

LA-5718-MS

Informal Report

UC-20

Reporting Date: August 1974

Issued: September 1974

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Laser Controlled
Thermonuclear Reactor System Studies

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UNITED STATES
ATOMIC ENERGY COMMISSION
CONTRACT W-7405-ENG. 36

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In the interest of prompt distribution, this LAMS report was not edited by the Technical Information staff.

Significant contributions to the work reported herein were made by F. T. Finch and J. S. Gilbert of L-5 and T. J. Merson of ENG-6.

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy \$4.00 Microfiche \$1.45

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LASER CONTROLLED THERMONUCLEAR REACTOR SYSTEM STUDIES

Compiled by

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ABSTRACT

Results of initial laser-fusion central station power plant feasibility and systems studies are discussed. The functional requirements of major plant subsystems are defined and conceptual performance characteristics of subsystem components that may satisfy these requirements are described. Several conceptual reactor cavities for microexplosion containment are considered, including a wetted-wall concept, a dry wall concept, a magnetically protected concept, and a lithium vortex or BLASCON concept. A 1000-MWe laser-fusion power plant, based on CO₂ laser technology and the wetted-wall reactor cavity design, is described. Preliminary assessments of laser-fusion technology requirements are made and critical technologies that require development are identified. The results of initial laser-fusion power plant parametric and tradeoff studies which use power cost as the primary figure of merit are presented.

I. INTRODUCTION

Development of laser fusion technology is progressing rapidly. Very-high-energy (10 to 100 kJ), short-pulse (0.1 to 10 ns) lasers are being developed in the US and abroad.¹⁻³ Theoretical pellet-compression and thermonuclear burn-physics research is advancing,³⁻⁶ and laser illumination of materials at Laser Controlled Thermonuclear Reactor (LCTR) intensities ($\sim 10^{16}$ W/cm²) are being conducted.⁷ Fusion-pellet illuminations at laser powers approaching 1 kJ in a nominal 1-ns pulse are imminent.⁸ However, the technical feasibility of achieving significant thermonuclear energy release from laser-driven fusion is yet to be demonstrated. Many challenging technological problems lie ahead in understanding the fundamental physics of high-energy, short-pulse lasers and fusion-pellet design. The purpose of this paper is to discuss some initial feasibility and systems studies of alternative LCTR and power-plant concepts.

Commercial power production from laser-driven fusion may ultimately be achieved by either of two major conceptual approaches. The approach which currently appears to offer the greatest potential for success is based on the use of lasers to compress and heat minute pellets of thermonuclear fuel to

thermonuclear ignition and burn conditions. The second approach - not discussed in this paper - utilizes laser energy to heat a magnetically confined plasma of thermonuclear fuel to sufficiently high temperatures for ignition to occur. This approach might more properly be referred to as laser-enhanced magnetically confined fusion.

In an LCTR, 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 the energy conversion cycle. Reactor cavities are surrounded by relatively thick blanket regions (containing lithium for the breeding of tritium) through which a coolant (which may be lithium) is circulated.

Very-high-energy, short-pulse lasers are necessary for the compression and heating of fusion pellets to thermonuclear ignition and burn conditions. The laser beams must be repetitively transported to and accurately focused on a pellet at the center of each reactor cavity. Cavities with penetrations for multiple, symmetrically arranged laser beams may be necessary to ensure efficient pellet compression and burn.

It may be necessary to operate cryogenic fuel-pellet injection systems in close proximity to relatively hostile cavity environments.

To a first approximation, many LCTR materials and engineering problems can be identified and characterized on the basis of extensive experience in fission-reactor materials performance and nuclear-weapons effects studies. However, as laser-fusion-physics programs progress, the capability to definitively evaluate reactor component performance under conditions similar to those in a reactor will be possible, and indeed, necessary. Before that time, the effects of competing and/or compensating damage mechanisms cannot be evaluated.

II. MAJOR LCTR SUBSYSTEMS AND FUNCTIONAL REQUIREMENTS

The major essential subsystems in a LCTR central-station power plant are:

- Reactor cavities and blankets,
- Fuel fabrication and injection systems,
- Laser systems,
- Laser-beam transport systems, and
- Heat-transfer and energy-conversion systems.

The time scale of events associated with each thermonuclear microexplosion from the time of fuel injection into the reactor cavity until the time the cavity environment is suitable for subsequent fuel injection is a major plant design consideration. Table I gives an example of the events to be considered. A number of additional aspects are noteworthy. First, thermonuclear burn occurs in ~ 10 ps resulting in the release of x rays traveling radially outward at the speed of light in a 10-ps time envelope. Second, 14-MeV neutrons arrive at the first wall (at 1 m radius) at 20 ns and release most of their energy by neutron interactions in blanket and structural materials, by ~ 100 ns. Both of these energy deposition times are short compared to hydrodynamic

times; thus, hydrodynamic stress waves will be produced in the cavity wall and blanket. Finally, in reactors in which the pellet debris has not interacted with either the cavity atmosphere or the blowoff layer formed due to x-ray-induced ablation, the debris will be absorbed in the first wall in a fraction of a microsecond. These phenomena play important roles in structural design analyses of LCTR concepts.

Reactor cavities will be required to contain repetitive thermonuclear microexplosions with energy releases in the range of from 10 to 1000 MJ. Inner cavity walls must withstand intense pulses of x rays, 14-MeV neutrons, 3.5-MeV alpha particles, and other energetic particles released by the thermonuclear reactions. There are economic incentives for maximizing pulse-repetition rates and for minimizing cavity diameters.

The fuel cycle which is receiving primary consideration for LCTR power plants at this time is the DT cycle. Deuterium is easily and cheaply obtained from conventional sources, but tritium is expensive to produce and is not available in large quantities. Thus, it is expected that tritium will be produced by reactions between neutrons and lithium which must be contained in blanket regions surrounding reactor cavities. Conceptual blanket designs provide for liquid lithium to be circulated through the blanket for the removal of heat and the breeding of tritium. There are also structural requirements for blanket regions related to the dissipation of the energy deposition in the blanket and in structural regions.

The DT fuel will be injected into the reactor cavities in the form of pellets, which can be compressed and heated to thermonuclear ignition and burn conditions by illumination with laser beams. Intensive analytical and experimental efforts are underway to design pellets with minimal requirements for laser-beam intensity and symmetry of pellet illumination. Preliminary LCTR design feasibility and systems studies have been based on the use of solid, cryogenic, stoichiometric DT pellets. A minimum laser-fusion-pellet energy gain in the range of 50 to 100 or greater will probably be necessary for economic power production.⁹ Energy release from bare DT pellets as a function of laser energy absorbed has been investigated analytically.⁴ Results of these calculations are shown in Fig. 1.

TABLE I
TIME SCALE OF EVENTS FOR LCTR PELLETT FUSION PULSE

Time	Primary Events	Secondary Events
-20 to -5 ns	Pellet enters cavity	
-150 ns	Laser pulse fired	
-10 ns	Laser pulse arrives at pellet surface	
0	Thermonuclear burn begins	
+ 10 ps	TN burn complete	
+ 6 ns	X rays strike first wall	
+ 30 ns	X rays strike last optical surface	Ablative material begins expansion from first wall
+ 20 to 100 ns	Neutrons deposited in reactor vessel	Shock wave induced in lithium
+ 60 ns	Neutrons strike last optical surface	
0.3 to 1.2 μ s	Pellet debris strikes first wall	Ablative material and pellet debris interact
+ 1 μ s	Cavity blowdown begins	Cavity atmosphere equilibrated
0.01 to 10 μ s	Restoration of original cavity conditions complete	Wetted-wall blowdown complete, lithium vortex restored, turbulence in rarified dry-wall cavity dissipated.

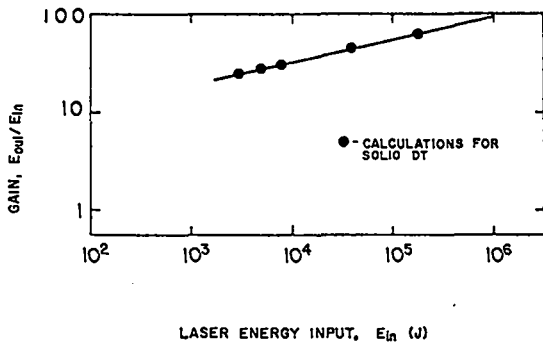


Fig. 1. Bare DT fusion pellet yield vs laser energy absorbed.

High-velocity pellet injection will probably be necessary to minimize pellet heating and to maintain stable pellet trajectories. Protection of pellet injection systems from the hostile cavity environments will also be required.

High-energy, short-pulse lasers will be required for the compression and heating of DT pellets to thermonuclear ignition and burn conditions. Laser research and development is advancing rapidly, and it is not possible to predict the specific type, or types, of lasers that may ultimately be most advantageous for application in LCTR systems. The laser-system technology that is currently developing most rapidly and which shows promise of achieving the required performance at reasonable cost and operating efficiency is that of the CO_2 system. A conceptual CO_2 laser design has been developed for use in reference LCTR design studies. Other potential laser technologies and their characteristics are shown in Table II.

TABLE II
LASER TECHNOLOGY

Characteristics	Type		
	CO_2	CO	Iodine
Typical wavelength, μm	10.6	5.4	1.32
Net efficiency, %	≤ 10	<20	~0.5
Pulse duration, ns	0.1-10	>10	~0.6
Extractable energy, J/l	30-50	>100	30
Operating pressure, atm	2-5	>1	---

Laser beams must be transported to, and accurately focused on, pellets at the center of each reactor cavity. Cavities with penetrations for multiple, symmetrically arranged laser beams may be necessary to ensure efficient pellet heating and compression.

An important criterion to be considered in the evaluation of cavity concepts is the repetition rates of pellet microexplosions which should be as high as practicable. Limitations on permissible microexplosion repetition rates will probably be determined by the time required to restore the cavity atmosphere to acceptable conditions for subsequent pellet injection and efficient laser-beam penetration. Depending on the concept, this could involve the expulsion of vaporized or ablated material, the formation of the lithium layer, or the restoration of a lithium vortex.

To prevent significant loss of tritium by diffusion through the reactor-containment and heat-transfer loops, very low tritium concentrations must be maintained in the circulating lithium. This requirement further complicates the difficult task of separating the tritium from the lithium. Several separation schemes have been proposed, but none has been demonstrated to be superior for this application.

Conventional energy conversion systems are currently receiving most attention for LCTR power plants. Heat from the reactor cavities is removed by flowing lithium and is transferred by intermediate heat exchangers to sodium. Steam is generated in sodium-water steam generators in secondary coolant loops. The steam then flows to conventional turbogenerators. Systems involving direct conversion have also been proposed but are not discussed in this report.

III. REFERENCE DESIGN LCTR SYSTEMS

Reactor Cavity and Blanket Designs

Several LCTR concepts are receiving consideration.^{9,10} They can be categorized according to the physical processes by which energy deposition from pellet microexplosions is accommodated by the cavity inner wall. Energy deposition by x rays, alpha particles, and 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 material volumes. The front surface of the cavity wall, to depths of a few μm , must be designed to withstand

repeated deposition of ~ 23% of the energy released by pellet fusion. Blanket-coolant regions must accommodate volumetric deposition of the remaining ~ 77% of pellet-energy release, in addition to heat conducted from cavity walls.

The wetted-wall concept, which has received the most extensive analysis of reactor phenomenology and assessment of potential technical feasibility of any LCTR concept to date, is characterized by evaporation and ablation of lithium from the inner surface of the cavity wall. The cavity is formed by a porous refractory metal (see Fig. 2) through which coolant lithium flows to form a protective coating on the inside surface. The protective layer of lithium absorbs the energy of the alpha particles, the pellet debris, and part of the x-ray energy; is ablated into the cavity; 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.

A dry-wall concept with an ablative cavity liner of a material such as carbon is also being considered. For such a design, a relatively small mass of cavity-liner material would be ablated by each pellet micro-explosion. The mass of material ablated would depend on characteristics of the pellet burn, on the ranges of ionized particles in the ablative material, and on cavity diameter. The cavity wall would cool sufficiently during the time intervals between successive pellet microexplosions to permit condensation of the ablated material. Before its credibility can be assessed, this concept requires much more detailed

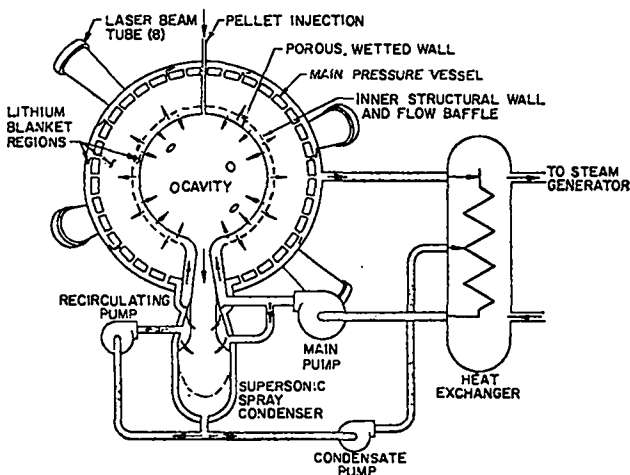


Fig. 2. Lithium-wetted-wall LCTR concept.

analysis of the ablation and condensation processes and of shock phenomena, which could result in excessive first-wall erosion or spallation.

Protection of reactor cavity walls from energetic ionized particles by means of magnetic fields is an attractive conceptual alternative to ablative cavity liners. A simple rendition of this concept is shown schematically in Fig. 3. The cavity is cylindrical, with an axial magnetic field, and is surrounded by a lithium blanket. The pellet injection system is located at the axial center of the cavity-blanket system, and the laser-beam-transport tubes are arranged symmetrically about the axial and radial center of the cavity. The magnetic field is generated by coils that are exterior to and concentric with the lithium blanket. Energy sinks are located at each end of the cylindrical cavity. Depending on how the magnetic field is tailored, the kinetic energy of the charged particles can either be deposited entirely in the axial energy sinks or it can be partially distributed along the cavity wall in a prescribed manner. Minimal cavity diameters will be constrained by allowable wall-surface

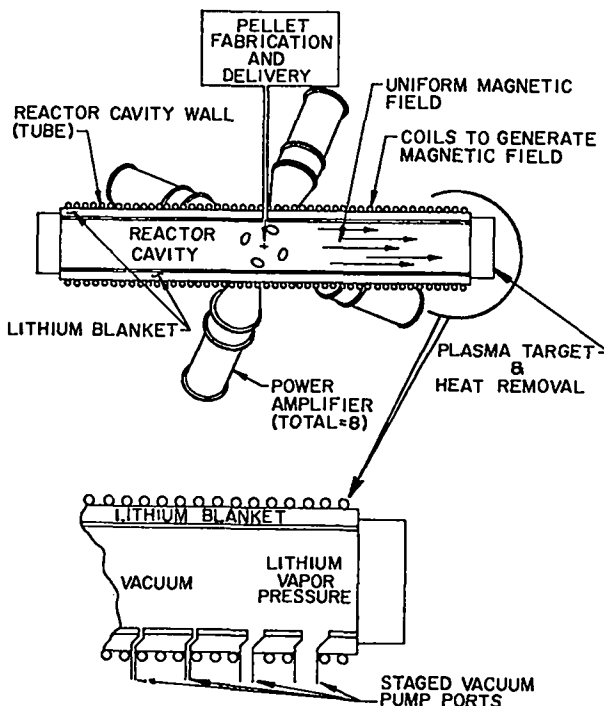


Fig. 3. LCTR concept with magnetically-protected cavity wall.

temperature increases due to x-ray energy deposition. Cavity liners of materials with low atomic number are useful for decreasing metal-wall surface temperature fluctuations.

Because of the high deposition-energy-density envisioned, the most attractive energy sinks are apparently evaporative and/or ablative materials. Lithium has a high heat of vaporization and is being considered for this purpose. Lithium is ablated from liquid-lithium surfaces that are maintained by axial flow from reservoirs. The lithium reservoirs also serve as axial neutron shields and as fertile material for the breeding of tritium. The ablated lithium vapor is removed from the cavity by a staged, continuously pumped vacuum system. A density gradient will exist in the vaporized lithium with the density in the thermonuclear burn region being maintained low enough to permit high pulse-repetition rates. After removal from the cavity, the lithium vapor is condensed and circulated through a heat exchanger before being returned to the heat-sink reservoirs.

Another reactor concept, generally referred to as the BLASCON,¹¹ shown schematically in Fig. 4, has

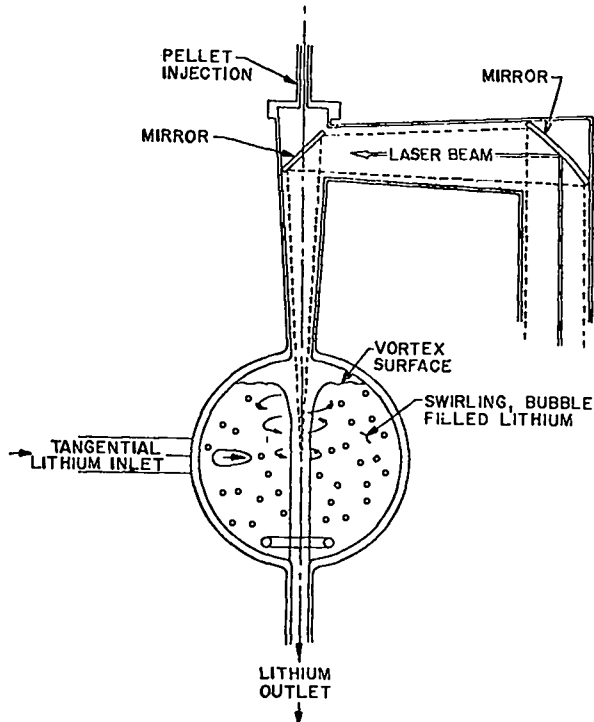


Fig. 4. BLASCON LCTR concept.

no cavity wall per se; rather, a cavity is formed by a vortex in a rotating pool of lithium in which pellet microexplosions take place. Rotational velocity is imparted to the circulating lithium by tangential injection at the periphery of the reactor pressure vessel. Bubbles are entrained in the rotating lithium to facilitate attenuation of the energy in shock waves created by pellet microexplosions. Energy deposition by x rays and charged particles results in evaporation of lithium from the interior surface of the vortex, but is of small consequence because a first-wall structure is not involved.

Conceptual blanket designs provide for the circulation of liquid lithium through the blanket regions and associated heat exchangers. Initial estimates indicate that acceptable tritium breeding ratios (1.07 to 1.40) can be obtained from designs containing natural lithium, whose structural requirements are satisfied by either stainless-steel or refractory metal components.

Pressure waves are produced in blanket regions (1) from impulses imparted to cavity walls due to energy deposition and ablation of protective liner materials, and (2) from pressures generated within the lithium through hydrodynamic coupling between walls and lithium expansion caused by neutron heating.

Alternative blanket compositions may be advantageous for some concepts, especially the magnetically protected design. Alternatives include stagnant lithium metal, lithium alloys, and lithium compounds, any of which could be combined with gas or heat-pipe cooling. In addition, circulating lithium salts may be considered.

Laser and Laser-Beam-Transport Systems

The electron-beam-sustained-discharge CO_2 system shows promise of achieving the required performance at reasonable cost and operating efficiency. Experimental CO_2 lasers now in existence at LASL provide the basis for designing larger laser systems. The annular power amplifier design, shown schematically in Figs. 5 and 6, is an extrapolation of this work.^{12,13,14} This conceptual CO_2 laser has been developed for use in reference LCTR design studies. The operational characteristics of the reference laser design are given in Table III. Eight laser amplifiers would be necessary to provide the reference design requirement of 1 MJ per pulse.

TABLE III

REFERENCE DESIGN LASER SYSTEM

Consists of oscillator, preamplifier, and power amplifier chain; power amplifier is an annular, subdivided cavity.

Laser cavity gas mixture	3:1/4:1 (He:N ₂ :CO ₂)
Output per power amplifier, MJ	0.125
Number of sectors per power amplifier	8
Laser pulse duration, ns	<1
Pulse repetition rate, s ⁻¹	30-50
Oscillator spectrum	Multiline, multiband
Beam flux at output window aperture, J/cm ²	<3
Length and outside diameter of cavity, m	3 x 1.5 to 3 x 4
Thermal energy removal requirement, MW	40
Laser energy Out vs electric energy In	10%*

* Current estimates for CO₂ lasers indicate a maximum efficiency of ~ 8%. Higher efficiencies may be attainable from other electrically pumped gas laser systems.

~ 3 J/cm² for repeated, short laser pulses. To reduce thermal stresses in windows, it will be necessary to provide cooling to prevent excessive temperature gradients.

The laser-beam-transport system transports laser light from the laser power amplifiers to each reactor cavity and focuses the laser pulse on the fusion pellet at the center of the cavity. Efficient beam transport requires a number of optical components and a system of evacuated light pipes. Optical elements are required for:

- Separation of gasses of different composition or pressure (windows);
- Beam focusing, diverging, deflection, and splitting (mirrors);
- Fast switching of beams; and
- Amplifier isolation to decouple the laser from reflected light.

The alkali halides are being developed for infrared-laser window materials and typical metallic reflectors are being developed for mirrors. Limits on beam intensity are imposed by damage thresholds for windows and mirrors from laser light, which results in requirements for large-diameter components.

Because the laser subsystem represents a significant fraction of the capital investment of a

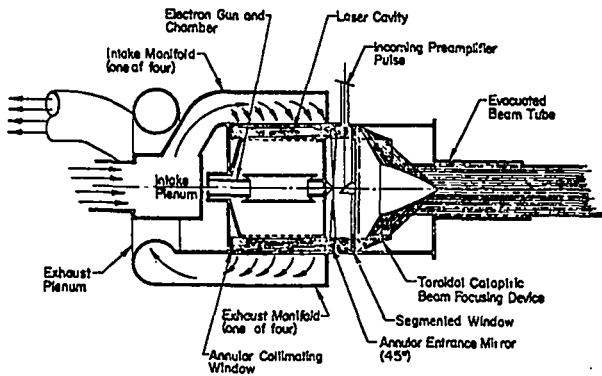


Fig. 5. Conceptual design of annular gas-laser power amplifier.

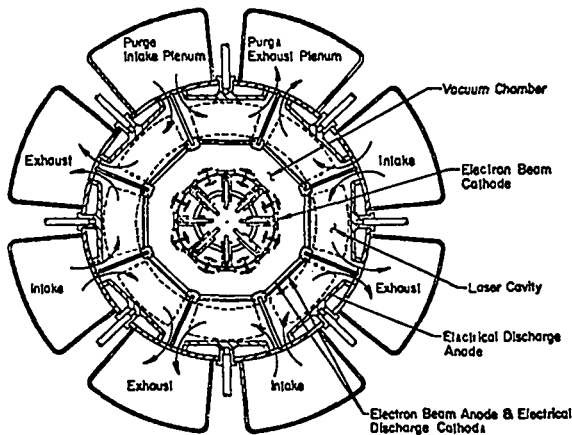


Fig. 6. Cross section of conceptual annular gas laser power amplifier.

The power amplifier is pumped by an electric discharge, with ionization provided by an electron beam. The annular lasing cavity is subdivided into eight subcavities, which can be pulsed simultaneously or individually in a programmed manner. Sequential pulsing of individual cavities may provide some capability for pulse-shaping by superimposing beams. Annular pulses are collected and focused by means of a toroidal, catoptric beam-focusing device. Laser-pulse repetition rates of from 35 to 50 per second appear to be desirable for power reactor applications. For pulse rates in this range, circulation of laser gas for convective cooling will be necessary. At 30 pps, the reference-design laser amplifier will require ~ 40 MW of cooling capacity. The anticipated gas temperature rise is ~ 125 K; thus, the required gas flow rate is ~ 400 m³/s.

One of the most restrictive limitations on laser amplifier design is set by laser light damage thresholds for window materials. The experimentally determined damage threshold for the alkali halides is

LCTR plant, it will probably be economically advantageous to centralize components so that each laser system serves several reactor cavities. A centralized laser system requires rapid beam-switching from laser power amplifiers to selected beam ports. Beam-switching might be accomplished by rotating mirrors. This scheme would require moving parts in a vacuum system with associated requirements for bearings and seals. Very long light pipes could also be required for large multicavity plants with centralized laser systems. It will be necessary to maintain precise alignment of optical components which, in turn, requires compensation for effects of temperature changes, earth tremors, and plant vibrations; and the laser beam-transport systems must penetrate, by indirect paths, the biological shielding surrounding reactor cavities to prevent radiation streaming.

Beam focusing on target will probably require sophisticated pointing and tracking systems with feedback servo systems controlling large mirrors in vacuum and radiation environments. The final optical surface with its associated blowback protection devices and contaminated vacuum and cooling systems may have to be engineered for frequent replacement.

Conceptual 1000-MWe Plant Design

Recent consideration of engineered power reactor systems has led to a conceptual design of a central-station power plant for the production of nominal 1000 MWe of electric energy. The main system design problems, which must be dealt with for LCTR power plants, have been identified; however, system concepts are evolving rapidly, and, at a given time, inconsistencies may therefore exist between assumptions used in the engineering reference design and the systems analysis. The concepts discussed in this section are not totally consistent with those for which the results of preliminary systems analyses are presented in Section V. However, discrepancies are minor, and include implied differences in cavity pulse-repetition rate and in installed capacitative energy storage. Important considerations which led to design choices included component reliability (high load factor), 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 overall plant layout is shown in Figs. 7 and 8. Figure 9 is an isometric view of the conceptual plant.

This version of a LCTR power-plant concept includes 16 separate laser systems, 16 reactor cavities with associated beam-transport systems, and 8 pairs of primary lithium-sodium and sodium-steam heat exchangers. A lithium-processing and tritium-removal system is associated with each lithium-sodium heat exchanger. Each set of heat exchangers and associated lithium processing equipment serves two reactor cavities.

A fuel-pellet injection system is mounted on each reactor cavity. Fuel-pellet illumination by laser light is accomplished by eight laser beams arranged in symmetrical array around each reactor cavity. Eight of the 16 lasers are fired simultaneously, and the laser beams are directed successively to respective laser cavities. Each laser has a redundant partner to achieve high reliability and ease of maintenance. The reactor cavities are designed for a duty factor of two microexplosions per second per cavity.

Mechanical and structural isolation is provided for each laser system, radioactive cavity and associated beam-transport and heat-transfer system, component-servicing facilities, and operational and control areas. It is essential that vibrational disturbances to the optical laser system be minimized; thus, laser systems, including power supplies, oscillators, power amplifiers, and waste-heat removal systems, are located in a mechanically isolated, centralized building which is anchored to bedrock. Reactor cavities are located in a separate, annular building which encloses the laser-system building. Each reactor cavity is in a biologically shielded enclosure with penetrations for laser beams, liquid-metal coolant, and the introduction of fuel. Heat is extracted from reactor cavities by flowing liquid lithium, is transferred to a sodium loop, and finally to steam generators. The heat exchangers and lithium-processing equipment for each pair of reactor cavities are located in a biologically shielded enclosure adjacent to the cavity enclosure. Components containing tritium are designed to minimize component sizes and piping lengths. Control rooms and other work areas are isolated from the reactor radioactive areas.

Overhead cranes are provided for removal and replacement of the laser power supplies. The laser power amplifiers and optical systems are accessible

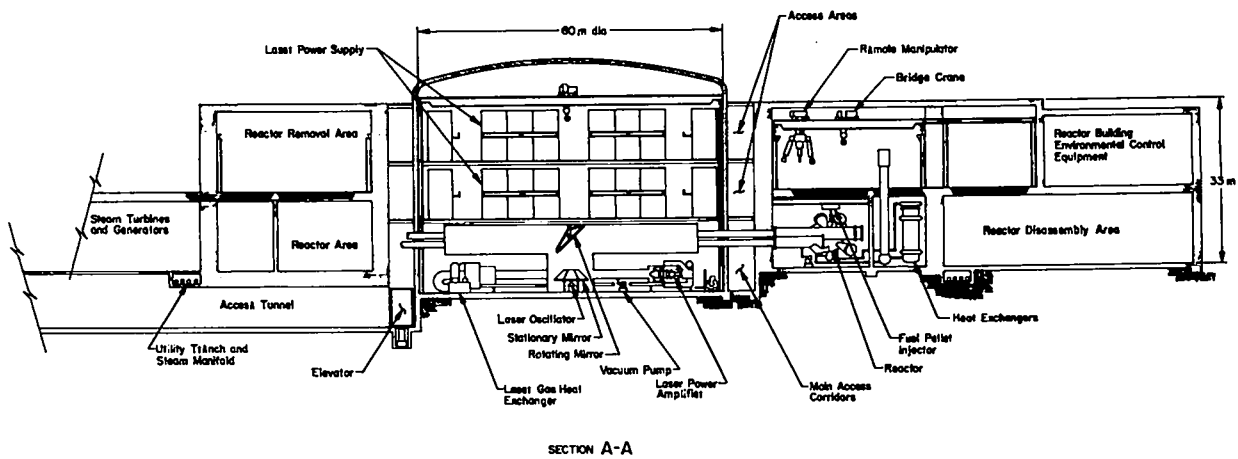


Fig. 7. Conceptual 1000-MW(e) LCTR power plant, sectional side view.

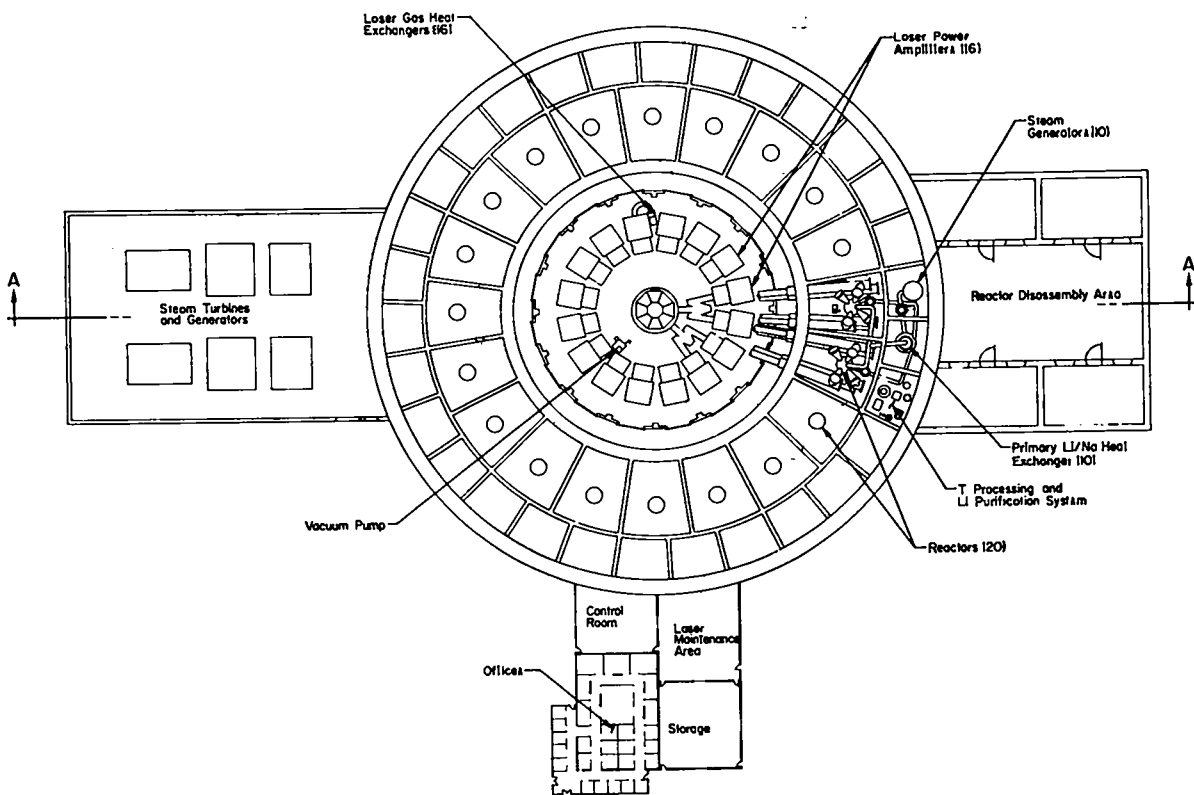


Fig. 8. Conceptual 1000-MW(e) LCTR power plant, sectional top view.

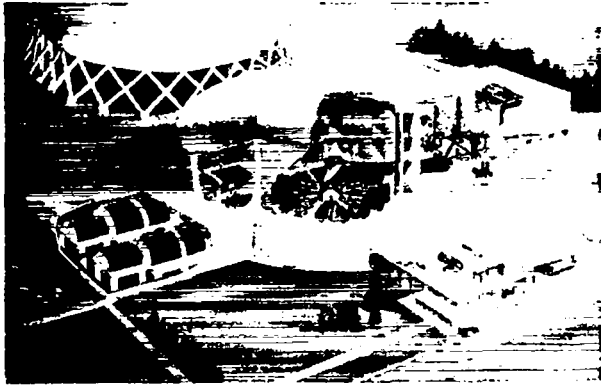


Fig. 9. Conceptual 1000-MWe LCTR power plant, perspective sketch.

through underground passages. Reactor cavities and cavity components can be removed remotely through removable shield plugs and transferred to shielded work areas by a crane. Each reactor cavity can be isolated from the system for service and/or replacement without affecting the operation of the remainder.

The conceptual beam-switching subsystem is shown in Fig. 10a. Eight of the 16 laser power amplifiers are pulsed simultaneously. The eight beams are reflected to mirrors mounted on a rotating assembly that successively directs the beams into the beam-transport tubes for each reactor cavity. For the reference design, the rotating mirror assembly must have a rotational velocity of 2 rps, and the laser systems must have a pulse repetition rate of 32 pps. Shown in Fig. 10b is the arrangement of mirrors allowing the selection of either of two laser power amplifiers to provide each of the eight beams required for each pulse.

Direct beam-transport path lengths between the beam-switching subsystem and a reactor cavity differ by a few meters, which could lead to differences in arrival times of laser beams incident on a pellet of the order of 10^{-8} s or ten times the pulse width. This is compensated for by increasing the shorter path lengths, with suitably placed mirrors, so that all path lengths are the same.

Shielding of the laser system from neutrons and γ rays originating in the reactor cavity enclosures is provided by thick walls and indirect laser-beam paths. A shielded beam path is illustrated in Fig. 11. A beam expander is necessary at this point to maintain beam intensity below the damage threshold for windows. The beam expander illustrated includes adequate shielding as well as beam-expansion components.

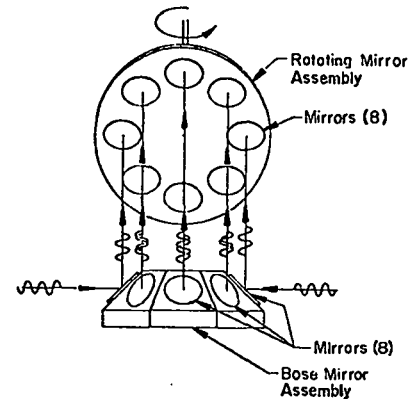


Fig. 10a. Conceptual beam-switching device for central laser system.

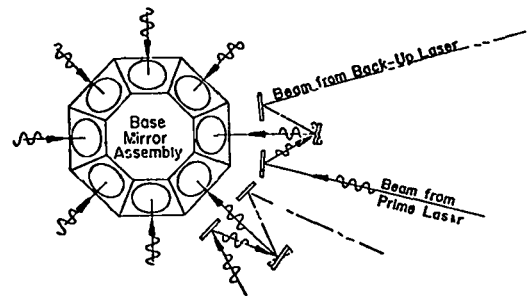


Fig. 10b. Method of switching prime to backup lasers.

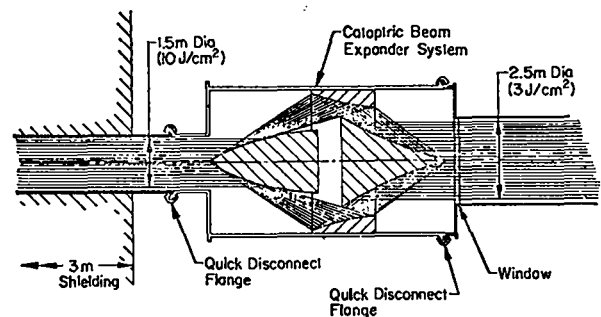


Fig. 11. Shielded laser-beam expander.

Accelerated, high-velocity injection of pellets will probably be required. Mechanical, pneumatic, or electrostatic methods could be used to obtain high pellet velocities. A pneumatic method is indicated in Fig. 12. Pellet guidance concepts include mechanical aiming of the pellet guide tube, electrostatic methods, electromagnetic methods, and laser beam guidance for pellets with suitable ablative outer layers. Pellet tracking and aiming of the lasers is also expected to be necessary.

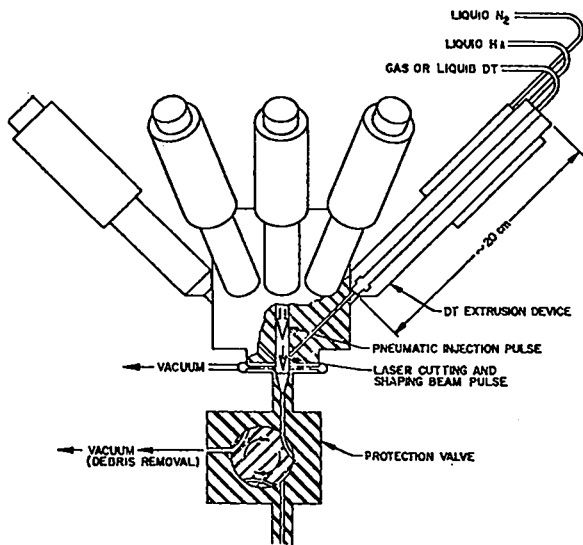


Fig. 12. Conceptual cryogenic pellet fabrication and injection.

A pellet injection system will require protection from cavity blowback. A blowback protection valve is also shown schematically in Fig. 12. The valve operates synchronously with pellet injection so that the pellet passes through the bore, but the injection device is never directly exposed to x rays or pellet debris.

The layout of major equipment in a tritium-separation and fuel-preparation cell for the reference LCTR plant is shown in Fig. 13. In this process, liquid lithium-liquid lithium salt extraction in a centrifugal contactor, with tritium separation from the salt by electrolysis, is utilized to separate tritium from the lithium.

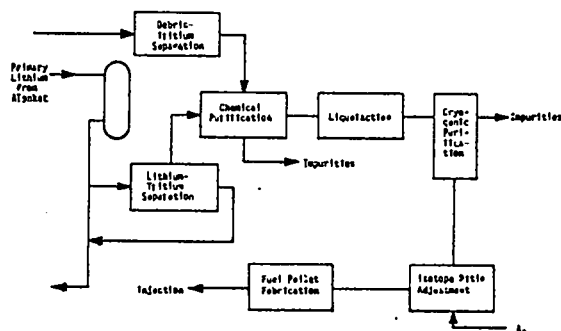


Fig. 13. Schematic of Tritium Recycle Subsystems.

IV. CRITICAL LCTR TECHNOLOGIES

Laser Systems

Laser performance requirements that characterize conceptual laser designs for reactor application are being defined by analytical and experimental studies of DT-pellet fusion. Important laser parameters that specify laser requirements are energy per beam, pulse repetition rate, and electrical-to-light conversion efficiency. Additional laser requirements, which are not as yet well defined, include acceptable laser-light wavelengths and pulse shapes.

Systems studies of reference-design, central-station power plants indicate that the production of economic electric energy from laser fusion will require laser system outputs of 0.1 to 1.0 MJ per pulse, a pulse width of ~ 1 ns, and an efficiency > 4%. A pulse repetition rate of 30 to 50 per second is desirable for large (~ 1000 MWe) power plants. Requirements on pulse shape may be such that most of the energy must be delivered in the final portion of the 1-ns pulse.

The CO₂ laser system is developing more rapidly than others and shows promise of achieving the required high energy performance at reasonable cost and operating efficiency. A conceptual CO₂ laser design has been developed for use in reference LCTR design studies based upon experimental CO₂ lasers now in existence and being designed at LASL. The reference power amplifier design, shown schematically in Figs. 5 and 6 (see also Table III) is the result of this work. A modelocking oscillator and preamplifier chain provides a 100-J pulse to drive the 0.125-MJ power amplifier. An electron beam is used to partially ionize the lasing medium and is followed by an electric discharge which pumps the N₂:He:CO₂ lasing medium.

Of particular importance with regard to laser efficiency is the design of the electrical storage and conditioning system used to pump the cavity gas in the annular amplifier. A pulse-forming network (PFN) is needed to provide a suitable electrical-discharge waveform with minimum circuit complexity. The ideal waveform would be a square wave with zero rise and fall times. The wave shape is important because pumping is efficient only within a range of applied electric fields. Thus, a slow rise time will cause energy to be deposited in the gas as

heat rather than as population inversion. Because pumping stops when the voltage falls below a certain value, a slow fall will mean that more energy is left in the bank when peak gain is reached. In general, better waveforms are achieved at the cost of more complex networks.

At 30 pps, the reference-design power amplifier will require circulation of the cavity gas for convective cooling. Approximately 40 MW of cooling capacity will be required for each power amplifier. Moreover, amplifier performance is significantly degraded by excessive temperatures. Inlet cavity-gas temperature requirements are expected to be in the range of from 300 to 350 K, and the temperature increase per pulse is expected to be ~ 125 K.

If 10%-efficient electrically pumped lasers are used, 10 MJ of electric energy must be generated, stored, conditioned, and switched for each 1-MJ laser pulse. For the reference-design power plant, PFNs composed of conventional capacitor banks and inductors are assumed. High-voltage PFN inductance effects limit the energy delivered per PFN module to the range of 100 to 200 kJ for efficient transfer on the required time scale. Power amplifiers requiring more energy for pumping than this can be supplied by parallel PFN modules. Electrical energy is transferred from the PFN modules to the load through low-inductance cables. Lifetimes of off-the-shelf capacitors are in the range of 10^6 pulses. This is two orders of magnitude less than the number of pulses required per month from a central laser system for a large power plant. Part of this increased capacity can be obtained by the installation of parallel components; however, it is obvious that significant extensions of electrical energy storage and handling technology are desirable and would have a significant effect on the cost of consumer power from laser-fusion power plants.

Turbine-driven homopolar generators coupled to superconducting inductive storage coils may offer alternative power supplies with more attractive long-term reliability. Homopolar generators can now be built to deliver currents in the 1-MA range at voltages in excess of 100 V and with pulse durations near 0.1 s. Superconducting inductive storage coils could provide the necessary voltage increase and pulse-shaping for discharging into lasers. The status of coil technology is characterized by experimental

100 kJ coils designed for operation at several pulses per second. Life-testing to establish reliability has not been undertaken; however, no fundamental physics limits have thus far been identified.

Alternative laser systems for LCTR application have not been considered in depth in our current study because other systems have not yet progressed to the point where engineering development of large lasers is warranted. There has been some discussion of the potential of chemical lasers, such as the HF laser, but the overall efficiency in converting chemical energy to light, and electrical energy back to chemical energy, has not been seriously evaluated. Electrically pumped gas laser systems show promise of having the high efficiency and low cost necessary for LCTR application. A vigorous program of developing alternative lasing media is necessary; and indeed exists in some areas, e.g., CO, iodine, and mercury, should CO₂ not prove adequate for LCTR application. Another attractive possibility, if wavelength effects prove significant, is a frequency-conversion technique such as harmonic generation which could be 50 - 80% efficient.

Optics and Laser-Beam Transport

The beam-transport system will consist of a number of optical elements which must accomplish the following:

- Separation of gases of different composition or pressure (windows);
- Beam focusing, diverging, static deflection, and splitting (mirrors);
- Fast switching of beams, pulse-shaping, and component isolation;
- Pointing and tracking of pellet; and
- Uniform pellet illumination.

Desirable characteristics for transmission and reflective optics are:

- Good optical transmission for windows and lenses, and high reflectivity for mirrors;
- Resistance to damage from intense laser light and possibly x rays, γ rays, neutrons, and cavity ablative material; and
- Mechanical and thermal properties compatible with other system requirements.

Promising materials for windows and lenses include the alkali halides (NaCl, KCl, etc.), germanium, and the chalcogenides (GaAs, CdSe, etc.). Reflecting elements will be made from typical

metallic reflecting materials including Cu, Au, Al, Ag, Ni, and alloys of these materials. Surface-finishing techniques include sputtering, polishing, and micromachining.

Prospective elements for fast switching, pulse-shaping, and component isolation are:

- Electro-optic (Pockels, Kerr effect),
- Acousto-optic (Bragg reflection),
- Magneto-optic (Faraday rotator),
- Saturable absorbers,
- Diffraction gratings, and
- Expendable membranes.

Beam-transport system components must be resistant to damage from intense laser light, x rays, γ rays, neutrons, and cavity ablative material. Damage mechanisms in windows and lenses from laser light are reasonably well understood and are listed in Table IV. The experimentally determined damage threshold¹⁴ for repeated, short (~ 1 ns) CO_2 laser pulses is $\sim 3 \text{ J/cm}^2$. Damage to reflecting elements from laser light at intensities below those that cause surface evaporation is not well understood, but appears to correlate with surface-temperature increases. Experimental data for repeated short pulses are lacking, but extrapolation of data for longer pulse widths indicates a damage threshold of $\sim 10 \text{ J/cm}^2$ for repeated, short (~ 1 ns) CO_2 laser pulses.¹⁵

The focusing element that "looks" into the reactor cavity will be exposed to x rays, secondary γ rays, neutrons, and possibly cavity atmosphere. Essentially no relevant data have been discovered

on which to base damage-threshold judgments for radiation damage to optical elements. Some preliminary x-ray energy deposition calculations have been done to estimate the severity of the problem. Permissible x-ray fluences were based on the criterion that the compressive stress induced in the mirror surface due to x-ray deposition shall not exceed one-half the yield strength of the material. The results of these calculations for several prospective mirror materials are given in Table V. From permissible x-ray fluences, x-ray yields from the pellet micro-explosion, and laser light thresholds, minimum focal lengths and f-numbers can be determined for the beam into the cavity. Values of these quantities for one- and eight-laser-beam systems are also given in Table V.

Minimum focal lengths and f-numbers for pure materials, with the exception of aluminum and niobium, are somewhat restrictive; however, several alloys listed in Table V appear to have acceptable properties with regard to x-ray absorption for a wide range of cavity and beam-transport designs.

The secondary γ -ray environment is due primarily to (n, γ) reactions and is not expected to pose significant problems for the beam-transport system, provided there is adequate cooling of components. Neutron damage to optical components has not been estimated; it is expected that the formation of color centers due to atomic dislocations may be important. The presence of cavity ablative material on optical surfaces could enhance damage from laser light as well as cause a general degradation of optical properties.

TABLE IV

WINDOWS AND LENSES

Damage Mechanisms from Laser Light

- Electrical avalanche breakdown induced by intense optical fields.
- Inclusions which absorb energy more efficiently than bulk material.
- Mechanical stress waves induced by interaction of laser light with surface layers or debris.
- Self-focusing of light beam to destructive intensities.
- Thermal expansion and subsequent mechanical distortion or fracture.

Damage Threshold

$\sim 3 \text{ J/cm}^2$ for repeated, short (~ 1 -ns)pulses.

TABLE V
IMPLICATIONS OF MIRROR CONSTRAINTS DUE TO X-RAY DEPOSITION
FROM 10^{-5} -J PELLET MICROEXPLOSIONS

Material	Permissible X-ray Fluence, J/cm^2 *	Minimum Focal Length, m	Minimum f-Number Eight Beams	Minimum f-Number One Beam
Cu	0.009	28.3	22.4	7.9
Ag	0.008-0.005**	30.0-11.4	23.8-9.1	8.4-3.2
Au	0.009-0.016**	29.9-21.1	23.7-16.8	8.4-5.9
Al	0.157	6.7	5.4	1.9
Ni ^{1A}	0.095	8.7	6.9	2.4
Al-7178	0.691	3.2	2.6	0.9
Be-Ni	0.138	7.2	5.7	2.0
Be-Cu	0.116	7.8	6.2	2.2

*Criterion: The compressive stress induced in the mirror surface due to x-ray deposition shall not exceed one-half the yield strength of the material.

**Ranges in value result from different hardening treatments.

The tradeoffs among laser light, x-ray fluence, and f-number are illustrated in Fig. 14, which plots the ratio of x-ray to laser-light fluence on the last optical surface versus f-number with the number of beams as a parameter. Lines of constant focal length are also shown. Designs below the dotted lines would indicate respective mirror materials that satisfy the x-ray criterion discussed above. The circles indicate reference design points adopted for system studies.

The reactor cavity atmosphere for each reactor concept being considered may contain ablative materials at the times that successive laser pulses occur. The highest densities of ablative material are expected in the BLASCON and wetted-wall concepts. Sufficient lithium is ablated by nominal pellet micro-explosions for these concepts to cause severe laser-beam unfocusing if insufficient time is allowed for expulsion of this material before the next pulse. Because it is desirable to have as high pulse rates as possible, pumpdown times are of critical importance.

Optimization of conditions for pulse propagation through cavity media will require detailed systems studies, because involved tradeoffs must be considered. A number of factors affect the amount of beam unfocusing that occurs in lithium vapor, the

most important being gas density in the cavity, wavelength of laser light, and beam intensity. A reduction by a factor F in light wavelength increases the allowable cavity density for the same fraction of beam on target by a factor of approximately F^2 . The more intense the laser beam, the more severe will be beam unfocusing. High f-numbers result in a larger fraction of the beam being at high intensity, and nonuniformities in beam profile result in high-intensity portions of beams.

Fuel Pellets

The DT fuel cycle is the only one seriously considered at this time for laser-fusion systems. The DT reaction is ~ 100 times more probable than the DD reaction in the temperature range of 10 to 100 keV. Even if the higher temperatures and compressions necessary for the DD cycle become feasible in the course of laser-fusion research and development, these conditions would also permit the burning of smaller DT pellets at higher pulse rates in smaller cavities.

For the DT cycle, the physical and chemical form of the fuel material has not yet been chosen. Molecular DT in gaseous, liquid, or solid form is preferred. Fuel pellets may be fabricated locally (cavity-coupled) or remotely and by batch or continuous processes. The selection of the processing method will be largely determined by the selection of pellet materials and design. Bare, solid DT spheres would be produced in a continuous, cavity-coupled cryogenic process. Requirements for fuel purity and design tolerances are expected to be strict and will affect the choice of fabrication method. Cavity-coupled fabrication methods would be expected to pose unique problems in sampling and rejection of pellets that fail to meet design specifications.

The domain of acceptable pellet parameters will be dependent on the available laser energy per beam, on wavelength, on beam symmetry, and on pulse shape in space and time. Compromises in pellet-design complexity may have to be accepted if the quality of laser beams is inadequate for good beam-pellet coupling with simple pellets.

Fusion Pellet Thermonuclear Energy Release

Reactor design analysis is dependent, to first order, on the following pellet design parameters;

- Total laser energy required for pellet fusion,

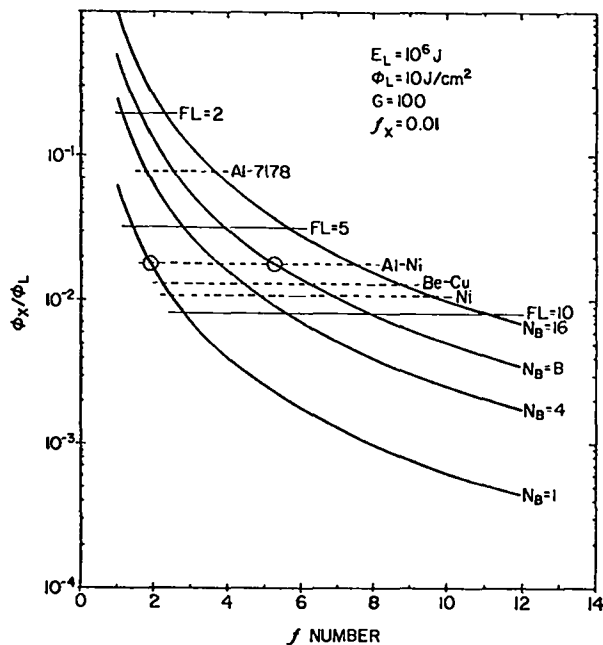


Fig. 14. Ratio of x-ray to laser light fluence vs final optics f-number.

- Net energy gain from pellet fusion, and
- Energy release forms and spectra from pellet fusion.

Knowledge of the total laser energy required for efficient pellet fusion is important because this sets the goals for lasers to be developed. Based on laser fusion-pellet calculations⁴ for bare DT spheres, the laser energy needed for significant thermonuclear energy gain is between 0.1 and 1 MJ per pulse. These calculations indicate that energy gains of between 50 and 100 are achievable with such lasers.

Calculations of fusion-pellet burn physics have been made for small DT spheres.^{4,5} The implosion efficiency of fusion pellets has been characterized as functions of laser-pulse time scale, shape, and intensity. For net energy release, the central region of the pellet must be compressed to very high densities (approximately 10^3 to 10^4 g/cm³), so that α particles and photons released by thermonuclear reactions are partially recaptured in the compressed pellet material, resulting in "boot-strap" heating. For efficient pellet burn, the laser pulse must also be tailored in time in such a manner that initial compression of the central pellet region is adiabatic, and shock-heating occurs primarily in the latter stages of the implosion.

Approximately 1 MJ of laser energy is required on a bare DT target for an energy gain of 100, i.e., for a 100-MJ thermonuclear energy release. Results of a typical calculation of energy release forms and spectra for a 100-MJ microexplosion are given in Table VI.

The energy released must pass through, or interact with, the material which was ablated during the pellet implosion and compression stage; pass through, or interact with, any ambient gas in the cavity; and, finally, interact with the cavity wall and structure. The expansion dynamics are important because the temporal profiles will determine the impulse on the cavity wall. The 14-MeV neutrons and the ~ 2-MeV α particles will pass essentially unaltered through the blowoff layer and ambient gas to the cavity wall. The photons and pellet debris may first interact with the blowoff layer. Such interactions are dependent on the blowoff gas density in the blowoff layer and on other particle species in the reactor cavity. High ambient gas densities will give rise to a spherically expanding hydroshock driven by the pellet

TABLE VI
TYPICAL ENERGY RELEASE SPECTRA FROM
A 99-MJ DT PELLETT MICROEXPLOSION

Mechanism	Fraction of Total Energy Release	Particles Per Pulse	Average Energy Per Particle	
X rays	0.01	-	~4 keV peak	
α particles that escape plasma	0.07	2.2×10^{19}	2 MeV	
Plasma kinetic energy	0.15			
α particles		1.3×10^{19}	Total Ave. 0.37 MeV	
Deuterons		1.2×10^{20}		0.6 MeV
Tritons		1.2×10^{20}		0.3 MeV
Neutrons	0.77	3.3×10^{19}		0.4 MeV
			14.1 MeV	

debris. Investigations are being carried out of the interactions between photons, pellet debris, and the several materials that may be present in the cavity as a result of previous pellet microexplosions to determine whether well-structured shocks can exist.

There are many aspects of fusion-pellet design and thermonuclear energy release yet to be thoroughly investigated, both analytically and experimentally. There is concern, e.g., that preheating and decoupling problems associated with the use of 10.6- μ m CO₂ laser light³ may exist; however, it is believed that such problems, if they in fact materialize, can be solved by appropriate fusion-pellet design. It is essential that theoretical investigations be verified by experiment.

Reactor Cavity and Blanket Design

Reactor Cavities - The reactor cavity is the most hostile environment associated with a LCTR power plant. Interactions between the products of fusion-pellet microexplosions and cavity-wall materials are expected to severely limit the lifetimes of high-power-density, minimum-size cavities.

Energy deposition by relatively soft x rays in stainless steels and refractory metals occurs in a very thin layer in the cavity wall, i.e., a large fraction of the x-ray energy resulting from a DT

microexplosion is deposited at the surface within a depth of $\sim 10 \mu\text{m}$. Energy deposition from x rays can lead to very large metal-surface temperature increases for unprotected surfaces; however, surface temperature fluctuations are reduced appreciably by protective layers of materials with low atomic number. Included among the materials being considered for this purpose are lithium, beryllium, and carbon.

Of crucial importance for determining cavity size limits for some concepts are x-ray spectra and fractional yields. Extrapolations from low-yield pellet-microexplosion calculations indicated that x-ray spectra could be approximated reasonably well by a 3-keV blackbody spectrum. The x-ray spectra from two $\sim 100\text{-MJ}$ pellet microexplosion calculations (Case A and Case B) are plotted in Fig. 15 together with a 3-keV blackbody spectrum for comparison showing that the blackbody spectrum is not a very good approximation of the x-ray spectra for these two cases. The spectrum from Case B is being used for x-ray energy deposition calculations.

Metal-surface temperature increases are given in Fig. 16 as functions of x-ray fluence for bare niobium and for niobium covered with 1 and 2 mm of liquid lithium. Equal metal-surface temperature increases result for bare niobium and niobium covered with 1 mm of lithium with a difference greater than a factor of two in x-ray fluence.

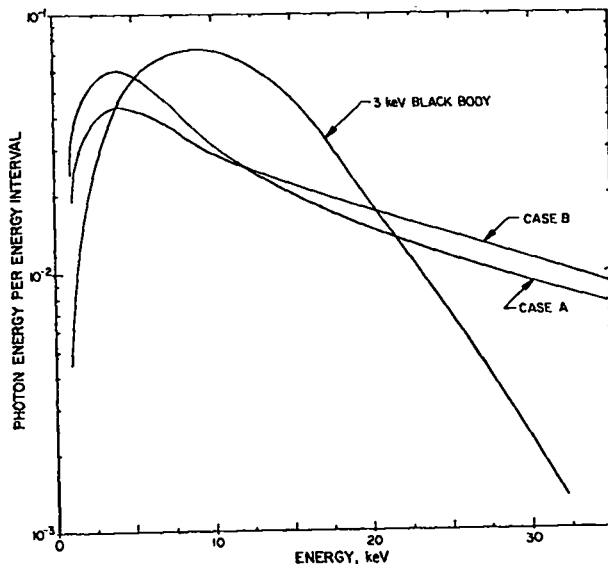


Fig. 15. Calculated x-ray spectra from $\sim 100\text{-MJ}$ pellet microexplosion and comparative black-body spectrum.

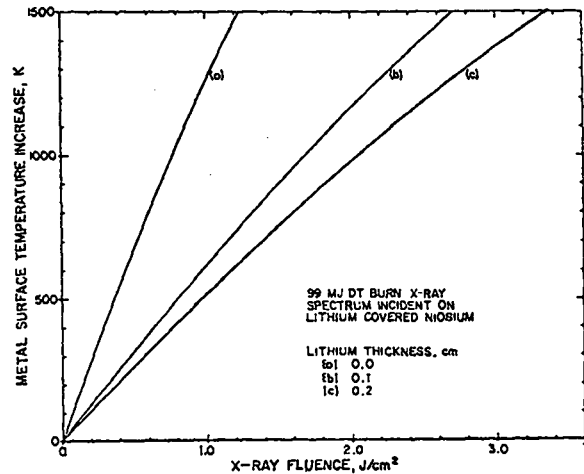


Fig. 16. Niobium surface-temperature increase versus x-ray fluence

The ranges in liquid metals and structural materials of the α particles and particles in the pellet debris described in Table VI are of the order of 1 mg/cm^2 leading to penetration depths less than $5 \mu\text{m}$ for materials of interest for LCTR cavity construction. This fusion-energy deposition mechanism constitutes one of the most severe constraints on LCTR cavity design. Recent experiments on helium ion irradiation of vanadium and niobium¹⁶ provide graphic evidence of the first-wall blistering problem which challenges reactor designers.

The considerations outlined above have led to reactor-cavity wall concepts which employ layers of evaporative or ablative materials to protect the interior surfaces of reactor cavities. Preliminary evaluations of both liquid-metal and solid cavity-wall protective layers have been made. The results of these analyses indicate that protection by a liquid metal such as lithium may be the most practical approach; however, experimental investigation of these findings should have a high priority.

Protection of cavity walls from energetic ionized particles by means of magnetic fields is an attractive conceptual alternative to ablative cavity liners. The results of preliminary calculations indicate that magnetic fields of less than 5 kG are adequate for this purpose and that the penalty in recirculating power is minimal. An aspect of such concepts, which has not been investigated carefully, is the performance of energy sinks into which the energetic charged particles are deposited.

The final current conceptual approach to the problem of accomodating energy deposition by x rays, α particles, and pellet debris is the BLASCON design in which pellet microexplosions take place in a vortex formed in a rotating pool of lithium. Outstanding unanswered questions for this concept relate to possible problems associated with the restoration of the lithium vortex between pellet microexplosions and the entrainment of bubbles in the rotating lithium to attenuate shock waves created by pellet microexplosions. Experimental work is being done at the Oak Ridge National Laboratory to investigate these problems. A fundamental disadvantage of the BLASCON concept is that it admits only one laser beam. One-sided illumination of pellets by a single laser beam accentuates all the problems of laser development, mirror design and construction, and pellet design. Depending on the outcome of current research, this aspect of the BLASCON concept may or may not be a limiting factor.

Blanket Design - Functional requirements for LCTR blanket regions include the breeding of tritium and the removal of heat. Other requirements are related to the dissipation of pressure wave energies which result from neutron-energy deposition in the blanket and structural region, and from cavity-related phenomena.

Conceptual blanket designs provide for the circulation of liquid lithium through the blanket, to remove heat and tritium produced by neutron reactions with the lithium. Containment of tritium within the blanket and associated piping and heat exchangers is of extreme importance both because of the biological hazard resulting from the release of tritium to the environment and because of the value of tritium to the DT fuel cycle.

Pressure waves are produced in the blanket region both from forces on the cavity wall due to energy deposition and ablation of protective liner materials, and from pressures generated within the lithium through hydrodynamic coupling between walls and lithium expansion caused by neutron heating. Wetted-wall reactor studies indicate that it may be difficult to prevent high-frequency oscillation (ringing) of inner and outer walls.

Neutronics - Calculations have been done to survey some neutronics aspects of laser-fusion reactors. Spherical calculational models were used, and a typical example of such a model (which was used to

represent the wetted-wall concept) is described in Table VII and Fig. 17. The basic reactor model is indicated by solid lines in Fig. 17. The wall indicated by dotted lines was included at constant thickness, but at variable radial position to determine the sensitivity of various neutronic responses to the introduction of additional structural material. The principal results of these calculations are: (1) tritium production as a function of radial position and overall tritium breeding ratio, (2) neutron economy, (3) energy deposition as a function of radial position, and (4) various neutron-damage effects.

TABLE VII
LCTR CALCULATIONAL MODEL

<u>Outer Radius, m</u>	<u>Material</u>	<u>Density, kg/m³x10⁻³</u>
0.989	Li vapor	0.0018
1.000	60:40 vol % Nb:Li	4.679: 0.224
(0.075-m-thick additional structure)*	90:10 vol % Nb:Li	7.713: 0.047
1.696	Li	0.478
1.796	90:10 vol % Nb:Li	7.713: 0.047
2.096	Li	0.472
2.121	Nb	8.570

* Radial position variable.

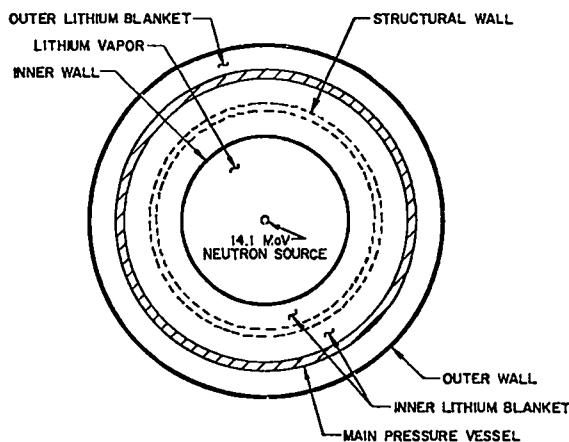


Fig. 17. LCTR calculational model.

The overall tritium breeding ratio for the basic design (i.e., without additional structure) is 1.48. There is approximately equal tritium production from ^6Li and ^7Li if natural lithium is used. The total energy deposition per original 14-MeV neutron is 23 MeV, consisting of 16 MeV directly from neutron interactions, 3.48 MeV from secondary γ -ray absorption, and 3.52 MeV from α particles. Introduction of the additional structural wall, as indicated in Fig. 17, reduces the tritium breeding ratio to the range of 1.07 to 1.40 as the outside radius of this wall varies from 1.075 to 1.695 m.

Neutron damage will be most severe for the wall surrounding the central cavity. Estimates have been made of neutron-damage effects in the first wall of each of the cavity concepts being evaluated, except the BLASCON which has no such structural component. These data are summarized in Table VIII; given for each cavity design for one year of operation at the indicated power level are 14-MeV neutron fluence, number of displaced atoms, and the amounts of interstitial gas production.

The neutron fluences and amounts of helium produced are quite large for some designs at the indicated power levels. As more information is accumulated, limiting design criteria are expected to evolve. The selection of optimum designs will require systems studies of tradeoffs between cavity power levels, cavity radii, and cavity replacement schedules.

The effects of 14-MeV neutron and 3.5-MeV α particle irradiations of structural materials are largely unknown. The data accumulated from the fission-reactor program are also of value for fusion

reactor design and analysis; but theoretical models are not yet adequate for correlating with confidence the irradiation data obtained in different neutron spectra. Additional high-neutron-energy irradiation data are urgently needed as a basis for improved theoretical models.

Materials Technology

Reactor cavity materials environments have been described previously (see Sections III and IV). Protection of cavity inner walls from damage by α particles and pellet debris is one of the most challenging problems facing designers of laser-fusion reactor cavities. Evaporation, ablation, and condensation of protective cavity liners will require extensive research for adequate understanding. The effects of essentially instantaneous energy deposition near surfaces of structural components also require investigation. Some problems may be associated with the design and fabrication of composite walls for the dry-wall and magnetically protected concepts. These problems arise from the mismatch in thermal expansion and irradiation-induced swelling between protective and structural materials, which might result in spall of the protective layer.

Cavity walls will also be subject to severe radiation damage from 14-MeV neutrons. Degradation in the physical and mechanical properties of structural materials can be expected. A large body of experimental data exists from the fission-reactor program on the effects of nuclear irradiation on the physical and mechanical properties of stainless steels, nickel-base alloys, and zirconium-base alloys. Very little information has been generated for the high-temperature refractory materials usually considered for fusion-reactor cavity walls. Based on the relatively small amount of data available, it appears that neutron irradiation may result in significant decreases in the elastic moduli, although these effects are apparently minimized if operating temperatures can be maintained above half the material melting point temperature.¹⁷

The greatest uncertainty with regard to the effects of neutron irradiation on structural materials is due to the production of copious amounts of interstitial gas from (n,p) and (n, α) reactions. Loss of ductility due to interstitial helium has been experimentally investigated by cyclotron

TABLE VIII
NEUTRON DAMAGE EFFECTS IN CAVITY WALL

Reactor Concept	Minimum Cavity Radius, m	Assumed Thermal Power Level per Cavity, MW	14 MeV nvt/ $\text{yr} \times 10^{-21}$	dpa, atoms/atom-yr	Gas Production ppm/yr	
					H_2	H_α
Dry Wall						
Carbon-lined	1.83	1000	27	172	938	271
Bare Niobium	5.95	1000	2.5	16	89	26
Magnetically protected bare wall (cylindrical)						
	2.4	1000	1.5 max	100 max	545 max	157 max
Wetted wall						
	1.67	100	3.2	21	112	32

irradiation with α particles.¹⁸ Stainless steel suffers a severe loss of ductility, which becomes progressively worse with increasing temperature and helium concentration. Loss of ductility due to helium implantations has been reported¹⁹ to be severe for vanadium and niobium alloys, but minimal for alloys of molybdenum (TZM).

Blanket Materials - The choice of blanket coolants is determined by anticipated operating temperatures (775 to 1275 K) and the necessity to breed tritium. Prospective materials are lithium, flibe ($\text{Li}_2\text{-BeF}_4$), helium, and (possibly) heat pipes containing potassium as the working fluid. Unless it is too costly or too difficult to remove tritium from circulating lithium, there are apparently fewer problems associated with the use of lithium than with flibe. The disadvantages of flibe result from its highly corrosive nature and from some of its transmutation products. Gas- and heat-pipe-cooling might be advantageous when coupled with tritium-breeding materials such as stagnant lithium, lithium alloys, or lithium compounds.

Techniques for fabricating large structures from refractory metals remain to be demonstrated. Some experience has been gained in fabricating large structures from niobium in the space program. Fabrication procedures such as welding apparently pose no significant problem for any of the prospective materials except molybdenum, which forms brittle weld zones. However, promising progress has recently been reported in developing brazing techniques for molybdenum.²⁰

Large amounts of hydrogen and tritium will be produced in the structural materials and in the lithium coolant. The formation of hydrides and the resulting embrittlement could be a serious problem. Niobium and vanadium do form stable hydrides at low temperatures; however, hydrogen solubility in these materials decreases rapidly with increasing temperature. If reactor cooldown can be programmed in such a manner that hydrogen is allowed to diffuse out of these materials during high-temperature operation and before room temperatures are reached, hydrogen embrittlement may not be a problem for these materials. Molybdenum does not form hydrides and has a very low hydrogen solubility. More information about the hydriding effect in steel is required.²¹

The problem of liquid-metal corrosion of structural materials must also be considered. Lithium is

compatible with the refractory metals up to temperatures of 1275 K or greater.²² The use of stainless steel presents difficulties because of solution-type corrosion and mass transfer at temperatures above 750 K. One of the major materials problems will remain that of maintaining corrosion resistances in welds and brazed joints that are necessary for fabrication of the walls. In general, corrosion in lithium is strongly dependent upon purity control. Therefore, lithium-purification equipment will have to be provided in reactor systems.

Note that the restrictions on blanket design due to the necessity of obtaining adequate breeding ratios appear much less demanding for LCTR concepts than for magnetically confined concepts. Assuming that tritium doubling times of the order of a year are satisfactory, very rugged cavity and blanket structures with natural lithium coolant are possible with acceptable breeding ratios.

Laser and Laser-Beam Transport Materials - Although laser designs for LCTR application have not been determined in detail, no particularly unique or demanding materials problems appear to be associated with CO_2 laser systems except for window materials. Windows must have good optical transmission and be resistant to damage from intense laser light and possibly from x rays, γ rays, and neutrons. They must also have mechanical and thermal properties compatible with other system requirements. Prospective materials include the alkali halides (NaCl , KCl , etc.), germanium, and the chalcogenides (GaAs , CdSe , etc.).

Damage from laser light to infrared window materials is generally assumed to be thermal in origin. Major importance is attached (1) to increasing the mechanical strength by developing polycrystalline materials and (2) to reducing the absorption constant to its lowest possible value.²³ Recent experience indicates that limitations on laser light intensity in infrared window materials are determined more by impurities than by intrinsic materials properties. Changes in window geometry and possible fracture are important problems resulting from temperature gradients due to repeated short pulses of intense laser light through large windows.

There has been substantial progress within the last few years in the understanding of laser damage mechanisms in window materials and in the development of materials which are resistant to such

damage. Continued improvement is expected, especially from better quality control.

Typical metallic reflectors (e.g., Cu, Au, Ni, Mo) are being developed for mirrors. Little is understood about damage from laser light to metallic surfaces, other than that it is believed to be thermal. There is also a lack of experimental damage data for repeated short laser pulses.

Very significant progress is being made in the development of mirrors. Surface-finishing techniques, including superpolishing, sputtering, and micro-machining are being rapidly improved. There has also been recent successful research in developing dielectric coatings for mirrors.²⁴ Coating with reflectivities greater than 99.8% can now be fabricated routinely.

The focusing mirror that "looks" into the reactor cavity is subject to damage from x rays, γ rays, neutrons, charged particles, and possibly cavity ablative material. Energy deposition on this reflecting surface may result in distortion and even surface spall. Atomic dislocations due to neutron collisions may result in damage to the optical surface as a result of the formation of color centers. The deposition of cavity ablative materials on the reflecting surface could enhance damage due to laser light. Essentially no data exist on which to base damage thresholds due to cavity-related phenomena. Experimental data must be generated to provide answers to these questions.

Tritium Processing Subsystems

Separation of tritium from the blanket material in a LCTR power plant is one of the major subsystems associated with laser-fusion power. The nature of the separation technique will be governed by requirements for low tritium concentration in the blanket-and reactor-coolant system. There are three reasons for maintaining a low tritium inventory; to minimize tritium leakage by diffusion to the environment during operation, to minimize the tritium inventory that could be released from the primary system in an accident, and to minimize the tritium fuel held in inventory so that for a given breeding ratio the overall doubling time is minimized.

The tritium handling subsystem may be subdivided into sub-subsystems; tritium separation from blanket (or cavity debris), purification, liquefaction and isotope adjustment, and fuel-pellet fabrication.

Recovery of unburned tritium from the fuel debris in the LCTR reactor cavities may be accomplished separately from the recovery of the tritium bred in the blanket material and may involve a different separation process from that applied to the blanket tritium.

J. S. Watson²⁵ of ORNL and J. L. Anderson²⁶ of LASL, have summarized tritium handling and lithium-tritium separation problems applicable to magnetically confined fusion-reactor systems. Their work also appears to be directly applicable to LCTR systems. Both researchers point out that, due to the scarcity of experimental data on tritium in lithium at low concentrations, significant uncertainties exist as to the feasibility and ranges of application of any of the known separation methods. Watson presents data favoring separation with semipermeable membrane technology, whereas Anderson proposes liquid-liquid extraction with a molten salt. Other methods have been suggested.

Because, at this time, experimental data do not exist to provide a basis for the selection of any one method, a research and development effort is required to acquire the basic physical chemical data and to investigate the several promising separation concepts.

Purification, liquefaction, and isotope adjustment in the tritium fuel cycle are based on more conventional technology.²⁷ The sequence of operations in the reference plant 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 is adjusted stoichiometrically by cryogenic distillation or by the addition of deuterium, as required, and the stoichiometric DT is then transported to the fuel-pellet fabrication and injection devices.

V. PARAMETER STUDIES AND TRADEOFFS

General

The first stages of LCTR performance and sensitivity studies have centered on the development of the tradeoff and analysis program TROFAN and on examination of several first-order effects of LCTR parameter variations. This program is designed to simulate energy, mass, and dollar flows for the reference LCTR central-station power plant. Figure

18 is a schematic of the energy and mass flows in a LCTR power plant. Power cost is calculated as the primary figure of merit by TROFAN.

Program TROFAN Organization

Version I of the program is oriented as follows:

TROFAN - The main program provides calculational organization, and energy and mass balances. It is designed as a system simulation to accommodate a large number of variable parameters. Laser-beam energy on target and net plant electrical power are fixed, and the necessary number and characteristics of reactor components are calculated. Calculations performed in TROFAN include:

- LAS - The energy and cost parameters associated with the laser subsystems. Laser capital cost for various laser system configurations. The laser system may be centralized with a single, or small number of lasers switching between a larger number

of reactor cavities; it may be completely distributed with each reactor cavity beam port being assigned to its own unique laser system; or it may be any combination of centralized or distributed electrical systems, power amplifiers, etc.

- BMT - The efficiency and cost of the beam-transport systems. The types and distributions of lasers and reactor-cavity beam ports. Constraints on the beam-transport system include maximum allowable mirror and window laser fluences. From these criteria and the number of optical surfaces, the beam transport costs are calculated.
- CAV - Cavity dimension, weight, and cost for three cavity types; wetted wall, magnetically-protected wall, and lithium vortex (BLASCON).
- CST - Energy produced and cost information are combined into a single objective function,

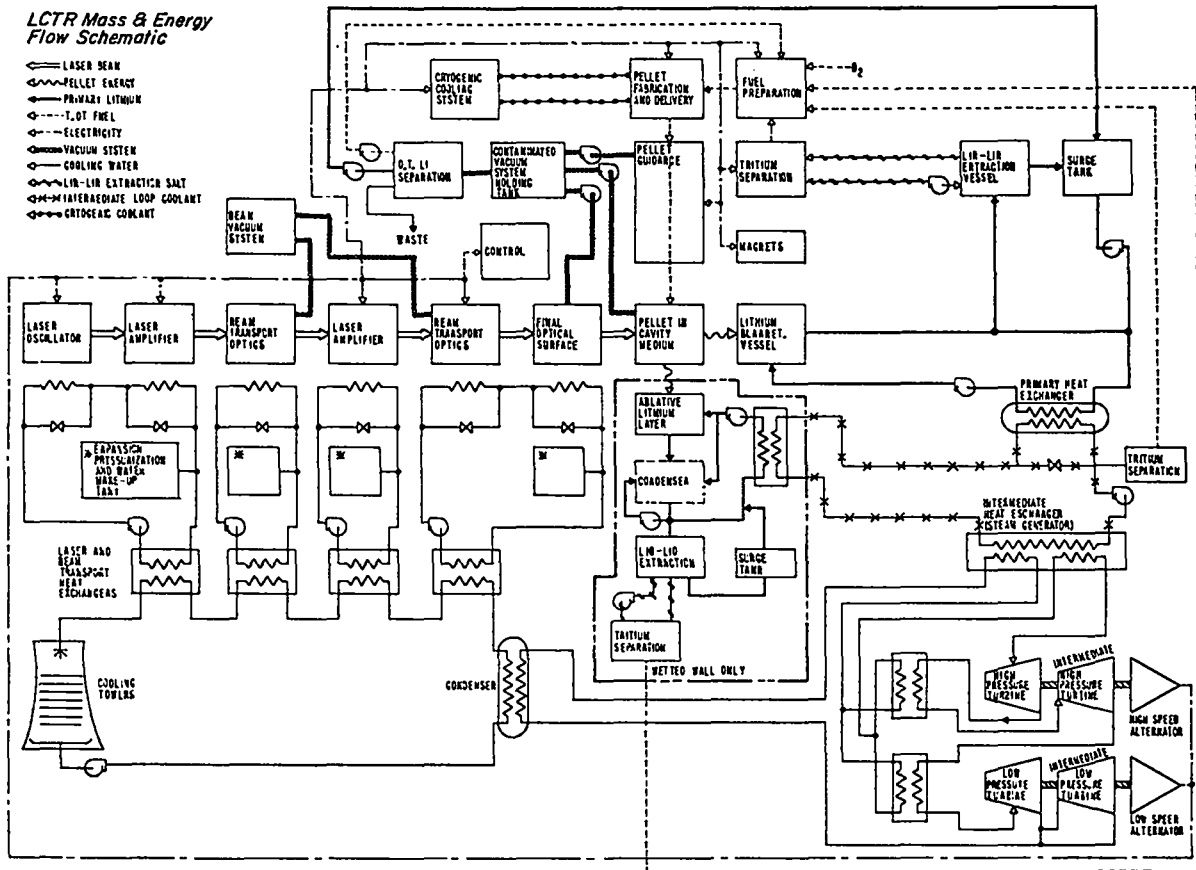


Fig. 18. LCTR mass and energy flow schematic.

net power cost. The operating cost is given as the sum of the amortized capital cost, fuel costs, estimated maintenance costs, laser and auxiliary (i.e., fuel system, magnetics, beam vacuum, etc.) costs, and other miscellaneous operating costs. Provision is made for variable amortization rates based on individual component mean-lifetime criteria and for individual duty cycles.

Tradeoff Analysis

The results presented in this section are taken from parametric studies in progress and are intended as an illustration of the systems studies methodology, not as being representative of final conclusions to be drawn from these studies.

More definitive LCTR models, being developed, will make meaningful comparisons of alternative reactor concepts possible. The parametric comparisons presented here will undoubtedly change.

Calculations were made to compare characteristics of nominal 1000-MWe plants with 1-MJ laser energy per pulse on bare DT spherical pellets. The nominal reference design parameters are listed in Table IX. Capital and power costs are summarized

TABLE IX
NOMINAL REFERENCE DESIGN PARAMETERS, 1150 MWe

	Wet Wall	Mag. Shield	BLASCON
Normal power per cavity, MW	100	1000	10
Net electrical power per cavity, MM	30	300	3
Number of cavities	35	4	345
Circulating power, %	27	29	27
Net plant efficiency, %	29	28.5	29
Thermal-electric conversion efficiency, %	40	40	40
Pulse rate, s ⁻¹	1	10	0.1
Pellet irradiation geometry	Spherical	Spherical	One-sided
Reactor dimensions			
Shape	Sphere	Cylinder	Sphere
Cavity radius, m	1.7	2.4	---
Lithium blanket thickness, m	1.0	1.0	1.
Outer radius, m	2.8	3.1	1.1

TABLE IX (cont.)

Vessel wall thicknesses, cm			
First wall	1.0	1.0	---
Inner vessel	5.0	5.0	---
Outer wall	10.0	10.0	25.4
Blanket envelope	2.5	2.5	2.5
First wall/liner parameters			
Energy deposition, J/cm ²	---	---	---
Affected thickness, mm	1	0	---
Reactor materials			
Structure	SS	SS	SS
First wall	Nb	Nb	---
Beams per cavity	8	8	1
Breeding ratio	>1.2	>1.2	>1.2
Reference Laser Design			
Central laser source; CO ₂ E-beam pumped			
Energy per pulse, MJ			0.125
Pulse repetition rate, s ⁻¹			30-40
Efficiency, %			10
Wavelength, μm			10.6
Pulse width, ns			0.1-1
Fluence on last optical surface, J/cm ²			10
Length x width x diameter, m			3 x 0.35 x 4
Reference Beam Transport System			
Number of beams per cavity			1 or 8
Number of mirrors per beam			8
Number of windows per beam			1
Reflectivity of mirrors			0.995
Transmissivity of windows			0.97
Maximum laser flux on windows, J/cm ²			3
Maximum laser flux on mirrors, J/cm ²			10
Transmissivity in reactor media			>0.98
Limiting x-ray flux, J/cm ²			0.16
Neutron flux, J/cm ²			
Final optical surface			Al/Ni mirror
Diameter of final optical surface, m			3.57 or 1.26
Focal length, m			6.7
Net beam transport efficiency, %			91
Reference Design Pellet			
Bare DT sphere			
Gain from fusion (1 MJ laser pulse)			100

TABLE X
REFERENCE REACTOR COST SUMMARY

	Wetted Wall	Mag. Protected Wall	BLASCON
<u>System Characteristics</u>			
Net elect. output, MWe	1160	1140	1150
No. of reactor vessels	40	4	397
Net eff., %	29	28.5	29
Circulating power fraction	0.274	0.287	0.274
<u>Capital Costs, 10⁶ \$</u>			
Lasers	22	22	22
Beam transport	20	3	184
Reactor	133	35	159
Generating plant	135	135	133
Fuel system	28	25	40
Magnetic system	---	10	---
Struct., elect.	182	182	181
Fixed costs	1	1	1
Total Capital Cost	520	413	721
<u>Power Costs, mills/kWh</u>			
Capital amortization	7.82	6.31	10.95
Fuel	0.25	0.25	0.25
Labor and maintenance	0.50	0.50	0.50
Net Power Cost	8.57	7.06	11.70

in Table X. The total net power costs vary by less than a factor of two, which is probably well within the range of uncertainties in the analysis at this time. The intent of this comparison is to show the capability of the code and not to indicate the relative ranking of the various concepts. The sensitivity studies discussed below are probably the most useful at this time.

From Fig. 19, it may be seen that the system is highly sensitive to reactor cavity pulse rate. The BLASCON is the only concept capable of economic operation at very low pulse rates, and the magnetically protected concept requires a relatively high pulse rate for economic operation. Choices of one pulse every ten seconds for BLASCON, one pulse per second for the wetted wall, and ten pulses per second for the magnetically protected concept were based on the best information available, but are necessarily somewhat arbitrary.

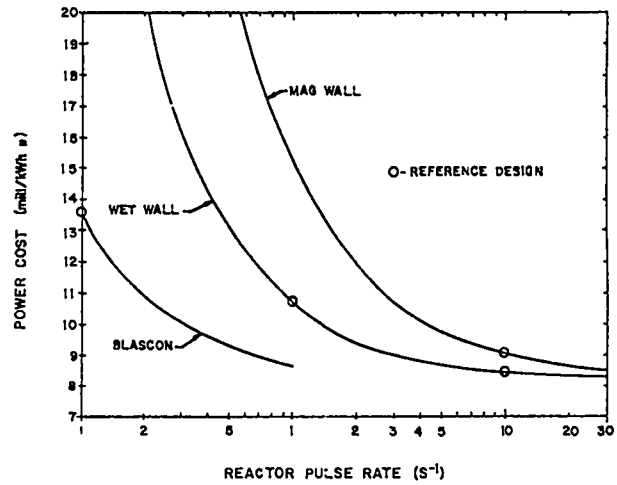


Fig. 19. Effect of reactor pulse rate on net power cost for reference reactor systems.

The sensitivity of power cost to pellet gain is shown in Fig. 20. A pellet gain of ~ 50 is required for economic operation. Note that the work to date has been confined to pure fusion systems. The additional gain in power that could be obtained in a hybrid fusion-fission reactor with depleted uranium or thorium in the blanket may warrant investigation. Figure 21 displays the tangents to the power cost vs gain curve at the nominal design point and indicates the relative sensitivity to pellet gain.

Power cost is plotted as a function of laser efficiency in Fig. 22. Laser efficiencies above 4% are apparently required for economic operation.

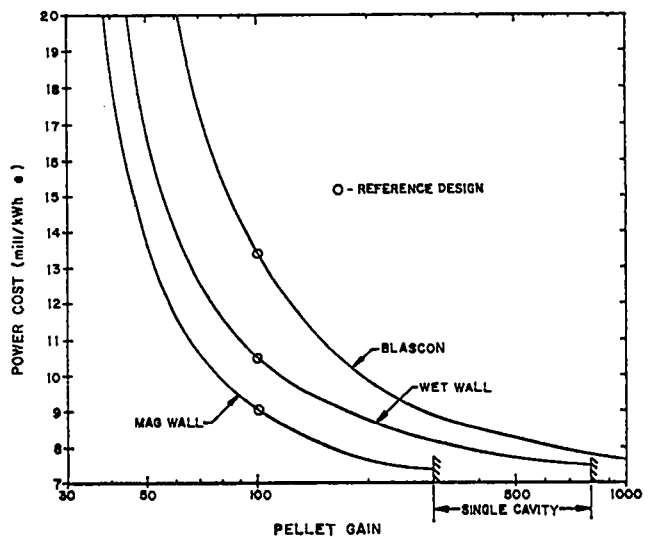


Fig. 20. Sensitivity of reference reactor power cost to pellet gain.

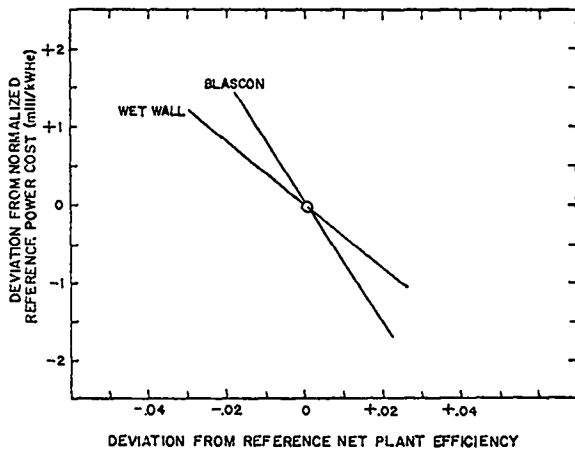


Fig. 21. Sensitivity of power cost to pellet gain component of net plant efficiency.

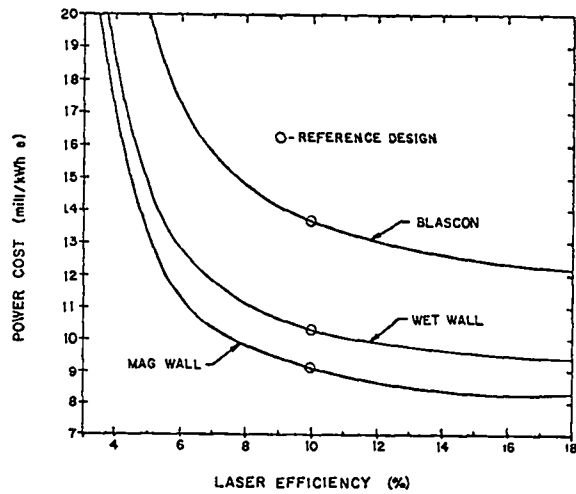


Fig. 22. Reference reactor power cost sensitivity to variation in laser efficiency.

The net LCTR plant efficiency is a function of pellet gain and of the efficiencies of the laser, beam transport, and electric-generating subsystems. Relative sensitivities are indicated in Fig. 23 for the wetted-wall design. The other concepts show similar behavior.

Figures 24 and 25 show the sensitivity of net power cost to laser system configuration and nominal unit laser costs. A more recent estimate of laser capital costs for megajoule systems indicates that the \$20/J reference design cost is apparently too low. Thirty dollars per joule may be realistic for

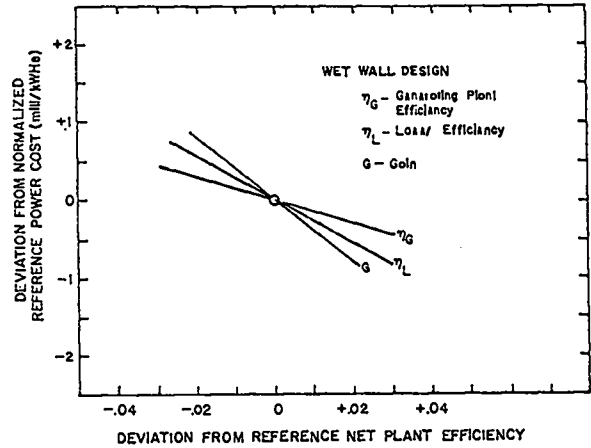


Fig. 23. Sensitivity of power costs to subsystem efficiencies.

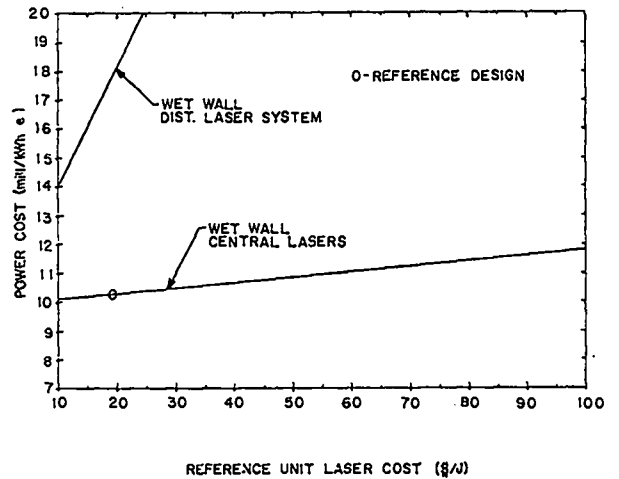


Fig. 24. Sensitivity of power cost to laser unit costs for distributed and central laser systems.

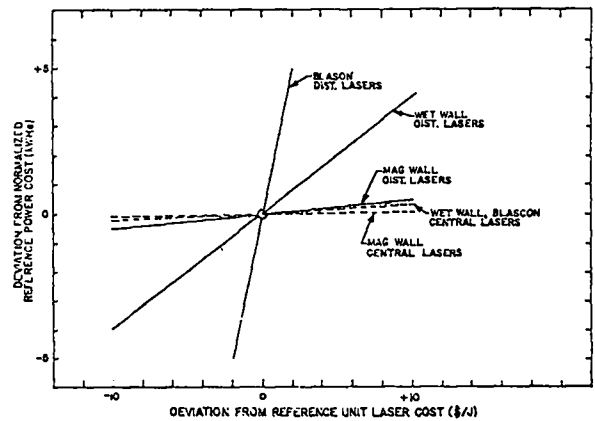


Fig. 25. Effect of laser unit cost variations on power cost.

advanced systems and \$50/J or more is representative of near-term technology.

For the systems considered in this initial tradeoff study, fuel pellet cost is not critical in the range examined (Fig. 26). Considerable investigation will be necessary before detailed evaluations of fuel cycle costs can be made. The nominal reference designs were based on stainless-steel construction (except for the first wall). The cost adjustment that is made when all walls of the wetted-wall concept are made of niobium is indicated in Table XI.

VI. SAFETY AND ENVIRONMENTAL CONSIDERATIONS

The potential environmental impact of laser fusion can be divided into the following areas of concern:

- Radioactive contamination,

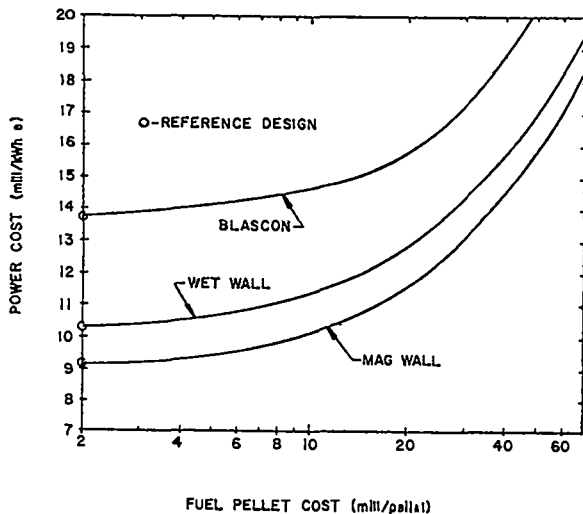


Fig. 26. Reference reactor power cost sensitivity to variation of individual fuel pellet cost.

TABLE XI
REFERENCE REACTOR COST ADJUSTMENT FOR
WETTED-WALL REACTOR FABRICATION
WITH NIOBIUM

I. Capital Costs (10^6 \$)	
Reactor system increment	+263
II. Power Cost (mill/kWh)	
Revised power cost	12.6
Increment in power cost	4.0

- Safety,
- Thermal pollution, and
- Resource utilization.

Considerations relating to radioactive contamination arise from neutron activation of structures and coolant, the production and handling of tritium, and radioactive waste disposal. Activation of structures and coolant is strongly dependent on the materials used. Historically, there has been widespread consideration of niobium structure in conceptual design studies, thus requiring evaluation of the niobium activation problem. Niobium activation would be comparable in magnitude to that of fuel elements and structures in a liquid metal fast breeder reactor of the same size.²⁸ Afterheat probably is not of sufficient magnitude to make loss-of-coolant considerations important; however, repair and replacement of reactor cavity and blanket components will have to be done remotely.

Materials other than niobium are being considered for reactor structures. The most attractive refractory material with regard to induced activity is vanadium. Afterheat and biological hazard for vanadium would be several orders of magnitude lower than for niobium for times after shutdown of ~ 100 days and longer.²⁹ Other alternatives for reactor structures include molybdenum and nonrefractory materials such as stainless steel and aluminum.

The greatest potential radioactive hazard is due to tritium. It will be necessary to minimize tritium leakage during normal operation and to minimize tritium inventories in order to reduce the effects of an accidental release. Conceptual LCTR power plants lend themselves very well to stringent tritium controls because of their modular nature. Because compact coolant loops and processing systems which minimize the lithium and tritium inventory can be conveniently designed, the conceptual plant described in Section III includes ten separate and independent tritium-handling systems.

The problem of waste disposal has been put in perspective by data presented in Refs. 28 and 30. For fission reactors the worst products are the long-lived isotopes of strontium, cesium, and plutonium.³¹ Their total cumulative steady-state waste level is ~ 0.15 Ci/W electrical of installed capacity. Similar considerations for a fusion

reactor would result in ~ 0.6 Ci/W electrical if the reactor were made entirely of niobium or in ~ 0.0006 Ci/W if it were made of vanadium. The problem for fusion reactors is diminished, probably by orders of magnitude, because the activated structural components in a fusion reactor are relatively easy to handle and to control when compared to the fission products that must be handled and processed in fission systems.

There is no imaginable way that a dangerously large amount of thermonuclear energy could be released inadvertently in a fusion power plant. Even if large amounts of thermonuclear fuel were injected into a reactor cavity, such fuel could not achieve thermonuclear burn conditions. Pellet microexplosions are limited in magnitude by pellet disassembly, and available data indicate that it will be difficult to burn more than a few percent of a fusion pellet under ideal and carefully controlled conditions.

However, an important safety consideration, other than the release of radioactivity, has been identified for laser-fusion reactors and is associated with the lithium coolant. Lithium burns vigorously in the presence of water, but is much less reactive than sodium, for instance. Again, the lithium inventories in a LCTR power plant are modularized so that the probability of a serious safety problem is minimized. There is, in addition, the likely possibility that gas- or heat-pipe-cooling will be used in conjunction with lithium alloys or lithium compounds for blanket construction, which will essentially eliminate this safety problem.

A safety problem for magnetically confined thermonuclear reactors, not present in laser-fusion systems, is that of superconductors which might go normal and bring about a sudden and possibly dangerous energy release.

The problem of thermal pollution calls attention to a disadvantage of laser-fusion power plants, as they are currently envisioned, when compared to magnetically confined fusion reactors. This disadvantage stems from the fact that laser-fusion power plants will have comparatively high recirculating power fractions; thus, the net efficiency, based on 40% efficient conversion, is expected to be only $\sim 30\%$. This problem may be alleviated by the development of lasers with higher efficiencies

than currently expected or by the development of fusion pellets with larger gains than now predicted, either or both of which are highly possible.

A potential environmental problem associated with LCTR power plants which has not been evaluated is that of noise pollution. A 1000-MWe plant will require ~ 40 1-MJ laser discharges and 100-MJ pellet microexplosions per second.

Resource utilization will be determined by the fuel cycle used and by the materials utilized for reactor structures. If the DT cycle is used, the necessity of breeding tritium requires the use of lithium. Known and inferred reserves of lithium in the US amounted in 1970 to $\sim 6 \times 10^9$ kg.³² These reserves are equivalent, in thermonuclear energy production from the DT cycle, to ~ 900 times the 1970 world-energy consumption and to ~ 3000 times that of the US. Some refractory metals, such as niobium, are not plentiful enough from resources now being mined to support an all-fusion economy. Present mining operations are relatively non-polluting; however, greatly increased demand might necessitate strip-mining to obtain low-grade deposits. Resources of molybdenum and vanadium are somewhat more plentiful.³³

VII. SUMMARY

General

Feasibility evaluations, engineering analyses, and systems studies of LCTR power plants are very preliminary. Significant technological advances must be made to satisfy the requirements for economical power from LCTR power plants. However, much of the technology developed in fission-reactor and space programs is also applicable to the fusion-reactor program.

The severity of materials problems can be estimated from studies of the various conceptual approaches. The results of these studies, together with overall plant systems studies, can be used as a guide to the planning of experimental investigations. The selection of materials investigations to be conducted will be determined, to some extent, by the availability of testing environments, and there are many opportunities for innovative approaches to obtaining the required LCTR materials data.

In fission-reactor technology development, there is a severe time lag between the initiation of experiments and the reduction of experimental data for use in engineering design. This is particularly true for such areas as radiation-, fatigue-, and corrosion-testing. This emphasizes the need for timely planning and initiation of programs to obtain required data. Fortunately, much of the required data will be applicable to the design of both magnetically confined and LCTR concepts.

Although much analytical and experimental investigation remains to be done, no problems have been discovered for which there are not reasonable conceptual solutions.

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