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DESIGN CONSIDERATIONS IN INERTIALLY-CONFINED FUSION REACTORS

JACK HOVINGH

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INTRODUCTION

Inertial confinement of thermonuclear reactions is becoming a viable alternate to magnetic confinement of thermonuclear reactions as a future energy source. Inertial confinement consists of compressing a tiny fueled pellet of deuterium-tritium to very high densities and temperature using intense beams of photons or particles. This beam can consist of photons¹⁻³, electrons⁴⁻⁶, or ions.^{7,8} At the present time, most of the inertially confined reactor design is orientated toward using photon beams, although some work has been published on design consideration of an electron-beam induced reactor system⁹, and a design study is being carried out on an ion-beam induced reactor system.¹⁰

This paper presents an overview of the materials problems in inertially-confined fusion reactors, with the emphasis placed on laser-initiated systems. Also presented are descriptions of several conceptual laser-fusion reactor designs, as well as a brief discussion of fusion-fission hybrids.

BEAM-PELLET INTERACTION AND MICROEXPLOSION

In a beam driven, inertially confined fusion-reaction, the high intensity beam is focused on a pellet containing fusible material, usually a mixture of deuterium and tritium. The surface of the pellet is instantaneously vaporized into a low density plasma atmosphere. As the ablated mass accelerates outward into the microexplosion cavity, it generates an equal and opposite force that drives the pellet toward its center, increasing the density of the pellet. The high temperature required for fusion will be obtained during the compression of the pellet

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Jack Hovingh
Lawrence Livermore Laboratory
University of California, Livermore, CA 94550

ABSTRACT

This paper discusses the effects of short time pulses of energetic particles and waves typical of inertially-confined thermonuclear reactions on the first wall, blanket and shield of conceptual reactors. Several reactor designs are presented which attempt to cope with the various problems from the microexplosion debris. Fusion-fission hybrid reactors are also discussed. Emphasis is placed on the first-wall problems of laser-initiated, inertially confined fusion reactors using the deuterium-tritium fuel cycle.

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by compressive work. Under the appropriate conditions, ignition at the center of the pellet occurs, and a thermonuclear burn front propagates outward from the center of the pellet by the energy deposition of the fusion products in the pellet material. The thermonuclear burn continues until the temperature and/or density of the fuel in the pellet decreases to a point where a thermonuclear reaction cannot occur.

ENERGY DISPOSITION FROM BEAM-PELLET INTERACTION AND MICROEXPLOSION

The energy partition and spectra of the laser-pellet interaction and microexplosion are dependent on several parameters. These include on the laser characteristics such as wavelength, energy and peak power as well as the pellet mass, composition and design. These characteristics will determine the amount of laser light reflected from the pellet, as well as the pellet compression and gain Q , defined as the ratio of thermonuclear yield to the laser energy on target. The physics of the laser induced implosion and thermonuclear burn of the pellet is very complex.¹¹ Thus large computer codes such as LASNEX have been developed to calculate the transport and interaction of laser photons, electrons, ions, x-rays and fusion reaction products, together with the magnetic and electric fields and the hydrodynamics behavior of the pellet.¹²

Basically, thermonuclear microexplosion scale as the density-radius product ρR . The rates of burn, energy deposition by charged reaction products and the electron-ion heating are proportional to the density, and the inertial confinement time is proportional to the radius of the compressed pellet. Consequently the burn efficiency, self heating and feasibility of the thermonuclear propagation are determined by ρR . For a power reactor,

the ρR must be on the order of 3 g/cm^2 such that the alpha particles can deposit their energy within the pellet to boot strap the thermonuclear reaction by heating additional fuel. The burn fraction of the pellet is approximately given by

$$f = \frac{\rho R}{6.3 + \rho R} \quad \rho R \sim 1 \text{ g/cm}^2 \quad (1)$$

The gain of the pellet G as a function of its compression for various laser energies on target is shown in Figure 1.¹³ These curves show that for a given laser energy on target E_a , there is an optimum pellet compression that results in a pellet peak gain. Plotting the peak gains shown in Figure 1 as a function of laser energy on target results in

$$G = 1.55 E_a^{2.14} \quad (10^3 \leq E_a \leq 10^6) \quad (2)$$

where G is the peak gain for a laser output energy E in joules. The yield per unit mass of the compressed pellet is¹⁴

$$\frac{E_f}{m} \approx 326 \frac{\rho R}{6.3 + \rho R} \quad \text{KJ/g} \quad (3)$$

The laser light can be reflected from the DT plasma surrounding the pellet by collective processes such as Brillouin and Raman instabilities before it reaches the critical plasma density. For a given case of an initial plasma temperature of 1 keV and effective density gradient of the inhomogeneous plasma of $16 \text{ } \mu\text{m}$, the induced reflection begins abruptly at an intensity of about $2 \times 10^{15} \text{ W/cm}^2$ and increases rapidly to about 50% for an intensity of 10^{16} W/cm^2 . For plasmas with longer density gradients, the reflection becomes even larger at this intensity and approaches a theoretical limit of over 90%. This reflection may persist for times on the order of 100 ps .¹⁵

Figure 1. Pellet Gain, G , as a Function of Compression for Several Laser Energies on Target, E_a .

The total x-ray energy of a typical laser-fusion reaction using a DT pellet is about 1% of the thermonuclear yield. Thus, in terms of the laser output energy, the X-ray energy E_x is

$$E_x \approx 0.01 Q E_L \quad (4)$$

where Q is the pellet gain and E_L is the laser output energy. Note that from equation (2), where r is the pellet reflectivity

$$Q = G(1-r); \quad E_L = \frac{E_a}{1-r} \quad (5)$$

The X-ray spectrum is shown in Figure 2. The bulk of these x-rays are produced during the thermonuclear burn, which typically lasts about 10 ps.

The neutron energy yield of a typical microexplosion is about 76% of the thermonuclear yield, or in terms of the laser output energy

$$E_n \approx 0.76 Q E_L \quad (6)$$

The neutron spectrum is shown in Figure 3 for a ρR of about 3. The mean free path length of the 14-MeV neutrons in the pellet is¹⁶

$$\frac{\lambda_n}{R} \approx \frac{4.6}{\rho R} \quad (7)$$

where R is the compressed pellet radius. The neutrons from a laser-fusion reaction are released during the burn time of 10 ps.

The pellet debris energy, including the unburned deuterons, tritons and alpha particles energy typically is about 23% of the thermonuclear yield. Thus, in terms of the laser output energy

$$E_{cp} \approx 0.23 Q E_L \quad \text{KJ} \quad (8)$$

Figure 2. X-Ray Pulse Spectrum of a Megajoule DT Fusion Microexplosion.

The mean free path length of the 3.5 MeV alpha particles in the pellet is,¹⁴
for an electron temperature of 10 keV,

$$\frac{\lambda}{R} \approx \frac{0.23}{\rho R} \quad (9)$$

Thus, for a ρR of 3, most of the alpha particle energy is deposited in the pellet, such that only a small fraction of alpha particles escape the pellet with energies significantly greater than the average pellet debris energy. The energy of the debris is nearly Maxwellian distributed with the average energy equal to the energy deposited in the pellet from the laser and burn divided by the number of pellet particles.

For an electron-beam induced fusion reactor system using a DT pellet covered with a thin layer of gold, the energy partition of the thermonuclear yield as estimated by Varnado and Carlson⁹ is given in Table I. The x-ray spectrum is typical of a 350 eV blackbody. The intensity as a function of time is roughly triangular, with a base width of 7 ns. The energy of the gold shell surrounding the DT fuel lies between 100 and 500 keV.

TABLE I
Results of Calculations for Electron-Beam-Induced Fusion Reaction

Energy Absorbed (MJ)	Thermonuclear Energy Released (MJ)	Deuteron Energy		Triton Energy		X-Ray Energy		Q
		(MJ)	(%)	(MJ)	(%)	(MJ)	(%)	
4.0	4.0	3.0	40.0	3.2	50.0	1.6	20.0	1
10.8	85.6	67.8	70.7	11.8	12.3	16.2	17.0	7.9

Figure 3. Neutron Pulse Spectrum of a MegaJoule DT Fusion Microexplosion.

ENERGY DEPOSITION FROM THE BEAM-PELLET INTERACTION AND MICROEXPLOSION¹⁷

The stresses and temperature rise in the reactor are a function of the energy deposition of the various laser/pellet interaction and burn products in the reactor. The present models used to estimate the energy deposition in the reactor for the laser light reflected from the pellet, x-rays and pellet debris from the microexplosion are described below.

Part of the laser light reflected from the pellet is deposited and part is reflected from the first wall. Thus, the photon energy will be deposited in a series of pulses, each with a diminished amplitude. This, by thermal diffusion of the photon energy reduces the temperature rise in the first wall due to the photons. The first-pulse energy density, q'' , of the photon deposition in the first wall is

$$q''_L(x) = \frac{rE_L \alpha \Sigma}{4-R^2} \exp(-\Sigma x) \quad \frac{\text{KJ}}{\text{m}^2} \quad (10)$$

where R is the first wall radius in meter, α is the absorptivity of the first wall surface, Σ is the photon energy attenuation coefficient in m^{-1} , r is the reflectivity of the pellet to the incident laser light, E_L is the laser output energy in KJ, and x is the depth into the first wall in m. From classical relationships for the propagation of electromagnetic radiation in homogeneous, isotropic, conducting media at rest,¹⁸

$$\begin{aligned} \Sigma &= 4\pi \cdot \frac{\omega^2}{c^2} \\ \alpha &= 2 \sqrt{\frac{c}{\lambda \sigma}} \end{aligned} \quad (11)$$

where μ is the magnetic permeability, σ is the electric conductivity, c is the velocity of light and λ is the wavelength of the photons. Combining the above three equations,

$$q_i''(x) = 2 \left(\frac{rE_L}{\lambda R^2} \right) \exp(-\Sigma x) \frac{KJ}{\text{cm}^3} \quad (12)$$

where λ is the wavelength in μm .

For the typical x-ray spectrum shown in Figure 2, using a code developed by Cole¹⁹ the energy deposition as a function of depth for several first-wall liner designs is shown in Figure 4 for a 100-MJ-yield microexplosion with a first-wall radius of 1 m (80 kJ/m² of x-rays). The results scale with x-ray flux. The fraction of the incident x-ray energy flux that escapes through the 0.7-mm liner is less than 10% for various liner material combinations, except for the solid graphite liner, which transmits about 60% of the incident x-ray energy flux.

The energy deposition at a depth x in the first wall is given by

$$q_{cp}''(x) = \frac{A_0}{4\pi R^2 \alpha_i} \left(\frac{m_i}{M_i} \right) \int_0^\infty \frac{1}{\sqrt{2\pi}} y^{1/2} \exp\left(-\frac{y^2}{2}\right) dy \quad (13)$$

$$\frac{A_0}{\alpha_i M_i} \left(\frac{M_i}{E_T} \right) \approx$$

where R = first wall radius

M_i = molecular weight of debris i

m_i = mass of debris i

M_T = mass of pellet

E_T = pellet energy

A_0 = Avogadro's number

α_i = range-energy constant for species i in first wall material

$q_i''(x)$ = energy deposition of species i at position x in first wall

Figure 1. X-Ray Energy Deposition for an X-Ray Fluence of 80 kJ/m²

Equation (13) was derived for a Maxwellian energy distribution of a given species of the microexplosion debris, assuming that these particles deposit their energy E uniformly over the range $P(E)$ in the first wall and that the range of the particles of a given species of debris is proportional to their energies such that $P_i(E_i) = \alpha_i E_i$.

The constant in front of the integral is the energy deposition at the surface, while the lower limit of the integral is the position normalized to the range of a particle whose energy is the average of the debris energy spectrum. The above equation is plotted in Figure 5. The total energy distribution in the first wall from the microexplosion debris is given by summing the above distribution over all species.

A better estimate of the energy deposition in the first wall from the microexplosion debris can be made using the methods of Brice²⁰ or Winterbon.²¹

The pulse time over which 90% of the debris energy arrives is

$$\tau = 0.01R(M_T/E_T)^{1/2} \quad \text{s}, \quad (14)$$

where M_T is the mass of the pellet in grams and E_T is the energy into the mass in joules. Note that the above expression for the pulse time neglects the lower 5% of the debris energy as well as 5% of the high-energy tails.

The first-wall 14 MeV neutron fluence per DT microexplosion is

$$\dot{n} = 2.0 \times 10^{13} \frac{QE_L}{R^2} \frac{n}{\text{m}^2 \cdot \text{pulse}} \quad (15)$$

Figure 5. Charged Particle Energy Deposition in First Wall.

The ordinate is the energy deposition normalized to the surface energy deposition, and the abscissa is the position normalized to the range of a particle whose energy is the average of the debris energy spectrum.

where R is the first wall radius in meters. The energy deposition per source neutron in a blanket assumed to be a homogeneous mixture of 95% natural lithium and 5% niobium behind a 5mm thick first wall located 2.2m from the micro explosion is shown in Figure 6. At the outer radius of the blanket is a 50 mm thick niobium shell. A point source of 14-MeV neutrons is assumed to be located at the point of the microexplosion. Coupled neutron-gamma transport calculations utilizing a P_3 - S_{16} * option of the discrete ordinates code ANISN²² were used to determine the neutron and gamma-ray fluence and energy density distributions in a one-dimensional spherical model of the blanket. The P_3 coupled cross-section set, consisting of 30 neutron energy groups and 15 gamma-ray energy groups, was generated from the LLL Evaluated Cross-Section Library.²³

EFFECTS OF ENERGY DEPOSITION TIME ON TEMPERATURE AND STRESS

The sudden deposition of the burn product energy in the first wall results in stress due to the thermal gradients in the material from non-uniform heating and conduction, as well as inertial effects. The boundary value problem is of considerable mathematical difficulty as it combines the theories of elasticity and viscoelasticity as well as heat conduction. Usual engineering solutions are obtained by omission of the mechanical coupling term in the energy equation and the inertia terms in the equation of motion. The basis for the omission of the mechanical coupling term and the inertial term is a consideration of the characteristic times of the system. These time considerations will be discussed below.

* P_3 represents the order of the Legendre expansion and S_{16} represents the order of angular quadrature.

Figure 6. neutron Energy Deposition Per Source Neutron in the Blanket Region of a LCTR. The First Wall Radius is 2.2 m From Source.

For each source of energy deposition in the first wall we assume over the pulse time τ that

$$q''(x) = q_0'' \exp[-\sigma x], = \frac{E\sigma}{4\pi R^2} \exp[-\sigma x] \quad (16)$$

where q_0'' is the energy deposition in the surface layer of the first wall, E is the energy from a given source and σ is the energy attenuation coefficient through the first wall as the ratio of the energy storage in the distance σ^{-1} , to the rate of heat conducted across the distance σ^{-1} , or

$$\tau_T = [\sigma^2 \alpha]^{-1}, \quad (17)$$

where α is the thermal diffusivity of the first-wall material. We also define the characteristic mechanical time of the energy deposition in the first wall as time required for a disturbance to propagate the distance σ^{-1} , or

$$\tau_m = [\sigma c]^{-1}, \quad (18)$$

where c is the wave velocity in the first-wall material. The typical energy attenuation coefficients, pulse times, and thermal and mechanical times are shown in Table II for fusion reaction products. The X-ray energy attenuation coefficient given is due primarily to the soft portion of the X-ray spectrum. For the purpose of this study, the alpha particles are assumed to be part of the charged-particle debris. For pellets that will be used in a reactor, most of the alpha-particle energies will be deposited in the pellet. Only about 5 to 10% of the alpha particles interacting with the first wall have an energy significantly greater than the average pellet debris energy. The neutron energy deposition in the first wall is small, but the data given in Table II are relevant to the interaction of the neutrons with the blanket material.

A qualitative comparison of the various times from Table II is shown in Table III. Also shown in Table III is the relative surface-layer energy deposition, which is simply the surface flux times the energy attenuation coefficient.

TABLE II

Energy Attenuation Factors and the Pulse Time, and Mechanical and Thermal Characteristic Times for Laser Fusion Reaction Products in Typical First Wall Materials

	<u>Photons</u>	<u>X-rays</u>	<u>Charged Particles</u>	<u>Neutrons</u>
σ, m^{-1}	10^8	10^5-10^6	10^5-10^6	$1-10$
τ, s	10^{-10}	10^{-11}	10^{-6}	10^{-11}
τ_m, s	10^{-11}	$10^{-9} - 10^{-8}$	$10^{-9} - 10^{-8}$	$10^{-4} - 10^{-3}$
τ_T, s	10^{-11}	$10^{-7} - 10^{-5}$	$10^{-7} - 10^{-5}$	10^3-10^5

TABLE III

A Relative Comparison of the Surface Layer Energy Deposition, and Qualitative Comparisons of Pulse, Mechanical and Thermal Characteristic Times of Burn Reaction Products

	<u>Surface Energy Deposition</u>	<u>Times</u>
Photons	$3 \times 10^7 (r/Q)$	$\tau \approx \tau_T \approx \tau_m$
X-rays	5×10^3	$\tau < \tau_m < \tau_T$
Charged Particles	$5 \times 10^5 [.2 + (1-r)/Q]$	$\tau_m < \tau_T \approx \tau$
Neutrons	1	$\tau < \tau_m < \tau_T$

r = pellet reflectivity to incident laser light

Q = thermonuclear gain of the pellet

The temperature rise and peak stress due to the energy deposition from the X-rays and neutrons can be estimated using very simple models because the pulse time is short compared to the characteristic mechanical and thermal times. The simple model for the temperature rise is given by

$$\Delta T(x) = \frac{q'''(x)}{\rho C_v} \quad (19)$$

where $q'''(x)$ is the energy deposition at position x in the first wall, and ρ and C_v are density and specific heat of the first wall material, respectively. Likewise, the simple model for the pressure rise is

$$\Delta p(x) = \Gamma q'''(x) \quad (20)$$

where Γ is the Gruneisen constant for the first wall material.

Note that for the x-rays and neutrons,

$$\tau_T \gg \tau_m > \tau \quad (21)$$

Thus the time variations effects produced by thermal diffusion are insignificant compared with the time variation effects in the pressure wave. Thus the approximate theory of uncoupled dynamic thermoelasticity and viscoelasticity^{24,25} can be used to determine the moving stress pulse produced by the x-ray and neutron energy deposition.

The stresses are attenuated very rapidly as the pulse moves through the first wall. The stress is reduced by a factor of two during the first pulse width of travel, attaining a tensile tail as it does. If, however the energy fluence is very large, such that the stress exceeds the elastic yield strength of the first wall material, the stress will be attenuated to the yield strength of the material, with the rate of attenuation a function of the pulse shape, with sharper profiles attenuating more quickly. An additional attenuation mechanism is the internal friction of the first wall material. Weertman has suggested that the amplitude of short wavelength thermoelastic stresses pulses produced at the inner surface of a niobium shell will attenuate at least an order of magnitude by the time the stress pulse has traveled 10 wavelengths.

The temperatures as a function of time and space can be determined using classical thermal diffusion theory.

For the reflected laser light from the pellet onto the first wall,

$$\tau \approx \tau_T \approx \tau_m \quad (22)$$

The use of the simple models for the stress and temperature due to the energy deposition from photons will result in overestimates of both the stress and temperature since there will be some stress relief and diffusion of heat during the photon pulse time.

To calculate the spatial-time history of the pressure and temperature in the first wall due to photons, coupled radiation diffusion hydrodynamic motion codes are available. One such code, CHART D, solves one dimensional problems using finite difference analogs of the Lagrangian equations of motion and

radiation diffusion.²⁶ CHART D treats elastic-plastic and porous materials with realistic equations of state. Thermal and electron conduction, spall and rejoin calculations are provided.

For the pellet debris,

$$\tau_m \ll \tau_T \approx \tau \quad (23)$$

The stress due to the charged particle energy deposition can be determined by quasi-static thermoelastic or viscoelastic theory.²⁷ The temperature history can be determined using classical thermal diffusion theory.²⁸

The largest surface-layer energy deposition will be from either the charged particles, or the laser photons reflected from the pellet, depending on the ratio of the pellet reflectivity to the thermonuclear gain, as shown in Figure 7. Note that for low gain pellets the breakeven reflectivity of the pellet where the surface energy deposition from photons is equal to that from the pellet debris is less than 10%. Thus, for low gain pellets, the photon surface energy deposition will be greater than that from the pellet debris, and conversely for the high gain pellets.

Figure 7. Breakeven Pellet Reflectivity.

MASS TRANSFER EFFECTS

The above equations for the temperature and pressure are appropriate provided there is no change of phase at the first wall surface. If there is a change in phase, an impulse is imparted to the first wall from the material that is ablated, or blown off the surface. The impulse transmitted to the first wall from ablation or blow-off depends on the mass and energy of the material blown-off. The ratio of the impulse of the blown-off material to that of the pellet debris is

$$A = \frac{I_b}{I_p} = \sqrt{\left(\frac{E_b}{E_p}\right) \frac{M_b}{M_p}} \quad (24)$$

Thus for the case where all the debris energy is dumped into the blown-off mass, the pressure amplification will scale approximately as the square root of the ratio of the blow-off mass to the debris mass. For large microexplosion chambers, the mass of the debris from the pellet becomes the total mass in the chamber volume.

OTHER SOURCES OF DYNAMIC STRESS

The pressure in the cavity from the microexplosion debris tends to force the first wall of the reactor chamber out, while the neutron energy deposition in the lithium blanket tends to heat and expand the lithium, which forces the first wall inward, and the outer shell containing the blanket outward. Because the energy deposition times are short ($\leq 10^{-6}$ s) compared to the natural frequencies of the shells ($\sim 10^{-3}$ s), the shells respond to the impulsive loads by ringing at essentially their natural frequencies, modified to the extent

that they are hydrodynamically coupled to the liquid lithium blanket.

If the shell structure is to be stable, the ringing hoop stresses must be damped between successive pellet burns. LASL has concluded that a damping factor of as low as 1% is satisfactory for wetted-wall pulse repetition rates of 1/s. Using their data, a damping factor of 4% should be adequate to allow a pulse repetition rate of 20/s.²⁹

MATERIAL SELECTION CONSIDERATIONS FOR INERTIALLY-CONFINED FUSION REACTORS

For first wall materials, there are several parameters that should be minimized that will reduce the temperature rise and stress per shot from the microexplosion energy deposited within the first wall. From Equations (16) and (20), the product of the Grüneisen constant and energy attenuation coefficient, $\Gamma\beta$, should be minimized to reduce the amplitude of the stress pulse. From Equations (16) and (19), the ratio of the energy attenuation coefficient to the specific heat at constant volume β/C_v , should be minimized to reduce the amplitude of the temperature pulse. Generally, for x-rays and pellet debris, this involves using materials of low atomic number.

For blanket materials, lithium metal, alloys and compounds must be used to furnish the tritium breeding for the fuel cycle. Most inertially confined fusion reactors use a liquid lithium breeding blanket and circulate the lithium through heat exchangers such that the energy is transferred to a secondary fluid. The disadvantage of the liquid lithium is the large pressure pulses produced in the blanket structures due to the sudden deposition of the neutron energy in the lithium, plus the lithium corrosion of the blanket structural materials. Lithium is compatible with the refractory metals to temperatures of 1300 K, or greater, but compatible with stainless steel only to temperatures of about 700 K.

Other considerations in the selection of materials for the reactor include neutron damage, induced activity, hydrogen embrittlement, and fatigue lifetime. These are discussed in an excellent paper by Williams and Frank.³⁰

The final optics in a laser fusion reactor are more vulnerable to damage from the microexplosion than the first wall. The final turning mirror surface must remain true to a quarter-wavelength of the incoming laser light. The damage to optics is discussed by Teitel.³¹

INERTIAL CONFINEMENT SYSTEMS

A basic power-flow diagram for inertially confined fusion reactors is shown in Figure 8. The simple expression shown in this figure gives the plant recirculating power fraction (P_{in}/P_g) as a function of laser efficiency η_L , pellet gain Q , thermal efficiency η_T , and blanket energy multiplication M . Plant recirculating power is a basic figure of merit for any power plant. Fossil-fueled power plants operate with recirculating powers of less than 5%, while the majority of present nuclear plants operate at or slightly above this figure. The laser system efficiency η_L is a lumped parameter that includes power conditioning, lasing, and optical transport efficiencies; blanket energy multiplication M is defined as the ratio of blanket thermal energy to fusion neutron energy.

The economic feasibility of laser-fusion power production will depend on the pellet energy gains achieved and the overall efficiencies at which large pulsed laser systems can operate. The product of laser efficiency (η_L) and pellet gain (Q) is an excellent figure of merit for gauging the commercial prospects.

where: η_L = laser system efficiency
 Q = pellet gain = $\frac{\text{thermonuclear energy}}{\text{laser light energy}}$
 M = blanket energy multiplication
 η_T = electrical conversion efficiency
 P_{in} = electrical power input to laser
 P_g = gross electrical power

$$\frac{P_{in}}{P_g} = \frac{1}{\eta_L Q \eta_T (.8M + 0.2)}$$

Figure 8. Power Flow Diagram for Laser Fusion Reactor System.
 P_{in}/P_g is the Recirculating Power Fraction.

This product, which we refer to as the fusion energy gain, represents the ratio of thermonuclear energy to laser input energy. In Figure 9, the recirculating power fraction is plotted as a function of fusion energy gain for power plants with a blanket energy multiplication of 1 and with several thermal efficiencies. Several reference designs for laser-fusion power plants have used recirculating power fractions in the neighborhood of 25%. However, it may be difficult to compete economically with current power plants at these high values because, in general, plant capital costs scale as the gross electrical power, while revenues scale as the net electrical power.

Typically, the fusion energy gain for laser fusion reactors is about the same as for the electron-beam fusion reactors. The pellet gain for the laser fusion system is about 10 times higher than that for the electron-beam system, but the electron beam system efficiency is expected to be about 10 times higher than the laser system efficiency.

CONCEPTUAL REACTOR DESIGNS FOR LASER FUSION SYSTEMS

Several conceptual designs have been proposed for pure laser-fusion reactors to cope with the characteristic first-wall problems typical of inertially confined fusion reactors. Three different types of first wall have been proposed: a dry wall, a wet wall and a magnetically shielded wall. These three approaches are distinguished by the way the blast chamber wall interfaces with the hot blast debris impinging on its surface.

Figure 9. Plant Recirculating Power Fraction as a Function of Fusion Energy Gain.

The dry wall concept involves using an unprotected wall between the blanket and microexplosion chamber. This wall may be fabricated from niobium, stainless steel, or another metal, or from a graphite or carbon curtain over a metal first wall.³² The advantage of a metal first wall is that fabrication is relatively simple and the vapor pressure is low, making the vacuum system power requirements small. The disadvantage to the metal first wall is that the helium ash from the thermonuclear burn that is deposited in the first wall does not diffuse into the vacuum chamber, but tends to concentrate until bubbles form, which fracture and spall the first surface materials. With the particle fluences and energies associated with the blast debris, a short first-wall lifetime must therefore be planned for. The disadvantage of a graphite covering over the first surface is that hydrogen isotope debris reacts with the carbon, forming methane and acetylene.³³ These compounds are more difficult to vacuum pump and to recover tritium from than the inorganic pellet debris.

The wet-wall concept for fusion reactors will allow the charged particle debris deposited in a liquid layer over the first wall to diffuse back into the vacuum chamber without building up pressure in blisters to fracture-producing stress levels in superficial layers that occurs in solids. The first wet wall concept, shown in Figure 10, was developed by LASL.^{34,35} It features a large energy fluence per pulse on a liquid-lithium-over-niobium first wall. This concept has received the most extensive analysis of any LCTR to date. The pulse repetition frequency is low, due to the large mass of lithium that is blown off the first surface after each microexplosion. This lithium must be pumped from the cavity until a pressure of less than 1 torr is achieved. Thus, the pulse repetition frequency is limited by vacuum-pumping considerations.

Figure 10. The LASL Lithium Wetted Wall LCTR Concept.

The suppressed ablation³⁶ system shown in Figure 11 is a modification to the wet wall concept that reduces the mass of lithium blown off from the wet wall. Lithium ablation is suppressed by using a liner consisting of pyramidal elements to effectively increase the surface area of the first wall. Thus, for a given reactor radius, this niobium liner covered with lithium lowers blast energy fluxes to a level where serious ablation does not occur. A conceptual suppressed-ablation laser-fusion reactor blanket element is shown in Figure 11. The major disadvantages of the wet-wall reactor concepts are (1) the large vacuum-pumping loads required due to the high vapor pressure of lithium and (2) complex first-wall designs which must allow the coolant to migrate from reservoirs to cover the first wall liners.

The magnetically shielded first wall concept³⁷ is shown in Figure 12. A solenoid surrounding a lithium blanket is used to divert the pellet debris from a niobium dry first wall. The energy of the pellet debris is deposited into conical surfaces at the ends of the cylinder. These surfaces are cooled by the reactor primary coolant. Note that in principle, the energy of the pellet debris can be converted directly to electricity by exhausting the debris into a MHD duct.¹¹ In general, the magnetically shielded first wall combined with direct conversion of the pellet debris is of greater interest when the bulk of the energy from the laser-pellet interaction and thermonuclear burn is in the short-ranged charged particle debris (as in the case of low-pellet-gain DT reactions or advanced fuel cycles such as DHe³ or pB¹¹). The magnetic-shield first-wall concept does not protect the first wall from the photon or soft x-ray flash during the microexplosion process. The disadvantage of a magnetic-shield first-wall is that if a liquid metal is selected as a coolant, the pumping power required to move the liquid metal will increase if movement occurs across magnetic field lines. A second disadvantage is that the blanket modules and first wall are more inaccessible than in the dry wall concept.

Figure 11. The LLL Suppressed-Ablation LCTR Concept.

Figure 12. Schematic of the LASL Magnetically Protected Cylindrical LCTR Cavity.

A comparison of four different reactor concepts is shown in Table IV. The net power of each of the plants is 1000 MWe, with a recirculating power fraction of 0.33 and a system efficiency of 0.27. Note that while the recirculating power fraction is too high to be of interest from a long-range point of view, these reference designs are valuable in that they initiate studies on the peripheral problems of laser fusion. The actual reactor designs for laser-fusion plants will probably use a combination of the above first-wall designs for laser-fusion plants will probably use a combination of the above first-wall designs, tailored to the specific laser-pellet design and fuel cycle.

FUSION-FISSION HYBRID REACTORS (J.A. Maniscalco)

Nuclear power-generating systems using fusion-produced neutrons to generate fission are generally classified as fusion-fission hybrids. Interest in hybrid systems, has been motivated primarily by their potential to relax fusion energy gain criteria significantly and to breed substantial quantities of fissile material. The principal advantages of a coupled system result from the fact that, taken separately, fission systems are inherently power rich (with 200 MeV per fission reaction) and neutron poor, while DT-burning fusion systems are comparatively power poor (with 17.6 MeV per fusion) and fast-neutron-rich. The term fast-neutron-rich should be emphasized because it is the 14.1-MeV neutrons from DT fusion that provide hybrid systems with the ability to generate substantial amounts of energy and fissile material from the abundant fertile materials ^{238}U and ^{232}Th , thereby, operating with low fissile material inventories in a subcritical fashion that provides an absolute guarantee against a nuclear excursion.

TABLE IV. NOMINAL REFERENCE SYSTEM PARAMETERS, 1000 Mc LCIR^a

	Drv Wall	Suppressed Ablation	Net Wall	Magnetically Protected
Number of chambers	4	5	24	4
Pulse rate, Hz/chamber	7.2	10	1.2	7.2
Fusion energy gain (Q^*)	6.5	7.0	6	6.5
Blanket gain, M	1.3	1.1	1.3	1.3
Tritium breeding ratio	1.2	1.45	1.1	1.2
Cavity shape	Sph.	Iron	Sph.	Cyl.
First wall radius, m	9.7	1.2	1.7	2.5
No. of Laser beams/cavity	6	12	4	8
Laser energy into cavity/pulse, MJ	1	0.1	1	1

^aAll of these systems have been normalized to a recirculating power fraction of 0.33 and a net system efficiency of 27%.

The hybrid concepts analyzed in our system studies could best be categorized as fast or thermal fission systems. Fast fission systems are defined as blankets in which more than half of the fusion energy amplification is derived from fast fissions ($E > 1$ MeV) in fertile materials. Thermal fission systems are defined as blankets in which more than half of the energy amplification results from thermal fissions in fissile materials.

Fast or thermal fission systems are of three types:

- 1) An electricity-consuming facility that produces fissile fuel.
- 2) An electrical break-even facility that produces fissile fuel.
- 3) A producer of fissile fuel and electricity.

Obviously, hybrid facilities of the first two types are classified as fissile fuel producers. Facilities of the third type are classified either as fissile-fuel or electrical-power producers. The distinction is made on the basis of which function accounts for the majority of the facility's revenues.

At present, it is unclear which hybrid will have the largest commercial impact. However, facilities of the first two types may have the potential for earlier commercial application because thermodynamic efficiency, reliability, and duty cycle requirements are not stringent for simple fissile-fuel producers.

Fusion-fission hybrids can be designed to maximize fissile-fuel production or fusion-neutron energy multiplication. In general, fissile fuel production (per unit of fusion energy) is maximized in fast fission blankets containing fertile materials, while energy multiplication is maximized in thermal fission blankets containing heterogeneous lattices of fissionable material and moderator.

Thorium and depleted uranium (i.e. diffusion plant tailings) are two of the most attractive fuels for fissile-fuel-producing fast-fission blankets. Relatively abundant thorium is attractive because it breeds ^{233}U , a better fissile fuel for thermal fission reactors than ^{235}U or ^{239}Pu . Depleted uranium is an attractive hybrid fuel because the U.S. has a national stockpile of this material amounting to more than a billion pounds.

A comparative summary of the operational characteristics of three fissile-fuel producers is shown in Table V.³⁸ The comparative summary shows that depleted uranium hybrids maximize energy multiplication and fissile production per unit of fusion energy, whereas thorium fast-fission concepts exhibit the best performance on the basis of fissile production per unit of thermal energy. Therefore, uranium-fueled fissile producers would appear to be more attractive if the laser and fusion associated costs dominate, whereas thorium-fueled fast-fission hybrids would be more attractive if the blanket and heat-removal costs dominate.

The most attractive feature of fusion breeders relative to fission breeders is that fusion breeders produce approximately 10 times more fissile material per unit production of thermal energy.

A scenario with laser-fusion driven hybrids providing fissile fuel for the currently available thermal fission reactors appears to be a viable alternative to the present nuclear power research and development strategy based on fission breeders providing adequate quantities of fissile fuel for themselves. The hybrid scenario would become increasingly attractive if fission breeders' cost much more than fissile burners and therefore produce more expensive electricity.

TABLE V. COMPARATIVE SUMMARY OF FISSILE FUEL PRODUCING BLANKETS

Operational Characteristics	Thorium nonfission	Thorium fast fission	Depleted Uranium fast fission
Blanket energy multiplication	1.3	2.3	10.0
Tritium breeding ratio	>1.0	>1.0	>1.0
Fissile production in kg per MW-yr of fusion energy	1.3	3.5	9.0
Fissile production in kg per MW-yr of blanket total energy	1.1	1.7	1.1
Maximum power density in fuel, ^a W/cm ³	12.7	29.3	135.0
Maximum fuel burnup, ^a aton t/yr	50.0	1.07	0.30
Fusion energy gain (Q_{LF}) for electrical breakeven	2.30	1.47	0.35

^aNormalized to a first-wall fusion neutron flux of 1 MW/m^2 .

Power-producing hybrids are defined as facilities which operate with recirculating power less than 25%. It becomes attractive to look beyond thorium and depleted-uranium fueled blanket concepts when we consider hybrid facilities that produce electrical power as well as fissile fuel. These include plutonium-enriched fast-fission blankets and thermal-fission blankets. In Table VI, neutronically optimized versions of these two power-producing hybrids are compared to the previously shown depleted-uranium fast-fission blanket now being operated at a high enough fusion energy gain to be a power producer.

The energy multiplication characteristics of all the neutronically analyzed³⁹ hybrid blankets are summarized in Figure 13. It gives the fusion energy gain requirements for laser-fusion power plants with various percentages of recirculating power as a function of blanket energy multiplication. The curves were generated from the expression for plant recirculating power given in Figure 8, with thermal efficiency set at 35%. Figure 13 dramatically points out the order-of-magnitude decreases that take place in required fusion energy gain as fission blankets with higher energy multiplication are employed. In Table V, we saw that thorium-fueled hybrids outperformed uranium-fueled hybrids on the basis of fissile fuel produced per unit of thermal energy. Figure 13 shows that uranium-fueled hybrids can produce fissile fuel in an energy breakeven mode with fusion energy gains that are two to six times lower than those required for thorium blankets.

The curves in Figure 13 indicate that plutonium-enriched hybrids have the potential to produce electrical power with the lowest fusion energy gains. At first glance, these neutronic characteristics make a plutonium-enriched blanket concept look very attractive. However, the large inventories of fissile material resulting from plutonium enrichments in the neighborhood of 10% make it necessary

TABLE VI. COMPARATIVE SUMMARY OF POWER PRODUCING FUSION-FISSION HYBRIDS

Operational Characteristics	Depleted uranium fast fission	Natural uranium thermal fission	Plutonium enriched fast fission
Blanket energy multiplication	10.0	25.0	80.0
Tritium breeding ratio	>1.0	>1.0	>1.0
Net fissile production in kg per MW-yr of fusion energy	9.0	4.6	20.1
Net fissile production in kg per MW-yr of blanket thermal energy	1.1	0.72	0.31
Maximum power density in fuel, ² W/cm ³	135.0	230.0	810.0
Maximum fuel burnup, ¹ atom %/yr	0.30	0.77	2.55
Fusion energy gain (Q_{10}) for 25% recirculating power	1.39	0.96	0.18
Fusion energy gain (Q_{10}) for 10% recirculating power	3.5	1.4	0.44

²Normalized to a first-wall fusion neutron flux of 1 MW/m^2 .

Figure 13. Fusion Energy Gain Requirements for Fusion-Fission Hybrid System.

to operate this blanket at much higher power densities with effective neutron multiplication factors (k_{eff}) very close to unity. This negates some of the inherent safety features of hybrid systems.

Thermal fissioning hybrid concepts exhibit the largest energy multiplications with the lowest fissile material inventories. In comparing thermal and fast-fission hybrids as power producers, Figure 13 shows that thermal fission blankets can efficiently produce power with fusion energy gains two to four times lower than those required for fast-fission blankets. However, the comparative summary (Table VI) indicates that the enhanced energy multiplication is gained at the expense of reduced fissile production and higher power-density requirements in larger, more complex blankets. Consequently a final ranking of these two hybrid concepts must await studies which treat the engineering and economic requirements, as well as the neutronic aspects.

DEVELOPMENT SCENARIO FOR LASER FUSION⁴⁰

In Figure 14, a development scenario for laser fusion is superimposed on the curves from Figure 13. The curves give fusion energy gain as a function of blanket energy multiplication for power plants with various percentages of recirculating power. The evolutionary path shown here is based on our belief that the most desirable laser-fusion development path is one that will allow this new technology to contribute to our energy needs in the shortest possible time. As such the major route to laser fusion production features a fusion test facility in the mid-1980's, demonstration fissile-fuel producers in the early 1990's,^{41,42} and a prototype laser-fusion power plant sometime after the turn of the century.

Figure 14. A Development Scenario for Laser Fusion.

Depleted-uranium-fueled hybrids have been chosen over other blanket concepts because they have the potential to operate economically with lower blanket energy multiplications along with fusion energy gains that are an order of magnitude lower than those required for pure laser fusion. When higher fusion energy gains are achieved, thorium fueled concepts could be considered. Power-producing hybrids represent another alternative, attractive once the reliability of laser fusion in the fissile fuel production mode has been established.

The scenario outlined here describes one possible developmental path for laser fusion that offers the possibility of near-term as well as long-term energy benefits. It is based on our belief that fusion energy gains in the neighborhood of one will be achieved in the next decade, whereas gains of ten or more lie somewhere in the unpredictable future.

CONCLUSION

The materials problems in an inertially confined fusion reactor are different from those in a magnetically confined fusion reactor with the same time-averaged first-wall neutron energy flux. These differences are due to the arrival of the charged particles, X-rays, and neutrons in extremely short-time pulses in the low-duty-cycle, inertially confined, laser-fusion reactor as opposed to the long-time pulse in the high-duty cycle typical of the magnetically confined fusion reactions.

Because of the complexity of the solution of the laser/pellet interaction and burn, as well as the interaction of photons, X-rays and burn debris with the first wall, the models presented here for the energy deposition in the first wall are only simple estimates. The response of the materials to the short pulse times will require obtaining better equation-of-state data for some proposed first wall materials, as well as the solutions to the mathematical behavior of continuous media under dynamic conditions. Finally, the analysis and lifetime of the first wall will need to be verified under experimental conditions using a laser fusion research facility.

A great deal of effort, patience, and invention will be required before pure laser-fusion reactors can contribute appreciably to our national energy supply. This effort, involving an interdisciplinary approach by scientists and engineers, will need to be focused on first-wall, pellet, and laser design and development. Because of the importance of materials in determining the overall reactor design, materials scientists will play an important role in the development of commercial laser-fusion power. In a surprise-free scenario, pure laser fusion may be able to meet 10% of the increase in our national demand for electrical power 20 to 30 years after the turn of the century.

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