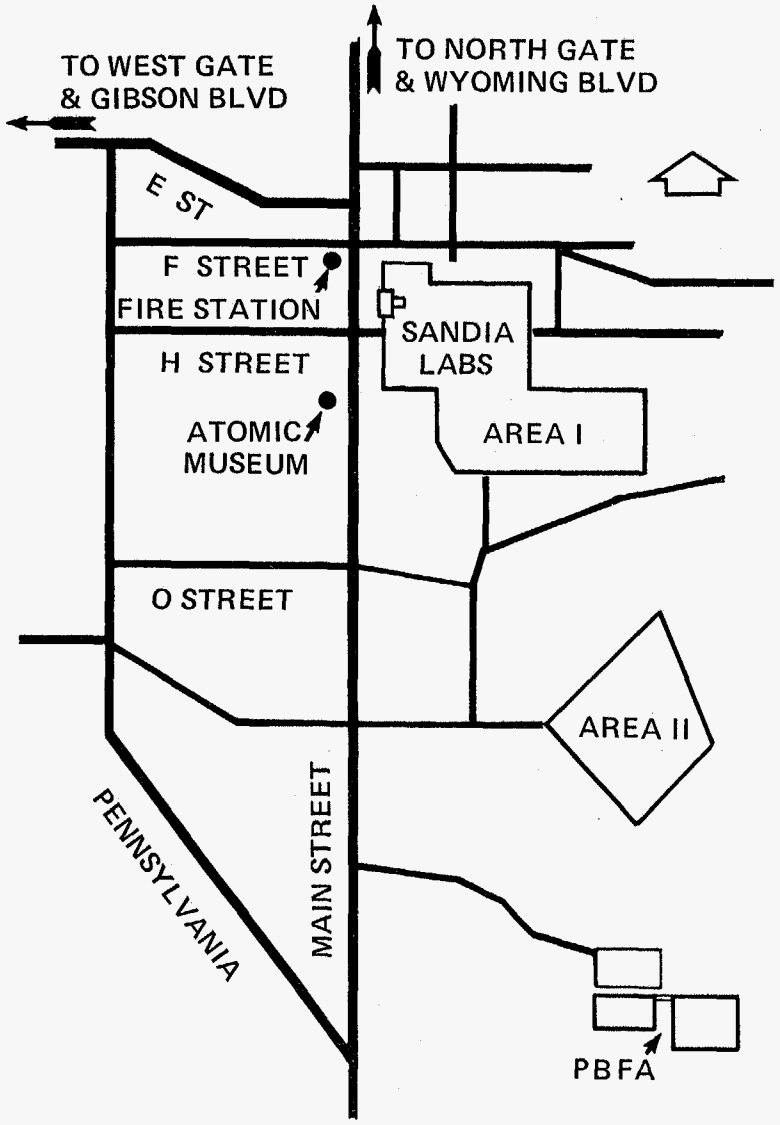
   F. W. Wiffen, *The Effects of CTR Irradiation on the Mechanical Properties of Structural Materials*, ORNL/TM-5624 (Oak Ridge: Oak Ridge National Laboratory, November 1976).
7. **Materials properties for the reaction vessel**
   D. L. Cook and M. A. Sweeney, "Critical Environmental Considerations for Particle-Beam-Driven ICF Reactor Materials," in *Proceedings of the ANS 1st Topical Meeting on Fusion Reactor Materials*, Miami Beach, Florida (January 1979).

   G. L. Kulcinski, "Fusion Reactors: Their Challenge to Materials Scientists," *Contemp Phys* 20(4):417-447 (1979).
8. **Environmental impact**
   T. Botts and J. Powell, "Effects of Waste Management on the Impact of Fusion Power," *Proceedings of the ANS 3rd Topical Meeting on the Technology of Controlled Nuclear Fusion*, Santa Fe, New Mexico, May 9-11, 1978, p 903.

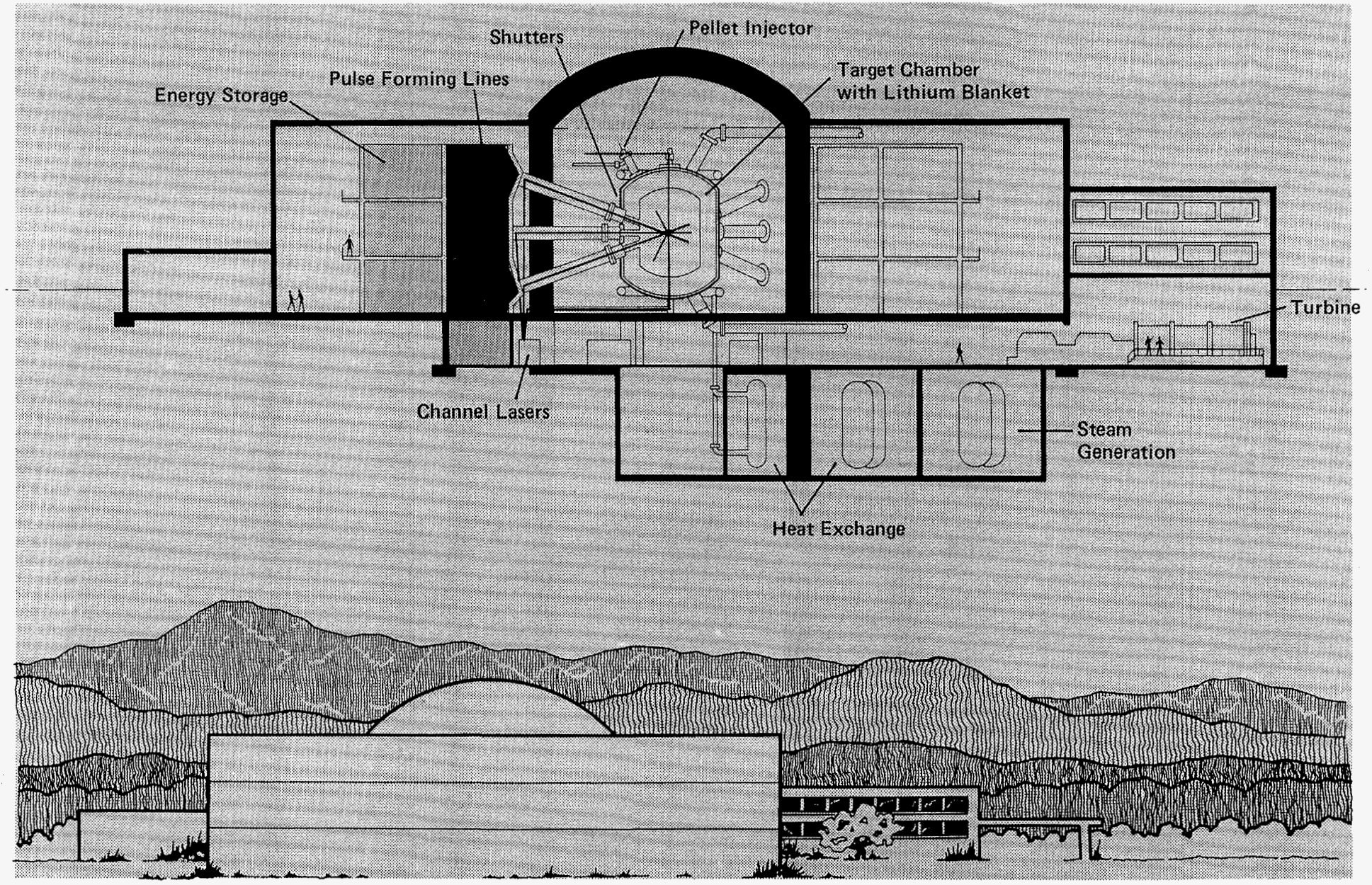
*As keyed to the subelements of technical skills called out in the "PBF Program Plans and Accomplishments" section.

Sandia Laboratories

Sandia Corporation, a subsidiary of Western Electric, operates Sandia Laboratories as a service to the U.S. Department of Energy on a non-profit, no-fee basis. As a multiprogram laboratory, Sandia's primary responsibilities are in research and development for nuclear weapons systems. Substantial efforts are also applied to energy research and other programs of national importance. Its main facilities are at Albuquerque, New Mexico and Livermore, California.



Compact 100 Megawatt Particle Beam Driven Fusion Power Reactor



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