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A TECHNOLOGY ASSESSMENT OF LASER-FUSION POWER PRODUCTION

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ABSTRACT

The inherent features 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. Technology developments for ultimate commercial application are outlined.

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A TECHNOLOGY ASSESSMENT OF LASER-FUSION POWER PRODUCTION

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I. INTRODUCTION

This paper describes the fundamentals of laser fusion, some laser-fusion reactor (LFR) concepts and attendant means of utilizing the thermonuclear energy for commercial electrical power generation, and necessary technological developments for utilization of laser-fusion energy. 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. 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.

For (D+T)-burning plants, two essential requirements for a LFR concept are similar to those for a reactor concept 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 into usable form. Both needs are satisfied by providing a "blanket" of lithium which surrounds the reaction cavity in the same manner as provided in magnetic fusion reactor designs.

A characterizing LFR feature that differs significantly from magnetic 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. INHERENT FEATURES OF LASER FUSION

Laser-Fusion Pellets

The (D+T) fuel for LFRs will be injected into the reactor 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 as well as the technical computational difficulties of treating multidimensional problems.[1-3] 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.[4-6] 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. As the results in Table I suggest, there is considerable flexibility in the design of structural pellets, and it is anticipated that pellet outputs can be tailored to accomodate specific cavity wall protection schemes.

Laser Requirements

The fundamental requirements on the laser system are established by the performance criteria of fusion pellets. These requirements 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 laser criteria are determined by the energy balance and economics of 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).

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.[7-9] 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 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. Although it may be possible, in principel, 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 listed 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.

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.[10] The CO_2 laser, although apparently having less favorable wavelength characteristics, is reasonably efficient and is easily adaptable to the high repetition rate and continuously renewable lasing medium required for economic energy applications. More importantly, the CO_2 laser is the only system that has been developed to the stage that can be scaled to the high power levels for commercial applications. Thus, for the present, the CO_2 laser has been chosen as the basis of LFR concept studies.

Laser-pumping power supplies - The laser criteria enumerated above that are determined by the energy balance and economics of laser-fusion electric generating stations imply that the laser will include some type of gas laser power amplifier with a continuously renewable lasing medium. Such lasers require some type of electric discharge for pumping.

Pumping times of a few μs are required. Pulse forming networks with long-lived switches and capacitors appear to offer the most attractive solution to the problem although some technology development will be required to provide desirable component lifetimes ($\sim 10^9$ pulses).

Power requirements for laser pumping constitute the major part of recirculating power requirements in laser-fusion generating stations. This power will probably be taken directly from the main generator outputs. Because the pumping power requirement is intermittant, it will probably be necessary to include some type of intermediate energy storage device with impedance matching for efficient charging of the capacitors and to provide a constant load on the main generators.

Beam transport systems - For symmetrical illumination of the fusion pellet, an eight-beam system provides the optimum geometric configuration. 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.

The last optical element in each beam port will be exposed to x rays, neutrons, and possibly pellet debris and lithium vapor. Consequently, the last optical element may require frequent replacement and should be simple, rugged, and inexpensive. If other elements are not excessively expensive, these requirements are best met by a plane, polished mirror with no coating. For focusing, an element well out of line of sight of the cavity interior and protected by pumping could be used. This element could be a converging lens or a toroidal, catoptric beam-focusing device.[11]

The alkali halides are being developed for window materials for 10.6-μm laser light and metallic reflectors (Cu, Au, Ni, etc.) are being developed for mirrors.

Limits on maximum beam intensity to remain below damage thresholds for windows and mirrors from laser light result in LFR requirements for large diameter optical components. Research on bulk and surface damage mechanisms is being actively pursued as is the search for materials with improved performance. Required elements for fast switching and component isolation include both active elements (electro-optic, acousto-optic, expendable membranes, etc.) and passive elements (saturable absorbers and diffraction gratings).

Reactor Concepts

Conceptual designs of LFRs are being investigated at several laboratories in the US[11,1 and in Europe.[13] 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. 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 with a yield of 100 MJ and the calculated characteristics of the energy release 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 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 subsequently exhausted through a personic nozzle into a condensor. The ablative layer is restored between pulses by dial inflow of lithium from the blanket region.

The minimum required thickness of the protective lithium layer is determined by the ount of lithium that could be vaporized by each pellet microexplosion and by the desired rotection of the cavity wall from surface heating by x rays. Analyses of lithium flow hrough the porous wall and along its inner surface indicate that 1 to 2 mm minimum-hickness lithium layers can be restored in less than 1 s.[5] The minimum thickness of ithium on the interior of the cavity wall and the maximum allowable wall-temperature in-reases due to x-ray energy deposition enable determination of the minimum permissible avity diameter. The minimum cavity diameter for pure (D+T) 100-MJ microexplosions is $\sim$3.4 m. The maximum amount of lithium that could be vaporized is $\sim$1.25 kg per micro-xplosion, 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.[5] Depending on the wave-ength of the laser light utilized to implode and heat the pellets, it may be necessary o evacuate the cavity to a lithium density of $\sim 10^{17}$ ~~μ~~ atoms/cm^3 for efficient penetration y the laser beams. The time required to restore the cavity to this condition after a ellet microexplosion is $\sim$0.8 s. From this and other considerations, it appears that 00-MJ pellet-microexplosion repetition rates of about one per second will be practical or the wetted-wall reactor concept.

Blanket structures have not been designed in detail, however, analyses have been made f conceptual designs in which the liquid lithium is contained between concentric struc-ural shells enclosing the reactor cavity.[14] Designs that have minimum structural masses nd that also have acceptable tritium breeding ratios include three structural shells in ddition to the porous cavity wall. The porous cavity wall is supported by the innermost tructural shell. The momentum from the ablation of lithium from the interior surface of he cavity wall is transmitted through the relatively incompressible lithium to other tructural components. Structural shell thicknesses have been calculated to contain 100-MJ pellet microexplosions without exceeding fatigue stress limits for either niobium, olybdenum, or stainless steel at temperatures up to 1000 K. Because the energy deposition imes are very short ($\sim 10^{-6}$ s) compared to shell natural frequencies ($\sim 10^{-3}$ s), the shells espond to the impulsive loads by ringing at essentially their natural frequencies, modi-fied to the extent that they are hydrodynamically coupled to the liquid-lithium blankets. If he shell structure is to be stable, the ringing hoop stresses must be damped between uccessive pellet burns. Dynamic analyses indicate that adequate damping does occur and hat the stresses are completely damped in less than 100 ms after pellet burn.[14]

Magnetically Protected Cavity Wall Concept - The essential features of a magnetically protected reactor concept are shown schematically in Fig. 2.[15] 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 ionized particles in the pellet debris resulting from fusion-pellet microexplosions are diverted by the magnetic fields to conical energy sinks in the ends of the cylindrical cavity.

During the time of flight, the debris plasma is initially streaming at an average velocity of $\sim 1.5\times10^6$ m/s. The debris plasma acts collectivley; 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 will have expanded out the ends of the cylinder to the energy-sink regions.[16]

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The cavity diameter (5 m) indicated in Fig. 2 was selected somewhat arbitrarily. Minima 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 minimiz problems relating to pumping a conducting fluid across magnetic field lines. The solid angle subtended by the energy sinks is only $\sim$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 (up to 10 Hz) and the elimination of involved procedures for removal of evaporated and/or ablated materials from the reactor cavity between successive pellet microexplosions.

Additional Reactor Concepts - A laser-fusion reactor concept, referred to as a suprresse ablation design,[12] has been proposed that is similar to the wetted-wall design described above. The diameter of this reactor cavity is somewhat larger ($\sim$4.4 m) than the diameter of the cavity in the wetted-wall design, and the cavity wall surface area is further increase 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 $\sim 300\ \mu m$ 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 per second is thought possible.

The SATURN reactor concept[13] 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,[17] has no cavity wall per se; 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 Hz.

III. FUEL CYCLE AND TRITIUM PROCESSING

This discussion will focus on the use of liquid lithium as a recirculting coolant as well as the fertile material for breeding tritium. Efficient extraction of tritium to low concentrations in the liquid lithium is important because (1) tritium is a valuable component of the fusion fuel cycle and is costly to produce, and (2) tritium is a radioactive isotope that constitutes a biological hazard when released to the environment by leakage or accident.

The fuel recycle system, shown schematically in Fig. 3, is divided into subsystems; tritium separation from the lithium blanket and cavity debris; purification, liquefaction and isotope adjustment; and fusion-pellet fabrication. Unburned tritium will be recovered from the fuel debris separately from the recovery of the tritium bred in the blanket material and will involve a different separation process than that applied to the blanket tritium.

The most promising methods for separation of tritium from the lithium blanket appear to be diffusion through metal membranes and liquid-liquid extraction.[18] Multiple layers of permeable materials may be combined with chemical methods of removal (e.g., reaction in oxygen) to reduce the otherwise very high vacuum requirements of the first method.

Detailed technical and economic comparisons between the use of diffusion through semipermeable membranes and liquid-liquid extraction for separation of tritium from lithium have not been made. Both methods appear to be feasible, but because it is more amenable to analysis, separation by diffusion has been assumed for most generating-station systems studies.

The recovery of the tritium (and deuterium) from the unburned fuel in the reactor cavity appears to present less severe problems for the concepts that avoid the use of liquid lithium in the reactor cavity. For those concepts with lithium in the reactor cavity, the technological problem of tritium recovery is similar to that for the blanket, although separate cleanup loops will probably be dictated by the presence of other impurities. Watson[19] has suggested the use of parallel cryosorption pumps which allow recovery of the cavity gases without adding impurities. Commercial pumps which meet the requirements are available at reasonable costs (assuming no scaling problems to the sizes required).

The sequence of operations following the separation of T_2 and DT from the lithium primary coolant and cavity debris is the chemical purification of the tritium followed by liquefaction and cryogenic purification to produce liquid T_2 and DT. This mixture can then be adjusted stoichiometrically by cryogenic distillation or with the addition of deuterium as required. The stoichiometric mixture of deuterium and tritium is then transported to the fuel-pellet fabrication system.

The fusion pellets may be fabricated locally (cavity-coupled); or remotely, and by batch or continuous processes. The selection of a processing method will be largely determined by the selection of pellet materials and design. While the number of pellets that will be required for operation of a large LFR central generating station ($\sim$2.5 million per day in a 1000-MWe plant using 100-MJ yield pellets) suggest a continuous operation, large scale batch manufacture of pellets may be preferred for some fuel pellet designs. Remote and/or batch fabrication of pellets would require larger storage capacity than local continuous production.

Requirements for fuel purity and design tolerances are expected to be strict and to dominate the choice of fabrication method and its design. Cavity-coupled methods, for example, would be expected to pose unique problems in sampling and rejection of pellets that fail to meet design specifications.

IV. ELECTRIC GENERATING STATION CONCEPTS

Important considerations for laser-fusion plant design include component reliability, redundancy of essential components, access to components for service

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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 encept is shown in Fig. 4.[11] 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 t efficiency of the energy conversion cycle and thus on the temperature of the react olant. Pairs of adjacent LFRs are served by a common heat-transfer loop, a steam ator, and lithium-processing and tritium-removal systems. Each reactor is in a b. gically 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 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.

An electric generating station concept based on the magnetically protected LFR is shown in Fig. 5. Four reactors with a thermal power output of $\sim$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 $\sim$~~150~~ 120 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 whi would be operated at one time to provide 8 laser beams for symmetric illumination of fusion pellets. Selector mirrors are used to direct the laser beams from operating las power amplifiers to the rotating mirror, also located on the third level. 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.

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 scientific feasibility, 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 econom attractiveness of commercial exploitation in the late 1990's or early twenty-first century.

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

- Conceptual LFRs are rleatively small, compact systems and lend themselves naturally to the design of generating stations for a range of power levels from approximately 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 reacto 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 the recovery of thermonuclear energy for commercial use appear to be feasible, and, moreover, to provide a basis for the conceptual design and evaluation of laser-fusion electric generating stations.

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.

The most important engineering technology developments (other than LFR designs) are:

- Very-high-energy (multi-kilojoule), short-pulse (1 ns) lasers are necessary for t efficient burn of fusion pellets. In commercial configurations, these lasers must operate reliably at high repetition rates (10 pps), thus requiring development of waste heat removal methods. Laser power supplies must reliably supply DC pulses at hundreds of kilovolts in microsecond durations at the same repetition rates. Economic factors dictate lifetimes of the order of 10^9 pulses.
- Sophisticated fuel pellet delivery and laser control systems must be developed so that the pellet and laser beams arrive at the cavity precisely in space and time. The last optical element that "looks" into the cavity must withstand the radiation emitting from the pellet.

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 ar 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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TABLE I

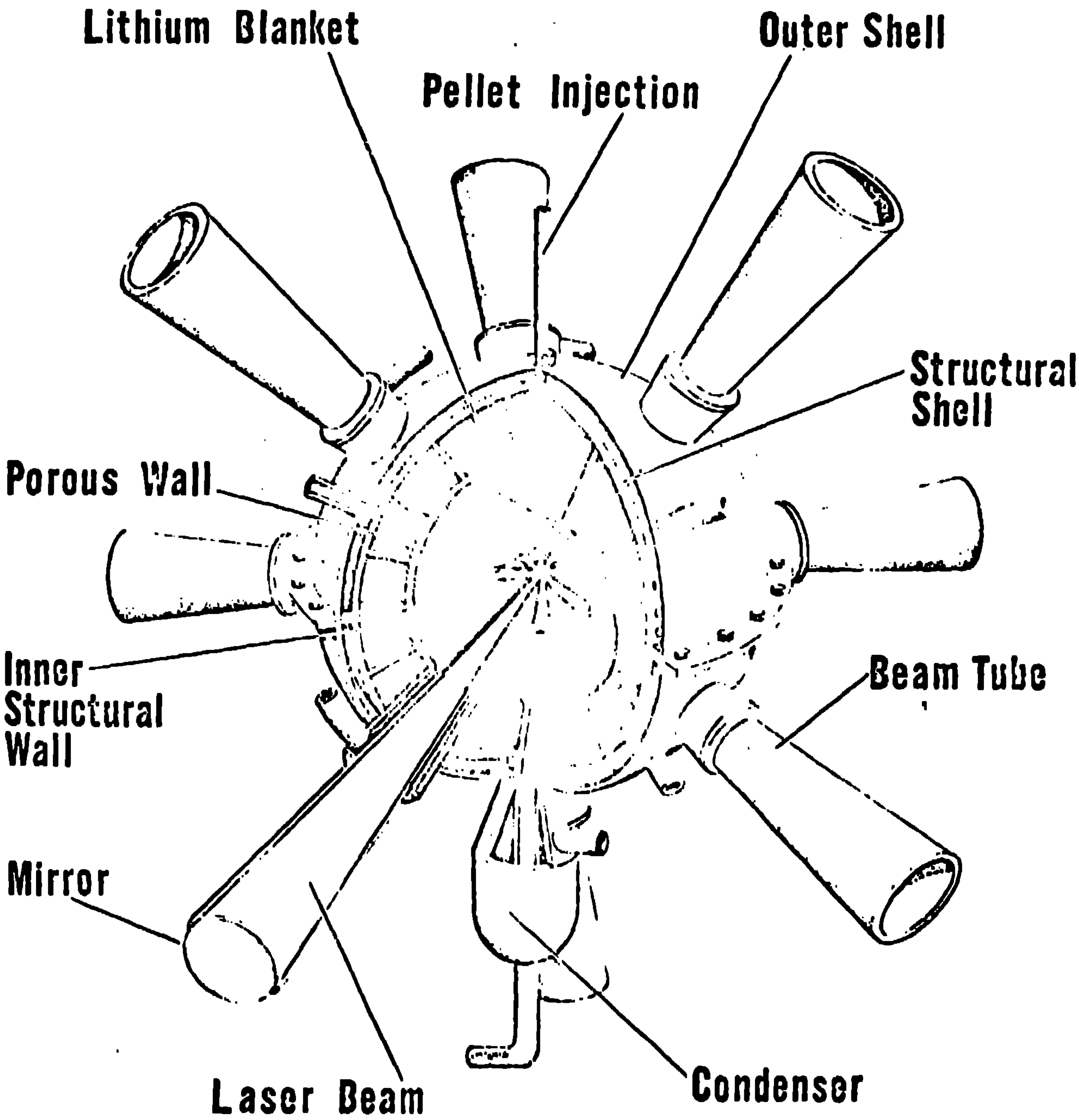
THEORETICAL ENERGY RELEASE FORMS FROM FUSION-PELLET MICROEXPLOSIONS

	BARE (FROZEN) DT		STRUCTURED PELLET	
	FRACTION OF TOTAL ENERGY	AVERAGE ENERGY	FRACTION OF TOTAL ENERGY	AVERAGE ENERGY
ENERGY ESCAPING PELLET				
PHOTONS	0.01	∼4 KEV ~~PEAK~~	.20 to .05 0.05	.05-10 keV (+ 1 MeV γ) ~~0.9 MEV~~
~~α PARTICLES~~	~~0.07~~	~~∼2 MEV~~	~~----~~	~~----~~
NEUTRONS	0.77	∼14 MEV	0.70 to 0.65	∼12 MEV
ENERGY DEPOSITED IN PELLET	22 0.15	50 KEV/PARTICLE	.05 to .30 ~~0.25~~	0.05 to 0.2 MEV/PARTICL

TABLE II

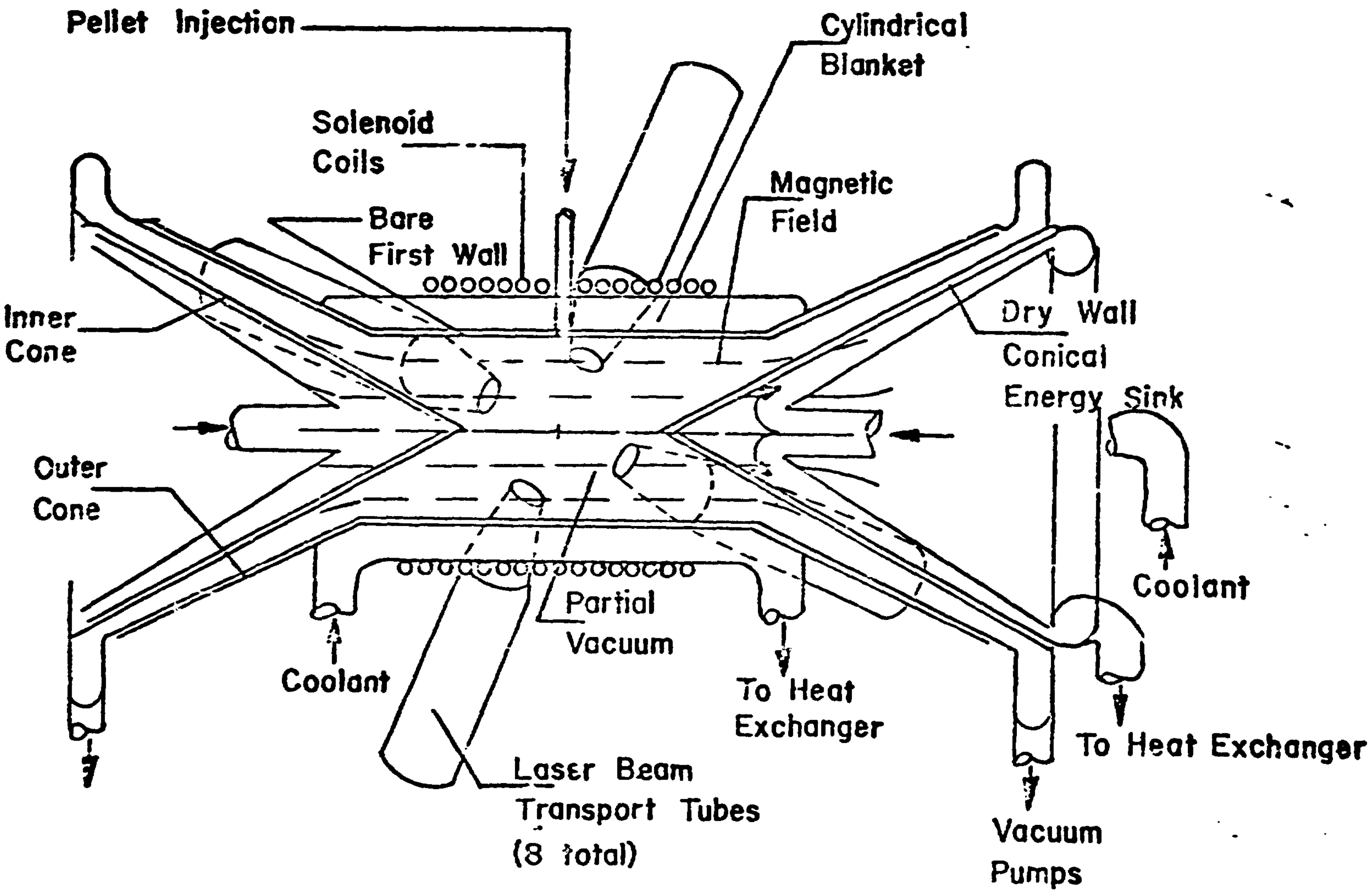
POTENTIAL LASERS FOR LASER FUSION

	STORED ENERGY (J/ℓ-ATM)	WAVELENGTH (μM)	PULSE LENGTH (NS)	EFFICIENCY (%)
CO_2	9	10.6	≤1	5-7
CHEMICAL	200 ~~6000~~	2.7-4.0	10-50	10
ATOMIC OXYGEN	10	0.5577	1	5
EXCIMER	18	0.173-.485	10	1
ATOMIC IODINE	6 18 J/ℓ	1.32	1	0.1-1


Lithium Blanket
Pellet Injection
Outer Shell
Structural Shell
Porous Wall
Inner Structural Wall
Beam Tube
Mirror
Laser Beam
Condenser

F1

F 2


Pellet Injection
Cylindrical Blanket
Solenoid Coils
Magnetic Field
Bare First Wall
Inner Cone
Dry Wall
Conical Energy Sink
Outer Cone
Coolant
Coolant
Partial Vacuum
To Heat Exchanger
To Heat Exchanger
Laser Beam Transport Tubes (8 total)
Vacuum Pumps

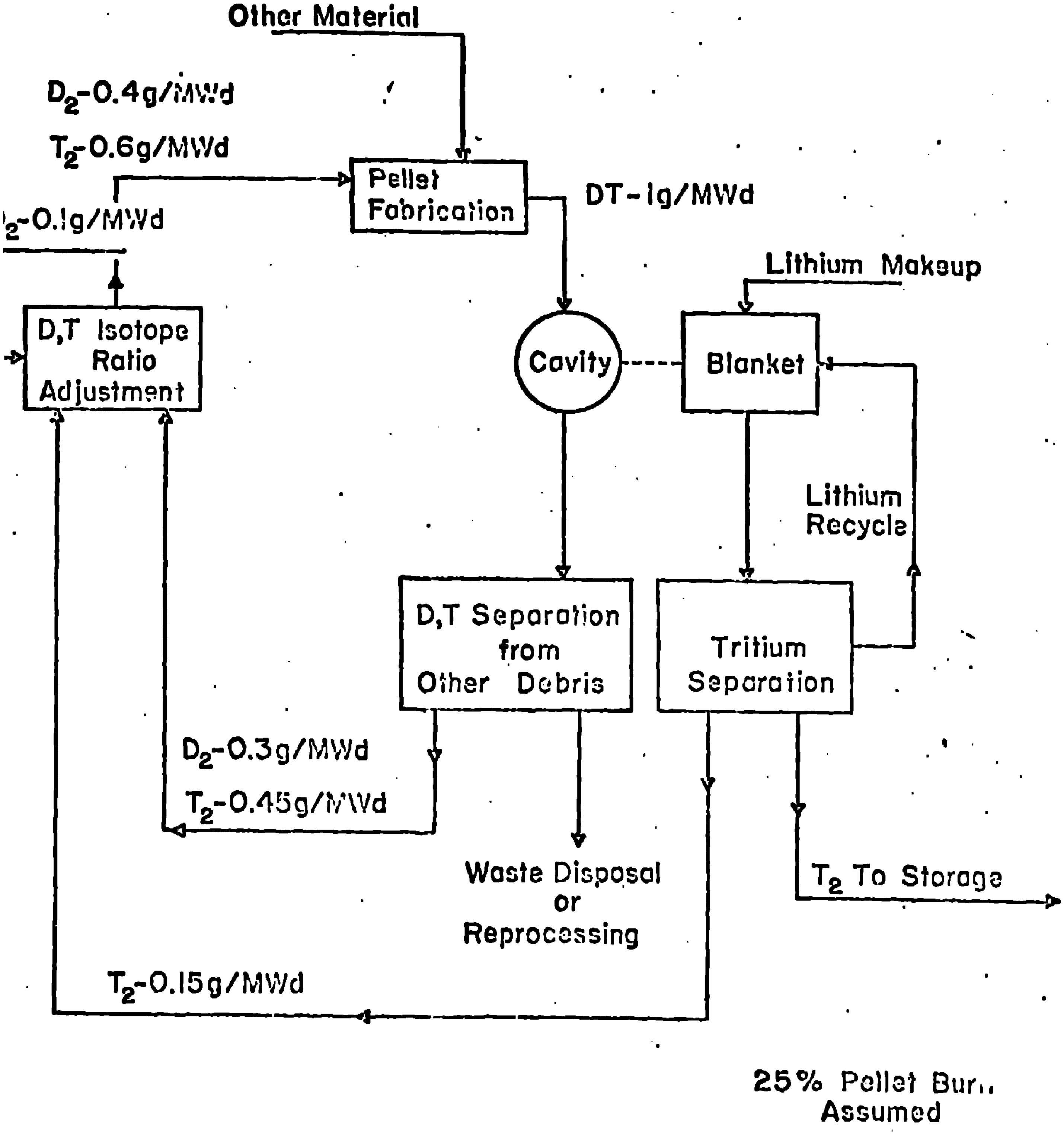
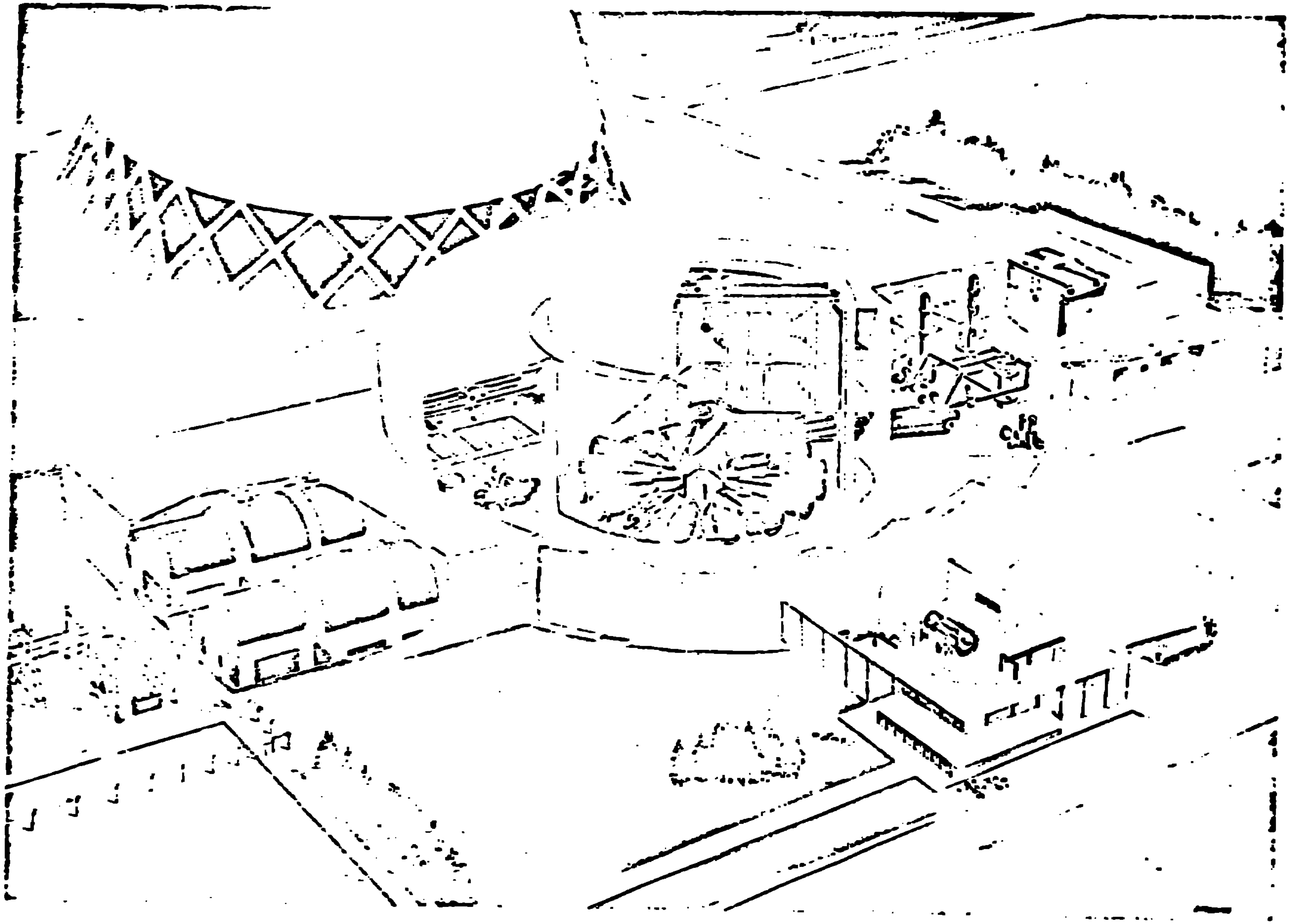


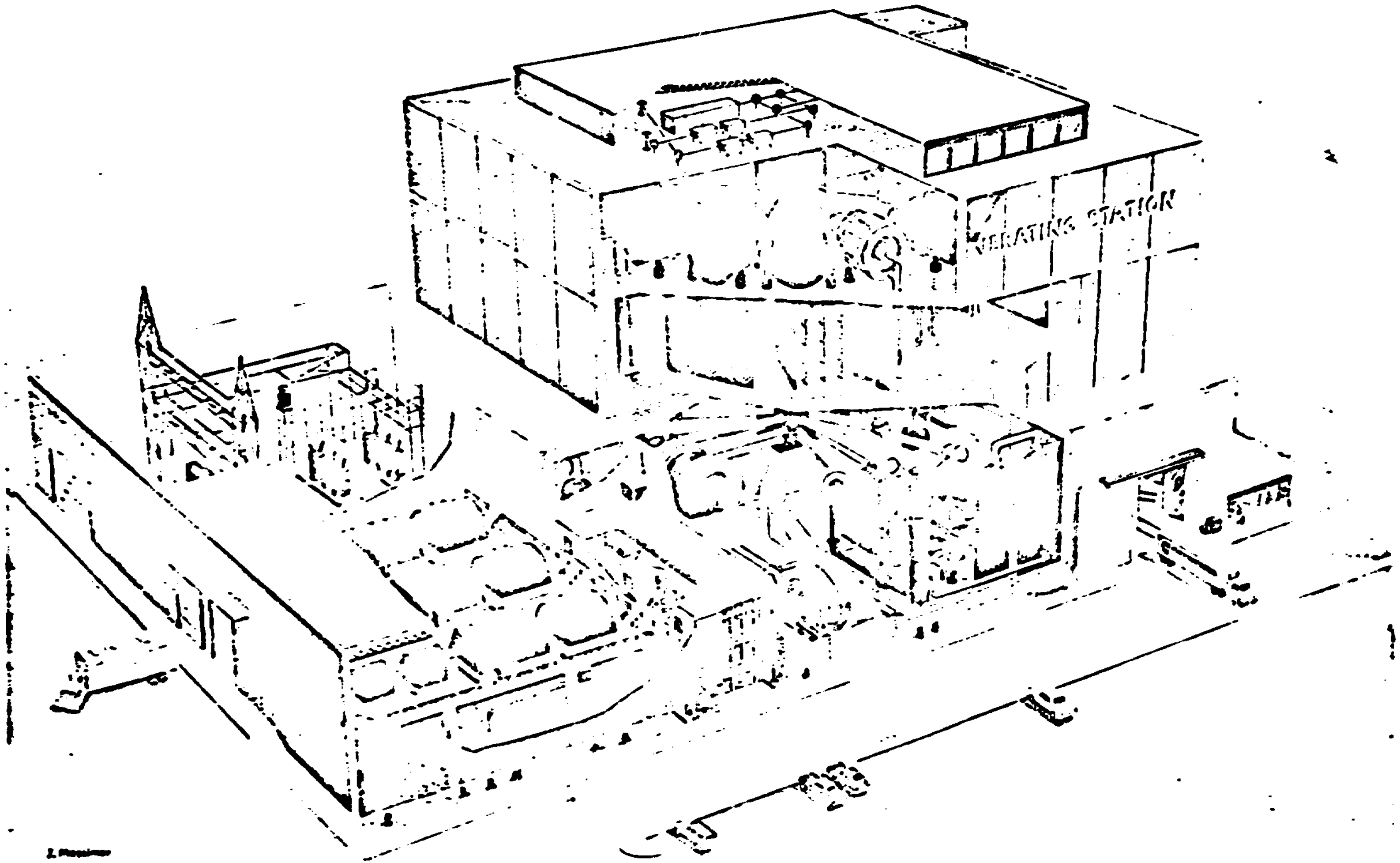
Fig. N3.

Laser-fusion-reactor fuel cycle

F4



CONCEPTUAL 1000 MW(e) LCTR POWER PLANT



CONCEPTUAL 1170 MW(e) LFR GENERATING STATION