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CIVILIAN APPLICATIONS OF LASER FUSION

J. Maniscalco, J. Blink, R. Buntzen, J. Hovingh,
W. Meier, M. Monsler, and P. Walker

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PREFACE

Controlled fusion is a potential solution to the world's energy needs. Its development represents a sophisticated and challenging problem in which the technical hurdles promise to be as demanding as the scientific groundwork. An enormous commitment of human and financial resources must be made to meet this challenge, but the problems and the efforts required to solve them are dwarfed by the significance of the payoff—an inexhaustible and affordable source of energy that is compatible with our environment.

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CIVILIAN APPLICATIONS OF LASER FUSION

ABSTRACT

We have evaluated the commercial aspects of laser fusion in an attempt to relate the end products (neutrons and energy) to significant commercial applications. We have found that by far the largest markets and highest payoffs for laser fusion are associated with electric power production. Hence, much of this report evaluates the prospects of producing commercial electricity with laser fusion. To this end, we have described in detail a new and promising laser fusion concept—the liquid lithium waterfall reactor. In addition, we have taken the most attractive features from our laser fusion studies and used them to compare laser fusion to other long-range sources of energy (breeder reactors and solar energy). It is our contention that all three sources of electrical energy should be developed to the point where the final selections are primarily based on economic competitiveness. The other potential applications of laser fusion (fissile fuel production, synthetic fuel production, actinide burning, and propulsion) are also discussed, and our preliminary plan for the engineering development of laser fusion is presented.

INTRODUCTION

Need For An Inexhaustible Energy Source

The increasing demand for energy in the United States coupled with a shrinking supply of fossil fuels has led this country to reassess our energy reserves and resources. The results of that reassessment (Figs. 1 and 2) show that our fossil fuels are limited. For example, in 1976, petroleum and natural gas supplied 77% of the total U. S. energy demand; yet Fig. 2 shows the total U. S. resources could not meet that fraction of the demand beyond the turn of the century. All of our exhaustible resources put together (petroleum, natural gas, coal, oil shale, geothermal, and uranium in fission burner reactors) could only meet the demand until somewhere between 2050 and 2225, depending on the demand growth rate. U. S. exhaustible reserves could only meet the demand until about 2040, even in the most optimistic scenario. Thus, it is apparent that "inexhaustible" sources such as fission breeders, solar energy, and fusion reactors are the only sources capable of meeting long-term U. S. energy demand.

Of course, the need to develop long-term sources of energy is not limited to the U. S. Indeed, world energy needs will increase much faster than the

U. S. rate because many third world nations will be greatly increasing their energy consumption during the next century, although their domestic energy supplies are smaller than ours. Therefore, unless inexhaustible sources are developed, the world energy shortfall will develop sooner than Fig. 2 indicates. The resulting socio-political stresses could lead to wars over dwindling energy sources. To meet our own and the world's energy needs, the U. S. is currently developing inexhaustible sources of energy including solar energy and fusion reactors.

The Payoff

Electrical energy consumption in the United States has been historically growing at approximately twice the rate of total energy consumption (7% per year for the last 25 years). However, a continuation of historical growth is highly unlikely. ERDA's most recent estimate¹ (April 1977) is that electrical capacity will grow from the present 530 GW_e to 1390 GW_e in 2000. These projections represent electrical demand growth rates of 5.3% from the present to 1985, 5% from 1985 to 1990, and 4% from 1990 to 2000. Even with these reduced growth

Fig. 1. U.S. exhaustible energy sources. Reserves refer to an assured supply of raw materials that can be converted to energy while resources refer to raw materials that may become recoverable at higher prices, with more exploration, or with new technology.

rates the electricity fraction of our total energy consumption is expected to increase from the present 27% to 44% by the end of the century.

In Table I we have extended ERDA's estimate of electrical energy capacity to 2050. The projections have been made at lower rates of growth in order to provide a lower bound estimate on the number of electrical installations that will be required in the first half of the next century. The significant feature of these projections is that even at zero annual

Table I. Projection of U.S. electrical capacity from 2000 to 2050.

Annual rate of growth, %	Installed capacity, GW _e	Cumulative number of GW _e installations ^a
3	6092	8141
1	2285	3520
0	1390	2307

^aAssumes 30-year plant lifetime.

growth from 2000 to 2050, more than 2000 power plants of GW_e size will have to be constructed. At a cost of a billion dollars per plant, the 2300 plants represent an investment of more than 2 trillion dollars.

In our development scenario, we have estimated that it will cost 10 to 20 billion dollars to develop inertial confinement fusion into a commercially available source of energy. This cost estimate is consistent with projected costs for the development of the fast breeder reactor (24 billion) and magnetic fusion energy (16 billion).² The point to be made is that development costs during the next 25 years for long-range sources of electrical energy will be in the tens of billions of dollars, whereas the pay-off to our children in the next century will come in the form of available energy at reasonable cost with savings in the trillions of dollars.

Fuel For Inertial Confinement Fusion

Early commercial fusion sources of energy will use deuterium-tritium (DT) fuel, in which the

Fig. 2. Inability of U.S. exhaustible energy sources to meet future energy demands. The high demand forecast is based on a growth rate in annual energy consumption of 3.4%, which corresponds to the historical growth rate from 1950 to 1973. The medium demand forecast uses a 2% annual growth rate that emphasizes conservation measures to reduce energy consumption without diminishing our standard of living. The third forecast follows a 2% growth curve until the year 2000 with zero growth thereafter.

tritium is bred from lithium by neutron capture in the blanket. Thus, DT fusion's basic fuels will be deuterium and lithium. Deuterium is present in sea water at a ratio of one part in every 6500 atoms of hydrogen. The oceans and other surface waters on earth contain more than 10^{13} tonnes of deuterium. This enormous quantity ensures an almost inexhaustible supply.

Lithium is commercially recovered in the United States from pegmatite and land-based brines. Present reserves are estimated³ to be on the order of 10^9 kg and to cost \$20/kg. This supply of lithium would last more than a hundred years in a full fusion economy. Additional resources of lithium recoverable at three times present prices have been estimated to be in excess of 4×10^9 kg.

Table 2. Inexhaustible resources available from the oceans.

Resource	Concentration, g/tonne	Thermal energy per gram, kWh/g	Thermal energy per tonne of seawater, kWh/tonne	Allowed cost ^a per tonne of seawater, \$/tonne	Energy available at 1976 consumption rate, years
Deuterium	34	261,000 ^b	8,920,000	4460 ^c	6×10^{11}
Lithium	0.17	83,000 ^b	14,100	7	9×10^8
Uranium (²³⁵ U)	0.000011	24,000	0.27	0.00014	1.7×10^4

^a Allowable cost for fuel is limited to 5% of the cost of electricity (1.5 mills/kWh).

^b Assumes that 40% of the tritium is bred in ⁷Li reactions.

^c Current cost of deuterium is about \$2 per tonne of seawater.

Like deuterium, the lithium resource in the ocean is virtually limitless. Table 2 compares the physical and potential economic properties of deuterium, lithium, and uranium extracted from the oceans. If we limit the price for lithium in a fusion reactor to less than 5% of the present cost of electricity (~ 1.5 mills/kWh), its value would still be more than \$17,000/kg. This is a price that appears more than adequate to assure the economic feasibility of extracting lithium from the oceans, thereby guaranteeing a virtually inexhaustible source of fuel for fusion.

Long-Range Plan

This report tries to answer the questions:

- Why do we need laser fusion?
- What are the potential applications of laser fusion?

These questions lead to a third question: How do we take laser fusion from the physics experiments of today to the commercial applications of tomorrow. At LLL, we have initiated a long-range plan (see Ap-

pendix) to help answer this question. The plan will guide the Laboratory in its attempts to keep the laser fusion program in line with changes in technical progress, national needs, and the nation's commitment to inertial confinement fusion.

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1. EXECUTIVE SUMMARY

In our evaluation of the commercial aspects of laser fusion, we have tried to relate the end products (neutrons and energy) to significant commercial applications. Some of the more attractive applications include electric power production, propulsion, high-temperature process heat, fissile fuel production, burnup of radioactive fission waste, and synthetic gas production. In Fig. 1-1 these applications have been separated into two categories: applications that use the fusion reaction for energy or for neutrons.

We have found that by far the largest markets and highest payoffs for inertial confinement fusion are associated with electric power production. Hence, a major portion of our effort has been devoted to evaluating the prospects of producing commercial electricity with laser fusion. In our systems studies, we have designed and analyzed high-average-power laser and reactor concepts that could be used in a laser fusion power plant. The most attractive features resulting from our laser and reactor design studies have been used to compare laser fusion to the other long-range sources of energy (breeder reactors and solar energy). The comparisons have been made on the basis of abundance, social costs (health, environment, and safety), technical feasibility, and economic competitiveness. As a result of these comparisons, we have found that while laser fusion technology is not as advanced as that of the fast breeder reactor it offers the following advantages over fission:

- No use of weapons grade material, thereby avoiding the possibility of diversion for blackmail or sabotage.
- No afterheat cooling problem in case of loss-of-coolant accident.
- No nuclear runaway from a reactivity insertion or criticality accident.
- An inexhaustible fuel supply that is available at low cost from the ocean.
- Significantly less radioactive byproducts with much shorter half-lives.

In comparison to solar electric energy, laser fusion offers the following advantages:

- Significantly reduced cost.
- Geographical and climatic independence.
- Significantly reduced land use.
- No effect on climate.
- More feasible as a base load facility (no energy storage systems required).
- Reduced transmission of electricity.

It is our contention that all three long-range sources of energy should be developed to the point where the final selections are primarily based on economic competitiveness.

Applications other than central station electric power offer the possibility of increasing the overall impact of laser fusion and of hastening its commercial application. Nonelectric applications that we have investigated in this report include fissile fuel production, actinide burning, synthetic fuel production, and propulsion systems. The decision to pursue any of these alternative applications in conjunction with the production of commercial electricity must be made by weighing the recognized benefits against the additional costs for development. In determining recognized benefits, we have considered:

- The need for the application.
- Alternatives to laser fusion for providing the application.
- The possibility of the application having an earlier impact than central station electric power.

The primary factors favoring early introduction of nonelectric applications are reduced laser fusion performance criteria and relaxed economic constraints.

Central Station Electric Power with Laser Fusion

Technical Feasibility of Laser Fusion

Fusion, like all of the advanced sources of electrical energy, is expected to be technically more

Fig. 1-1. Applications of laser fusion.

complex than existing light water reactors (LWRs) or fossil-fueled power plants. The technical feasibility of laser fusion power plants requires development of an efficient reactor system that operates reliably at high average power. As an alternative to magnetic confinement fusion, laser fusion offers features that could significantly reduce its technical complexity, thereby reducing the amount of advanced technological development that will be required to produce a technically successful fusion power plant. These features include:

- No magnets* (asterisked items are design dependent)

- Sizing flexibility (i.e., lower power units)
- Possibility of multiple chambers to provide higher availability

- Flexible geometry
- No direct conversion required
- Reduced vacuum pumping requirements*
- Reduced radioactivity from neutron activation*

- Reduced neutron damage to structural materials*

In Chapter 2 we describe a reactor design concept that features all of the advantages listed above. The major technical problems associated with a laser fusion power plant that must be solved to realize all of the above advantages include the development of:

- A high-average-power driver with the required efficiency (>1%) and reliability (>70%).

- A first-wall able to withstand the effects of x rays, debris, and neutrons from the fusion microexplosion.

- Structural materials that can withstand the cumulative damage effects of high-energy neutrons and cyclical stresses.

- Final-focusing elements that can be placed far enough away from the microexplosion or protected so that they can last a reasonable length of time.

- The technology to cheaply mass-produce fusion targets.

Sufficient solutions to the technical problems listed above will allow laser fusion power plants to efficiently produce electricity with high plant availability. The overall efficiency of such a plant can be evaluated through a basic power flow diagram like the one shown in Fig. 1-2. 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), neutron energy fraction (f_n), and blanket energy multiplication (M_B); i.e.,

$$RPF = \frac{P_{in}}{P_g} = \frac{1}{\eta_L Q \eta_t [1 + f_n (M_B - 1)]}$$

Recirculating power fraction is a basic figure-of-merit for any power plant. For reference purposes, fossil-fueled power plants operate with recirculating powers less than 5% while the majority of present nuclear plants operate at or slightly above this figure. Laser system efficiency (η_L) is a lumped parameter that includes power conditioning, medium regeneration, lasing, and optical transport efficiencies. It is defined as the ratio of focusable

where:

η_L = laser system efficiency

Q = pellet gain = $\frac{\text{thermonuclear energy}}{\text{laser light energy}}$

f_n = $\frac{\text{neutron energy}}{\text{thermonuclear energy}}$

M_B = blanket energy multiplication

η_t = electrical conversion efficiency

P_{in} = electrical power input to laser

P_g = gross electrical power

$$RPF = P_{in}/P_g = 1/\eta_L Q \eta_t [1 + f_n (M_B - 1)]$$

*Assuming most of the power recirculated is used by the laser.

Fig. 1-2. Laser fusion power flow diagram.

beam energy to electrical energy input. Blanket energy multiplication (M_B) is defined as the ratio of blanket thermal energy to fusion neutron energy. The overall system efficiency (η_s) of a laser fusion power plant can be related to the recirculating power fraction (RPF) by the equation:

$$\eta_s \approx \eta_l (1 - \text{RPF})$$

From the expressions for recirculating power fraction and system efficiency, it logically follows that the product of laser efficiency (η_l) and pellet gain (Q) should provide an excellent figure-of-merit for gauging the prospects of efficiently generating electrical power with laser fusion. This product, which is called fusion energy gain, represents the ratio of thermonuclear energy produced to electrical energy input to the laser. Fusion energy gain is an extremely revealing performance parameter because economic power production with laser fusion will fundamentally lie with the pellet energy gains achieved and the overall efficiencies at which large pulsed ignition sources can operate. In Fig. 1-3 the recirculating power fraction is plotted as a function of fusion energy gain for power plants with a blanket energy multiplication of 1.0 and several thermal efficiencies. Reference designs for laser fusion power plants have used recirculating power fractions in the neighborhood of 25%. However, it may be difficult to compete economically at these high values because in general, plant capital costs scale with the gross electrical power while revenues scale with the net electrical power.

Cost Comparisons with Breeders and Solar

Like fission reactors, all of the long range sources of energy will be capital intensive. The cost of electricity from capital intensive power plants is directly proportional to plant cost and inversely proportional to plant capacity factor. We have used this relationship to compare the cost of electricity from laser fusion, breeder reactors, and solar energy. A detailed cost analysis of a laser fusion power plant has not been performed. Instead, we have focused on identifying the economic constraints which will ultimately prevail. In line with this objective, we have concentrated on providing estimates of the allowed cost of the laser and reactor portions of an economically attractive power plant. Our results show that a GW_e laser fusion power plant can generate electricity at costs that are within 50% of present prices with laser and reactor systems whose combined costs are as much as 800 million dollars.

Capital costs for liquid metal fast breeder reactors (LMFBRs) are estimated to be 50 to 75% more

than those of LWRs. Therefore, LMFBRs with capacity factors similar to LWRs (70%) can be expected to generate electricity at costs that are 20 to 40% more than present prices. Present estimates indicate that solar power plants will cost two to three times more than LWRs presently cost. Moreover, they will operate with capacity factors that are less than 30% because of the diurnal variation of insolation. As a result solar electric power plants can be expected to generate electricity that costs some six to nine times more than present prices.

From the cost comparisons presented here, it is obvious that the electricity generated by any of the

Fig. 1-3. Plant recirculating power requirements as a function of fusion energy gain. A blanket energy multiplication factor of 1.0 was used.

long-range sources of energy will be significantly more expensive than electricity is now. However, within a factor of two, the cost of energy in the U. S. economy is much less critical than assured supply. Present total energy costs are only 5% of the U. S. gross national product, and it has been estimated that a doubling of energy costs would result in a 2 or 3% reduction in consumption with little effect on economic growth in the long run.

Lasers for Laser Fusion Power Plants

The development of a driver for an inertial confinement fusion reactor is technologically challenging. The driver must be capable of taking a small fraction of the power generated by the reactor

system, form it into pulses of energy at the rate of 1 to 10 per second, concentrate the energy into a pulse a billionth of a second in duration, and project it onto a target a millimeter or so in diameter from a safe distance. Three kinds of beam generators have the potential to be an inertial confinement fusion driver: ion beams, electron beams, and lasers. Solid state lasers are currently being used for scientific feasibility experiments because they offer the quickest and most cost-effective way of attaining high-gain microexplosions and scientific breakthroughs.

The driver characteristics are determined primarily by target design. Target calculations together with economic and system constraints have established preliminary laser system performance requirements for commercial electric power production. The nominal requirements include

- Wavelength 250-2000 nm
- Pulse duration ≤ 10 ns
- Pulse energy 300-3000 kJ
- Pulse power >200 TW
- Pulse repetition rate 1-10 Hz
- Average power 1-10 MW
- Overall efficiency $>1\%$

These requirements continue to evolve, reflecting new knowledge in target and laser physics, materials and laser engineering, systems analysis, and economics.

There is no laser that currently satisfies all these requirements. Design of such a laser should be based on two aspects: efficiency and scalability. A laser system of high efficiency will have lower recirculating power needs and lower capital equipment costs. The efficiency depends on the losses due to power conditioning, fluorescence production, coupling to the laser molecule, optical extraction, and pumping, cooling, and chemical regeneration of the flowing gases.

Scalability to large size is important because a laser built with a large single-aperture size and high energy per pulse lowers costs by reducing the number of beams and components. The scalability depends on optical and e-beam foil damage limits, pump constraints, flow and gas uniformity constraints, parasitic suppression, thermal distortion, and arrival at a configuration that simultaneously pushes all the important technology barriers.

In the search for a laser that can meet the above requirement, several laser media appear to be promising. Depending on the medium, three different kinds of stimulated emission can occur:

- Electric dipole forbidden transitions (e.g., magnetic dipole or electric quadrupole)
- Optically induced transitions (e.g., Raman scattering, frequency tripling, etc.)

Examples of laser media that fall into the first category include rare gas and rare gas halogen excimers.* These laser media are volumetrically scalable and efficient only when operated with relatively long pulse durations (>50 ns)—pulses too long for direct coupling to fusion pellets. To be useful, the radiation from this first type of medium must be converted to a proper pulse format by acting as a pump source for laser media of the second or third types. Laser media of the second type include iodine, Group VI atoms, and the trivalent rare earth ions in molecular vapors and in selected solid state hosts. These active species have the property of being able to integrate pump excitation energy for times a hundred- or a thousand-fold longer than characteristic fusion pulse widths, and thus to act as "intermediate-energy-stores" for power amplification. The third medium type includes electronic Raman scattering in mercury excimers and backward wave Raman pulse compression in methane gas.

From among these various media options, we have singled out several type 2 laser media for detailed presentation in Chapter 2. The examples chosen are oxygen, sulfur, selenium (Group VI atoms), and iodine. Emphasis in our preliminary evaluation is on the efficiency and scalability. In Table 1-1, we list features of photolytic lasers that recommend them for fusion power plants. These features include favorable target coupling characteristics, high-energy storage per aperture, promising overall efficiency, and a choice of lasing atom and pump molecule combinations.

Table 1-2 presents the major results of the evaluation. The maximum overall system efficiency and the maximum overall stored energy for a single amplifier module is given for the specific case of a fluorescer-pumped windowless configuration.

These calculations emphasize obtaining maximum size; higher efficiencies would result even for the same configuration, if we trade off scalability for efficiency. Amplifiers can conceivably be built large enough to reach 1 MJ in a reasonable number of beams. Obtaining adequate efficiency will be the most difficult task; only the selenium system promises an overall efficiency above 1%, and even then this value is at the high end of a range of estimated efficiencies. The iodine system requires a

An excimer is a molecule which only exists in the excited state; e.g., Xe_2^ , where the asterisk indicates the molecule is in the excited state.

- Electric dipole allowed transitions

Table 1-1. Features of photolytic lasers.

1. Choice of system:

Lasing atom	Lasing wavelength, nm	Parent molecule	Fluorescer excimer	Fluorescer wavelength, nm
Iodine	1130	C_3F_7I	$XeBr^*$	280
Oxygen	558	N_2O	Ar_2^*	130
Sulfur	772	COS	Kr_2^*	150
Selenium	489	$COSe$	Xe_2^*	170

2. Favorable target coupling characteristics:

- Wavelength: $\lambda = 0.5 - 1.3 \mu m$
- Short pulse duration: $\tau \sim 1 - 10 ns$

3. High-energy storage:

- $F_{saturation} \sim 1-10 J/cm^2$

4. Favorable scaling characteristics:

- Configurations allow flowing, high-average-power systems.
- Can use low-pressure ($\sim 1 atm$), low-temperature ($\sim 300 K$), low-index gases (e.g., helium) for good beam quality.
- Beam quality and gain uniformity limited by gas density uniformity, not by e-beam deposition uniformity.
- Aperture scaling limited by materials and gain constraints rather than by properties of the atoms and molecules.

5. Efficiency $> 1\%$ possible from the physics.

Table 1-2. Efficiency and scalability of photolytically pumped Group VI lasers.

	Oxygen	Sulfur	Selenium	Iodine
Maximum amplifier size	350 kJ	130 kJ	210 kJ	140 kJ
Overall laser system efficiency	0.33%	0.72%	1.53%	0.14%

tenfold higher power input than the selenium system. This could only be accomplished by operating at 10 times the recirculating power or 10 times the fusion pellet gain, circumstances that are either economically or physically unlikely.

This evaluation has been instrumental in showing that a fluorescence-pumped photolytic laser has the potential to be a full size fusion driver. There are significant uncertainties remaining, and much experimental work on kinetics, gain measurements, self absorption, bleaching wave dynamics and beam quality remains to be done. However, if the experiments now being undertaken bear fruit, fusion laser amplifiers of significant size ($\geq 10^5 J$) and adequate efficiency are possible.

The crucial issue is to improve the overall efficiency—both the electrical and flow efficiencies. The best chance of doing this involves improving the coupling of the pump radiation to the laser

species, a problem amenable to some innovative thought. Excimer laser pumping is one possibility—better directionality of the pump beam will help immensely, although excimer laser efficiencies are less than excimer fluorescer efficiencies for all the rare gases. Accordingly, we have developed several ideas for pumping geometries that use both sides of the slab of fluorescer gas, a stratagem which can raise both the electrical efficiency and the flow efficiency by nearly a factor of two, provided no deleterious electron scattering processes are found in the storage media. This would put the selenium laser in the 3% overall efficiency range, making it an attractive prospect for a commercial power plant driver.

In addition to the photolytic energy-storage laser media singled out for more detailed discussion in Chapter 2, the scalability and efficiency of several other laser media and concepts have also been

assessed at LLL in the past year. These media/concepts and the specific systems analyzed are shown in Table 1-3.

To assess these systems on a comparative basis, preliminary device and systems models were developed for each system. These models were then exercised for a number of alternate device geometries in an iterative fashion to arrive at preliminary technical designs. Throughout these analyses, new experimental and theoretical data generated for these media in on-going parallel research efforts were integrated in the comparative assessment. Each system was also examined for any major physics or technological breakpoints in scaling to energies in excess of 100 kJ per beam line.

Three specific designs of lasers utilizing trivalent rare earth ions as the active species were examined in the study. A XeF excimer laser-pumped, Tm³⁺-glass laser system characterized by a relatively low specific thermal loading of the glass medium was explored.¹ This system can be directly compared with the rare earth molecular vapor laser systems in which the average power-thermal loading problem is solved by flow cooling of the laser medium.¹ Designs based on two different molecular carriers of the optically active terbium (Tb³⁺) ion were explored to illustrate the issues associated with the distinct chemical, physical, and kinetic properties of these vapors. As a final system, we analyzed the performance of a backward wave pulsed Raman stacker-compressor laser using the KrF excimer medium as a pump and methane gas (CH₄) as the Raman medium.^{1,2}

The major conclusions of our analyses of these laser systems can be drawn from the summary data presented in Table 1-4. In this table, we have divided the laser efficiency into two parts—that of the pump source and that of the laser medium which converts the pump radiation into a format useful for target irradiation. These two subsystem blocks are further broken down into several constituent efficiencies or factors in order to display which processes or subsystems dominate the reduction of the overall system efficiency and thereby command our future attention. For each system, we have identified an approach to significantly improve on the most limiting process or subsystem efficiency; these items are identified by parentheses containing a higher projected efficiency.

The first conclusion to be drawn from this data is that, based on information available to date, all of the analyzed systems (including the Group IV selenium laser) have the potential for meeting or exceeding the minimum efficiency requirement of 1%. They also all appear to be technologically scalable

in energy to reactor class systems, albeit with differing technological issues.

The second major conclusion is that, on an "equal risk" basis, the KrF/CH₄ Raman stacker/compressor laser system concept is judged to offer a system efficiency significantly higher than the others, possibly reaching as high as 4–6%. When coupled with the fact that this laser system operates at the shortest wave length (0.27 μm), and enjoys an intrinsic, large range of system architectures and technological options for implementation, we conclude that this system concept has the highest potential of those studied to meet anticipated fusion application needs.

The third major conclusion of our analyses is that the projected system efficiencies are as low as they are (1–6%) primarily due to basic inefficiencies of the coherent pumping sources. The laser medium which converts this coherent radiation into a useful format for use in fusion applications is, by comparison, relatively efficient. One is therefore compelled to seek and identify intrinsically more efficient coherent pump sources, find more efficient processes for utilizing efficiently produced radiation from incoherent pump sources or develop laser media which operate in a fusion pulse format using conditioned electrical energy directly.

An Inertial Confinement Fusion Reactor Concept

Approximately 32% of the energy from a DT thermonuclear microexplosion is in the form of x rays and energetic debris. Most of this energy is deposited over a short range in the first wall causing high temperatures, ablation, and cyclical stresses. Several different approaches to the first wall problem have been considered including wet wall, magnetically protected wall, dry wall, and fluid wall concepts. These approaches differ primarily in the way the inner surface of the vacuum chamber interacts with the x rays and microexplosion debris. The wet wall concept features a thin layer of liquid metal over a metal wall. This layer protects the wall from the blistering and ablation that would normally occur. In the magnetically protected wall approach, a solenoid diverts the pellet debris from the radial portion of a cylindrical blanket to conical collectors at the top and bottom. In the dry wall approach, a sacrificial metallic or ceramic liner is placed between the fusion chamber and the blanket.

The fluid wall concept is a new and promising approach which has been developed in our scoping studies. In this approach, the first structural wall is shielded from x rays, neutrons, plasma, and shock effects by a thick falling region of lithium in liquid

Table 1-3. Laser media and concepts analyzed.

Generic species/concept	Active species	Pump source	Medium type
Rare earth molecular vapors	Tb-Al-Cl, TbThd ₃	E-beam driven rare gas Monohalide excimer (KrF)	Storage
Rare earth solid state hybrids	Tm ³⁺ : glass, crystal	E-beam driven rare gas Monohalide excimer (XeF)	Storage
Raman stacker/compressors	Methane (CH ₄)	E-beam driven rare gas Monohalide excimer (KrF)	Nonstorage

Table 1-4. Projected system efficiencies of several potential fusion lasers.

Subsystem	Rare earth ions			Raman
	XeF pumped Tm ³⁺ :glass	KrF pumped TbThd ₃	KrF pumped Tb-Al-Cl	KrF/CH ₄ compressor
E-beam generation, transport and deposition	65	65	65	65
Pump medium-electron to light conversion	5-7.5 (15) ^a	10-15 (25)	10-15 (25)	10-15 (25)
Pump electrical efficiency	3.3-4.9 (9.8)	6.6-9.8 (16)	6.6-9.8 (16)	6.6-9.8 (16)
Total pump efficiency	3.0-4.4 (8)	6-8 (12)	6-8 (12)	6-8 (12)
Transport/coupling	90	90	90	90
Fill factor	80	80	80	80
(Extraction) • (Quantum)	35	28 ^b	28	55-75 ^c
Laser system electrical	0.8-1.0 (2.0)	1.2-1.6 (2.4)	1.2-1.6 (2.4)	2.1-4 (6)
Total system after flow	0.8-1.0 (2.0)	1.1-1.5 (2.3)	1.1-1.5 (2.3)	2.0-4 (6)

^aNumbers in parentheses indicate percent efficiency with possible breakthrough.

^bAssumes unit quantum efficiency.

^cSecond Stokes gain suppression.

or solid pellet form. The fall contains enough moderating material to degrade the fusion neutron spectrum to the point where neutron damage levels in structural materials will be low. These lower levels allow consideration of smaller blanket structures which could last for the useful lifetime of the plant.

The liquid lithium waterfall reactor is shown in Fig. 1-4. The principal feature of this design is a thick continuously recyclable first wall of lithium. On each shot the waterfall is disassembled; between each shot it is reestablished. The lithium is continuously pumped to the top of the vacuum chamber through a reservoir region which separates the first wall from the pressure vessel. A small fraction of the lithium in the fall and reservoir regions is cir-

culated to the heat exchanger which in turn transfers heat to the steam generation cycle. Liquid lithium serves as the primary coolant, the neutron moderator, and the fertile material for tritium breeding. It also protects the structural wall.

Our calculations show that a 60-cm thick region of falling liquid lithium can be maintained with less than 5% of the plant's output power. The fusion neutrons deposit the majority of their energy in the falling lithium region, thereby mitigating the problems associated with neutron damage and activation of the structure. For example, our neutronics calculations show that the 60 cm region attenuates the fusion neutron flux to a point where the blanket structure can last the lifetime of the plant (30 yrs).

Fig. 1-4. Liquid lithium waterfall concept.

As one might suspect, the liquid lithium waterfall concept has excellent tritium breeding characteristics and inherently good cooling characteristics. With no structural material between the fusion neutrons and the lithium fall, the design takes full advantage of the lithium tritium breeding reactions. In fact, this reactor concept will produce enough excess tritium ($T > 1.5$) to relieve other applications such as propulsion and synthetic gas production of

the burden of breeding and recovering their own tritium.

Lithium is compatible with stainless steel to temperatures approaching 800 K; this compatibility allows thermal to electrical conversion efficiencies approaching 40%. With an operating temperature in the neighborhood of 750 K, the vapor pressure of lithium is sufficiently low ($\sim 10^{-3}$ Torr) to maintain adequate vacuum conditions in the laser fusion

chamber. In fact, the lithium waterfall will itself act as a vacuum pump by condensing the lithium that is vaporized from the microexplosion.

Chapter 2 presents a preliminary conceptual design of a laser fusion power plant that incorporates the liquid lithium waterfall reactor concept. After selecting a representative set of laser and target parameters, we found that the plant could produce 1160 MW of thermal power. The thermal energy is converted to electrical energy with an efficiency of 38%. Of the total 440 MW_e produced, 80 MW of electrical power is recirculated for plant operation (lasers and lithium flow). This results in a power plant with a net electrical production of 360 MW_e and an overall system efficiency of 31%.

Fusion-Fission Hybrid Reactors

Fusion-fission hybrid reactors can be viewed as subcritical fission blankets. They are driven and controlled by an internal source of high energy neutrons, the fusion reactor. The hybrid reactor combines naturally the power-richness of fission systems with the fast-neutron-richness of fusion power sources. The term *fast-neutron-rich* should be emphasized because it is the 14.1-MeV neutrons from DT-fusion reactions that provide the reactor

with the ability to generate substantial amounts of power and fissile fuels from the abundant fertile materials: ²³²Th and ²³⁸U. Since the hybrid reactor operates in a subcritical mode with a low fissile-material inventory, there is an absolute guarantee against a nuclear excursion.

For several years, we have been investigating potential of producing fissile fuel and electricity in a laser-fusion-driven subcritical fission blanket (i.e., a hybrid reactor). Our earlier studies ³⁻⁵ primarily used neutronic methods of analysis to identify attractive systems and provide an upper-bound estimate of performance. They also demonstrated that fusion-fission hybrids could be designed to meet a broad spectrum of fissile-fuel-producing and energy-multiplying requirements. The following are the three most significant features that emerged from our neutronic scoping studies:

1. Laser fusion hybrids produce 10 times more fissile fuel (per unit of thermal energy generated) than fission breeder reactors.
2. Laser-fusion hybrids economically produce electricity with much lower laser efficiencies and pellet gains than those required for pure fusion.
3. Inertially confined fusion systems can more easily accommodate a fission blanket than magnetically confined systems.

Fig. 1-5. Laser fusion energy gain requirements for hybrid fusion-fission systems.

Fig. 1-6. The production and consumption of fissile fuel.

The energy-multiplication characteristics of all the hybrid blankets we have neutronically analyzed are summarized in Fig. 1-5. As the figure dramatically points out, much less fusion energy gain is required if the fission blanket is constructed of fissile material with a high energy-multiplication capability (M_B). For example, in an energy breakeven mode, the required fusion energy gain for a depleted uranium-fueled hybrid is 2 to 10 times less than the fusion energy gain required for a thorium fueled hybrid.

Figure 1-6 shows the production capabilities of laser-driven hybrids 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.) In Fig. 1-5, we saw that depleted uranium-fueled hybrids can operate with much lower fusion energy gains than those required for thorium blankets. Figure 1-6 shows that thorium-fueled hybrids outperform uranium-fueled hybrids on the basis of fissile fuel produced per unit of thermal energy.

It is interesting to match the consumption requirements of the fission reactors to the production capabilities of the breeders. A thorium fast-fission hybrid provides enough fissile material to fuel 20 high-temperature gas-cooled reactors (HTGRs) of equivalent thermal power while a depleted uranium-

fueled hybrid produces enough fissile material to fuel seven light water reactors (LWRs) of equivalent thermal power. Conversely, if fast breeder reactors (FBRs) were used to fuel LWRs, they would not produce enough excess fissile material to fuel even one LWR of equivalent thermal power.*

Our 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 also require studies of the engineering, safety, and economic issues. With this in mind, Bechtel Corporation was engaged to assist us in a conceptual design study of a laser fusion hybrid. The design that evolved is a depleted-uranium-fueled, fast-fission blanket which produces fissile plutonium and electricity. The fission blanket surrounding the fusion chamber was designed with current fission technology so as to simplify the assessment of the hybrid system's technical feasibility.

One of the study's objectives was to determine if fissile fuel could be produced with laser fusion. This part of the study consisted of analyzing the integrated engineering performance of the conceptual design and identifying the required laser/pellet performance. The performance of the laser fusion hybrid was also compared to a typical fast breeder reactor. The results from the conceptual design

*The excess fissile material produced in an FBR is best used to fuel a new FBR.

study substantiate the previously given upper-bound neutronic results. They show that the laser fusion hybrid produces enough fissile material to fuel more than six light water reactors (LWRs) 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.

We also found that the hybrid will be two to three times more expensive than a light water reactor. The cost estimate varies primarily because of the uncertainties in the design of the pellet production facility and the laser system. However, the cost of electricity is more important than the hybrid's capital cost in a scenario in which hybrids provide fuel for LWRs. In Fig. 1-7, the cost of electricity has been plotted as a function of the cost of LWR fissile fuel for hybrids with varying capital costs. The results indicate that the cost of electricity is 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 two to three times more than the LWR.

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 ^{238}U in uranium to fissile plutonium the hybrid could extend the fissile fuel supply for economically proven LWRs by two orders of magnitude. Fast breeder reactors also offer the prospect of more fully utilizing the uranium resources; however, they will not provide fissile fuel

for LWRs. Therefore, the usefulness of fast breeder reactors will be entirely dependent on their economic competitiveness as power plants.

Actinide Burning

The neutrons from DT fusion systems can be used to transmute or change the long lived waste products from fission reactors (primarily actinides) to short lived or stable isotopes. This method has been proposed as an alternative to geological storage for the long lived waste. Since actinides have half lives that are long compared to geological events such as ice ages and earthquake fault movement, the acceptability of a geographical disposal concept is debatable.

If all the waste products from fission reactors are allowed to decay, the actinide waste will comprise most of the radiological hazard after 400 years. Thus, if the actinides can be transmuted into stable isotopes or fissioned into relatively short lived fission products, the duration of the radioactive hazard can be reduced substantially. Several studies have investigated the possibility of recycling actinide waste in thermal fission reactors and fast breeder reactors. These studies have shown that actinide burning in fission reactors is feasible and most efficient in the harder neutron spectra of fast breeder reactors. It logically follows that fast-neutron-rich fusion systems could even more effectively serve the same role.

Three studies of actinide burning in fusion reactors have been completed. Battelle Northwest Laboratory (BNWL) performed a study of actinide burning in a beryllium blanket with a first wall fusion neutron flux of 10 MW/m^2 and an irradiation time of 500 days. They concluded that the first wall loading was an order of magnitude too small for effective transmutation in the moderated neutron spectrum of the beryllium blanket. The Fusion Power Division of Westinghouse (WFPS) has recently completed an investigation of actinide burning in a fast spectrum. The irradiation time in the study was 30 years with first wall neutron fluxes of 1.1, 5, and 10 MW/m^2 in a Tokamak configuration. The WFPS reactor blanket produced $13,000 \text{ MW}_t$ of power. Their results for the 1.15 MW/m^2 case were similar to that of the BNWL study, which shows a hazard index no better than that of natural decay of the waste in the 10^5 year period. However, for the 10 MW/m^2 case, the hazard index of the waste is reduced about three orders of magnitude. A comparison of the relative ingestion hazards from actinides as a function of decay time for various fusion neutron first wall fluxes following 30 years of irradiation is shown in Fig. 1-8. Note that the injection hazards of the unirradiated actinides are

Fig. 1-7. Cost of fissile fuel and electricity from a hybrid. The intersection points of the curves determine the cost of electricity and fissile fuel in the hybrid-LWR scenario. For example, the cost of electricity increases by only 20 to 40% when the capital cost of the hybrid ranges from two to three times more than the LWR.

reduced to those of the parent ore within 100 years and become increasingly less hazardous with time thereafter.* These results clearly demonstrate that for effective burning of actinide waste the product of irradiation time and first wall flux must be on the order of 300 MW-year/m².

A third study by Berwald and Duderstadt of the University of Michigan utilized a laser fusion driven actinide burner in which the actinides are dissolved in a liquid tin solution. Their neutronic results confirm and extend the Westinghouse work. Because inertially confined fusion systems can operate at higher wall loadings and more easily accommodate fissioning blankets, they will be more effective actinide burners than magnetically confined fusion systems.

An alternative scheme for burning actinide waste in an inertially confined fusion system is to incorporate the actinide waste into the fusion target. This option has the advantage of increasing the neutron fluence per shot by more than nine orders of magnitude. Calculations have shown that much of the actinide material seeded into the target can be burned. The disadvantages of burning the actinides in the target are that pellet fabrication and processing of fission product waste becomes more complicated than burning the actinides in a blanket and that the actinide mass burn rate is small due to limits on the amount that can be compressed.

It appears that the inertially confined fusion reactor would be more attractive for actinide burning applications than alternative systems (LWR, LMFBR, and magnetically confined fusion). However, the actinide burning process is of questionable desirability for the following reasons:

- High-level wastes would be handled more often than they would be if all fission reactor waste were immediately encapsulated and stored.
 - The short-term hazards increase during early irradiation as a result of the production of additional actinides from neutron capture.
 - Applications for actinides exist.
 - Reduction of effective half-life from the natural half-life for actinides is of questionable value. Even without irradiation, the actinide ingestion hazard decays to the hazard of the parent ore after a relatively short storage period (100 years).
- If society deems the long-term radiological hazards from fission reactor actinides high enough to merit construction of actinide burners, then inertially confined fusion technology could best perform the required irradiation.

*The actinide hazard is concentrated rather than diluted in a large volume like the parent ore.

Fig. 1-8. Comparison of relative ingestion hazards from actinides as functions of decay time.

Synthetic Fuel Production

Our oil and natural gas supplies are declining rapidly. Hence, the ability to produce large quantities of portable chemical fuels for our homes, industries, and vehicles will be a necessity within the next 100 years. Natural gas has been the preferred fuel for residential heating and industrial process heat because it is environmentally acceptable, easy to use, and, up until recently, inexpensive and reliable. Depletion of natural reserves has given added emphasis to the search for an alternative fuel, and the potential role of hydrogen has been discussed in this respect, both as a fuel itself and as an intermediate product used in the production of synthetic fuels.

Hydrogen production processes can be classified on the basis of the form of primary energy used: thermochemical, electrolytic, or radiolytic. Hydrogen production by radiolysis can be achieved in several schemes which require an intense source of radiation and generally employ water as the starting material because of its abundance. The penetrating neutron radiation of an inertial confinement fusion reactor could be used for radiolysis by incorporating sufficient quantities of H₂O in the blanket regions surrounding the fusion vacuum chamber. More than 25% of the energy released by the fusion microexplosion is carried by the pellet debris, alpha particles and x rays. This energy is deposited in the vacuum chamber wall and thus would not be available for radiolytic decomposition.

A concept often used in the discussion of radiation-induced chemical processes is the G value. The G value for the formation of a chemical species is defined as the number of molecules produced per 100 eV of energy deposited in the production regions by incoming radiation. The generally accepted G value for H_2 from water is 0.45 while G values as high as 13.6 have been measured in experiments using pure steam exposed to high-energy neutrons. The conversion efficiency of nuclear energy deposited in the hydrogen producing regions to usable chemical energy is equal to 0.01 Gh, where h is the heat of combustion of H_2 (2.5 eV). Thus for a G factor of 13.6, 34% of the energy deposited in the steam is converted to the potential combustion energy of H_2 , while 66% of it appears as the thermal energy of the steam.

Note that only a fraction of the available neutron energy would actually be deposited in the steam blankets: the remainder would be deposited in reactor structural materials and, thus, would be unavailable for radiolysis of H_2O . The system efficiency for hydrogen power production, defined as the ratio of usable chemical energy produced to the energy deposited in all regions of the reactor, is on

the order of 15% for the $G = 13.6$ steam system.

The hydrogen production efficiencies presented here can be put into perspective by comparing them to thermochemical processes which produce synthetic fuels with efficiencies ranging from 30% to over 60%, and electrolysis of water which produces hydrogen with efficiencies of 50-100%. Assuming a 40% thermal-to-electric conversion efficiency, the electrolysis process produces hydrogen with an overall efficiency up to 40%. An interesting alternative to the simple radiolysis process would be to convert the thermal energy deposited in the system to electricity and use the electricity to produce hydrogen by electrolysis (radiolysis/electrolysis hybrid). Figure 1-9 compares the various conversion processes on the basis of recoverable energy per unit of thermal energy available.

Current costs of natural gas supplies are in the area of \$1/million Btu but may climb to \$3/million Btu before the end of the century. The present estimated cost of synthetic gas from coal gasification plants ranges from about \$4.50/million Btu for the current process to as low as \$3.50/million Btu for future plants. *In situ* coal gasification may be able to produce gas at a cost of about \$2/million Btu.

Fig. 1-9. Combustion energy of hydrogen recoverable per unit of fusion reactor thermal energy. The fraction of the neutron energy deposited in hydrogen processing regions is generously assumed to be 100% for radiolysis of water and 60% for radiolysis of steam. It is unlikely that a dedicated radiolysis hydrogen production facility could ever prove practical unless a liquid medium with a higher G value is found. Therefore, a hypothetical $G = 20$ liquid medium system is shown.

Table 1-5. Energy source component of the cost of hydrogen.

	Cost of source energy, \$/MBtu	Energy conversion efficiency	Energy source component of hydrogen cost, \$/MBtu ^a
Thermochemical	2.46	0.30-0.65	3.80-8.20
Electrolysis	2.93	0.24-0.40	7.30-12.20
Radiolysis	2.46	0.16-0.38 ^b	6.50-15.40
Radiolysis/electrolysis	2.93	0.36-0.50	5.90-8.10

^aDoes not include cost of chemical processing plant, electrolysis units or radiolysis components required.

^b0.16 and 0.38 correspond to G values of 13.6 and 20, respectively.

The cost of hydrogen produced by the various laser fusion driven processes is, at minimum, equal to the cost of energy from the fusion reactor divided by the overall energy conversion efficiency. For the sake of providing a lower bound estimate of cost, assume that a laser fusion power plant can produce electricity at the same price as an LWR (~25 mills/kWh). Table 1-3 gives the source energy cost of producing hydrogen by the various processes. These values reflect only the cost of using the laser fusion reactor as the source of energy for the various processes. Additional costs will vary for the different processes depending on the cost of the components required. Large electrolysis units, for example, will add about \$1/million Btu to the cost of hydrogen. It should also be noted that the cost of source energy for the processes that do not require electrical energy have been reduced from \$2.93 to \$2.46/million Btu because the electrical power generating equipment (turbine generators and turbine buildings) accounts for 20% of the capital cost of an LWR and the total capital cost is about 80% of the price of electricity.

It is clear that there is no economic incentive for the production of synthetic fuels with laser fusion at the current price of natural gas nor at the projected cost of gas from coal gasification. Even so, such a system may eventually be required. Oil and natural gas currently account for about 75% of this nation's energy consumption. As these fuels are depleted, the ability to produce large quantities of portable fuel will become a necessity. Laser fusion driven hydrogen production processes represent a virtually inexhaustible supply of portable fuel.

Propulsion Systems

Propulsion systems powered by laser fusion reactors could be used to drive large aircraft, ships, and extraterrestrial craft. Technically, such systems could be installed in military ships before laser fusion electric power plants become a reality because of relaxed economic constraints. However, introduction of laser fusion propelled ships is unlikely unless fission propulsion systems become unacceptable due to environmental considerations. In addition, fusion propelled ships deployed prior to fusion electric plants must breed their own tritium or suffer tremendous economic penalties.

A fusion power system for propulsion must be designed for minimum specific volume and mass. Thus, the reactor must operate with a high first wall loading. A summary of the performance characteristics of advanced propulsion systems for several applications is presented in Table 1-6.

Use of laser fusion for marine propulsion could be technically competitive with fission propulsion while offering significant environmental advantages due to its lower inventory of less hazardous radionuclides. The listed marine requirements in Table 1-6 appear to be well within projected efficiencies and scaling laws for laser fusion power systems. The more spacious and mass tolerant shipboard environments permit use of a helium-cooled, graphite moderated version of a laser fusion reactor operating on a closed Brayton cycle. This reactor will be radioactively cleaner than a liquid-metal-cooled system. Moreover, the use of helium will allow high temperatures and avoid the problems associated with liquid metals in water environments. From gravitational considerations, the first wall of the reactor should be a dry wall rather than a wet or fluid wall concept. Lithium will not be required because this high-performance reactor will operate on a parasitic deuterium-tritium fuel cycle.

Aircraft propulsion systems powered by laser fusion reactors do not appear to be an attractive alternative to chemically fueled or fission powered systems. In addition to the environmental unacceptability of an airborne nuclear system (fission or fusion), fusion plants will require a much larger specific volume and mass than current chemically fueled propulsion plants. The portions of the fusion power plant whose weight and volume must be traded off against the chemical fuel load include the laser system, pulsed power supply, reactor, coolant, and payload shielding. Preliminary calculations show that it will be difficult for the reactor alone to meet the mass and volume constraints, even for first wall thermal fluxes as high as 10 MW/m^2 .

Two space applications of fusion propulsion are being considered: an earth-moon shuttle or ferry and an interplanetary space craft for manned missions. These applications can take advantage of the

Table 1-6. Summary of propulsion system characteristics.

Application	Technical risk	Power ^a	Specific mass, kg/kW	Specific volume, m ³ /MW
Marine				
Navy	Moderate	90 MW _s	30	80
Commercial	Low	90 MW _s	90	200
Airborne	High	360 MW	0.4	0.6
Space	Highest	130 GW	0.05	Not critical

^aSubscript s refers to shaft power.

enormous specific impulse* relative to that of chemical rockets. Nucleons are accelerated in fusion reactions to velocities on the order of 10^7 m/s, making a specific impulse on the order of 10^6 s obtainable in principle. Chemical rockets have specific impulses limited to less than 450 s. Fission systems will be limited to specific impulses of less than 2000 s.

A high-performance vehicle, powered by a laser fusion propulsion system has been postulated. Figure 1-10 gives the calculated performance for a system that produces 130 GW_e. For a super-high-performance propulsion system of this kind, interplanetary trajectories may be quite accurately calculated by neglecting solar and planetary gravitation effects. As shown in the figure, a round trip from Earth to any point in the solar system may be made in less than one year by a system that carries a 100-ton payload and has a propulsion system mass of 300 tons. An initial fuel loading of 200 tons of deuterium is sufficient for such maximum missions. Interstellar missions of a few decades of total time are also feasible.

* Specific impulse = impulse per unit weight; i.e., $(ma) \Delta t / (mg) = (\Delta v / \Delta t) \Delta t / g = \Delta v / g$ (unit is time).

Fig. 1-10. Extraterrestrial laser-fusion-powered vehicle performance.

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2. CENTRAL STATION ELECTRIC POWER WITH LASER FUSION

A Comparison of Long-Range Sources of Electrical Energy

The criteria used to compare laser fusion to other long-range sources of electrical energy include abundance, social costs, technical feasibility, and the cost of electricity. The term "social costs" is used to denote burdens borne by society that are not directly reflected in the cost of electricity. These include health risks, environmental issues, safety, and nuclear weapons proliferation. The technical feasibility of a future source of electrical energy can be assessed by the degree of engineering complexity and the amount of advanced technology required for high-average-power operation in an efficient manner. All of the long-range sources of energy are capital intensive. As a result, the cost at which they produce electricity is dominated by their capital costs and plant capacity factors.

Social Costs

The generation of electricity inevitably results in risks to human health and adverse effects on the environment. A meaningful assessment of producing electricity with laser fusion requires that its social costs be compared to those of alternative sources of energy. The health effects considered in the comparison involve prompt and delayed deaths, genetic diseases, serious illness, and discomfort. Environmental effects range from land use and resource depletion to world-wide climate changes. Some of the social costs, such as improving safety and reducing air pollution, are reflected in the cost of electricity; however, in general the social costs show up as hazards to life and damage to the environment.

Characteristics of inertially confined fusion power plants on a deuterium-tritium fuel cycle that significantly affect their social costs include:

- High-energy neutrons which cause structural damage and activation
- Kilogram quantities of tritium present in the power plant
- Large lithium inventories
- Electricity generation via thermal energy conversion
- A self-contained fuel cycle
- Large reactor structures

In Table 2-1 we have quantified the most important social costs that result from a laser fusion power plant with the characteristics presented above. Here, we compare laser fusion with the long-

range alternatives (breeders, solar energy, and magnetic fusion) and the major existing producers of electricity (coal and LWRs). The majority of the entries in Table 2-1 were obtained from an ERDA sponsored study recently completed at Battelle Northwest Laboratories.¹ The major differences between laser and magnetic fusion result from our contention that the problems associated with fusion neutron damage and activation can be reduced by an order of magnitude in a laser fusion system. A reactor concept that emphasizes this feature is presented later in this chapter.

Land Use

Solar and coal-fueled power plants use an order of magnitude more land than the other energy producers. The large variance in land use for solar power plants results from the differences in the degree of insolation and whether thermal-electric or photovoltaic systems are used. The fuel needs of a GW_e coal plant require the mining of some 100 to 400 acres of land each year. At present uranium ore concentrations (0.2%), some 20 to 50 acres of land must be mined annually for a GW_e LWR. As high-grade uranium ore is depleted, the land requirements for an LWR will approach and may even surpass those of coal.

Transportation Requirements

A GW_e coal-fired power plant requires more than 10,000 tonnes of coal per day of operation. As a result coal transportation presently accounts for approximately 10% of the freight car haulage in the United States. The large difference in the transportation requirements for laser and magnetic fusion primarily results from the requirement to replace the neutron-damaged blanket structure in the magnetic fusion power plant periodically (1 to 5 years).

Gaseous Effluents

This category identifies air pollution problems that contribute to the overall health risk. Air pollution has long been known to be a cause of illness and death as well as discomfort. The principal health effects of coal-fired plants are thought to result from sulfur-related pollutants. These account for approximately 75% of the gaseous effluents of a coal plant with scrubbers.

Table 2-1. The social costs (health, environment and safety) of generating 1 GW_e of electricity.

	Coal	LWR	Breeder reactor	Solar	Magnetic fusion	Laser fusion
Land use (acres)						
Power plant	300	100-200	100-200	6,000-19,000	100-200	100-200
Fuel cycle (30 years life)	3,000-12,000	600-12,000	15	0	0	0
Transportation requirements (tonne/yr)						
	3×10^6	200	23	Unknown	100-400	10
Gaseous effluents						
Nonradioactive (tonne/yr)	40,000	21	5	Unknown	0	0
Radioactive (Ci/yr)						
Tritium	0	15,700	2000	0	1000	1000
Other	?	350,000	150,000	0	0	0
Solid waste						
Nonradioactive (tonne/yr)	1×10^6	91,000	9,100	Unknown	Negligible	Negligible
Radioactive (m ³ /yr)	0	340-1100	450-1200	0	450	30
Safety						
Accident consequences	Low	Very high	Very high	Very low	Low	Low
Accident probability	High	Very low	Very low	Very low	Very low	Very low
Proliferation hazard	No	Yes	Yes	No	No	No

The release of CO₂ from the coal burning process may pose an even more serious long-term problem by causing significant climate changes. CO₂ in the atmosphere heats the earth by the so-called greenhouse effect because it is transparent to the incident solar radiation but absorbs the heat reradiated from the earth. Whether the effect of increasing the amount of CO₂ in the atmosphere will combine with natural changes and other causes to produce an adverse effect on our climate remains to be demonstrated. This uncertainty could take on an overriding significance in the comparison between coal and nuclear fission. Specifically, it argues against complete reliance on coal at this time.

Solar power plants will not release any significant quantities of gaseous effluents; however, they can be expected to adversely affect the local climate by changing the absorption and reradiation properties of the earth's surface in their vicinity. Solar-energy collectors that would cover half the surface in any given area could be expected to alter the temperature and the surface wind conditions.

Fusion reactors will contain kilogram quantities of tritium within their confines, and it is inevitable that some of this radioactive material will be released to the environment in gaseous form. Battelle² has estimated that the tritium release from a GW_e Tokamak fusion reactor will be approximately 1000 Ci/yr. We have assumed the same tritium release for laser fusion. The potential

health risk of this relatively small amount of tritium can be put into perspective by noting that the natural production of tritium by cosmic rays yields a steady-state inventory of 10⁸ Ci, which accounts for 0.02% of the radiation dose we receive from natural sources. Tritium is a radioactive material with a uniquely low biological hazard. It has a half-life of 12.26 years and emits a weak beta (18.6 keV). Tritium is readily absorbed by biological systems, but it has a very short biological half-life: less than 1 day for T₂ and about 8 days for HTO.

The relatively large releases of tritium from fission reactors occur when the spent reactor fuel is reprocessed. However, these releases of tritium are small compared to the gaseous fission products (primarily ⁸⁵Kr) that are also released from the irradiated fuel.

Solid Radioactive Waste

An LWR uses 30 tonnes of fuel per year. At reactor shutdown, a tonne of spent fuel contains 3.0×10^8 Ci of radioactive wastes. After 10 years, its radioactivity has decayed to 3×10^5 Ci. The high-level wastes (primarily fission products) constitute the majority of the radioactivity for the first few hundred years. However, high-level wastes constitute less than 1% of the volume of radioactive material listed in Table 2-1. The major health hazards from the remaining low-level wastes result from the actinides. These transuranic elements, in

general, exhibit very long half-lives and are extremely toxic.

The major source of solid radioactive waste in fusion power plants is neutron activation of the blanket structure. When exposed to first-wall fusion neutron fluxes that support acceptable power densities ($> 1 \text{ MW/m}^2$), these blanket structures are expected to survive from 1 to 5 years.³ Later in this chapter, we present a laser fusion reactor concept that reduces the fusion neutron flux on the blanket structure by an order-of-magnitude, thereby allowing us to consider structures that could last the lifetime of the power plant.

Safety

Mining and transportation accidents constitute the major health hazards from coal-fired power plants. These events have been estimated to cause approximately two deaths per GW_e plant-year.⁴ To date the safety record of LWRs has been excellent. No accidents causing death have occurred in more than 200 reactor years of commercial operation. However, the fact that fission reactor accidents could have serious consequences for public health has long been recognized. The Rasmussen Reactor Safety Study⁵ estimated that an extremely serious accident (a sequence of events leading to core meltdown and breaching the secondary containment) under very adverse conditions would kill as many as 3,000 to 4,000 people in a few weeks and tens of thousands of people over a 30-year period. The probability of this type of accident occurring is so low that the report estimates the accidental death rate from LWR operation to be more than two orders of magnitude lower than for coal. Nevertheless, there are some people who believe that the consequences of a fission reactor accident are so great that the risks are unacceptable no matter how low the probability of occurrence.

A comprehensive accident analysis of fusion power plants cannot be made yet because detailed plant designs and site descriptions are required. However, preliminary assessments of possible accidents indicate that both the probability and consequences of a catastrophic accident in a fusion reactor would be substantially lower than for a fission reactor. Features of fusion systems that lead to this conclusion are:

- Significantly less radioactive byproducts; i.e., no fission products or actinides
- The relatively low biological hazard of tritium (the release of kilogram quantities of tritium would result in maximum doses in the 10's of rems—well below lethal levels)
- No afterheat cooling problem in case of a loss-of-coolant accident

- No nuclear runaway or power excursion from a reactivity insertion or criticality accident.

Liquid metal fires appear to be the most probable cause of a serious accident in a laser fusion power plant. Combustion of the liquid metal in the blanket could release kilogram quantities of tritium and much larger quantities of chemically hazardous hydroxides. The radioactivity bound up in the blanket structure would not be vaporized because the flame temperature of liquid lithium is lower than the vaporization temperature of candidate structural materials. The toxic LiOH produced in the combustion of lithium could be more lethal than the tritium; LiOH is present in the smoke, and it causes lung burns when inhaled. Therefore, its lethal consequences can be avoided with a gas mask and protective clothing, and it can be expected to dissipate as rapidly as the smoke from a conventional fire.

Proliferation

This entry in Table 2-1 emphasizes the fact that fusion does not require fissile materials which can be used to make nuclear weapons. Thus, the following problems associated with fission reactors can be avoided:

- Increasing nuclear weapons proliferation
- Diversion of nuclear weapons material
- Sabotage of nuclear facilities

Proponents of fission reactors argue that the hazard of nuclear weapon proliferation exists independent of American nuclear power. They point out that restrictions on U. S. nuclear programs or exports simply reduce our influence over nuclear power developments abroad, thus diminishing our ability to deal with the important problems of sabotage and diversion by terrorist groups.

In summary, a cursory comparison of the systems and data in Table 2-1 seems to indicate that the social costs of solar energy, magnetic fusion, and laser fusion are significantly lower than alternative sources. A more precise comparison and ranking of these three sources is not possible at this time for two reasons. First, the technical design of large-scale solar or fusion power plants has not progressed far enough for a detailed analysis of social costs. Second, the social costs themselves vary with time and present a difficult and complex pattern of interrelated factors.

The central point to be recognized at this initial stage is that social costs, which are intimately linked to the cultural and political processes in society, may become the controlling factors in the development of energy technologies. The adoption of a relatively expensive system (within a factor of two) in terms of capital investment and electricity cost to

the consumer may, in terms of social costs, be the wisest course of action for society in meeting future energy needs.

Technical Feasibility of Laser Fusion

Fusion, like all advanced sources of electrical energy, is expected to be technically more complex than existing LWR or fossil-fueled power plants. The technical feasibility of laser fusion power plants rests primarily with the developments required for high-average-power operation in an efficient and reliable manner. As an alternative to magnetic confinement, laser fusion offers features that could significantly reduce its technical complexity, thereby reducing the amount of advanced technological development that will be required to produce a technically successful fusion power plant. These features include:

- No magnets* (asterisked items are design-dependent)
- Sizing flexibility (i.e., lower power units)
- Possibility of multiple chambers to provide higher availability
- Flexible geometry
- No direct conversion required
- Reduced vacuum pumping requirements*
- Reduced radioactivity from neutron activation*
- Reduced neutron damage to structural materials*

Later in this chapter, we describe a reactor design concept that features all of the advantages listed above. Before these advantages can be realized, the major technical problems associated with a laser fusion power plant must be solved. These include the development of:

1. A high-average-power driver with the required efficiency ($>1\%$) and reliability ($>70\%$)
2. A first wall able to withstand the effects of x rays, debris, and neutrons from the microexplosion
3. Structural materials that can withstand the cumulative damage effects of high-energy neutrons and cyclical stresses
4. Final-focusing elements that can be placed far enough away from the microexplosion or protected so that they can last a reasonable length of time
5. The technology to cheaply mass-produce fusion targets

In the next section, we analyze and compare laser systems that have the potential to be high-average-power drivers for a power plant. The material damage and final focusing element problems (2 through 4) will be dealt with in the final section of

this chapter where we present the results of studies that have focused on identifying and analyzing reactor concepts for laser fusion.

In our development scenario for inertial confinement fusion (Appendix), we show that the technology to cheaply mass-produce fusion targets could become the pacing element in the engineering and commercial phases of development.

Solutions to the technical problems listed above will allow laser fusion power plants to efficiently produce electricity with high plant capacity factors. The overall efficiency of a laser fusion power plant can be evaluated through a basic power flow diagram like the one shown in Fig. 2-1. 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), neutron energy fraction (f_n), and blanket energy multiplication (M_B): i.e.,

$$\frac{P_{in}}{P_g} = \frac{1}{\eta_L Q \eta_T (1 + f_n(M_B - 1))}$$

Recirculating power fraction is a basic figure-of-merit for any power plant. For reference purposes, fossil-fueled power plants operate with recirculating powers less than 5% while the majority of present nuclear plants operate at or slightly above this figure. Laser system efficiency (η_L) is a lumped parameter that includes power conditioning, medium regeneration, lasing, and optical transport efficiencies. It is defined as the ratio of focusable beam energy to electrical energy input. Blanket energy multiplication (M_B) is defined as the ratio of blanket thermal energy to fusion neutron energy. The overall system efficiency (η_s) of a laser fusion power plant can be related to the recirculating power fraction (RPF) by the equation:

$$\eta_s = \eta_L (1 - \text{RPF}).$$

From the expressions for recirculating power fraction and system efficiency, it logically follows that the product of laser efficiency (η_L) and pellet gain (Q) should provide an excellent figure-of-merit for gauging the prospects of efficiently generating electrical power with laser fusion. This product, which we shall label fusion energy gain, represents the ratio of thermonuclear energy output to electrical energy input to the laser. Fusion energy gain is an extremely revealing performance parameter because economical power production with laser fusion will fundamentally lie with the pellet energy gains achieved and the overall efficiencies at which

where:

η_L = laser system efficiency

Q = pellet gain = $\frac{\text{thermonuclear energy}}{\text{laser light energy}}$

f_n = $\frac{\text{neutron energy}}{\text{thermonuclear energy}}$

M_B = blanket energy multiplication

η_T = electrical conversion efficiency

P_{in} = electrical power input to laser

P_g = gross electrical power

$$RPF = P_{in}/P_g = 1/\eta_L Q \eta_T (1 + f_n (M_B - 1))$$

Fig. 2-1. Laser fusion power flow diagram.

large pulsed ignition sources can operate. In Fig. 2-2, the recirculating power fraction is plotted as a function of fusion energy gain for power plants with a blanket energy multiplication of 1.0 and several thermal efficiencies. Reference designs for laser fusion power plants have used recirculating power fractions in the neighborhood of 25%. However, it may be difficult to compete economically at these high values because, in general, plant capital costs scale with the gross electrical power while revenues scale with the net electrical power.

Cost of Electricity

The cost of electricity from a power plant is determined by the revenue required to provide for a return on capital investment, the cost of fuel, and the cost of operation and maintenance. Like fission reactors, all potential long-range sources of energy will be capital intensive; therefore, the cost at which they produce electricity will be primarily determined by their capital charges. The capital investment component of the cost of electricity is determined from the simple relationship:

$$C_E \text{ (mills/kWh)} = \frac{(0.114) \cdot C_p \cdot R}{C_f}$$

where

C_p is the total capital cost (direct and indirect) of the plant in \$/kW

R is the fractional rate of return on capital per year

C_f is the capacity factor, defined as the ratio of electricity actually produced in a fixed period to the amount that would be produced if the plant operated continuously at full capacity

For a commercial power plant, the rate of return on capital must be sufficient to pay interest, allow for depreciation, provide a return on the equity, and pay income tax. This translates into an effective capital charge rate that varies depending on the financial structure of the utility: 15% is fairly typical.

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

In Table 2-2, we present a recent Bechtel Corporation estimate⁶ of the capital and operating costs (in 1976 dollars) of an LWR ordered in 1976 for operation in 1985. The capital portion of the operating cost is based on a capital charge rate of 15% per year and a capacity factor of 70%. The fuel costs are based on charges of \$40/lb for U_3O_8 (3.2 mills/kWh), \$100/kg/SWU* for uranium enrichment (2.4 mills/kWh), and \$100/kg for fuel fabrication (0.50 mills/kWh). It is interesting to compare the cost of generating electricity from this capital intensive LWR to that of its current competitor—a fuel intensive coal-fired plant. The cost of electricity in mills/kWh for a coal plant (with scrubbers) operating in 1985 breaks down as follows⁷:

Capital charges	13.7
Fuel	12.0
Operation and maintenance	2.8
Total	28.5 mills/kWh

Cost of Electricity from Laser Fusion

We have not performed a detailed cost analysis of a laser fusion power plant. Our cost analyses have

*SWU = separative work unit.

Table 2-2. Capital and operating costs of a 1200-MW_e LWR ordered in 1976 for operation in 1985 (1976 dollars).

• Capital costs	Cost, 10 ⁶ \$
Nuclear steam supply system (NSSS)	78
Other mechanical	101
Civil and structural	142
Piping	77
Instrumentation	9
Electrical	43
Total direct	450
Indirect costs	503 (9 yr)
Total capital cost	953
• Capital cost per kW installed	\$794/kW _e
• Total cost	Cost, mills/kWh
Capital	19.42
Fuel	6.3
Operating and maintenance	1.5
Total cost	27.22

primarily focused on identifying the economic constraints that will ultimately prevail. In line with this objective we have concentrated on providing upper bound estimates on the allowed costs of the laser and reactor portions of an economically attractive fusion power plant.

In Fig. 2-3 the allowed capital cost difference in \$/kW between laser fusion and the reference LWR in Table 2-2 has been plotted as a function of the cost of uranium in \$/lb. The following are the assumptions used to generate the curves in the figure:

- The laser fusion fuel cycle accounts for 3 mills/kWh.
- Operation and maintenance costs for laser fusion are the same as those for the LWR (1.5 mills/kWh).
- Both power plants operate with a capacity factor of 70% and a capital charge rate of 15% per year.

For a laser fusion power plant with a system efficiency of 36%, a fuel cycle cost of 3 mills/kWh will allow a pellet fabrication cost of 0.03¢ per MJ of yield. This allowed value translates to fabrication costs ranging from 12¢ to \$1.20 for pellet yields from 400 to 4000 MJ.

Some perspective for the relationships shown in Fig. 2-3 can be obtained by noting that uranium at \$30/lb contributes 2.5 mills/kWh to the cost of electricity. This fueling cost is equivalent to a capital cost difference of \$100/kW at a capital charge rate of 15% and a capacity factor of 0.7. Estimates of reasonably assured supplies of high-grade uranium ore (0.08 to 0.2% uranium) indicate that there will be enough uranium at prices below \$100/lb to fuel LWRs through this century. At higher prices, lower

Fig. 2-3. Allowed capital cost difference between an inertial confinement fusion reactor and an LWR.

grades of ore could be used. However, their use would increase the mining and land use requirements of LWRs to the point where they would surpass those of coal-fired plants. At uranium prices greater than \$500/lb, it may be possible to extract uranium from sea water, thus guaranteeing a virtually inexhaustible supply.

The nuclear steam supply system (reactor and primary coolant loop) of the reference LWR costs \$138/kW (indirect and direct costs) and it accounts for approximately 20% of the total cost. In Fig. 2-4 we have plotted the allowed cost of the nuclear-island equivalent of a laser fusion power plant (lasers and reactor system) as a function of the cost of uranium. These curves were generated by adding the capital cost differences in Fig. 2-3 to the cost of the LWR nuclear island. As such they provide an upper bound estimate of the allowed cost of the nuclear island equivalent of a laser fusion power plant. The results show that a GW_e laser fusion power plant can generate electricity at costs that are within 50% of present prices with laser and reactor systems whose combined costs are as much as 800 million dollars.

Cost Comparisons With Breeders and Solar Electric Power Plants

Capital costs for liquid metal fast breeder reactors (LMFBRs) are expected to be significantly higher than those of LWRs. Direct estimates from the EPRI/ERDA cooperative design projects currently in progress indicate that LMFBRs will cost from \$400 to \$600 per kW_e more than an LWR, with fuel cycle costs ranging from 1.5 to 5 mills/kWh.^{8,9} By assuming a fuel cycle cost of 3 mills/kWh we can use the information in Fig. 2-3 to determine the cost of electricity from LMFBRs. The results show that breeders will generate electricity at costs that are 20 to 40% more than present prices and that they will not economically compete with LWRs until uranium prices are more than \$120/lb—well into the next century. These economic results when coupled with the larger social costs associated with plutonium reprocessing and recycle argue strongly for deferring the commercial introduction of the LMFBR for 10 or 20 years, thereby allowing the U. S. to pursue a broader R & D program. Such a program could provide a range of attractive choices with introduction dates extending into the next century.

Two processes for converting solar energy into electricity have been proposed: solar thermal-electric and solar voltaic. Solar thermal-electric systems use fixed or movable arrays of mirrors to reflect the sun's energy onto a central tower, which heats a working fluid that produces electricity in a

conventional steam cycle. Present estimates indicate that these power plants will cost about \$2000/kW, 2 to 3 times more than an LWR.¹⁰ Moreover, solar power plants will exhibit a capacity factor of less than 30% because of the diurnal variation of insolation. As a result solar thermal-electric power plants can be expected to produce electricity that costs some six to nine times more than present prices.

Solar voltaic systems use crystals (silicon, gallium arsenide, and polycrystalline substances) to directly convert solar energy into electricity. Conversion efficiencies of about 10% have been achieved. Nevertheless photovoltaic methods are presently far less competitive than solar thermal-electric systems; however, substantial improvements may be possible with new techniques that could substantially reduce the cost of collectors and increase their efficiency. The cost of solar collectors must be reduced to about \$1/ft²—several hundred to a thousand times less than the present cost before they can produce competitively priced electricity.

From the cost comparisons presented here, it is obvious that the electricity generated by any of the long-range sources of energy will be significantly more expensive than electricity is now. However, within a factor of two, the cost of energy in the U. S. economy is much less critical than assured supply. Present total energy costs are only 5% of the U. S. gross national product, and it has been estimated that a doubling of energy costs would result in a 2 or 3% reduction in consumption with little effect on economic growth in the long run.¹⁰

Fig. 2-4. Maximum allowed cost of nuclear-island-equivalent of inertial confinement fusion reactor. Assumptions:

- ICF nuclear island includes driver, reactor vessel, and primary coolant loop
- ICF fuel cycle cost = 3 mills/kWh
- Nuclear island cost depletes allowed cost difference

Lasers for Laser Fusion

The purpose of the driver system in an inertially confined fusion power plant is conceptually simple. It must take a small fraction of the steady state electrical power produced by the reactor, form it into pulses of energy at the rate of 1 to 10 per second, concentrate the energy into pulses ten-billionths of a second in duration, and concentrate the energy in space by projecting it tens of meters onto a target a half-centimeter or so in diameter. Three types of driver systems can potentially accomplish this concentration of energy in time and space: ion beams, electron beams, and photon beams.

It is premature to thoroughly compare these different systems: we shall not do so here. We will, however, indicate why we feel that lasers are a desirable choice for the near, intermediate, and far-term applications. Of course, it is also too early to discard any contender, for each system has different advantages and disadvantages that will determine the system's development. For example, suitable heavy ion accelerators of ≤ 100 GeV beam energy appear to be technologically feasible. The ion beam system draws on the most mature physics and engineering base and is therefore easier to visualize in full scale. The efficiency is projected to be high, $>10\%$, which will allow a low recirculating power fraction. Accelerators would have the capability for high repetition rate, reliability, and operating lifetime required for a commercial power plant. Unfortunately, all existing heavy ion accelerators are relatively low-current devices. Consequently, it is uncertain that the high beam current required for inertial confinement fusion can be accelerated, transported, and focused onto the target. Moreover, large accelerators are quite expensive, and significant research will be required to determine whether high-current accelerators can be built at reasonable cost. Nevertheless, the potential high efficiency, high-average-power capability and moderate technical risk compel us to examine this option carefully.

Electron beams are also attractive alternatives from the standpoint of size, simplicity, and efficiency. Progress is being made at Sandia in scaling 20- to 30-ns E-beams to substantial energies per pulse. The crucial problem is the inability to focus beams of electrons from far enough away to allow the generating diode to survive. Either a breakthrough in the physics or an engineering innovation allowing renewable or regenerative electron guns is required. The expected efficiency is attractive and the average power capability is fine as long as the diode is not destroyed on every shot. The electron beam needs a focusing element that can concentrate

the energy onto the pellet from a safe distance.

A laser system appears to be an ideal way to concentrate energy in space from a safe distance. The system might take the form of a gas laser driven by a broad area long pulse width electron beam: such E-beams are technologically less demanding.

Laser-induced fusion can be approached using many different target concepts which, in terms of projected applications, dictate a range of laser-system performance requirements. During the next few years, the viability of the various target concepts will be evaluated through fusion experiments (using the Janus, Argus, and Shiva laser systems) and target design iteration. Our target calculations and reactor system studies have established preliminary laser system performance requirements for commercial electric power production. The nominal requirements are

• Wavelength	250-2000 nm
• Pulse duration	~ 10 ns
• Pulse energy	300-3000 kJ
• Pulse power	>200 TW
• Pulse repetition rate	1-10 Hz
• Average power	1-10 MW
• Overall efficiency	$>1\%$

These requirements continue to evolve, reflecting new knowledge in target and laser physics, materials and laser engineering, systems analysis, and economics. Important constraints are encountered in each area. For example, in the case of the laser wavelength, the physics constraints favor short wavelengths to compress the pellet with the least energy. Short wavelengths prompt investigation of transitions between electronic energy states. However, the material and technological constraints limit us to consideration of wavelengths larger than about 250 nm because of severe two-photon optical absorption effects. Operation with short wavelengths also impacts the system and economics constraints because the short wavelength gas lasers we know today are somewhat less efficient than infrared lasers. For each laser parameter, there is a similar balance and interplay between the physics technology and systems constraints, which often seems to leave very little room in parameter space to realize an acceptable solution. In fact, no current laser concept is perfect, but we have identified some promising candidates.

The medium in which the laser beam is amplified significantly affects the laser's ability to satisfy the fusion power plant requirements. Depending on the medium, stimulated emission can occur on

- Electric dipole allowed transitions
- Electric dipole forbidden transitions such as magnetic dipole or electric quadrupole transitions
- Optically induced transitions such as Raman scattering or frequency tripling

Laser media of the first type, including the rare-gas and rare-gas-halogen excimers, exhibit stimulated-emission cross sections in the range 10^{-16} to 10^{-17} cm^2 , with upper-laser-level radiative lifetimes of tens of nanoseconds and instantaneous stored energy densities of less than 1 J/liter under efficient excitation conditions. In contrast, laser media of the second type, including iodine, Group VI-A atoms, and rare-earth molecular vapors, exhibit stimulated-emission cross sections in the range 10^{-18} to 10^{-20} cm^2 , with upper-laser-level radiative lifetimes up to hundreds of microseconds, and instantaneous stored energy densities up to tens of J/liter under reasonable pumping conditions. The third type, including Antistokes electronic Raman Scattering in Hg_2^+ , is more difficult to evaluate since it is in an early research stage. The radically different physical and kinetic properties of the first two types of laser media dictate distinctly different laser-system concepts and technologies.

Of the three types of advanced laser media sketched above, the photolytic Group VI-A laser has the largest information base. An evaluation of the efficiency and scalability of one version of this laser follows in a later section, but first it is valuable to shift focus from the physics considerations to the systems viewpoint of evaluating a laser candidate on the basis of overall efficiency.

There are two important and separate aspects to a large laser system: efficiency and scalability. A power plant laser system of high efficiency will have lower recirculating power needs and lower capital equipment costs. For the photolytically pumped Group VI laser, the efficiency depends on losses due to power conditioning, generation of the electron beam, optical pump photon production, coupling to the lasing molecule, optical extraction, and the pumping, cooling, and chemical regeneration of the flowing gases.

Scalability refers to the ability to reach the high pulse energies required by a laser fusion reactor with power amplifier modules of reasonable size. A laser built with a large aperture and pulse energy lowers costs by reducing the number of beams and components. Thus, in a commercial system, 10 beams in a few beam clusters would be superior to 100 individual beams. The scalability depends on mirror and e-beam foil damage limitations, pump constraints, flow and gas uniformity constraints, parasitic suppression, thermal distortion, and

arrival at a configuration that simultaneously pushes all the important technology barriers.

In any given laser system, it is usually possible to trade off efficiency vs scalability to achieve an optimal system. It now appears that achieving high efficiency rather than high energy per pulse or high average power will be the most difficult for visible gas laser systems.

There are a number of considerations in the determination of overall laser system efficiency which are often overlooked. A high average power gas laser system can be thought of as three separate subsystems: optical conditioning, electrical conditioning, and gas conditioning (Fig. 2-5). The optical train transports the beam from the final amplifier aperture through isolators that prevent return of reflected light, through a port to the final focusing element, and then through the chamber background gas to the target pellet. Losses include absorption and scattering of lenses and mirrors, as well as beam-shaping and diffraction-spillage losses. A typical optical train might require ten optical elements. The optical conditioning efficiency is the ratio of power on target P_0 to the laser power P_L .

$$\eta_{oc} = P_0/P_L$$

In a well designed system, the optical efficiency might be in the range of 90-95%.

The electrical conditioning efficiency is the ratio of laser radiation produced to the electrical power provided for the pulse forming network. It is the product of the component efficiencies for the pulse forming network, E-beam, optical pump, quantum

Fig. 2-5. Laser system power flow diagram.

transfer, and optical extraction

$$\eta_{EC} = \frac{P_L}{P_{EC}} = \eta_{PF} \eta_{EB} \eta_{OP} \eta_Q \eta_{EX} \cdot$$

The flow conditioning efficiency is the ratio of the laser radiation produced to the electrical power required to circulate the gas, to remove the entropy and waste heat, and to chemically regenerate the gas if required

$$\eta_{FC} = P_L / P_{FC}$$

The overall laser system efficiency is the combination of these subsystem efficiencies

$$\eta_{\text{Laser System}} = \frac{P_0}{P_{EC} + P_{FC}} = \frac{(P_0/P_L)}{\left(\frac{P_{EC}}{P_L}\right) + \frac{P_{FC}}{P_L}} = \frac{1}{\left(\frac{1}{\eta_{EC}} + \frac{1}{\eta_{FC}}\right)}$$

The laser system efficiency is effectively the product of the optical train efficiency and the smaller of the electrical or flow subsystem efficiencies. It is therefore quite possible for a poorly designed flow and chemical regeneration system to overwhelm the electrical losses.

The flow conditioning efficiency is often expressed in terms of the volumetric efficiency of a laser cavity (pulse energy per unit volume and per unit pressure, E). The average power leaving the laser can be written in terms of the volumetric efficiency (usually in joules per liter-atmosphere).

$$P_L = E p (h \ell L) \text{ PRF},$$

where p is pressure, PRF is the pulse repetition frequency, and (h, \ell, L) are the dimensions of the optical cavity of the laser in the pump, flow, and optical, directions respectively. Note that although E is usually expressed in joules per liter-atm, it is properly dimensionless (E = 1 corresponds to E = 100 J/liter-atm).

The flow conditioning power is proportional to the mass flow rate \dot{m} and the stagnation temperature of the gas T_0

$$P_{FC} = \xi \dot{m} C_p T_0,$$

where C_p is the specific heat at constant pressure and \xi is the fraction of the circulating power re-

quired to return the fluid to its initial state on each round trip. It is the sum of the fraction required for pumping and cooling, \xi_{PC}, and for chemical regeneration, \xi_{CR}.

$$\xi = \xi_{PC} + \xi_{CR}.$$

The mass flow rate can be written in terms of the pressure, velocity (u) and ratio of specific heats (\gamma) as follows:

$$\dot{m} = \left(\frac{\gamma}{\gamma - 1}\right) \frac{p u h L}{C_p T_0}.$$

The circulating power can be written in terms of the pressure, velocity and ratio of specific heats as

$$\dot{m} C_p T_0 = \frac{\gamma}{\gamma - 1} p u h L,$$

using an approximation good for subsonic mach numbers considerably less than unity.

The most efficient flow velocity is the minimum speed allowed by the pulse repetition frequency

$$u = f \ell \text{ (PRF)},$$

where the flush factor f is the ratio of distance flowed between pulses to the optical cavity size in the flow direction \ell. Flush factors of f = 1.3 to 2 are typical of subsonic gas lasers. Using these expressions, we relate the flow conditioning efficiency to the volumetric efficiency E as follows

$$\eta_{FC} = \frac{E}{\frac{\gamma}{\gamma - 1} f (\xi_{PC} + \xi_{CR})}.$$

The pumping, cooling, and chemical regeneration requirements vary from laser to laser: as an estimate, we use some typical numbers characteristic of flowing gas lasers used in other applications. To obtain high beam quality (small density fluctuations in the gas) a nozzle and flow screen arrangement having a substantial pressure drop appears to be necessary. For a 30-psi total pressure drop around the wind tunnel circuit a pressure ratio of three is required for the pumps. This results in a loss factor¹¹ for pumping and cooling of \xi_{PC} = 0.55. The requirements of pulsed laser acoustic damping and optical medium uniformity may dictate these large

pressure drops. If it is possible to achieve a 5-psi pressure drop typical of an ordinary subsonic wind tunnel, the loss factor is reduced substantially to $\xi_{PC} = 0.20$. Lasers operating at low total pressure will have the advantages of lower mass flow rates and lower pumping power requirements, but they will suffer greater temperature rises during the pulse.

We are now in a position to demonstrate the relationship of the overall laser system efficiency to the optical, electrical, and gas flow subsystem efficiencies. The gas conditioning efficiency is expressed in terms of the volumetric efficiency E . Figure 2-6 shows the overall laser system efficiency as a function of the electrical subsystem efficiency with the volumetric efficiency as a parameter.

For example, imagine a visible laser system with an electrical efficiency of 5% and $E = 0.10$ (10 J per liter-atm). This results in an overall efficiency of 3.6%. If the volumetric efficiency drops to 2.2%, a factor of two lower than if we consider only the electrical efficiency. As a second example, a multiline CO_2 laser system might have an electrical efficiency of 6.3% and a volumetric efficiency of 8.5 J/liter-atm, corresponding to an overall efficiency of 3.8%. The overall efficiency is the proper number to use in fusion reactor calculations. There is clearly a strong incentive to design efficient low-pressure-drop flow systems, or better yet, to find laser media with extremely high volumetric efficiency.

Scaling Analysis of Photolytic Group VI-A and Iodine Fusion Lasers

A completely suitable high-average-power gas laser for fusion power plants has not yet been identified. Deficiencies are apparent in all concepts, usually manifested in insufficient overall efficiency rather than scalability to high pulse energy or average power. Although fusion gas laser technology is still young, we believe it is not premature—using the most promising short-wavelength gas lasers—to begin the problem-finding process that accompanies the conceptual design of full-scale systems.¹² We have launched such an investigation, with the following objectives:

- To construct a simple systems model of a high-average-power gas laser system [400 to 1000 kJ, 1 to 10 pps (pulses per second)], which can be used to compare candidate lasers on a consistent and realistic basis.
- To define laser subsystem requirements, including electrical power conditioning, gas conditioning, chemical regeneration, and optical interfacing with a reactor.
- To perform initial system performance and cost tradeoffs within the laser system and in con-

Fig. 2-6. Overall laser system efficiency: $\eta_o = 0.95$, $f = 1.3$, $\xi = 0.20$.

junction with the reactor system.

- To identify key technical issues for advanced gas laser research and development.

To fulfill these objectives, we begin with the generic class of fluorescer-pumped photolytic lasers. We assert that, as a class, they adequately present the pulsed power, E-beam, gas flow, chemical regeneration, optical quality, and damage problems characteristic of many high-average-power fusion laser systems, thus allowing assessment of the applicability of this technology to commercial power generation systems. A companion study is being performed for laser-pumped photolytic lasers.

The laser medium chosen for the first comparison study consists of atomic species radiating on electronic transitions. These excited atoms are formed by photolytic dissociation from the parent molecule which is carried in a rare-gas buffer.^{13,14} The four atoms of interest are oxygen, sulfur, selenium, and iodine. The source of photolytic photons is fluorescence from an E-beam-excited rare gas, possibly doped with another molecule to enhance fluorescence radiation in the absorption band of the molecule to be photolyzed.

Table 2-3 lists the features of photolytic lasers that recommend them for fusion power plants. These features include favorable target coupling characteristics, high energy storage per aperture, promising overall efficiency, and a choice of lasing atom and pump molecule combinations.

Figure 2-7 shows one possible configuration of a high-average-power photolytic laser system that appears very scalable to large volumes and high energy per pulse. The fluorescer gas and laser gas regions are kept apart by the stability of collowing streams of different gases. The pressure and velocity of the two gases are matched; the density, temperature,

Fig. 2-7. Flowing windowless geometry.

Table 2-3. Features of photolytic lasers.

1. Choice of system:

Lasing atom	Lasing wavelength, nm	Parent molecule	Fluorescer excimer	Fluorescer wavelength, nm
Iodine	1130	C_3F_7I	XeBr*	280
Oxygen	558	N_2O	Ar ₂ ⁺	130
Sulfur	772	COSe	Kr ₂ ⁺	150
Selenium	489	COSe	Xe ₂ ⁺	170

2. Favorable target coupling characteristics:

- Wavelength: $\lambda = 0.5 - 1.3 \mu m$
- Short pulse duration: $\tau \sim 1 - 10 ns$

3. High-energy storage:

- $F_{saturation} \sim 1-10 J/cm^2$

4. Favorable scaling characteristics:

- Configurations allow flowing, high-average-power systems.
- Can use low-pressure ($\sim 1 atm$), low-temperature ($\sim 300 K$), low-index gases (e.g., helium) for good beam quality.
- Beam quality and gain uniformity limited by gas density uniformity, not by e-beam deposition uniformity.
- Aperture scaling limited by materials and gain constraints rather than by properties of the atoms and molecules.

5. Efficiency $\geq 1\%$ possible from the physics.

and Mach number differ. The laser does not need uv transmitting windows—a tremendous advantage since such windows probably would not be able to withstand damage from high fluence levels of photons and 1-MeV electrons in addition to the steady and shock pressure loads over the large spans (greater than 30 cm). On the other hand, it must be demonstrated that the laser medium can be buffered at a high enough pressure to allow for adequate electron beam pumping of the rare gas fluorescer. Operation at a high (~1 atm) buffer pressure will also impose a flow energy penalty relative to a design based on a solid window, because of the extra gas in the laser region.

If a window can be found that allows operation of the laser gas at a significantly lower pressure than the fluorescer gas, or if an efficient UV laser pumped scheme can be devised, higher overall efficiencies may result. The flowing windowless fluorescer pumped geometry was chosen for this first study because we have substantial information on fluorescer efficiency but not on rare gas laser efficiencies. Furthermore, the configuration appears scalable to high average power. Comparisons between calculated efficiencies for different laser atoms will be more important than the absolute levels. Additional improvements in efficiency will no doubt come through future innovation in pumping configuration.

The lasing sequence is begun by the firing of two opposed 1-MeV E-beams for approximately 1 μ s. In the case of the selenium laser sketched in Fig. 2-7, electrons radiolyze the xenon, resulting in copious xenon excimer (Xe_2^*) fluorescence radiation. The lasing medium consists of approximately 3×10^{16} cm⁻³ of COSe in 1 atm of helium buffer gas, which provides a pressure match to the fluorescer and provides sufficient heat capacity to minimize the increase in gas temperature. The fluorescence radiation dissociates the parent molecule; the resulting excited Se* atom stores the energy for $10 \sim 10^3$ ns.

The molecular absorber is optically thick to the fluorescence radiation. The photolysis occurs by a bleaching wave that is driven into the medium, dissociating the molecule and causing the mixture to become transparent. The sequence ends with injection of a short laser pulse that depopulates the medium during amplification. The laser system using O*, and S* operate similarly.

Note that the configuration shown in Fig. 2-7 is a classic scalable geometry with the pump, flow, and optical extraction axes mutually orthogonal. This is a convenient way to decouple these important processes and reach the largest possible sizes based solely on constraints of the individual processes.

Efficiency. Figure 2-8 is a power flow diagram of a photolytic laser system. Electrical power is taken continuously from the power plant's generating system and dissipated by the electrical power conditioning (P_{EC}), the fluorescer gas conditioning (P_{FGC}), and the laser gas conditioning (P_{LGC}). The laser system output is the laser radiation focusable on target after the optical train P_0 . The overall laser system efficiency is then:

$$\eta_{LS} = \frac{P_0}{P_{EC} + P_{FGC} + P_{LGC}},$$

which can be written as in the previous section

$$\eta_{LS} = \left(\frac{1}{\eta_{EC}} + \frac{1}{\eta_{FC}} \right)^{-1}$$

The optical system efficiency is simply the ratio of the power on target divided by that emerging from the final laser aperture, which takes into account the losses in the optical transport system required to get the beam into the reactor building and focused on target. These losses include absorption and scattering of lenses and mirrors, as well as beam-shaping and diffraction-spillage losses. A typical optical train might require ten optical elements. As in the previous general analysis, we have assigned a value of 95% to this optical efficiency.

The electrical system efficiency is the ratio of laser radiation produced to electrical power provided to the pulse-forming network. It is the product of the pulse-forming network, E-beam, fluorescer, coupling geometry, quantum, and extraction efficiencies, as follows:

$$\eta_{EC} = \eta_{PF} \eta_{EB} \eta_F \eta_C \eta_Q \eta_{EX}$$

In Table 2-4, these efficiencies are estimated for the four candidate photolytic lasers. A range of values is given for each laser: the lower figure represents today's technology whereas the upper figure is the goal: a reasonable number believed achievable with future development. The larger number in a sense represents the best that is envisioned for the configuration assumed in Fig. 2-7; further innovation would be needed to improve these estimates substantially.

The efficiency of the optical pump is the product of the intrinsic fluorescence efficiency of the gas, η_F (40 to 50% for the rare gases, 15% for XeBr in Ar)¹⁵⁻¹⁷ and a geometrical factor, η_C . The latter accounts for the loss of fluorescence radiation not directed at the laser medium (15 to 40%). The extraction efficiency is determined from the level degeneracies and the fill factor.

Fig. 2-8. Fluorescer pumped laser power flow.

Table 2-4. Electrical to laser efficiencies for photolytic lasers.

Parameter		Efficiency, %			
		Oxygen	Sulfur	Selenium	Iodine
Pulse forming	η_{PF}	80-90	80-90	80-90	80-90
E-beam diode and foil holder	η_{EB}	75-80	75-80	75-80	75-80
Intrinsic fluorescence	η_F	40-50	40-50	40-50	10-15
Fluorescence geometric coupling	η_C	15-40	15-40	15-40	15-40
Quantum efficiency	η_Q	20	19	35	21
Extraction efficiency	η_{EX}	83	83	75	67
Total electrical to laser efficiency	η_{EC}	0.6-2.4	0.6-2.4	0.95-3.8	0.13-0.61

Two conclusions are immediately apparent from Table 2-4. The selenium laser is electrically superior because its quantum efficiency is 50% higher than that of the other Group VI atoms. This is due, in turn, to operation on the transauroral line rather than the auroral line, which is not likely in the oxygen or sulfur systems because of the greater gain of the auroral transitions in these atoms. The sulfur laser might also be operated on the transauroral line for higher quantum efficiency, but the scaling is then limited by the fact that the amplifier must be sized to compensate for the gain on the auroral line, which is 15 times greater. The iodine laser seems inferior for two reasons. First, the match between the XeBr^* fluorescence band and the $\text{C}_3\text{F}_7\text{I}$ absorption band is not nearly so close as for the Group VI atoms, resulting in two to three times lower fluorescence efficiency. Second, the quantum and extraction efficiencies are not as favorable. For example, the degeneracies in the iodine levels at best allow for only 67% extraction of the inverted population compared with 75 to 83% for the Group VI atoms.

The flow system efficiency is simply

$$\eta_{\text{FC}} = \frac{P_L}{P_{\text{FGC}} + P_{\text{LGC}}}$$

The required fluorescence and laser gas flow conditioning power are of two kinds. The first is the pumping power needed to make up stagnation pressure losses (entropy generation) due to screens and flow straighteners, friction in the heat exchangers required to cool the flow, the laser waste heat addition, acoustic absorbers, and the like. This loss is proportional to the circulating flow power. The second power is that needed for chemically regenerating the parent molecule dissociated in the laser process. This is proportional to the number density of molecules and is otherwise very dependent on details of the chemical engineering. Because our estimates of these losses for N_2O , COS , COSe , XeBr , and $\text{C}_3\text{F}_7\text{I}$ are not yet firm, and because the recombination fraction is still uncertain, we omit these losses from this analysis. They may overwhelm the pumping power losses, particularly for the iodine laser, even though the parent molecule density is only 10^{16} to 10^{17} per cm^3 .

Generalizing the flow efficiency expressions from the previous analysis to two streams, we obtain

$$\eta_{\text{FC}} = \frac{1}{\frac{2\gamma}{\gamma - 1} \left(\frac{\xi_F W_F}{W_L} + \xi_L \right) \left(\frac{p}{n_{\text{ex}} h \nu_L N^*} \right)},$$

where p is the gas pressure, γ the ratio of specific heats, W_F and W_L the widths of the fluorescer and laser streams, $h \nu_L N^*$ is the energy stored per unit volume in excited states and, as before, n_{ex} is the fraction of the stored energy that can be extracted.

The flow efficiency depends on the relative sizes and pressure drops of the two streams and on the ratio of overall pressure to excited-state density (more precisely, on the ratio of transitional energy density to the extractable energy density of excited states). Obviously, it is desirable to operate at low helium pressure and high laser molecule density. Note that the flow efficiency is independent of cavity volume or pulse repetition frequency, if the laser is operated at the minimum mass flow.

The flow system efficiency calculation depends on the results of scaling relationships such as the relative widths of the laser and fluorescer streams, the pressure (1 atm), and the parent molecule number density. However, in order to keep the discussion of efficiency self contained, we give the results of the flow efficiency calculations in Table 2-5 for the four lasers of interest, exclusive of any chemical regeneration losses. The electrical and optical efficiency losses are repeated in this table in order to display the overall efficiency.

We immediately note that the flow efficiencies are so poor for this configuration that they significantly influence the overall efficiencies. Because the fluorescer flow and laser flow must be pressure-matched in a windowless system, one must operate at high enough total pressures (and therefore mass flows) to stop the E-beam efficiently in the fluorescer flow region. This makes it difficult to reduce the total pressure much below the assumed value of 1 atm. In addition, the oxygen and iodine lasers use argon, a relatively low-atomic-weight fluorescer which requires a much greater width of gas to stop the electrons, and therefore have a concomitant larger pumping power requirement. Other configurations, perhaps using windows and low-pressure laser gases, would have higher flow and overall efficiencies.

Scalability. Four factors dominate the sizing of photolytic lasers: parasitics, beam quality, E-beam foil damage, and the decay time of the population inversion. We have considered these factors in an analysis of the feasibility of constructing 100-kJ pulse amplifiers. The results are encouraging; it appears that it will be less difficult to obtain size than efficiency.

Parasitic oscillations must be suppressed in large laser amplifiers to prevent unwanted premature depopulation of the excited states. In the laser direction, it is quite likely that saturable absorbers will be used to isolate amplifier stages and prevent target

Table 2-5. Overall laser system efficiencies for windowless fluorescence-pumped photolytic lasers.

Subsystem		Efficiency, %			
		Oxygen	Sulfur	Selenium	Iodine
Electrical	η_{EC}	2.4	2.4	3.8	0.61
Flow	η_{FC}	0.40	1.1	2.8	0.2
Optical	η_0	95.	95.	95.	95.
Overall laser system efficiency		0.33	0.72	1.53	0.14

$$\eta_{LS} = \frac{\eta_0}{\left(\frac{1}{\eta_{EC}} + \frac{1}{\eta_{FC}} \right)}$$

preheating. This allows the use of high gain length-products, particularly if aerowindows rather than solid windows are used, for they eliminate the back-reflecting problem. Consequently, we use the product of the small signal-gain and length, $g_0L = 6$ as the parasitic limit on maximum length. This is a large but not unreasonable limit.

Parasitic oscillations must also be prevented in the transverse directions, particularly in the high gain fluorescer region. The flow direction is bounded in the upstream direction by a nozzle wall that may reflect light. However, the downstream direction is bounded by an aerodynamic diffuser full of hot absorbing gas, so we would anticipate no reflected radiation. In the pump direction, the laser cavity is bounded by fluorescent gas regions, which may or may not be transparent to the laser radiation depending on the ion density in the fluorescing gas. If they are transparent, the laser radiation could reflect off the E-beam foils, which have some reflectivity in the visible spectrum. We use a parasitic limit of $g_0W_L = 3$ to be conservative, where W_L is the width of the active laser gas in the pump direction.

There are other limitations on the width in the pump direction, such as quenching of the excited states of the photolyzed gas by the parent molecule during the pump pulse. This limit can be overcome by pumping harder for shorter times, provided two-photon absorption does not set in. One pumping constraint is the E-beam foil damage (F_E) limit of 20 J/cm^2 , corresponding to 20 A/cm^2 for $1 \mu\text{s}$ or 200 A/cm^2 for $0.1 \mu\text{s}$ at electron energies of about 1 MeV. The bleaching-wave velocity is simply the fluorescent photon number flux divided by the absorber (parent molecule) density. With an E-beam fluence limit of 20 J/cm^2 , a bleaching wave can be

driven $>60 \text{ cm}$ into a gas with 3×10^{16} absorbers per cm^3 . This result is relatively independent of the pumping time, which can be chosen to minimize quenching problems.

Mirror damage limits are not really of concern in this example because there is enough freedom to choose an input fluence such that high efficiency is achieved while maintaining an output fluence less than the mirror threshold.

Beam quality is an important constraint for large lasers. The chief sources of phase degradation and angular spread for the coherent beam are the surface finish and thermal distortion of mirrors and density fluctuations in the gas. The latter cause non-random linear fluctuations in the index of refraction.

Each optical component is allowed part of an overall distortion budget, calculated from the greatest beam-quality loss that can be tolerated while still focusing on a fusion target. As an example, we performed the following linearized analysis. Assume that the optical train needed for interfacing with the fusion reactor is composed of ten mirrors, the last of which is a 2-m-diam focusing mirror.¹⁸ This final mirror might be located 100 m from the center of the target chamber to minimize the chamber's open wall area, through which neutrons can escape. The beam is focused on a 5.0-mm-diam target.

The gas laser amplifier is assumed to have an input beam of zero phase variance and a minimum local gas density variation level ($\Delta\rho/\rho$) due to flow noise of 10^{-3} . This level is reasonable since 10^{-4} has been achieved. Helium is used as the buffer gas because argon produces 7.5 times more fluctuation in the index of refraction than helium at the same

average density and density-fluctuation level. It appears that 5 to 10 meter-atmospheres of laser gas can be tolerated from these considerations.

The length, height, width, and number density considerations may be combined to calculate the maximum storable energy per amplifier module: i.e., in a single aperture (Fig. 2-9). Oxygen, the system with the lowest gain, stores the greatest energy because oxygen systems—limited in both flow length and laser length by gain constraints—store more energy per module by reducing the lasing molecule density and increasing the volume by a proportionately greater amount. In fact, only the oxygen system can store more energy than can be extracted, because of a mirror-damage fluence threshold of 10 J/cm^2 . Consequently, for the oxygen-system curve in Fig. 2-9, only number densities less than about 8×10^{16} represent extractable energies.

Conclusion of Photolytic Group IV Scaling Analysis. Figure 2-10 presents a graphic summary of results of this initial study of high-average-power photolytic gas lasers. Amplifiers can be built large enough to achieve 1 MJ with less than a dozen beams. Obtaining adequate efficiency will be the most difficult task: only the selenium system promises an overall efficiency above 1% for this windowless configuration. The iodine system requires a tenfold higher power input than the

selenium system. This could be accomplished only by operating at ten times the recirculating power or ten times the fusion pellet gain, circumstances that are either economically or physically unlikely.

This study has been instrumental in showing that a fluorescence-pumped photolytic laser has the potential to be a full-size fusion driver. There are significant physical uncertainties remaining, and much experimental work on kinetics, gain measurements, self absorption, bleaching wave dynamics, and beam quality must be done. But we are confident that if the experiments now being undertaken bear fruit, fusion laser amplifiers of significant size ($\geq 10^5 \text{ J}$) and adequate efficiency are possible.

A crucial issue is the improvement of the overall efficiency—both the electrical and flow efficiencies. The greatest leverage we have in this area is in improving the coupling of the pump radiation to the laser species, a problem amenable to some innovative thought. Excimer laser pumping is one possibility—better directionality of the pump beam will help immensely, although the excimer laser efficiencies are less than excimer fluorescer efficiencies for all the rare gases. We have examined pumping geometries which use both sides of the slab of fluorescer gas, a stratagem that can raise both the electrical efficiency and the flow efficiency by nearly a factor of two, provided deleterious electron scattering processes do not interfere with the storage medium kinetics. This would put the selenium laser in the 3% overall efficiency range, making it a truly attractive prospect for an advanced gas laser system.

Fig. 2-9. Maximum stored energy per aperture for photolytic laser systems.

Fig. 2-10. Efficiency and scalability of photolytic gas laser systems. A fluorescer pumped windowless geometry was used.

Reactor Concepts For Laser Fusion

During the last year, we initiated scoping studies to identify attractive reactor concepts for producing electric power with laser fusion. These studies were carried out by developing several exploratory reactor concepts and then subjecting them to the criteria we presented earlier for comparing long-range sources of electrical energy: abundance, social costs, technical feasibility, and economic competitiveness. The major problems affecting the technical feasibility of a laser fusion power plant were presented earlier. In this section we explore solutions to the two major reactor vessel problems:

- The effects of high-energy neutrons and cyclic stresses on the blanket structure
- The effects of x rays and debris from the fusion microexplosion on the first-wall

Our level of confidence in developing the technology to solve these problems has been determined by the amount of system development required beyond the state-of-the-art. Economic feasibility will be strongly dependent on the solution to these technical problems: it has been assessed in terms of factors including reactor size, power density, first-wall and blanket lifetimes, duty cycle, fabrication costs, stored energy requirements, and recirculating power fractions.

The reactor concepts include:

- A liquid-lithium-cooled stainless steel manifold
- A gas-cooled graphite manifold
- Fluid wall concepts, such as a liquid lithium waterfall, or a ceramic-lithium pellet waterfall

Before describing these concepts, we introduce some background information on fusion reactor technology and the design parameters and constraints that are common to all of the reactor concepts. This discussion of reactor technology deals primarily with the functions that a blanket system is required to perform and the problems associated with performing these functions in the hostile environment created by the fusion microexplosion.

All of these reactor concepts are based on an inertially confined deuterium-tritium fusion reaction. We have selected thermonuclear yields ranging from 400 to 4000 MJ and pulse repetition rates from 1 to 10 Hz. Selected combinations of these parameters result in reactor systems that produce 400 to 4000 MW of thermal power and 120 to 1500 MW of electrical power with net efficiencies ranging from 30 to 40%. The variance in net efficiency results from the different thermal efficiencies and recirculating power requirements of the various concepts. At fuel pellet yields of 400 to 4000

MJ, a fuel cycle cost of 3 mills/kWh will allow fuel pellet fabrication costs ranging from 12¢ to \$1.20. The selected parameter space for fusion neutron flux at the first wall ranges from 1 to 10 MW/m², resulting in first wall radii ranging from 1.5 to 15 m.

The effects of neutrons, x rays, and debris from the thermonuclear microexplosion represent the primary technical concerns that must be dealt with in laser fusion reactor concepts. All of our reactor concepts employ large focal length optics to mitigate the damaging effects to the final focusing elements. At a focal length of 10 m, the final optics would survive the microexplosion, but they may have to be replaced at relatively short intervals. At $f = 100$ m the damaging effects are reduced by two orders of magnitude, thus assuring the survival of the final focusing elements for intervals that are long enough not to adversely affect the plant availability factor. High-energy neutrons also damage and activate most structural materials. The large amounts of low-level radioactive waste thus generated represent a maintenance and disposal problem that is common to all types of DT fusion systems. X-ray and debris damage to first wall materials is a problem primarily associated with inertial confinement fusion systems.

Several different approaches to the first wall problem have been discussed in the literature, including use of a dry wall,¹⁹ wetted wall,^{20,21} and magnetically protected wall.²² These approaches differ primarily in the way in which the inner surface of the first wall interacts with the x rays and microexplosion debris. In the dry wall approach a sacrificial metal or ceramic liner is placed between the fusion chamber and the blanket. The wet wall concepts feature a thin layer of liquid metal that covers the metal wall and protects it from the blistering and structural ablation that would otherwise occur. The magnetic protection concept uses a solenoid to divert the pellet debris away from the sides of a cylindrical blanket and into conical collectors at the top and bottom.

The fluid wall concept is a new and promising approach developed in our scoping studies. In this approach, the first structural wall is shielded from x rays, neutrons, and debris by a thick waterfall of lithium in liquid or solid pellet form. The fall contains enough moderating material to degrade the fusion neutron spectrum to the point where neutron damage levels in the structural materials are significantly reduced. These lower damage levels allow consideration of smaller blanket structures which could last for the useful lifetime of the plant.

The blanket system must perform several functions while coping with the hostile environment created by the fusion microexplosion. It must:

- Convert the fusion energy into thermal energy
- Provide for efficient removal of the thermal energy
- Breed enough tritium to replace that which was burned in the fusion reaction
- Maintain the required vacuum in the fusion chamber

Sixty-five to seventy-five percent of the fusion energy is in the form of high-energy neutrons. Therefore, a neutron-moderating material is required to convert kinetic energy to thermal energy. In general, elements with low atomic numbers and high scattering cross sections are effective moderators; water, hydrides, beryllium, and graphite are common examples. Although somewhat less effective, lithium can also be considered as a neutron-moderating material.

Because there is no significant natural supply of tritium, a DT fusion reactor must breed its own tritium. Several neutron reactions produce tritium, but the only tritium-producing reactions with high enough cross sections to be useful are those involving lithium. Natural lithium is 7.4% ^6Li and 92.6% ^7Li , and tritium can be produced from either isotope by:

The ^7Li reaction has a threshold of approximately 4 MeV and a much lower cross section than the ^6Li reaction; nevertheless, it is very important because it produces a tritium atom without depleting the neutron population. If the neutrons are moderated before reaching the fertile lithium, the ^7Li reaction is not utilized (since it requires a high-energy neutron) and any leakage neutrons result in a tritium-breeding ratio less than 1.0. In such cases, the blanket must also contain a neutron multiplier to maintain an adequate breeding ratio. Beryllium and lead with high (n, 2n) and low capture cross sections are examples of good neutron multipliers. However, beryllium is a limited resource material whose use could significantly reduce fusion's potential as a long-range source of energy.

The vacuum requirements in the fusion chamber are primarily determined by considerations of laser beam propagation and damage to the injected fuel pellet. If the DT fuel can be incorporated into the pellet in a noncryogenic or insulated form, and hence be less subject to heat damage, laser beam propagation will be the primary factor determining the vacuum requirements in the fusion chamber. Our results²³ indicate that beam defocusing and at-

tenuation of 1 μm light by cascade breakdown and/or thermal blooming can be reduced to acceptable levels with fusion chamber pressures of 0.1 Torr or less. The pumping requirements needed to maintain this vacuum will depend on the material vaporized and the type of pump used. For a lithium-wetted first wall concept, the 0.1-Torr vacuum can be maintained under the worst conditions with a vacuum pump that requires about 2% of the gross electrical power and approximately 10% of the surface area (the worst conditions assume all the debris and x-ray energy is used to vaporize lithium).

Liquid-Lithium-Cooled Stainless Steel Manifold

This concept (Fig. 2-11) represents a conventional approach to a laser fusion power plant, requiring less advanced technology than the fluid wall concepts. In this concept, the microexplosion is surrounded by a cylindrical annulus of stainless steel into which vertical coolant channels have been drilled to form a manifold. Liquid lithium flows down these channels and is recirculated to the top through a bulk coolant region that separates the annular manifold from an outer pressure vessel. Liquid lithium serves as primary coolant, neutron moderator, and fertile material.

The stainless steel manifold concept is compatible with either a dry or wet first wall approach. In the

Fig. 2-11. Liquid lithium cooled stainless steel manifold concept.

dry wall approach, we have analyzed a graphite liner that is supported by stainless steel and cooled with liquid lithium. The graphite liner is designed for an operational lifetime of one year. In the wet wall approach, we have investigated the possibility and effects of maintaining a thin (3-mm) film of liquid lithium on the inner surface of the manifold.

Tritium-breeding considerations limit the thickness of a solid stainless steel structural wall to less than 10 cm. However, it would be impossible to utilize a structural wall even this thin without internal cooling. The solid manifold design was conceived to provide additional cooling and improve the tritium-breeding performance for a given mass of structural material. In fact, we have calculated tritium-breeding ratios greater than 1.0 for 40-cm-thick manifolds containing 50% stainless steel and 50% lithium by volume. The calculations were made using the TART Monte Carlo neutron transport code²⁴ with the LLL-ENDL cross section library.²⁵

The stainless steel manifold will operate at a neutron first wall loading of 1 to 2 MW/m², and this will require a relatively large chamber radius (10 to 15 m for a 4000 MW_t system). A major disadvantage will result if cyclic stresses and neutron damage limit the lifetime of the manifold to a few full-power years; this concept will then produce large amounts of low-level radioactive waste in the form of activated steel. It should also be noted that lithium is an element whose corrosive effects increase with increasing temperature. For use with stainless steel, lithium temperatures must be limited to about 500°C. This peak temperature corresponds to a conventional steam cycle thermal efficiency of 38%.²⁶

Gas-cooled Graphite Manifold

The graphite manifold (Fig. 2-12) is similar to the stainless steel manifold concept except that the vertical coolant channels are drilled into an array of graphite blocks that make up the fusion chamber. The vacuum vessel is an outer shell of reinforced, prestressed concrete. High-pressure helium gas is pumped through the coolant channels, some or all of which are filled with pellets of a lithium-bearing ceramic. As the tritium diffuses out of the lithium compound in which it is bred, it is removed from the channels by the gas coolant.

The graphite manifold design is a reactor concept that exhibits low activation and low tritium inventories. Moreover, the possibility of an accident occurring that could release radioactivity to the environment is greatly reduced because the lithium is present in less reactive (solid) form (Li₂O, LiAl₂O₃ for example). The graphite moderates the neutrons below activation energy levels. It also moderates the

neutrons to energies below the threshold for the ⁷Li tritium-producing reaction. This makes it advantageous to enrich the lithium in ⁶Li,* thereby reducing the required lithium and tritium inventories. Depending on the particular design, a neutron multiplier such as beryllium may be required to maintain a tritium-breeding ratio greater than 1.0. The use of a gas coolant will allow high operating temperatures and result in high thermal conversion efficiencies.

Some problems with this concept have been identified. The use of beryllium to multiply neutrons and enhance tritium-breeding presents a problem in terms of beryllium's toxicity and relative scarcity. We are investigating the possibility of using lead as the neutron-multiplying material. Large amounts of pumping power will be required to cool the system and purge the tritium from the pellet-filled channels. Finally, the structural integrity of the graphite chamber in the microexplosion environment may be inadequate.

Fluid Wall Concepts

Wet walls and sacrificial dry wall liners have previously been proposed as methods of protecting the metallic first wall from the soft x rays and pellet debris of fusion microexplosions. The fluid wall concepts were conceived to protect the first metallic wall from high-energy neutrons in addition to the x rays and debris. We have investigated two types of

*Natural lithium contains 7.4% ⁶Li.

Fig. 2-12. Gas-cooled graphite manifold concept.

fluid walls: the ceramic-lithium pellet waterfall and the liquid lithium waterfall. It has been demonstrated in the nuclear fission industry that once scientific feasibility has been achieved, the materials development program paces the demonstration of technical and economic feasibility. Fluid wall concepts will be less dependent on materials development because radiation damage is significantly reduced. The analysis of the liquid lithium system is further simplified by the availability of data on the properties of liquid lithium and the existence of liquid-metal experimental facilities constructed in support of the LMFBF program.

The principal feature of the ceramic-lithium pellet waterfall (Fig. 2-13) is a thick layer of falling solid ceramic-lithium pellets that shields the first structural wall from the microexplosion. The pellets are continuously recirculated to the top of the vacuum chamber through a reservoir region between the first wall and the pressure vessel. The pellets are either transported through heat exchangers or cooled by the flow of high-pressure helium gas in the reservoir region. Tritium is bred in the ceramic lithium compound and recovered as it diffuses out. Preliminary calculations indicate a tritium breeding ratio greater than 1.0 can easily be achieved.

The thick region of falling pellets will moderate and absorb neutrons before they reach the first structural wall, resulting in a significant reduction in the degree of first wall damage and possibly the amount of radioactive waste produced by neutron activation. The use of lithium in a ceramic form is an important feature of this concept in that it eliminates the corrosive problems of liquid lithium and significantly reduces the associated chemical hazard.

Major questions, such as tritium diffusion from the pellets and structural integrity of the ceramic compound, cannot be answered satisfactorily with existing data. A means of efficiently transporting the pellets, particularly into and out of the vacuum chamber, is another area of major uncertainty.

The liquid lithium waterfall concept (Fig. 2-14) has emerged as an extremely promising reactor concept for a laser-fusion power plant. It features a thick continuous fall of liquid lithium that protects the first structural wall from direct exposure to the microexplosion. The principal purpose of the fall is to reduce the neutron radiation damage in the first structural wall, allowing it to last for the useful life of the plant. Besides moderating neutrons the fall also absorbs the photons (x rays and reflected laser light), pellet debris (alpha particles, unburned fuel, and other pellet material) and any blast wave emitted by the microexplosion. Because the fall is kept

Fig. 2-13. Falling balls concept.

off the chamber wall, any shock wave generated in the fall is not directly transmitted to the structural wall. The majority of the fusion energy is thus deposited in the liquid lithium, which serves as primary coolant, fertile material for tritium breeding, and first wall.

Note that fluids other than liquid lithium could certainly be used to perform the neutron moderating function of the fall. The primary constraints on the fall material are that the substance must:

- Have a reasonably low melting point so the fluid state can be effectively maintained.
 - Have a low enough vapor pressure at the selected operating temperature ($>400^{\circ}\text{C}$ but as high as possible) to permit an adequate vacuum condition to be maintained.
 - Have neutronic characteristics that permit an adequate tritium breeding ratio to be achieved.
- Tritium breeding considerations preclude the use of a neutron absorber and require that lithium be incorporated in the reactor system in a suitable manner.

One possibility is to use lead as the primary constituent of the fall; the lead effectively degrades the

Fig. 2-14. Liquid lithium waterfall concept.

high-energy neutron spectrum through $(n, 2n)$ reactions and inelastic scatterings. Our TART²⁴ calculations indicate that a few vol% of ^6Li in the Pb fall would be enough to maintain a tritium breeding ratio greater than one. Alternatively, a small vol% of lead could be added to the lithium fall to more efficiently moderate the neutron spectrum. The use of Pb-Li alloys would decrease the system tritium inventory. On the negative side, recirculation pumping power would increase, and grain

boundary corrosion of steels might present compatibility problems. The various aspects of such a system are being investigated. For the present, however, the discussion will be confined to a natural liquid lithium fall.

Laser fusion reactors have a flexible geometry that is not available in magnetic confinement reactors. While a point source of energy is more effectively utilized in spherical geometry, we have selected the cylindrical geometry shown in Fig. 2-14

for several reasons. A vortex generator injects a sheet of lithium to protect the top of the reactor (primarily from x rays and debris). This sheet is thinner than the waterfall and does not provide the same degree of protection from neutron damage. Therefore, it is advantageous to have the top of the chamber farther from the microexplosion than are the side walls. The spherical end-cap on the cylindrical chamber effectively accomplishes this. The lithium is in direct contact with the walls at the bottom of the vacuum chamber, and shock waves can be directly transmitted to the chamber walls at this point. However, the chamber is well supported structurally in this area. Furthermore, by moving the bottom region farther away and decreasing the surface area of the lithium pool at the bottom, the effects of the directly transmitted shock wave are reduced.

Horizontal irradiation of the target will be required to take advantage of long-focal-length final optics. The tips of the laser beam tubes must penetrate the waterfall and be directly exposed to the microexplosion at a distance less than the chamber wall radius. Fortunately, these high damage areas represent only a minute fraction of the total surface area (a few hundredths of a percent) and sophisticated measures and special materials could be used to protect them. Alternatively, sacrificial tube ends could be used and remotely fed inward as the tips slowly vaporize.

The attenuation of the high-energy neutron flux as the neutrons pass through lithium is shown in Fig. 2-15. The plotted flux has been multiplied by $4\pi R^2$ to eliminate the geometric attenuation factor and generalize the curves for different radii to the lithium surface. These curves are also normalized to an unattenuated 14-MeV flux (no target, lithium, or geometric attenuation). The three curves include the flux of all neutrons above the indicated energies. Note that 70 cm of lithium is sufficient to attenuate the high-energy (> 10 MeV) neutron flux by nearly an order of magnitude.

First Structural Wall Lifetime. Of course, the parameter of real importance for determining the life of the first structural wall is not merely the flux but rather the damage resulting from the tempered flux. The primary neutron damage mechanisms are atomic displacements and gas production (primarily helium). Displacement damage is expressed as displacements per atom (dpa), and gas production is expressed as atom-parts-per-million (appm). The damage limits for 316-SS at an operating temperature of 500°C are estimated to be 150 dpa and 500 appm helium.³ For an unprotected first wall of 316-SS, at a neutron wall loading of 1 MW/m^2 , the displacement damage rate is about 10 dpa per full

Fig. 2-15. High-energy neutron flux in the lithium waterfall.

power year, and the helium production rate is about 220 appm per full power year.³ The damage limits for He production would thus be reached in only 2.3 years at this wall loading.

By softening and depleting the fusion neutron spectrum, the lithium waterfall concept allows the stainless steel wall to remain below the damage limits for much longer periods of operation, even at smaller wall radii. To make it easier to compare our concept to others, we quote structural wall loadings in terms of equivalent dry wall 14-MeV neutron loading. That is

$$L = \frac{0.8 P}{4\pi R^2},$$

where

L = wall loading, MW/m^2

P = thermonuclear power, MW (80% in neutrons)

R = chamber radius, m

Of course, our actual wall loading is considerably less as a result of neutron interactions in the compressed fusion target and the lithium fall.

As seen in Fig. 2-16, the allowable first wall fluence increases exponentially with lithium thickness. Note that 40 cm of lithium is required to reduce helium production to the point where the

Fig. 2-16. Allowed first wall fluence as a function of lithium thickness. The allowed fluence increases exponentially.

first structural wall could last for 30 years at 1 MW/m^2 (at 70% capacity factor). Displacement damage is less restrictive.

We have evaluated the requirements of a system that maintains a minimum protective lithium thickness of 60 cm. In determining the neutron damage to the structural first wall, we have also taken advantage of the fact that the emitted 14 MeV neutrons are attenuated by the compressed DT fuel, a characteristic unique to inertial confinement fusion. Our Monte-Carlo neutronics calculations indicate that a fusion target with a compressed fuel density-radius product, ρR , of about 3 g/cm^2 is roughly equivalent to 13 cm of Li in terms of reducing helium production; hence, the compressed target increases the effective blanket thickness to 73 cm. Since helium production dominates, the allowable fluence is 90 MW-yr/m^2 . In other words, the system could be operated at 4.3 MW/m^2 for the 30-year plant life at a 70% capacity factor.

As a candidate reactor vessel for our reference power plant design, we have selected a reactor system producing 1000 MW of thermonuclear power (700 MJ yield, 1.4 pulses per second) in a cylindrical chamber with a radius of 4 m. This corresponds to a neutron first wall loading of 4.0 MW/m^2 and represents a design in which the blanket structure could last for the life of the plant.

In the process of attenuating neutrons and interacting with the microexplosion plasma, the lithium fall absorbs a large fraction of the total nuclear energy deposited in the reactor. Figure 2-17 presents the cumulative energy deposition through the lithium fall and blanket region as a function of

the distance from the front surface of the fall. Again, a compressed target ρR of 3.0 has been assumed, resulting in a neutron energy deposition in the target of 2.2 MeV per DT reaction. This plus the 3.5-MeV alpha energy per DT reaction accounts for 32% of the thermonuclear yield which is deposited essentially at the surface of the lithium fall in the form of x rays, alpha particles, and other energetic debris. The remaining fusion neutron energy, accounting for approximately 68% of the total yield, is multiplied by 1.24, primarily as a result of exoergic tritium-producing reactions with ^6Li :

The total energy deposited in the reactor is 20.5 MeV per fusion reaction, giving a system energy multiplication factor* of 1.16. As indicated, the majority of this energy is deposited in the 60-cm-thick lithium fall. Because lithium is the primary coolant, the system does not rely on conduction of heat through structural materials to remove the thermal energy. Lithium is in fact an excellent coolant with a specific heat capacity equal to that of water and three times better than that of sodium. A major advantage of absorbing all the x-ray and debris energy and much of the neutron energy in the coolant is that the cyclical thermal stresses in the structural walls are essentially eliminated.

*System Multiplication Factor = Thermal energy/Thermonuclear energy.

Fig. 2-17. Cumulative energy deposition. The energy absorbed is greater than the thermonuclear energy because the neutron absorption reaction in ^6Li is exoergic. The vapor region between the fall and stainless steel wall does not absorb much energy and, therefore, is not shown in the figure.

An alternative scheme proposed by the University of Wisconsin³ for the liquid lithium waterfall is to make the fall thick enough (>80 cm) to absorb over 90% of the total energy. In this way, the recirculating reservoir region would not be required for tritium breeding or energy removal, and the structural first wall could be independently cooled at a lower temperature. A decrease in the wall temperature would significantly relax radiation damage limits for dpa and appm He.³ The first wall could then be operated at a higher wall loading and thus increase the power density of the reactor system. Naturally a higher power density results in a smaller reactor vessel size for a given power system; therefore, the capital cost of the reactor is reduced.

Tritium Breeding. As one might suspect, the liquid lithium waterfall concept has excellent tritium breeding characteristics. With no structural material between the fusion neutrons and the lithium fall, the design takes full advantage of the ${}^7\text{Li}(n,n'\alpha)\text{T}$ reaction that only occurs with high-energy neutrons. Figure 2-18 shows the distribution of tritium breeding from ${}^6\text{Li}$ and ${}^7\text{Li}$ reactions in a 50-cm lithium fall and 100-cm recirculating lithium blanket region. A one-dimensional spherical model was used in this Monte Carlo calculation,²⁴ and a compressed target ρR of 3.0 g/cm^2 was assumed. A tritium breeding ratio of 1.0 is obtained in the fall alone, and the total tritium breeding ratio is 1.7. The excess tritium produced in this reactor could in fact supply fuel for other laser fusion applications where tritium breeding is difficult or impractical. Two examples of such applications are radiolytic hydrogen production where it is desirable to deposit the neutron energy in steam rather than lithium blankets, and propulsion applications where weight and volume considerations are extremely important.

The total equilibrium tritium inventory in the liquid lithium will depend on the quantity of lithium required for the reactor system and the tritium reprocessing efficiency. The total lithium inventory is roughly estimated at 600 metric tons for the 1160-MW_t (1000 MW of thermonuclear power), 4-m-radius system. At a tritium reprocessing capability of 10 appm, this corresponds to about 2.5 kg of tritium, which is equivalent to the amount of tritium injected as fuel pellets in just 4 days of operation of this system (assuming 25% pellet burn).

Chamber Vacuum. As previously stated, the vacuum condition required for laser beam propagation is on the order of 0.1 Torr. Figure 2-19 shows that the vapor pressure of lithium is orders of magnitude less than 0.1 Torr at reasonably high

Fig. 2-18. Tritium breeding performance.

temperatures. Corrosion considerations require that, for use with stainless steel, lithium temperatures must be limited to less than 500°C. The vapor pressure at this temperature is less than 5×10^{-3} Torr.

Fig. 2-19. Lithium vapor pressure vs. temperature. All temperatures shown are in degrees Kelvin. The equation plotted is $P_v (\text{Torr}) = 8.19 \times 10^7 \exp(-18444/T)$.

Each microexplosion will vaporize a certain amount of lithium, thus increasing the chamber pressure above the required 0.1-Torr vacuum condition. The amount of lithium vaporized and the resulting chamber pressure will depend on the initial system conditions and on the way the fusion energy couples with the liquid lithium. Various portions of the fusion energy could conceivably be used to heat liquid lithium, vaporize lithium, and heat lithium vapor. If the chamber pressure equals the liquid vapor pressure prior to the microexplosion, even deposited neutron energy could vaporize lithium. The debris and x-ray energy, which is deposited over a very short range at the fluid surface, will effectively blow off lithium vapor.

After the initial transient events, a certain amount of lithium vapor will exist in the chamber. The amount of lithium vaporized and the resulting quasi-equilibrium pressure rise in the chamber are determined as follows:

With respect to liquid lithium at some temperature T_0 , the enthalpy change as the lithium is vaporized and heated is:

$$\Delta h = \int_{T_0}^{T_v} C_p(\text{liq})dT + h_{vg} + \int_{T_v}^T C_p(\text{gas})dT,$$

where

Δh = enthalpy change of lithium (MJ/kg)

T_v = temperature at which lithium vaporizes (K)

C_p = heat capacity (MJ/kg·K)

h_g = heat of vaporization (MJ/kg)

Δm = mass vaporized (kg) = $E/\Delta h$

E = fraction of the fusion energy used to:

(1) heat liquid lithium and vaporize it,

(2) vaporize lithium without heating,

and/or (3) superheat lithium vapor;

E does not include deposited energy

used to heat liquid without

vaporizing it.

The resulting "equilibrium" chamber pressure rise is

$$\Delta p = \frac{\Delta m R T}{M V},$$

where

$R = 8.315 \text{ J/mole}\cdot\text{K}$

$M = 6.941 \times 10^{-3} \text{ kg/mole}$

V = chamber volume (m^3)

Δp = pressure rise (N/m^2).

The maximum mass will be vaporized if the liquid is initially at the vaporization temperature associated with the chamber pressure and if no energy is expended to heat lithium vapor. A condition of supersaturation would result with the gas and liquid at the same temperature:

$$\Delta m_{\max} = \frac{E}{h_{vg}}.$$

If the liquid is at the vaporization temperature corresponding to the chamber pressure and if C_p (gas) is constant, the equilibrium pressure rise may be written in terms of the mass vaporized, Δm :

$$\Delta p = \frac{\Delta m R}{M V} \left[T_v + \frac{1}{C_p(\text{gas})} \left(\frac{E}{\Delta m} - h_{vg} \right) \right]$$

or rearranging terms

$$\Delta p = \frac{R}{M V} \left[\frac{E}{C_p(\text{gas})} - \Delta m \left(\frac{h_{vg}}{C_p(\text{gas})} - T_v \right) \right]$$

Since $h_{vg}/C_p(\text{gas}) > T_v$, the maximum equilibrium pressure rise results if no lithium is vaporized and all the energy is used to heat the vapor already in the chamber:

$$\Delta p_{\max} = \frac{R}{M V} \left[\frac{E}{C_p(\text{gas})} \right].$$

If the entire fusion pulse energy heats the vapor (in our reference design—700 MJ in 400 m^3), the maximum equilibrium pressure rise is about 7 atm. In the more likely case of only x-ray and debris energy heating the vapor, the maximum equilibrium pressure rise is about 2 atm.

Whatever the chamber pressure is after the microexplosion, it must be reduced to the required vacuum condition of 0.1 Torr before the next pulse. As will be discussed later, there is so much liquid lithium in the chamber at the time of the microexplosion that the mixed-mean temperature rise of the fall per pulse is quite small. (For example in the 4-m reference chamber at 4.0 MW/m^2 , ΔT is less than 5°C). The supersaturated vapor therefore recondenses on the liquid lithium in the chamber. In effect, the liquid lithium waterfall acts as a condensing vacuum pump for the chamber.

The effectiveness of the lithium liquid in condensing the vaporized lithium will depend on the condition of the fall (bulk temperature, surface temperature, whether or not it is disassembling) and on

the condition of the vapor (temperature, pressure) shortly after the microexplosion. The liquid fall conditions are important for determining the vapor pressure of the liquid and the sticking coefficient, defined as the probability that a gas molecule incident on the liquid surface will stick. In general the sticking coefficient must be determined experimentally with the gas at sufficiently low pressure that free molecular flow conditions exist.²⁷ In addition, these experiments require a small cryosurface so that negligible pressure gradients exist and the temperature of the gas is equal to the temperature of the vessel wall.

These conditions, however, do not describe the lithium waterfall chamber because the "cryosurface" is, in fact, large and the vapor will exist in the continuum pressure region where molecular collisions are very important. By general definition, continuum conditions exist when some characteristic dimension of the vacuum chamber is at least 100 times the mean-free-path of the gas molecules. For lithium gas at 700 K in a 4-m-radius vessel, continuum conditions exist at pressures greater than about 6×10^{-3} Torr. As the pressure increases from the free molecular flow region to the continuum region, the pressure gradient pushes the gas at increasing speed towards the cryosurface. Because this increases the rate of collisions with the condensing surface, the pumping speed increases if the sticking coefficient does not decrease significantly. The pumping speed reaches a limiting value and levels off as the speed of the gas stream reaches the local sonic velocity at the condensing surface. This condition is analogous to choked flow through an orifice and will exist when²⁷:

$$\frac{p_d}{p_u} = (1 - S) < \sigma_c$$

where

p_u = upstream pressure

p_d = downstream pressure

S = sticking coefficient

σ_c = critical pressure ratio

$$\sigma_c = \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma}{\gamma - 1}}$$

γ = specific heat ratio

These expressions are for frictionless adiabatic flow, which may be a good approximation to the flow-through transition in the condensing process.²⁸ The plateau in the pumping speed curve will thus be reached when $S > 0.51$ for a monatomic ideal gas ($\gamma = 1.67$) or when $S > 0.47$ for a diatomic ideal gas ($\gamma = 1.40$). The maximum pumping speed ($S = 1$) is given by²⁸:

$$\dot{m} = pA \left[\frac{\gamma M}{RT} \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma + 1}{\gamma - 1}} \right]^{1/2}$$

where

$\dot{m}$ = mass removal rate, kg/s

p = chamber pressure, N/m²

A = condensing surface area, m²

M = molecular weight, kg/mole

R = gas constant, 8.315 J/mole-K

T = gas temperature, K.

As lithium vapor is condensed the density of the gas in the chamber decreases according to²¹:

$$\frac{V dp}{dt} = -\dot{m}$$

Using the expressions for an adiabatic process,

$$\frac{p}{p_0} = \left(\frac{\rho}{\rho_0} \right)^\gamma \text{ and } \frac{T}{T_0} = \left(\frac{\rho}{\rho_0} \right)^{\gamma - 1}$$

in the expression for $\dot{m}$ and integrating the differential equation gives an expression for the chamber pressure as a function of time after the microexplosion. Assuming the lithium vapor behaves as an ideal monatomic gas, we find that the pressure decays according to:

$$\frac{p}{p_0} = \left[\frac{t}{3\tau} + 1 \right]^{-5}$$

where

$$\tau = \frac{0.04 V}{AS\sqrt{T}} \text{ seconds.}$$

p_0 is the "equilibrium" chamber pressure immediately after the microexplosion but before recondensation begins. p_0 is essentially equal to Δp

because the background pressure before the pulse is so low.

Figure 2-20 shows the pressure decay as vaporized lithium is recondensed by the fall. These curves represent worst-case calculations in which all the fusion energy (700 MJ in a 4-m chamber) is used to vaporize lithium at 700 K. While an increase in vapor temperature would result in a higher value of P_0 , the sonic velocity of the gas would also be higher and the gas would condense more quickly. The sticking coefficient of 0.5 is pessimistically low for a liquid metal vapor. Also, if the fall is disassembled by the neutron energy deposition, the condensing

$$P/P_0 = \left[\left(\frac{8.33 AS \sqrt{T}}{V} \right) t + 1 \right]^{-5}$$

A = condensing surface area = fall surface area - m²

S = sticking coefficient = 0.5

T = vapor temperature = 700 K

V = vacuum chamber volume - m³

t = time - s

$P_0 = \frac{ERT}{hMV}$

E = energy used for vaporization = 700 MJ

R = gas constant = 8.315 J/mole K

h = heat of vaporization = 19.6 MJ/kg

M = molecular weight = 6.941×10^{-3} kg/mole

Fig. 2-20. Pressure decay as vaporized lithium is recondensed by the fall.

surface area will be much larger than the original surface area of the fall assumed here.

Even with these assumptions the vacuum conditions return to the required 0.1 Torr in about 0.1 s for the 4-m chamber. Thus while the exact time-dependent chamber conditions have not been determined, this analysis indicates that vacuum conditions can be maintained and are in fact aided by the presence of the liquid lithium fall.

Pumping Power. We now turn our attention to what is required in terms of pumping power and flow rates to maintain the thick fluid wall of lithium. Figure 2-21 shows the model and constraints used to calculate the pumping power required to recirculate the lithium fall. The fall protects the cylindrical portion of the chamber wall, which has a height-to-diameter ratio of one. (Recall that a vortex-generated sheet of lithium protects the top hemispherical end-cap, and a pool of lithium protects the bottom). The flow inlet forms an annulus of thickness ΔR_0 , with the inner edge of the ring at one-half the chamber wall radius, R_w . With this geometry, the region at the top protected just by the vortex generator represents only about 5% of the total solid angle. The fall is injected vertically downward with an inlet velocity V_0 . If it is assumed that the flow maintains its original inner radius as it falls, then continuity requires that the thickness of the annulus decrease as the fluid is accelerated by gravity.

The pumping power is estimated from:

$$P.P. = \left(\frac{1}{2} V_0^2 + gH_0 \right) \rho V_0 A_0$$

where

H_0 = fall height = $2R_w$

A_0 = inlet flow area = $\pi \left[\left(\frac{1}{2} R_w + \Delta R_0 \right)^2 - \left(\frac{1}{2} R_w \right)^2 \right]$

This expression accounts only for the kinetic and static heads required for the flow. In comparison, frictional losses in the recirculating reservoir region will be small. The piping to and from the recirculating pumps will also have losses (due to friction, bends, and fittings such as valves), which are proportional to V^2 , where V is the fluid velocity in the pipe. The exact heat loss will depend on the type of pipe and the specific plumbing layout. Large flow area piping will allow the velocity to remain low for a given mass flow rate and help minimize these losses.

Preliminary calculations indicate that the fall may be disassembled by the microexplosion. If this is the case, the inlet velocity must be sufficient to allow the fall to reestablish itself prior to the next microexplosion. A clearing ratio of unity should be adequate. The first constraint is therefore:

$$H_0 = 2R_w \leq V_0 \tau + 1/2 g \tau^2,$$

where

$$1/\tau = \text{pulse repetition rate.}$$

As previously noted, 60 cm of lithium is thick enough to provide adequate protection to the first structural wall up to 4.3 MW/m². Therefore, the second constraint is that source neutrons must be attenuated by at least 60 cm of lithium at any point through the fall.

Figure 2-22 shows how the fall thickness decreases as a function of distance from the inlet for various inlet velocities. The thickness at any point is plotted as the fraction of the inlet thickness:

$$\frac{\Delta R}{\Delta R_0} = \frac{V_0}{\sqrt{V_0^2 + 2gH}},$$

where H is the distance from the inlet. The intersection of the dashed lines with the curves gives the distance traveled from the inlet in 0.5 s and 1.0 s and thus indicates the inlet velocity required for pulse repetition rates of 2 Hz and 1 Hz, respectively, for a given required distance.

The effective attenuating thickness of the fall is $\Delta R/\cos\theta$, where θ is the angle of incidence of the source neutrons. Figure 2-23 is an example of the effective thickness for a 5-m-radius chamber, with the center of the fall at a radius of 3 m and an inlet velocity of 5 m/s (as required by the first constraint for a 1-Hz pulse rate). Note that the minimum thickness occurs very near the horizontal midplane. The exact position depends on the particular geometry and inlet velocity but is always close to the midplane. The constraint on minimum effective thickness has therefore been taken at the midplane to simplify the calculations. The second constraint is:

$$\Delta R_m \geq 60 \text{ cm.}$$

When the reference 4-m-radius reactor is used as an example, the required inlet velocity at a repetition rate of 1.4 Hz is about 8 m/s. For 60 cm at the midplane, an inlet thickness of 0.9 m is required

(inlet area = 14 m²), resulting in a pumping power of about 6 MW, which is about 1% of the gross electrical power. Other losses in the loop might double this figure but the result is still only a small percent of the gross power.

For smaller chambers the clearing ratio constraint is less important than the midplane thickness and total inlet thickness constraints. For example a 3-m-radius chamber requires an inlet velocity of only about 1 m/s. At this velocity, however, the midplane thickness is only 13% of the inlet

$$\text{Pumping power} \simeq (1/2 V_0^2 + gH_0) \rho V_0 A_0$$

Constraints:

- Fall clearing ratio of at least unity
 $H_0 \leq V_0 \tau + 1/2 g \tau^2$
 where $1/\tau = \text{repetition rate}$
- Fall thickness at midplane of at least 60 cm
 $\Delta R_m \geq 60 \text{ cm}$
- Inlet thickness less than $1/2 R_w$
 $\Delta R_0 < 1/2 R_w$

Fig. 2-21. Recirculation pumping power calculation—single fall.

Fig. 2-22. Fall thickness as a function of distance for various inlet velocities.

thickness, which would have to be over 4.6 m thick to provide 60 cm of protection at the midplane. Because this is larger than one-half the chamber radius, a higher inlet velocity must be used in calculating the pumping power.

The pumping power required to recirculate the lithium fall is presented in Fig. 2-24 for systems with chamber radii ranging from 4 to 10 m. At 1 Hz the pumping powers are acceptably low for all chamber sizes. At the higher repetition rate the inlet velocity required to cover the length of the chamber in the 1/2 s between microexplosions is so great that the pumping power becomes quite large.

For equivalent first wall loadings the gross power produced by reactors of varying size is proportional to R_w^3 . The fraction of the gross power required to recirculate the fall for the various sized reactors is plotted in Fig. 2-25. A gross power of 440 MW_e for a 4-m-radius chamber is used as the basis (1160 MW_{th} at 38% thermal conversion efficiency). As indicated, at 1 Hz the pumping power is only a few percent of the gross electric power. At higher repetition rates the fraction becomes prohibitive for large chambers that require very high inlet velocities.

The possible advantages of using multiple falls entering the chamber at different vertical positions have also been investigated. The primary advantage is a reduction in the velocity head required to obtain a clearing ratio of one. Each fall is required to reestablish only to the inlet of the next lower fall. This is especially important at higher repetition rates. A second advantage is that the static head requirement is reduced for the fraction of the flow delivered to the lower falls. Also, if the primary injected fall should tend to break up into separate streams instead of forming a continuous curtain, the lower falls could replenish it.

A calculation model for a system with two falls, one entering at the top as before and one at the midplane, is illustrated in Fig. 2-26. The constraints on the fall are the same as for the single-fall case, with the actual positions of minimum effective thickness used to determine the required inlet thicknesses. As before, the inlet thickness (now equal to the sum of ΔR_{10} and ΔR_{20}) must be less than $1/2 R_w$.

The fraction of the gross power required to recirculate the double fall is shown in Fig. 2-27. Note particularly the substantial reduction in pumping power for the larger chambers at 2 Hz (5% compared to 14% for the 10-m-radius chamber). The advantages of reduced velocity and static heads have been offset by larger flow area requirements for the smaller chambers at a repetition rate of 1 Hz.

Note that the double-fall geometry is not by any means optimal. It is presented only to illustrate the possible advantages of multiple falls. Also note that these theoretical pumping power calculations do not include the efficiency of the pump or drive motor. These factors will depend on the specific design, but for large axial flow pumps the combined efficiency could be about 80%.³⁰

The flow rate required to maintain the lithium fall is plotted in Fig. 2-28. These rates are for the single-fall geometry and are based on the velocity and inlet flow area determined from the model and constraints (Fig. 2-21) previously discussed. A flow rate of about 110 m³/s is required for a 4-m-radius reference design that operates at 1.4 pulses per second. Large-flow-rate liquid metal pumps have been designed. Some typical parameters of a specific design supplied to us by the Liquid Metal Engineering Center are listed in Table 2-6.²⁹ The basic stage of this design develops a 50-ft head; if higher heads are required several stages may be used in series. At

Fig. 2-23. Effective thickness of the fall.

Fig. 2-24. Pumping power required to recirculate liquid lithium fall.

Fig. 2-25. Fraction of gross power required to circulate a single liquid lithium fall.

$110 \text{ m}^3/\text{s}$, the reference reactor would require seven of these large pumps operating at $15.8 \text{ m}^3/\text{s}$ (250,000 gpm) each.

The lithium flow rate to the heat exchangers is only a fraction of the flow rate required to recirculate and maintain the fall. For a given temperature drop in the heat exchanger, the primary coolant flow rate is directly proportional to the rate at which energy must be removed from the reactor vessel:

$$\dot{m} = \frac{P}{C_p \Delta T} \text{ kg/s},$$

where

P = reactor power, MW_{th}

C_p = specific heat capacity, MJ/kg·°C

ΔT = temperature drop at heat exchanger, °C.

$$\text{Pumping power} \approx (1/2 V_0^2 + g H_e) \rho V_0 A_0$$

Constraints:

- Fall clearing ratio of at least unity

$$R_w \leq V_0 \tau + 1/2 g \tau^2$$

where $1/\tau$ = repetition rate

- Minimum effective fall thickness of at least 60 cm

$$\Delta R_{1m} \geq 60 \text{ cm}$$

$$\Delta R_{2m} \geq 60 \text{ cm}$$

$$\frac{\Delta R_{2m}}{\cos \theta_m} \geq 60 \text{ cm}$$

- Total inlet thickness less than $1/2 R_w$

$$\Delta R_{10} + \Delta R_{20} < 1/2 R_w$$

Fig. 2-26. Recirculation pumping power calculation—double fall. The equivalent height is H_e , considering the multiple falls.

The required lithium flow rate to the heat exchangers is plotted in Fig. 2-29 for an assumed ΔT of 200°C. Since the total reactor thermal power, P , is proportional to the neutron wall loading, L , it follows from the previous equation that the coolant flow rate is also proportional to L . For a system

Fig. 2-27. Fraction of gross power required to recirculate liquid lithium fall-double fall.

Fig. 2-29. Lithium flow rate to heat exchanger.

Fig. 2-28. Lithium flow rate required for the fall.

Table 2-6. Typical pump parameters of a specific reactor design.

Typical pump parameters		Unit
Specific speed	$S_N = 8000$	
Suction head	NPSH = 37 ft	
Flow rate	$Q = 250,000$ gpm	
Developed head	$H = 50$ ft	
Brake horsepower	$P = 2100$ hp	
Per Stage	$(\rho = 0.49 \text{ g/cm}^3)$	
	Pump and drive weight	$W = 75$ tons
	Pump length	$L = 8$ ft
	Pump diameter	$D = 9$ ft
	Shaft speed	$S = 260$ rpm

operating at other than 1 MW/n^2 , the values in Fig. 2-29 must be multiplied by the appropriate value of L . Thus, our reference 4-m-radius system operating at 4 MW/m^2 (1160 MW/n^2) requires a primary circuit flow rate of $2.8 \text{ m}^3/\text{s}$; this is less than 3% of the flow rate required to recirculate the fall.

As previously noted, a single microexplosion causes only a small temperature change in the lithium in the vacuum chamber (assuming complete mixing). From the fall flow conditions and reactor dimensions, the amount of lithium in the chamber at the time of the microexplosion can be determined. For most cases, it is equal to the mass flow rate divided by the pulse repetition rate. The reference reactor design at about $110 \text{ m}^3/\text{s}$ and 1.4 pulses per second contains about 40 metric tons of lithium at the time of the microexplosion. The 700-MJ pulse deposits the majority of its energy in the fall (see Fig. 2-17) but only raises the temperature

4°C . Of course the reason this is so much less than the 200°C ΔT at the heat exchanger is that the flow rate of the fall is about 40 times greater than the primary coolant flow rate for this particular case.

Areas of Future Investigation. This initial evaluation of the liquid lithium waterfall concept has been encouraging. The protection afforded by the thick fluid curtain of lithium will allow first wall and blanket structures to retain their integrity for the life of the plant. In addition, constraints on vacuum conditions, tritium breeding, and energy removal are easily met. Analysis of the liquid lithium waterfall concept is continuing; some aspects currently being investigated include:

- The hydrodynamic response of the fall to x-ray, debris, and neutron energy deposition.
- The formation and stability of free surface annular flow.
- The compatibility of various metals with lithium and Pb-Li alloys.

- Methods of recovering tritium from the fluid stream.
- Neutron activation analysis.

Preliminary Conceptual Design of a Liquid Lithium Waterfall Reactor

To evaluate the performance of the liquid lithium waterfall reactor concept in the context of a power plant, a preliminary conceptual design study of a laser fusion power plant (Fig. 2-30) that incorporates this reactor concept has been completed. The characteristics of this conceptual power plant are presented in Table 2-7. Energy processing begins with the input of electrical power from the switchyard to the laser system. The laser system requires 70 MW of input electrical power to produce coherent light energy with an overall efficiency of 2%. The light energy interacts with the deuterium-tritium fuel in the reactor to produce thermal energy with a gain of $Q = 700$. Specifically, fusion targets producing 700 MJ of thermonuclear energy are ignited by a 1-MJ laser at the rate of 1.4 pulses per

second. The fusion neutron energy, accounting for approximately 68% of the total yield, is multiplied by 1.24 in the lithium blanket, resulting in a power plant with a single-chamber thermal power output of 1160 MW. The thermal energy is converted to electrical energy at 38% efficiency. The laser waste heat is discharged at an average temperature of 350°C. As a result, this waste heat can be converted to electrical energy with an overall efficiency of approximately 25%. Of the total 460 MW_e produced, 80 MW of electrical power is recirculated for plant operation (laser and lithium flow). This results in a power plant with a net electrical production of 380 MW_e and an overall system efficiency of 31%.

A significant feature of the plant layout shown in Fig. 2-30 is that the laser system is not housed in the reactor containment building. Several advantages result from separating the large volume laser system from the reactor. First, building costs and construction time are substantially reduced; second, access to the laser system for maintenance and operation is increased; finally, it becomes easier to isolate the final optics from vibrational disturbances.

Fig. 2-30. Conceptual layout of a laser fusion power plant.

Table 2-7. Characteristics of a conceptual power plant.

<u>Overall Performance</u>	
Thermal power	1160 MW _t
Fusion thermal power	1000 MW _t
Gross electrical power	460 MW _e
Net electrical power	380 MW _e
Thermal efficiency	38%
Recirculating power fraction	17%
System efficiency	31%

<u>Laser and Pellet Parameters</u>	
Total laser energy	1 MJ
Pulse repetition rate	1.4 Hz
Total laser power	1.4 MW
Pellet gain (Q)	700
Pellet yield	700
Laser system efficiency (η_L)	2%
Number of laser modules	10
Number of two-beam transport tubes	4

<u>Reactor Parameters</u>	
<u>Geometry</u>	<u>Cylindrical</u>
Inner radius	4 m
Height	8 m
Lithium salt thickness	0.6 m
Equivalent structural wall flux ^a	4.0 MW/m ²
Tritium breeding ratio	1.7
Blanket energy multiplication	1.24
Reactor materials	
Structure	Stainless steel
Coolant	Lithium

^aFlux on a dry wall at 4 m radius from a 14 MeV source that includes 80% of the 1000 MW_t fusion power.

The laser light is transported to the reactor via evacuated pipes. The final focusing mirrors are located at the turning point of the beam tubes in a direct pathway to the thermonuclear microexplosion. As a result, these mirrors will be exposed to the x rays, debris, and neutrons from the fusion reaction. Therefore, they have been placed far enough away from the microexplosion (~100 m) to reduce the damage rates by two orders of magnitude, thus assuring their survival. Optical components such as spatial filters prevent radiation leakage from entering the laser building via the laser beam paths.

In conclusion, a preliminary conceptual design of a laser fusion power plant based on advanced high-gain targets has been completed. A parametric analysis of this system was conducted to reveal attractive design points and to show the sensitivity of the design to uncertainties in both the physics and technology. Although still highly conceptual, this power plant design has provided preliminary understanding of the integrated engineering requirements and potential problems. We are encouraged by the fact that no major problems were found for which there are not reasonable conceptual solutions.

On the basis of the encouraging results of this study, a more definitive conceptual design study will be carried out during the coming year. The liquid lithium waterfall reactor will be coupled with one of the more promising laboratory stage lasers, and the major power plant components (reactor, laser, lithium system, and optical transport system) will be analyzed in detail. The plant layout and costing of the design will also be included. Because we want to take advantage of the relevant expertise and developed technology in the nuclear fission industry, we intend to engage a reactor vendor and a power plant architect-engineer to assist us with the reactor design, plant layout, and costing portions of the conceptual design.

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3. A CONCEPTUAL DESIGN STUDY FOR A LASER-FUSION HYBRID

Neutronic results assessing the potential of a laser-driven fusion-fission hybrid reactor have been previously published^{1,2} and are presented in the executive summary. However, more accurate assessments are needed, as well as a definitive ranking of the more promising concepts. This requires studies dealing with engineering, safety, and economic issues, as well as neutronic results. With this in mind, we undertook a conceptual design study of a laser-fusion hybrid in cooperation with Bechtel Corporation. The study was to provide enough design detail to realistically gauge the value of a laser-fusion hybrid in a power-generation economy based on fission reactors. The joint effort began in July 1975. This chapter describes and analyzes the laser-fusion hybrid design which has evolved.

The hybrid concept chosen for this study is a depleted-uranium-fueled, fast-fission blanket that produces fissile plutonium and electricity. It emphasizes fissile-material generation by maximizing fuel production at the expense of energy production. Selection of this blanket material was based on reported neutronic results^{1,2} that indicated it could provide enough fissile fuel to extend LWR energy production as much as two orders of magnitude.

A comparative analysis¹ of the neutronic properties of several hybrid concepts has shown that depleted-uranium, fast-fission blankets produce large amounts of fissile fuel (per unit of thermal energy) with low laser-efficiency and target-gain requirements. The depleted-uranium blanket selected for our conceptual design produces enough fissile material to continuously fuel more than six LWRs of equivalent thermal power. Thorium-fueled hybrids produce more fissile fuel per unit of thermal energy, but have a lower energy-multiplying capability and require a higher performance (more costly) laser-fusion system. Blanket concepts exist with higher energy-multiplication capabilities than depleted-uranium blankets, but they enhance energy multiplication at the expense of fissile production.

Light-water reactors will be the major, and most likely the only, source of commercial, nuclear electric power this century. Their growth will strongly depend on the supply of fissile fuel. By converting the ²³⁸U in natural uranium to fissile plutonium, the hybrid could extend the fissile-fuel supply for the economical LWRs. Fast breeder reactors also offer the prospect of more fully utilizing the uranium resources, but they will not provide fissile fuel for LWRs. Excess material from a fast breeder

reactor is best used to fuel another fast breeder reactor. Therefore, the growth of fast breeder reactors will depend entirely on their economic competitiveness with other power plants.

The Laser-Fusion-Hybrid Power-Plant Design

In the joint laser-fusion, hybrid-design study, LLL 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, the capital involved, and the operating costs. Bechtel's contribution to the laser-fusion hybrid design is fully documented in their final report.³

The four major objectives in the design study were:

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

These objectives defined the level of design detail and costing analysis for the study.

In addition, a few philosophical points of view significantly affected our design choices. First, we wanted to operate the laser-fusion hybrid in a regime that, compared to pure fusion, required an order-of-magnitude lower laser/pellet performance, i.e., fusion energy gains in the neighborhood of 1.0. This meant the blanket energy multiplication had to be about 10.0. Second, we wanted to use state-of-the-art fission technology in the design of the hybrid blanket. In keeping with this principle, 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 with the same safety standards and environmental impact as the fissile burning reactors for which it is providing fuel. Only a negligible improvement in

the overall environmental impact results from making the hybrid environmentally more attractive than the more numerous LWR's.

Hybrid Reactor Design

The functional shape of the laser-fusion hybrid chosen for final evaluation is shown in Fig. 3-1. 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.

The basic features of the hybrid reactor are displayed in Fig. 3-2. A depleted-uranium-fueled, fast-fission blanket radially surrounds 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 flows from the lower plenum to the upper plenum through hexagonal process tubes.

Lithium-cooled, graphite-moderated blankets are positioned in the top and bottom of the reactor and behind the fission zone. These lithium blankets capture neutrons and breed tritium. The laser beams and pellet injectors penetrate the top and bottom blankets leaving the radial fission blanket unencumbered. We had originally intended to also use fission blankets in the top and bottom regions, but maintaining coolant flow while removing the top blanket for access to the fusion chamber would have been difficult. In addition, this would have required an unconventional fission blanket design, which was not in keeping with our desire to use state-of-the-art technology. Our decision resulted in a 30% reduction in both fissile fuel and energy production.

As shown in Fig. 3-3, the entire blanket system is enclosed in a spherical stainless-steel vacuum vessel with 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 to allow replacement.

Fission-Blanket Design

An expanded side view and top view of the radial fission blanket are shown in Figs. 3-4 and 3-5. The fission zone consists of two rows of hexagonal process tubes that contain the depleted uranium as stainless-steel-clad fuel pins. The process tubes in the inner row are protected from the fusion microexplosion by a stainless-steel-supported graphite liner.

Our neutronic calculations indicate that energy multiplication and fissile-fuel production are maximized by using uranium-metal as fuel instead of oxides or carbides and by maximizing the ratio of

Fig. 3-1. The geometry used in the LLL/Bechtel laser-fusion hybrid.

uranium volume to structural material. Increasing the residence time of the fuel also increases the average energy multiplication since more energy is produced as plutonium 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 8 W/g or about 150 W/cm^3 of uranium metal. The average power density in the blanket is less than 4 W/g . Five full-power years of blanket operation would result in an average burnup of less than $7,000 \text{ MWD/tonne}$ of uranium. This low rate of burnup favors the choice of metallic fuel.

The low power density and burnup capabilities of a depleted-uranium (or a natural-uranium) blanket demand more care in minimizing fuel-cycle costs, including fabrication cost. Thus, large fuel rods are favored over small rods, and long fuel elements have some advantage over short elements.

Fig. 3-2. Side view of a conceptual laser-fusion hybrid.

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. If a thick pressure-vessel wall is introduced between the blanket and the fusion core, neutronic performance is severely reduced. The fuel element must therefore operate and be cooled within a surrounding vacuum. Thin process tubes and low-pressure coolants seem to be the most reasonable design approach, but coolant leaks and process-tube reliability will always be potential problems. We expect that the melting of the fuel after loss of coolant will be the most serious safety issue with the hybrid.

Selection of a Fuel Material

Our goal was to design a system that would maximize neutron energy multiplication, minimize fuel-cycle costs, and be licensed by the Nuclear Regulatory Commission. This goal led to selection of uranium-metal fuel elements with sodium as the coolant. LMFBR technology and balance-of-plant design concepts were used as much as possible. The selected fuel element is a 19-rod cluster similar to those developed during the early 1960s for use in sodium-graphite reactors (SGR). Fuel rods 18 feet long were developed at that time. However, because of their flexibility and tendency to buckle if not kept

Fig. 3-3. Vacuum vessel for the laser-fusion hybrid reactor.

Fig. 3-4. Side view of a fission blanket in the laser-fusion hybrid reactor.

vertical, they required extra care in handling. Adapting this experience to a blanket design with larger diameter fuel rods and a thicker cladding, we decided to use 7-m (23-ft)-long fuel rods and assemblies; this determined the height of the fusion-reactor core. A three dimensional view of a fuel assembly is shown in Fig. 3-6.

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 fuel element chosen can accept 30-mm-diameter fuel slugs of each of these materials interchangeably. The U-7 Mo fuel should be capable of burnups to 20,000 MWD/tonne of uranium at maximum center temperatures of 650°C. This burnup would require at least eight full-power years, a period the cladding probably could not tolerate. The U-7 Mo alloy was the reference fuel for the Dounreay fast reactor and performed satisfactorily at the conditions noted. This alloy has energy multiplication and plutonium-production rates that are reduced, compared to those of uranium metal; it is also more expensive to fabricate and reprocess. Uranium carbide fuel would be capable of more than 100,000

Fig. 3-5. Top view of a fission blanket in the laser-fusion hybrid reactor.

Fig. 3-6. Fuel element and process tube configuration.

MWD/tonne of uranium burnup 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 chosen blanket, the higher burnup 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 MW/m² or fissile-enriched uranium fuel), or if gas cooling were used, UC would probably have been chosen.

Uranium metal, adjusted with minor alloying additions to control swelling, was chosen as the fuel material for several reasons: its multiplication and breeding performance were superior, and its burnup capability was judged to be adequate and a good fit to the blanket's low-power density. Finally, it was cheaper to fabricate and reprocess.

Pure uranium metal begins to swell disastrously at temperatures greater than 400°C and burnups greater than 1,000 MWD/tonne of uranium (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 1960s 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 burnups of 5,000 to 6,500 MWD/tonne of uranium 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 burnup of 6,000 MWD/tonne of uranium were chosen as a design basis for the blanket. A volume increase (swelling) of 4% is expected at this burnup. However, a volume increase of 8 to 10% is easily tolerated by the sodium-bonded fuel rod. A maximum burnup of 6,000 to 6,500 MWD/tonne of uranium is probably a reasonable expectation for this fuel. Sodium bonding of the cladding to the fuel rod was chosen over contact bonding to accommodate fuel swelling without straining the cladding; with sodium bonding, a thinner cladding could be used.

Lithium-Cooled Radial Blanket

The lithium-cooled radial blanket located behind the fission blanket extends from the top to the bottom of the sodium plenums. The blanket consists of a cylindrical stainless-steel container 62 cm wide and 750 cm high. On the inside of the blanket there is first a 2-cm-thick stainless-steel inner wall, then 6 cm of lithium, 50 cm of stainless-steel-clad graphite, 2 cm of lithium, and finally, a 2-cm-thick stainless-steel outer wall. The lithium, which is enriched to 50% Li⁶, 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.

Top and Bottom Blankets

The top and bottom blankets are cylindrical, curved pancake-shaped plenums. The shell is 2 cm thick, and from the inside, each blanket is constructed with 2 cm of stainless-steel, 10 cm of beryllium, 70 cm of graphite, 10 cm of lithium, and the 2-cm stainless-steel outer shell. The blankets are located 350 cm 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 makes it possible to use a thicker fission zone, thereby increasing the fissile fuel-production capability of the reactor.

Final Laser Optical System

Six horizontal laser beams enter the reactor through a double-mirror system located outside the

reactor. The laser light is focused on the fusion target by six metal mirrors, three each at the top and bottom of the reactor; radiation shields are provided for each beam. The focal length of the mirrors is 12 m, and the final mirror is designed to accommodate a beam diameter of 1.2 m and a maximum energy flux of 1.5 J/cm^2 .

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 susceptible 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 emanating 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 must 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 to use special designs such as rotating mirrors, gas windows, magnetic-field directors, and special remote handling for replacing mirrors. We have not considered optical-system design here, except for layout and basic laser-system functional purposes surrounding the reactor.

Pellet Apparatus

The pellets of DT 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 0.1 Torr. No apparatus is available today that fulfills these requirements.

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 calculated the radiation-exposure capabilities of several first-wall materials and have chosen a 2-cm-thick graphite liner 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 1 MW/m^2 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 that escape the pellet.

We have calculated 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 estimates are presented in Refs. 4 and 5. 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 including:

- 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.⁶ LASNEX is a Lagrangian hydrodynamic code that incorporates the principal physical processes occurring in laser-produced plasmas; it also 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, as well as the induced magnetic and electric fields and the hydrodynamic behavior of the pellet.

We selected a laser target that 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 particles to interact with the cavity gas at 0.1 Torr. The resulting spectra and pulse widths were then input into the first-wall calculations. The results indicated that thermal ablation of a graphite curtain 3.5 m from the microexplosion will result in a surface-recession of less than 1 cm/yr. Spallation of the graphite by temperature-induced stresses has also been considered in these first-wall calculations.

Another factor limiting first-wall lifetime will be erosion by the formation of hydrocarbons. For a DT target with 5% burn, the graphite will erode at a rate less than 1 cm/yr, assuming that all the hydrogen reacts with the curtain to form acetylene.

The graphite curtain must be flexible enough to withstand the thermal stress caused by reflected light and x-ray loadings, as well as 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-cm-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 3-1. A thermal output of

Table 3-1. 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, s ⁻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

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-Hz 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 3-1 can be placed in perspective by comparing the laser-fusion hybrid to a typical fast breeder reactor. This comparison is shown in Table 3-2 where both systems have been normalized 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 its driving laser requires 19% of the gross power. This inferior performance in power generation results from design choices that 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 3-2. Specifically, the hybrid produces 10 times more fissile material, requires no initial fissile-fuel loading, and operates at one-tenth the power density. Because there is no initial fissile inventory, it is possible to operate the hybrid in a regime where both criticality 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 that provides much more time to recover from a loss-of-coolant

Table 3-2. 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.

accident. In fact, it is technologically feasible, and perhaps economically feasible, to design a hybrid blanket that passively copes with a loss-of-coolant accident.

Economic Analysis

Bechtel's preliminary cost analysis of the 1400-MW_e laser-fusion hybrid design revealed that some of the design choices had severe economic penalties. A survey of the high-cost items indicated that the reactor-containment structure and several of the other buildings were 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 that show an electrical-power plant is more economical in the 1200-MW_e range and, where possible, in twin units.

These results led us to perform a more detailed cost analysis on a hybrid with a larger output power. We scaled our conceptual design to a gross power of 1300 MW_e and a net power of 950 MW_e. This output was obtained from the original design by increasing the laser energy from 100 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 4.9 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, and cooling and auxiliary systems; therefore, cost estimates can be based on background experience. Because the fusion reactor, the laser-interface, and the fusion fuel cycle are conceptual, their costs have been estimated on a first-of-a-kind cost basis. The operating costs of the laser-fusion hybrid reactor are based upon its nuclear fuel-cycle and equipment-replacement costs in addition to capital charge rates and general operating and maintenance costs similar to those of LMFBR reactors.

Capital Costs. The results of the cost analysis are summarized in Table 3-3. The costs of the laser-fusion hybrid are compared to 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 includes the reactor vessel with its internals, and the primary-coolant loop with its associated pumps, motors, heat exchangers, and steam generators. Major items included in the "other mechanical" category are the turbine generators, the vacuum system, the tritium system, and the cooling towers. Site improvements, the reactor-containment structure, and all other buildings make up the "civil and structural" category.

The indirect costs in Table 3-3 were estimated on the basis of a nine-year construction of the LWR and a 10.5-year construction of the more complex laser-fusion hybrid. Thus, the indirect costs for the hybrid account for a larger fraction of the total capital cost. Field costs are the items in the construction cost which cannot be directly ascribed to the capital costs. They include temporary construction facilities, supply and maintenance of construction equipment and tools, field-office operation,

Table 3-3. Capital and operating cost analysis.

Capital cost item (M\$)	LWR, 1200 MW _e	Laser-fusion hybrid, 950 MW _e
Nuclear Steam Supply System (NSSS)	78	268
Other Mechanical	101	201
Civil and Structural	142	158
Piping	77	105
Instrumentation	9	11
Electrical	43	72
Total direct costs	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 costs	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 costs	27.22	55.00

and acceptance testing. The engineering services include all engineering 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 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/kWh. 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 revenues are 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 3-4. 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. The spent-fuel shipping and reprocessing costs are less for the hybrid because it operates at lower average burnups (6,000 vs 33,000 MWD/tonne of uranium).

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 when hybrids are providing fissile fuel for existing burner reactors. In Fig. 3-7, the cost of electricity has been plotted as a function of the cost of fissile fuel for hybrids with varying capital costs. 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 of the LLL/Bechtel Study

The production of fissile fuel by a hybrid is a promising step in the development of fusion. This design study has shown that the addition of a depleted-uranium fission blanket to a laser-fusion system has several advantages:

- The hybrid operates in a regime which requires an order of magnitude lower laser and pellet performance than a pure laser-fusion system.
- First-wall requirements and 14-MeV-neutron damage are less severe in a laser-fusion system with a fission blanket.
- The laser-fusion hybrid produces a large amount of fissile material—enough to fuel more than six LWRs of equivalent size.
- When laser-fusion hybrids are producing fuel for existing reactors, the cost of electricity is insensitive to the capital cost of the hybrid.
- The laser-fusion hybrid would extend the total energy available from economical LWRs 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 to assess the technological feasibility of

Table 3-4. Fuel cycle cost bases for pressurized-water and boiling-water fission and a hybrid reactor.

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_1 (PWR)
	\$26.95/g Pu_1 (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/kg U
Spent-fuel shipping	\$ 10/kg U
Reprocessing	\$125/kg U
Plutonium credit	\$30/g Pu_f

the laser-fusion hybrid. However, a definitive statement regarding the feasibility of fissile-fuel production with laser fusion cannot be made without further study. The laser and optical systems must 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, particularly of system failures which could result in a release of radioactive nuclides to the environment. The most obvious release mechanism is the 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 reactor is estimated to be three times more expensive than an LWR, yet the *cost of electricity* will be only 40% more than the present price. Nevertheless, substantial economic gains would be realized if the laser-fusion hybrid costs could be decreased to twice that of an LWR. Possibilities for reducing capital cost that should be explored in future studies include:

- Replacement of the coolant and tritium-breeding systems with helium cooling and a solid lithium blanket.
- Investigation of fission blankets that enhance energy multiplication.
- Consideration of blanket geometries that more efficiently utilize the point source from laser fusion.

Alternate Approaches Permitting A Long-Term Fission Economy

Fission reactors operating on a throwaway uranium fuel cycle will exhaust their supply of economically accessible fuel in less than 100 years. Therefore, to extend the useful life of this economic source of electricity, the throwaway uranium fuel cycle must be replaced. Until the recent shift in government policy, the United States has concentrated on developing the LMFBF (which uses the plutonium fuel cycle), and on reprocessing spent reactor fuel to allow recycling of unburned ^{235}U and Pu through LWRs. The President has introduced a program calling for indefinite deferral of the reprocessing and recycling of plutonium and the acceleration of research into alternative nuclear fuel cycles.

Although the fast breeder reactor involves a full commitment to the plutonium fuel cycle, hybrids do not require any fissile enrichment. Therefore, they can use uranium and thorium resources without reprocessing. To date, we have not examined these

Fig. 3-7. Cost of fissile fuel and electricity from a hybrid. The intersection points of the curves determine the cost of electricity and fissile fuel in the hybrid-LWR scenario. For example, the cost of electricity increases by only 20 to 40% when the capital cost of the hybrid ranges from two to three times more than the LWR.

nonreprocessing options in any detail because, in general, they exhibit a lower fissile fuel production and result in more costly electricity than the reprocessing options. However, in light of the recent policy change, we briefly describe a few nonrecycling schemes for hybrids that appear plausible.

The most straightforward approach is to use hybrids strictly as power producers with throwaway fuel cycles. These hybrid power plants could be fueled with thorium, depleted uranium, or spent fuel from LWRs; therefore, they could take advantage of the fusion energy multiplying characteristics of fuels that are abundant and cheap. Hybrid systems will be significantly more expensive than LWRs. Hence, power-producing hybrids without fissile fuel revenues can be expected to generate electricity at substantially higher costs.

Another nonreprocessing scheme involves the fissile enriching of depleted uranium fuel by irradiation in a hybrid for subsequent burnup in an LWR. The feasibility of this approach primarily rests with the development of high-burnup fuel elements that could operate in both the hybrid and LWR environments. Alternatively, the enriched hybrid fuel could be decayed, ground up, homogenized and compacted into LWR fuel pins. All of these operations would have to be conducted at high cost in shielded hot cells. Fissile fuel-producing hybrids utilizing either of these nonreprocessing schemes are expected to provide enough fissile material to fuel two LWRs of equivalent size. This represents a factor-of-three reduction in the fissile fueling capability that would be obtained with reprocessing.

The ^{233}U /thorium cycle with reprocessing of spent fuel has been proposed as a "less proliferating" nuclear fission option. If so, thorium-fueled hybrids could advantageously produce ^{233}U for efficient-burning thermal fission reactors. In this approach, hybrids located in secure areas would supply fission burner reactors with ^{233}U that has been denatured with ^{238}U to one part in six. As a result, weapons-grade material will not be present in the fuel supplied to the burner reactors. Because plutonium will be produced in the thermal fission reactors, the spent fuel must be returned to secure areas where the plutonium can be extracted and either utilized or stored. On the other hand, Cohen, in a recent presentation at the Atomic Industrial Forum Fuel Cycle '77, pointed out that denatured uranium is only about 12 separative work units away from weapons-grade material and that a crude centrifuge plant costing about 4 million dollars could be used to produce enough fissile material for a weapon in less than six weeks.

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4. ACTINIDE BURNING

The neutrons from DT-fusion systems can change long-lived fission waste products (primarily actinides) to short-lived or stable isotopes. This method could serve as a mechanism to relax requirements for long-term geological storage of high-level radioactive wastes. Actinide half-lives are quite long, even in comparison to such geological phenomena as ice ages and earthquake fault movements. Storage of long-lived wastes is difficult because these events can render a disposal area unacceptable.

Introduction

If the fission products in disposed high-level waste generated from spent commercial power reactor fuels are allowed to naturally decay, the long-lived actinides in the waste will dominate the hazard after only 400 years. Although it is not possible to eliminate the long-term hazard, it can be substantially reduced (more than two orders of magnitude) via a two step waste recycling process consisting of waste partitioning (or separation) followed by actinide transmutation (primarily burning by fission). In the partitioning step, the bulk of actinides are separated from the disposed waste. They are then shipped to an actinide transmutation reactor to be destroyed. To achieve the desired reduction in the disposed waste hazard, separation factors of 99.99% plutonium; 99.9% uranium, americium, curium, and iodine (a fission product); and 95% neptunium are required.¹ Because this represents a considerable advancement beyond the 99.5% separations currently achieved for uranium and plutonium, it is expected that partitioning technology will require significant development.

Ideally, to achieve the maximum possible disposed waste hazard reductions, the separated actinides should be entirely destroyed in the actinide burner. However, the actinides cannot be entirely fissioned during a single fuel cycle period that is limited by the fuel element damage rate and fission product buildup. Thus, the remainder of the actinides (unburned) are discharged from the actinide burner. These will be reprocessed again, supplemented with fresh actinides from fission reactors, and charged as fresh fuel to the actinide burner. Some actinides initially charged to the actinide burner will constitute an additional feed to the disposed waste stream due to the reprocessing inefficiency.

A consequence of the above is that a principal figure of merit for an actinide burner will be the average, or mean, life of an actinide atom in the actinide burner divided by the actinide burner fuel cycle period.² This ratio determines the actinide burn-up, which in turn determines the additional number of recycles that an average actinide atom in the system experiences before it is burned. In this sense, the total long-lived hazard of a unit of disposed fission fuel is a function of the separation factor and the number of recycles required.

To minimize the total disposed hazard, three goals for an actinide partitioning transmutation scheme are apparent:

- High separation factors
- Short in-reactor actinide meanlife
- Long fuel cycle period (high burnup)

In addition, a fourth goal would be to maximize the actinide throughput to service as many fission reactors as possible. Finally, a fifth goal, relevant to the case in which a final charge of actinides is to be burned *in situ*, is that the long-term hazard of irradiated actinides should be several orders of magnitude less than the hazard associated with a full charge of unirradiated actinides. Of course, these goals neglect the significant, and perhaps prohibitive, short-term hazards associated with the increased circulation of actinide wastes during the partitioning and transmutation process.

Several studies have investigated the possibility of recycling actinide wastes in thermal fission reactors³ and fast breeder reactors.⁴ These studies have shown that it is possible to burn actinides in fission reactors and that the process is more efficient in the harder neutron spectra of fast breeder reactors. Logically, fast-neutron-rich fusion systems could even more effectively serve the same role. Two studies of actinide burning in fast spectrum fusion reactor blankets have been completed.

WFPS Study⁵

An EPRI-sponsored Westinghouse study was based on a beam-driven Tokamak fusion-fission hybrid reactor used for actinide depletion. Intended for mid-to-late 1980's technology, this reactor provides a fusion neutron wall loading of approximately 1 MW/m^2 , corresponding to approximately $10^{14} \text{ n/cm}^2\text{-s}$ in the 14 MeV energy range.

The fission blanket is fueled with actinides contained in the high-level waste from the LWR-U cycle. The Mo-TZM clad actinide oxide fuel is primarily comprised of ^{237}Np , ^{241}Am , and ^{243}Am , which represent almost 90% of the partitioned actinides and are the principal contributors to the very long-term radioactive hazards in LWR waste. These actinides are the only fissionable material contained in the helium-cooled blanket, but they provide sufficient neutron multiplication for neutron fluxes in the range of $10^{15} \text{ n/cm}^2\text{-s}$.

The WFPS report analyzed the reduction of the long-term hazard of actinides charged to the reactor rather than the reduction of the overall long-term hazard of the disposed waste (including the actinides added to the disposed waste after each recycle of the fuel). In this sense, the long-term hazard of actinide waste irradiated for 30 years at 1.15, 5, and 10 MW/m^2 was investigated. For all three cases the same average thermal blanket power ($13,000 \text{ MW}_t$) was achieved by lowering the actinide "enrichment" (and thus blanket criticality) with increasing wall loadings. The relative ingestion hazard vs decay time is shown for the three wall loadings in Fig. 4-1. The relative ingestion hazard is an index that consists of the ratio of the ingestion hazard of a given amount of high-level nuclear waste to the ingestion hazard of the amount of naturally-occurring parent uranium ore from which the wastes were produced. Formulation of a relative hazard index on this basis is considered to be a realistic measure of the effects of high-level wastes because it compares the hazard potential of wastes with that of naturally occurring radioactive substances which would exist if the uranium was not used in the LWR. However, concentration effects which make the waste hazard per unit volume much greater for the irradiated waste than the parent ore are not indicated through the use of this index.

For a neutron wall loading of 1.15 MW/m^2 the hazard index of the irradiated actinides initially decreased relative to the natural decay curve. At 10^5 years, however, it increased back to the natural decay level. These results were similar to those generated in a BNWL study of actinide irradiation in a moderated neutron spectrum, beryllium blanket.⁶

Although the initial depletion rates of actinide species loaded into the Westinghouse actinide burner are several orders of magnitude higher than the natural decay rates, it was found that neutron absorption dominates over fission. Because of this effect, considerable quantities of ^{238}Pu , ^{244}Cm and ^{242}Cm are produced before ultimately fissioning. The net effect of producing these nuclides is a significant increase in the hazard index in the first few

Fig. 4-1. A comparison of the relative ingestion hazards from actinides as functions of decay time.

years of irradiation due to the relatively shorter half-lives of ^{242}Cm , ^{244}Cm and ^{238}Pu when compared to the other actinides. Additionally, the $^{242}\text{Cm}/^{238}\text{Pu}$ decay chain gives rise to very radiotoxic long-term daughter products. In fact, all the actinides associated with fission reactor waste will create a dozen or so radioactive daughter products before decaying to stable Pb or Bi isotopes. Thus, in a meaningful evaluation of the long-term radiotoxicity, one must follow the decay chains for approximately 10^6 years to see the effects of radioactive daughter products on the potential ingestion hazard.

In the case of a 10-MW/m^2 wall loading, the Tokamak actinide burner benefits from two effects related to lower actinide concentrations (for constant power) in the blanket. Because lower concentrations (by about a factor of four) lead to lower criticality, the neutron spectrum will harden due to an increase in the ratio of 14 MeV fusion neutrons to about 1 MeV fission neutrons. In the harder spectrum, the capture to fission ratio decreases while neutron multiplication due to the $(n,2n)$ reaction increases. Also, lower actinide concentrations at constant power imply that the actinide mean life decreases. This has the effect of depleting the actinides, including nuclides produced in the actinide burner itself, more quickly. For example, the destruction (i.e., capture and fission) half life for ^{238}Pu decreases from almost 7 years to 2 years

when the wall loading is increased from 1.15 to 10 MW/m².

The Westinghouse group reports that the post irradiation decay hazard index of actinides irradiated for 30 years at 10 MW/m² can be reduced by three orders of magnitude relative to natural decay (Figs. 4-1 and 4-2). They conclude that a wall loading of 1.15 MW/m² or shorter irradiation periods are only marginally attractive, and that a total first wall fluence approaching 300 MW·yr/m² is required for effective reduction of the hazard associated with actinide waste charged to the actinide burner.

The WFPS study has shown that, from the standpoint of economics, the actinide burner can produce a very large amount of useful energy (approximately 13,000 MW_e). Moreover, this energy can be supplied at conditions of fluid temperature and pressure suitable for useful power generation. The plant WFPS used with the actinide burner provides 1050 MW_e for its required circulating power, as well as a surplus of approximately 10,000 MW_e for useful export. In view of the extremely large power of the plant, it was not considered reasonable to supply this export power in the form of electricity. Instead, a hydrogen production plant was coupled to the reactor to create a marketable product from its power. The total capital cost for the reactor and plant (excluding escalation and interest during construction) was estimated to be approximately \$4.7 billion in 1975 dollars. On the basis of capital costs per unit of thermal output, this figure is approximately three times that of an LWR. Assuming a 10-year design and construction period, with operation in the mid-1980's (which is extremely optimistic), provision for escalation would require \$4.6 billion and the interest during construction another \$3.9 billion. This represents a total plant cost of \$13.2 billion. If one examines operating costs, including amortization of the \$13.2-billion investment over a 30-year plant life and credits the hydrogen production at the same price per Btu content as that for oil, there is a net operating deficit of \$1.9 billion per year, which can be assigned as the incremental cost for disposing of the actinide inventory.

To put this cost in perspective, the actinide burner has the capability to fission 4 metric tons of actinide per year, based on a power generation of 13,000 MW_e with an availability of 80%. Since depletion of these actinides by fission corresponds to disposal of fission-reactor actinide waste produced in the generation of 1.5·10¹² kWh,* a

* Two hundred and twenty two plants (1 GW_e each) operating at 75% capacity produce 1.5·10¹² kWh/yr. Each produces about 0.018 MT/yr of actinides in the LWR-U fuel cycle.

Fig. 4-2. The effect of irradiation with a 10 MW/m² fusion neutron wall loading on the long-term ingestion hazard potential of LWR actinides following 30 years of irradiation in the actinide burner.

1.3-mills/kWh incremental cost can be assigned to the fission-reactor power plant for actinide burning. This is about a 4% increase in the total generation cost for a nuclear plant scheduled for 1985 startup. However, the actinide burner concept has not been optimized, and significant cost improvements may be feasible.

Laser Fusion Driven Actinide Burner Study

At present, laser fusion appears to be capable of attaining a 5- to 10-MW/m² fusion neutron wall loading. In addition, the ability to utilize simple geometry makes the laser fusion reactor an attractive candidate for actinide burning. Recognizing these attributes, Berwald and Duderstadt (University of Michigan) have performed scoping studies⁷ for an actinide burner adapted from a University of Wisconsin pure laser fusion reactor design. The goal was to identify a fusion driven actinide burner system that could be expected to perform efficiently within the framework of anticipated fusion technology. Reasonable extrapolations in technologies that could be expected to develop during the same time frame as the fusion driver itself were utilized.

The laser fusion driven actinide waste burner (LDAB) system investigated uses partitioned fission reactor generated actinide wastes dissolved in a molten tin alloy as fuel. A novel fuel processing concept based upon work by Anderson and Pa lee⁸ concerning the high-temperature precipitation of "actinide-nitrides" from a liquid tin solution is proposed. This concept will allow for fission product removal to be performed at high burnup within the device. Thus, the LDAB actinide transmutation process may represent less short-term hazards than solid fuel systems with a fixed fuel cycle period because the need to refabricate and transport actinide wastes once charged to the system is eliminated.

The LDAB is a power producing hybrid reactor. With an equilibrium blanket energy multiplication of thirty in actinide fission regions about the axial midplane of a cylindrical cavity, a total system blanket energy multiplication of twelve is attained. This corresponds to a reduction in the laser system recirculating power fraction from 24% (pure fusion reactor) to 2.7%. The equilibrium neutron wall loading of 5.7 MW/m^2 represents an average flux of $6.4 \times 10^{15} \text{ n/cm}^2 \cdot \text{s}$ in the fission regions. The overall system power is approximately $22,000 \text{ MW}_{\text{th}}$ with an average fission power density of 287 W/cm^3 in the actinide fuel regions.

No attempt has been made to optimize this system, but potential performance seems impressive. In one possible fuel management scenario, the LDAB attains an effective equilibrium composition in 15 years. The equilibrium LDAB consumes 7.60 MT/yr of actinide waste; corresponding to the waste output from 134 LWR's operating with full plutonium recycle (1000 MW_e , $33,000 \text{ MW} \cdot \text{d/t}$, 33% thermal efficiency, 75% capacity factor). With an actinide loading of 34 t, the mean life of an actinide atom in the system is only 4.5 yr.

If the 134 LWR's and one LDAB are evaluated as one system, the LDAB will produce 5.5% of the system power. If the cost of LDAB power generation is three times that of LWR power generation, then the system power generation cost will be 11% above the LWR power generation costs. If the LDAB burns LWR-uranium recycle waste instead of LWR-plutonium recycle waste, it might serve 420 reactors with only a 3.7% increment in power generation costs. As in the WFPS design study, the blanket thermal power could also be utilized for synthetic fuel production.

Although the LDAB has the potential to efficiently burn actinide wastes, process the wastes generated in a large system of commercial reactors, and reduce the short-term hazard due to

transporting and fabricating actinide fuels, its performance represents an optimistic goal. Its realization will require significant development in the fields of high-level waste partitioning, laser fusion and hybrid systems, fusion environment materials, and pyroprocessing. However, these results suggest that high-burnup solid-fuel hybrid blanket designs with considerably less technological risk might attain adequate performance as actinide burners. In particular, HTGR fuel pellets appear to have burn-up capabilities in excess of 25%.⁹

Comparison of the Two Studies

The LDAB's efficiency as an actinide burner is compared with the efficiencies of the WFPS Tokamak and other actinide burner systems in Table 4-1, which is taken from Ref. 2. The fully loaded Tokamak actinide burner designs evaluated by Westinghouse relate to initial rather than equilibrium blanket compositions. However, the quality of actinide fuel improves dramatically during the evolution to equilibrium. For example, the LDAB is able to reduce its actinide and neutron wall loadings by 60% and 43%, respectively, while still achieving its initial power density (or equivalently its initial actinide throughput) during its evolution to equilibrium. Since the actinide mean life is the actinide loading divided by the throughput, it follows that the mean life in an equilibrium actinide burner is quite improved over that of a design based on initial conditions only. Also, the reactor can be designed for a relaxed evolution wall loading with only a slightly longer evolution to equilibrium.

Thus, for consistency in comparison, data for equilibrium composition Tokamak actinide burners is required. To satisfy this requirement, calculated performances for the two Tokamak designs shown in Table 4-1 were deduced from Ref. 5 and the LDAB evolutionary performance. The 5.7 MW/m^2 Tokamak has the same wall loading as the LDAB. This wall loading is optimistic for a beam-driven Tokamak design, but the results indicate that the neutronic performance of actinide oxide fueled blankets may be similar to the molten tin-actinide alloy blanket. The major difference in the LDAB and the Tokamak relates to the possibility for higher fractional burnup in the molten tin LDAB fuel (25%) as opposed to the oxide Tokamak fuel (10%). Of course, the Tokamak results are only indicative of equilibrium performance. Better estimates will require detailed neutronics studies.

As shown in the table, fusion reactors can burn two orders of magnitude more actinide waste than

Table 4-1. Equilibrium actinide burner performance.

	LWR ^a	LMFBR ^a	TOKAMAK ^b (5.7 MW/m ²)	LDAB (5.7 MW/m ²)
Actinide inventory (MT)	1.8	0.48	24	34
Power density (W/cm ³)	—	—	230	285
Actinide throughput (MT/yr)	0.057	0.056	4.7	7.6
One GW _e LWR's served	1 ^c	4.8 ^c	261 ^d	134 ^d
Actinide mean life (yr)	31	8.6	5.1	4.5
Fractional fuel burnup (%)	9.6	13 ^e	11	25 ^f
Fuel irradiation period (yr)	3	1.1	0.55	1.5
Additional reprocessing cycles	9.4	6.8	8.3	3

^aLWR and LMFBR analysis discussed in Refs. 2 and 7.

^bTokamak performance deduced from nonequilibrium results presented in Ref. 5 and adjusted for equilibrium cycle using Ref. 2 results. Wall loading equivalent to LDAB.

^cLWR-Pu burns self-generated waste. LMFBR (1200 MW_e) burns self-generated waste plus waste from three 1200 MW_e LWR-U.

^dTokamak burns LWR-U cycle waste (0.18 MT/GW_e yr). LDAB burns LWR-Pu cycle waste (0.057 MT/GW_e yr).

^eBurnup applies to waste actinides only. LWR and LMFBR regular fuel burnup (33,000 and 100,000 MWD/MT, respectively) determines fuel irradiation period.

^fNominal 25% burnup assumption requires further investigation.

fission reactors because they are fueled entirely with actinides. Thus, fusion driven actinide burner schemes would employ only a few reactors devoted solely to this task. Note that although the LDAB has a larger actinide throughput, it serves fewer LWR's than the Tokamaks. This is due to the larger actinide production in plutonium vs uranium burning reactors.

Actinide Burning in Laser Fusion Pellets

An additional technique for burning actinide wastes in an ICF reactor is to burn the actinides in a fusion fuel pellet. This technique increases the neutron fluence per shot in the actinides by a factor greater than 10^9 . Calculations have shown that much of the actinide materials seeded into the pellet can be burned. The disadvantage of burning the actinide in pellet form is that pellet fabrication and processing of fission product waste becomes more complicated. This process is important because a given mass of actinides will need to be reprocessed several times before it is completely fissioned. In addition, the rate of actinide mass burned in pellets will be much less than that in a blanket because there is a limit to the pellet mass that can be compressed by a given ignitor-beam energy.

Discussion

The preceding discussion of actinide depletion is based on the premise that all actinide isotopes that contribute to the hazard index are undesirable nuclides. On the other hand, ^{238}Pu , ^{244}Cm and ^{242}Cm have identifiable commercial applications as beneficial radioisotopes. For example, ^{238}Pu is useful for portable and remote power sources that include pacemakers, artificial hearts, and space and terrestrial power stations. The principal deterrent to the use of these nuclides has been their unavailability and high cost. The actinide burner may be a prolific source of these radioisotopes, which are produced by actinide transmutation. The ^{238}Pu isotope is the principal contributor to the increase in the hazard index during irradiation, and its daughter product, ^{226}Ra , is largely responsible for a secondary peak in the hazard index at approximately 10^5 years (Fig. 4-2).

Thus, a value judgment is needed to weigh the beneficial and potentially detrimental attributes of nuclear materials. In fact, Fig. 4-1 suggests that, in terms of the relative hazard index defined earlier, even unirradiated actinides represent a comparatively small long-term radiotoxic hazard. In

view of these considerations and recent studies of waste transport into the ecosystem, the issue of long-term hazard potential from actinides should be reexamined.

The environmental and safety considerations associated with the actinide burners pose a variety of new problems, although there are parallels with present fission reactor plants. The most significant environmental constraint will be the need to contain large inventories of fission products and tritium. These inventories will be one and several orders of magnitude higher than the corresponding inventories for a current fission reactor power plant. Therefore, features such as multiple containment and cleanup systems must be carefully designed. With regard to safety considerations, the actinide burner power will be several times the 3800 MW, currently imposed as an upper limit for LWR's. Furthermore, the actinide-fuel inventory represents a very large collection of those components of high-level radioactive wastes having the most adverse long-term toxicity characteristics. Thus, we anticipate that a serious program to design, develop, and construct such a plant would have to include provision for an extensive review of the regulatory implications. The principal consideration in the 3800-MW_e limit is the desire to obtain operating experience with reactors up to that size in a comparatively mature LWR technology. The possibility of constructing actinide burner blanket segments on a smaller modular scale and at lower power density should be considered. On the other hand, a single actinide burner of the type described in this study could service a large number of LWR's and would not be restricted by siting constraints that tend to favor location near electrical load centers.

Conclusions

The most effective means of reducing the long term radiotoxicity from the actinides is depletion by fissioning the actinides. To effectively burn actinides in a fusion reactor, the product of irradiation time and first-wall fusion neutron flux must be on the order of 300 MW yr m^{-2} (10 MJ/m^2). The fusion reactors that burn actinides will be very large with power levels from 10 to 50 GW_e. Because of their size, they will generate too much power to be tied to a grid. The excess energy can be used for hydrogen production (see Section 5) by electrolysis or for desalinization of water to help reduce the incremental cost assigned to LWR power plants for waste disposal.

It appears that the ICF reactor will be more attractive for actinide-burning application than alternative systems (LWR, LMFB, and magnetically

confined fusion). However, the actinide-burning process is of questionable desirability for the following reasons:

- Compared to immediate encapsulation and storage of actinides, increased handling of high-level wastes is required.

- The short-term hazards increase during early irradiation because of the production of additional actinides from neutron capture.

- Some actinide isotopes are quite useful and should not be burned.

- Reduction of effective half-life from the natural half-life for actinides is of questionable value. Even without irradiation, the actinides present the same ingestion hazard as the parent ore after a relatively short storage period (100 years).

If society decides that the long-term radiological hazards from fission-reactor actinide wastes are high enough to merit construction of actinide burners, then inertially confined fusion technology can best perform the required irradiation.

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5. SYNTHETIC FUEL PRODUCTION

Our oil and natural-gas supplies are declining rapidly. Hence, the ability to produce large quantities of portable chemical fuels for our homes, industries, and vehicles will be a necessity within the next 100 years. Natural gas has been the preferred fuel for residential heating and industrial-process heat; it is environmentally acceptable, convenient to use, and, until recently, low in cost and in ample supply as a natural resource. Depletion of natural reserves has added emphasis to the search for alternative fuels. The role of hydrogen, both as a fuel and as an intermediate product used in the production of synthetic fuels, is being considered. An example of synthetic fuel production is the reduction of both carbon and carbon monoxide by hydrogen at high temperatures to form methane (CH_4). Methane is the principal constituent (typically about 85%) of natural gas.

Any large-scale, long-range scheme for the production of synthetic fuels should not require further depletion of fossil-fuel reserves. It is inconsistent, for example, to use natural gas when producing hydrogen for use as a substitute fuel. However, the abundance and general availability of water make it an ideal feedstock for hydrogen production processes. A laser-fusion reactor could supply the energy necessary to decompose the water, and such a system would represent a virtually inexhaustible source of hydrogen.

Depending on how energy from the fusion reaction is used: water-cracking processes can be classified as thermochemical, electrolytic, or radiolytic. Figure 5-1 compares the various conversion processes, on the basis of recoverable hydrogen-combustion energy per unit of thermal energy available.

The thermal energy from the reactor could support a sequence of high-temperature chemical reactions in various hydrogen-producing thermochemical processes. The system of reactions known as the Mark-I cycle is typical of the processes involved:¹

The net process is the decomposition of water

The maximum temperature required (730°C) could be achieved in a gas-cooled laser-fusion reactor.

A large number of alternate chemical processes could ultimately produce hydrogen and oxygen from water. While these thermochemical processes generally do not consume the chemical reactants, they often use large quantities of hazardous and corrosive chemicals. Practical energy-conversion efficiencies for typical thermochemical processes range from about 30 to 65%.^{1,2} In other words, up to 65% of the fusion energy is recoverable as thermal energy by burning the hydrogen produced.

Laser-fusion reactors could also generate electricity for subsequent electrolysis of water to produce hydrogen. The electricity simply supplies the energy required to decompose water according to

This reaction absorbs 68 kcal per mole of hydrogen produced. For existing electrolysis plants, the combustion energy of the hydrogen produced is 60 to 100% of the electrical energy input.^{1,3} Assuming a 40% thermal-to-electric conversion efficiency for the laser-fusion power plant, the electrolysis process produces hydrogen with an overall energy-conversion efficiency of 24 to 40%.

Hydrogen production by radiolysis can be achieved in several ways, but all require an intense source of radiation. The penetrating neutron radiation of a laser-fusion reactor could be utilized for radiolysis by incorporating sufficient quantities of H_2O in the blanket regions surrounding the fusion vacuum chamber.^{2,4}

A concept often used in the discussion of radiation-induced chemical processes is the G value. The G value for the formation of a chemical species is defined as the number of molecules produced per 100 eV of energy deposited in the production regions by incoming radiation. The generally accepted G value for H_2 from water is 0.45, while G values as high as 13.6 have been measured in experiments using pure steam exposed to high-energy neutrons.⁴ Radiolytic hydrogen production is clearly more efficient in steam than in liquid water.

Fig. 5-1. The combustion energy of hydrogen recoverable from one unit of fusion-reactor thermal energy. The fraction of the neutron energy deposited in hydrogen processing regions is generously assumed to be 100% for radiolysis of water and 60% for radiolysis of steam. It is unlikely that a dedicated radiolysis hydrogen-production facility could ever prove practical unless a liquid medium with a higher G value is found. Therefore, a hypothetical $G = 20$ liquid medium system is shown.

Figure 5-2 is a power-flow diagram for a laser-fusion hydrogen-production plant that also generates electricity. Note that more than 25% of the energy released by the fusion microexplosion is carried by the pellet debris, alpha particles, and x rays. This energy is deposited in the vacuum chamber wall and thus is not available for radiolytic decomposition.

Figure 5-2 also shows that P_n is the total energy deposited in the reactor as a result of neutron interactions with blanket materials. It is important to note that only a fraction, α , of the available neutron energy is actually deposited in the steam blankets; the remainder is deposited in reactor structural materials and thus is unavailable for radiolysis of H_2O . For example, less than 40% of the fusion neutron energy would be deposited in a 3-m-thick region of pressurized steam at 1000 psia. Not all of the nuclear energy deposited in the steam is used in subsequent radiolysis and H_2 production. The term η_H is the conversion efficiency of nuclear energy deposited in the steam to potential combustion energy of the hydrogen produced. It is related to the G value for the formation of H_2 by

$$\eta_H = \frac{Gh}{100}$$

where h = heat of combustion of an H_2 molecule = 2.5 eV.

The primary reaction in the radiolysis of water vapor is the breaking of O-H bonds to give H, O, and OH radicals. The minimum energy required to break the first O-H bond in H_2O is 5.2 eV, whereas the net energy consumed in the production of an H_2 molecule from $H_2O(g)$ is equal to the heat of combustion of H_2 and is only 2.5 eV. The difference

results from subsequent exoergic H_2 - and O_2 -producing reactions. Because the chemical energy released in these reactions is ineffective in breaking additional H_2O molecules, the conversion efficiency of nuclear energy deposited to usable chemical energy (combustion heat of H_2) is less than unity (100%). If a radiolytic reaction requires the minimum 5.2 eV to break a single O-H bond in H_2O , and the resulting H and OH radicals chemically react by

then 2.5 eV of potential combustion energy is produced from 5.2 eV of nuclear energy. Hence, the maximum value of η_H is about 48%.

The maximum experimental G -value of 13.6 results in a value of $\eta_H = 0.34$. In other words, 34% of the energy deposited in the steam is converted to potential hydrogen combustion energy while 66% appears as thermal energy in the system. The total fraction of P_n that is converted into thermal energy is

$$(1 - \alpha) + (1 - \eta_H) \alpha = 1 - \eta_H \alpha$$

The product $\eta_H \alpha$ is an indication of the system efficiency for hydrogen power production, reflecting not only the efficiency in converting deposited nuclear energy to hydrogen but also the efficiency at which this energy is deposited in the hydrogen-producing regions. The overall energy-conversion efficiency is the ratio of the potential combustion energy of produced hydrogen to the total nuclear energy deposited in all regions of the reactor. As

Fig. 5-2. The power flow diagram for a laser fusion radiolysis facility which also generates electricity.

shown in Fig. 5-2, the combustion energy of hydrogen produced is

$$P_H = \eta_H \alpha P_n,$$

while the total energy deposited is

$$P_T = P_n + 0.25 P_{in} \eta_L Q = P_n + \frac{P_n}{3M}.$$

The overall energy-conversion efficiency is then

$$\eta = \frac{P_H}{P_T} = \eta_H \alpha \left(\frac{3M}{3M + 1} \right).$$

The blanket energy multiplication M can be increased above 1.0 by adding boron to the steam blankets. Thermal neutrons absorbed by ^{10}B release 2.35 MeV of high LET radiation according to the reaction

Thus, values of M as high as 1.2 might be possible.

Using the values of $\eta_H = 0.34$ (corresponding to $G = 13.6$ in steam), $M = 1.2$, and generously assuming $\alpha = 0.6$ for a steam blanket, the overall energy-conversion efficiency is only 16%. Liquid water blankets have much lower efficiencies (even though α may be nearly unity) as a result of the very low G value of 0.45. This gives a value of $\eta_H = 0.01$, and for $\alpha = 1$ results in an overall energy-conversion efficiency of less than 0.8%.

If tritium-breeding zones are required, they would reduce the fraction, α , of neutron energy available for hydrogen production. Because lithium is vigorously reactive with water, special precautions would be required to reduce the potential hazard. Also, because boron absorbs the neutrons required to breed tritium, it could not be used as an energy multiplier. A net reduction in the overall energy conversion efficiency for radiolysis results when tritium breeding requirements are considered.

Therefore, while radiolytic hydrogen production by a laser-fusion reactor may be technically feasible, it is unlikely that a radiolysis facility using H₂O could prove practical. Near term R&D efforts in neutron radiolysis should concentrate on chemical schemes that could yield much higher G values, preferably in liquid media. Chemicals with hydrogen bond energies less than those in H₂O would be likely candidates, and the use of a liquid would offer more efficient energy absorption than a gaseous medium. For example, with a G value of 20 in a liquid medium, laser-fusion radiolysis would have an overall energy-conversion efficiency of 37.5%, which is competitive with the alternative processes for producing hydrogen in a laser fusion reactor (see Fig. 5-1).

An option for the water-based radiolysis system would be the use of the remaining thermal energy ($\geq 85\%$ of the total) for the production of electricity. The electricity could be sold on the electric power grid or used to generate more hydrogen by electrolysis. The overall energy-conversion efficiency of a radiolysis/electrolysis hybrid system is given by the sum of the overall radiolysis efficiency and the overall electrolysis efficiency applied to the remaining thermal energy; i.e.,

$$\eta = \alpha\eta_{II} \left(\frac{3M}{3M+1} \right) + \eta_E\eta_{Th} \left[1 - \alpha\eta_{II} \left(\frac{3M}{3M+1} \right) \right],$$

where α , η_{II} , M are defined as before, and

η_E = electric-to-hydrogen conversion efficiency

η_{Th} = thermal-to-electric conversion efficiency

Thus, when the overall radiolysis conversion efficiency is 16%,

$$\eta = 0.16 + 0.84\eta_E\eta_{Th}$$

As before, if we assume $\eta_{Th} = 0.4$ and $\eta_E = 0.6$ to 1.0, the overall energy-conversion efficiency for the radiolysis/electrolysis hybrid system is 36 to 50%.

Current natural-gas costs are about \$1 per million Btu but may climb to \$3 per million Btu before the end of the century.⁵ The present estimated cost of synthetic gas from coal gasification plants is about \$4.5 per million Btu for the current process to as low as \$3.5 per million Btu for future plants.⁶ *In situ* coal gasification may be able to produce gas at a cost of about \$2 per million Btu.⁷

The cost of hydrogen produced by the various laser-fusion-driven processes is at least equal to the cost of energy from the fusion reactor divided by the overall energy-conversion efficiency. For comparison, assume a laser-fusion power plant produces electricity at a cost of 25 mills/kWh. (This is comparable to the estimated cost of electricity from LWR and coal stations ordered in 1976 and online in 1985, quoted in 1976 dollars.) Also, assume that the capital component of the electricity cost is 80% of the total and that the electrical power generation equipment comprises 20% of this capital cost. (The turbine generators and building comprise about 20% of a typical LWR capital cost.)⁸ At a thermal-to-electrical conversion efficiency, η_{Th} , equal to 0.4, the cost of energy is \$2.93 per million Btu for processes requiring electrical energy and \$2.46 per million Btu for processes requiring only thermal energy.

Table 5-1 gives the source-energy component of the cost of hydrogen produced by the various processes. These values reflect only the cost of using a laser-fusion reactor as the source of energy for the various processes. Additional costs will vary for the different processes depending on the cost of the components required. Large electrolysis units, for example, will add approximately \$1 per million Btu to the cost of hydrogen.⁶

Table 5-1. Energy source component of the cost of hydrogen.

	Cost of source energy (\$/million Btu)	Energy conversion efficiency	Energy source component of hydrogen cost (\$/million Btu) ^a
Thermochemical	2.46	0.30-0.65	3.80-8.20
Electrolysis	2.93	0.24-0.40	7.30-12.20
Radiolysis	2.46	0.16-0.38 ^b	6.50-15.40
Radiolysis/electrolysis	2.93	0.36-0.50	5.90-8.10

^aDoes not include cost of chemical processing plant, electrolysis units, or radiolysis components required.

^b0.16 and 0.38 correspond to G values of 13.6 and 20, respectively.

It is clear there is no economic incentive for the production of synthetic fuels with laser fusion at the current price of natural gas, nor at the projected cost of gas from coal gasification. Even so, such a system may eventually be required. Oil and natural gas currently account for about 75% of this nation's energy consumption. As these fuels are depleted the ability to produce large quantities of portable fuel will become a necessity. Laser-fusion-driven hydrogen-production processes represent a virtually inexhaustible supply of portable fuel.

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6. PROPULSION SYSTEMS

As the cost of the fossil fuels generally used for transportation continues to increase, the demand for nuclear fuels will also increase. To date, fission power has been the only nuclear fuel. Fusion will have no decisive economic advantage (in cost or power density) over fission for marine propulsion, which is the only near-term propulsion application. Furthermore, fission propulsion technology will be well entrenched when fusion becomes available. Therefore, we don't expect deployment of fusion powered ships unless fission power is eliminated as an alternative due to social or environmental concerns. The established fission propulsion technology could be fueled from laser fusion hybrid reactors to insure a long term fuel supply if fission propulsion continues to be socially acceptable.

Fusion powered aircraft do not appear to be feasible from both engineering and environmental viewpoints. Fusion powered extraterrestrial propulsion systems could be a long-term application of laser fusion.

Nuclear systems of any kind present a potential environmental hazard. In this respect, however, fusion systems have an advantage over fission systems because they use and produce smaller amounts of radioactive elements. The radiation hazards in fusion systems are primarily the tritium supply and radionuclides in the blanket material. A 0.1-kg mass of tritium in the fusion fuel supply amounts to 10^6 Ci of uniquely low level biological hazard activity, but that level represents around 1.5 million kWh of usable fusion energy. The blanket material only has 10^7 Ci of radionuclides and represents a nonvolatile, localized hazard. A fission reactor, on the other hand, has 10^{10} Ci of very volatile fission products for a power rating of 10^9 W₁ (3×10^5 mechanical hp).¹

Nuclear-power propulsion systems will become more and more attractive as the price of oil rises, and less environmentally sensitive countries might pursue such alternatives vigorously. Ultimately fusion, fission and fossil powered systems will have to compete on a system by system basis. Tradeoffs of performance, cost, and environmental effects will be used to select a system for a given role.

A propulsion plant must be capable of operating at a range of power levels. Laser fusion will have power level flexibility through the ability to quickly vary either the pulse rate or the pellet yield.

Much of the considerable experience gained in marine nuclear-fission propulsion is applicable to the fusion-system concept. Both fission and fusion systems have high technology costs, high fixed costs, and low fuel costs relative to fossil systems. Fusion-fuel costs for material consumed will be negligible, but production costs might be quite high. Nuclear power (and fusion in particular) is essentially clean power, reducing pollution caused by fossil-fuel combustion. Moreover, the prime candidates for marine nuclear propulsion are ships of high horsepower—larger, faster ships. This implies a reduction in the absolute number of ships needed to carry any given cargo tonnage, a situation that has safety and environmental advantages.

Engineering Considerations for Fusion Propulsion

In general, a fusion-reactor power plant for a propulsion system must be designed for minimum specific volume and mass. Thus, the reactor will operate with a high first-wall loading. Details on the specific volumes and masses for several types of propulsion applications are shown in Table 6-1.

Fusion gain $\eta_1 Q$ (the ratio of the thermonuclear yield to the electric power driving the laser system) must be large for a reasonable system efficiency and a small specific volume and mass. For anticipated laser-system efficiencies, the volume and mass of the laser system per unit of power input to the laser (power stored) is roughly constant. Therefore, the larger the fusion energy gain, the smaller the laser system specific mass and volume.

Reactor-chamber optical and first-wall materials, in which the short-ranged microexplosion energy is deposited, must have long lifetimes to increase the vehicle availability and decrease the operating costs. Shielding must be provided to protect cargo, as well as passengers, from the high-energy neutrons. In addition, the reactor system and other vehicle components that are subject to neutron activation or that collect activated material must be easily accessible and designed for remote maintenance. Although these considerations are not discussed in detail in this report, they must be considered in designs of fusion-propulsion applications.

Table 6-1. Summary of propulsion system characteristics.

Application	Technical risk	Power	Constraints ^a	
			Maximum specific mass	Maximum specific volume
Marine				
Navy	Moderate	90 MW _s	30 kg/kW _s	80 m ³ /MW _s
Commercial	Low	90 MW _s	90 kg/kW _s	200 m ³ /MW _s
Airborne	High	130 MW _s	0.4 kg/kW _s	1.5 m ³ /MW _s
Space	Highest	130 GW _t	0.05 kg/kW _t	Not critical

^aMaximum permitted for competitiveness with other options. Conversion factors: 1 kg/kW = 1.6 lb/hp; 1 m³/MW = 26 ft³/khp.

Terrestrial Laser-Fusion Propulsion

Terrestrial propulsion systems, including marine and aircraft propulsion, will probably operate on a parasitic, DT fuel cycle using tritium produced in larger stationary fusion reactors. The first wall of the reactor will be a dry wall and will either be magnetically protected or covered with a sacrificial liner. The use of a wet wall or fluid wall will be possible only if the reactor is mounted on a stable platform.

The reactors will operate on a Brayton cycle with helium, rather than a liquid metal as a cooling medium to minimize the hazard in the event of an accident.

The blanket for thermalizing the 14-MeV neutrons will consist of graphite with cooling passages for the helium. The porosity of the 2-m-thick blanket will be about 50%, and it will be divided into two zones of equal thickness. The inner half of the blanket will be graphite to thermalize the neutrons. The outer half of the blanket will be B₄C which will thermalize and capture the remaining neutrons.

To minimize the specific volume and mass, the reactor must operate with a high first-wall flux. To achieve a long lifetime with a given power and flux, it is desirable to operate with a small microexplosion and a high PRF. The size of the microexplosions and reactor gain decrease with a decrease in the laser-output energy. Thus, a reactor performance can be determined explicitly for a specific mass, volume, and lifetime. This reactor performance must be checked with laser energy-pellet gain relationships to determine that the reactor performance will satisfy the total-system power requirements.

Approximately two-thirds of the tritium used in the pellets will not be burned. The unburned tritium from the microexplosions must be collected by a vacuum system and stored aboard the vehicle while it is in transit. This requirement is based on the cost of tritium, as well as the radiological hazards associated with the tritium.

Advanced systems may directly convert the charged-debris energy to drive the lasers and the vehicle auxiliaries. The neutron energy will be used to drive the turbines using a Brayton cycle.

Marine Laser-Fusion Propulsion

Fission-powered ships are already in wide use, and laser fusion reactors will have environmental advantages over their fission counterparts. Furthermore, the cost and performance of laser fusion reactors are estimated to be comparable to fission reactors. With the continuing rise in fossil fuel prices, both fission and fusion propulsion systems promise to be economically competitive. They have the additional advantage that refueling at sea or in foreign ports is not required.

The technology involved in marine laser-fusion applications closely follows the development of fission marine propulsion systems. Design requirements for fusion-propelled ships are based on what has been learned from the widespread fission marine technology.

Requirements, however, differ according to the needs of the ship owners. Ships intended for military use have different requirements than those intended for commercial use (see Table 6-1). Military ships need to be fast and maneuverable, with low specific-weight and specific-volume propulsion systems. Commercial uses tend to emphasize the economic aspects of the laser-fusion-driven propulsion units.

Naval Propulsion Systems. Superconductivity will strongly influence Navy power in the future because, above about 20,000 hp, it provides the minimum weight, space, and component systems to convert mechanical to electrical energy and vice versa. This will provide more flexibility and operational freedom.

A number of new ship concepts will be tested by the Navy in the next decade. Successful designs will be placed in service near the end of this century and potentially could be propelled by fusion-power plants. Table 6-2 lists these ship concepts and their planned displacement and speed ranges.

The shaft horsepower (shp) requirement for each ship concept varies considerably and depends on internal design features, such as weapons/sensor suite and auxiliary power loads. Figure 6-1 shows the specific power requirements of the ships from which shaft horse power (shp) requirements can be identified. The ship is related to the cube of the speed for

conventional displacement vessels so that very sophisticated propulsion systems will be needed to meet such a range of requirements. By the year 2000, Navy vessels will require higher speed capabilities to retain certain attack options, and surface-effects ships (SES) or hydrofoils may be utilized.² If the SES and hydrofoils are powered by nuclear reactors having low specific weight and volume ratios, they could exhibit essentially unlimited range, rapid response speed, and no need of fuel supply ships and foreign ports.

Figure 6-1 includes the fuel weight for conventional ships. Depending on endurance, a considerable amount of fuel is consumed on conventional ships that could be part of a fusion propulsion plant of increased payload fraction.

The trend in naval propulsion is to greater shp and lower specific weights and volumes. Fusion systems, on this basis alone, must have performance goals that equal the minimum requirements for the

Fig. 6-1. Propulsion-system specific weights for Navy vessels.

Table 6-2. Ship types under consideration by the Navy.

	Displacement, tons	Speed, knots	shp 10 ³ hp
Conventional displacement	>50,000 (carrier)	< 35	250
	>10,000 (escort)	< 35	100
	> 3,000 (patrol)	< 35	40
Small waterplane area twin hull (SWATH)	>10,000 (carrier)	< 35	200
	> 3,000 (escort)	< 50	120
Hydrofoil	< 3,000 (patrol)	< 65	300
Surface-effects ship (SES)	2,000 (patrol)	<100	140
	8,000 (escort)	<100	800
	<10,000 (FBM)	< 30	60
Submarine	< 4,000 (attack)	< 50	120

larger combatants of the future. These ships will probably fall in the 10,000 ton displacement range and require 100,000 to 500,000 shp at specific weights and volumes of less than 30 kg/kW_s (50 lb/shp) and 80 m³/MW_s (2 ft³/shp). Presently, for instance, a 4000-ton nuclear submarine has a power-plant specific volume of 160 m³/MW_s (4 ft³/shp).

An SES weighing 8000 tons and powered by four low-specific-weight fission units of 200,000 hp each has been studied. It would have a payload capability of 1900 tons. For comparison, a fossil-fueled ship, carrying the same payload 3500 nautical miles with the same speed capability, would have a gross weight of about 17,600 tons and would require at least 1.5 million hp. The lower ship cost and reduced fuel costs of the nuclear propelled ships are substantial economic advantages and are well worth development effort by the Navy.³

Commercial Marine Propulsion. Fusion propulsion systems for commercial marine applications, unlike those for military applications, are not built to the lowest specific weight or volume specification. Economics are a much more important consideration. As before, the discussions about the potential for fusion-powered commercial ships are based on analysis and experience with nuclear-fission propulsion.

The commercial maritime industry has been unable to sustain major research and development efforts; consequently, most important advances have been adapted from other industrial or military technology. Naval propulsion-machinery research and development programs have been particularly significant. Therefore, fusion propulsion systems

will probably not be installed in commercial ships unless they are first developed for military use.

The selection of ship size and speed are the most important design decisions confronting a prospective owner. Conventionally, with fossil-fuel systems, the speed has been kept lower than is commercially desirable because of the high costs required to increase them only slightly. There has been, however, a steady increase in the size of ships because larger sizes take only a little more power. Typical relationships between size, speed, and power for conventional bulk carriers are illustrated in Fig. 6-2.⁴ The dramatic increase in the power required for increased speed is clearly shown. Fusion-powered container ships and tankers will probably be economic in the 250,000 to 450,000 dwt class with propulsion power of about 120,000 hp.

Fusion propulsion in the sea-going submersible cargo/tanker ship would be feasible in the 25- to 30-knot range. Below that, the speed-power ratio is too low to benefit from the addition of fusion propulsion.

Another future concept applies to tankers operating in icing conditions. It is projected that a single 400,000-ton displacement, semi-submerged tanker⁵ could transport more than twice as much as two conventional tankers. The propulsion requirement for this ship is, again, in the 125,000 shp range.

It appears that, if nuclear (fission) propulsion becomes competitive with fossil-fuel propulsion for merchant ships, the breakeven point will occur first for ships with the following characteristics.⁶

- High power requirements: 100,000 to 120,000 shp or more.

Fig. 6-2. Displacement vs speed and shaft horsepower for bulk carriers.

- *High ship utilization:* short turn-around time in port, small numbers of loading and discharge ports per voyage, and high load factors; i.e., a high ratio of cargo carried to available ship space.

- *Large (relative) size:* for container ships or other quick-turn-around liner vessels, 15,000 dwt or more; and for tankers, from 150,000 dwt to 300,000 dwt and up.

- *Longer trade routes.*

- *Subsidies:* reduce the shipowner's risk and reduce the break-even point at which the higher capital costs of the nuclear-powered ship are offset by fuel cost savings.

These requirements will most likely hold for commercial fusion propulsion applications as well. Specific weight and volume requirements will be relaxed over those given for Navy ships by a factor of two or more.

Marine Propulsion Reactor Design. A marine fusion-reactor propulsion system will operate on a closed Brayton cycle. For a thermal converter efficiency of 35% and propulsion power of 120,000 shp, the reactor thermal power required will be 260 MW_t. In addition, assuming a power to the laser of 100 MW and to the auxiliary equipment of 50 MW, the total thermal power required from the fusion reactor will be 700 MW_t. The electric power for the laser and auxiliaries will be produced from a turboalternator.

The thermal power cycle can either consist of only a primary coolant cycle where the reactor coolant is circulated directly through the turbine-compressor system or a cycle where the primary coolant heats a secondary coolant, which is circulated through the turbine-compressor system. The tradeoff between the alternative power cycles is a smaller system specific volume and specific mass because of the elimination of a heat exchanger versus the requirement of remote maintenance for the turbine-compressor system.

The laser-system specific volume and mass are about 10 m³/MW and 0.3 kg/kW, respectively, based on the power *input* to the laser. The specific mass of the reactor system controls the design (for the nonoptimum system selected). With a first-wall flux of 1 MW/m², the specific volume and mass of the combined laser and reactor system are 50 m³/MW and 30 kg/kW_s, respectively. The anticipated lifetime of the first wall is about 25 years for a pulse repetition frequency of 10 Hz.

Based on these simple calculations for a nonoptimized, highly conceptual fusion-reactor system, it appears that small inertially confined fusion reactors with fusion energy gains of about seven could compete with advanced fission propulsion systems.

The reactor proposed for marine propulsion also appears to be attractive as a small stationary power plant for isolated military and civilian applications. Therefore, the development of small stationary power plants can be a spinoff from, or result in the spinoff of, fusion-powered propulsion plants.

Aircraft Propulsion

As with marine propulsion, some experience gained in the development of fission reactors for aircraft propulsion can be applied to the development of fusion reactors. This experience is embodied in what remains from the Aircraft Nuclear Propulsion (ANP) project, which was terminated in the early 1960's. This program was plagued with unpredictable technical problems associated with the helium and liquid-metal-cooled reactors of that era and with components, such as air-heat exchangers, bearings, pumps, seals, and the reactor-shield assembly. These problems, as well as uncertain cost benefits and, finally, public concern about the risk involved, led to the demise of the program. The latter problem is still of concern with aircraft nuclear propulsion.

Because of increased public environmental awareness, it is unlikely that any nuclear powered aircraft (fission or fusion) will be built even if it is technically feasible. If these concerns disappear, the following potential applications for long-range nuclear-powered aircraft can be visualized for both land-based and sea planes:

- Logistic aircraft employed for carrying commercial cargo and for rapid military-force deployment.

- Patrol aircraft for forward defense against submarine-launched ballistic missiles, terminal defense against ballistic missiles, command and control, warning and command, and ICBM launch surveillance.

- A strategic-missile carrier.

In this report, we discuss only the commercial cargo application. The allowable fusion reactor mass is based on the chemical fuel it displaces. Reactor masses and powers are converted to maximum allowable specific mass for several large proposed aircraft in Table 6-3. The table shows that as aircraft size (hence, reactor size) increases, the allowable reactor specific mass decreases. However, since larger systems will use their mass more efficiently, this relationship is not immediately prohibitive. Small reactor systems probably cannot compete economically with chemically fueled aircraft because of their high capital cost per unit of

Table 6-3. Maximum fusion reactor specific mass for several aircraft gross weights.

Aircraft gross weight (10 ⁶ lb)	0.8	1	2	10
Total aircraft cruise power, MW _t	170	200	360	1600
Maximum reactor specific mass ^a (kg/kW _t)	0.9	0.5	0.4	0.25

^aChemical fuel carried for chemically assisted takeoff is considered part of the payload. Alternatively, the ICF reactor may be operated at a higher PRT during takeoff. The specific mass shown is based on the nominal design power, i.e., cruise power.

power. The increase in fossil fuel prices over the last decade could change that evaluation; however, the higher cost estimated for fusion reactors compared to fission systems* will offset the chemical fuel price increase to some degree. Therefore, we consider the design of an ICF reactor for a two-million-pound aircraft. This design must have a specific mass of less than about 0.4 kg/kW_t[†] to avoid displacing payload. A maximum specific volume constraint of about 0.5 m³/MW_t must also be satisfied, but it is more speculative because the reactor mass distribution will not match the chemical-fuel load distribution it replaces.

Aircraft Propulsion Reactor Design. A fusion-reactor for an aircraft propulsion system will operate on an open Brayton cycle. Assuming a thermal-converter efficiency of 35% for a cruise power of 125 MW_s, the reactor thermal power will be 360 MW_t. For a laser input power of 95 MW and auxiliary equipment input of 10 MW, the total thermal power required from the reactor is 650 MW_t. The electric power for the lasers and auxiliaries will be produced from a turboalternator.

The energy transfer from the reactor to the air passing through the compressor-turbine combination can consist of a primary cycle to the combustion chamber, or of a closed primary cycle powering an open secondary loop to the combustion chamber. The one-loop cycle is desirable because of its lower specific volume and mass.

For the reference reactor, the first-wall flux must be greater than 10 MW/m² even if only the reactor (without the laser system) is to satisfy the maximum specific volume and mass constraints. If the effective density of the blanket material were somehow reduced by a factor of 5 without degrading performance, the product of thermal-converter efficiency and fusion gain must be 3.3 for the reactor alone to satisfy the maximum specific mass constraint with a first-wall flux of 10 MW/m². However, the specific volume of the reactor alone would still be higher than the maximum permitted specific volume.

Thus, based on these kinds of calculations, it appears that a laser-fusion power plant for aircraft propulsion is not technically feasible because it will not be able to compete with chemical or fission systems on a specific mass or volume basis.*

Extraterrestrial Laser-Fusion Propulsion

Two primary applications of fusion propulsion in space are presently visualized: an earth-moon shuttle or ferry and an interplanetary spacecraft for manned missions. These applications can take advantage of the enormous gain in specific impulses relative to chemical rockets. Nucleons are accelerated in fusion reactions to velocities on the order of 10⁷ m/s, theoretically making impulses on the order of 10⁶ s obtainable.¹ Chemical rockets have specific impulses limited to less than 450 s. Fission systems are limited to specific impulses of less than 2000 s.⁷

Spacecraft capacity is normally measured in terms of ΔV .[†] This index is the sum of all propulsive energy required for translations between stable orbits throughout the entire mission in units of feet per second. The ΔV is a function of the specific impulse of the propulsion system and the payload and spacecraft structure fractions. Approximate ΔV 's for various missions are given in Table 6-4.

Chemical systems, because of their low specific impulses, have ΔV values most suitable to near-earth operations. For example, if a chemical system was designed to make a manned Venus reconnaissance, the payload fraction would be negligible. Even with an advanced fission/chemical staged rocket (nuclear stage specific impulse of approximately 1200 s) the payload would only be about 2% of the total vehicle weight.

*Based on cost estimates of a laser fusion hybrid electrical plant (Chapter 3).

†The specific mass based on power supplied to the engines during cruising. Power recirculated to the fusion reactor and temporary power surges during takeoffs are not considered.

*This assumes that the same fraction of the aircraft is devoted to payload.

†This is the spacecraft ΔV . In the definition of specific impulse (given in the executive summary), Δv refers to the velocity of the driving particles.

Table 6-4. Spacecraft capability required for various missions.

Mission	ΔV , f/s ^a
Escape from Earth's gravity	40×10^3
Round trip from an Earth orbit to the Moon's surface	40×10^3
Manned Venus reconnaissance	150×10^3

^aAdditional ΔV can be used during the mission to reduce the transit time.

Reasonable translunar shuttle times should be on the order of 24 hours. A fission system with a ΔV of 43,000 f/s, i.e., 3,000 f/s more than required, could make the trip in the 24 hours specified. Fusion systems with abundant ΔV could make the trip much faster so that local maneuvers would consume a large part of the transit time. Such a high-performance vehicle has been postulated using a laser-fusion propulsion system. Figure 6-3 gives the calculated performance for a 0.55×10^6 specific-impulse system which produces 130 GW_t and weighs approximately 300 tons.

Fig. 6-3 Laser-fusion-powered spacecraft performance.

Reactor Design for Spacecraft

A laser-fusion extraterrestrial propulsion system will consist of a sustained series of fusion microex-

plosions within an axially asymmetric magnetic mirror (Fig. 6-4). The thrust of the vehicle is produced by the redirection of the charged plasma debris from the microexplosion through the larger of the mirror-loss cones and out the rear of the spacecraft.

The power plant of a specific-impulse-maximizing spacecraft bears very little resemblance to that used in terrestrial propulsion systems. Thrust is no longer produced as a by-product of a thermal cycle, but directly in the form of plasma debris from the fuel pellet. Neutrons and x rays produced in the fireball are worse than useless; if intercepted, their energy must be rejected to space. The target design must maximize the ratio of ion energy to neutron and x-ray energy, while at the same time minimizing required laser energy. Vehicle mass is dominated by the need for heat rejection to space—which must be done radiatively. Waste heat is developed in two ways: component inefficiencies and neutron and x-ray interception. The above factors dictate an unenclosed thrust chamber so that less than 2% of the solid angle seen by the microexplosion is occupied. Thus, while charged particles are redirected by the magnetic mirror providing thrust, most of the unwanted neutrons and x rays escape to space harmlessly. Only 2% of the neutrons hit the superconducting-magnet radiation shields, payload shadow shields and laser beam mirrors. Even this 2% represents a large heat-rejection load, but it has some value because it permits tritium breeding in the lithium shields.

The optimal pellet is an intermediate ρR design, mostly deuterium with just enough tritium to facilitate ignition. Such a pellet burns far more efficiently than low ρR pellets that require a smaller specific laser size. Furthermore it allows laser reexcitation energy to be produced by direct conversion from the interaction of the charged plasma debris with an induction coil. Between 50 and 70% of the fusion energy is in charged debris from the microexplosion.

Hyde, Wood, and Nuckolls did two studies on rocket propulsion with laser-fusion microexplosions.^{2,11} Their design utilizes heat-pipe radiation to dump the neutron and photon heat from the structure, radiation shields, and lasers into space. The lithium for tritium breeding is circulated using MHD pumps utilizing the existing mirror magnetic field.

Three major propulsion-system components are vulnerable to meteoroid damage. The laser and coil shield must be made almost invulnerable to

Fig. 6-4. Extraterrestrial vehicle thrust chamber.

meteoroid damage; therefore, they are protected by a double-wall bumper shield. The heat pipes are protected by only a single wall, and the loss of a portion of them has been anticipated in the design.

Hyde, *et al.*, estimates the total propulsion-system mass to be 300 tons, distributed as shown in Table 6-5. About 112 tons of the laser-system mass and 14 tons of the thrust chamber mass are from their heat-rejection systems. Thus, the mass of the heat-rejection system constitutes 40% of the total mass of the propulsion system. The mass of the neutron shields in the thrust chamber is 20 tons while the mass of the coils in the thrust chamber is about 15 tons.

The specific-impulse-maximizing spacecraft study includes a pellet design which requires 1 MJ of laser light from a 33% efficient electron-beam-excited system. The total yield from the microexplosion is 260 MJ, with 120 MJ producing thrust. The power needs of the propulsion system are almost exclusively those of the laser because refrigeration and Li^6 -pumping power are negligible. For a PRF of 500, the system develops 2.2 tons of thrust at a specific impulse of 3.5×10^5 s, or an exhaust velocity of 6×10^6 m/s. For a spacecraft with a 300-ton propulsion system and a 200-ton deuterium fuel load, a payload of 100 tons can make a round trip to any point in the solar system in one year. Interstellar missions of a few decades in transit time are also feasible with a laser-fusion propulsion system.

Conclusions

Laser-fusion reactors for propulsion (as they are now viewed) would operate in a low-yield, high-PRF mode with high first-wall fluxes. From inertial considerations, the first wall should be a dry wall rather than a wet or fluid wall. These reactors could operate on a parasitic fuel cycle from larger stationary fusion-power reactors.

Although there is an apparent need for advanced, low-fuel-cost propulsion systems, it is too early to determine if laser fusion will be an economical alternative to future chemical or fission plants for marine propulsion. Aircraft applications appear even more uncertain because of the stringent specific volume and mass technical constraints. Laser-fusion propulsion plants for extraterrestrial propulsion are possible, provided there is a demand for intrasolar system or interstellar missions.

Table 6-5. Spacecraft fusion-propulsion-system mass.

Component	Mass, tons
Propulsion system (total)	300
Laser system	151
Thrust chamber	54
Energy distributor	17
Refrigeration	9
Tanks	25
Miscellaneous parts	44

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APPENDIX

A DEVELOPMENT SCENARIO FOR INERTIAL CONFINEMENT FUSION

Long-Range Plan

As the inertial-confinement fusion (ICF) program approaches a demonstration of scientific feasibility, it becomes increasingly important to prepare long-range plans. The plans should be able to accommodate optional technical approaches to commercial fusion-power production and provide for varied paces of technological development and application. The latter provision would allow management to keep the program in line with changes in technical progress, national needs, and the nation's commitment to inertial confinement fusion (ICF). The plan should also establish the goals and milestones required for commercial applications. Establishing goals would enable us to identify the requirements and tasks in the early (scientific) stages of development, working back from the application dates. Finally, we wanted a plan that would identify the major issues and decision points. Moreover, the achievement of these objectives completely defines the scope of our long-range plan.

In addition to these objectives, there were a few assumptions and guidelines that significantly influenced the development of this long-range plan for ICF.

- The ICF program will be competing with other long-term sources of energy, and we must anticipate major priority decisions.
- Commercial ICF power production will be developed by an industry that is working in conjunction with government, national laboratories, and utilities.
- The ICF program will go through several phases of research and development before commercial power is achieved. Key decisions will be required in each phase.
- A broad technology base must be established that will both feed and be fed by the various developments in the program.

The flow of logic for several optional paths to commercial fusion power is diagrammed in Fig. A-1. This logic is based on the premise that experiments to verify the scientific feasibility of initiating high-gain microexplosions are independent of the development of high-average-power ignition sources.

In addition, solid-state laser technology represents the most highly developed short-pulse, high-peak-power driver technology in existence. Consequently, the series of solid-state laser-fusion facilities at LLL (from Janus to Nova) is expected to provide the earliest understanding of implosion physics and demonstrate the scientific feasibility of ICF. Once the physics of inertial confinement fusion are understood, and, after high-gain microexplosions have been demonstrated, the program can progress to the engineering phases of development and selection of the most promising high-average-power driver for an experimental power reactor. Potential ignition sources for high-average-power operation of the experimental reactor include ion beams, gas lasers, and electron beams.

The Phases of Development

A more comprehensive scenario for developing inertial-confinement fusion is presented in Fig. A-2. In this plan, the program progresses through several phases: exploratory development, advanced development, engineering development, and commercial development. The demonstration of technical feasibility has been split between the advanced and engineering phases because of the prevailing assumption that two experimental power reactors will be needed before a demonstration power reactor can be built. As shown, this long-range plan provides for optional technical paths to commercial fusion. Moreover, the plan is based on the premise that a broad scientific base must be established in the earliest phase of development and must then be allowed to operate through a technical framework that will both feed and be fed by the various developments.

Exploratory Development

Those criteria required to demonstrate the scientific feasibility of inertial confinement fusion will be met in the exploratory development phase. Scientific feasibility will be demonstrated when a high-gain ($G > 20$)

Fig. A-1. Inertial confinement fusion development logic.

thermonuclear microexplosion is achieved and a suitable high-average-power ignition source is developed. These accomplishments obviously must precede the decision to build an experimental power reactor.

The major program elements in the exploratory phase are separated into three distinct segments: inertial-confinement physics, source-coupling physics, and source feasibility. Neodymium:glass lasers operating at 1.06 μm with low-average-power capabilities will be the primary tools in the inertial-confinement physics program. Nova, the largest of the Nd:glass laser facilities is projected to provide the on-target energies and power required to drive pellets suitable for commercial power plants on a single-shot basis. The Nova facility will also be capable of driving significant national security experiments.

The source-coupling physics program will be concerned primarily with quantifying and maximizing the efficiencies of coupling other forms of energy—different-wavelength lasers, ion beams, and electron beams—to the fusion target. In the source-feasibility program, several high-average-power sources (gas lasers, ion beams, and electron beams) will be developed and analyzed.

The facility for pellet development will support work in the exploratory phase by providing 10 pellets per day for Nova. This facility must also develop the technology to produce pellets at the increased rates required by the first experimental power reactor (1000 pellets per day).

The major program elements initiated in this exploratory development phase will continue throughout the development of ICF, thereby forming a foundation of continually expanding technology. The decision to proceed into the next phases (advanced and engineering development) will be based on the successful demonstration of a high-gain microexplosion and on the development of a suitable high-average-power driver.

Advanced Development

The first experimental power reactor based on the ICF concept, EPR I, will be undertaken in the advanced development phase. This reactor will be the first of a series of major experimental facilities required to verify the physics and engineering principles that are required to commercially develop ICF. The primary function of EPR I will be to provide information on the integrated engineering performance of a complete

Fig. A-2. Phases of development in the long-range plan for inertial confinement fusion.

ICF system (source, target, and reactor). In addition, EPR I will be expected to demonstrate the capability to produce electric power. An experimental power reactor supporting these objectives will:

- Operate at approximately 10^3 pulses/day
- Generate ≈ 10 MW of thermonuclear power
- Have limited plant availability $\approx 20\%$
- Obtain a fusion-energy gain $\geq 3^*$
- Achieve high-temperature operation
- Cost approximately 500 million dollars.

In the advanced development phase, pellet technology will consist primarily of producing 1000 pellets per day for EPR I. The capability to produce pellets even more rapidly (10^5 pellets/day) will have to be developed to meet the requirements of the next experimental power reactor.

*Fusion-energy gain is defined as the product of pellet gain and laser-system efficiency. As such, it represents the ratio of thermonuclear-energy output to electrical-energy input.

A test and engineering facility also will be built and operated to investigate the effects of the thermonuclear environment on the final focusing elements, the first wall, and the blanket structure. This facility will not have a high-average-power capability and therefore will be used to investigate single-pulse phenomena (<10 pulses/day). These test and engineering requirements could be met most economically by utilizing the present Nova laser fusion facility.

Engineering Development

This third phase of the program will focus primarily on the major technical problems associated with an ICF power plant. These include the development of:

- A high-average-power driver with the required efficiency ($>1\%$) and reliability ($>70\%$).
- A first wall able to withstand the effects of x rays, debris, and neutrons from the microexplosion.
- Structural materials that can withstand the cumulative damage effects of high-energy neutrons and cyclical stresses.
- Final-focusing elements that can be placed far enough away from the microexplosion that they can last a reasonable length of time.
- The technology to cheaply mass-produce the fusion targets.

The second experimental power reactor, EPR II, will be built to demonstrate limited steady-state electrical generation in a smaller and less costly mode than is available with a demonstration power reactor. The experimental power reactor that can accomplish this objective will:

- Operate at 10^5 pulses/day.
- Generate considerable thermonuclear power (>100 MW_t and tens of MW_e).
- Increase plant availability to $>40\%$.
- Achieve fusion-energy gain ≥ 6 .
- Demonstrate tritium regeneration and recovery.
- Cost approximately 1 billion dollars.

In addition, a test and engineering facility will be started in this phase to qualify materials for commercial power-plant operation. This facility will:

- Generate ≈ 10 MW of thermonuclear power.
- Consume ≤ 100 MW of electric power off-line.
- Achieve fusion-energy gain ≥ 0.1 .
- Extend plant availability to $\approx 70\%$.
- Test materials for commercial operation to 10^{23} neutrons/cm².
- Cost approximately 500 million dollars.

Long lead times are generally required to develop and test new materials. Therefore, it would be desirable to construct this high-average-power test facility much earlier in the program. Unfortunately, it is difficult to project a more rapid development of the technology that is required to operate at 70% plant availability.

The pellet production facilities in this phase will provide 10^5 targets per day for both EPR II and the materials test facility. At this stage, we must develop the technology for a fuel factory to mass-produce targets cheaply enough to allow economical power production.

Nonelectric applications of ICF have been identified, including propulsion, fissile-fuel production, high-temperature process heat, burnup of radioactive fission waste, and synthetic-gas production. The technical feasibility and economic incentives for developing these alternative applications will be evaluated during this phase. The decision to pursue any of the alternative applications in conjunction with the production of commercial electricity must be made by weighing the recognized benefits against the additional costs for development.

Commercial Development

The major efforts in this final phase of development will be associated with planning, constructing, and operating a demonstration power reactor. This facility will be required to demonstrate the potential for economically produced ICF electricity over alternative long-range sources of energy by operating in a safe, reliable, and environmentally acceptable manner. In short, the demonstration power reactor (DPR) will:

- Generate 500 to 1000 MW (several 100 MW_e) of thermonuclear power.
- Reach a plant availability $\approx 70\%$.
- Breed tritium.

- Be fully licensed as a power reactor.
- Consume less than 25% of generated power as recirculating power.
- Achieve a fusion-energy gain >10 .
- Cost less than 2 billion dollars.

Time Schedules and Options

For planning purposes, alternate time schedules for major engineering facilities are projected in Fig. A-3. The three planning options are designated as cautious, aggressive (midrange), and accelerated.

In the cautious plan, the decision to begin the *design* of a major engineering facility is made only after the preceding facility has achieved the milestones required for scientific justification. For example, the planning and design phase of the EPR II would not begin until EPR I had operated and achieved its objectives. In this plan, technical progress is limited by the availability of funds and the demonstration power plant would not operate until after the turn of the century.

In the aggressive plan, the decision to begin *construction* of a major engineering facility would not be made until the preceding facility had achieved the milestones required for scientific justification. With this logic, construction of EPR II would not begin until EPR I had achieved its objectives. Funding is adequate and new projects are undertaken when their success is reasonably assured. A demonstration plant would operate at the turn of the century.

In the accelerated plan, the need for a new energy source is extremely urgent. Major engineering facilities are addressed in parallel, and new facilities are begun as soon as their *need* is defined. Thus, planning for EPR I would begin in 1983, before the scientific feasibility of such a plant has been demonstrated. Reasonable scientific justification would be obtained by extrapolating results from previous facilities. Funding is available

Fig. A-3. Engineering facilities for three long-range planning options.

and adequate for the construction of major facilities in parallel. Following this plan, a demonstration plant would operate in the mid-1990s.

Comparing these three plans, we note that from the slowest to fastest option, there is a difference of 11 years in the operational date of the demonstration power reactor. However, in the accelerated plan, the decrease in time to the DPR is gained at the expense of parallel development of major facilities. This high-risk strategy would seriously impact the rate of spending in the program, as well as the rate of employing the technology base of manpower and production capabilities.

In Fig. A-4, the time schedule for the engineering facilities in the aggressive (midrange) plan is presented together with the time schedule for the development and operation of the required scientific facilities. Here we see that the decision to begin EPR I is made after Nova has been operating long enough to demonstrate a high-gain microexplosion adequately, and after all of the potential high-average-power sources have been operating long enough to be evaluated. Pellet development is the only major engineering technology that strongly overlaps the design and construction of the scientific facilities. From this, it is evident that we must begin to develop the technology to mass-produce targets immediately so that it will be available when the decision to build EPR I is made. We have estimated the timing for all the pellet-development facilities assuming that current pellet technology can be developed rapidly enough to prevent pellet availability from becoming a pacing element in the program.

Fig. A-4. Scientific and engineering facilities for the aggressive option.