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A CONCEPTUAL DESIGN STUDY FOR A LASER FUSION HYBRID

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Lawrence Livermore Laboratory and Bechtel Corporation have been involved in a joint effort to conceptually design a laser fusion hybrid reactor. The design which has evolved is a depleted-uranium fueled fast-fission blanket which produces fissile plutonium and electricity. A major objective of the design study was to evaluate the feasibility of producing fissile fuel with laser fusion. This feasibility evaluation was carried out by analyzing the integrated engineering performance of the complete conceptual design and by identifying the required laser/pellet performance. The performance of the laser fusion hybrid has also been compared to a typical fast breeder reactor. The results show that the laser fusion hybrid produces enough fissile material to fuel more than six light water reactors (LWR's) of equivalent thermal power while operating in a regime which requires an order of magnitude less laser and pellet performance than pure laser fusion. In comparison to a fast breeder reactor the hybrid produces 10 times more fissile fuel. An economic analysis of the design shows that the cost of electricity in a combined hybrid - LWR scenario is insensitive to the capital cost of the hybrid, increasing by only 20 to 40% when the capital cost of the hybrid ranges from 2 to 3 times more than an LWR.

INTRODUCTION

The possibility of producing fissile fuel and electricity by placing a subcritical fission blanket around a fusion chamber has emerged as a promising application of fusion. Fusion-fission hybrid systems naturally combine the "power richness" of fission with the "neutron richness" of fusion. In system studies for laser fusion at Lawrence Livermore Laboratory we have evaluated the potential of fusion-fission hybrids that make sense as part of the evolution of a fusion power economy. Earlier studies[1,2,3] primarily utilized neutronic methods of analysis to identify more attractive hybrid systems and to provide an upper bound estimate on performance. These earlier studies identified several promising concepts. They also demonstrated that fusion-fission hybrids could be designed to meet a broad spectrum of fissile fuel producing and energy multiplying requirements. The two most significant features which emerged from our neutronic scoping studies were:

1. Laser fusion hybrids produce 10 times more fissile fuel (per unit of thermal energy generated) than fission breeder reactors.
2. Laser fusion hybrids produce electricity with much lower laser efficiencies

and pellet gains than required for pure laser fusion.

The neutronic results were encouraging but it was apparent that a more accurate assessment of the hybrid's potential and a definitive ranking of the more promising concepts would require studies which deal with the engineering safety and economic issues as well as the neutronic aspects. With this in mind, Bechtel Corporation was engaged to assist us in a conceptual design study of a fusion hybrid. The scope of the study was defined by the requirement to provide enough design detail to realistically gauge the value of a laser fusion hybrid in a fission power generation economy. The joint effort has been underway since July 1975. This paper will describe and analyze the laser fusion hybrid design which has evolved.

The hybrid concept chosen for this design study is a depleted-uranium fueled fast-fission blanket which produces fissile plutonium and electricity. It emphasizes fissile material generation by maximizing for fuel production at the expense of energy multiplication. This blanket selection was based on reported neutronic results[4,5] which indicated that a depleted uranium fueled fast fission blanket could provide enough fissile fuel to extend the energy available from economically proven light water reactors (LWR's) by as much as two orders of magnitude.

A comparative analysis[4] of the neutronic properties of several hybrid concepts has shown that depleted uranium fast fission blankets provide the largest amount of fissile fuel (per unit of thermal energy) with the lowest laser efficiency and pellet gain requirements. The depleted uranium blanket selected for our conceptual design produces enough fissile material to fuel more than six LWR's of equivalent thermal power. Thorium fueled hybrids produce more fissile fuel per unit of thermal energy but their fusion energy multiplying capabilities are much lower. Hence, they require a higher performing laser fusion system. There are blanket concepts which have higher energy multiplication capabilities than depleted uranium blankets. These blankets could efficiently produce electricity with lower fusion energy gains; however, their enhanced energy multiplication is gained at the expense of decreased fissile production.

Light water reactors will be the major and most likely the only, source of commercial nuclear electric power for the remainder of this century. Their dominance over coal fired plants as base load electrical generators will be strongly dependent on the adequacy of their long term fissile fuel supply. By converting the U^{238} in natural uranium to fissile plutonium, the hybrid could extend the fissile fuel supply for economically proven LWR's by two orders of magnitude. Fast breeder reactors also offer the prospect of more fully utilizing the uranium resources but they will not provide fissile fuel for LWR's. Therefore, the usefulness of fast breeder reactors will be entirely dependent on their economic competitiveness as power plants.

THE LASER FUSION HYBRID DESIGN

Work in the joint laser fusion hybrid design study was apportioned as follows: Lawrence Livermore Laboratory provided the overall direction, the neutronics data, and the fusion portions of the design. Bechtel Corporation provided the fission portion of the hybrid, the design of the thermal energy transport and conversion system, the tritium recovery system, and the layout of the complete power plant. They also analyzed the fuel cycle, capital, and operating cost. Bechtel's contribution to the laser fusion hybrid design is fully documented in their final report to Lawrence Livermore Laboratory[6].

We set for ourselves four major objectives by which to gauge our success in the design study:

1. Identify the laser/pellet performance required to economically produce fissile fuel and power with a hybrid.
2. Evaluate the integrated engineering performance of a complete conceptual design.
3. Compare a laser fusion hybrid to existing fission breeder options (LMFBR, GCFBR, LWBR).
4. Identify major technological problems associated with a laser fusion hybrid.

Achievement of these objectives completely defined the level of design detail and costing analysis for the study.

In addition to these objectives there were a few philosophical points of view which significantly affected our design choices. First, we wanted to operate the laser fusion hybrid in a regime which required an order-of-magnitude less laser/pellet performance, i.e., fusion energy gains in the neighborhood of 1.0. This implied blanket energy multiplications approaching 10.0. Second, we wanted to utilize state-of-the-art fission technology in the design of the hybrid blanket. In keeping with this principal, we chose stainless steel as the structural and cladding material instead of higher performing refractory metals. Finally, we believed that a hybrid reactor which produces fissile fuel should be designed to be as safe as and with the same environmental impact as the fissile burning reactors which it is providing fuel for. Here we note that a negligible improvement in the overall environmental impact results from making the hybrid environmentally more attractive than the larger number of light water reactors it is supplying fuel for.

HYBRID REACTOR DESIGN

The functional shape of the laser fusion hybrid chosen for final evaluation is shown in Fig. 1. In its simplest form it is a cylinder with a height-to-diameter ratio of 1.0. The center of the fusion chamber is the focal point for a six beam, 100 KJ laser system which irradiates the fusion target from the top and bottom of the cylinder.

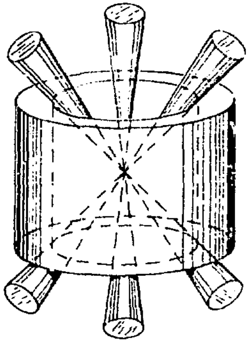

FIGURE 1. Geometry Used In The Laser Fusion Hybrid

The basic features of the hybrid reactor are displayed in Fig. 2. A depleted uranium fueled fast-fission blanket has been positioned radially around the fusion chamber. The energy in the fission zone (amounting to 90% of the total energy) is removed with a sodium coolant system. The liquid sodium enters into the fission zone from the lower plenum and flows to the upper plenum through hexogonally shaped process tubes.

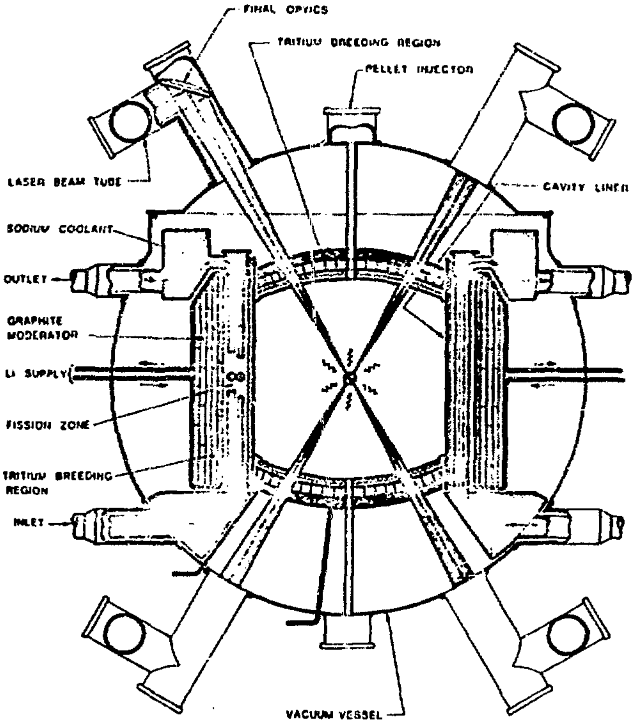

FIGURE 2. Side View of a Conceptual Laser Fusion Hybrid Reactor

Lithium-cooled graphite-moderate blankets are positioned in the top and bottom of the reactor and behind the fission zone. These lithium blankets moderate and capture neutrons and breed tritium. All penetrations for the laser beams and pellet injectors are made through the top and bottom blankets thereby leaving the radial fission blanket unencumbered. We had originally intended to use fission blankets in the top and bottom regions; however, the difficulties of maintaining coolant flow while the top blanket was being removed for access into the fusion chamber along with the requirements for unconventional fission blanket design led to our choice of lower performing nonfissioning blankets for these regions. The decision not to use fissionable fuel in these regions resulted in a 30% reduction in both fissile fuel and energy production; nevertheless, the decision was consistent with our desire to utilize state-of-the-art fission technology in the hybrid design.

As shown in Figure 3 the entire blanket system is enclosed within a spherically shaped stainless steel vacuum vessel which has a removable top. The final focusing mirrors are placed in beam tubes outside the vacuum vessel to minimize damage caused by the fusion microexplosion and provide for easier replacement.

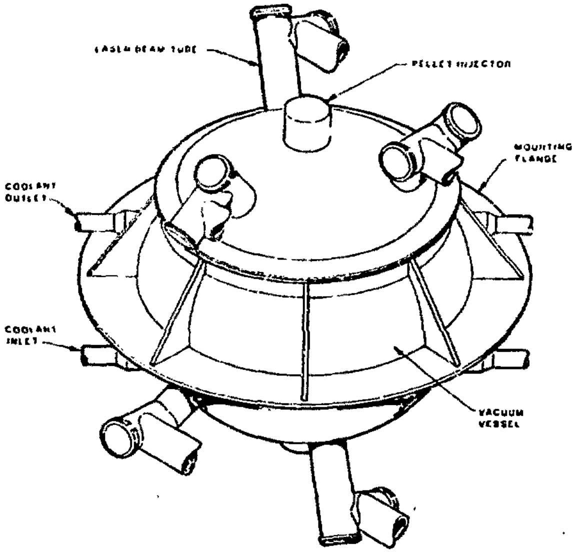

FIGURE 3. Vacuum Vessel for the Laser Fusion Hybrid Reactor

FISSION BLANKET DESIGN

An expanded side view and a top view of the radial fission blanket are shown in Figures 4 and 5. As shown, the fission zone is made up of two rows of hexagonally shaped process tubes which contain the depleted uranium in the form of stainless steel clad fuel pins. The process tubes in the innder row are protected from the fusion cavity environment by a stainless steel supported graphite liner.

Our neutronics calculations indicated that energy multiplication and fissile fuel production are maximized by using uranium metal fuel instead of oxides or carbides and by maximizing the ratio of the volume fraction of uranium to structural material. Increasing the residence time of the fuel also increases the average energy multiplication since more

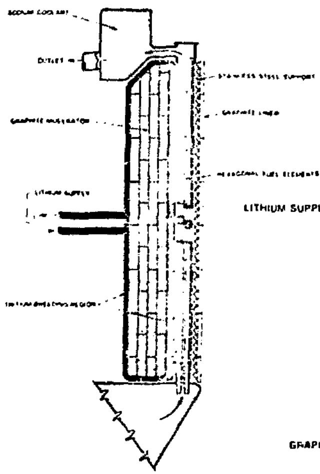

FIGURE 4. Side View of Fission Blanket In Laser Fusion Hybrid Reactor

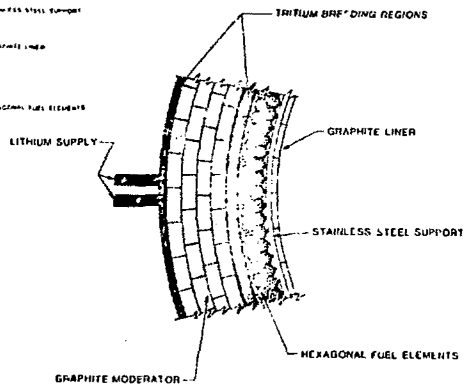

FIGURE 5. Top View of Fission Blanket In Laser Fusion Hybrid Reactor

energy is produced as plutonium is bred, accumulates, and fissions in the blanket.

Fast neutron damage may limit the useful life of stainless steel and other structural metals in a fusion reactor. A common design criteria for both laser and magnetic fusion reactors is a first wall neutron flux limitation of 1 MW/m^2 and an expected lifetime of less than five full-power years. Neutronic calculations at a first wall loading of 1 MW/m^2 show a maximum power density in a depleted uranium blanket of about eight watts per gram or about 150 watts per cubic centimeter of uranium metal. The average power density in a blanket is less than four watts per gram. Five full-power years of blanket operation would result in an average burn-up of less than 7,000 MWD/MTU. This low burn-up limitation favors the choice of metallic fuel.

The low power density burn-up capabilities of a depleted uranium (or a natural uranium) blanket demand care in minimizing fuel cycle costs, including fabrication cost. Large fuel rods would thus be favored over small rods, and long fuel elements would have some advantage over short elements. The basic configuration of a laser fusion reactor--a vacuum chamber with laser beams converging from several angles --introduces difficulties in the mechanical design of the blanket. Neutronic calculations show a severe reduction in performance if a thick pressure vessel wall is introduced between the blanket and the fusion core. The fuel element must therefore operate and be cooled within a surrounding vacuum. Thin process tubes and low pressure coolants would appear to be the most reasonable design approach, but coolant leaks and process tube reliability will always be potential problems. It is expected that melting of the fuel due to loss of coolant will be the most serious safety issue with the hybrid.

SELECTION OF A FUEL MATERIAL

The general design considerations of maximizing neutron energy multiplication, minimizing fuel cycle costs, and developing a concept that could be licensed by the Nuclear Regulatory Commission led to the selection of uranium metal fuel elements with sodium as the coolant. LMFBR technology and balance-of-plant design concepts were used to the maximum extent possible. The selected fuel element is a 19-rod cluster similar to those developed during the early 1960's for use in sodium-graphite reactors(SGR). Fuel rods 18-feet long were developed at that time and required care in handling because of the flexibility of the rods and the tendency to buckle if they were not handled vertically. Adapting this experience to a blanket design with larger diameter fuel rods and a thicker cladding, it was estimated that 7-meter (23-ft) long fuel rods and fuel assemblies were feasible; this determined the reference height of the fusion reactor core. A full size cross section and a three dimensional view of the fuel assembly are shown in Figures 6 and 7.

Uranium metal, uranium with 7 wt% molybdenum alloy (U-7 Mo) and uranium carbide (UC) were all considered as fuel materials for the sodium cooled blanket, and all are satisfactory. The reference fuel element can accept 30-millimeter diameter fuel slugs of each of these materials interchangeably. The U-7 Mo fuel should be capable of burn-ups to 20,000 MWD/MTU at maximum center temperatures of 650°C. This burn-up would require at least 8 full-power years to achieve, which the cladding probably could not tolerate. The U-7 Mo

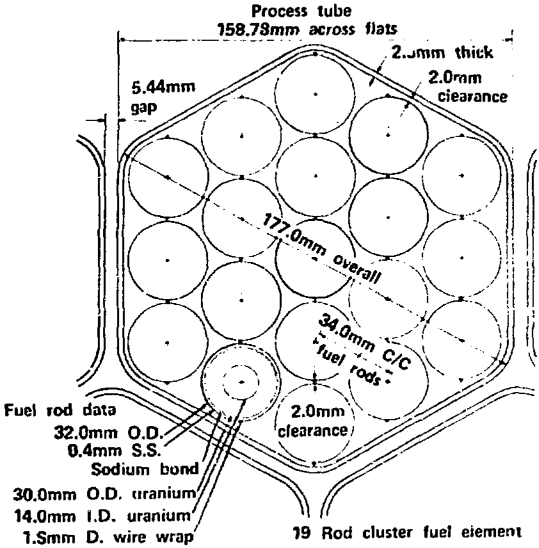

FIGURE 6. Fuel Assembly Cross Section (Full Size)

alloy was the reference fuel for the Dounreay fast reactor and performed satisfactorily at the conditions noted. This alloy has a reduced energy multiplication and plutonium production rate compared to uranium metal, and is also more expensive to fabricate and reprocess. Uranium carbide fuel would be capable of more than 100,000 MWD/MTU burn-up at maximum temperatures of 1,000°C (with a sodium bond) if the cladding were adequately strong. However, its energy multiplication is 30% less than uranium metal. In the low-power-density configuration of the reference blanket, the higher burn-up capabilities of U-7 Mo and UC cannot be used effectively. If higher power densities were possible, by using first-wall fluxes of 3 to 4 megawatts per square meter, or by using fissile enriched uranium fuel, or if gas cooling were chosen UC would probably be the fuel material of choice.

Uranium metal, "adjusted" with minor alloying additions in order to control swelling, was chosen as the reference fuel material for several reasons: first, because its multiplication and breeding performance were superior, second, because its burn-up capability was judged adequate and a good fit to the blanket's low power density, and finally, because it was cheaper to fabricate and reprocess.

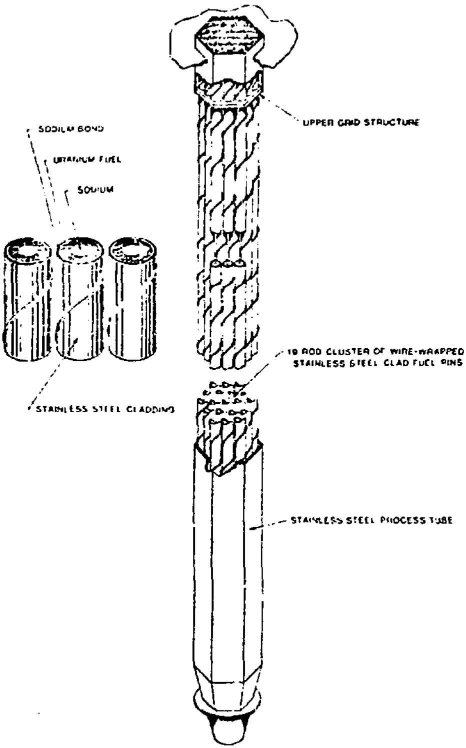

FIGURE 7. Fuel Element and Process Tube Configuration

Pure uranium metal begins to swell disasterously at temperatures greater than 400° C and burn-ups greater than 1,000 MWD/MTU (about 0.1 atom percent fissions). The British development of "adjusted" uranium metal as a fuel for their gas-cooled Magnox reactors during the early 1960's demonstrated that additions of 800 to 1,000 ppm Al, 350 to 500 ppm Fe, and approximately 500 ppm carbon could control this swelling and allow burn-ups of 5,000 to 6,500 MWD/MTU at temperatures of 600°C. Extensive development of similar alloys using Al, Fe, and Si (and sometimes Mo) have taken place at the Savannah River Laboratory and at Battelle Northwest Laboratory confirming the satisfactory performance of these fuels. A maximum fuel temperature of 600°C and a maximum burn-up of 6,000 MWD/MTU were chosen as a design basis for the blanket. A volume increase (swelling) of 4 percent is expected at this burn-up. However, a volume increase of 8 to 10 percent is easily tolerated by the sodium-bonded fuel rod. A maximum burn-up of 6,000 to 6,500 MWD/MTU is probably a reasonable expectation for this fuel. Sodium bonding was chosen over contact bonding of the cladding to the fuel rod in order to accommodate fuel swelling without straining the cladding and in order to use a thin cladding.

LITHIUM-COOLED RADIAL BLANKET

The lithium-cooled radial blanket located behind the fission blanket extends from the top to the bottom sodium plenums. The blanket consists of a cylindrical stainless steel container 62 centimeters wide and 750 centimeters high. From the inside face of the blanket there is first a 2-centimeter thick stainless steel inner wall, then 6 centimeters of lithium, 50 centimeters of stainless steel-clad graphite, 2 centimeters of lithium, and a 2-centimeter thick stainless steel outer wall. The lithium which is enriched to 50% Li^6 enters the reactor from an inlet header and is fed into a plenum at the bottom of the radial blanket. Lithium flows upward through the two channels provided on either side of the clad graphite and into the top plenum. The radial blanket is stiffened internally with stainless steel plates and is primarily supported from the bottom sodium plenum.

TOP AND BOTTOM BLANKETS

The top and bottom blankets are cylindrical curved pancake shaped plenums. The shell is 2 centimeters thick, and from the center of the reactor each blanket has the identical construction of 2 centimeters of stainless steel, 10 centimeters of beryllium, 70 centimeters of graphite, 10 centimeters of lithium, and 2 centimeters of stainless steel shell. The blankets are located 350 centimeters from the center of the reactor. The use of beryllium in these blankets provides a tritium breeding ratio of 1.5. This allows the radial blanket to operate with a tritium breeding ratio of 0.95 and still maintain an overall tritium breeding ratio of 1.1. Reducing the tritium breeding requirements in the radial blanket make it possible to use a thicker fission zone, thereby increasing the fissile fuel production capability of the reactor.

FINAL LASER OPTICAL SYSTEM

Six laser beams approach the reactor from one side of the reactor containment facility. A radiation shield is provided for each beam to prevent radiological hazard in the laser facility. The horizontal beams enter the reactor through a double mirror system located on the outside of the reactor. The laser light is focused on the fusion target by six metal mirrors located at the top and bottom of the reactor. The focal length of the mirrors is 12 meters, and the final mirror is designed to accommodate a beam diameter of 1.2 meters, and a maximum energy flux of 1.5 joules per square centimeter.

To be good reflecting and focusing elements, mirrors must be smooth to approximately one-fourth of the wavelength of the laser light impinging on them. Highly polished metal surfaces are susceptable to all types of radiation damage and we are currently investigating the effects of the neutrons, x-rays, and energetic debris from the fusion microexplosion. The damage caused by this loading has been lessened somewhat by placing the mirror at a point where the radiation fluxes emmenating from the fusion target are more than an order of magnitude lower than the first wall fluxes. An additional problem uncovered by our preliminary optical studies involves damage to the mirrors from the laser light as debris from the fusion chamber accumulates on the mirror surface. A mechanism for removing the debris between shots will have to be devised.

Removing and replacing mirrors will be expensive because of the handling required. Replacing the mirrors at the bottom of the reactor will be difficult without special equipment. The lifetime of the mirrors will determine whether it is necessary for special designs to be used such as rotating mirrors, gas windows, magnetic field director and special remote handling for replacing mirrors. No consideration has been made within this report for optical system design except for layout and basic laser system functional purposes surrounding the reactor.

PELLET APPARATUS

The pellets of deuterium-tritium must be injected into the reactor at a nominal 20 times a second and must reach an exact location without error. The apparatus must be insulated from the reactor (if frozen pellets are used) and must remain correctly aligned with the laser beams during the expansion of the reactor caused by internal heat load. The apparatus is also subject to thermonuclear blast and the nominal reactor vacuum of 0.. torr. No apparatus is available today for this purpose.

FIRST WALL CONSIDERATIONS

The technological and economic feasibility of the laser fusion hybrid are critically dependent on the design and performance of the first wall because its radius and lifetime determine both the size of the reactor for a given output power and the availability of the power plant. We have performed calculations to determine the radiation exposure capabilities of several first wall materials. The results of these calculations have led us to choose a 2 cm thick graphite liner which is supported by stainless steel and cooled with lithium. The graphite first wall is designed for an operational lifetime of one year with a neutron wall loading of one megawatt per square meter and a repetition rate of 20 Hz. The nominal charged particle loading is then 0.25 MW/m^2 or 12.5 KJ/m^2 per pulse. The charged particle energy is carried in the form of pellet debris and alpha particles which escape the pellet.

Calculations have been performed to determine the temperature rises, the stresses and the amount of material vaporized by the interaction of x-rays, charged particles, and reflected light with the first wall material. The analytical methods used for these estimations have been developed by Hovingh and they are presented in Reference 7. The rate and depth of energy deposition in the first wall from the thermonuclear burn products and the reflected laser light is dependent on several parameters. They include:

- laser wavelength
- laser energy and power
- thermonuclear yield
- pellet mass and composition
- gas pressure in the fusion cavity
- first wall composition and configuration

A computer code called LASNEX has been developed at LLL to explore this complex parameter space[8]. LASNEX is a Lagrangian hydrodynamic code which incorporates the principal physical processes that occur in laser produced plasmas and computes the time evolution of the basic physical characteristics of the plasma. By using LASNEX, it is possible to calculate the transport and interaction of laser photons, electrons, ions, x-rays, and fusion reaction products along with the induced magnetic and electric fields and the hydrodynamic behavior of the pellet.

We have selected a laser target which LASNEX predicts will yield 10 MJ of thermonuclear energy from an implosion caused by a few hundred kilojoules of 1 μm laser light. One percent of the fusion energy is released in the form of x-rays, 23% in charged particles, and 76% in 14 MeV neutrons. The energy spectra and pulse widths occurring at the first wall have been determined by continuing the LASNEX calculation long enough for the x-rays and charged particle to interact with the cavity gas at 0.1 torr. The resulting spectra and pulse width have then been input into the first wall calculations and the results indicate that the temperature rise in a graphite wall 3.5 meters from the microexplosion can be kept below the vaporization temperature of 3500°K. Spallation of the graphite caused by the temperature indiced stresses has not been considered in these first wall calculations.

With the graphite held below its vaporization temperature and spallation not considered, the major factor limiting first wall lifetime will be erosion from the formation of hydrocarbon .

For a DT pellet with five percent burn, the graphite will erode at a rate of less than one centimeter per full-power year, assuming that all the hydrogen reacts with the curtain to form acetylene.

The graphite curtain must be flexible to withstand the thermal stress caused by reflected light and x-ray loadings, as well as by charged particle loading. A weave of graphite fibers has been proposed for this purpose, but the transmission of heat through such a cloth is uncertain. It may be preferable to use a one-layer, two-dimensional weave that is continuously replaceable as it erodes.

In summary, the first wall is assumed to be a 2-centimeter thick graphite curtain supported on a stainless steel backing. The design of a cooling system for this structure is not included, and the structural design for sufficient flexibility has not been considered in detail.

ANALYSIS OF THE DESIGN

SYSTEM PERFORMANCE

The overall performance and the more significant design parameters of the laser fusion hybrid are summarized in Table 1. A thermal output of 1400 MW was chosen to emphasize that a laser fusion driven hybrid could operate as a relatively small power unit. The fusion targets are irradiated by a 6 beam, 100 KJ, 20 hertz laser with an overall efficiency of 2%. The fusion energy gain (i.e. the product of laser system efficiency and pellet gain) for this reactor is 2.0. This results in a plant recirculating power fraction of 25% and a net system efficiency of 29%. If the fusion energy gain were increased to 4.0, the recirculating power would decrease to 16% and the net system efficiency would increase to 32%.

The performance and the design parameters presented in Table 1 can be placed in perspective by comparing the laser fusion hybrid to a typical fast breeder reactor. This comparison is shown in Table 2 where both systems have been normalized

TABLE 1

LASER FUSION HYBRID DESIGN PARAMETERS

SYSTEM PERFORMANCE

Thermal Power, MW_t	1400
Fusion Thermal Power MW_t	200
Gross Electrical Power, MW_e	535
Net Electrical Power, MW_e	400
Recirculating Power Fraction	0.25
System Efficiency, %	0.29
Average Blanket Energy Multiplication	8.7
Net Plutonium Production, Kg/yr	1300
Total Tritium Production, Kg/yr	8.0
Laser Energy, KJ	100
Laser System Efficiency, %	2.0
Power Supply Energy, MJ	5.0
Pulse Repetition Rate, sec^{-1}	20
Pellet Gain, Q	100
Fusion Energy Gain	2.0
OPTICAL TRANSPORT SYSTEM	
Number of Beams	6
Maximum Energy Flux, J/cm^2	1.5
Beam Diameter, m	1.2
Focal Length of Final Mirrors, m	12.0

TABLE 2

COMPARISON OF LASER FUSION HYBRID AND FISSION BREEDER PERFORMANCE

	HYBRID	FISSION BREEDER
Thermal Power, MW_t	2500	2500
Net Electrical Power, MW_e	725	1000
System Efficiency	0.29	0.40
Net Fissile Production, Kg/yr	2300	260
Fissile Fuel Loading	0.0	2500
Maximum Power Density in Fuel, W/cm^3	150	1500
Average Power Density, W/cm^3	30	∿ 300

The fission breeder used in this comparison is an LMFBR with a breeding ratio of 1.2.

to a thermal output power of 2500 MW. The fast breeder reactor used in this comparison is an LMFBR with a breeding ratio of 1.2. As shown, the laser fusion hybrid generates 30% less electrical power because it is being driven by a laser which requires 19% of the gross power. This inferior performance in power generation results from design choices which were influenced by our desire to emphasize fissile fuel production at the expense of energy multiplication. The advantages of the laser fusion hybrid over the LMFBR are readily apparent from Table 2. Specifically, the hybrid produces 10 times more fissile material, requires no initial fissile fuel loading, and operates at one-tenth the power density. With no initial fissile inventory it becomes possible to operate the hybrid in a regime where both critically accidents and core disruptive accidents are impossible. Moreover, control rods are not required. The lower power densities make it possible to design a hybrid blanket which provides much more time to recover from a loss of coolant accident. In fact, it is technologically feasible, and it may be econmically feasible, to design a hybrid blanket which passively copes with a loss of coolant accident.

ECONOMIC ANALYSIS

The capital and operating costs of the laser fusion hybrid in this conceptual design were estimated by Bechtel Corporation. Their preliminary economic analysis of the reference 1400 MW(t) design revealed that severe economic penalties resulted from some of the design choices. A survey of the high cost items indicated that the reactor containment structure and several of the other buildings had been sized much too large for the nominal output power of 400 MW(e). In addition, there were several other balance of plant items whose costs were relatively independent of output power, thereby implying that a larger plant output power would be more economical. These results agree with scaling factors for other nuclear power reactors in that an electrical power plant is more economical in the 1200 MW(e) range and, where possible, in twin units.

The results presented above led us to perform our more detailed cost analysis on a hybrid with a larger output power. We scaled our conceptual design to a size which had a gross yield of 1300 MW(e) and a net yield of 950 MW(e). This output was obtained from the original design by increasing the laser energy from 100 KJ to 200 KJ increasing the average pulse repetition rate from 20 to 25 Hz and increasing the inner radius of the blanket from 3.5 to 6.0 m.

CAPITAL AND OPERATING COSTS

The capital cost of the laser fusion hybrid reactor plant has been estimated from conceptual design and engineering information. A large portion of the power plant consists of conventional technology such as thermal energy transfer, electrical generation, cooling systems, and auxiliary systems; therefore, cost estimating can be based on background experience. The fusion reactor and the laser interface fusion fuel cycle being conceptual have been estimated on a first-of-a-kind cost basis. The operating costs of the laser fusion hybrid reactor plant are based upon nuclear fuel cycle and equipment replacement costs of this reactor, capital charge rates, and general operating and maintenance cost similar to those of LMFBR reactors.

CAPITAL COSTS

The results of the cost analysis are summarized in Table 3. For comparative purposes the costs of the laser fusion hybrid have been presented along with cost estimates for a typical LWR. All of the cost estimates have been made at first quarter, 1976, price and wage levels and no allowance has been made for future escalation. The Nuclear Steam Supply System (NSSS) category for the hybrid primarily consists of the reactor vessel with its internals, and the primary coolant loop with its associated pumps, motors, heat exchangers, and steam generators. Major items included the category "other

TABLE 3

CAPITAL AND OPERATING COST ANALYSIS

Capital Cost Item (10^6\$)	LWR 1200 MW(e)	Laser Fusion Hybrid 950 MW(e)
Nuclear Steam Supply System (NSSS)	78	268
Other Mechanical	101	201
Civil andStructural	142	158
Piping	77	105
Instrumentation	9	11
Electrical	43	72
Total Direct	450	815
Field Costs	79	171
Engineering Services	80	197
Contingency	91	272
Owners Cost at 7%	56	116
Interest During Construction at 8%	197 (9 yr)	487 (10.5 yr)
Total Indirect	503	1243
TOTAL COST	953	2058
Cost per KW installed (\$)	794	2166
Operating Cost Item (mills/kWh)		
Capital	19.42	55.77
Fuel	6.3	(-3.17)
Operating and Maintenance	1.5	2.40
Total Operating	27.22	55.00

mechanical" are the turbine generators, the vacuum system, the tritium system, and the cooling towers. Site improvements, the reactor containment structure and all the buildings make up the civil and structural category.

The indirect costs in Table 3 were estimated on the basis of a nine year construction time for the LWR and a 10.5 year construction for the more complex laser fusion hybrid. As a result of this, the indirect costs for the hybrid account for a larger fraction of the total capital cost. Field costs are those items of construction cost which cannot be ascribed to the direct portions of the facility. They include temporary construction facilities, supply and main tenance of construction equipment and tools, field office operation and acceptance testing. The engineering services include all engineering costs and home office costs and fees. Included in the indirect cost is a contingency allowance for the uncertainty that exists within the conceptual design in quantity, pricing, or productivity.

The total capital cost of the laser fusion hybrid is estimated to be $2,058 million. Thus on a cost-per-kilowatt installed basis, the hybrid is 2.7 times more expensive than the LWR. It should be noted that this cost estimate does not include the laser system or the pellet manufacturing facility. If $200 million dollars are allowed for these omitted facilities the laser fusion hybrid would cost approximately three times more than a typical LWR.

OPERATING COST

The cost of electricity from the hybrid is 55 mills/KW-hr. This is approximately twice as much as the cost of electricity from the LWR. The capital portion of the operating cost is by far the dominant factor in the cost of electricity. It has been estimated for both reactors on the basis of a 15% rate of return on the capital invested. The fuel cycle cost for the laser fusion hybrid is negative because of revenues obtained from the sale of the plutonium it produces. The cost bases used to estimate the fuel cycle cost for both the LWR and the hybrid are presented in Table 4. The fabrication cost for the hybrid is cheaper because the cladding material is stainless steel and the cross sectional area of the fuel pin is much larger. Both the spent fuel shipping and the reprocessing costs are less for the hybrid because its fuel is being operated at lower average burn-ups (6000 vs 33,000 MWD/MTU).

The major issue concerning a laser fusion hybrid is not how much it will cost nor the price at which it can generate electricity, but rather the cost of electricity in a scenario which hybrids providing fissile fuel for existing burner reactors. In Figure 8, the cost of electricity has been plotted as a function of the cost of fissile fuel for an LWR and hybrids with varying capital costs. The intersection points of the curves determine the cost of electricity and fissile fuel in the hybrid-LWR scenario. These results indicate that the cost of electricity is quite insensitive to the capital cost of the laser fusion hybrid. Specifically, the cost of electricity increases by only 20 to 40% when the capital cost of the hybrid ranges from 2 to 3 times more than the LWR.

CONCLUSIONS

The production of fissile fuel by a hybrid is a promising step in the development of fusion. This study has disclosed a number of advantages resulting from the addition of a depleted uranium fission

TABLE 4

FUEL CYCLE COST BASES PWR/BWR REACTORS

Uranium		$40/lb U_3O_8
Conversion		$4.50/kg U
Enrichment		$100/SWU
Fabrication		$100/kg U (PWR)
		$ 80/kg U (BWR)
Spent Fuel Shipping		$ 20/kg U
Reprocessing		$225/kg U
Plutonium Credit		$34.25/g Pu_f(PWR)
		$26.95/g Pu_f(BWR)
70% Plant Capacity Factor		
17.4% Working Capital Charge Rate		
Process Losses:	Conversion	0.2%
	Fabrication	0.5%
	Reprocessing	0.5%

Laser Fusion Hybrid Reactor

Fabrication	$30/kgU
Spent Fuel Shipping	$10/kg U
Reprocessing	$125/kg U
Plutonium Credit	$30.00/g Pu_f

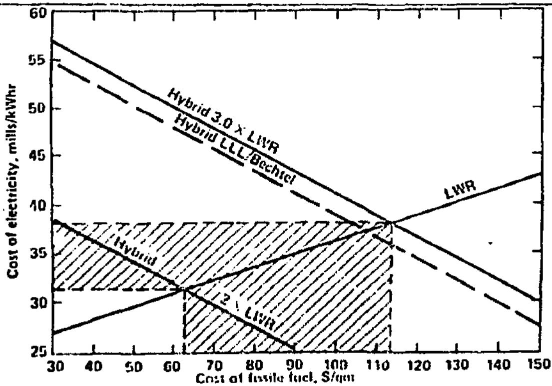

FIGURE 8. Cost of Fissile Fuel and Electricity from a Hybrid

blanket to a laser fusion system. These include:

1. The hybrid operates in a regime which requires an order of magnitude less laser/pellet performance than a pure laser fusion system.
2. First wall requirements and 14 MeV neutron damage are less severe in a laser fusion system with a fission blanket.
3. The laser fusion hybrid produces a large amount of fissile material - enough to fuel more than six LWR's of equivalent size.
4. In a scenario with laser fusion hybrids producing fuel for existing reactors the cost of electricity is insensitive to the capital cost of the hybrid.
5. The laser fusion hybrid would extend the total energy available from economically proven light water reactors by two orders of magnitude.

The feasibility of the laser fusion hybrid should be evaluated from three points of view: Scientific, technological and economic. The scientific feasibility of the laser fusion hybrid is dependent on (1) achieving pellet gains in the neighborhood of 100, and (2) developing suitable lasers with overall system efficiencies greater than 1%.

The fission blanket surrounding the fusion chamber was designed with state-of-the-art fission technology. This was done to facilitate a straight forward assessment of the technological feasibility of the laser fusion hybrid, but a definitive statement regarding the feasibility of fissile fuel production with laser fusion cannot be made without further study. The laser and optical systems need to be conceptually designed. The pellet manufacturing and injection systems need to be considered. A more detailed analysis of the first wall design should be carried out. Finally, a safety analysis of the design is required with particular attention being given to system failures which could result in a release of radioactive nuclides to the environment. The most obvious release mechanism being melting of the fuel in a loss of coolant accident.

The economic analysis shows that the cost of electricity in a hybrid-LWR scenario is insensitive to the capital cost of the hybrid. The laser-fusion is estimated to be three times more expensive than an LWR. The cost of electricity is shown to be only 40% more than the present price. Nevertheless, substantial economic gains would be realized if the laser fusion hybrid's cost could be decreased to twice that of an LWR. Possibilities for reducing capital cost which should be explored in future studies include:

1. Replacement of the reference coolant and tritium breeding systems with helium cooling and a solid lithium blanket.
2. Investigation of fission blankets which enhance energy multiplication, and
3. *Consideration of blanket geometries* which more efficiently utilize the point source from laser fusion.

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