Conf-760723--1

LA-UR-76-1459

TITLE: COMMERCIAL APPLICATION OF LASER FUSION

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SUBMITTED TO: To be presented at Advisory Group Meeting on the Technology of Inertial Confinement Experiments (sponsored by IAEA), Dubna, USSR, July 19-23, 1976 (Invited Paper).

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UNITED STATES
ENERGY RESEARCH AND
DEVELOPMENT ADMINISTRATION
CONTRACT W-7405-ENG. 36

COMMERCIAL APPLICATION OF LASER FUSION*

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ABSTRACT

The fundamentals of laser-induced fusion, some laser-fusion reactor concepts, and attendant means of utilizing the thermonuclear energy for commercial electric power generation are discussed. Theoretical fusion-pellet microexplosion energy release characteristics are described and the effects of pellet design options on pellet-microexplosion characteristics are discussed. The results of analyses to assess the engineering feasibility of reactor cavities for which protection of cavity components is provided either by suitable ablative materials or by diversion of plasmas by magnetic fields are presented. Two conceptual laser-fusion electric generating stations, based on different laser-fusion reactor concepts, are described.

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*Work done under the auspices of the U.S. Energy Research and Development Administration, Contract Number W7405ENG36.

COMMERCIAL APPLICATION OF LASER FUSION

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I. INTRODUCTION

The development of laser-fusion technology is progressing in an orderly manner with the time required to develop and construct high-power-level, short-pulse lasers pacing the program. Significant numbers of thermonuclear neutrons have been produced by fusion-pellet irradiations with laser power levels less than 1 TW. New and unprecedented lasers with power levels as large as 200 TW are scheduled for completion during the next five years. Achievement of the important milestone of scientific breakeven (thermonuclear energy release equal to laser energy input) is expected with this new generation of lasers. Although the technical feasibility of producing commercially useful thermonuclear energy releases from laser-induced fusion has not been demonstrated, theoretical predictions of fusion-pellet-microexplosion characteristics are being used in preliminary reactor design and evaluation studies.

This paper describes some laser-fusion reactor (LFR) concepts, and attendant means of utilizing the thermonuclear energy for commercial electrical power generation. The conceptual LFRs discussed in this paper include 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 concept are similar to those for a reactor concept based on magnetic confinement:

- The need to produce tritium artificially because natural supplies are insufficient to support a large-scale power-generation industry, and
- The need to convert the 14-MeV neutron energy into usable form.

Both needs are satisfied by providing a "blanket" of lithium which surrounds the reaction cavity. 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 a form useful to the direct consumer.

A characterizing LFR feature that differs significantly from magnetically confined fusion reactor concepts is the fact that fusion-pellet microexplosions represent substantial amounts of energy released on a very short time scale. The minimum energy release, determined by both physical and economic considerations, is probably about 100 MJ. Although the hydrodynamic blast created by the pellet microexplosion 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. A major design problem in containing this energy is posed by the need for a low-pressure cavity in which the pellet can be heated and compressed by a laser pulse without prohibitive laser-energy loss along the beam path, while, at the same time, maintaining a finite layer of blanket material that surrounds the cavity.

II. CHARACTERISTICS OF LASER FUSION

Pellet Design

In contrast to magnetically confined fusion where the (D+T) fuel would normally be injected into the reactor in gaseous form, laser-fusion fuel would be injected in "solid" form, i.e., as cryogenic-solid (D+T) spheres or as (D+T) gas encapsulated under pressure in more complex structures of high-Z material shells.

The understanding of the physics of laser-induced fusion is incomplete so that definitive specification of neither the laser parameters nor the target design can be made with certainty. Sophisticated calculational techniques to analyze laser-induced fusion have been developed but suffer from lack of corroborating experimental data.[1] In this regard the situation is similar to that found in the controlled thermonuclear research programs in that progress must be based primarily on experimental investigations with the theory serving principally as a guide rather than the converse where experiments are used to confirm theoretical predictions.

Theoretical energy-release forms from pellet microexplosions are described in Table I.[2-4] For the bare (D+T) pellet, prompt x rays would be observed first. Next in time would follow the 14-MeV neutrons, then the plasma of pellet debris. For structured pellets, the energy release mechanisms observed just outside the expanding pellet will depend on the pellet yield and on the composition and mass of the structural container. The fractional energy release as x rays will be larger than for the bare pellet, but with softer spectra. However, a high-energy gamma-ray component appears due to (n,γ) scattering reactions. Most of the 14-MeV neutrons escape the pellet with slight degradation in energy.

Laser Requirements

The fundamental requirements on the laser system are established by the characteristics of fusion pellets. These requirements will vary to some extent, depending on fuel-pellet design and size. The basic pellet-determined requirements for the laser system are concerned with: (1) pulse intensity, (2) pulse duration, (3) wavelength, and (4) spatial and temporal pulse shape. A second set of criteria are those which are determined by the energy balance and economics in a laser-fusion electric generation station: (1) net laser efficiency, (2) pulse repetition rate, (3) costs (capital and operating), and (4) reliability and mean lifetime of components (especially power supplies and switches).

TABLE I

THEORETICAL ENERGY RELEASE FORMS FROM FUSION-PELLET MICROEXPLOSIONS

	Bare (Frozen) DT		Structured Pellet	
	Fraction of Total Energy	Average Energy	Fraction of Total Energy	Average Energy
Energy excaping pellet				
Photons	0.01	∿ 4 keV peak	0.05	0.9 MeV
Neutrons	0.77	∿ 14 MeV	0.70	∿ 12 MeV
Energy deposited in pellet	0.22	50 keV/particle	0.25	0.2 MeV/particle

The most demanding requirement is the generation of high-energy pulses of a nanosecond or less duration which necessitates the achievement of the inverted population state nearly simultaneously throughout the lasing medium. Several types of laser systems are being studied in laser-fusion programs throughout the world.[5-7] These systems differ in the physical approach utilized to produce population inversions in the respective lasing media. In general, pulse shaping and power amplification are performed in separate laser stages. The initial stage is a low-power oscillator with modulators placed in a resonant cavity to produce a single, short (mode-locked) pulse with a controlled pulse shape. This initial pulse is amplified in passing through one or more amplifier stages.

Solid-state and liquid lasers are normally pumped with photons from flashlamps. Some gas lasers, e.g., CO_2, are pumped with electrons from an electric discharge. Other gas lasers, e.g., HF, use exothermic chemical energy for pumping. The most common laser for current laser fusion research utilizes neodymium-doped glass as the lasing medium. Xenon flash lamps optically pump neodymium ions which are embedded in glass rods or disks. Laser pulses with energies in hundreds of joules and pulse durations of 10^{-9} to 10^{-11} s are obtained. Although it may be possible, in principle, to increase the energy level of the neodymium-glass system to that needed for successful pellet fusion, the efficiency (laser energy output to electrical energy input) of this system is fundamentally limited to about 0.1 to 0.2%. This limitation, along with inherent limitations on pulse repetition rate and glass damage from self focusing makes it a poor candidate for commercial power generation. The CO_2 laser, although having less favorable wavelength characteristics, is much more energetically efficient (potentially 5-7%) and is easily adaptable to the high repetition rate and continuously renewable lasing medium required for economic energy applications. Thus, for the present, the CO_2 laser has been chosen as the basis of LFR concept studies.

Laser development is advancing rapidly, and it is impossible to predict the specific laser type, or types, that may ultimately be most advantageous for application in LFR systems. Lasing media now being evaluated experimentally include CO_2, HF, oxygen, excimers, and iodine with characteristics tabulated in Table II.[8]

III. LASER FUSION REACTOR CONCEPTS

Conceptual designs of LFRs and electric generating stations are being investigated at several laboratories in the US[9,10] and in Europe.[11] Differences in projected fusion-pellet design and microexplosion energy-release characteristics between various investigators have resulted in different basic approaches to the design of reactor cavities and other generating station subsystems. There are economic incentives for maximizing pellet-microexplosion repetition rates.

The feasibility studies of reactor cavity and blanket concepts discussed here are based on the use of fusion pellets consisting of solid spheres of (D+T) with a yield of 100 MJ. The calculated characteristics of the energy release mechanisms are those given in Table I.

Although pellet designs for ultimate commercial application may differ substantially from that chosen for these studies, the pellet output characteristics will be sufficiently similar (i.e., the major fraction will still be 14-MeV neutrons) that LFR engineering concepts based on this pellet concept should be generally applicable to other reactor concepts.

Wetted Wall Reactor Concept

The wetted-wall LFR concept is shown in Fig. 1. The reaction chamber or reactor cavity is spherical and is surrounded by a blanket region consisting of liquid lithium and structural components. The cavity wall is formed by a porous refractory metal through which coolant lithium flows to form a protective coating on the inside surface. The protective layer of lithium absorbs the energy of the high-energy alpha particles, 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

TABLE II

POTENTIAL LASERS FOR LASER FUSION

	Stored Energy (J/ℓ-atm)	Wavelength (μm)	Pulse Length (ns)	Efficiency (%)
CO_2	9	10.6	$\lesssim 1$	5-7
Chemical	6000	2.7-4.0	10-50	10
Atomic oxygen	10	0.5577	1	5
Excimer	18	0.173-0.485	10	1
Atomic iodine	18 J/ℓ	1.3	1	0.1-1

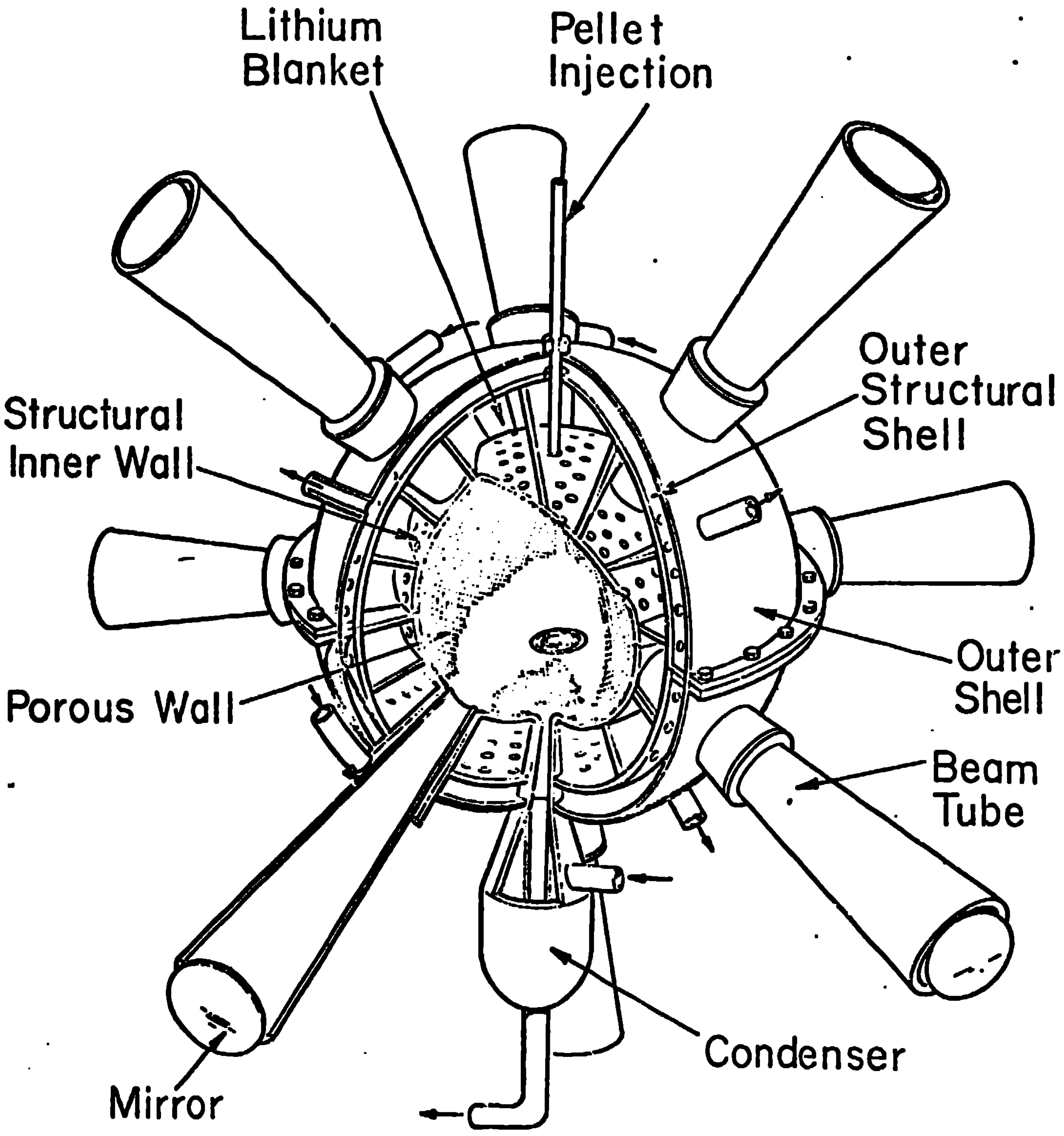

Fig. 1.
Wetted-wall laser fusion reactor concept.

microexplosion and is subsequently exhausted through a supersonic nozzle into a condenser. The ablative layer is restored between pulses by radial inflow of lithium from the blanket region.

The minimum required thickness of the protective lithium layer is determined by the amount of lithium that could be vaporized by each pellet microexplosion and by the desired protection of the cavity wall from surface heating by x rays. Analyses of lithium flow through the porous wall and along its inner surface indicate that 1 to 2 mm minimum-thickness lithium layers can be restored in less than 1 s.[3] The minimum thickness of lithium on the interior of the cavity wall and the maximum allowable wall-temperature increase due to x-ray energy deposition enable determination of the minimum permissible cavity diameter. The minimum cavity diameter for pure (D+T) 100-MJ microexplosions is ∿ 3.4 m. The maximum amount of lithium that could be vaporized is ∿ 1.25 kg per microexplosion, which corresponds to a layer on the inner cavity wall less than 0.1 mm thick.

Analyses have also been made of cavity blowdown phenomena.[3] Depending on the wavelength of the laser light utilized to implode and heat the pellets, it may be necessary to evacuate the cavity to a lithium density of ∿ 10^{17} atoms/cm^3 for efficient penetration by the laser beams. The time required to restore the cavity to this condition after a pellet microexplosion is ∿ 0.8 s. From this and other considerations, it appears that 100-MJ pellet-microexplosion repetition rates of about one per second, corresponding to a thermal power level of 100 MW per cavity, will be practical for the wetted-wall reactor concept.

Conceptual reactor designs include a tube through which pellets are injected pneumatically. Pellet guidance and tracking systems will also be required. To provide reasonably symmetric illumination of the pellet by laser light, eight laser-beam-transport tubes are arranged symmetrically around the reactor cavity.

Blanket structures have not been designed in detail, however, analyses have been made of conceptual designs in which the liquid lithium is contained between concentric structural shells enclosing the reactor cavity.[12] Designs that have minimum structural masses and that also have acceptable tritium breeding ratios include three structural shells in addition to the porous cavity wall. The porous cavity wall is supported by the innermost structural shell. The momentum from the ablation of lithium from the interior surface of the cavity wall is transmitted through the relatively incompressible lithium to other structural components. Structural shell thicknesses have been calculated to contain 100-MJ pellet microexplosions without exceeding fatigue stress limits for either niobium, molybdenum, or stainless steel at temperatures up to 1000 K. Because the energy deposition times are very short ($\leq 10^{-6}$ s) compared to shell natural frequencies ($\sim 10^{-3}$ s), the shells respond to the impulsive loads by ringing at essentially their natural frequencies, modified to the extent that they are hydrodynamically coupled to the liquid-lithium blankets. If the shell structure is to be stable, the ringing hoop stresses must be damped between successive pellet burns. Dynamic analyses indicate that adequate damping does occur and that the stresses are completely damped in less than 100 ms after pellet burn.[12]

The lithium flow path envisioned for the wetted-wall reactor introduces the lithium at the outer surface of the porous cavity wall by means of structures concentric with the beam-transport tubes. The lithium then flows radially outward through the blanket. Uniform radial flow is achieved by including sufficient impedance to flow in the successive structural shells.

Magnetically Protected Cavity Wall Concept

Protection of reactor cavity walls from energy deposition and erosion by energetic charged particles by means of magnetic fields is an attractive conceptual alternative to ablative cavity liners. The essential features of a magnetically protected reactor concept are shown schematically in Fig. 2. The central portion of the cavity is cylindrical, with an impressed steady-state magnetic field (B_z) produced by a solenoid located concentric with and exterior to a lithium blanket region. The alpha particles and the ionized particles in the pellet debris resulting from fusion-pellet microexplosions are diverted by the

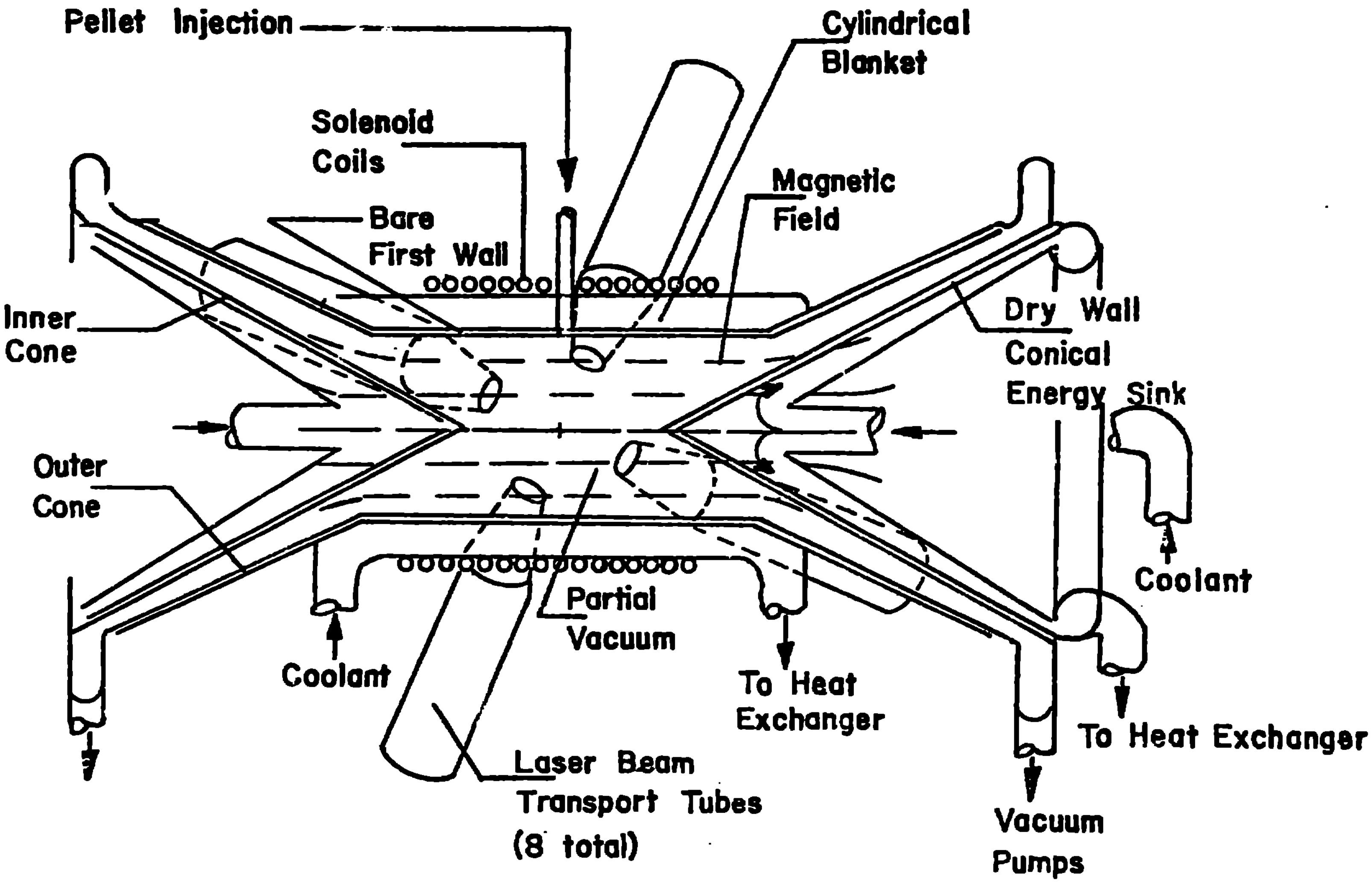

Fig. 2.
Magnetically protected laser fusion reactor concept.

magnetic fields to conical energy sinks in the ends of the cylindrical cavity.

Cavity phenomena have been investigated for operation with low ambient gas pressure ($< 10^{12}$ atoms/cm^3) and with the maximum cavity gas pressure ($\sim 10^{17}$ atoms/cm^3) through which intense laser beams can be transported efficiently.

The high-energy alpha particles expand with an average initial radial velocity of $\sim 9.8 \times 10^6$ m/s. Computer simulations for low ambient gas density show that the high-energy alpha particles act as single particles, going into gyro-orbits (radius ~ 1 m for $B_Z = 0.2$ T) and spiraling out the ends to the conical energy sinks.[14] During the time of flight ($\sim 5 \times 10^{-7}$ s) of the bulk of the alpha-particle plasma to the conical energy sinks, the slower debris plasma is initially streaming at an average velocity of $\sim 1.5 \times 10^6$ m/s. The debris plasma acts collectively; it excludes and then compresses the magnetic field between the plasma and cavity wall with pressure balance occuring at $\sim$ 2-m radius for $B_Z = 0.2$ T. After several cycles of successive radial expansions and compressions of the debris plasma, it too will have expanded out the ends of the cylinder to the energy-sink regions.

The cavity diameter (5 m) indicated in Fig. 2 was selected somewhat arbitrarily. Minimal cavity diameters will be constrained by allowable wall-surface temperature increases due to x-ray energy deposition. Cavity liners of materials with low atomic number (e.g., carbon) are useful for decreasing metal-wall surface-temperature fluctuations. The geometry shown in Fig. 2 permits energy sinks to be designed with large surface areas. The surface area of each cone available for energy deposition by charged particles is more than ten times the cross sectional area of the cylindrical portion of the cavity. A high-temperature material such as a refractory metal carbide is envisioned for the energy-sink surface. Fringing of the magnetic field should permit tailoring the energy deposition density over the surfaces of the energy sinks.

Liquid lithium might be used as a coolant and fertile material for the breeding of tritium in the annular blanket regions. Axial flow of lithium in the blanket annulus minimizes problems relating to pumping a conducting fluid across magnetic field lines. The solid angle subtended by the energy sinks is only ~ 10% of the 4π steradians through which the neutrons from pellet microexplosions expand. Preliminary estimates indicate that adequate tritium breeding ratios to sustain the fuel cycle can be obtained from nuclear reactions with lithium in the annular blanket regions alone. Thus, the conical energy sinks could be cooled by a fluid other than lithium, e.g., helium.

There are several potential advantages of magnetic protection of cavity walls compared to other reactor concepts that have been considered. It is anticipated that thermonuclear-reactor component lifetimes will be severely limited by the rate at which damage occurs from products of fusion. Because power costs are dominated by capital investment, component replacement schedules, and duty factors, it is important to design simple, long-lived reactor cavities of minimum size with expendable components incorporated in a manner permitting rapid and convenient replacement. The conical energy sinks are readily accessible for replacement without disturbing the lithium blanket, the laser-beam optics, the solenoid, or the fuel injection system.

Other major advantages of this concept are the possibility of achieving high pellet-fusion repetition rates and the elimination of involved procedures for removal of evaporated and/or ablated materials from the reactor cavity between successive pellet microexplosions. Also, the use of magnetic fields in this manner will eliminate streaming of charged particles through the laser-beam-transport tubes which might otherwise damage last optical surfaces. Computer simulations show that the effects of the magnetic field introduce a time spread over which the plasma reaches the energy sinks compared to free-streaming particles. This time spread may be helpful in reducing energy sink surface deterioration by allowing time for conductive heat transfer.

Additional Reactor Concepts

A laser-fusion reactor concept, referred to as a suppressed-ablation design,[9] has been proposed that is similar to the wetted-wall design described above.

The diameter of the reactor cavity for the suppressed ablation concept is somewhat larger (∿ 4.4 m) than the diameter of the cavity in the wetted-wall design, and the cavity wall surface area is further increased by constructing it from pyramidal surfaces whose triangular bases form the first wall plane. The interior surface of the first wall is protected by an ∿ 300 μm thick layer of lithium that is pumped by capillary action from reservoirs. Each fusion-pellet microexplosion releases 7 MJ of thermonuclear energy. Because of increased cavity wall surface area, enhanced thermal conduction from the protective lithium layer to the bulk coolant, and lower pellet yield, lithium evaporation is diminished considerably. Thus, the time required after a pellet microexplosion to return the cavity to conditions permitting a subsequent pellet microexplosion is much shorter than for the wetted-wall design, and a pulse repetition rate of 10 microexplosions/s is thought possible.

The reactor blanket is icosahedral with 12 laser beams that penetrate the blanket at the vertices of the icosahedron. The blanket is of modular construction and consists of 20 equilateral truncated triangular prisms. The blanket modules are constructed of niobium and can be extracted singly for replacement in the event of damage. The blanket coolant is liquid ltihium.

The SATURN reactor concept[11] represents an extension of some aspects of the suppressed-ablation design. The cavity and blanket are formed from polygonal shaped power and vacuum modules. Each power module, of which there are ∿ 1100, contains a blanket portion and a complete power conversion system (turbine and generator). The blanket portion is cooled by neon for energy conversion in a Brayton cycle. There are ∿ 70 vacuum modules with pumping ports in the blanket portions and pumps instead of power conversion systems. The cavity diameter is ∿ 20 m, and the inner surface of the cavity wall is not protected from x rays and charged particles. A pellet yield of 50 MJ and a pulse repetition frequency in the range of 10 to 100 Hz are proposed.

A unique reactor cavity concept, called a lithium vortex reactor or BLASCON,[15] has no cavity wall <u>per se</u>; rather a cavity is formed by a vortex in a rotating pool of lithium in which fusion-pellet microexplosions take place. Rotational velocity is imparted to the circulating lithium by tangential injection at the periphery of the reactor pressure vessel. The lithium flows out of the spherical pressure vessel through a central port at the bottom. Bubbles of inert gas are injected into the lithium jets entering the vessel to provide an average void fraction of 2 or 3%. These bubbles serve to cushion the shock wave from the pellet microexplosion and thus reduce the stresses in the pressure vessel.

Fusion pellets are injected into the lithium vortex through the top of the reactor vessel, and a single laser beam illuminates the pellet, also from the top. This concept has been proposed for fusion-pellet yields of ∿ 1000 MJ and pulse rates of 2 microexplosions per second.

IV. ELECTRIC GENERATING STATION CONCEPTS

A simplified energy and mass flow diagram is shown in Fig. 3. Important considerations which lead 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.

A conceptual electric generating station design based on the wetted-wall LFR concept is shown in Fig. 4.[10] The reactors are located in a separate, annular building which encloses the laser system building. The number of reactors required for a given net power output depends on the efficiency of the energy conversion cycle and thus on the temperature of the reactor coolant. Pairs of adjacent LFRs 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.

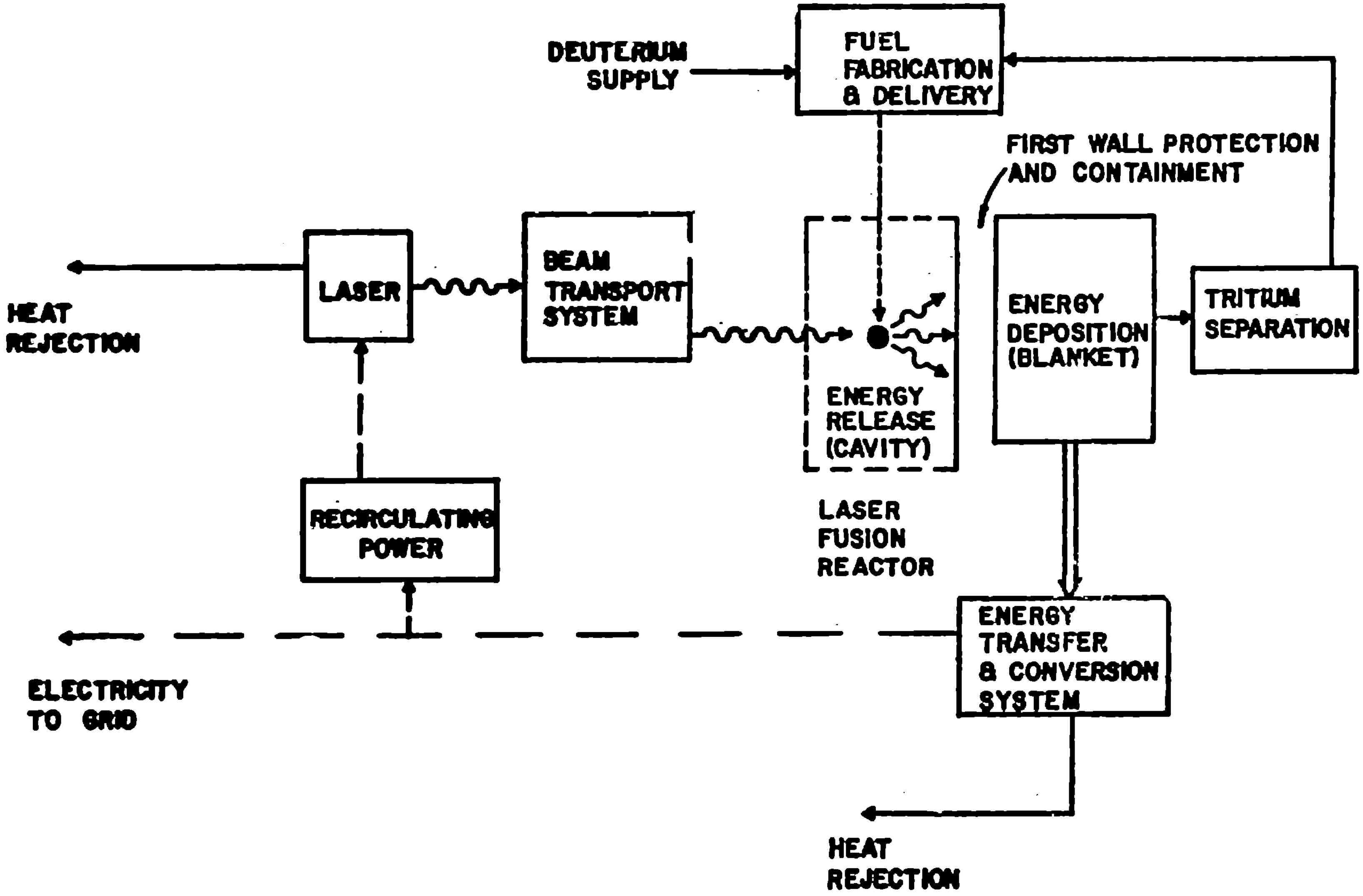

Fig. 3.
Simplified energy and mass flow diagram for laser-fusion electric generating station.

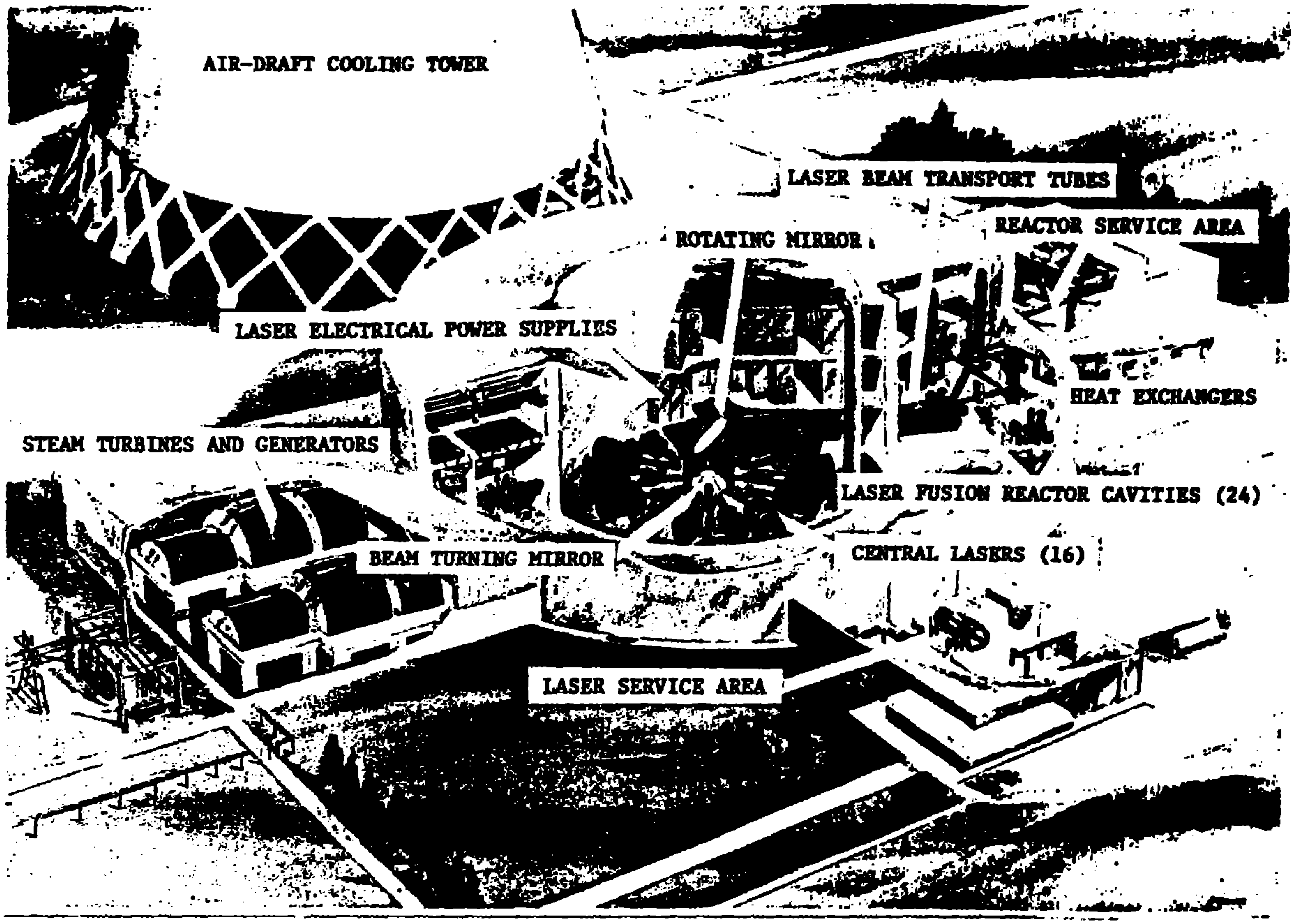

Fig. 4.
Electric generating station based on wetted-wall laser fusion reactors.

The laser system includes 16 separate main CO_2 laser power amplifiers. Eight of these 16 lasers are fired simultaneously, and the eight laser beams are directed successively to respective reactor cavities by a rotating mirror. Each laser has a redundant partner to achieve high reliability and ease of maintenance.

The laser power supplies are located in the laser building above the main laser power amplifiers.

Mechanical and structural isolation is provided for the laser system and the reactors and associated beam-transport and heat-transfer systems. Control rooms and other work areas are isolated from the reactor radioactive areas. Reactors and reactor components can be removed remotely through removable shield plugs and transferred to shielded work areas by a crane. Each reactor can be isolated from the system for service and/or replacement without affecting the operation of the remainder.

Since the laser subsystem represents a significant fraction of a LFR generating station, it is economically advantageous to centralize components so that each laser system serves several reactors. Centralized laser systems require fast beam switching from laser power amplifiers to selected beam ports. Laser-beam switching in preliminary generating station concepts is accomplished by rotating mirrors. The rotating mirror assembly consists of eight elliptical plane mirrors spaced uniformly about a rotating ellipse at 45 degrees to the beam direction toward the reactors. A stationary 45 degree mirror below the rotating mirror also consists of eight elliptical mirrors spaced around a circle.

To achieve simultaneity of beam arrival at the fusion pellet within a small fraction of a nanosecond or less, the net path-length differences between various laser beams must be compensated. The most economical arrangement appears to be to adjust the path lengths between a master oscillator and the main laser power amplifiers. Arrangements for splitting the oscillator pulse into eight parts traveling different distances are easily devised.

An electric generating station concept based on the magnetically protected LFR is shown in Fig. 5. Four reactors with a thermal power output of ∿ 1250 MW each are included in the station (compared with the wetted-wall reactor generating station concept which includes 20 reactors with a thermal power output of ∿ 150 MW each). 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.

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 magnetically-protected LFR energy-sink cones and other radioactive components are also on this level. Tracks are provided for movement of energy-sink cones between reactors and maintenance areas. Single-loop lithium heat-transfer systems are used between the reactors and the steam generators, and semipermeable membrane lithium-tritium separators are included in the lithium loops. Separate heat-exchanger and lithium-tritium separator systems are provided for each reactor.

The pulse-forming networks are located on the second level and the main laser power amplifiers on the third level. There are 16 CO_2 laser power amplifiers, 8 of which would be operated at one time to provide 8 laser beams for quasi-symmetric illumination of fusion pellets. Selector mirrors are used to direct the laser beams from operating laser power amplifiers to the rotating mirror, also located on the third level. The required rotational velocity of the mirror is 10 revolutions per second. For the design laser-beam length, the laser beam focal spot travels only ∿ 1×10^{-4} mm during a 1.0-ns pulse; thus, the focused beam will not move significantly off a millimeter-size target during the arrival time of a laser pulse. A laser-power-amplifier and pulse-forming-network maintenance area is located on the third level which is serviced from ground level by a freight elevator.

The front-end system, i.e., the oscillator and preamplifiers, is located on the top level. Differences in beam path length from the

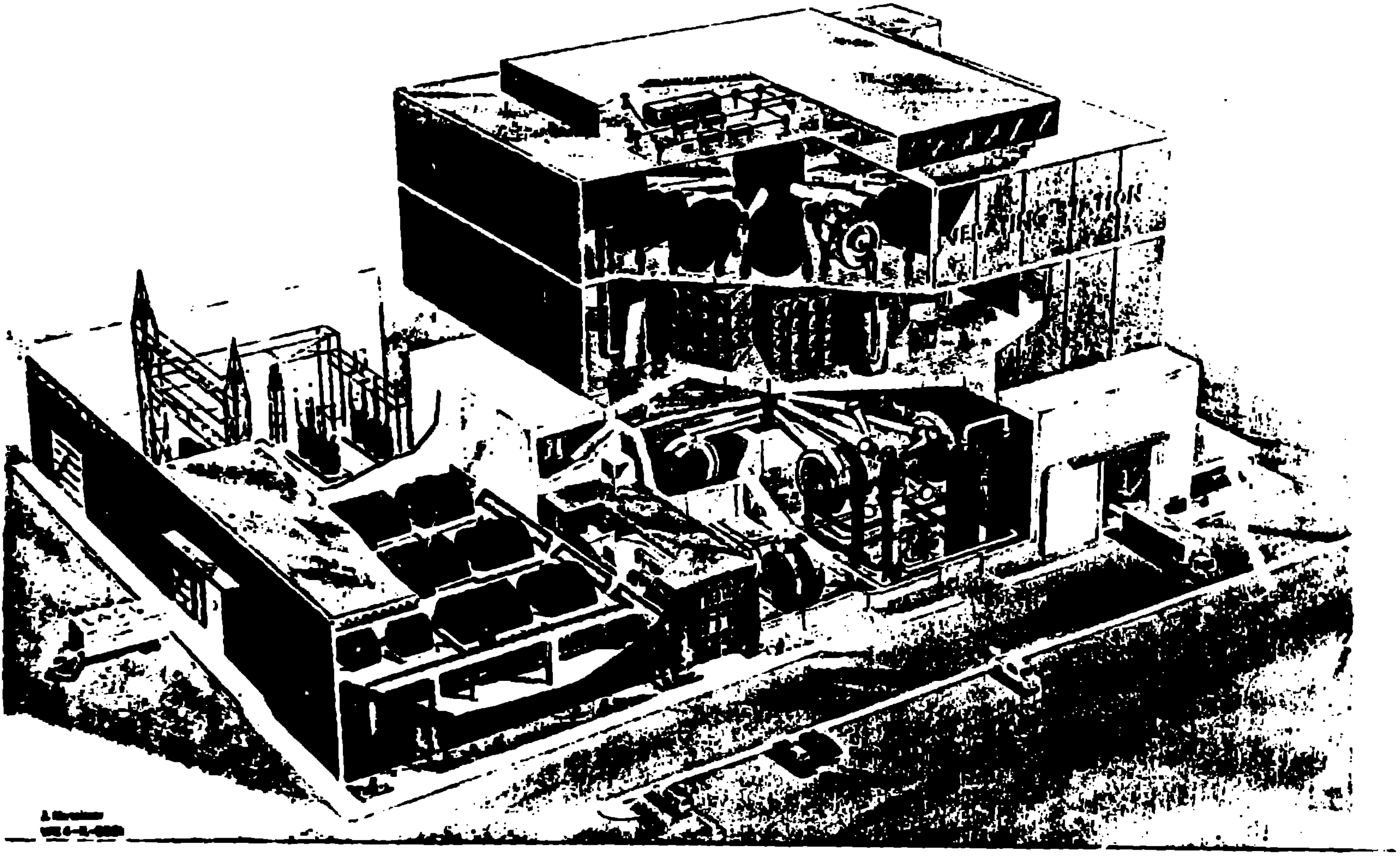

Fig. 5.
Electric generating station based on magnetically protected laser-fusion reactors.

laser power amplifiers to the reactor cavity centers are compensated by corresponding differences in path lengths in the front end system (oscillator and preamplifiers) so that amplified laser pulses arrive at the cavity centers simultaneously.

Each reactor can be isolated from the system for service without affecting the operation of the remainder.

V. SUMMARY AND CONCLUSIONS

The most critical unsatisfied technology requirements for laser fusion are those related to achieving significant fusion-pellet burn. These requirements include advances in laser technology and in fusion-pellet design and fabrication techniques. To date, laser-fusion experiments have yielded up to 10^7 neutrons with laser systems operating at a few tens of joules. These results, of course, have not indicated feasibility for commercial applications, but understanding of the fundamental physics of the laser-pellet interaction is being developed. Within the next few years, 10 kJ laser systems will be operational and a clearer understanding of fundamentals will be gained. The major milestone of scientific breakeven, i.e., thermonuclear output equal to exceeding incident beam energy, is expected to require laser systems at powers exceeding 100 TW. Such a laser facility is planned for operation in the early 1980's. With the achievement of this milestone, the laser-fusion program would proceed from the research to the technology development phase, aimed at demonstrating the economic attractiveness of commercial exploitation in the late 1990's or early twenty-first century.

The most critical parameter affecting the economics of a laser-fusion generating station is the product of laser efficiency and pellet gain. Obviously, this product must be greater than one for a net output of electricity and must be greater than two for commercial feasibility. Because laser efficiencies are likely to be less than 0.1, laser pellet gains must be greater than 20. Because it is felt that pellet gains greater than 100 are probably not achievable, the minimum laser efficiency of any proposed laser system must be greater than 0.02.

Based on our current knowledge of the laser/pellet interaction, certain features of laser-fusion generating stations appear certain:

- Conceptual LFRs are relatively small, compact systems and lend themselves naturally to the design of generating stations for a range of power levels from ∿ 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 both prevents excessive damage to reactor components and permits recovery of the energy in a form suitable for utilization in an energy conversion cycle. Very-high-energy, short-pulse lasers are necessary 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 reactor cavities.
- The fuel cycle that is receiving primary consideration is the deuterium-tritium cycle. Deuterium is easily and cheaply obtained from conventional sources; but it is expected that tritium will be produced, as needed, by reactions between fusion neutrons and lithium, which must be contained in blanket regions surrounding 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.

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 known as the wetted-wall and the magnetically protected LFRs. These two fundamental approaches, together with variations, to the containment of fusion-pellet microexplosions and tho recovery of thermonuclear energy for commercial use appear to bo feasible and, moreover, to provide a basis for the conceptual design and evaluation of laser-fusion electric generating stations.

While the direct production of electricity from LFRs in central generating stations is a principal objective of the Laser Fusion Program, there are other potential commercial applications that may prove to be no less important. Among such applications are the production of synthetic fuels, such as hydrogen, and providing high-temperature process heat that might be utilized in a variety of ways. Fusion neutrons can be used to breed ^{239}Pu from ^{238}U and ^{233}U from ^{232}Th. Systems designed for this purpose may be attractive compared to liquid-metal fast-breeder reactors. It is anticipated that many more significant applications of this nature will be discovered as laser fusion is developed and conventional fuels become more scarce.

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