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Commercial Applications of Inertial Confinement Fusion

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EXECUTIVE SUMMARY

Although the Inertial Confinement Fusion Program is directed at satisfying national needs in both civilian and military sectors, the major long-range goal is commercial central-station electric power generation. In addition, other potential commercial fusion-energy applications also exist, for example, in providing high-temperature process heat for synthetic fuel production and in producing fissile fuel in fusion-fission hybrid reactors. In this presentation we discuss the commercial utilization of inertial confinement fusion energy, as opposed to magnetic-confinement schemes. Powerful lasers are emphasized as the driver source for initiating thermonuclear burn within a pellet located at the center of a reaction cavity in an engineered reactor system, herein called a laser fusion reactor (LFR).

Two essential requirements for a LFR are similar to those for a reactor based on magnetic confinement: (1) the need to produce tritium because natural supplies are very scarce; and (2) the need to convert the 14-MeV neutron energy released in pellet microexplosions into usable form. Both needs are satisfied by surrounding the reaction cavity with a "blanket" of lithium in the same manner as in magnetic fusion reactors. Because the major fraction (~ 80%) of the energy release is in the form of 14-MeV neutrons and because these neutrons escape the reaction cavity with little degradation of energy, the reactor designer is free to utilize this energy regardless of cavity design constraints. Furthermore, in specifying the blanket, the designer of an LFR is free from the constraints of intense magnetic fields and plasma scaling parameters. Finally, in a LFR, the neutron energy may be absorbed in materials isolated from the reactor structure, thus providing the feasibility of creating a very-high-temperature source that can be used, in principle, for process-heat applications.

The most important fusion pellet output characteristic for commercial utilization is the relationship of pellet gain (i.e., pellet output/incident beam energy) to input laser energy. However, the most critical parameter affecting the economics of laser fusion generating stations is the product of laser efficiency times pellet gain. For an electrical/thermal efficiency of 0.4, this product must obviously be greater than 2.5 for a net output of electricity and must be greater than 5 for commercial feasibility. Because laser efficiencies are likely to be less than 0.1, pellet gains must be higher than 50.

Other important pellet output characteristics may be categorized as: (1) those affecting the laser system design, and (2) those affecting the reactor cavity first-wall protection.

Pellet characteristics affecting laser system design are: (1) the relationship of pellet gain to laser input energies, (2) the geometric configuration of beams for pellet illumination, (3) focal-spot size, (4) pulse intensity, (5) pulse duration, (6) wavelength, and (7) spatial and temporal pulse shape.

The important pellet output characteristic affecting cavity first-wall design is energy deposition by x rays and pellet debris, which may result in evaporation and/or sputtering of exposed material surfaces and thereby impose constraints on some reactor cavity concepts. For reactor concepts including cavity walls that are subject to surface evaporation and sputtering, there are tradeoffs for minimum damage to structures between relative x-ray and pellet debris energy yields and their energy spectra. These tradeoffs lead to different optimum fusion pellet designs for different reactor cavity concepts.

Laser fusion reactor designs may be divided into two major categories with regard to accommodating the pellet output photon and debris energy: (1) first-wall designs in which the energy absorbing surfaces are regenerated; and (2) those in which the photon and debris energies are either directly absorbed or diverted. In the first category the first-wall surface is removed (or ablated) during a microexplosion and restored prior to the next firing. In this category (which includes the lithium wetted wall, thick lithium cavity wall, and gas-filled cavity concept), the designer is confronted with complicated cavity phenomena, with pulse-rate limitations, and with potential contamination of the last optical surface by the ablated material. In the second category (which includes bare-wall and sacrificial liner concepts), the photon yield, photon spectra, debris mass, debris yield, and debris particle energy determine cavity wall diameters and lifetimes--both of which have economic significance. A variant in this category is the magnetically protected wall concept in which the pellet debris is diverted out the ends of a cylindrical cavity to engineered "energy sink" surfaces, and the cylindrical first wall is exposed only on the photon energy. The major advantage of the concepts in Category 2 is the lack of a constraint on the maximum pulse repetition rate.

Several LFR concepts are being evaluated to assess their feasibility, to define technology requirements, and to determine their practicability for use in various applications. The two concepts that have been studied most extensively are the wetted-wall and the magnetically protected LFRs. Both approaches appear technically feasible, and, moreover, to provide a basis for the conceptual design and evaluation of laser-fusion electric generating stations.

Our present knowledge of laser/pellet output characteristics seems to identify the following features of laser fusion generating stations:

- Laser fusion reactors (LFRs) can be relatively small, compact systems that lend themselves naturally to the design of electric generating stations for a range of power levels from about one hundred to several thousand megawatts. Redundancy of essential components can be easily and economically incorporated in large power plants.
- In a LFR, fusion pellet microexplosions must be contained in a manner that prevents excessive damage to reactor components while permitting recovery of the energy in a form suitable for utilization in an energy conversion cycle. Very-high-energy, short-pulse lasers are required for the compression and heating of fusion pellets to thermonuclear ignition conditions. The laser beams must be repetitively transported to and focused on pellets inside the reactor cavities.
- The fuel cycle receiving primary consideration is the deuterium-tritium cycle. Deuterium is easily and cheaply obtained from conventional sources; but tritium will have to be produced as needed by reactions between fusion neutrons and lithium, which must be contained in blanket regions surrounding the reactor cavities. Inner cavity walls must withstand pulses of x rays, 14-MeV neutrons, and energetic ionized particles that are released by the thermonuclear reactions.

While the direct production of electricity from an inertial confinement fusion source in central generating stations is a principal objective of the Inertial Confinement Fusion Program, other potential commercial applications may be no less important.

The production of synthetic fuels (e.g., hydrogen or methane) or of process heat (which might be utilized in a variety of ways) is important because our present end-use energy consumption is about 75% directly in the form of oil and natural gas (e.g., transportation, residential heating and cooling, and industrial process heat). Although this pattern will surely change with decreases in this fraction as these fossil reserves are depleted, it is unlikely that our end-use pattern can change rapidly enough to result in replacement by electricity of this use of transportable fuels before oil and gas reserves are depleted to the extent that their use will become economically infeasible. Therefore, it is particularly important that the utilization of fusion energy to produce synthetic transportable fuels or to replace oil and gas end-use consumption by other means such as direct process-heat applications be considered as well as for the production of electricity.

Fusion neutrons can also be used to produce fissionable fuels (^{239}Pu from ^{238}U or ^{233}U from ^{232}Th). Although the production of ^{239}Pu, in general, causes grave political concern because of the danger of proliferation of a weapons-grade material by hijacking, it seems possible to design fusion-fission hybrids in which plutonium (bred into a natural uranium region) is recycled only within the fuel-production plant, and is thus secure. The fissile fuel output of such a plant is ^{233}U (bred from thorium) that can be made unsuitable as a weapons-grade material (but still suitable as a reactor fuel) by adding natural uranium.

The environmental effects of conceptual laser fusion generating stations have been assessed in a preliminary manner and compared with those of magnetic-confinement fusion, fission (LWR and LMFBR), fossil-fired, or solar plants, where appropriate. Land use, resources and transportation, thermal pollution, chemical hazards, radioactive hazards, and the causes and results of accidents were considered.

Land use and thermal pollution are about the same for the plants considered (except for solar plants which require much more land), whereas the effects on resources and transportation are generally much less for LFRs. Chemical hazards are comparable to those of LMFBRs and somewhat lower than those of magnetic-confinement reactors, whereas radioactive hazards are much lower than those of fission reactors and slightly lower than those of magnetic-confinement reactors.

The largest amounts of radioactivity are those from activated reactor structural material; however, because these materials are high-melting-point metals that are not subject to significant dispersal in case of an accident, radiation protection of the public will be straightforward and not a primary concern. Protection from tritium hazards will require engineered safeguards; conservative assumptions of accident releases, however, indicate minimal doses released to uncontrolled areas. The maximum credible accident is deemed a lithium fire in which lethal doses of lithium compounds are received by the destruction of tissue. In such an accident the lithium poisoning effect could be far more hazardous than the concomitant hazard of radioactive materials.

The most critical unsatisfied technology requirement for laser fusion is a significant fusion-pellet burn. This requirement demands advances in laser technology and in fusion-pellet design and fabrication techniques. To date, laser fusion experiments have yielded up to 10^9 neutrons with first-generation neodymium-glass laser systems operating at a few terawatts. Although these results, of course, have not indicated scientific feasibility, they have enhanced an understanding of the fundamental physics of laser-pellet interactions. Within the next year, a second-generation gas laser system of 10- to 20-TW output will be operational at Los Alamos and will provide a clearer understanding of fundamentals. The major milestone of scientific breakeven, i.e., a performance in which the thermonuclear output is equal to or exceeds the incident beam energy, is expected to require laser systems at powers of ~ 100 TW. Such a gas-laser facility is planned to operate at Los Alamos in the early 1980s. Thereafter, the laser-fusion program can proceed from research to a technology development phase, aimed at demonstrating the economic attractiveness of commercial exploitation in the late 1990s or early twenty-first century.

The most important engineering technology developments for laser-fusion systems (other than LFR designs) are summarized below.

- Very-high-energy (multikilojoule) short-pulse (~ 1 ns) lasers are necessary for the efficient burn of fusion pellets. In commercial configurations, these lasers must operate reliably at high repetition rates (~ 10 pps), thus requiring the development of waste-heat removal methods. Laser power supplies must reliably supply electrical (direct current) pulses at hundreds of kilovolts in microseconds at the same repetition rates. Economic factors dictate lifetimes of at least 10^9 pulses. The only systems that can be operated at such repetition rates are gas lasers that permit continuous circulation of the lasing medium for the removal of impurities and waste heat. Currently, the CO_2 laser is the best developed for this purpose and possesses the potential for operating at efficiencies required for commercial use (5% or greater).
- Sophisticated fuel pellet delivery and laser control systems must be developed so that the pellet and laser beams arrive at the cavity precisely coordinated in space and time. The last optical element that "looks" into the cavity must withstand the x-ray and neutron radiation emitted by the pellet.
- Fuel pellets must be mass-produced at a rate of $\sim 10^6$/day at a cost of a few mil/kWh. This requirement may severely restrict the complexity of pellets.
- Materials damage research at appropriate neutron energies and dose rates must be conducted to ensure the survivability of reactor structural materials.
- Economic feasibility must be demonstrated by successfully integrated system performance.

COMMERCIAL APPLICATIONS OF INERTIAL CONFINEMENT FUSION

Compiled by

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I. INTRODUCTION

Ever since the realization that the energy of the sun, and of stars in general, is produced by fusion reactions, scientists have been fascinated by the problem of creating energy from such reactions on earth. In the early 1950s, the development of thermonuclear explosives demonstrated the feasibility of producing energy from fusion. In 1955, United States' efforts to develop controlled thermonuclear energy were declassified and an international cooperative program was initiated in which magnetic forces were to be used to compress and to heat thermonuclear material to ignition conditions and to confine the resultant plasma. Although much progress has been made in the magnetic fusion energy program and many of the phenomena are well understood, plasma confinement times and energy levels attained are insufficient by far to demonstrate that power production by this scheme is practical.

Since the late 1960s, a new concept has been under development: the use of an intense laser pulse to compress and to heat a small pellet of fusion fuel to ignition conditions. The fuel, once ignited, would be confined for a short time by its own inertia--long enough to permit a significant portion of it to burn before the heated pellet would fly apart. As with magnetic-confinement methods, significant thermonuclear energy release for practical applications has yet to be demonstrated.

This report describes the fundamentals of inertial-confinement fusion, some laser-fusion reactor (LFR) concepts, and attendant means of utilizing the thermonuclear energy for commercial electric power generation. In addition, we discuss other commercial energy-related applications, such as the production of fissionable fuels, of synthetic hydrocarbon-based fuels, and of process heat for a variety of uses, as well as the environmental and safety aspects of fusion energy. Finally, we discuss the requirements for commercialization of laser fusion technology.

The conceptual LFRs discussed in this report consist of a reaction cavity, in which the thermonuclear energy is released from deuterium-tritium (D+T) reactions within a pellet located at the center of the cavity, with thermonuclear burn initiated by a laser pulse.

For (D+T)-burning plants, two essential requirements for a LFR are similar to those for a reactor based on magnetic confinement:

1. the need to produce tritium artificially because natural supplies are insufficient to support a large-scale power-generation industry; and
2. the need to convert the 14-MeV neutron energy released during pellet burn into usable form.

Both needs are satisfied by providing a "blanket" of lithium which surrounds the source of fusion neutrons. Tritium is generated in a major fraction of reactions between neutrons and lithium; and lithium, being a light element, also converts neutron kinetic energy to thermal energy by means of elastic-scattering reactions. Furthermore, additional thermal energy is produced by exoergic neutron reactions with the lithium. It is essential that at least as much tritium be generated as is burned and lost, and that as much as possible of the neutron energy be converted into high-grade thermal energy for ultimate conversion to electricity.

II. COMMERCIAL APPLICATIONS

A. General Considerations

Inertial-confinement fusion is characterized by compressing and heating the thermonuclear fuel contained in a minute pellet by inertial forces generated during interaction of an intense, pulsed beam energy source (or driver) with the pellet. The fusion pellet contains a stoichiometric mixture of deuterium and tritium (D+T), either in cryogenic solid or gaseous form, encapsulated in structures of high-Z materials. The outer region of a fusion pellet consists of an absorber-ablator material in which energy from the driver source is deposited. This material is blown off, thereby creating a recoil impulse which, together with the plasma pressure, heats and compresses the (D+T) core. Thermonuclear ignition occurs at the center of the compressed core and propagates radially outward in a time that is short compared to the time required for the pellet core to disassemble, resulting in fusion of an appreciable fraction of the (D+T) fuel.

The fusion of a deuterium and a tritium atom results in the release of 17.6 MeV of energy, appearing as the kinetic energy of an alpha particle (3.5 MeV) and a neutron (14.1 MeV). For the thermonuclear burn to propagate from the center of the compressed pellet core, the density-times-radius product of the fuel pellet must greatly exceed the range of the 3.5-MeV alpha particles. Energy deposition by the alpha particles in the pellet core results in very high temperatures with subsequent additional thermonuclear reactions. The 14-MeV neutrons escape the pellet with only slight degradation in energy.

The energy released as photons can be as high as 20% of the thermonuclear yield; in general, larger fractional energy releases as photons are accompanied by higher photon energies. Photon energy release occurs from fusion pellets with yields of a few hundred megajoules in time intervals of a few shakes (1 shake = 10^{-8} s). The initial photon release has a blackbody spectrum, but, after initial release, most of the photons are not in equilibrium with the temperature of the outer surface of the pellet. Any degradation of the 14-MeV neutron energy by inelastic scattering interactions with the pellet structural material results in the emission of high-energy (~ 1 MeV) gamma rays. The thermonuclear energy not released as photons or high-energy neutrons is deposited in the pellet debris. Essentially all the debris energy is converted to kinetic energy. Debris particle arrival times at cavity wall surfaces may extend over several tens of microseconds.

Obviously, one of the most important pellet characteristics is the relationship of pellet gain (thermonuclear output/incident beam energy) to input beam energy. Theoretical calculations for high-gain pellets are not very extensive, but preliminary results at both Los Alamos Scientific Laboratory and Lawrence Livermore Laboratory are encouraging. Calculations indicate that maximum gain is in the range of 400 to 600. Although a high degree of uncertainty exists in these calculations, pellet gains of up to 100 for an input laser energy of 1 MJ and a gain of 300 for 5 MJ of laser energy have been indicated in one-dimensional calculations (LASNEX and LACER).[1]

B. Reactor Concepts

For commercial applications, fusion-pellet microexplosions must be contained in reactor cavities in a manner that prevents severe damage to reactor components, yet permits convenient recovery of the energy for conversion to electricity or to some other usable form. Reactor cavities must be surrounded by regions (blankets) containing lithium, which are designed for the breeding of tritium for the fuel cycle and for the collection and multiplication of fusion energy. It is essential that a fusion economy be self-sufficient in tritium, i.e., for each fusion reaction, at least one atom of tritium must be produced by nuclear transmutation of lithium. Although the hydrodynamic blast created by pellet microexplosions can be controlled with relative ease (because the energy is carried by a small mass of high-energy particles), large stresses can result from high rates of energy deposition in the blankets and structural materials. Energy deposition by x rays and particles in the pellet debris occurs at, or very near, free surfaces of incidence in structural and coolant materials; whereas the kinetic energy of 14-MeV neutrons is deposited throughout relatively large volumes.

The most challenging reactor design consideration is protection of the cavity wall from the various energy forms as released by the pellet and

TABLE I

EFFECTS OF AMBIENT CAVITY CONDITIONS ON FUSION-PELLET ENERGY RELEASE MECHANISMS

Cavity "Atmosphere"	X rays	Neutrons	Plasma Debris
Vacuum	No effect	No effect	No effect
Ambient gas	Some attenuation	No effect	Energy transfer
Vapor	Attenuation	Little effect	Energy transfer
Liquid	Absorption	Attenuation and absorption	Energy transfer
Magnetic fields	No effect	No effect	Diversion possible

as affected by the reaction-chamber phenomena. These phenomena depend on both the design and the yield of the pellet, as well as on ambient conditions in the chamber at the time of the pellet microexplosion. The effects on pellet energy-release mechanisms of various reaction chamber atmosphere options are summarized in Table I.

Other important design considerations are pellet yield and energy release forms (which determine reactor size), pellet firing repetition rate (which determines power level), and pellet gain (which generally increases with incident beam energy and has a great effect on plant economics). The minimum practical yield, determined by both physical and economic considerations, is about 100 MJ, and the minimum pellet gain for economically viable laser fusion, at a minimum laser efficiency of 5%, is about 100. There are no fundamental physical constraints on maximum yield; however, economic penalties associated with the containment of very large energy releases will result in an optimum pellet yield for a given combination of the relationship between pellet gain and driver energy level, driver efficiency, and firing-pulse repetition rate. There is an incentive to maximize the pellet firing repetition rate, which would maximize the power level; however, this repetition rate may be constrained by cavity phenomena as discussed below.

The most important effect of pellet output on cavity design is energy deposition by x rays and pellet debris, which may result in evaporation and/or sputtering of material surfaces of incidence and thereby impose constraints on some reactor cavity concepts. For reactor concepts with cavity walls exposed to surface evaporation and sputtering, there are tradeoffs for minimum damage to structures between relative x-ray and debris energy yields and their energy spectra. These tradeoffs lead to different optimum fusion-pellet designs for different reactor cavity concepts. In general, heating and vaporization from x-ray deposition increases as x-ray energy decreases because surface temperatures become higher at lower x-ray energies. Higher surface temperatures are the result of less heat capacity, caused by decreasing x-ray penetration depth with decreasing x-ray energy.

The effects of pellet output on sputtering erosion rates are more complex, depending on the Z-number, mass, velocity, and angle of incidence of pellet debris constituents, and on the Z-number of the target-surface material.[2] In general, erosion rates increase with increasing mass and energy yield, but may increase or decrease with the Z-number of pellet materials, depending on the kinetic energy of the particles upon incidence. Sputtering erosion decreases as the atomic number of the target surface material decreases. Results of analyses, based on well understood theory and on some experimental data, indicate that sputtering erosion is important in the design of bare-wall and sacrificial-liner first-wall concepts. For high yield pellets (~ 4000 MJ) with heavy metal shells, sputtering erosion is the dominant damage mechanism on a carbon sacrificial-liner surface, accumulating to several centimeters per year at one pulse per second.

A bare cavity wall (consisting of, e.g., a bare refractory metal) would be the simplest of reaction-chamber enclosures. However, if the density of the ambient gas is low, the cavity wall will be very susceptible to evaporation from x-ray heating and debris energy deposition as well as to erosion from sputtering by high-energy plasma ions. Thus, either cavities of very large diameter will be required or an appropriate atmosphere (e.g., buffer gas) has to be placed between the pellet microexplosion and the first wall to transpose the x-ray and ion kinetic energy into different forms and to permit their efficient utilization. One might think of operating the reactor at the highest permissible chamber gas density (determined by the necessity to transmit beam energy efficiently), allowing a spherical blast wave to develop. Calculations show, however, that the blast-wave-heated gas would reside at the chamber wall only a very short time--too short for sufficient thermal conduction into the wall.[3] Steady-state operation with repeated fusion-pellet microexplosions would result in a very turbulent, hot cavity medium whose energy would be transported to the chamber walls by radiation and thermal conduction, complicating pellet injection and illumination by laser beams. And, if the heated gas had to be vented from the chamber after each pellet microexplosion, the microexplosion repetition rate might be severely restricted. Other, more easily analyzed reaction-chamber concepts appear to be practical and have therefore been adopted for initial study.

Several reactor cavity concepts employ evaporative and/or ablative materials to protect interior cavity wall surfaces. The protective material in such designs must be either renewable between pellet microexplosions or the amount of protective material evaporated and/or sputtered by each microexplosion must be small enough so that the cavity wall lifetime will be long enough for economic operation. Protection of exposed surfaces by a liquid metal such as lithium has many attractive features and is used in the wetted-wall concept proposed by LASL[4] and in the suppressed ablation concept proposed by LLL.[5]

As an alternative to liquid-metal films one could use a sacrificial, solid-state liner to protect the cavity wall. Desirable properties of the protective material are: low Z-number (sputtering yields decrease and x-ray penetration depths increase as the atomic number decreases), high thermal conductivity and heat capacity, high-temperature resistance (to maximize heat transfer and minimize evaporation during energy deposition), low cost, and ease of fabrication. These properties appear to be satisfied best by carbon, which has therefore been chosen for studies of sacrificial-liner concepts.

Cavity walls can be protected by externally applied magnetic fields in a cylindrical cavity from energy deposition and from sputtering due to impinging ionized pellet debris.[6] The pellet debris is diverted out the ends of the cylindrical cavity to energy-sink surfaces, leaving only the x-ray energy to be accomodated by the cavity wall surface.

In a totally different approach to conceptual reactor designs, a thick layer of lithium or a lithium-lead mixture is interposed between the pellet microexplosion and the reactor structure. Examples of such designs are the BLASCON proposed by the Oak Ridge National Laboratory,[7] the lithium-fall concept proposed by LLL, and the liquid lead-lithium fall concept proposed by the Brookhaven National Laboratory. The region in which pellet microexplosions occur is evacuated by some dynamic process such as rotation of the protective fluid (with the formation of a vortex) or its circulation by pumps and gravity with a fluid fall inside the cavity.

A summary of the effects of pellet output energy forms on these generic classes of cavity concepts and discussion of their advantages and disadvantages is presented in Table II.

In most conceptual fusion reactor designs, circulating liquid lithium is being considered for the breeding of tritium and the removal of heat in blanket regions surrounding the reaction chambers. Lithium is a relatively good neutron moderator, has good heat-transfer properties, and is reasonably abundant. Other blanket concepts consider lithium compounds, such as Li_2O or $LiAlO_2$, and a gas coolant, such as helium.

The ratio of tritium atoms produced to tritium atoms burned is called the tritium breeding ratio. Because only one neutron is produced in each fusion reaction, blankets must be designed for good neutron utilization. The proper use of neutron-multiplying and moderating materials is therefore a significant consideration. The most important sources of neutrons in blanket regions are (n,2n) reactions in structural materials and in materials such as beryllium and sodium specifically provided for this purpose. Tritium breeding ratios ranging from 1.1 to 1.5 can be obtained in blankets con-

TABLE II

CHARACTERISTICS OF REACTOR CAVITY CONCEPTS

Generic Class	X-ray Heating	Sputtering by Pellet Debris	Impulse from Ablated Material	Pulse Repetition Rate Limitations	Major Advantages	Major Disadvantages
Lithium wetted wall	Soft x rays absorbed in lithium film	Prevented by lithium film	Significant but not severe. Structural requirements determined by blanket phenomena	Limited to $\sim$1/s by requirement to evacuate cavity of ablated lithium	Small cavity size possible, surface damage to cavity wall by evaporation and sputtering eliminated	Pulse repetition rate limited, damage of last optical surface by pellet debris and contamination by lithium vapor
Magnetically protected wall	Determines minimum cavity diameter	Avoided by deflecting ions away from walls	No	Not serious. Repetition rate of 10/s probably feasible	Protection of last optical surface from energetic ions, high pulse repetition rate possible, cavity wall accessible for repair or replacement	Magnetic fields necessary, energy-sink replacement will increase power production costs.
Gas filled	Diminished or eliminated by attenuation in gas	No, debris energy deposited in gas	No	Possibly, energy removal from cavity not well established	Surface damage to cavity wall by evaporation and sputtering eliminated	Complicated cavity phenomena, may require removal of hot cavity gas between pulses, damage and contamination of last optical surface
Bare metal wall	Determines minimum cavity diameter and cavity lifetime		Trivial	Probably not, depends on final disposition of ablated wall material	High pulse repetition rate possible, simple design	Large cavity diameter required, damage and contamination of last optical surface
Sacrificial liner	Determines minimum cavity diameter and cavity lifetime. Smaller minimum cavity diameter than for bare metal wall		Trivial	Probably not, depends on condensation and removal of ablated wall material	Relatively small cavity size possible, evaporation and sputtering confined to liner, high pulse repetition rate possible	Damage and contamination of last optical surface, liner replacement will increase power production cost
Thick lithium cavity wall	X-ray and debris energy absorbed in lithium first wall		May be very severe, total pellet yield deposited in lithium first wall	Limited by requirement to evacuate cavity of vaporized lithium	Surface damage to cavity wall by evaporation and sputtering eliminated. Radiation damage of structure essentially eliminated	Severe limits on pulse repetition rate, complicated cavity phenomena--difficult to analyze, damage and contamination of last optical surface and cavity components, pumping power required to maintain cavity configuration, limited access for beam transport

sisting of structural materials and natural lithium with thicknesses less than 1 m, and breeding ratios exceeding 2.0 can be obtained in blankets containing lithium enriched in ^{6}Li combined with a neutron-multiplying and moderating material such as beryllium.[8] For blanket designs containing lithium compounds, a neutron multiplier (e.g., beryllium) is usually required to obtain tritium breeding ratios exceeding unity.

The total energy released per fusion reaction can be increased significantly by including materials that undergo exoergic neutron reactions. Tritium production by neutron capture in ^{6}Li results in a net release of energy so that total energy release per fusion reaction generally increases with increases in breeding ratio. Other nuclear reactions that increase the total energy include (n,γ) reactions in structural materials.

Reactor blankets must withstand repeated stresses due to the cyclic nature of laser fusion reactor operation. Energy deposition on reaction-chamber interior surfaces greatly increases their temperature which, in turn, produces high thermoelastic stresses. If a protective coating is ablated (as, e.g., in the wetted-wall concept), an impulse is transmitted to the cavity structure. Neutron-energy deposition in liquid-lithium regions results in heating and expansion of the lithium. Because energy deposition in the lithium has a radial gradient, pressure waves are created that travel between structural components. For gas-cooled blankets containing solid lithium compounds, the stresses in structural components are much lower than for blankets containing liquid lithium; however, the extent to which the lithium compounds may be damaged by neutron irradiation or may sinter, resulting in difficult tritium removal, are not known.

Possible blanket structural materials include such refractory metals as niobium, molybdenum, and vanadium and alloys of these materials. Stainless steels may also be used. Considerations that will be important in determining final choices include: temperature limitations, corrosion resistance, fatigue strength, radiation damage effects, neutron-induced radioactivity and afterheat, and availability. Niobium is attractive because of its compatibility with lithium at high temperatures and its desirable neutronics characteristics; however, it may not be sufficiently abundant to satisfy requirements and has some long-lived neutron-induced radioactive isotopes. Molybdenum, of which there is an abundant supply in the continental United States, is also an attractive blanket structural material: It is compatible with lithium, has good high-temperature mechanical properties, is relatively impermeable to the diffusion of hydrogen isotopes, and has a large (n,2n) cross section for high-energy neutrons. Stainless steels are limited to operation below ~750 K because of limitations due to lithium corrosion; however, their susceptibility to high-temperature corrosion might be alleviated by refractory-metal claddings.

The extent to which structural materials are damaged by the products of fusion reactions is largely unknown, but damage resistance is expected to be very important in determining material choices and component lifetimes. Large amounts of protium and tritium will be produced in the structural materials and in the lithium coolant. The formation of hydrides and the resultant embrittlement could pose serious structural problems. Niobium and vanadium form stable hydrides at low temperatures; however, hydrogen solubility in these materials decreases rapidly with increasing temperature. If reactor cooldowns could be programmed to allow hydrogen to diffuse out of these materials before ambient temperatures are reached, the hydrogen embrittlement problem may not be severe. Molybdenum does not form hydrides and has a very low hydrogen solubility.

Two laser-fusion reactor concepts conceived at LASL have been submitted to detailed engineering feasibility evaluations: the wetted-wall and the magnetically protected reactor. The wetted-wall concept is illustrated in Fig. 1. The spherical reactor cavity is surrounded by a blanket region of liquid lithium and structural components. The cavity wall is lined with a porous refractory metal through which coolant lithium flows from the blanket into the reaction chamber to form a protective coating on its inside surface. The protective lithium layer absorbs the energy of the pellet debris and part of the x-ray energy. Part of the lithium layer is evaporated and ablated into the cavity by each pellet microexplosion and is subse-

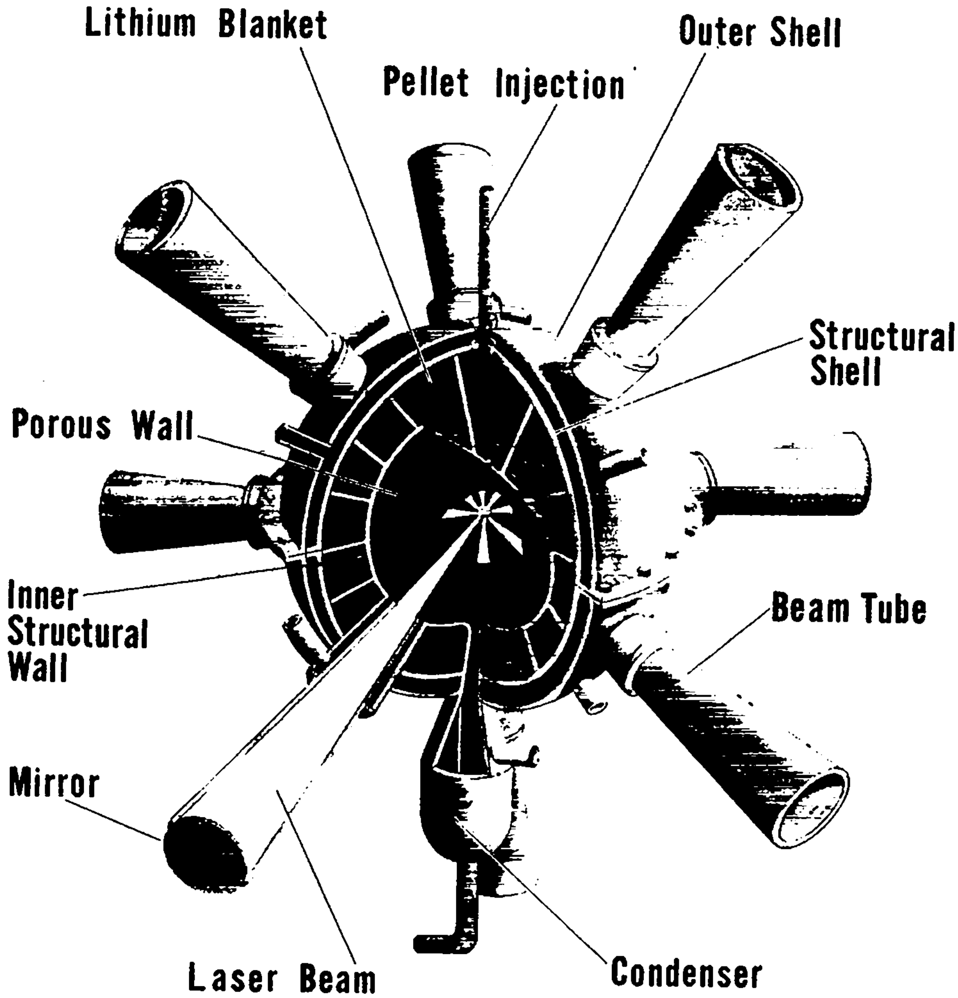

Fig. 1. Wetted-wall laser fusion reactor concept.

quently exhausted through a supersonic nozzle into a condenser. The protective layer is restored between pulses by radial inflow of lithium from the blanket. If laser beams are used to initiate pellet fusion, it may be necessary to evacuate the cavity to a lithium density of $\sim 10^{16}$ atoms/cm^3 between microexplosions for efficient penetration by the laser beams. The time required to restore the cavity to this condition after a pellet micro-explosion is $\sim$ 0.8 s. From this and other considerations it appears that 100-MJ repetition rates of about one microexplosion per second will be practical for the wetted-wall reactor concept, resulting in a minimum average thermal power level of 100 MW.

The essential features of a laser-driven magnetically protected reactor concept are shown schematically in Fig. 2. The pellet debris is diverted out the ends of the cylindrical cavity to energy-sink surfaces leaving only the x-ray energy to be accomodated by the cavity wall surface. The geometry shown in Fig. 2 permits energy sinks to be

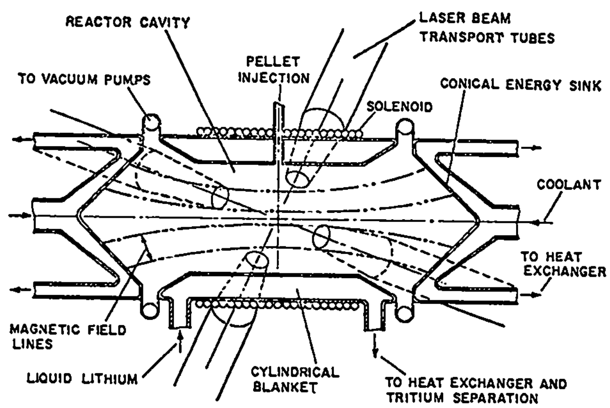

Fig. 2. Magnetically protected wall laser-fusion reactor concept.

designed with large surface areas. Fringing of the magnetic field is used to tailor the energy deposition density over the surfaces of the energy sinks.

The conical energy sinks are readily accessible for replacement without disturbing the lithium blanket, the beam optics, the solenoid, or the fuel injection system. Other advantages of this concept include the possibility of high pellet microexplosion repetition rates, elimination of involved procedures for removal of evaporated and/or ablated materials from the reactor cavity between successive pellet microexplosions, and protection of the beam optics from the pellet debris. A minimum thermal power level of ~ 1000 MW has been determined feasible at a pulse firing rate of 10 Hz.

C. Electric Power Generation

The major fraction of the fusion energy will be converted to thermal energy in reactor blankets. The thermonuclear energy will be converted to electricity primarily by means of a heat engine in a thermodynamic cycle. For some reactor concepts it may be practical to convert part of the energy directly to electricity; however, the amount thus converted will be only a minor fraction of the total energy released. A simplified energy and mass flow diagram is shown in Fig. 3.

Important guidance for a research and development program such as the Laser Fusion Program, which has an ultimate goal of widespread commercial application, can be provided by parametric and sensitivity studies. Mathematical models describing economic scaling and operating conditions have been derived for each of the subsystems in a laser-fusion electric generating station. These models are related by a systems code with which the dependence of power production costs on variations in operating and economic conditions can be determined.

Typical results of sensitivity calculations for laser fusion generating stations based on CO_2 laser technology and on either the wetted-wall reactor (WWR) or the magnetically protected wall reactor (MPWR) concepts are shown in Figs. 4 through 8. The generating stations include centralized laser systems that serve multiple reactors. The

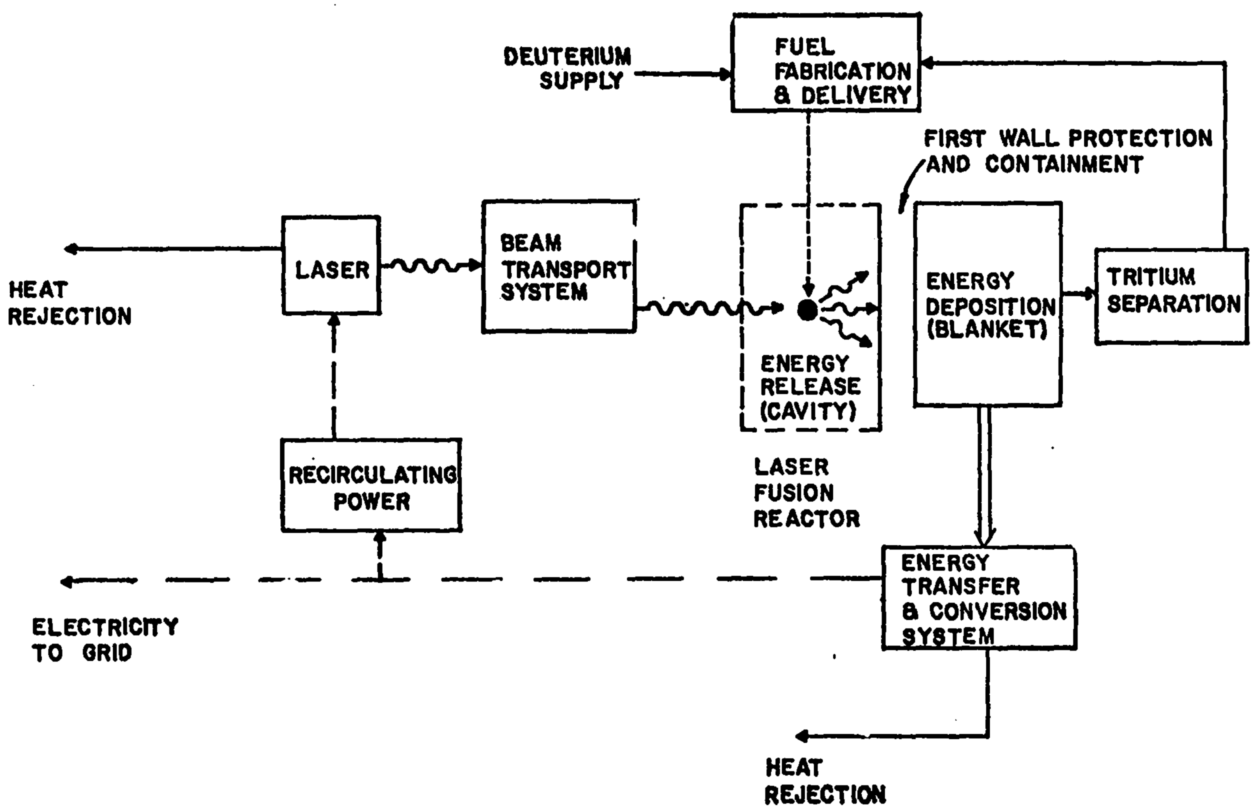

Fig. 3. Schematic energy and mass flow diagram.

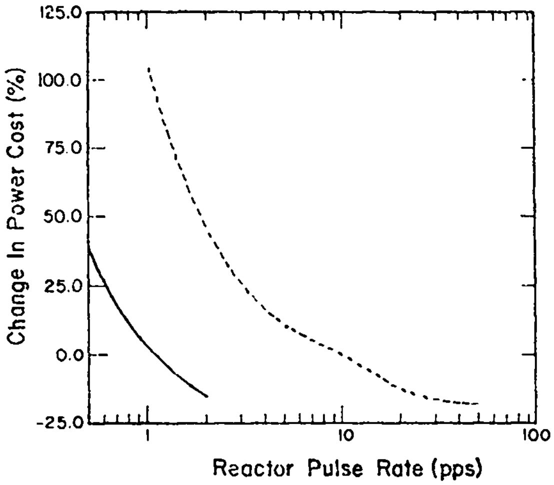

Fig. 4. Effect of pellet firing repetition rate on power production cost.

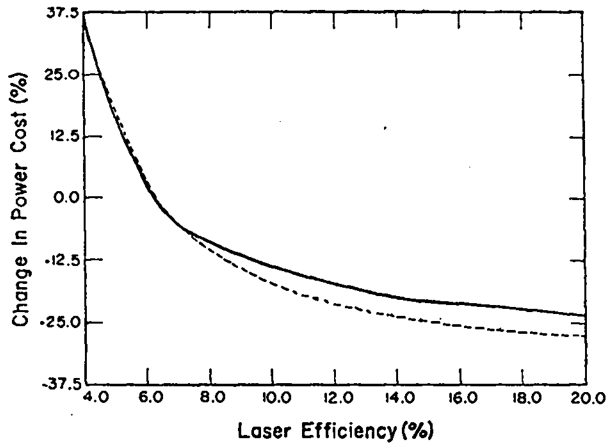

Fig. 5. Effect of laser efficiency on power production cost.

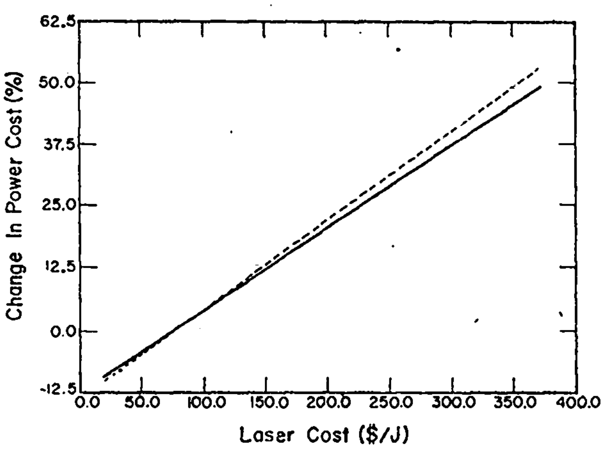

Fig. 6. Effect of laser capital cost on power production cost.

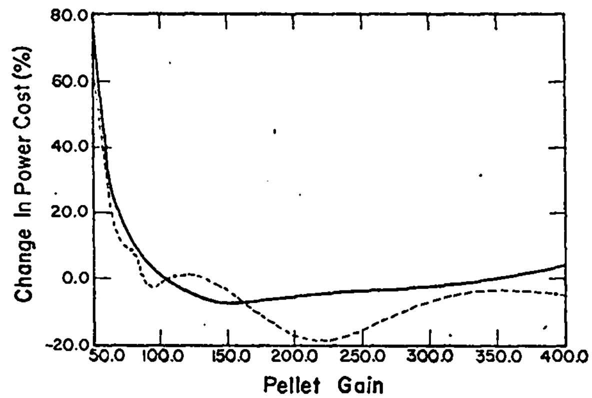

Fig. 7. Effect of pellet gain on power production cost.

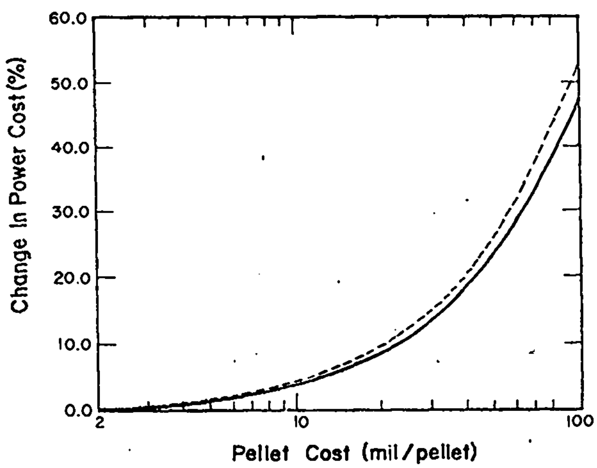

Fig. 8. Effect of pellet cost on power production cost.

number of reactors included in each station is the minimum number required to produce at least 1000 MWe net. In Figs. 4 through 8, the solid and dashed lines refer to generating stations based on the WWR wall and MPWR concepts, respectively.

Figure 4 indicates the percent change in power costs as the microexplosion repetition rates in individual cavities are varied. Nominal values are 1.2 and 10.0/s for the WWR and the MPWR concepts, respectively. Severe penalties result from decreases in repetition rate below nominal values. Production costs are reduced about 20% by doubling the repetition rates over nominal values, but further increases result in only marginal improvement, i.e., reactor-cavity wall lifetimes become very short at high repetition rates due to neutron damage resulting in increased maintenance costs and decreased duty factor.

The effect of laser efficiency on power production costs is shown in Fig. 5 and the effect of laser capital cost in Fig. 6. Nominal laser efficiency is 6.3%. A decrease to 4% in laser efficiency would increase power production costs by more than 30%. To decrease power production costs by 20% would require laser efficiency increases of 11 and 14%, respectively, for generating stations based on the MPWR and the WWR concepts. Further increases in laser efficiency do not decrease production costs significantly. Power production costs are not very sensitive to laser capital costs. Doubling the laser capital costs from a nominal value of 80 $/J would increase power production costs by only about 13%. This relationship reflects the fact that laser capital costs are not a large fraction of total plant capital costs. Plants based on MPWRs are more sensitive to laser efficiency and laser capital costs because their lasers and power supplies require a larger fraction of total capital costs than plants based on WWRs. Also, MPWRs offer a higher power output per reactor module resulting in generally larger total power output for plants constrained to produce at least 1000 MWe. For larger power outputs economic advantages accrue due to the size of, e.g., turbines, and generators.

Variations in fusion-pellet gain and pellet manufacturing costs affect power production costs, as shown in Figs. 7 and 8. The nominal pellet gain assumed for these calculations was 100. Power production costs are very sensitive to pellet gain in the range 50 to 150. Decreases in pellet gain to a value of 50 increase the cost of power production by about 70%. The optimum pellet gain for plants based on wetted-wall reactors is about 150, with further increases resulting in increased production costs due to rapidly increasing reactor capital costs as pellet yield increases. The optimum pellet gain for plants based on magnetically protected wall reactors is about 220; the undulations in the curve are due to rapidly changing total power output as reactor modules are eliminated from the plant. In contrast, the lower power output per unit for wetted-wall reactors permits relatively smooth transitions in output as the number of reactors is changed. In no case are power production costs reduced by as much as 20% if pellet gains exceed the nominal value of 100. Power production costs are not sensitive to pellet fabrication costs below 20 mil per pellet; however, higher pellet costs result in rapidly increasing production costs. Pellet costs constitute a larger fraction of production costs for MPWR plants than for plants based on WWRs.

Self-consistent studies of two conceptual laser-fusion electric generating stations have been made at LASL.[9] Artists' renditions of these two generating stations are shown in Figs. 9 and 10. Important considerations which led to plant design choices include component reliability, redundancy of essential components, access to components for service and/or replacement, and minimization of hazards from radioactive materials to the environment and to operating personnel.

The electric generating station design shown in Fig. 9 is based on the wetted-wall laser fusion reactor concept. The reactors are located in a separate, annular building that encloses the laser system building. Between 20 and 30 reactors are required to produce 1000 MWe, depending on the efficiency of the energy conversion cycle and thus on the temperature of the reactor coolant. Pairs of adjacent reactors are served by a common heat-transfer loop, a steam generator, and lithium-processing and tritium-removal systems. Each reactor is in a biologically shielded enclosure with penetrations for laser beams, liquid-metal coolant, and the introduction of fuel. The heat exchangers and lithium processing equipment for each pair of reactors are located in a biologically shielded enclosure adjacent to the reactor enclosures. Components containing tritium are designed to minimize component sizes and piping lengths.

The CO_2 lasers are in the centrally-located laser system building. Eight lasers are fired simultaneously, and the eight laser beams are directed successively to respective reactor cavities by a rotating mirror. Each main laser power amplifier has a redundant partner to achieve high reliability and ease of maintenance. The laser power supplies are located on the level above the main laser power amplifiers.

The laser system and the reactors with their associated beam-transport and heat-transfer systems are isolated mechanically and structurally; so are

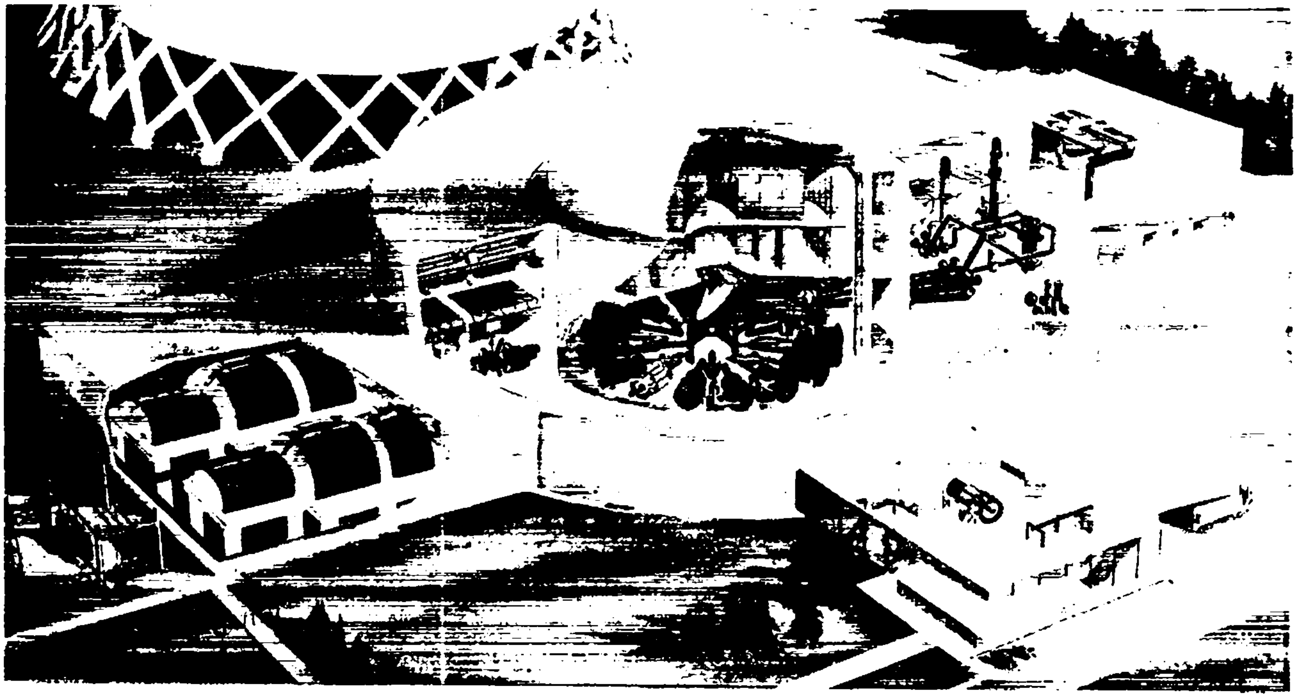

Fig. 9. Laser fusion generating station based on the wetted-wall reactor concept.

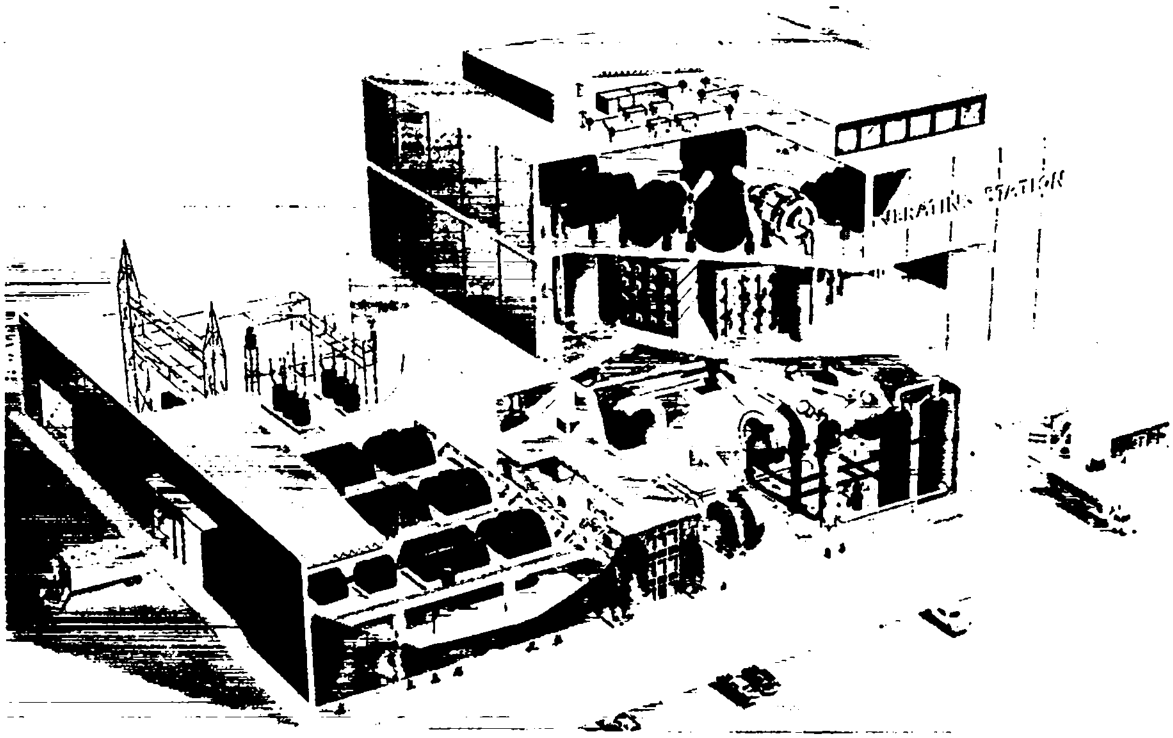

Fig. 10. Laser fusion generating station based on the magnetically protected wall reactor concept.

control rooms and other work areas to eliminate radioactive exposure. Overhead cranes are provided for removal and replacement of the laser power supplies. The laser power amplifiers and optical systems are accessible through underground passages. Reactors and reactor components can be removed under remote control through removable shield plugs and are transferred to shielded work areas by crane. Each reactor can be isolated from the system for service and/or replacement without affecting the operation of the remainder.

The generating station shown in Fig. 10 is based on CO_2 laser technology and the laser-fusion reactor concept with magnetically protected cavity walls. Four reactors with a thermal power output of ~ 1080 MW each are included in the station. The major differences between this concept and the one based on the wetted-wall reactor design result from differences in the degree of modularization which lead to differences in the optimum number of redundant components and the potential advantages of centralizing components.

Because the concept in Fig. 10 includes only four reactors, the incentive to centralize the laser system with laser beams directed from one set of laser power amplifiers sequentially to respective reactors is diminished. However, the cost of providing eight complete laser power amplifier systems for each of the four reactors (with a centralized power supply) is ~ 10% higher than providing a centralized laser system. Therefore, the plant concept in Fig. 10 includes a centralized laser system similar to that in Fig. 9 (with 16 main laser power amplifiers for 100% redundancy).

The reactors, heat exchangers, lithium-tritium separators, control room, and energy conversion equipment are located on the first level of the station. Hot-cell maintenance areas for periodic servicing of the energy-sink cones and other radioactive components are also on this level. Tracks are provided for moving the energy-sink cones between reactors and maintenance areas. Single-loop lithium heat-transfer systems are used between the reactors and the steam generators, and semi-permeable-membrane lithium-tritium separators are included in the lithium loops. Separate heat-exchanger and lithium-tritium separator systems are provided for each reactor.

TABLE III

ELECTRIC GENERATING STATION PERFORMANCE BASED ON A HIGH-TEMPERATURE BINARY ENERGY-CONVERSION CYCLE

	Wetted-Wall Reactor Plant	Magnetically Protected Wall Reactor Plant
Number of wetted-wall reactors	26	4
Total thermal power, MW	3081	4309
Net electric power, MW	1017	1423
Net plant efficiency, %	33	33
Recirculating power fraction	0.35	0.35
Laser efficiency, %	6.3	6.3
Laser beam transport efficiency, %	92.7	92.7
Laser energy per pulse, MJ	1.08	1.08
Relative power production cost	1.0	0.83

The pulse-forming networks are located on the second level and the main laser power amplifiers on the third. A laser power-amplifier and pulse-forming-network maintenance area is located on the third level serviced from the ground by a freight elevator. The front-end system, i.e., the oscillator and preamplifiers, is located on the top level. Shielding of the reactor enclosures and hot-cell maintenance areas is provided by thick concrete walls. Each reactor can be isolated from the system for service without affecting the operation of the remainder.

The operating characteristics of these electric generating stations with a high-temperature binary energy-conversion cycle are given in Table III. The energy-conversion cycle consists of a potassium-Rankine topping cycle and a high-temperature conventional steam cycle. The lithium coolant leaves the reactors at 1100 K in this design. The relatively large number of reactors emphasizes the modular nature of laser fusion reactor generating stations. A potential disadvantage of laser fusion reactor generating stations is the large recirculating power fraction. The recirculating power fraction is essentially determined by the laser efficiency. If the laser efficiency should be significantly lower than currently estimated, the circulating power fraction will increase and the economic viability of pure laser fusion power may become questionable.

D. Other Commercial Applications

1. Fusion-fission hybrids

A promising variant of laser-fusion reactors is the laser fusion hybrid reactor, which includes fissile and/or fissile-breeding material in the blanket region. The principal advantages of fusion-fission hybrid reactors compared to either pure fusion or fission breeder reactors result from combining "fast-neutron-rich" but "power-poor" fusion systems with "power-rich" but "fast-neutron-poor" fission systems. A laser fusion fissile/breeding blanket can be designed to enhance the energy output of a fusion reactor or as a source of fuel for a fission economy, or both. When designed primarily to produce power, laser fusion hybrids may significantly relax the requirements on fusion-pellet gain for economically viable systems. As a fissile fuel producer, laser fusion hybrids can be designed to breed substantial quantities of fissile material without some of the disadvantages associated with fast-fission breeder reactors.

Either the uranium or the thorium fuel cycles can be used in laser fusion hybrids. For the uranium cycle ^{238}U is converted to ^{239}Pu, and for the thorium cycle ^{232}Th is converted to ^{233}U. The optimum design depends, to some extent, on the incentive (price) for producing a particular fissile isotope and on the environmental and ecological implications of particular fuel cycles. Projections of market values of ^{239}Pu and ^{233}U are very uncertain and depend on projections of the extent to which fast-fission breeder reactors and high-temperature gas-cooled reactors will be used and other variables. A high-temperature gas-cooled reactor fission economy is attractive because it may offer higher net efficiency and lower environmental hazards, giving some impetus to the study of thorium-cycle fusion hybrids.

A fusion-fission hybrid concept that has been investigated at LASL is known as a ^{239}Pu burner-^{233}U breeder. Reactor blankets are spherical shells based on the wetted-wall laser fusion reactor concept. These designs include a lithium-cooled driver region of stainless-steel-clad rods of $^{238}UO_2$ with the equilibrium concentration of $^{239}PuO_2$ adjacent to the reactor cavity, followed by a region of either ^{232}ThC or $^{232}ThO_2$ rods, also clad in stainless steel and cooled by lithium.

TABLE IV

PERFORMANCE FOR VARIOUS THORIUM BREEDING REGION OPTIONS

	Fuel Form in Breeding Region	
	ThO_2	ThC
Equilibrium PuO_2 concentration in driver region, %	9.62	9.50
^{233}U production per fusion neutron	1.28	1.27
^{233}U production per year, kg (85% duty cycle)	451	448
Thermal power output, MW	3586	3366
Neutron multiplication factor without coolant	0.92	0.90
Tritium breeding ratio	1.48	1.38
Thermonuclear power, MW	95	95

The plutonium in the driver region is continuously recycled in the fuel fabrication and processing cycles, and serves only to amplify the neutron population and to produce thermal power. Leakage neutrons from the driver region are captured in the thorium region and cause the breeding of ^{233}U. Tritium for the fusion fuel cycle is produced by neutron capture in the lithium coolant.

The performance of a reactor with a cavity radius of 2 m, a driver region 30-cm thick, and a thorium breeding-region thickness of 40 cm is outlined in Table IV.[10]

The ^{239}Pu burner-^{233}U breeder concept, producing large amounts of thermal power and fuel for thermal fission reactors, may be attractive as a direct substitute for the liquid-metal fast breeder reactor. The concept could also be adapted to the production of ^{239}Pu from ^{238}U. It does, however, have essentially all the disadvantages of the breeder reactor, except that it does not operate as a critical system. Such reactors would be economically competitive with fission reactors, even with fusion pellets of relatively poor performance, and may provide a useful intermediate phase in the development of fusion power.

Another fusion-fission hybrid concept that may be attractive if fission-fuel reprocessing is not permitted would include a blanket region consisting of $^{238}UO_2$ or ^{232}ThC rods fabricated for direct use in light-water reactors. Only sufficient ^{239}Pu or ^{233}U would be bred in these rods to satisfy enrichment requirements for light-water power reactors. The plutonium or ^{233}U thus produced would be imbedded in a highly radioactive matrix, thus effectively eliminating the threat of hijacking. This concept has not been carefully evaluated but may have potential as a fuel producer, depending on political decisions relating to plutonium recycle.

2. Production of synthetic fuels

The unique output energy forms characteristic of fusion reactors using the (D+T) fuel cycle are x rays, hot ionized plasmas, and high-energy neutrons. These energy forms might be utilized directly for the radiolytic decomposition of reactants such as H_2O and CO_2 to produce synthetic fuels such as H_2 and CO (leading to methane or methanol, if desired).

Radiolytic decomposition of reactants could be accomplished directly with any of the primary energy forms released by (D+T) fusion. However, it is difficult to imagine engineering concepts using the primary x-ray and plasma energies inside the reactor cavities where they would necessarily be produced. High-energy neutrons penetrate reactor cavity walls with essentially no energy loss and can be utilized in blanket regions. The availability of these 14-MeV neutrons outside the reactor cavity is a unique characteristic of fusion reactors. Neutron energy can be transferred to reactants by scattering interactions, which create high-energy ions that, in turn, cause further ionization. If hydrogen is present, for example, energetic protons are created by neutron scattering. Gamma radiation, produced by neutron capture, streams throughout the reactor and is also available for utilization free of cavity restraints. However, gamma-radiation interaction cross sections are too low for such radiation to be an effective mechanism of energy transfer for the endothermic chemical reactions required in the production of synthetic fuel.

Preliminary economic analyses have been made of laser fusion reactors dedicated to radiolytic decomposition of H_2O to produce H_2. Such a radiolytic system would require the recirculation of a significant amount of electric power, which could be satisfied, in part, by conversion of the plasma and x-ray energies trapped in the reactor cavity, with the remainder provided either by siphoning off part of the neutron energy for conversion or by purchase of electric power from another source.

A somewhat simplistic model of a production plant has been analyzed to provide estimates of the costs of producing neutrons for radiolytic applications.[11] The plant includes four laser fusion reactors with magnetically protected cavity components, a common CO_2 laser system with sequential switching of laser beams to successive reactors, and adequate heat-exchanger and power conversion capacity to generate the electrical recirculating power needed to operate the plant. The reactor blankets consist simply of the structures normally required to contain circulating liquid lithium in power-producing reactors. Except for the wall surrounding the reactor cavity, which consists of niobium, all structures are made of stainless steel. No special apparatus was included for handling chemical reactants or for separating the products of radiolysis.

The thermonuclear energy release per fusion pellet was assumed to be 100 MJ, at a pulse repetition rate of 10 per second per reactor. Thus, the total thermonuclear power level is 4000 MW. It was assumed that tritium would be purchased from laser fusion electric generating stations with excess tritium production; costs were determined from the additional costs incurred by the generating station in producing such excess tritium.

Neutron production cost in 1973 dollars would be 2.2 dollars per million Btu of neutron energy, if neutron energy were converted to electricity in the amount necessary to provide the required recirculating power.

Current estimates of production costs of synthetic fuel (either H_2 or methane) from coal by standard processes range from 1.0 to 1.5 dollars per million Btu (1973 dollars) for commercial operation in the 1980s. Thus, even if the neutron energy is utilized at 100% efficiency for decomposition of H_2O or CO_2, no back-reactions occur, and the H_2 or CO is recovered at 100% efficiency, this form of synthetic-fuel production with laser fusion reactors would not be competitive within the context of this price structure. Moreover, because the overall efficiency of standard coal-gasification (thermochemical) processes ranges from 55 to 70%

and demonstrated radiolytic conversion efficiencies are less than 35%, it would appear more reasonable for the foreseeable future to convert neutron energy to thermal energy for thermochemical cycles than to use it in radiolytic processes.

Radiolysis has been suggested as an attractive method to produce H_2 as a topping cycle in laser fusion reactors where the main purpose is the production of steam for process heat or for electrical conversion. A preliminary economic analysis of a system that produces both H_2 and electricity revealed that such a system, although economically more attractive than H_2 production alone from dedicated plants, offers no incentive per se for this mode of operation unless an abnormal price structure (in terms of current relative values) should develop. There seems to be no reason to seriously consider H_2 production from topping cycles, unless H_2 is produced in copious quantities as an unavoidable byproduct in a system optimized from other considerations. Costs of producing methane by alternative processes (in 1973 dollars) are compared in Fig. 11. Methane costs are plotted as functions of the

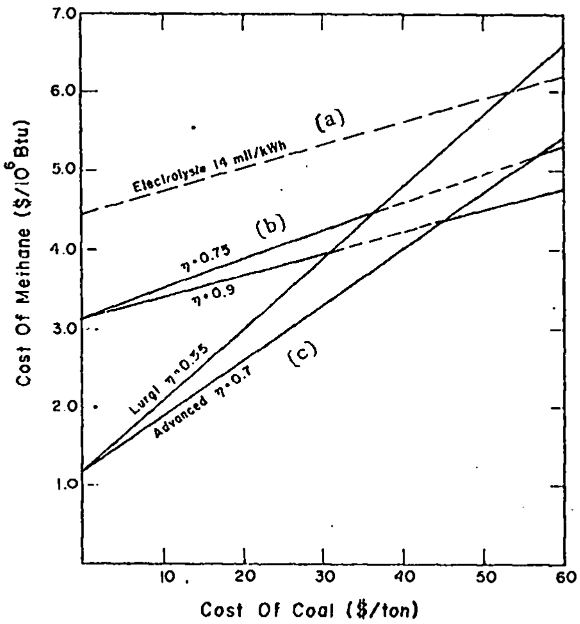

Fig. 11. Costs of producing methane by various methods as functions of the cost of feed coal: (a) electrolytically produced H_2 followed by direct hydrogenation at η=0.9, (b) radiolytically produced H_2 at η=0.35 followed by direct hydrogenation with waste heat converted to electricity and sold for 14 mil/kWh, and (c) standard coal gasification (η=efficiency).

cost of coal for standard coal gasification processes, e.g., Lurgi, and for radiolytically produced H_2 in laser fusion reactors at 35% efficiency followed by direct hydrogenation at between 75 and 90% efficiency, with the remainder of the fusion energy converted to electricity and sold at 14 mil/kWh. Also, indicated is the cost of methane produced by direct hydrogenation at 90% efficiency, where the hydrogen is produced by electrolysis at an electricity cost of 14 mil/kWh. Current costs of coal are 10 to 15 dollars per ton with strip-mined western coal as low as 2 to 3 dollars per ton. These results indicate that radiolytically produced H_2 for direct hydrogenation will not be competitive until coal costs increase to the 35 to 45 dollar per ton range. These conclusions could be reversed by dramatic changes in relative market values, or by scarcities of feed materials such as coal.

3. Sources of process heat

About 28% of the nation's energy consumption is used directly for process heat and another 9% is used in industrial applications in the form of electricity. The utilization of process heat would be even greater if an economical high-temperature heat source were available. Laser fusion reactors could provide process heat up to temperature limits that are imposed only by the properties of refractory materials.

The highest fission-reactor temperatures that have been proposed for use as process-heat sources (from high-temperature gas-cooled reactors) are in the range of 1550 to 1650 K. Temperatures in this range are adequate for many industrial processes; however, there are also many processes that require higher temperatures that are currently provided either by such inefficient sources as electric arcs or are not now economically competitive.

It is conceptually possible to convert all energy release forms from pellet fusion into high-temperature heat; however, the most straightforward engineering designs are based on the utilization of the neutron and gamma-ray energy. Fusion neutrons pass through cavity walls with essentially no energy loss and can be utilized in blanket regions. In addition, there are exoergic reactions between neutrons and appropriately chosen blanket constituents that result in increased energy deposition in blanket regions. About 80% of the total energy

TABLE V

OPERATING CONDITIONS AND PERFORMANCE OF SPHERICAL LASER FUSION-REACTOR RADIATION HEAT SOURCES WITH 2000-K PROCESS STREAMS

Thermal Radiation Power (MW)	Radiation Surface Temperature (K)	Blanket Thickness (m)*	Type of Graphite	Maximum Blanket Temperature (K)
91.3	2262	1.05	Pyrolytic, conduction along crystal planes.	3210
23.9	2087	0.76	AGOT, conduction normal to axis of extrusion	4000
46.7	2171	0.58	AGOT, conduction parallel to axis of extrusion	4000

produced in typical laser fusion reactor designs is available for use free of cavity restraints. This is a unique characteristic of fusion reactors.

A variation of process-heat sources that utilizes the neutron and gamma-ray energy produced in a laser-fusion reactor by (n,γ) reactions between neutrons and structural materials could be based on the use of high-temperature radiation. For this concept, the blanket region is replaced by a refractory material in which neutron and gamma-ray energy is deposited, and energy transfer from this region to an adjacent region of process fluid or chemical reactants is accomplished by radiation.

Conceptual radiation sources that include carbon and a material with a high absorption cross section for thermal neutrons as the principal energy-deposition materials have been investigated. The 14-MeV fusion neutrons give up their kinetic energy to the carbon by elastic collisions and are finally captured by the thermal-neutron absorber. Initial calculations have been performed for systems with two regions in the blanket, a pure carbon region next to the reactor cavity followed by a 5-cm-thick region of 90-vol% carbon and 10-vol% boron carbide. Boron carbide was selected because of its high melting temperature (2625 K), its large thermal-neutron absorption cross section, and because thermal-neutron capture in boron is exoergic with 2.5 MeV deposited locally by charged particles. Some neutrons will inevitably leak from such a blanket and might affect a process stream adversely. Neutron leakage is reduced to less than 0.2% for a blanket including a 1-m-thick carbon region surrounding a 4-m-diam cavity in spherical geometry.

*Reactor cavity radius is 4 m.

Calculated temperature distributions in the carbon and boron carbide for several cases of blanket thickness, type of carbon (graphite), and radiative power level are given in Table V. Maximum blanket temperatures are determined by the power level, the geometry, and the physical properties of the blanket. Systems with the best performance include pyrolytic graphite with thermal conduction along the crystal planes. Maximum blanket temperatures were limited to 4000 K, which is approximately the sublimation temperature of carbon. Analyses have also been made of the effects of pulsed operation on maximum blanket temperatures. Because of the extremely large heat capacities of such systems, fluctuations in temperature due to pulsed operation are trivially small.

Energy deposition by plasma debris has been ignored in these preliminary calculations. The most attractive concept for using high-temperature radiation is probably the magnetically protected cavity. For such a system, the radiating heat source would be cylindrical and the kinetic energy of the plasma debris would be deposited in the energy-sink regions. This energy could be used in conjunction with energy deposition in the blanket, e.g., in preheating the process stream or for other purposes.

It may be possible to breed tritium by replacing the boron carbide with a high-melting-point lithium compound, e.g., lithium oxide; however, it is doubtful that a breeding ratio as large as unity could be obtained, and the inclusion of lithium oxide may restrict permissible operating temperatures below those obtainable with other systems.

4. Applications of thermionic conversion

Thermionic emission has been utilized in space-power research programs for the past two decades. This research led to the development of devices for converting heat to electricity generally referred to as thermionic converters. Emphasis in thermionic-conversion research by ERDA contractors is currently placed on the design of systems to be used as topping cycles for electric generating stations. Thermionic conversion for this application is attractive because the heat-rejection temperatures are high enough to permit normal operation of conventional conversion cycles with the heat rejected from the thermionic converters.

Conceptual laser-fusion reactors may offer significant advantages compared to fission reactors for utilizing thermionic-conversion topping cycles. These advantages stem from the performance characteristics of thermionic converters with increasing efficiency and output resulting from higher-temperature operation and from the absence in laser fusion reactors of high-temperature limitations due to fuel-element distortion (or melting) and fission-product release. Temperatures in fusion reactors are limited, in principle, only by the properties of refractory metals.

The normal electric output of thermionic converters is low-voltage direct current. The reactor concepts investigated would produce (1) low-voltage direct current from a thermionic topping cycle for electrochemical processing and (2) conventional commercial electric power with the reject heat from the topping cycle.

A high-temperature, refractory reactor blanket is required to gain maximum benefit from the thermionic topping cycle. The conceptual blanket studied includes a 0.5-m-thick graphite region enclosing the reactor cavity.[12] The graphite, in turn, is enclosed by a 0.05-m-thick region consisting of boron carbide and graphite, in which neutrons thermalized in the intervening graphite region are captured. The thermionic diodes are supported on the surface of the boron carbide-graphite region. It was assumed that the thermionic-diode structures completely enclose the radiating graphite surface and that 90% of the surface of these structures consists of thermionic emitters. Heat rejection from the thermionic-diode collectors is by conduction to an intermediate heat-transfer loop containing circulating sodium. The entire system is enclosed by a stainless steel structure.

The converter performance assumed is typified by units that have been tested in the laboratory and are being developed for power-plant application. The thermionic emitter and collector temperatures in the study ranged from 1400 to 1800 K and from 700 to 920 K, respectively. The diode power output per unit of emitter area was based on experimental data. The net thermionic conversion efficiency was estimated to be 42% of Carnot efficiency.

The diodes were assumed constructed from 0.127-cm-thick refractory-metal plates with the properties of molybdenum. The necessary radiator surface temperatures and the radiating power level were determined from the thermionic-diode output and efficiency. The maximum temperature in the carbon blanket was well below the sublimation temperature ($\sim$ 4000 K) of carbon in all cases.

Conversion of the heat rejected by the thermionic diodes, ohmic losses in the conductors, and the energy of the pellet debris in a steam-turbine generating plant were evaluated with a temperature-dependent model used in laser fusion reactor parametric studies.

Capital costs of the reactors, of heat-transfer and steam generating equipment, and of the steam-turbine generating equipment were estimated in terms of 1973 dollars. Capital costs of the thermionic systems were estimated to be $160/kWe.

Energy deposition in the graphite blanket from 100-MJ fusion-pellet microexplosions was calculated to be 90 MJ per microexplosion. In addition, 23 MJ is recovered directly from the cavity from each microexplosion. Thus, exoergic nuclear reactions in the blanket result in an enhancement of the fusion yield by 13%.

Performance evaluations were based on a conceptual power plant containing 14 reactor cavities. The thermal-to-electric conversion efficiency for the combined cycles is shown in Fig. 12 as a function of diode collector temperature for the extremes of emitter temperature considered.

Economic analyses were made assuming that the direct-current output of the thermionic diodes would be used in an electrochemical process rather than being conditioned for distribution in a power

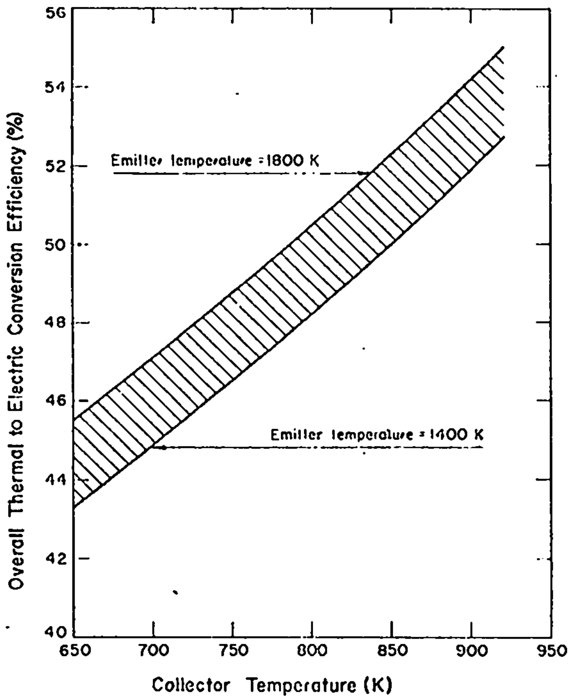

Fig. 12. Thermal-to-electric conversion efficiency of combined cycles as functions of thermionic-diode operating conditions.

grid; thus, the thermionic output was evaluated separately from the steam-turbine output. Because the reactor concept considered does not include a provision for tritium breeding, the fuel cost was increased to account for the purchase of tritium from another source.

No attempts were made to estimate component lifetimes or replacement schedules so that calculated power-production costs are too low by the amount of maintenance costs. A duty factor of 85% was assumed. Typical results of the economic analysis (in 1973 dollars) are given in Fig. 13, which plots production costs of thermionic power as functions of diode collector temperature, with the value of the power produced by the steam turbines as a parameter. The diode emitter temperature for these calculations was 1800 K.

For the example analyzed, net conversion efficiencies of combined thermionic and steam-turbine cycles in an electric generating station are very high, and the costs of producing direct current as a byproduct are low. For example, if conventional electric power is sold at 21 mil/kWh

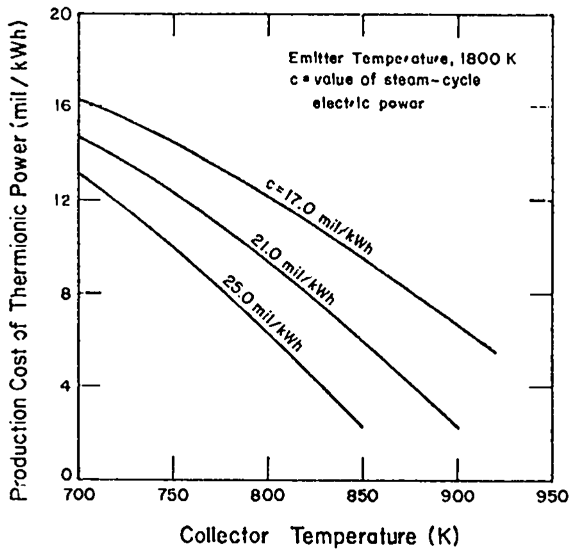

Fig. 13. Production costs of byproduct thermionic power with the value of conventional power as a parameter.

and the thermionic-diode emitter and collector temperatures are 1800 and 875 K, respectively, the production cost of direct current is 4 mil/kWh. If this direct current were used to electrolyze water to produce hydrogen at 75% efficiency, the hydrogen production costs (neglecting additional capital amortization due to electrolysis equipment) would be $1.5/10^6$ Btu energy content of the product.

E. Environment and Safety

1. General

There are three principal reasons for the attractiveness of thermonuclear generating stations as a major source of consumable energy: (1) the fuel supply is virtually unlimited at low cost, (2) fusion energy systems are potentially economically competitive with other advanced energy systems, and (3) the environmental impact of fusion reactors will be more acceptable than that of most other advanced energy sources.

The first of these reasons depends on the fusion fuel cycle used and on the available (planetary) resources of such fuels. The first generation of fusion reactors, regardless of type or design, will almost certainly use the heavy isotopes of hydrogen, deuterium and tritium, because the deuterium-tritium fusion reaction has a higher cross section at lower temperatures than the alternatives. Tritium, which does not occur naturally (except in

TABLE VI

COMPARISON OF ENVIRONMENTAL EFFECTS (NON-RADIOACTIVE) OF VARIOUS THERMAL ENERGY SOURCES (BASED ON 1000 MWe OUTPUT)

	Laser Fusion	Tokamak	LMFBR	LWR	Fossil	Solar
Land use (number of acres)	~100	~100	~200	~200	~200	> 2000[a]
Thermal pollution waste heat rejected (MW)	3300 to 4000	2800 to 3500	2560	3125	2380	(2380)[b] 4000
Stored chemical potential energy (MJ)	10^7 (lithium)	$2(10)^7$ (lithium)	10^6 (sodium)	negligible	$8(10)^9$ (oil)	negligible
Resources-fuel (metric ton/day)	0.3 (lithium ore)	0.3 (lithium ore)	2.2[d] (uranium ore)	210[e] (uranium ore)	12 000 (coal)	none
	33[c] (seawater)	33 (seawater)			6 000 (oil)	

[a]At maximum insolation of 700 cal/cm^2 per day.

[b]Using concentrators to produce 839-K steam.

[c]Based on natural abundance of 1 part in 6000.

[d]Based on 2/3 utilization of ^{238}U.

[e]Based on natural abundance of ^{235}U (1 part in 140).

very small concentrations in the upper atmosphere where it is produced by cosmic radiation), will probably be bred from lithium during normal operations. Lithium, like deuterium, is a plentiful material. Analyses of conceptual fusion generating stations indicate economic competitiveness with fission reactors within the framework of available technical information. Economic analyses will be continually updated as fusion technology is developed.

The third reason, the issue of environmental impact, is almost totally dependent on the production and emission of radioactive materials from fusion generating stations which is, in turn, strongly dependent on detailed designs and operating conditions of particular plants. Nonradioactive environmental effects are summarized in Table VI. Of these effects, the most significant potential hazard is chemical poisoning as the result of a lithium "fire." In the case of a major lithium spill, lithium will react with air, water, and concrete, forming a cloud of Li_2O and LiOH smoke, which, if released to the atmosphere, will all be converted to LiOH. Lithium hydroxide reacts with organic tissue and is <u>lethal</u> to humans exposed to a dose of 200 $\mu g/m^3$ for one hour. This concentration could occur at 100 m from the leak of 1% of the lithium inventory in the wetted-wall reactor plant (Fig. 9) if converted to LiOH. Engineered safeguards for the protection of plant personnel must therefore be provided to prevent lithium fires.

2. <u>Potential radioactivity hazards</u>

Radioactive outputs from projected LFR commercial generating stations during normal operation can be categorized as follows:

- Tritium readily diffuses through structural materials at elevated temperatures, and the control of tritium leakage is expected to be a major environmental concern.
- The coolant lithium will contain tritium in concentrations of a few parts per million, impurities that may become activated, and corrosion products that may be or may become activated. Impurities will be continuously removed from coolant streams and will pose only trivial radioactive storage and disposal requirements.
- A significant source of radioactive waste from LFR generating stations will be due to recycling and/or disposal of irradiated structural materials and optical components. Reactor components that are exposed to intense radiation fields will suffer radiation damage and will require periodic replacement.
- There are other relatively unimportant and easily managed sources of radioactive effluent

from LFR generating stations such as liquid-metal cover-gas systems and various purification and processing systems.

The inventory of tritium and activated structural material for a wetted-wall reactor generating station is summarized in Table VII. Although activated reactor structural materials represent the largest amounts of radioactivity produced in a laser-fusion plant, these materials will present only a handling and disposal problem for operating personnel because they are solid, immobile, and not readily dispersed. However, because of some very long half-life activation products (up to 10^5 yr), these waste materials must be carefully managed.

Tritium is present in sufficient quantities to require engineered safeguards minimizing its release. Preliminary estimates of tritium release from operating laser fusion plants indicate no significant economic penalties for designs to limit tritium release to ~ 2 Ci/day, which are the current standards for LWR plants. This release rate would result in a maximum body dose (8-h period) of ~ 10^{-7} rem if released through a 100-m stack or of ~ 10^{-3} rem at 100 m from a ground-level release.

Some perspective of tritium hazards is gained if the tritium inventories predicted for the year 2000 in the world-wide environment are examined. Tritium is naturally produced in the atmosphere at a rate of about 6 MCi/yr, resulting in a steady-state inventory of ~ 100 MCi. At present (1977), tritium content in man's biosphere is ~ 1160 MCi due to testing of nuclear weapons in the atmosphere. This residual is decreasing and, by the year 2000, the amount of tritium in man's environment due to weapons testing will be about equal to that due to natural background (assuming no further weapons testing is conducted in the interim). Also, by the year 2000 about 100 MCi of tritium will have been generated by LWRs. It is assumed that most of this inventory will be withheld from the general environment in effective waste-management programs, resulting in a release of only about 5 MCi from this source. Although fusion power plants could become significant contributors of tritium to the environment, the tritium background level in the biosphere will not be significantly increased if release from fusion plants is held to that from LWRs.

TABLE VII

RADIOACTIVE INVENTORIES DURING STEADY-STATE OPERATION OF 1000-MWe GENERATING STATIONS

	Laser Fusion	Tokamak
Structure (SS or Nb), MCi	~ 3750	7500 to 40 000
Tritium		
Blankets, MCi	~ 4	~ 8
Fuel supply, MCi	~ 20	100 to 200
Impurities in lithium coolant		
^{38}Cl, MCi	~ 0.03	~ 0.06
Others, MCi	~ 0.03	~ 0.06
Corrosion products in lithium cool-and, MCi	~0.012	~ 0.02
Air activation		
^{41}Ar, Ci	~ 200	~ 250
^{14}C, Ci	~ 0.07	~ 0.08

A more quantitative measure of the radiobiological hazard, which is convenient for comparison between different systems, is the biological hazard potential, BHP. The BHP is the ratio of radioactivity produced per thermal watt to the maximum permissible concentration, as specified by Radiation Protection standards, and indicates the degree of dilution required to ensure against detectable biological effects. A comparison of the BHP for laser fusion plants, magnetic-fusion systems (Tokamaks) and fission reactors is given in Fig. 14.[13] These results indicate that the BHP at shutdown of LFR structures is about one tenth that for structures of magnetically confined fusion reactors, almost two orders of magnitude less than for fission products, and more than two orders of magnitude less than for plutonium in an LMFBR. The BHP at shutdown of tritium in an LFR plant is about one tenth that in Tokamak fusion reactor plants and even less for the LFR structure. Also, the BHP of the LFR structure is reduced two orders of magnitude in one hundred years, whereas the BHP of plutonium in the LMFBR is reduced during the same time span by only a factor of two.

3. Accidents

Detailed analyses of accidents and of their effects on the environment for a laser-fusion plant cannot be much more than exploratory at this time. The lack of complete designs, of knowledge of system operation, and of a data base for component

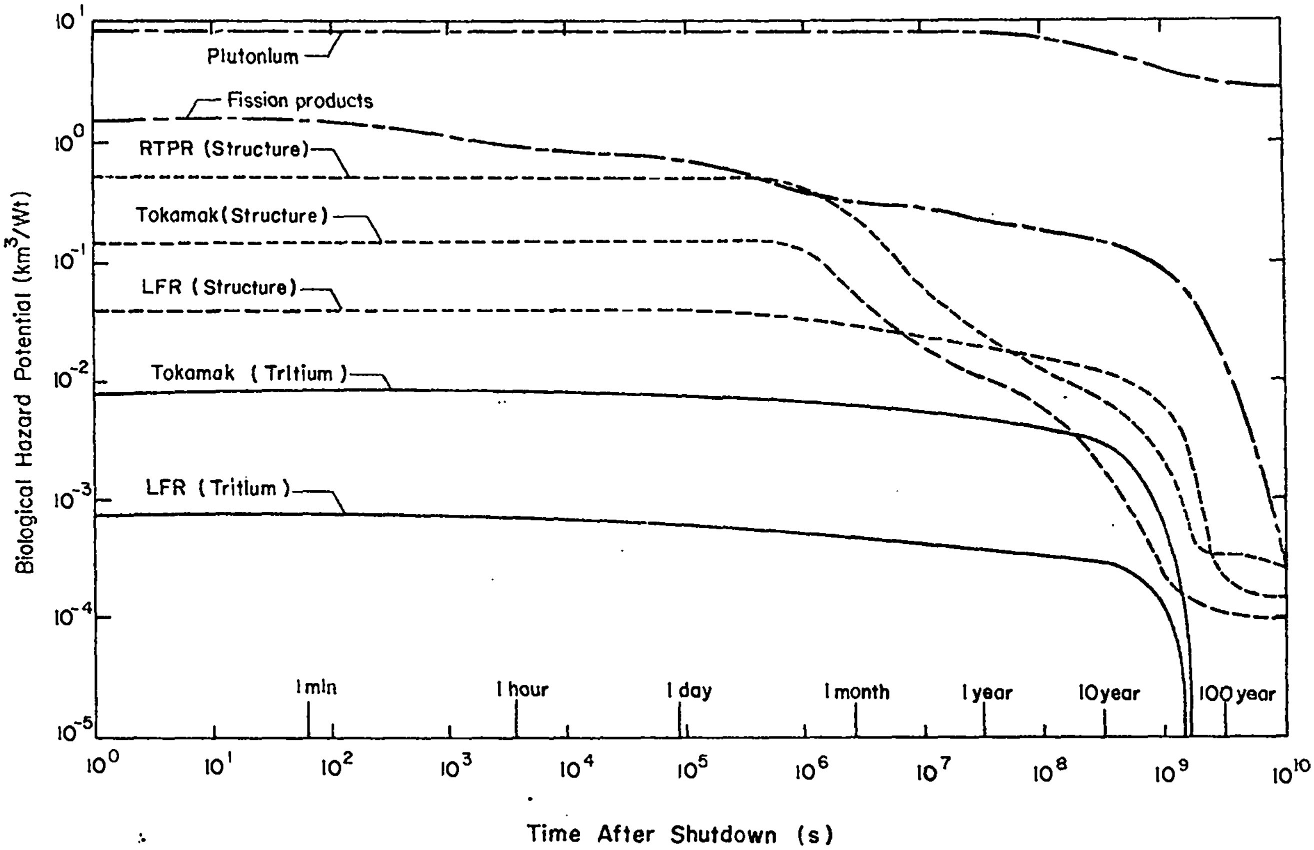

Fig. 14. Comparison of biological hazard potential (BHP) for fusion and fission power plants.

performance, precludes rigorous analyses. However, guided by methodology developed for fission-plant preliminary hazards analyses, partial accident analyses for laser fusion plants can be initiated. Adequate source terms (described in Table VII) can be postulated, assuming an appropriate amount, chemical form, and rate of release of a contaminant. A partial analysis can be performed essentially independently of any accident scenario at a laser fusion plant including its probability of occurence. Insights into the consequences to the public are gained by applying, to these source terms, the modeling developed for accident analyses performed for fission reactors. Useful perspectives and guides for system safety designs for laser fusion plants will evolve from this approach. It has been noted that accidents in laser fusion plants involving stored chemical energies, i.e., hot liquid-metal reactions with air, water, concrete, and other materials, can generate large amounts of radioactive and nonradioactive contaminants in releasable form. Such accidents develop the greatest threat to the environment. Current technology and information from liquid-metal-cooled fission reactors is expected to contribute to safe designs. The uncontrolled releases of other forms of stored energy at laser fusion plants do not, as single occurences, appear to be significant threats to the environment. Although detailed analyses of accidents in laser fusion plants are not now possible, the effects of traditional postulated nuclear accidents can be estimated semiquantitatively. A discussion of these accidents follows.

Significant, uncontrolled, nuclear excursions of fusion pellets are effectively impossible because of extremely small size, the high symmetry of implosion required, the difficulty of getting a small device to react, and the high degree of reaction completion (burnup) in normal operation.

A loss-of-coolant accident in a LFR is not significant because the level of afterheat in a fusion reactor is 10 to 30 times less than in a fission reactor and occurs only in the structural material of the reactor. Analysis indicates that maximum temperature rises only a few hundred kelvin after the coolant is completely lost, resulting in maximum temperatures that are much lower than the melting points of reactor materials. Actually, with liquid lithium systems, some cooling will occur by natural convection, reducing the temperature increase to a negligible amount.

The release of tritium in gaseous form from fuel inventory (~ 2 kg) through a stack, as is conventionally done in fission plants, would result in a maximum dose of $\sim 10^{-5}$ rem. The release of the fuel inventory in the case of an accident in the form of oxides (assuming complete burning of the inventory, which is very unlikely) under the same conditions as gaseous tritium could result in a maximum dose of 10 rem; however, tritiated water is easily removed from effluent gases, and this radiation dose could readily be reduced by a factor of at least 1000, as is conventionally done in tritium-processing facilities.

The most serious accident would involve the combustion of blanket lithium, resulting in the formation of LiOH upon release. The hazard from LiOH exceeds that of the corresponding LiOT to such a degree that by the time one receives a lethal dose from LiOH, the dose from tritium is only 10^{-4} rem.

Accidents could in principle occur during transport of the initial tritium inventory required for plant startup. However, considerable experience has already been gained in the safe transport of relatively large amounts of tritium. The several kilograms of tritium required for startup could be delivered in small shipments to minimize consequences of an incident. Estimates of the probabilities of various types of accident during transportation and assessments of the consequences of such accidents are available, and the problem may be considered to be well-understood and the tritium-handling technology relatively mature.

Although activated structures represent the highest level of radioactivity, the mechanism for vaporizing significant quantities of these materials requires the adiabatic transfer of a major fraction of the lithium combustion energy (flame temperature, ~ 2700 K; metal vaporization temperature ~ 5000 K). Conservative assumptions indicate that, at most, 0.1% of structural material will be vaporized, with only ~ 100 Ci escaping the trapping systems. This activity is less than the tritium activity that would escape and (as for the case with tritium) would be a negligible hazard compared to the LiOH poison hazard.

III. REQUIREMENTS FOR COMMERCIALIZATION

A. Current Status

The program to achieve controlled thermonuclear fusion by inertial confinement is unique among large national undertakings because of the extent to which its success depends on results of basic research in unexplored areas of physics such as radiation-matter interaction at high energy and matter densities. In the current stages of this program, progress towards attainment of its goals and objectives depends more on scientific breakthroughs than on coordination of technology developments, as was the case, for example, in the Nuclear Submarine-Polaris Missile or Space-Lunar Landings programs.

Consistent with the research nature of the current ignition-source development and pellet-design phases of the program, the strategy is based on parallel investigations considering four ignition sources; these are:

- Nd:glass lasers,
- CO_2 gas lasers,
- The search for new gas lasers, here called Brand X, and
- Electron beams.

High-energy ion beams are a fifth possible ignition source, but they are omitted from this discussion because of their present relative insignificance. Different ignition sources operate in different regimes of physical parameter space. Different energy-matter interactions are involved, each requiring somewhat different pellet designs. Therefore, pellet design is considered separately with each ignition source.

Neodymium-glass laser systems require large investments in optical components and in large glass amplifiers. They are inherently limited to a maximum efficiency of a few tenths of a percent and cannot be operated at high repetition rates. These features, along with uneconomical power-scaling constraints, make glass lasers unsuitable for commercial applications. However, the Nd:glass laser is capable of providing light pulses of precisely specified high intensity for initial studies of radiation-matter interaction and fuel-pellet design.

The CO_2 gas laser is currently the best developed among the gas lasers, and CO_2 laser investigation, therefore, forms a key component of the Program. Gas lasers are the only ones that can be operated at repetition rates required for commercial application. Being a gas, the lasing medium can be circulated continuously for the removal of impurities and waste heat. Short-pulse CO_2 lasers have been developed for fusion-pellet experiments and to establish the gas-laser technology required for commercial applications. Furthermore, CO_2 lasers may reach efficiencies of 5% or higher. Questions relating to specific CO_2 laser suitability for commercial applications will be addressed early in the experimental program. These questions involve achievable laser efficiencies in large systems as well as laser-matter interactions with targets at breakeven power levels (and beyond).

Although the quantum efficiency is $\sim 40\%$, CO_2 lasers are expected to be only about 5 to 7% efficient when pulsed with pulsewidths on the order of a nanosecond, even when lasing with dual-band multiline output. The reason for the relatively low laser efficiency obtainable in the short-pulse mode is ascribed to the fact that the lasing rotational-vibrational excited states have no opportunity to be repopulated by collisional processes during the pulse after the energy has been extracted from excited vibrational levels in the CO_2 molecule. Only the energy stored in the lasing levels at the initiation of the pulse is available for extraction in that pulse. Several schemes have been suggested for more efficient extraction of the molecular vibration energy in CO_2 lasers based on, e.g., the initiation of a series of pulses spaced several tens of nanoseconds apart. The energy of successive individual pulses would decrease somewhat, but the net electrical-to-light efficiency of a pulse train might be significantly enhanced over that of single-pulse operation.

A four-stage, 0.2-TW, CO_2 laser was designed in 1971 and has been operating since 1973. The technology development program on which the design is based began in 1969 with the invention of the electron beam-sustained, electric-discharge pumping technique that permits efficient pumping of large CO_2 laser amplifiers for short-pulse operation. This laser is currently being operated at 0.2 TW with a 200-J output and a 1-ns pulsewidth.

The technology that has been developed by building and operating this system has served as the basis for designing and building larger systems. Included among the more important studies that have been conducted with the 0.2-TW system are:

- Short-pulse amplification,
- Window and mirror damage thresholds,
- Target interaction experiments,
- Mechanical, electrical, and optical engineering problems,
- Interstage and target isolation techniques,
- Electron beam-sustained electric-discharge pumping techniques,
- Cold-cathode electron beam guns, and
- Multiline, multiband energy extraction.

The 8- to 20-TW CO_2 laser system depicted in Fig. 15 represents an extension of the electron beam-sustained, electric-discharge pumped laser technology developed in the 0.2-TW four-stage amplifier program. The 8- to 20-TW system will consist of four dual-beam, high-power amplifiers driven by a common oscillator-preamplifier system to obtain eight beams with a pulse length of $\lesssim 1$ ns.

The laser is being developed in two phases. While the facility for the full 8- to 20-TW system is being built, experiments are being carried out with a single dual-beam amplifier module plus oscillator-preamplifier system. The primary objective of this system is to verify the engineering and optical design of the dual-beam module and of associated components. Secondary goals include the study of short-pulse (0.1 to 0.3 ns) schemes, the propagation of such pulses in high-power amplifiers, parasitic- and stray pulse supression techniques, focusing and target isolation schemes, and two-beam target interactions at 1 ns or less. The operation of the full 8- to 20-TW system is scheduled for FY 1978. It will be the first gas laser system that might be powerful enough to achieve ignition of fusion targets, with emphasis on the development of

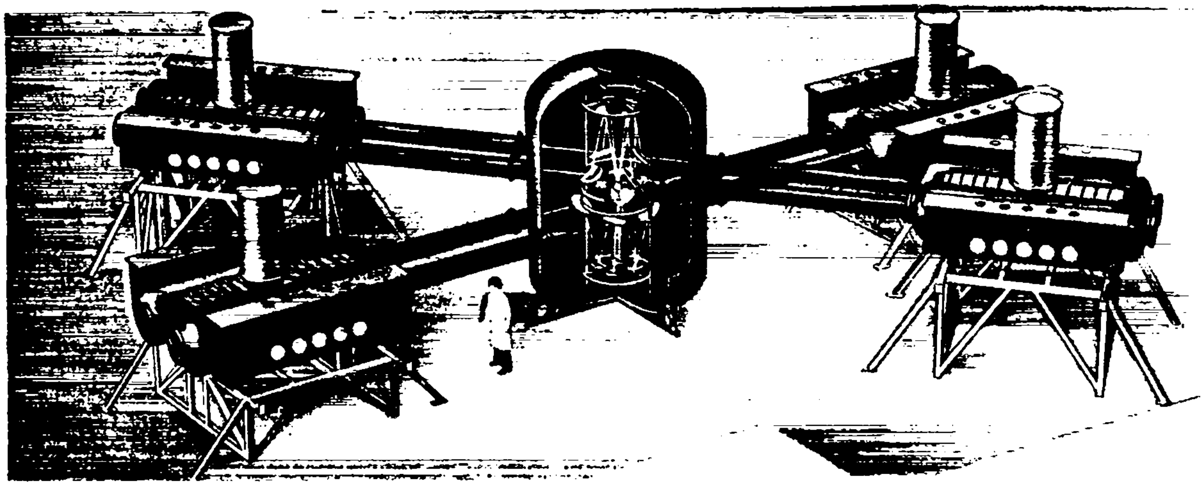

Fig. 15. Ten kilojoule, 8-beam CO_2 laser and target chamber.

targets for the LASL High Energy Gas Laser Facility (HEGLF).

The program objective for the HEGLF, depicted in Fig. 16, is an extension of present CO_2 laser capabilities to power levels at which fusion experiments can be expected to release thermonuclear energy in a range required for demonstrating the important goal of scientific breakeven (defined as equality between the thermonuclear energy output and the laser-beam energy incident on target). By extending the investigation of laser fusion to these levels we will gain a more complete understanding of the physics involved so that laser and target design parameters can be established with confidence. The program specifically calls for the construction of a six-beam 100- to 200-TW CO_2 laser and associated

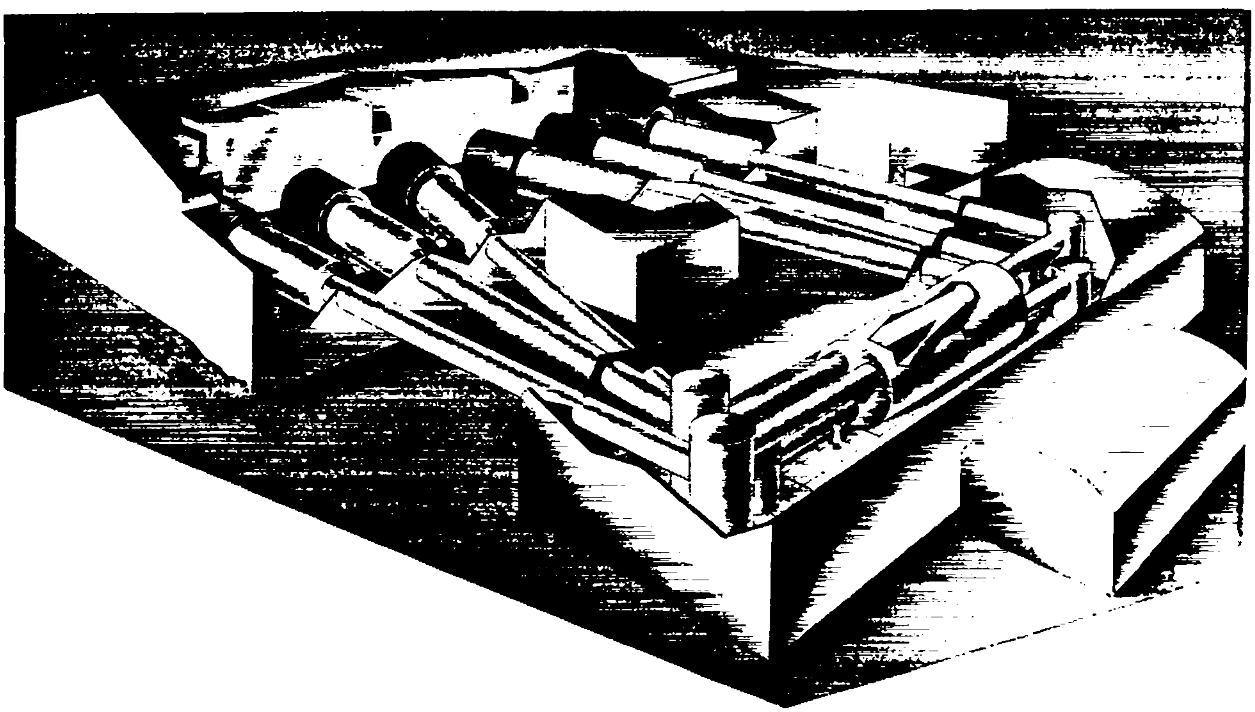

Fig. 16. High-energy gas laser facility.

target irradiation facility.

If the CO_2 laser proves to be infeasible for economic energy production, a new laser (Brand X) must be identified whose laser medium can be circulated to remove waste heat. This laser will necessarily be a gas laser and will probably be pumped electrically (electron beam-sustained discharge or relativistic electron beam). Requirements for the so-called Brand-X laser include demonstration of saturated pulse output at the proper width, successful target experiments at 10% of the required intensity for breakeven gain, scalability to power levels greater than 100 TW per beam, repetition rates of 1 pps or faster, and an efficiency of at least a few percent.

Relativistic electron beams (REBs) are an alternative to lasers for initiating fusion-pellet microexplosions. Electron beam accelerators are simple, efficient, and inexpensive compared to high-power laser systems. However, electron beams can be focused adequately for pellet initiation only if either the electrodes or clouds of plasma or metal vapor are in contact with the pellet. Conceptual approaches to plasma production in electron beam diodes have been suggested, but further research and design studies will be required to ensure that pellet microexplosions can be isolated to prevent damage to electron beam pulse-forming lines and cathodes.

B. Systems Technology Development

Major commitment in systems technology development is constrained by the choice between the CO_2 laser, the Brand-X laser, or electron beam ignition and the achievement of a sufficiently high pellet gain so that pellet designs can be scaled confidently to gains required for commercial applications.

Major areas of necessary systems technology development are: development of long-life, high-repetition-rate capabilities (1 pps or faster) for the driver and pellet injection systems, development of economical pellet mass-production techniques, confirmation of a reactor first-wall protection and blanket design, and development of balance-of-plant systems for energy extraction and tritium handling. Most balance-of-plant systems (i.e., tritium extraction and containment systems and components such as heat exchangers, steam generators, pumps, and valves), are common to both inertial- and magnetic-confinement concepts, and a systems technology development program can therefore be planned and scheduled to supplement appropriate programs sponsored by ERDA's Division of Magnetic Fusion Energy (DMFE).

The requirements for high-repetition-rate capabilities for driver systems and pellet mass production are 10^5 to 10^6 pulses/day for total lifetimes of 10^8 to 10^9 pulses. These requirements are particularly stringent for driver power-supply switching systems, which must perform at 10 to 50 pps at voltages of at least a few hundred kilovolts.

Reactor development will require a facility for the testing of protection schemes for the reactor-cavity first wall and the last optical surfaces in the laser train from impacting pellet debris and shock-induced stresses in liquid blankets. These effects can probably be simulated with HE-driven sources and exploding wires.

C. Commercial Demonstration

The major capital expenditures in the commercial feasibility demonstration phase are for two facilities, an Experimental Test Reactor (ETR) and the Demonstration Plant (DEMO). The detailed design of these facilities will be based on results of the research and technology-development phases and should therefore await successful achievement of intermediate milestones. Final design and construction-start of these facilities before the essential technologies are successfully developed would constitute an unacceptable risk of major capital expenditure. The start of construction of the DEMO would further depend on the successful completion of initial experiments in the ETR to demonstrate the engineering feasibility of the integrated reactor and ignition-source driver systems by sustained operation for a significant period of time (e.g., 6 months).

If construction of the DEMO is to be completed by the year 2000, the system technology development areas should be successfully completed by 1990 because of the length of time involved in the construction of the ETR and DEMO plants. If we assume that about seven years is reasonable for the development of systems technology (including facility construction), the choice of an ignition driver source should not be beyond 1983. If a Brand-X

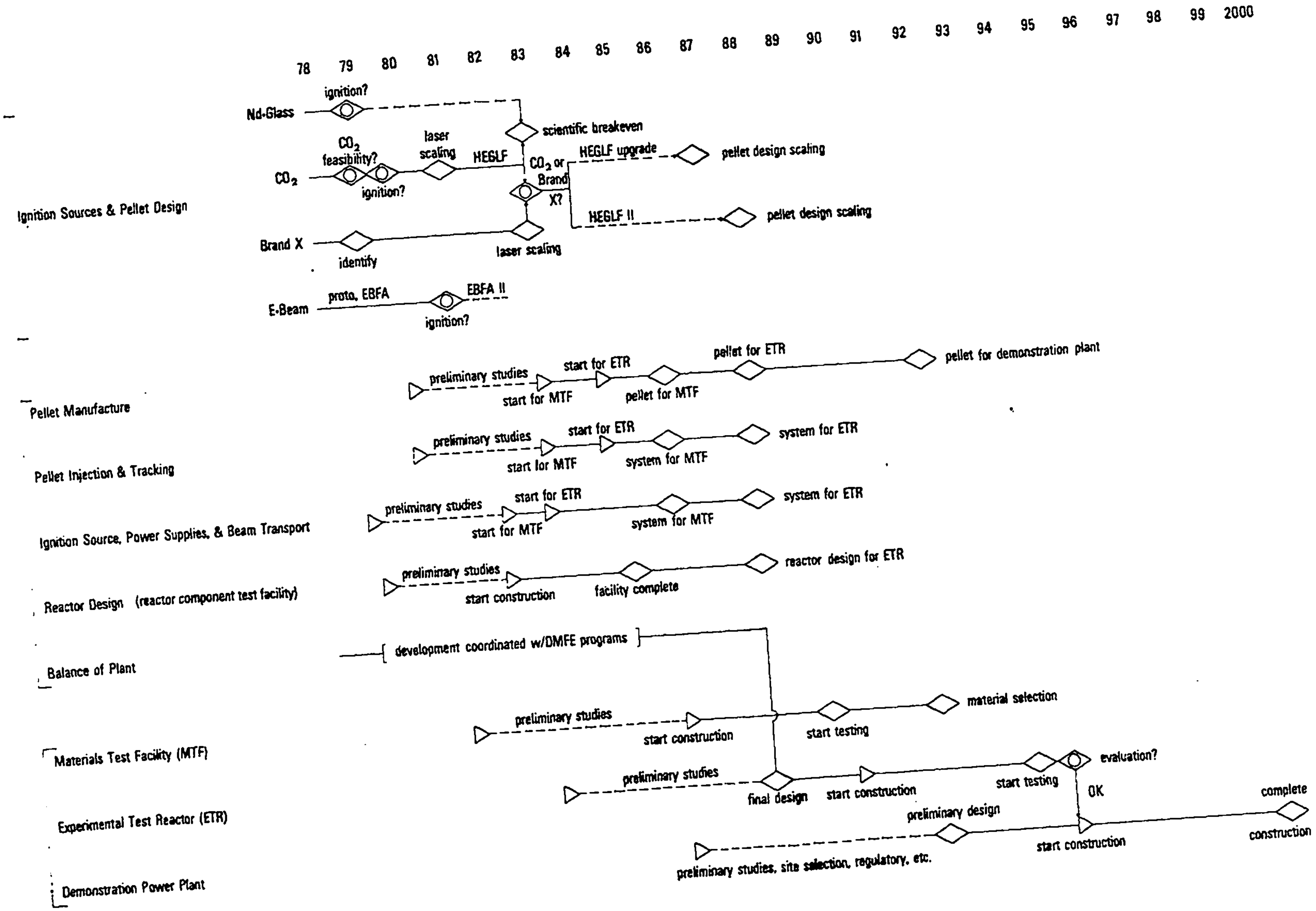

Fig. 17. An inertial confinement fusion program.

laser proves to be necessary, it should be identified by 1978 to provide a reasonable length of time (~ 5 years) for establishing laser scaling parameters for the high energies (hundreds of kilojoules) of a prototype system. Scaling parameters for CO_2 lasers will be established prior to 1983 during development of the power amplifier module for the High Energy Gas Laser Facility (HEGLF).

Although several facilities are planned for materials damage research in DMFE programs, none simulates the high rates and pulsed energy deposition from pellet-fusion microexplosions. An exception may be the proposed LASL Weapons Neutron Research (WNR) facility, in which the dose rates can be simulated, but in which the neutron energy spectra probably cannot be duplicated. The WNR may be in operation within the next few years, providing early information on neutron damage effects.

Materials damage research at appropriate dose rates <u>and</u> neutron spectra must eventually be conducted. It might become necessary to conduct this research in a dedicated facility, free of constraints imposed by other programs. Pellet yields of the order of 1 MJ, corresponding to fusion neutron yields of $\sim 3 \times 10^{17}$, at a repetition rate of 1 pps would provide a fluence of $\sim 10^{22}$ n/cm^2 on centimeter-size samples in about four months of irradiation time. Laser fusion pellet yields in the HEGLF are expected to range from 300 to 800 kJ. Thus, a Materials Test Facility (MTF) with a 1-pps CO_2 laser system at the 100-TW energy level could provide useful data on neutron damage in laser fusion reactors. With larger pellet yields, a more versatile MTF could be designed that would permit variations in the testing environment, e.g., the use of magnetic fields to deflect pellet debris would permit investigation of the synergistic effects of neutron irradiation and pellet debris striking the irradiation target.

The MTF can be constructed and operated in parallel with systems technology development and construction of the ETR. Completion of testing programs would be constrained by the construction-start of the DEMO (~ 1995).

Analysis of the requirements for commercialization of Inertial Confinement Fusion and efforts to devise an implementation plan consistent with the nature and objectives of the program lead to the following observations:

- The program is research based and therefore requires several parallel lines of investigation to ensure a reasonable probability of success.
- The parallel lines of investigation should provide convenient opportunities to change emphasis and apply results obtained along one line towards progress along another should research findings indicate an increasing probability of success along that line.
- Significant progress will depend to a large extent on expected and unexpected scientific discoveries, and therefore the program schedule should not be constrained rigidly either in time or in achievement of particular numerical values of certain characteristic parameters.
- The program is long-range and more speculative than some other federal technical programs of comparable magnitude and duration. To maintain viability of the program, intermediate practical objectives should be identified in addition to the ultimate goals; the attainment of such objectives will provide some payoff and will help ensure continued national interest.

The above-outlined criteria emerge as essential to the successful development and completion of the program. They are neither unduly restrictive nor contradictive and therefore do not preclude the possibility of establishing and maintaining a viable plan to achieve commercial utilization of inertially confined thermonuclear fusion processes by the end of this century. Such a Program Plan, as indicated in Fig. 17, will command continued national interest and will meet the civilian and military goals in a timely manner.

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