

Laser-induced thermonuclear fusion

Can focused laser pulses in the gigawatt range be used to compress hydrogen droplets by a thousand-fold to create energy-producing reactions?

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Laser-induced fusion has recently joined magnetic-confinement fusion as a prime prospect for generating controlled thermonuclear power. During the past three years, the Atomic Energy Commission has accelerated the national laser-fusion program more than tenfold, to about \$30 million annually,¹ and the Soviet Union has a program of comparable size.

In contemporary nuclear power plants, uranium is the primary fuel and fission reactions provide the nuclear energy. Fusion reactions between the heavy isotopes of hydrogen are another source of nuclear energy, one whose utilization for electricity generation lies in the future. Fusion power is important because, as Richard F. Post pointed out in his recent *PHYSICS TODAY* article,² the deuterium contained in the oceans is a virtually inexhaustible, low-cost, relatively clean fuel.

Fusion reactions are demonstrated in thermonuclear explosions and are thought to be the source of stellar energy. For the past twenty years, the thrust of controlled fusion research has been toward magnetic confinement of plasmas heated sufficiently (to about 10^8 K temperatures) to achieve fuel ignition. Laser-induced fusion, which exploits inertial confinement, has received increased public interest recently with the AEC declassification of important concepts and calculations. The key idea is to use laser light to

isentropically implode pellets of deuterium and tritium to approximately 10 000 times liquid density and thereby induce efficient thermonuclear burning. Fusion energies 50–100 times larger than laser input energies of 10^5 – 10^6 joules have been achieved in sophisticated computer simulation calculations. There is as yet no experimental confirmation, but 10 000-joule lasers are being planned at the Livermore and Los Alamos Laboratories and at the Lebedev Institute in the USSR to explore laser-induced fusion.

The laser fusion implosion system consists of a tiny spherical pellet of deuterium-tritium surrounded by a low-density atmosphere extending to several pellet radii, located in a large vacuum chamber and a laser capable of generating an optimally time-tailored pulse of light energy. Before the main pulse occurs, the atmosphere may be produced by ablating the pellet surface with a laser prepulse. Most of the dense pellet is isentropically compressed to a high-density Fermi-degenerate state and thermonuclear burn is initiated in the central region. A thermonuclear burn front propagates radially outward from the central region igniting the dense fuel.

With 10^5 – 10^6 joule laser pulses initiating 10^7 – 10^8 joule fusion pulses, gigawatt electrical power levels may be generated by initiating 100 pulses per second, possibly ten per second in each of ten combustion chambers. The combustion chambers would have a diameter of a few meters and walls wetted with lithium to withstand the nuclear radiation and debris. For economic operation the pellets would have to cost less than a cent each, and they could be fabricated in a drop tower.

Electricity would be generated via neutron-heated lithium blankets as in conventional controlled thermonuclear reaction schemes, or by direct conversion in advanced power-plant schemes.

The implosion of bubbles in water was considered by William Henry Besant in 1859⁴ and Lord Rayleigh in 1917.⁵ A self-similar solution to an imploding shock wave was developed by G. Guderley who made some relevant calculations in 1942.⁶ Early work on fission weapons at Los Alamos began by Seth Neddemeyer, John Von Neumann and Edward Teller and others explored spherical implosion systems driven by high explosives.⁷ Subsequently, moderately high compressions were experimentally demonstrated and utilized. However, compressions approaching 10 000 fold (relative to liquid or solid densities)—which are required for practical laser fusion power reactors—have not been experimentally achieved.

The invention of the pulsed laser in the early 1960's stimulated further implosion calculations and a proposal of a laser fusion engine for CTR and propulsion applications. Nearly all laser-fusion implosion calculations remained classified until reported recently.^{3,8} Experimental work began in 1963, and by the mid-1960's, Ray Kidder and S. W. Mead constructed a twelve-beam implosion-oriented laser at Livermore.⁹ In 1972, Nikolai Basov and his colleagues reported implosion of a 100-micron diameter CD_2 microsphere with a few hundred joule, few nanosecond, nine-beam laser pulse.¹⁰

Implosions and thermonuclear burn

Conditions involving pressure, symmetry and stability must be satisfied

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to implode a DT sphere to a state at 10^4 times liquid density, in which both Fermi-degeneracy and thermonuclear propagation can be exploited to achieve maximum gain.

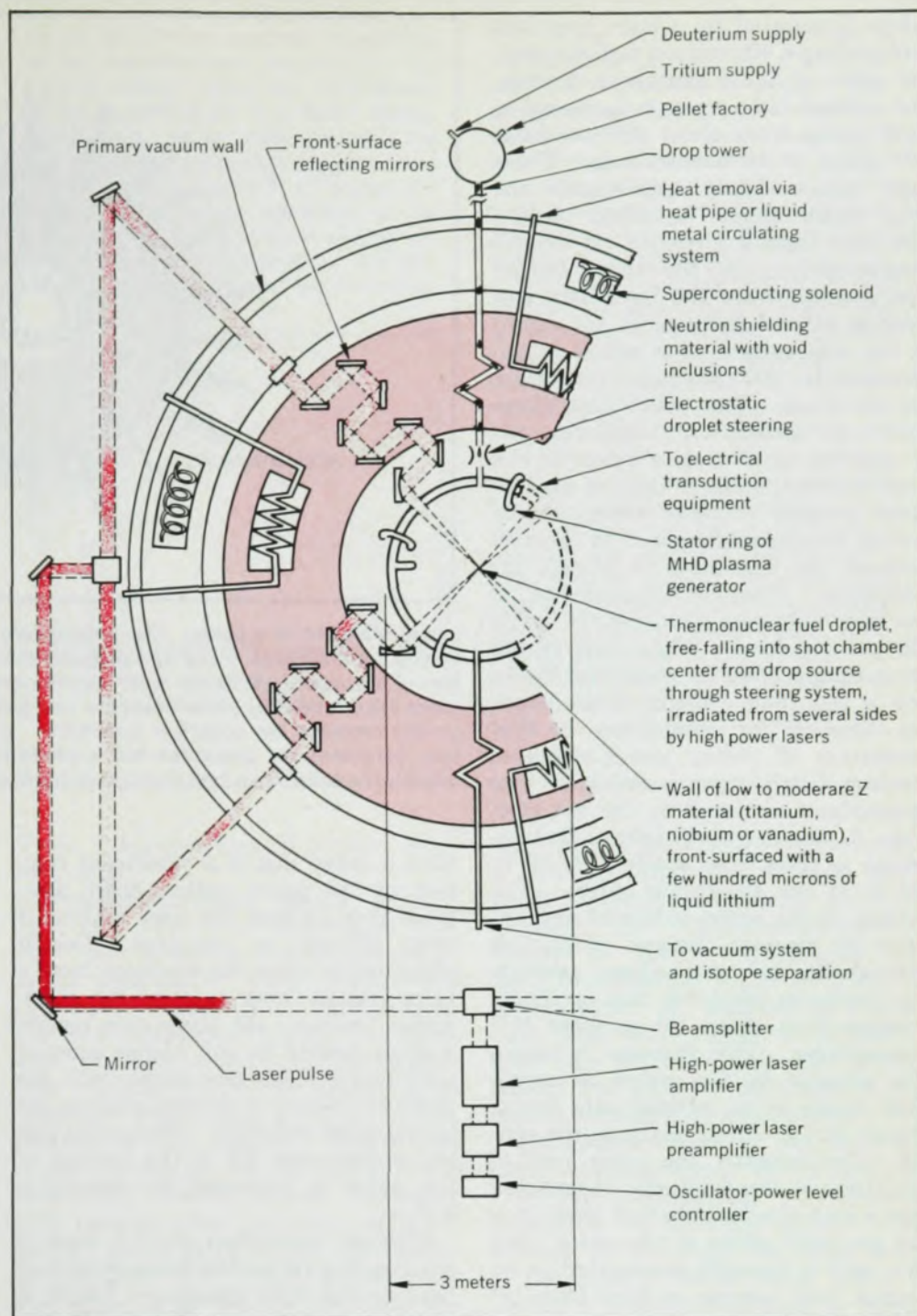
The optimum laser pulse shape generates an initial shock, which is near-sonic ($1/2 \times 10^6$ cm/sec) in the outer part of the pellet. This shock produces an entropy change sufficiently small that subsequent compression to a Fermi-degenerate state is possible. As this shock converges toward the center of the pellet it becomes sufficiently strong to produce significant heating. The pulse shape also generates a maximum implosion velocity of about 3.5×10^7 cm/sec, corresponding to the required average energy density of 6×10^7 joules/gram (see box). The implosion velocity is increased from the initial to the maximum value at such a rate that the hydrodynamic characteristics in the compressing pellet coalesce to form a strong shock near maximum compression, at a distance from the center approximately equal to the range of 10-keV alpha particles in DT. By numerous computer calculations of laser implosions, we know that the optimum pulse shape is approximately

$$E = E_0 \tau^{-s}$$

where E is the laser power, $\tau = 1 - (t/t')$, t is time, t' is the collapse time, and s is approximately 2.¹¹ No satisfactory analytic derivation of this equation is known. Figure 3 shows how this pulse shape may be approximated with sufficient accuracy by a histogram of 5-10 pulses.

The compression and burn processes that have been described are illustrated in figure 4 by results of a typical computer-simulation calculation of the implosion of a fusion pellet to 10 000 times liquid density, and of the resulting thermonuclear microexplosion. This calculation was carried out at the Livermore Laboratory by Albert Thiessen with a program developed by George Zimmerman.¹² The program includes the following physical processes:

- ▶ Hydrodynamics—Lagrangian; real and generalized Von Neumann artificial viscosities; ponderomotive, electron, ion, photon, magnetic and alpha-particle pressures.
- ▶ Laser light—absorption via inverse bremsstrahlung and plasma instabilities; reflection at critical density.
- ▶ Coulomb coupling of charged-particle species.
- ▶ Suprathermal electrons—multigroup flux-limited diffusion with self-consistent electric fields; non-Maxwellian electron spectra determined by results of plasma-simulation calculations for laser-light absorption by plasma instabilities; inverse bremsstrahlung elec-



Conceptual design of a laser-fusion power-plant. One hundred laser-induced micro-explosions per second will produce 1000 megawatts of electrical power. The pulse of laser light, which is shown here in deep color, is shaped in time to yield optimum implosion and thermonuclear burning of the pellet. Several processes can be used to convert the explosion energy into electricity, such as thermal and MHD plasma conversion.

Figure 1

tron spectrum for classical absorption.

▶ Thermal electrons and ions—flux-limited diffusion.

▶ Magnetic field—includes modification of all charged-particle transport coefficients, as well as most of the equilibrium MHD effects described by S. Braginskii.¹³

▶ Photonics—Multigroup flux-limited diffusion; LTE non-LTE average-atom opacities for free-free, bound-free, and bound-bound processes; Fokker-Planck treatment of Compton scattering.

▶ Fusion—Maxwell velocity-averaged reaction rates; the DT alpha particle is

transported by a one-group flux-limited diffusion model with appropriate energy deposition into the electron and ion fields; one group transport of the 14 MeV neutron.

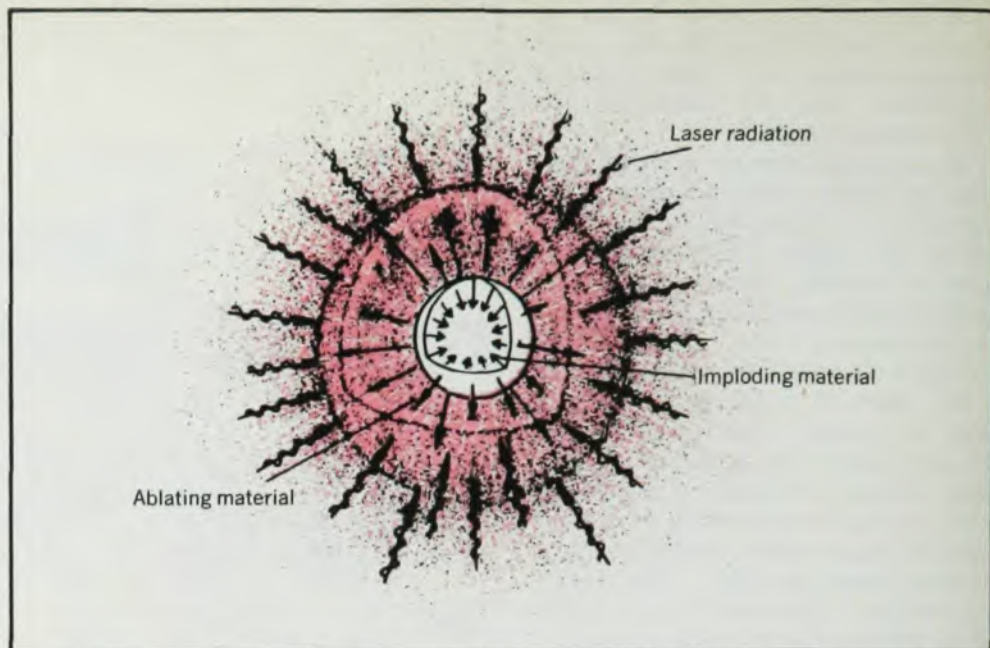
▶ Material properties—opacities, pressures, specific heats, and other properties of matter are used, with nuclear, Coulomb, degeneracy, partial ionization, and other significant effects taken into account.

In this implosion-burn calculation, a 10kJ, short-wavelength (1/2 micron), frequency-modulated, pulse of laser light is focussed symmetrically onto a 1200-micron radius low-density atmo-

sphere (generated by a laser prepulse) surrounding a 400-micron radius spherical pellet of liquid deuterium-tritium. The applied laser power is increased in eight pulses from about 10^{11} to about 10^{15} watts in 10 nanoseconds. These eight pulses closely approximate the ideal pulse shape described earlier. The laser light is absorbed via inverse bremsstrahlung near the critical density (the density where the laser light and electron plasma frequencies are equal) in the atmosphere, at a radius of approximately 600 microns, generating hot electrons. The pellet and atmosphere are seeded with small amounts of material of Z greater than 10 and short-wavelength laser light is used to make possible efficient absorption by inverse bremsstrahlung and in order to increase the thresholds of plasma instabilities. Frequency modulation of the laser light also increases the instability thresholds.¹⁴ When these effects are accounted for, the peak laser intensity is less than a factor of ten above the threshold for instabilities—so that generation of strong non-Maxwellian electron distributions is avoided. The atmosphere is heated by the hot electrons to electron temperatures that increase in time from about 3×10^6 to 10^8 K at the absorption radius. The surface of the pellet is heated and ablated by electron thermal conduction through the hot atmosphere, generating implosion pressures that optimally increase from about 10^6 to about 10^{11} atmospheres. This increase in implosion pressure by five orders of magnitude occurs at an optimal rate during transit of the initial shock to the center. Consequently the outer part of the pellet is isentropically compressed into a high-density spherical shell ($\rho > 100 \text{ gm/cm}^3$) while at the same time this shell is inwardly accelerated to velocities that increase in time from 10^6 to $3.5 \times 10^7 \text{ cm/s}$.

As the internal pressure becomes larger than the ablation pressure the rapidly converging shell slows down and is compressed nearly isentropically, at sub-Fermi temperatures, to densities greater than 1000 gm/cm^3 . The inner region is compressed by the outer shell to densities approaching 1000 gm/cm^3 , and heated to ion temperatures greater than 10^8 K, initiating thermonuclear burn. A thermonuclear burn front then propagates outward. About 1200 kilojoules of fusion energy are produced in less than 10^{-11} seconds. The energy gain is about 20-fold.

There are, however, other effects that may reduce this gain; this is especially so for long-wavelength laser light such as the 10.6-micron CO_2 line. The pellet compression and energy gain might be strongly degraded by electron preheat¹⁵ and decoupling.¹⁶ Preheat occurs when the laser-heated electrons



Laser implosion of a pellet. The atmosphere extends to several pellet radii and is formed before the main laser pulse by a prepulse that ablates some of the pellet surface. Absorption of the laser light in the outer atmosphere generates hot electrons. As the electrons move inward heating the atmosphere and pellet surface, scattering and solid-angle effects greatly increase the spherical symmetry. Violent ablation and blowoff of the pellet surface generates the pressures that implode the pellet; the effect is similar to a spherical rocket. The pellet core then undergoes thermonuclear burn.

Figure 2

have a range that is a significant fraction of the pellet radius; these electrons then preheat the fuel, making it more difficult to compress. Decoupling occurs when the electrons have a large enough range to cross the atmosphere, re-enter the absorption region, and are heated to still higher energies with longer mean free paths until the pellet is effectively decoupled from the laser-heated electrons. Decoupling can be compensated for if the volume of the pellet is increased by making it hollow.

Efficient absorption of CO_2 light is not possible via inverse bremsstrahlung because the light absorption length is too long ($\gg 1 \text{ cm}$ at 10 keV).¹⁷ Absorption is possible via plasma instabilities.¹⁸ However, if the thresholds for these instabilities are greatly exceeded, then plasma-simulation computer codes indicate that non-Maxwellian electron spectra may be generated, with high-energy tails extending beyond 100 times the thermal electron energy.¹⁹ Experiments are needed to determine the electron spectra reliably in such situations. If excessive numbers of superthermal electrons are not generated, then long-wavelength lasers may be suitable for CTR applications, provided that the hollow pellet can be constructed cheaply enough.

In compression of a sphere by 10^4 -fold, the radius decreases somewhat more than 20-fold. If, after compression, spherical symmetry is required to within half of the compressed radius—or $1/40$ the initial radius—then the implosion velocity (and time) must be

spatially uniform and synchronized to about one part in 40, or a few percent. The outer atmosphere may be heated uniformly to 10% to 20% by a many-sided irradiation system, consisting of beam splitters, mirrors, lenses, and other optical elements. This error is then reduced to less than 1% by physical processes occurring inside the atmosphere.^{3,20} Asymmetries are reduced during electron energy transport through several scattering mean free paths of atmosphere to heat the surface of the pellet. In addition, since the atmosphere has a large radius compared to the pellet, each point on the pellet surface is heated by electrons coming from almost 2π steradians of the hot absorbing region in the outer atmosphere. Finally, during most of the implosion, the electron mean free path in the absorbing region is a significant fraction of the absorption radius.

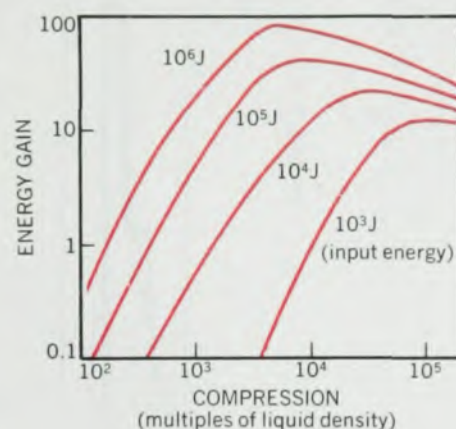
The implosion of the pellet by diffusion-driven pressures generated by ablation is hydrodynamically stable, except for relatively long-wavelength surface perturbations.^{3,20} Fortunately, these perturbations grow too slowly to be damaging if the pellet is imploded in one sonic transit time. In part, ablative stabilization occurs because the peaks of surface perturbations are effectively closer to the heat source than are the valleys, so that the ablation-driving temperature gradient is steeper. Consequently, the amplitude of the perturbation is reduced, both because the peak is more rapidly ablated and because the ablation pressure is higher on the peak.

Laser-imploded pellets

Thermonuclear micro-explosions scale as the density-radius product ρR . The rates of burn, energy deposition by charged reaction products, and electron-ion heating are proportional to the density, and the inertial confinement time is proportional to the radius of the pellet. Consequently, the burn efficiency, self-heating, and feasibility of thermonuclear propagation are determined by ρR . If ρR is very much greater than 0.3 gm/cm^2 , then only 0.3 gm/cm^2 in the central region of the pellet need be heated to approximately 10 keV to initiate a radially propagating burn front that ignites the entire pellet. In this case, 1.6×10^{10} joules/gm of fusion energy will be released from the central region; one fifth of this energy is in alpha particles, sufficient to heat three times more DT to 10 keV. The alpha particles will deposit their energy in approximately this mass since their range at 10 keV is about 0.3 g/cm^2 .

When ρR is approximately 3 gm/cm^2 the fusion energy released is about 10^{11}

joules/gm. If we assume propagation of the thermonuclear reaction from the 10-keV central region and compression of the remaining DT to a Fermi degenerate state, all at 1000 gm/cm^3 , the minimum average energy of ignition and compression is about 6×10^7 joules/gm. (If the degeneracy condition is not satisfied the compressional energy will exceed the ignition energy.) The gain is then about 1500, but approximately



95% of the laser energy absorbed by the pellet during implosion is lost to kinetic and internal energy blowoff. Consequently, the energy gain relative to the laser energy employed is about 75 fold. This is sufficient for CTR applications with a 10% efficient laser, a 40% thermal-to-electric efficiency and about 30% of the electrical energy circulated internally to pump the laser.

The figure shows the variation of gain (relative to laser light energy) with compression and with laser-light energy.^{3,11} The curves have been normalized to computer calculations of the implosion and burn. Gains approaching 100 are predicted for laser energies of 10^6 joules. The calculations indicate that less than 1 kilojoule of laser light may be sufficient for breakeven (gain ≈ 1) and 10^5 joules may be sufficient to generate net electrical energy with a 10% efficient laser. These predicted gains are probably upper limits to what can be achieved. Similar gain curves may be generated for D_2 and DHe^3 pellets seeded with a small percentage of tritium to facilitate ignition.

Laser technology

The development of lasers for high-density laser-fusion application poses a special set of problems that have not previously received much attention in the laser R&D community. In the optimum pulse shape, about half the total energy is produced in the final 100 picoseconds. Thus, in terms of a single pulse, a CRT laser has to be capable of producing at least 50 kilojoules in 100 picoseconds. In addition, the optimum plasma heating process may require short-wavelength lasers. Such lasers do not exist at present; however, development of short wavelength devices is receiving increasing attention in the US and several other countries.

The salient characteristics of four laser systems presently under consideration are indicated in Table 1. These systems are representative of the diversity that exists in the laser world. What is interesting to note about these laser systems is the almost total lack of overlap in the technologies required for the development of each. Thus, extensive development effort applied to one of these systems is not usually applicable to another. Also shown in Table 1 are the desired characteristics of a hypothetical laser system that matches the requirements of laser fusion as presently envisioned. The primary characteristics of this hypothetical laser system are high efficiency, high average power, short wavelength and high energy. It is clear that none of the real lasers in

Table 1 demonstrates all of these characteristics.

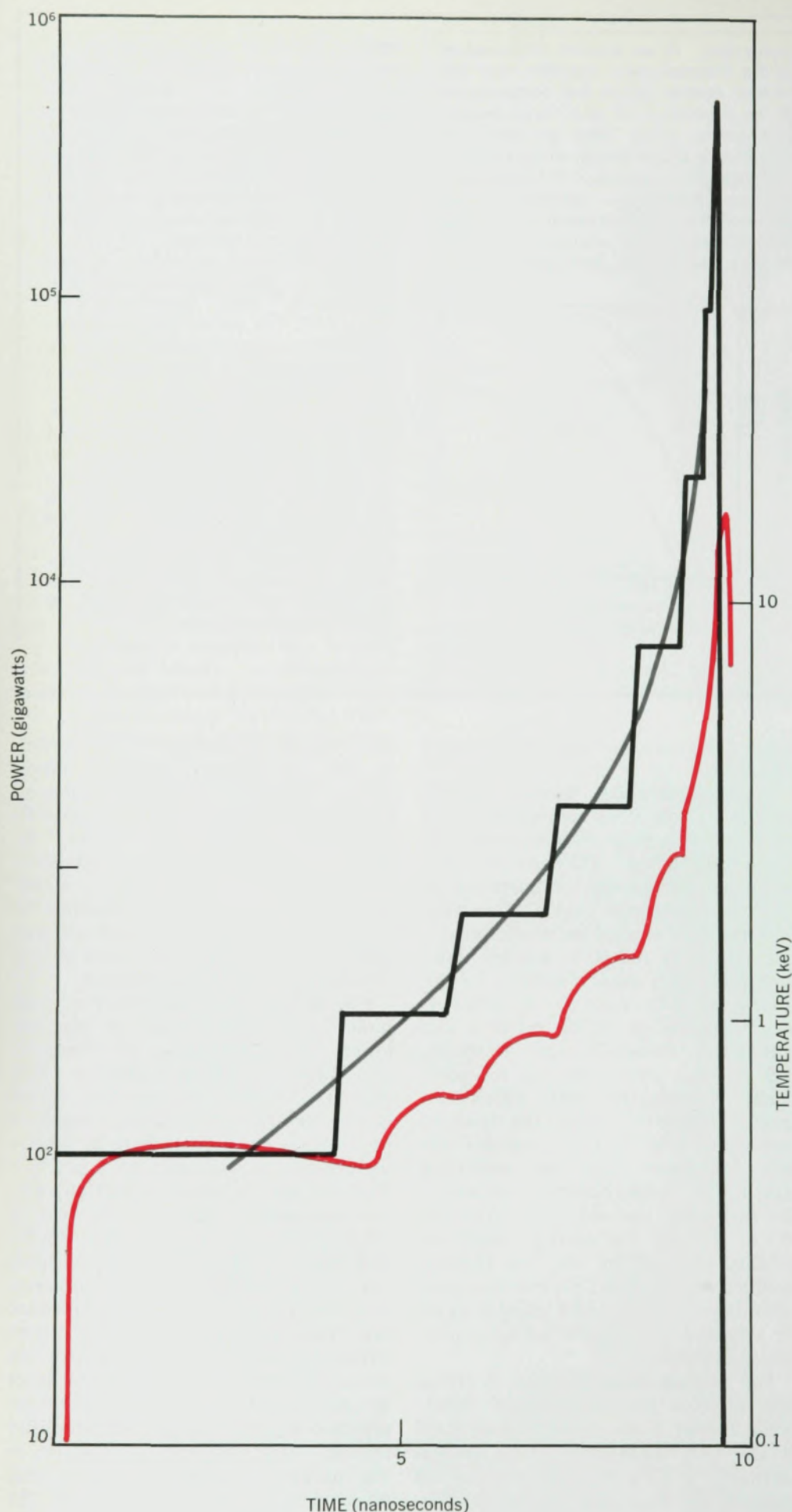
Neodymium-glass lasers develop gain at 1.06-microns wavelength with Nd^{3+} ions in a glass matrix pumped by xenon flash lamps. They have the best developed technology for operation in the sub-nanosecond region. In addition, the high second-harmonic conversion efficiency (60-80%) already demonstrated offers great potential for operation at 0.53 micron. Fourth-harmonic generation (0.265 micron) and stimulated Stokes-Raman scattering (1.9 micron) offer potential for additional wavelengths with efficiencies greater than 20%. Thus, the neodymium-glass laser system provides the best laboratory tool for near-term laser-fusion experiments. However, the extremely low energy of efficiency (0.1%) and the low average power capability (limited by the low thermal conductivity of glass) prevent any consideration of neodymium-glass systems for eventual laser fusion power-generation applications.

The carbon-dioxide laser develops gain at 10.6 microns between vibrational energy levels of the ground state of the CO_2 molecules. This system (actually a CO_2-N_2-He mixture) is pumped by relatively low-power electrical discharges in the gas. This laser has demonstrated efficiencies of approximately 5% for one-nanosecond duration pulses. Operation in the nanosecond regime has yet to be demonstrated. With the addition of high-speed gas flow, CO_2 lasers have the capability to generate high average power

ers. The major liability of the system is the 10.6-micron emission wavelength. Efforts are currently underway to convert the 10.6-micron energy efficiently to shorter wavelengths, although success has yet to be achieved. Development of high-energy, short-pulse CO_2 lasers continues because of their high efficiency and high average power. The ultimate usefulness of this system remains to be determined.

The iodine laser has recently come under consideration as a possible lower-cost replacement for neodymium-glass. It develops gain at 1.315 microns between the electronic levels of the neutral iodine atom, which is produced in an excited state by photodissociation of molecules such as CF_3I . The emission wavelength and efficiencies are similar; however, the cost of CF_3I is much below that of neodymium-glass. The stimulated-emission cross section of I^* , even in the presence of a few atmospheres of a line-broadening buffer gas, is much larger than neodymium-glass. This necessitates an entire different approach to the laser design, in order to control parasitic oscillation within a single laser amplifier section. With the eventual solution to the parasitic oscillation problem and more detailed understanding of the pumping requirements of the system, it is possible that iodine lasers may be built in the 1-10 kilojoule regime.

Recent interest in the xenon laser stems from the short wavelength (1722 Å) and predicted high pumping efficiency (25%).²¹ Little detailed information is available on this system, and



Laser pulse power rise in steps to approximate the ideal shape, which is shown in grey. The corresponding electron temperature in the critical density region is shown in color. These curves were generated by computer calculations and the assumption of a 10 000-fold compression of a fusion pellet. This time-tailored pulse is composed of eight subpulses that form the steps. The first step is a 500-joule pulse that lasts for 4200 picoseconds, and the remaining steps are formed by the following subpulses: 500 J-1600 psec, 1 kJ-1400 psec, 24 kJ-1200 psec, 4kJ-650 psec, 8kJ-330 psec, and finally 30kJ-65 psec.

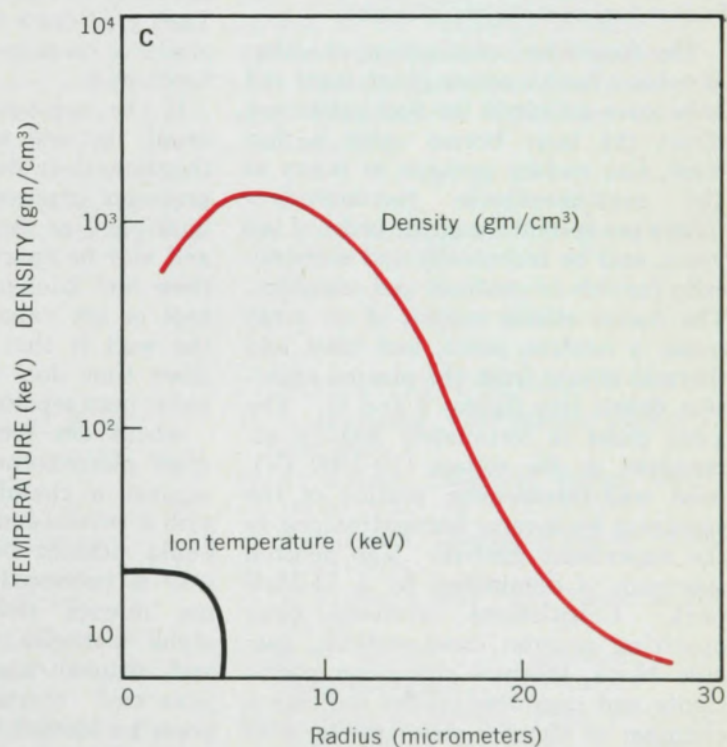
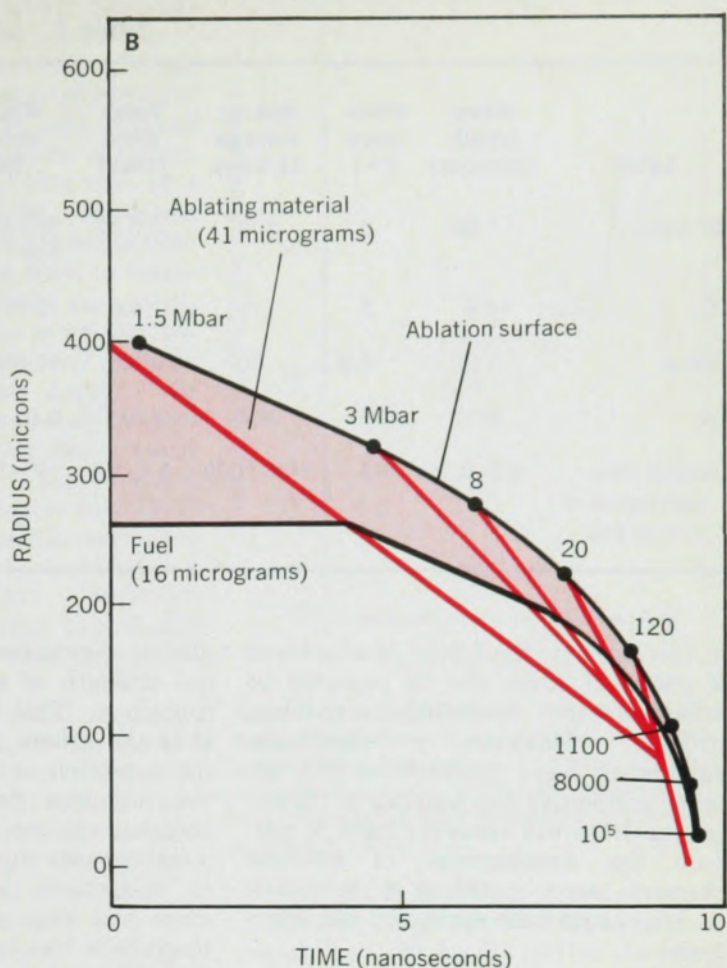
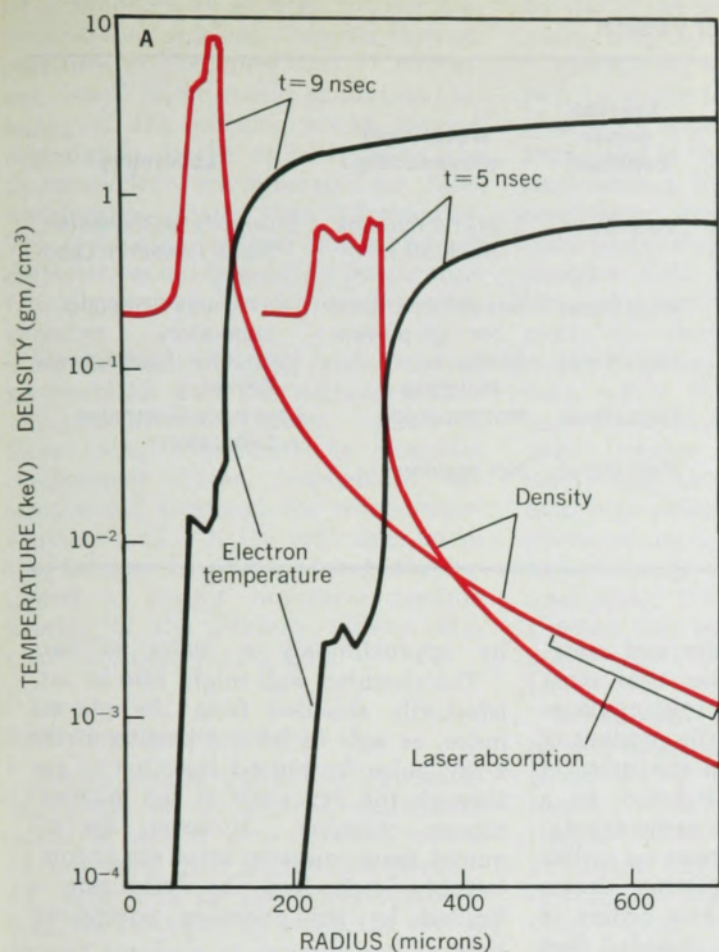
Figure 3

the technology for the generation of subnanosecond pulses has yet to be developed in this region of the spectrum. Two comments are, however, appropriate. First, the stimulated-emission cross section is approximately $3 \times 10^{-18} \text{ cm}^2$. Thus, a large high-energy amplifier will be severely limited in performance by superfluorescence (amplified spontaneous emission) and parasitic oscillation. Second, lasers useful for fusion applications must operate at flux levels of $10^{10} \text{ watts/cm}^2$ (1 J/cm^2 , 100 psec) or greater. At this flux level and 1722 Å wavelength, all transparent materials (window, lenses, coatings) from LiF to Al_2O_3 will exhibit two-photon absorption coefficients in the $1\text{--}25 \text{ cm}^{-1}$ range. Thus, to use such a short wavelength, a new optical technology of gas lenses and aerodynamic windows will have to be developed.

From the foregoing discussion we may draw several conclusions. Clearly, neodymium-glass laser systems provide the best technology base for the near-term laser-fusion experiments. The wide range of pulse widths obtainable (20 psec–20 nsec) and the range of wavelengths (0.265–1.9 microns) render it an almost ideal laboratory tool. For these reasons large multi-aperture neodymium-glass laser systems with energies of 10 kilojoules are in design or construction stages both in the US and the USSR. At the Lawrence Livermore Laboratory, a 10-kilojoule subnanosecond facility is being designed for spherical irradiation. Funds for it have been requested in the President's fiscal 1974 budget submitted to Congress. With this instrument, the important milestone of significant thermonuclear burn and scientific breakeven (fusion energy equals laser energy) will be achieved.

The high efficiency and high average-power capability of CO_2 lasers warrant their further study. The technology of high-energy, short-pulse CO_2 lasers is being aggressively pursued by the Los Alamos Scientific Laboratory. A ten kilojoule, one-nanosecond multiaperture device is being developed to answer the fundamental questions associated with the use of such long wavelengths for high density laser fusion.

The iodine laser system is under intensive development at the Institut für Plasma Physik, Garching, where the objective is a one-kilojoule, one-nanosecond device for laser-fusion experiments. Additional low-level investigations of this system are being carried out in many laboratories, both in the US and abroad. However, the only flexibility currently provided by this system is a lower-cost laser medium. This may be more than offset by the increased cost of capacitor banks and



Compression of the fusion pellet from the beginning of the laser pulse and through absorption until thermonuclear ignition. These curves were generated by a computer and the assumption of a 10 000-fold compression. Part A shows the density and electron temperature versus the radius at times, five and nine nanoseconds after the start of the laser pulse but before ignition. In part B, the radius is plotted against time. The colored lines in this figure represent weak shocks from the steps of the pulse power. The inner curve represents that part of the pellet which undergoes thermonuclear burning, and the outer curve represents the outer region of the pellet; all the material in between is ablated away and is indicated by the colored region. The pressures at different stages of the compression are shown in megabars. In part C, the density and electron temperatures are plotted at the time of ignition.

Figure 4

flashlamps for the short pulse excitation required.

The xenon laser system is too new to make any meaningful projections as to its ultimate usefulness for laser fusion. It will obviously have significant applications to high-density plasma diagnostics where its short wavelength may be essential.

The development of new lasers is required if laser-fusion power production is to become a reality. The xenon laser represents a class of possible la-

sers based on the weakly bound or van der Waals molecules. Laser action has already been achieved from Xe_2^* and Kr_2^* , and it may be expected from some of the similar dimer systems of mercury, cadmium and zinc. Other non-dimer systems such as LiXe or HgXe also look attractive. These systems are pumped by efficient, high-current relativistic electron-beam machines, which have been extensively developed during the last decade. The availability of an efficient pump source

and short wavelength of emission makes these systems of great interest for laser fusion. However, it is clear that stimulated emission cross sections smaller than those in the xenon system will be necessary, as will extensive development of a means of reducing parasitic oscillation and superfluorescence.

Probably the most important characteristic of any new laser system developed for laser-fusion applications will be the ability to use energy efficiently.

Table 1. Lasers for Fusion

Laser	Wave-length (microns)	Efficiency (%)	Energy storage (J/liter)	Pulse width (nsec)	Max. output short pulse (joules)	Average power capability	Wavelength convertability	Laboratory
Nd:glass	1.06	0.2	500	≥ 0.02	350 (0.1 nsec) 350 (1.0 nsec)	Very low	0.26–1.9 microns (40% eff.)	University of Rochester; Naval Research Laboratory
CO ₂	10.6	5	15	≥ 1.0	17 (1 nsec)	High (flow)	Not demonstrated for high powers	Los Alamos Scientific Laboratory
Iodine	1.32	0.5	30	0.6	12 (10 nsec)	High (flow)	Similar to Nd:glass	Institut für Plasmaphysik, Garching
Xe ₂	0.17	<20	300	≈ 10	0.01 (10 nsec)	High (flow)	Not required	Lawrence Livermore Laboratory
Desired characteristics of a new laser	0.3–0.5	>5	100–1000	0.1–1.0	10^4 – 10^6	High (flow)	Not required	

In this context, the future development of chemical lasers can be expected to influence the laser-fusion problem strongly. However, a significant amount of basic research on the detailed energetics and kinetics of chemical reactions will certainly have to precede the development of efficient chemical lasers operating in the visible or near-ultraviolet region of the spectrum.

Fusion-fuel combustion chamber

The fusion-fuel combustion chamber of a laser-fusion power plant must not only serve to admit the fuel pellet and direct the laser beams upon it, but must also endure perhaps as many as 100 multimegajoule thermonuclear pulses per second for of the order of ten years, and be technically and economically feasible to construct and maintain. The fusion effects consist of an x-ray pulse, a neutron pulse, and blast and thermal effects from the plasma explosion debris (see figures 5 and 6). The x-ray pulse is fortunately heavily attenuated in the softest (10–1000 eV), most wall-threatening, portion of the spectrum by inverse bremsstrahlung in the superdense fireball. The neutron spectrum is dominated by a 14-MeV peak. Calculations involving x-ray opacities, neutron cross sections, specific heats, thermal expansion coefficients and compressibilities indicate a chamber of about 3-meter radius with a wall of a few layers of properly chosen low-to-moderate atomic-number materials (for example about 0.01 cm of beryllium backed by titanium, niobium or vanadium) will endure the x-ray and neutron pulses of a 10^7 -joule microexplosion. If surfaced with a thin, low-Z liquid layer (for example lithium a few hundred microns thick) by continuous exudation, the plasma pulse of a 10^7 -joule explosion may also be repetitively endured by the combustion chamber.²²

The impulse associated with an ex-

plosion determines the size and material strength of a chamber that must contain it. This impulse is proportional to the square root of the product of the explosion energy and the mass of the explosion debris. Relative to a chemical explosion of the same energy, a fusion pulse involves about six orders of magnitude less explosive debris mass and thus about three orders of magnitude less impulse, provided that the surface of the wall is not vaporized. Then a 10^7 -joule fusion micro-explosion produces no more impulse than a large firecracker.

If the combustion chamber is too small, the wall will be ablated by the thermonuclear debris. Then the peak pressures imposed on the wall may be multiplied as much as a thousandfold and may be unacceptably high (greater than one kilobar). A crucial advantage of not vaporizing the lithium on the wall is that the chamber pump-down time does not severely limit the pellet burn repetition rate.

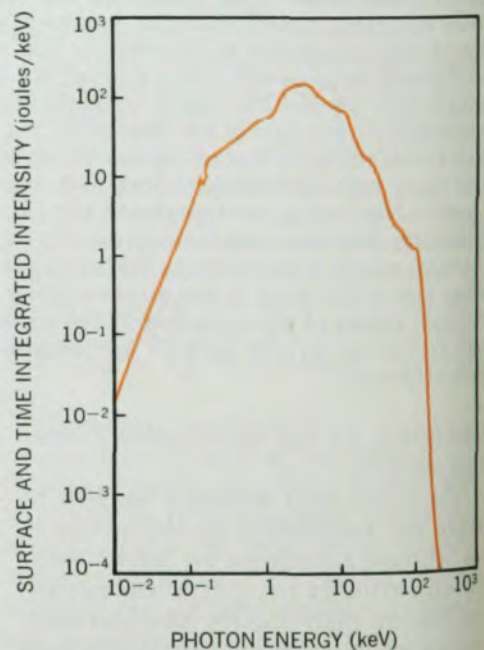
About one joule/cm² of thermonuclear plasma energy may be directed against a chamber wall "moistened" with a several-hundred-micron layer of liquid lithium before significant blowoff is produced. The suprathermal ion fluence (for example 3.5-MeV alpha particles, knock-on deuterons and tritons) associated with a one joule/cm² thermal plasma fluence poses no blowoff hazard, since it penetrates the moist layer relatively deeply and deposits its energy in a large amount of matter. Moistened-wall combustion chambers, rated for ten-megajoule pulses of approximately 3-meter radius would thus be satisfactory from a plasma wall-loading standpoint.

If the combustion chamber wall is shielded from the pellet debris by a minimum-B magnetic field, the surface-area requirement for the explosion chamber is determined by x-ray loading considerations. The combustion chamber radius may then be reduced

by approximately a factor of two.

The chamber wall might also be satisfactorily shielded from the plasma pulse, as well as from a portion of the x-ray pulse by pulsed injection of gas through the dry walls of the microexplosion chamber. However, the required mass injection rates are uncomfortably large, and the firing rate is limited by the chamber pumpdown time.

A very important problem for laser-fusion reactor design is how to arrange for input of the laser light and the target pellet while at the same time maintaining adequate neutron and x-ray shielding. Laser beams might be admitted through cheap, replaceable windows in the outer vacuum wall, passed through the neutron shield in neutronic-baffling dogleg tunnels on mirror trains, and focused onto the pel-



X-ray pulse spectrum of a megajoule DT-fusion microexplosion as calculated by a computer code; note the large self-absorption of the superdense fireball at low photon energies. Figure 5

let atmosphere by aspheric mirrors facing into the explosion chamber through apertures in the inner wall. Continuous, low- Z liquid-metal exudation-surfacing of the mirrors would prevent degradation of the reflectivity by the thermonuclear environment for laser wavelengths greater than 0.2 microns. The fuel pellet, several millimeters in diameter, would free-fall or be electrostatically projected into the combustion chamber.

For tritium breeding and recovery necessary for pure DT burning, a lithium-rich neutron blanket similar to those being considered for magnetic confinement fusion power-plant designs would surround the combustion-chamber wall. A 1% void fraction in the lithium blanket is probably required to permit impulsive neutron heating of the lithium without mechanical damage to the wall.

Fusion energy conversion

Fusion energy pulses, as extremely high-grade energy sources, apparently admit of several very different means of converting their energy into electricity, depending on pellet-fuel composition, the ρR value at which the fuel is burned (product of density and pellet radius, see box) and the combustion-chamber system design and operation. Three types of systems have been identified so far: They are ordinary thermal conversion, MHD hot-gas-generator conversion and MHD plasma conversion.

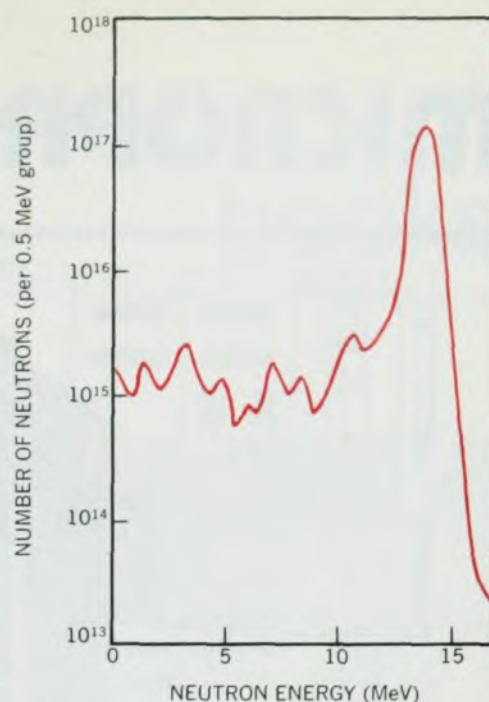
For first-generation laser-fusion power plants, which would burn DT pellets, ordinary steam-thermal conversion of fusion energy deposited by neutrons in the lithium blanket appears preferable. Such systems would have capital costs of several hundred dollars per kilowatt and energy-conversion efficiencies of up to 40%, which is comparable to conventional and fission-reactor systems.

If the combustion-chamber wall is shielded from the plasma pulse by injected gas, the heated gas might be exhausted from the chamber through a relatively inexpensive, pulsed MHD hot-gas generator. Several atmospheres stagnation pressure at a few thousand degrees temperature could be produced. Such a system might permit electricity generation with higher total efficiency (approximately 60%) for moderate ρR (approximately 10 gm/cm²) DT or DD pellet burning, or for a 5 gm/cm², high-charged-particle-fraction (for example D-He³) pellet burning. Such ρR 's may be obtained with a few-hundred-kilojoule lasers if the pellet is compressed to 10⁴ gm/cm³ densities. However, at these high ρR 's, 10-30% of the fusion energy is radiated as x rays. Hence the ultimate efficiency of this approach is limited

by the efficiency with which the x-ray energy may be converted to electricity.

The rapidly expanding fusion fireball may be made to do magnetohydrodynamic work on a magnetic field imposed from outside the combustion chamber, transforming its energy into that of a compressed magnetic field. Induction coils suspended from the combustion-chamber walls might be used to transform the compressed-field energy directly into electricity, in a manner basically very similar to the way an ordinary power transformer works. The basic feasibility of such fireball-to-electricity energy conversion has already been demonstrated.²³ Low capital cost, high efficiency (greater than 70%) electrical energy generation may thus be ultimately attainable, in advanced laser-fusion CTR systems. Various estimates also indicate that laser-fusion power plants will be economically feasible.²⁴

In the mid 1970's crucial superhigh density laser-implosion experiments will be carried out with lasers now being designed. Edward Teller has recently emphasized the importance of these experiments when he said, "A third of a century ago liquids were considered incompressible for all practical purposes. We are talking now about at least a thousand-fold compression if laser fusion is to be practical. This is a challenge we cannot afford to ignore. I believe that we shall succeed and that the effort will profoundly change our views on how man and matter can interact." Practical power production also depends on the success of programs now underway to develop pulsed lasers with



Neutron pulse spectrum of a megajoule DT-fusion microexplosion calculated by a computer code; note the neutron energy peaks produced by single and double 14-MeV neutron scatterings from deuterons and tritons and the 3.5 MeV peak. Figure 6

sufficiently high power, energy, frequency and efficiency, and on the engineering of economic reactors. We are excited by the challenge of these difficult and complex tasks, and by the prospect that the mastery of fusion may be more important to Man than the harnessing of fire.

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