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J. A. Maniscalco
J. Hovingh
R. R. Buntzen

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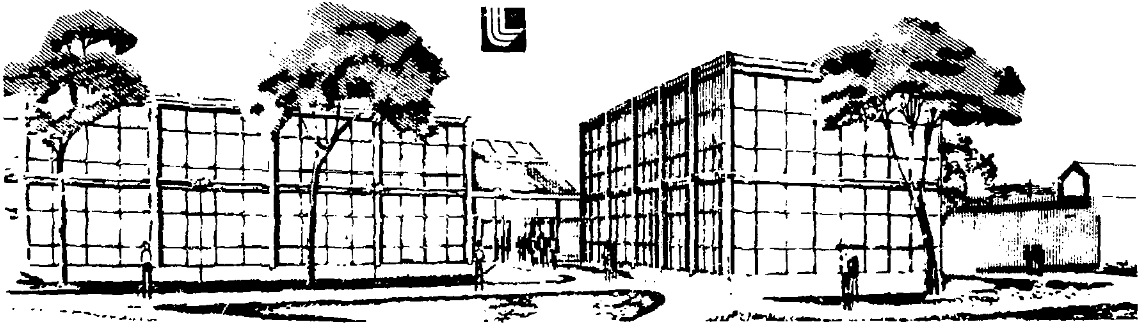

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A DEVELOPMENT SCENARIO FOR LASER FUSION*

J. A. Maniscalco, J. Hovingh, and R. R. Buntzen

Lawrence Livermore Laboratory, University of California
Livermore, California 94550
United States of America

ABSTRACT

System studies at the Lawrence Livermore Laboratory have focused on formulating and analyzing conceptual designs for laser-fusion power plants and on developing fusion-fission hybrid concepts that make sense as part of the evolution to a fusion power economy. We discuss here a development scenario for laser fusion based on these studies. Our scenario proposes establishment of test and engineering facilities to (1) investigate the technological problems associated with laser fusion, (2) demonstrate fissile fuel production, and (3) demonstrate competitive electrical power production. Such facilities would be major milestones along the road to a laser-fusion power economy.

The relevant engineering and economic aspects of each of these research and development facilities are discussed. Pellet design and gain predictions corresponding to the most promising laser systems are presented for each plant. Our results show that laser fusion has the potential to make a significant contribution to our energy needs. Beginning in the early 1990's, this new technology could be used to produce fissile fuel, and after the turn of the century it could be used to generate electrical power.

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1. INTRODUCTION

The laser-fusion program sponsored by the United States Energy Research and Development Administration (ERDA) is primarily concerned with (1) demonstrating the scientific feasibility of initiating thermonuclear burn in a fuel pellet by irradiating it with a high-power pulse of laser light and (2) providing the scientific data base to develop and evaluate new lasers. System studies are being carried out by national laboratories, private industry, and several universities to identify attractive military and commercial applications of laser-fusion technology. The major commercial applications are being evaluated on the basis of required laser/target performance, as well as technology and economic feasibility. These applications include electrical power production, fissile fuel production, hydrogen production, propulsion, burnup of radioactive fission waste, and high-temperature process heat production.

To be a viable source of energy for the future, laser fusion must be scientifically feasible, technologically feasible, and economically competitive with existing energy producers. The phases of research and development leading to significant commercial use of laser fusion in the field of electric power generation are shown in Table 1. The majority of the system studies performed to date have dealt with conceptual designs of laser-fusion power plants. These conceptual designs have been very helpful in identifying critical-path items on the road to a viable laser-fusion energy option.

Comparing the various designs, it has been useful to view a laser-fusion power plant in terms of a basic power-flow diagram shown in Fig. 1. 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. This product, which we refer to as the fusion energy gain, represents the ratio of thermonuclear energy to laser input energy. In Fig. 2, 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 [1-3] 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.

Sophisticated computer programs [4] can mathematically simulate DT pellet microexplosions and provide estimates of Q for various pellet designs and laser irradiations. As shown in Fig. 3, these programs predict that energy gains approaching 50 are possible when DT micropellets are symmetrically irradiated with a 100-kJ pulse of short-wavelength light ($\lambda < 1$ μm) that is properly shaped in time ($t < 1$ns). Pellet gains as high as 100 may be possible with laser energy pulses approaching 1000 kJ.

With pellet gains limited to 100, laser fusion power plants with less than 25% recirculating power will require lasers with overall efficiencies greater than 10%. Lasers presently being pursued and developed are described in Section 2. A development scenario for laser-fusion is then outlined in Section 3.

2. LASER AND TARGET DESIGN

The target and laser subsystems required for a laser-fusion power plant govern nearly all other component designs. Target irradiation requirements and debris spectra dictate many of the design constraints for a reactor; target performance and laser system efficiency specify economical plant operating conditions.

The dynamics of target compression and the difficulties associated with achieving large thermonuclear gains, have been described in detail elsewhere [5].

Two types of targets, solid and hollow microspheres containing stoichiometric mixtures of deuterium and tritium, have been extensively investigated at LLL. Figure 4 shows a sample calculation made for a solid DT (~1 mg) target. A low energy prepulse (~20 J) explodes a thin outer shell, creating an atmosphere around the target. This atmosphere is heated by another prepulse to ensure rapid electron thermal conduction. The implosion is started by 2-μm-wavelength light and continues until the unablated target surface is roughly half the critical density for 1-μm light. A frequency-doubled pulse is then used for further compression, and it is doubled twice again to maintain symmetry and to assure good coupling with the plasma. The target thermonuclear energy release Y is 40 MJ with a 0.9 MJ energy input from the laser E_{in} for a gain Q of 44. Solid targets are attractive for laser-fusion power-plant applications because of their ease of fabrication and potentially low cost. Unfortunately, the peak intensity during the final phase of the implosion exceeds that where back scattering due to Brillouin instabilities can occur. At these high intensities, as much as 50% of the incident laser energy might be reflected, reducing the estimated gain given above.

Because of the backscatter problem at high laser intensities, hollow targets containing more surface area have been investigated. Although these targets might require roughly an order of magnitude less laser power and do not induce significant plasma instabilities, they are limited in performance by fluid instabilities. To date, there exists no known mechanism for dealing with these instabilities in high-gain targets.

The present consensus is that for laser pulse energies between 100 kJ and 1 MJ, the best of these targets might achieve gains in the range of 70 to 120. Such performance must be evaluated in light of the fusion energy gain figure of merit, $\eta_L Q$ for the application of interest (see Fig. 2).

The standard procedure for determining laser system requirements for laser fusion systems has always been to use target performance as a baseline from which the laser requirements can be calculated. For example, from the fusion energy gain product, low-recirculating-power (less than 25%) reactors will require lasers with efficiencies between 10 and 15%. In Fig. 4, we see that the laser system must be able to irradiate the target in a particular way to achieve high gains. Two prepulses are required (20 J and 1.5 kJ);

then, in a precisely timed and controlled fashion, the laser intensity and wavelength must vary over orders of magnitude of five and one, respectively. Twelve or more beams are required to maintain symmetry during the implosion, and a laser with very high brightness is needed to focus on the small targets.

The lasers presently being most actively pursued for laser fusion experiments are listed in Table II. Nd:glass systems have been developed to produce powerful beams of light with very good focusability (10^{18} W/cm^2 ster) for target irradiation experiments [6]. Focusability is important because of the need to concentrate the output power of the laser on a spot approximately 50 μm in diameter. Single-pulse CO_2 systems have also been used for target experiments. High-average-power experiments for developing gas-flow equipment, power conditioning, and optical subsystems have not been conducted to date. Examination of Table II shows that the currently operating gas lasers fall short of the requirements illustrated in Fig. 4.

Extrapolations of the characteristics of various lasers, including an oxygen system [7], are summarized in Table III. An estimate of ideal laser properties (i.e., those required to yield fusion energy gains greater than 10) is also given. Nd:glass lasers have not been listed in Table III. Major factors precluding the use of this highly developed laser technology for laser fusion power applications include:

(1) The relatively large nonlinear index of refraction of the glass medium.

(2) The very low average power capabilities resulting from the low laser efficiency and the low thermal conductivity of the glass medium.

The oxygen laser (O) in Table III is one new laser being developed for laser fusion. It will be many years, however, before it is available for large-scale experiments. Table IV presents several of the more promising generic laser media discovered at LLL. Because scalable pumping techniques strongly impact the viability of a laser system, lasers should be categorized by the pumping technique employed as well as by the working laser medium. The generic techniques for pumping the working gas laser medium include: (1) direct electron beam pumping, (2) optical pumping (using electron-beam-driven radiating substances), and (3) electron discharges.

The properties of the auroral lines of the Group VI elements were reported in Ref. [5]. When the atoms of these elements are excited to the $^1S_0$ state, they exhibit many of the desired properties of the ideal laser. Some of the more promising photolytic pumping schemes investigated for the Group VI elements include vacuum ultraviolet excimer fluorescence from Ar, Kr, or Xe.

In the rare gas-Group VI atom excimers, excitation to the $^1S_0$ state results from energy transfer processes following ionization of the mixtures by an electron beam. Coherent oscillation has been observed in rare gas oxide media [5,8]. As a result, detailed experimental and theoretical studies are presently being performed at LLL on the krypton oxide (KrO) laser medium.

The major factors precluding the extension of Nd:glass laser technology to performance levels required of lasers for laser fusion power applications were listed earlier. Closer scrutiny quickly reveals that these limitations result primarily from the dielectric properties of the glass host and not from the rare earth ions. This observation has prompted investigations [9] of the suitability of rare earth molecular lasers for laser fusion power applications. Calculations have been carried out and reported in Ref. [9] for the classes of rare earth molecular lasers listed in Table IV. The *calculations indicate that these vapor systems should be viable candidates* for laser-fusion power applications. Experiments to demonstrate laser action in these media have been initiated, and they are expected to provide confirmation of the basic phenomenological models.

The prospects of developing new lasers with suitable wavelengths and efficiencies in the neighborhood of 1% look very good. However, with the targets described previously ($Q < 100$), fusion energy gains will still be insufficient for commercial power plant operation. Technical problems *associated with developing* the needed high-efficiency, highly-controlled (space, time, and frequency) lasers with associated low-F-number optical systems that run at high average power, appear overwhelming at this time. While target design is in its infancy, the question should be asked whether or not targets can be designed to produce useful applications with the laser systems that will certainly be available in the 1980's and 1990's. A summary of the options in laser/target system research and development is given in Table V.

Atomic iodine is a laser medium that could be available in the 1980's and 90's. It is different from CO_2 (which has a considerable development base), because of the much shorter wavelength produced (1.32 μm for iodine versus 10.6 μm for CO_2). Theoretical analyses predict considerable difficulties in producing gain at 10.6 μm wavelengths [10] because of unfavorable electron spectra created during the photon absorption process. Such problems are less severe at 1.32 μm, and efficient frequency doubling is possible at the shorter wavelength. Although iodine presently has a low efficiency (0.1%), various photolytic pumping schemes under study promise significant increases in efficiency such that final system efficiency (η_L) could be as high as 1%. Improvements beyond this might be possible using different pump/laser media in essentially the same system configuration. Iodine is scalable in pulse energy and peak power, and it can be extended to high average power. Scaling in energy/power is easier than achieving higher efficiency such that 0.1 to 1 MJ, 10 Hz systems can be envisioned with form factors comparable to CO_2 lasers.

With the characteristics of a near-term iodine laser in mind (see Table III), we could orient target design work toward maximizing pellet gain. If we ignore the target economical constraint for the moment, more expensive complex targets might be possible that achieve higher gains. If advanced high-risk target designs for use with low-risk laser systems can be developed, the laser-fusion applications are significant. This approach should be explored.

3. A DEVELOPMENT SCENARIO

Table VI outlines a development scenario for laser fusion. The completion dates given are estimated on the basis of the magnitude of the required fusion energy gains, the availability of the laser systems needed to achieve these gains, and the need for a substantial time gap between establishment of the laser-fusion test facility (LFTF) and the hybrid demonstration plant. Fusion-fission hybrids will have the potential to produce fissile fuel and energy with fusion energy gains an order of magnitude lower than those required for pure laser fusion; hence, they will not be entirely dependent upon the availability of advanced lasers.

1986 is the earliest low-risk completion date for a LFTF, which would be in the planning and design stages for 4 years and under construction for 4 years more. An earlier complation date would require that construction begin before adequate experimental verification of the laser/pellet interaction performance had been obtained.

The CO_2 laser is the only high-average-power laser system that could be available for LFTF before 1986. Iodine and some of the new lasers previously discussed could be attractive candidates for a LFTF completed in 1986 or later. A 10-TW (10 kJ in 1 ns) CO_2 laser facility is presently being built at the Los Alamos Scientific Laboratory (LASL). It is scheduled for completion in late 1977. If target-irradiation experiments are successful, a 100-TW CO_2 laser facility could be completed in 1981 and used for pellet experiments in 1982. The building phase of a LFTF scheduled for completion before 1986 would have to start before 1982 without the benefit of experimental results from the 100 TW facility. This would require that large sums of money be committed on the basis of fusion energy gain estimates theoretically extrapolated from experimental results obtained with the 10-TW facility.

A laser-fusion test facility

As indicated in Table VI, the first step in a logical scenario for the development of laser-fusion power plants is a laser fusion test [11,12]. This facility would be used to study:

- 14-MeV neutron damage.
- 14-MeV neutron activation.
- Neutron-energy direct-conversion schemes.
- Charged-particle-energy direct-conversion schemes.
- Laser-fusion blankets and first walls.
- Neutronic pumping schemes for lasers.

Meaningful 14-MeV neutron damage experiments would impose the greatest demands on the LFTF. Typical conceptual D-T laser-fusion reactor power plants [1,2,13] operate with a time-averaged 14-MeV neutron flux of about 5×10^{17} $n/m^2 \cdot s$. There is little experience with 14-MeV neutron damage in candidate first-wall materials at these flux levels. Current 14-MeV neutron generators produce on very small samples, a flux one order of magnitude lower than that listed above [14]. This means that we must increase the experimental time by an order of magnitude to achieve the time-integrated flux that the first wall of a fusion-reactor power plant may be required to withstand. Since lifetimes longer than 1 year are desired for the first wall of fusion-reactor power plants, a 14-MeV neutron generator capable of producing a flux of at least 5×10^{17} $n/m \cdot s$ is required, and greater fluxes are desired. Such a generator would be useful for studying the bulk and surface effects of pulses of 14-MeV neutrons on candidate reactor first wall materials. It would also be useful for examining x-ray flash damage and pellet debris damage as well as the damage from laser light reflected from the pellet on the first wall. Neutron activation studies would be useful in waste management analysis for fusion reactors.

The 14-MeV neutron generator could be used to investigate schemes (such as that of the Compton generator proposed by Wood and Weaver [15]) for converting neutron energy directly into electrical power. Additional uses of the 14-MeV neutrons would be to study neutronic pumping schemes proposed by Wells [16] and conventional and hybrid blanket concepts proposed by Maniscalco [17]. The charged particles from the fusion reaction and pellet debris can be used to study schemes for converting the charged-particle energy directly into electrical power (e.g., the expansion of the fusion fireball against a magnetic field imposed from outside the first wall [18]).

A first-wall time-averaged 14-MeV neutron flux of 1.8×10^{18} n/m^2·s was chosen in our reference design for LFTF. This flux is roughly three times greater than that currently anticipated for fusion power plants. Thus LFTF must operate with a "plant factor" of greater than 0.26 to accumulate damage data in the same real-time that will occur in a fusion power plant operating with a "plant factor" of 0.8. Each of the major subsystems in a LFTF, must have a reliability factor of 0.85 to yield a plant factor greater than 0.26. For reasonable sized experiments, about 1 m^2 of experimental area is required. Allowing 2π steradians for pellet irradiation plus 0.3 steradian for vacuum pumping, the required first-wall radius is 0.4. This radius, coupled with a time-averaged first-wall neutron flux of 1.8×10^{18} n/m^2·s, results in a thermonuclear power requirement of 10 MW.

Figure 5 shows the plant power and laser input power requirements for LFTF as a function of fusion gain. Note that the plant power is proportional to the fusion gain and is, when considering the electrical power factor, virtually the same as the laser input power. The plant cost for a thermonuclear power of 10 MW and a first-wall neutron flux of 1.8×10^{18} n/m^2·s, is shown in Figure 6 as a function of fusion gain. The important thing to note in this figure is that for fusion gains greater than 0.1 (laser input powers less than 100 MW) the plant cost is virtually unaffected by the fusion energy gain.

The results shown in Figures 5 and 6 indicate that 0.1 is a minimum fusion gain for a practical system with 10 MW of fusion power. Higher fusion gains are of interest, but the performance risks increase with increasing fusion gain. To obtain 10 MW of fusion power from a system with a fusion gain of 0.10, the power into the laser must be 100 MW. The total power requirement for such a facility is 135 MVA, 90% of which can be termed laser power requirements. The total cost of the system has been estimated at 165 M$, with 40% of this figure in the laser system and 25% in the tritium-handling system.

There are several possible gas laser systems capable of operating in a pulsed mode with nanosecond pulse lengths. One laser system assumed in our reference design studies is the CO_2 laser. As mentioned already, another likely candidate is the iodine laser. A summary of the requirements for these two laser systems in a LFTF is given in Table VII. Both systems yield a fusion energy gain of 0.1 and provide 10 MW of thermonuclear power from 100 MW of laser input power.

Freiwald and Kern [12] have investigated laser-fusion sources for CTR surface and bulk damage testing. Their reference design features a 0.5-m-radius cylindrical first-wall protected from the pellet debris by 0.8-tesla solenoid. The experimental area is about 1.65 m^2. The laser output energy is 100 kJ. There is a pulse repetition frequency of 1 Hz. Freiwald considers two separate laser systems: CO_2 and HF. For a CO_2 laser system, he establishes a laser system efficiency η_L of 0.063 and a gain Q of 2 resulting in a fusion gain of 0.13. The power required by the laser system is 1.6 MW, and the peak first wall neutron flux is 2.2×10^{16} $n/m^2 \cdot s$ for an experimental production rate of 3.6×10^{16} n/s. Using an HF laser system with an efficiency of 0.069 and a pellet gain of 8, the fusion gain is 0.55. The power required by the HF laser system is 1.4 MW, and the peak neutron flux is 8.9×10^{16} $n/m^2 \cdot s$ with an experimental neutron production rate of 1.5×10^{17} n/s. Freiwald estimates a total capital cost of about 53 M$ for the LASL reference design, and a total electrical power requirement with a

CO_2 laser of 1.9 MWe and with an HF laser of 2.1 MWe. With a power factor of 0.83, the total electrical power requirement becomes 2.3 and 2.5 MVA for CO_2 and HF, respectively.

The effectiveness of the various facilities can be measured in four different ways: neutron flux per unit of plant power required $(n/m^2 \cdot MJ)$; neutron flux per unit plant cost $(n/m^2 \cdot s \cdot M\$)$; experimental neutron production rate per unit of plant power required (n/MJ); and experimental neutron production rate per unit plant cost $(n/s \cdot M\$)$. A summary of the performance parameters for the reference facilities is given in Table VIII. Note that the costs and power requirements are not necessarily consistent between the LFTF and the LASL systems.

For a time-averaged neutron flux of 1.8×10^{18} $n/m^2 \cdot s$, the time-averaged first wall energy flux for neutrons and charged particles, respectively, is 4.1 and 1.1 MW/m^2. The amount of neutron energy deposited in the first wall is negligible relative to that deposited by the charged particles. Hoffmann [19] notes that a tantalum-tungsten alloy has a maximum heat flux capability of about 36 MW/m^2, while stainless steels have heat flux capabilities between 10 MW/m^2 for specified geometries and water cooling [20]. Thus, higher neutron fluxes may be considered for these facilities in the future, although experimental probes can be injected through the first wall to achieve time averaged neutron fluxes as high as 6.5×10^{19} $n/m^2 \cdot s$. This is two orders of magnitude greater than the neutron fluxes of proposed fusion reactor designs.

A laser-fusion engineering research facility could be built in the mid 1980's using near-term short-pulse gas-laser technology, producing 10 MW of thermonuclear power with fusion gains of approximately 0.1.

Fusion-Fission Hybrid Reactors

Nuclear power-generating systems using fusion-produced neutrons to generate fission are generally classified as *fusion-fission hybrids*. Interest in hybrid systems, dating back to the early 1950's [21,22], 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.

Our system studies have been directed toward neutronic analysis and comparison of hybrid concepts for laser-induced fusion that use energy-multiplying and fissile-breeding blankets based on different fission reactor technologies (liquid-metal and gas-cooled fast breeder reactors, high-temperature gas-cooled reactors, liquid-metal-cooled thermal reactors, etc.).

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. Figures 7 and 8 show the configurations and material choices for hybrid blankets which fall into one of these two categories. The conceptual designs and material choices, as presented, encompass so many different fission reactor technologies (HTGR, LMFBR, GCFBR, etc.) that it will be fitting to give the reasons for excluding light water reactor (LWR) technology, since it is the most widely used and established fission technology. Blankets for DT-burning fusion devices must breed tritium, and they will therefore contain substantial quantities of lithium. Water has not been listed as a possible coolant because of the possibility of tritium contamination and the hazards posed by its generally high chemical reactivity with liquid metals, particularly lithium.

Refractory metals such as niobium, tungsten, and molybdenum have been chosen as structural materials in several fusion reactor conceptual designs because of their physical and chemical properties at high temperatures. These metals have also been considered as potential structural materials for hybrid blankets; however, it is anticipated that stainless steel will be the structural material of choice for first-generation hybrid reactors. The selection of stainless steel limits the high-temperature operation of a hybrid blanket to values currently achieved in fission reactors. Nevertheless, it is consistent with our desire to consider hybrid concepts which could be built in the near future with minimal extensions of the state-of-the-art technology developed in the fission-power economies.

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 thorium-fueled non-fissioning blanket is another type of fissile-fuel producer. Strictly speaking, it is not a fusion-fission hybrid. It is usually referred to as a symbiotic system, indicating that fuel is produced for consumption in physically separate fission reactors. Fissioning is suppressed in this type of fusion blanket by moderating the fusion neutrons to energies below the fission threshold in thorium and by continuously removing the bred ^{233}U. In comparison to hybrids, symbiotic devices provide very little, if any, energy multiplication and produce less fissile fuel per unit of fusion energy. However, proponents of symbiotic systems claim that the lower production capability may be offset by lower blanket and fuel reprocessing costs resulting from the absence of fission products.

A comparative summary of the operational characteristics of the three fissile-fuel producers described above is shown in Table IX. The fissile fuel producers shown can be considered to be neutronically optimized in that they have resulted from more than 100 separate transport calculations described in a previous paper [23]. All of the neutronics calculations were performed with the TART Monte Carlo Code [24] and with cross sections from the Evaluated Nuclear Data Library [25] at LLL. 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.

Figure 9 gives the production capabilities of laser-driven fissile-fuel producers and fission breeder reactors along with the consumption requirements of thermal burner and converter reactors. (Reactors are considered "burners" for values of $C < 0.8$, converters for $0.8 < C < 1.0$ and breeders for $C \geq 1.0$ where C, the conversion ratio, is defined as the ratio of fissile atoms produced to fissile atoms destroyed.) The left portion of Fig. 9 displays the net fissile production capabilities of both fusion and fission breeders normalized to a unit of thermal energy. On this basis, thorium fast-fission hybrids outperform uranium-fueled concepts.

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.

The fissile consumption requirements of present burner and advanced converter reactors are presented in the right side of Fig. 9. It is interesting to match the consumption requirements of the fissile burners to the production capabilities of the breeders. Here we see that a thorium fast-fission hybrid provides enough fissile material to fuel 23 HTGR's of equivalent thermal power, while a depleted-uranium-fueled hybrid produces enough fissile material to fuel 8 LWR's of equivalent thermal power. Conversely, fast breeder reactors do not produce enough excess fissile material to fuel even one LWR of equivalent thermal power. (It is well known that the excess fissile material produced in FBR is best used to fuel another FBR.)

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.

The energy multiplication characteristics of all the neutronically analyzed [17] hybrid blankets are summarized in Fig. 10. 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 Fig. 1, with thermal efficiency set at 35%.

Figure 10 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 Figure 9, we saw that thorium-fueled hybrids outperformed uranium-fueled hybrids on the basis of fissile fuel produced per unit of thermal energy. Figure 10 shows that uranium-fueled hybrids can produce fissile fuel in an energy breakeven mode with fusion energy gains that are 2 to 6 times lower than those required for thorium blankets.

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 X, 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. Plutonium-enriched fast-fission blankets could best be characterized as source-driven fast breeder reactors (LMFBR or GCFBR). They exhibit the largest energy multiplication and fissile production per unit of fusion energy. The curves in Figure 10 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 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 10 shows that thermal fission blankets can efficiently produce power with fusion energy gains 2 to [illegible] times lower than those required for fast-fission blankets. However, the comparative summary (Table X) 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.

A Pure Laser Fusion Reactor

The ultimate goal of laser-fusion research is a pure laser-fusion reactor power plant. To achieve this goal, a fusion energy gain of at least 10 is required. At the present time, lasers meeting the requirements for a pure laser-fusion reactor system are not available, but there have been several conceptual designs proposed. The basic differences are primarily in the design of the first wall that separates the blanket from the microexplosion chamber.

Three different approaches to the combustion-chamber first-wall design have been discussed: dry wall, wet wall, and 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.

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 [13]. 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 [26]. 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 11, was developed by LASL [2]. 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.

The suppressed ablation [1] system shown in Fig. 12 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 13. 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 concept [3] is shown in Fig. 14. 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 [18]. 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 DHe^3 or pB^{11}). 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.

A comparison of four different reactor concepts is shown in Table XI. 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, the [illegible] 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, tailored to the specific laser-pellet design and fuel cycle.

A great deal of effort, patience and invention will be needed before pure laser-fusion reactors will contribute appreciably to our national energy picture. This interdisciplinary effort should be focussed on first-wall, pellet and laser design and development. 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.

4. CONCLUSIONS

In Fig. 15, a development scenario for laser fusion is superimposed on the curves from Fig. 10. 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, and a prototype laser-fusion power plant sometime after the turn of the century.

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 10 or more lie somewhere in the unpredictable future.

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TABLE I. THE PHASES OF RESEARCH AND DEVELOPMENT FOR LASER FUSION

Scientific Feasibility

- Providing the scientific data base to understand the underlying physics of interaction between laser light and plasma.
- Providing the scientific data base to develop and evaluate lasers for laser fusion.

Engineering Feasibility

- Research facilities to evaluate the technological problems associated with laser fusion.
- Experimental power reactors to investigate the integrated engineering performance of a laser-fusion power plant.

Commercial Feasibility

- Prototype laser fusion power plants to compare the concept to competitive alternatives.

TABLE II. CURRENT STATUS OF LASERS

Laser	Wavelength, μm	Max power (single beam), TW	Efficiency, %	Pulse energy, J	Focusability	Wavelength convertibility, μm
Nd:Glass	1.06	1.2[a]	~0.1	80(65 Ps)	Very good	0.53 ~ 50% efficiency
		0.2–0.3[b]		60 Total	Nominal	0.35 ~ 30%
		0.4[c]	-	150 (0.4 ns)	Unknown	0.27 ~ 20%
CO_2	10.6	0.15[d]	1–2	250 (1.6 ns)	Good	Not demonstrated at high power
Iodine	1.32	0.3[e]	0.1	300 (1 ns)	Poor	Similar to Nd:Glass
HF	2.7	0.15[f]	~3	4000 (26 ns)	Very poor	Not evaluated

[a] Lawrence Livermore Laboratory

[b] *KMS-F (uses pulse stack)*

[c] University of Rochester

[d] Los Alamos Scientific Laboratory

[e] *Institute fur plasmaphysik, Garching*

[f] Sandia Laboratories, Albuquerque

TABLE III. POTENTIAL LASERS FOR LASER FUSION

Laser System	CO_2	HF	I	O	Ideal
Properties					
Wavelength, μm	10.6	2.7	1.3	0.56	0.3
Energy, J	10^5	10^5	10^5	10^5	10^5-10^6
Pulse width, ns	1.0	1.0	0.1-1.0	0.1-1.0	0.1-1.0
PRF, sec^{-1}	>10	>10	>10	>10	>10
Efficiency, %	5-8	5-13	1.0	>1.0	10-15
Fusion energy gain (estimate)	0.1	~1	~1	>1.0	>10

TABLE IV. GENERIC LASER FUSION MEDIA IDENTIFIED AT LLL

- Group VI atoms (optical pumping)

  O, S, Se, Te, C, Ge, Sn, Si

- Rare gas -- Group VI atom excimers (electron beam pumping)

  ArO, KrO, XeO, KrS, etc.

- *Rare earth molecular gases (optical and E-beam pumping)*

  Rare earth trihalogens

  Rare earth-transition metal trihalogen complexes

  Rare earth vapor chelates

TABLE V. LASER/TARGET SYSTEM OPTIONS

	Option A: Matching laser to near-term target technology	Option B: Matching target to near-term laser technology
Target characteristics	• Potentially inexpensive and easy to fabricate	• Potentially expensive and difficult to fabricate
	• Gain appears limited by Rayleigh-Taylor instabilities and high induced reflectivity	• Higher gain, improved coupling
	• Highly uniform near-normal irradiation required	• Non-normal illumination
Laser system characteristics	• High efficiency	• Low efficiency
	• Numerous beams	• Longer pulse
	• Low f number optics	• High f number optics
	• *Multiple frequency*	• *Reduced* number of beams
	• Pulse shaping	
	• High Brightness	

TABLE VI. A DEVELOPMENT SCENARIO FOR LASER FUSION

Facilities	Required fusion energy gain ($\eta_L Q$)	Candidate lasers	Earliest completion date
● Laser fusion test facilities to investigate the technological problems associated with laser fusion.	≥ 0.1	CO_2 or I	1986
● Fusion-fission hybrid reactors to produce fissile fuel and/or power with laser fusion.	≥ 1.0	I or new laser	1994
● Prototype laser fusion power plants to compare the concept to competitive alternatives.	≥ 10.0	Ideal laser	2000

TABLE VII. LASERS FOR LFTF REFERENCE DESIGN

Laser	CO_2	Iodine
Pellet gain (Q)	2	10
Laser efficiency (η_L)	0.05	0.01
Laser output energy, kJ	100	100
Repetition rate, Hz	50	10

Fusion energy gain = $Q\eta_L$ = 0.1

Laser input power 100 MW

TABLE VIII. SUMMARY OF PERFORMANCE PARAMETERS FOR THE REFERENCE FACILITIES

	LFTF	LASL-CO_2	LASL-HP
First-wall neutron flux, $n/m^2 \cdot s$	1.8×10^{18}	2.2×10^{16}	8.9×10^{16}
First-wall radius, m	0.40	0.50	0.50
Experimental area, m^2	0.94	1.65	1.65
Laser input power, MW	100	1.6	1.4
Fusion energy gain	0.1	0.13	.55
Plant power required, MVA	135	2.3	2.5
Plant cost, M$	164	53	53
Experimental neutrons, n/s	1.7×10^{18}	3.6×10^{16}	1.5×10^{17}
Effectiveness ratios:			
Flux/plant cost, $n/m^2 \cdot s \cdot M\$$	1.1×10^{16}	4.1×10^{14}	1.7×10^{15}
Flux/plant power, $n/m^2 \cdot MJ$	1.3×10^{16}	9.4×10^{15}	3.6×10^{16}
Experimental neutrons/plant cost, $n/s \cdot M\$$	1.0×10^{16}	6.7×10^{14}	2.8×10^{15}
Experimental neutrons/plant power, n/MJ	1.3×10^{16}	1.5×10^{16}	5.9×10^{16}

TABLE IX. 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 thermal energy	1.1	1.7	1.1
Maximum power density in fuel,[a] W/cm^3	12.7	25.3	135.0
Maximum fuel burnup,[a] atom %/yr	≈0.0	0.07	0.30
Fusion energy gain $(Q\eta_L)$ for electrical breakeven	2.30	1.40	0.35

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

TABLE X. 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	0.22	0.31
Maximum power density in fuel,[a] W/cm^3	135.0	230.0	810.0
Maximum fuel burnup,[a] atom %/yr	0.30	0.77	2.55
Fusion energy gain ($\eta_L Q$) for 25% recirculating power	1.39	0.56	0.18
Fusion energy gain $\eta_L Q$ for 10% recirculating power	3.5	1.4	0.44

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

TABLE XI. NOMINAL REFERENCE SYSTEM PARAMETERS, 1000 MWe LCTR[a]

	Dry Wall	Suppressed Ablation	Wet Wall	Magnetically Protected
Number of chambers	4	50	24	4
Pulse rate, Hz/chamber	7.2	10	1.2	7.2
Fusion energy gain ($Q\eta_L$)	6.5	7.0	6.5	6.5
Blanket gain, M	1.3	1.1	1.3	1.3
Tritium breeding ratio	1.2	1.45	1.2	1.2
Cavity shape	Sph.	Icos.	Sph.	Cyl.
First wall radius, m	9.7	2.2	1.7	2.5
No. of Laser beams/cavity	8	12	8	8
Laser energy into cavity/pulse, MJ	1	0.1	1	1

[a] All of these systems have been normalized to a recirculating power fraction of 0.33 and a net system efficiency of 27%.

FIGURE CAPTIONS

Fig. 1 Laser-fusion power-flow diagram: 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; P_B = net electrical power; $P_{in}/P_g = [\eta_L Q \eta_T \, (0.8M + 0.2)]^{-1}$.

Fig. 2 Plant recirculating power requirements as a function of fusion energy gain.

Fig. 3 Pellet gain versus compression for short-wavelength-light pulses of varying energies.

Fig. 4 Sample calculation for the solid DT target shown (from Ref. 5); E_{in} = 0.9 MJ, Y = 40 MJ, and Q = 44.

Fig. 5 Power requirements for LFTF as a function of fusion energy gain. Results are for a first-wall 14-MeV neutron flux of 1.8×10^{18} n/m^2·s at a radius of 0.4 m (10 MW thermonuclear power).

Fig. 6 Cost of LFTF as a function of fusion energy gain. Cost is normalized to a first-wall 14 MeV neutron flux of 1.8×10^{18} n/m^2·s at a radius of 0.4 m (10 MW thermonuclear power).

Fig. 7 Fast fission blankets: configuration and material choices.

Fig. 8 Thermal fission blankets: configuration and material choices.

Fig. 9 The production and consumption of fissile fuel.

Fig. 10 Laser-fusion energy gain requirements for hybrid fusion/fission systems.

Fig. 11 The lithium wetted-wall LCTR concept.

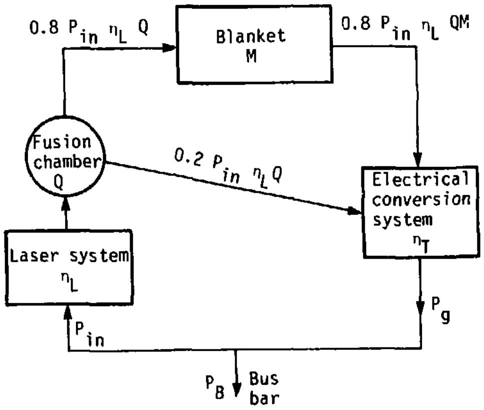
Fig. 12 A conceptual suppressed-ablation laser-fusion reactor.

Fig. 13 A conceptual suppressed-ablation laser-fusion reactor blanket element.

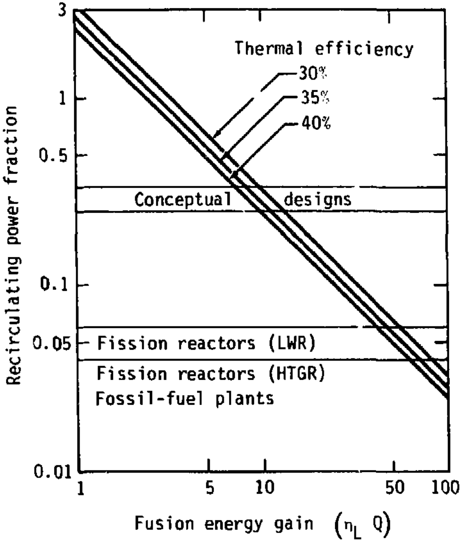
Fig. 14 Schematic of cylindrical magnetically protected LCTR cavity.

Fig. 15 A development scenario for laser fusion.

KM/sc/po/mla



Maniscalco, Fig. 1



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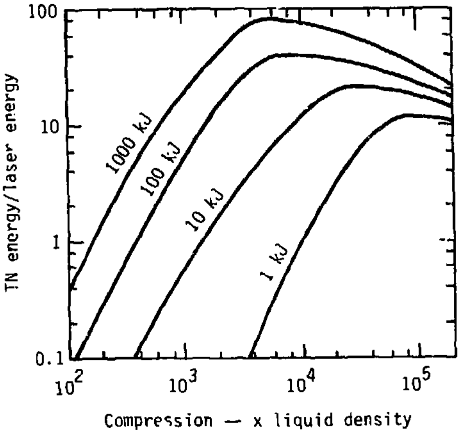

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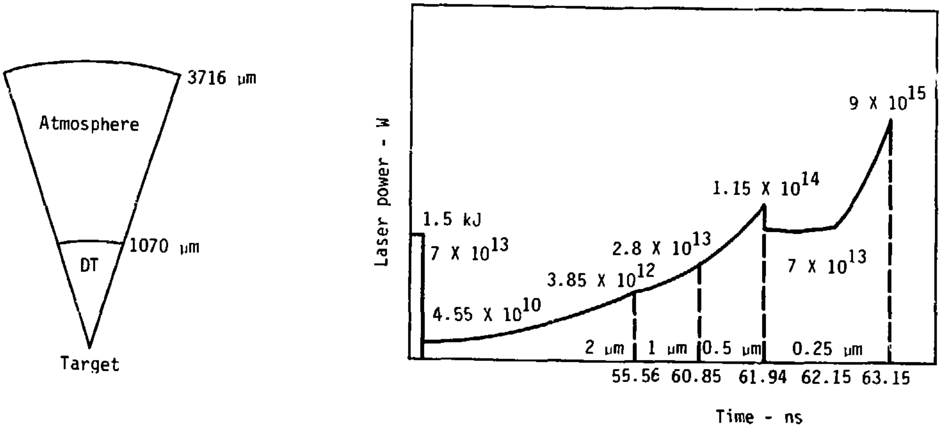

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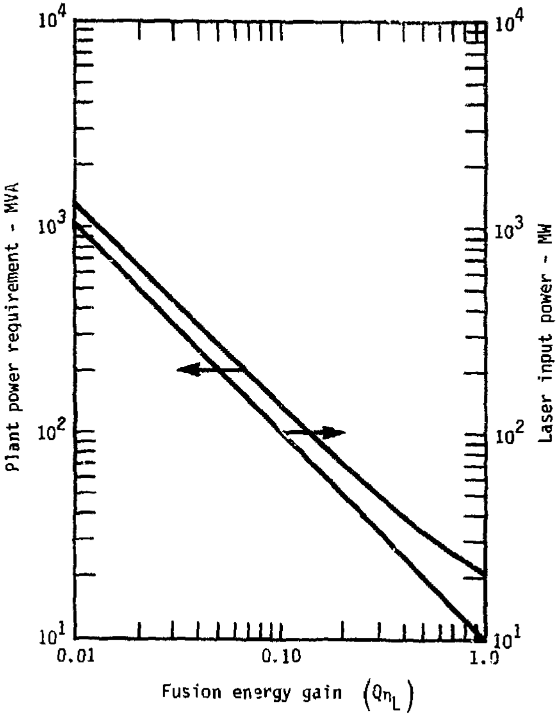

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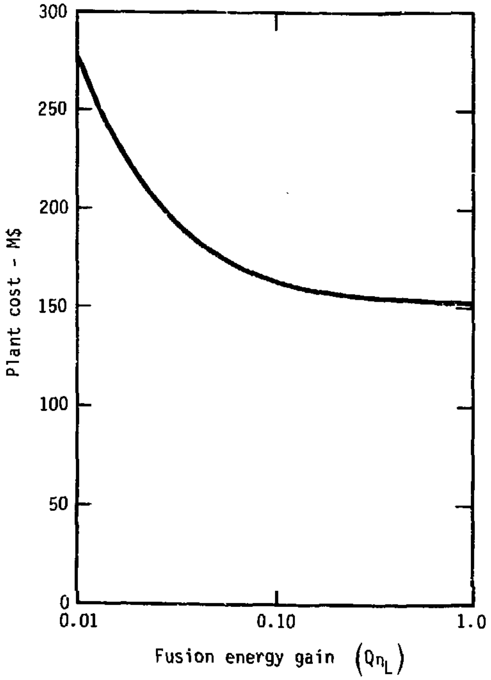

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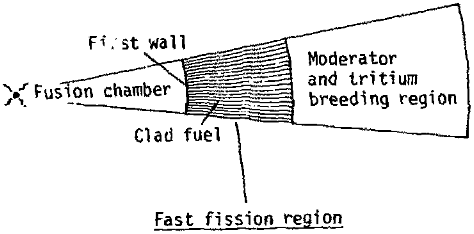
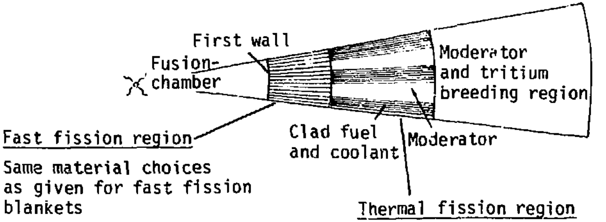


Fuels:
  Type: metals, oxides, or carbides
  Fertile isotopes: ^{232}Th or ^{238}U
  Fissile isotopes: ^{233}U, ^{235}U, or ^{239}Pu
  Cladding: stainless steel or refractory metals

Coolants: gas or liquid metal

Structure: stainless steel or refractory metals

Maniscalco, Fig. 7



Same material choices as given for fast fission blankets

Fuels:

Type: oxides or carbides

Fertile isotopes: ^{232}Th or ^{238}U

Fissile isotopes: ^{233}U, ^{235}U, ^{239}Pu

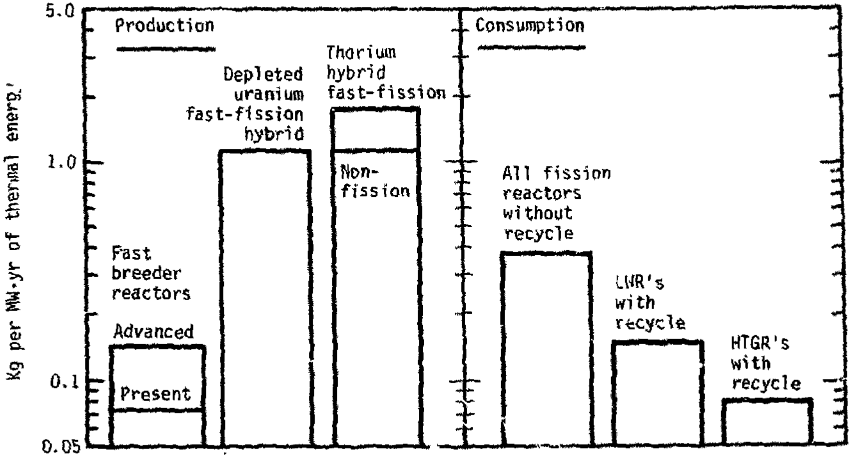
Cladding: graphite, zirconium, or stainless steel

Moderators: graphite or hydrides

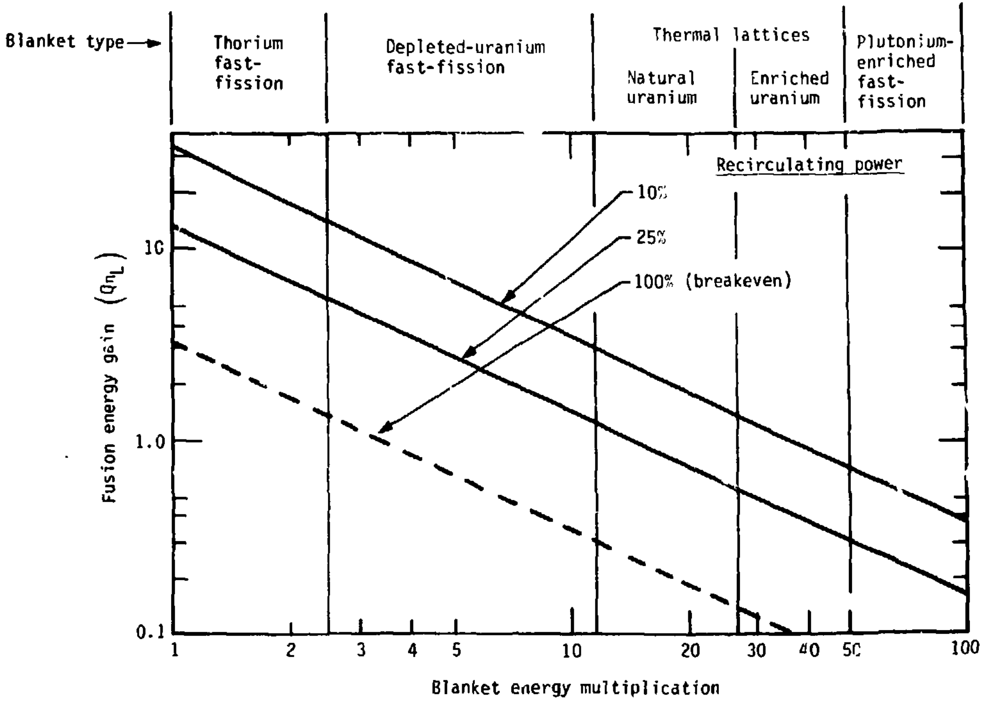
Coolants: gas or liquid metal

Structure: materials with low thermal neutron absorption

Maniscalco, Fig. 8



Maniscalco, Fig. 9



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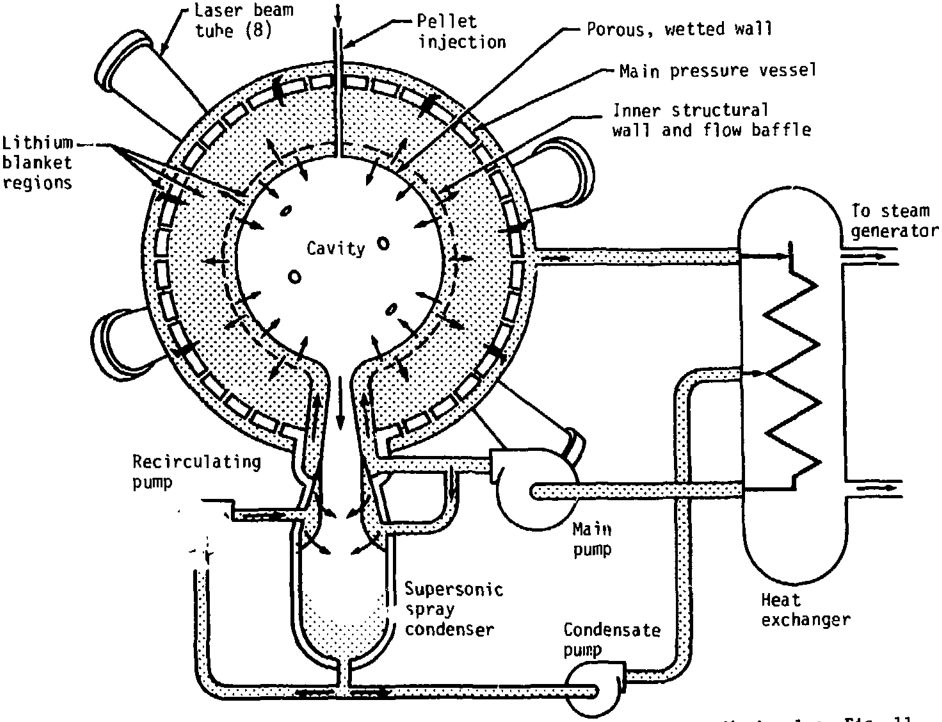

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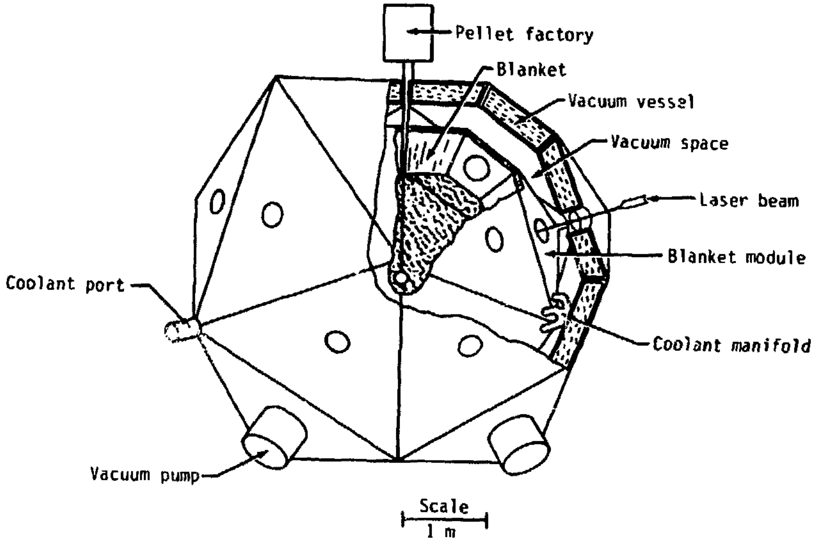

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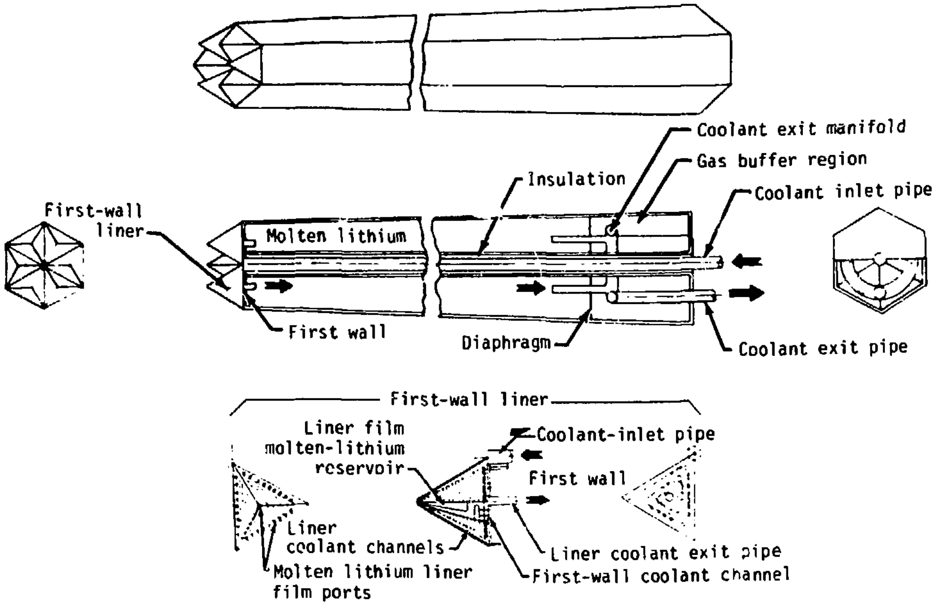

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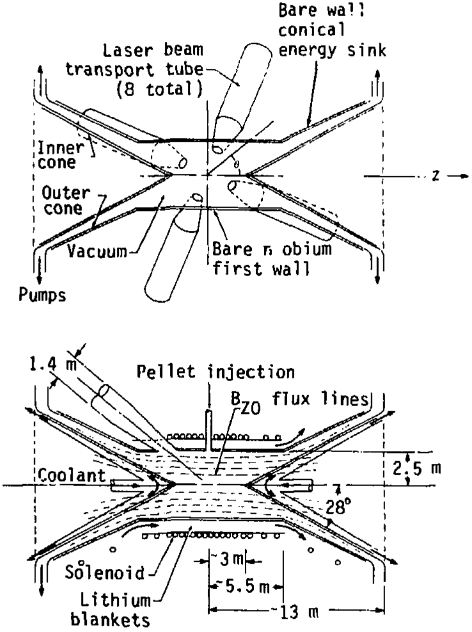

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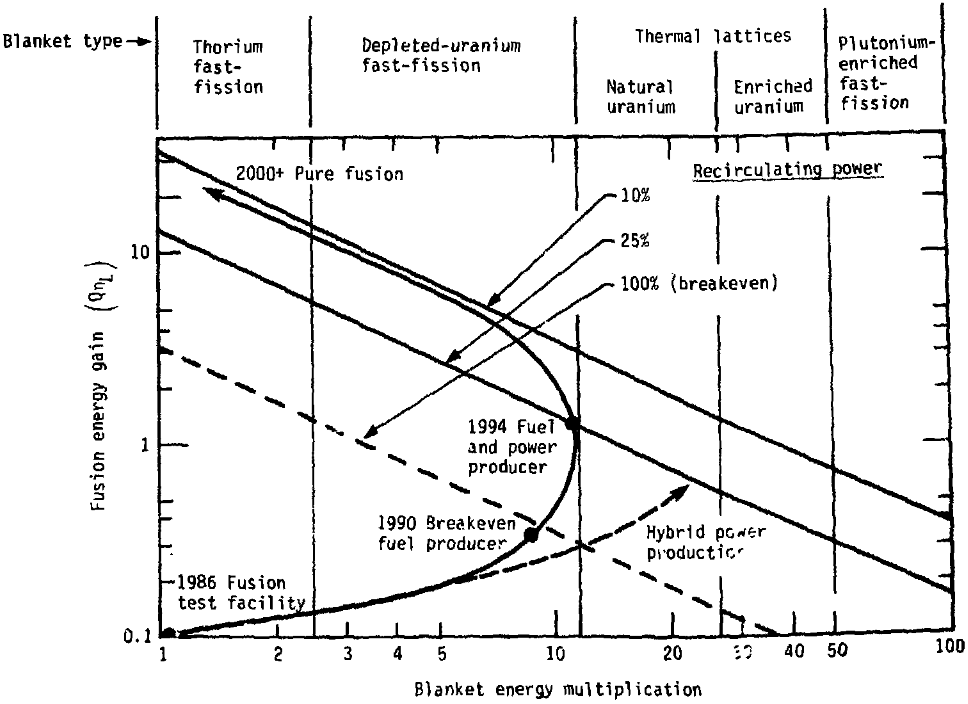

Mariscalco, Fig. 15