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REQUIREMENTS FOR LOW COST ELECTRICITY AND HYDROGEN FUEL PRODUCTION FROM MULTI-UNIT INERTIAL FUSION ENERGY PLANTS WITH A SHARED DRIVER AND TARGET FACTORY*

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ABSTRACT

This work explores the economy of scale for multi-unit inertial fusion energy power plants based on the molten salt HYLIFE-II fusion chamber concept, for the purpose of producing lower cost electricity and hydrogen fuel. The cost of electricity (CoE) is minimized with a new IFE systems code IFEFUEL5 for a matrix of plant cases with one to eight fusion chambers of 250 to 2000 MW_e net output each, sharing a common heavy-ion driver and target factory. Improvements to previous HYLIFE-II models include a recirculating induction linac driver optimized as a function of driver energy and rep-rate (average driver power), inclusion of beam switchyard costs, a fusion chamber cost scaling dependence on both thermal power and fusion yield, and a more accurate bypass pump power scaling with chamber rep-rate. A CoE less than 3 cents/kW_eh is found for plant outputs greater than 2 GW_e, allowing hydrogen fuel production by water electrolysis to provide lower fuel cost per mile for higher efficiency hydrogen engines compared to gasoline engines. These multi-unit, multi-GW_e IFE plants allow staged utility plant deployment, lower optimum chamber rep-rates, less sensitivity to driver and target fabrication costs, and a CoE possibly lower than future fission, fossil, and solar competitors.

I. BACKGROUND AND CONCEPT

A. Motivation

This report extends earlier work [1] on a generic model for a multi-unit Inertial Fusion Energy (IFE) plant producing electricity and hydrogen fuel to include subsystem costs for a specific IFE target chamber concept called HYLIFE-II.[2] This work revisits use of one driver and target factory for several fusion (target) chambers as was first considered in the HIBALL study,[3] and later by Meier and Hogan.[4] This study exploits lower cost heavy-ion drivers based on optimized heavy-ion recirculating induction accelerators (RIA),[5] together with all-liquid-wall HYLIFE-II fusion chambers[2] for lower maintenance cost, higher availability, and tolerance for higher optimum fusion yields. This work is motivated to justify fusion development addressing two new future energy needs:

1. Fusion development needs to be reoriented to compete better with utility deregulation, which will promote stiffer competition for lowest CoE. When natural gas becomes too costly for smaller, dispersed gas turbine plants, large independent "fusion energy parks" could be built to sell power to several adjacent utilities.

2. Fusion, along with fission breeders and solar, is one of only three inexhaustible sources of electricity. Using water electrolysis with sufficiently-low-cost electricity, fusion could provide both electricity and renewable hydrogen for electric and hydrogen-powered vehicles, thereby reducing US dependence on foreign oil imports, the associated trade deficit, and urban air pollution. Development costs for IFE hydrogen plants might be supported by large oil companies (who currently reinvest > $20 B/yr on development), after fusion ignition demonstration (the mission of the U.S. National Ignition Facility), and when a larger fraction of low emission vehicles become mandated by law.

B. Concept

Figure 1 depicts a conceptual multi-unit IFE plant producing both electricity for the grid as well as hydrogen with a water-electrolysis plant. Higher average revenues for such a plant might be achieved by selling electricity during peak hours of the day, and selling hydrogen into distribution pipelines for storage at night. Interconnected

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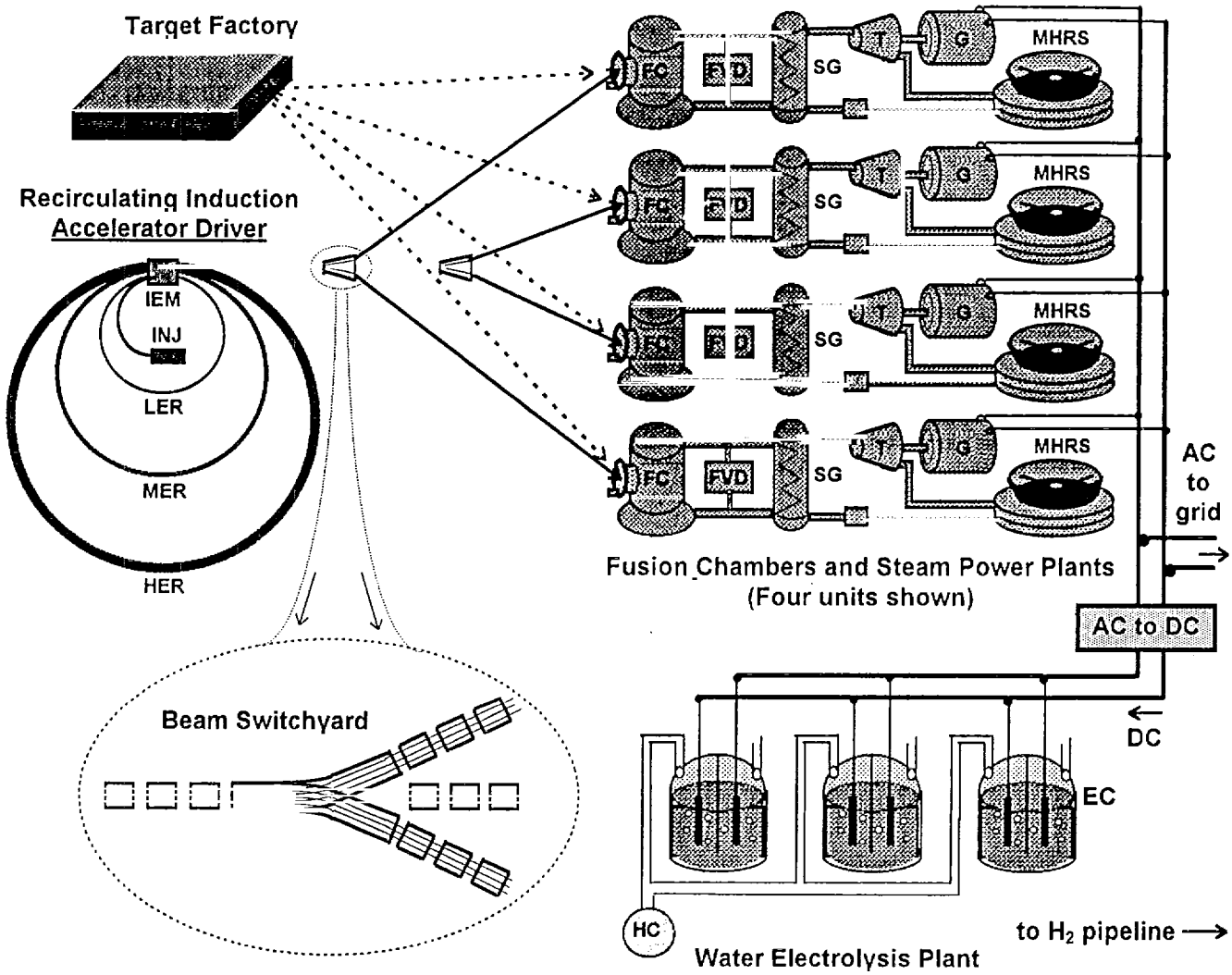


Fig. 1: A conceptual multi-unit IFE plant sharing a driver (through a beam switchyard) and a target factory, producing both electricity for the grid, and hydrogen fuel by water electrolysis. The recirculating induction accelerator driver consists of an injector (INJ), a low, medium and high energy ring (LER, MER, and HER, respectively), and a insertion/extraction magnet (IEM). Each identical and separate unit includes a HYLIFE-II-type fusion chamber (FC), Flibe vacuum disengagers (FVD) for tritium removal, steam generators (SG), steam turbines (T), generators (G), and a main heat rejection system (MHRS). The water electrolysis plant consists of an AC to DC rectifier, banks of electrolyzer cells (EC), and a hydrogen compressor (HC). The electrolysis plant could be a few to several hundred miles distant from the electric plant.

hydrogen pipelines might buffer unscheduled plant outages at least as large as outages of typical 200,000 bbl/day oil refineries tolerated today (>10 GW in fuel energy-equivalent production rates). Large commercial electrolysis plants have achieved 80 % conversion efficiency of electricity to hydrogen,[6] or 34 % overall efficiency including a 43 % net thermal conversion efficiency, and higher electrolysis efficiencies are thought to be possible with further development. Advanced thermochemical cycles with about 40% overall efficiency have also been considered for water splitting using high temperature fusion heat directly.[7] However, water electrolysis is a conservative choice for this study to avoid any possible tritium contamination of the hydrogen fuel product. It may be desirable to transmit electricity from the electric plant to more than one water-electrolyzer plant several hundred miles closer to urban areas of use, to minimize distances of new hydrogen pipelines.

C. Economics goal

Figure 2 shows the relationship used in this study between the cost of electricity and the cost of delivered hydrogen (assuming no taxes on hydrogen), including large scale water electrolyzers at 250$/kW$_e$ total capital cost, hydrogen transportation by pipelines, and compressed storage (all costs in this paper will be quoted in 1993$). Fig. 2 is based on the work of Plass,[8] adjusted for 80% efficient electrolysis instead of the 70% Plass assumed. The cost of hydrogen (CoH) is minimized in this study by minimizing CoE, the dominant contributor to CoH. The capital costs for the water electrolyzer plants, generally small compared to the electric plant, are contained in the CoH. A goal of delivered CoH =$13.4 /GJ

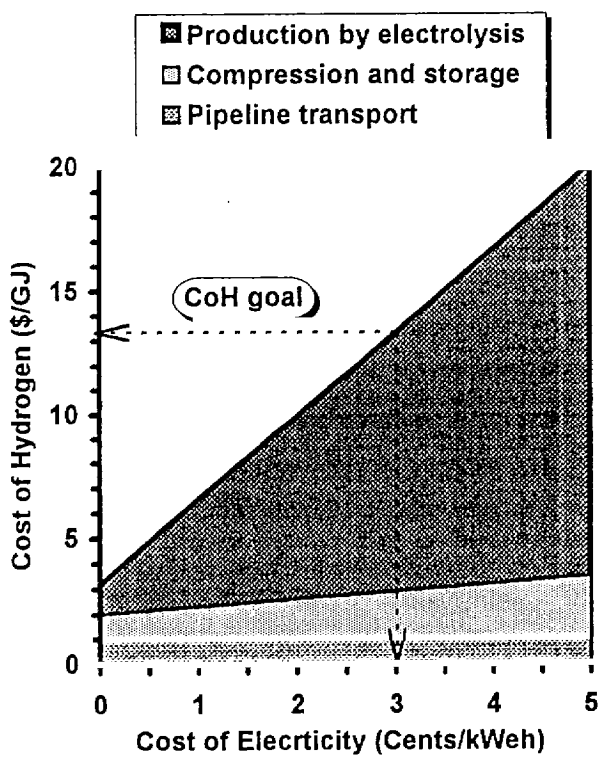


Fig. 2: Cost of hydrogen (CoH) by water electrolysis as a function of the cost of electricity (CoE). (No H_2 taxes)

(no taxes) as marked in Fig.2 corresponds to a CoE = 3 cents/kW$_e$h. This assumes hydrogen is not taxed, which could be the case to provide an environmental credit. Gasoline costing $1.3 /gallon at the pump corresponds to 10.8 $/GJ, but since hydrogen-optimized internal combustion engines or hydrogen fuel cells would be 45% efficient, versus 25% for optimized gasoline engines in otherwise-equivalent hybrid vehicles,[9] a CoH=$13.4 /GJ corresponds to less consumer fuel cost per mile for hydrogen. A recent energy-pathway benchmark analysis[10] derives the CoE requirement for equal H_2 fuel cost per mile, *including equal taxes*, to be 2.3 cents/kW$_e$hr, giving delivered CoH = $19.4 /GJ. This study adopts the 3 cents/kW$_e$h mark as the initial goal for hydrogen electrolysis plants (assuming an initial environmental tax credit), with 2.3 cents as the ultimate goal including taxes when hydrogen would become the dominant fuel use.

Given that previous fusion plant designs for either IFE or MFE have tended to produce CoE's in the range of 5 to 7 cents/kW$_e$h, meeting the goal for electrolytic hydrogen of 3 cents/kW$_e$h presents a very significant challenge. The strongest leverage to lower CoE that has ever been found in fusion plant designs has been the economy of scale for plant outputs greater than 1 GW$_e$. Fortunately, the fuels market is sufficiently larger than the electricity market that one may contemplate fusion hydrogen plants on the energy scale of oil refineries (10 GW$_e$ equivalent).[10] For IFE, once investment for driver energy exceeds the threshold for significant target fusion gain, higher average power output is obtainable with small additional driver investments by increasing the shot repetition rate (rep-rate), resulting in strongly decreasing CoE with power output.[4] However, higher rep-rate can be exploited only up to some practical upper limit on the chamber clearing rate, probably < 10 Hz for 1 GW$_e$ output. To exploit the economy of scale further than 1 GW$_e$, the driver beam can be switched between N_u -fusion chamber units, as long as the driver recovery and cooling allows N_u-times higher driver rep-rate. Steady-state cooled induction-core modules similar to those used in heavy-ion accelerator designs have been demonstrated at Sandia[11] at 100 Hz, more than needed for cases of interest here.

D. Driver Choice

The choice of driver for multi-unit plants is heavily influenced by the desire to keep the routing of beams from one driver to several fusion chambers as simple as possible. Indirect drive, especially for heavy-ion hohlraum targets, affords the possibility of single-sided illumination of double-ended targets,[12] assuming such targets can be designed with target fusion energy gains close to that with two-sided illumination.[2] The driver in Fig.1 is a schematic drawing of a heavy-ion RIA driver[5] driving four fusion chambers. A cluster of four to 12 beams is injected and accelerated successively in low, medium, and high energy rings to a final 5 to 8 GeV energy. The beams are then extracted by a kicker magnet shown at the top of the large ring, and directed to a beam switchyard, with detail shown expanded below. This type of heavy ion driver concept was used for this study because a comprehensive RIA

design study[13] completed earlier by LLNL and LBL indicated 50% reduced costs relative to linear induction heavy-ion accelerators, an important advantage to help meet the CoH goal. However, future improvements to linear induction accelerators, optimizing ion masses and beam currents for specific target designs, and with technology advances such as higher acceleration gradients or using a larger number of smaller beams to achieve higher current at lower beam energy, may equally well lead to similar reduced driver costs.

The switchyard example shown in Fig.1, based on the conceptual work of Leber,[14] employs two switch magnets. One switch magnet can feed three beam lines with their final focus systems, so that N-switch magnets can feed up to 2N+1 chambers. In this example, the second switch magnet feeds only two beamlines for a four chamber plant. The costs of the switch magnets and extra transport magnets are relatively small compared to the RIA accelerator itself. However, care will be needed in the detailed design of the beam switches for acceptably-small beam emittance growth to avoid any significant increase of the beam focal spot size.

E. Fusion Chamber Choice

Fig.3 shows a cutaway view of the HYLIFE-II fusion chambers represented in Fig.1. Inside the vessel is an array of fixed and oscillating jets of Flibe molten salt (Li_2BeF_4) which protect the vessel walls from direct neutrons, soft xrays, and plasma debris from the targets. The oscillating Flibe jets form periodic cavities in the center for targets to be illuminated by a cluster of heavy-ion beamlets entering from the lower right through the rotating shutter. See references 2 and 17 for more details. Note the array of pumps around the base of the vessel. These bypass pumps recirculate Flibe molten salt coolant through the chamber on a short loop many times faster than the flow required to transfer heat to steam generators. This large bypass flow is needed to inject the Flibe with a sufficient downward speed to clear the chamber of liquid splash between shots. This study incorporates an improved bypass pumping model (updating the earlier model used in ref. 2).

Multiple fusion chambers of the HYLIFE-II-type are chosen for this study because (a) with all renewable-liquid Flibe jets protecting the walls, no solid materials needed near the targets leads to lower maintenance cost and higher plant availability, which is very important to the

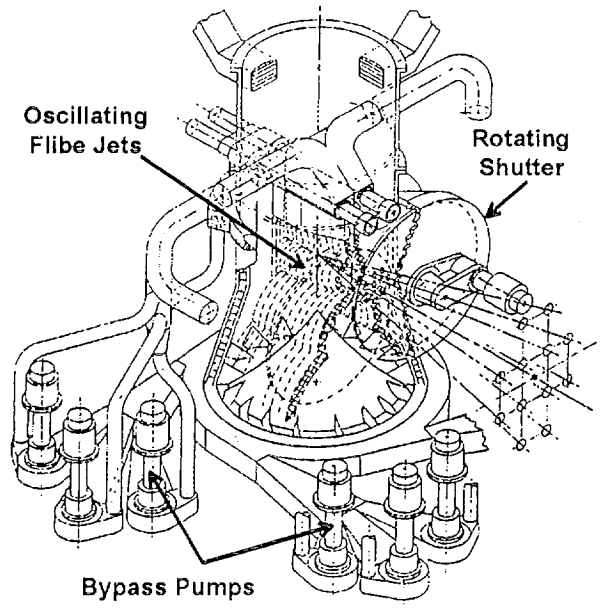


Fig.3: The HYLIFE-II fusion chamber: Oscillating Flibe molten salt jets create periodic cavities in the liquid for targets. Arrays of bypass pumps increase the circulation rate of Flibe to speed chamber clearing.

goal of achieving low CoE for hydrogen production. Although other IFE schemes with mostly-renewable fluid or granular walls such as OSIRIS[15] and CASCADE[16] may also prove to have low equivalent fusion chamber maintenance costs, the all-liquid-wall HYLIFE-II target chamber concept[2] should have the least materials lifetime uncertainties and the highest availability. The equivalent "fusion fuel cost" of replacing blankets must be minimized if fusion is ever to beat fission fuel-cycle costs. Fuel costs become a key potential fusion CoE advantage over fission at larger plant sizes (fuel costs are nearly zero for fusion, but contribute about 0.7 cents/kW_ehr to the CoE from fission). (b) Previous work has shown that large IFE plants will optimize to higher driver energies and fusion yields than small plants.[1] The HYLIFE-II liquid-jet-filled chambers are designed to tolerate high yields, as in the original High Yield Lithium Injection Fusion Energy concept.[17] (c) Previous work[1] has also shown that the fusion chamber and balance-of-plant costs become more dominant for larger IFE plants. The low tritium inventories in the HYLIFE-II Flibe coolant, and efficient tritium removal by two stage vacuum disengagers, allows the HYLIFE-II fusion chambers, main heat transport system, and steam generators to be classified as non-nuclear grade,[2,12] further reducing costs.

The next Section II describes the power balance model, the subsystem costs, and the basic CoE minimization procedure used in the IFEFUEL5 systems code[18] to assess the potential economics and economy-of-scale for multi-unit HYLIFE-II power plants. Section III descibes the results of the economic surveys for a matrix of plants with one to eight units and net powers per unit of 0.25 to 2 GW_e. Section IV summarizes findings, critical issues and associated development requirements. Recommendations for future work are discussed in Appendix I.

II. COST MODEL AND OPTIMIZATION

A. Power Flows

Given a target fusion energy gain G as a function of the driver energy E_d delivered to a specific choice of target, the canonical independent variables that control IFE plant cost and performance are the desired average net electric power $P_{e(net)}$ and either the driver energy E_d or the fusion chamber rep-rate RR_{ch}, the latter two variables each being determined in terms of the other through a power balance relation (Eq.1) giving the desired $P_{e(net)}$. This study determines the optimum E_d and RR_{ch} by minimizing CoE with respect to E_d as the chosen prime independent variable. Figure 4 plots the target energy gain G and associated fusion yield Y as a function of E_d, which are used in this study for a heavy-ion driven, indirect drive target with a 2 mm radius spot size (reproduced from Fig.9 in ref. 2). Both E_d and Y are expressed in MJ. Also shown is the fusion chamber rep-rate RR_{ch} for a reference 1 GWe single unit electric plant, based on the power balance relationships given in Eqs.1-9.

The total net electric power output $P_{e(net)tot}$ from a multi-unit IFE electric plant is the total gross electric power $P_{e(gross)tot}$ minus the recirculating electric power $P_{e(rec)tot}$:

$$P_{e(net)tot} = P_{e(gross)tot} - P_{e(rec)tot} \quad , \tag{1}$$

(all electric powers in MW_e ; thermal powers in MW_{th}). The total gross electric power is given by:

$$P_{e(gross)tot} = \eta_{spp} N_u E_d RR_{ch} (GM_t + 1) \quad , \tag{2}$$

where η_{spp} is the net steam power plant efficiency, taking into account all the internal auxiliary power requirements of the steam cycle, and where M_t is the total blanket energy

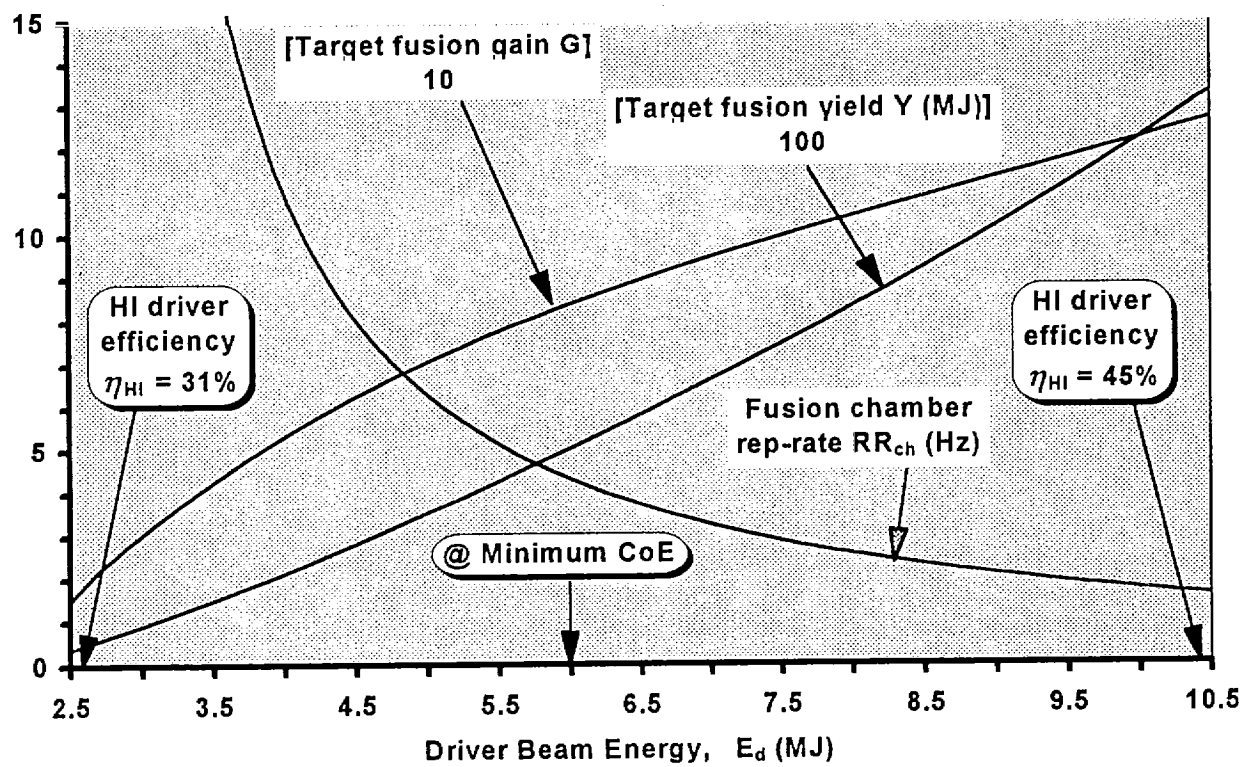


Fig. 4: Indirect drive target fusion energy gain G/10 and yield Y/100, with fusion chamber rep-rate RR_{ch} for a 1 GW_e single unit plant, plotted as a function of the driver beam energy E_d. The driver energy minimizing CoE is indicated.

multiplication factor. The total recirculating power is:

$$P_{e(rec)tot} = N_u\,[P_{BPP} + P_{loop} + P_{aux}]_{unit} + P_{driver} \quad , \qquad (3)$$

where P_{BPP} is the bypass pump power per unit:

$$P_{BPP} = (6.83 + 0.794 RR_{ch} + 0.229 RR_{ch}^2)\eta_p^{-1} \, , \qquad (4)$$

with η_p the pump efficiency; P_{loop} is the pumping power per unit for the Flibe flow to the steam generators:

$$P_{loop} = 3.55(P_{th}/1000)\eta_p^{-1} \quad , \qquad (5)$$

with P_{th} the thermal power per unit given by:

$$P_{th} = E_d RR_{ch}(GM_t + 1) \quad ; \qquad (6)$$

P_{aux} is the auxiliary power per unit (excluding that for the steam power plants, which is already contained in the definition of η_{spp}):

$$P_{aux} = 0.0072 P_{th} \quad ; \qquad (7)$$

P_{driver} is the electric power consumed by the shared driver operating at a driver rep-rate = $N_u\,RR_{ch}$:

$$P_{driver} = E_d\, N_u\, RR_{ch}\, \eta_{HI}^{-1} \quad , \qquad (8)$$

where the driver efficiency (energy delivered to the target/ electrical energy into the driver) is a function of the driver energy, since the induction core losses become relatively smaller the more beam energy passing through them: [19]

$$\eta_{HI} = 0.35\,(E_d/4)^{0.25} \quad . \qquad (9)$$

The value of η_{HI} is given at E_d = 2.5 and 10.5 MJ in Fig. 4.

The above power flow models are similar to those used to construct the HYLIFE-II power flow diagram (Fig. 5 in ref. 2), except that the 8 MW of chamber wall loss is now estimated to be negligible, the heavy-ion driver efficiency η_{HI} is now correctly a function of the beam energy, the bypass pumping power P_{BPP} now scales correctly with chamber rep-rate, and there is now a separate pumping term, P_{loop}, for the Flibe flow to the steam generators.

B. The IFEFUEL5 Systems Code Cost Model

A Windows MathCAD systems code called IFEFUEL5 (ref 18) was constructed to solve the above power balance Eqs. 1-9 for a matrix of 60 or more driver energies, for one to eight unit plants, and for net powers per unit of 250 to 2000 MWe. Twenty-three subsystems are costed and summed to get the total direct capital cost for each point, and then the driver energy is selected for each case which minimizes the CoE. IFEFUEL5 was carefully benchmarked against the original QUATTRO PRO cost spreadsheet [20] "MGEM5" used by Hoffman for HYLIFE-II reference cases.[2] The documented IFEFUEL5 code in reference 18 includes cost-scaling relationships for the 23 subsystems, most of which are the same as used in MGEM5 for the previous HYLIFE-II report,[2] but also includes the improvements to the power flows as noted above, and also improvements to the cost scaling of several subsystems. Due to length limitations for this paper, we refer the reader to the detailed costing of all subsystems in reference 18, which comes as close to "bottoms up" costing as most fusion studies of this kind can afford to do.

Both in IFEFUEL5 and in some of the reporting of direct costs in the following Section III, the costs of the 23 subsystems are segregated into three groups to help graphically visualize the different relative costs of major portions of the plant with driver energy and plant size: a Driver Group consisting of the driver, driver building, beam switchyard, and target injector systems; a Fusion Chamber Group consisting of the fusion chambers and buildings, bypass pumps and piping, target factory and target factory building, main heat transport system, tritium management system, remote maintenance equipment, and steam generators; a Steam Plant Group consisting of the turbine generators and buildings, electric plant equipment, miscellaneous equipment and main heat rejection system. We avoid the term "Balance-of-Plant" in referring to the steam plant group, since some definitions of balance-of-plant include the steam generators and some main heat transport equipment we have put into the fusion chamber group. Later on, we will also report the subsystem costs for two reference cases in the traditional fusion plant cost accounting system to allow the reader to make direct comparisons with other fusion studies. Since the 30-page IFEFUEL5 model is too lengthy to reproduce here, we will discuss in the following only the important improvements and changes in the IFEFUEL5 model compared to those used in the earlier HYLIFE-II.[2]

1. *Multi-unit cost credits.* There has long been a common industrial experience that manufacturing costs decrease per unit in a regular logarithmic fashion with the production of larger numbers of identical units. We assume there would be as many multi-unit HYLIFE-II plants as the 4 to 6 oil refineries that typically provide transportation fuel to each major metropolitan area.Thus, we assume that our multi-unit plants costs are more N^{th}-of-a-kind than first-of-a-kind costs. However, to credit the fact that the total number of individual units manufactured is Nu-times larger than the number of multi-unit plants, we apply cost

reduction factors to the direct costs of replicated units in our multi-unit plants, factors suggested to us by Delene[21] that apply to the total direct costs for multi-unit fission plants: we take the direct cost of N_u - replicated units in one multi-unit plant to be a function $cd(N_u)$ times the cost of a single unit, given in Table 1 versus N_u , where

$$cd(N_u) = 0.2 + 0.8\, N_u\, 0.97^{\left[\ln(N_u)/\ln(2)\right]} \quad . \tag{10}$$

Table 1: Multi-unit cost reduction factors

N_u	cd(Nu)	$cd(N_u)/N_u$
1	1	1
2	1.752	0.876
4	3.211	0.803
8	6.041	0.755

However, we do not apply the multi-unit cost credits given by Eq.(10) to the entire HYLIFE-II multi-unit plant, even though they apply to entire multi-unit fission plants, since we felt that there should be no cost credit given to the common driver and target factory in our multi-unit plants, which have no analog in the fission case. Thus, in what follows, we apply Eq.10 explicity to each subsystem which is replicated Nu-times in our multi-unit model, e.g., to the fusion chamber group and steam plant group subsystems, but not to the shared driver and target factory. We recognize the uncertainty in applying fission-derived multi-unit cost credits selectively in this way, but if we err, we err on the conservative side, since exempting the driver and target factory significantly diminishes the impact of these multi-unit credits. Meier and Hogan applied similar "learning curve" cost reductions to both direct and indirect costs in earlier multi-unit IFE plant economic studies.[4] We apply Eq. 10 only to direct costs. We do not assume indirect cost reductions for multi-units.

2. ***Driver group***. Since the driver rep-rate in a multi-unit plant will be N_u-times larger than an individual fusion chamber rep-rate, it is important to include explicit driver cost dependence on the accelerator average power affecting the size of the driver power supplies and cooling systems. The following cost model for the RIA heavy-ion beam driver is normalized to give the same direct costs at 5 Hz rep-rate as Bieri's designs[5] optimized with driver energy (escalated to 1993$), but scales the costs of power supplies and cooling subsystems in a separate term with driver average power ~ $(N_u RR_{ch} E_d/\eta_{HI})$ to a 0.67 economy-of-scale exponent typical for generic power supplies and cooling systems (all cost expressions give direct capital costs in millions of 1993 dollars):

$$C_{HIB} = 342\left(\frac{E_d}{4}\right)^{0.4} + 59.4\left(\frac{0.35\, N_u\, RR_{ch}\, E_d}{20\, \eta_{HI}}\right)^{0.67} \quad . \tag{11}$$

The $59.4 M coefficient of the second term was obtained from the power supply and cooling system costs of the detailed RIA point design in ref. 13. Similarly, the cost portion of the point design in ref. 13 for the beam transport and focusing system is taken to be the coefficient in the beam switchyard costs for Nu units according to:

$$C_{BSY} = 22.6\, cd(N_u) \quad . \tag{12}$$

The cost sensitivities of multi-unit IFE plants to driver and beam switchyard costs will be addressed in Section III. In the driver group, we add a target injector system cost derived from the work of Petzoldt:[22]

$$C_{INJ} = 5.09(RR_{ch}/5)^{0.7} cd(N_u) \quad , \tag{13}$$

and a driver building cost increasing with driver energy:

$$C_{DRB} = 29.7(E_d/4)^{0.5} \quad . \tag{14}$$

Figure 5 plots the driver group costs (sum of Eqs. 11-14) as a function of driver energy for a reference case single-unit 1 GW_e electric plant, and for a reference case hydrogen plant with one driver driving four- 2 GW_e units (8 GW_e total plant output). Fig. 5 shows that, at any given driver beam energy, the multi-unit plant driver group costs are higher due to the higher average driver power, increasing power supply and cooling system costs. These average power costs increase sharply at low E_d where the target gain is low and the required rep-rate to maintain constant net power increases sharply (see Fig. 4). This effect results in driver cost minima with E_d, rather than driver costs decreasing monotonically with decreasing driver energy. However, recirculating power dependence on E_d results in CoE minima for each case occurring at somewhat higher values of E_d than where the driver costs minimize, as indicated in Fig. 5.

3. ***Fusion chamber group***. The Fusion Chamber Group (FCG) is defined to consist of the fusion target chambers and associated bypass pumps and piping, the target factory, Flibe coolant, tritium management system, remote maintenance equipment, the heat transport system including the steam generators, and the buildings associated with these systems. Thus, the FCG includes all subsystems found in the usual "Reactor Plant Equipment Cost Account 22 plus the associated buildings (part of Cost Account 21). For a multi-unit plant, all FCG subsystems receive multi-unit reduced costs using Eq. 10, except for

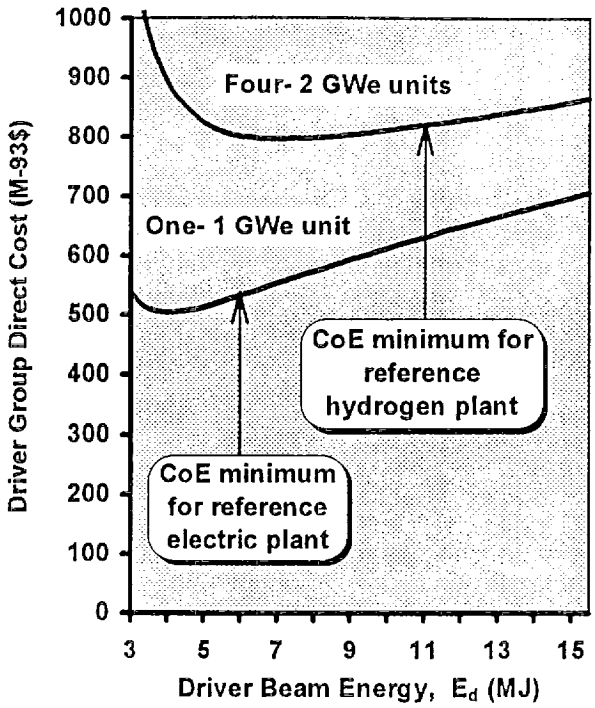


Fig. 5 : Driver group direct costs for a 1 GW_e reference electric plant and for an 8 GW_e, four-unit reference hydrogen plant, as a function of driver beam energy. Including driver cost dependence on average power raises costs at low E_d and at high N_uRR_{ch}, resulting in cost minima in both curves.

the target factory and the common portion of the remote maintenance equipment.

Since the HYLIFE-II fusion chamber is expected to have a 30 year life, most of the remote maintenance equipment is expected to be used only infrequently due to off-normal outages. Somewhat arbitrarily, we take 80 % of the remote maintenance equipment to be general purpose manipulators shared by all the units, with only 20 % of the remote maintenance equipment built into each unit and therefore replicated Nu-times. Furthermore, to credit the fact that the HYLIFE-II chamber has no solid blanket components requiring regular replacement, we have reduced the total remote maintenance equipment allowance to 53 M$ from the usual 106 M$ used in 1 GW_e designs that do require such replacements,[19] taking a cost scaling:

$$C_{RME} = 42\left(\frac{P_{e(net)u}}{1000}\right)^{0.6} + 10.6\left(\frac{P_{e(net)u}}{1000}\right)^{0.6} cd(N_u). \quad (15)$$

The FCG design in this paper includes most of the other recent improvements made in the HYLIFE-II Reference Design by Moir,[23] and by Hoffman.[24] These include a highly efficient two-stage Flibe vacuum disengager designed to separate 0.99999 of the tritium from the Flibe.[25] Because of this, and the fact that the thick Flibe jets greatly reduce activation of the steel, the HYLIFE-II fusion chamber is calculated to be non-nuclear grade. Non-nuclear grade costs are used for those subsystems whose failure in a maximum-credible accident was calculated to not lead to a dose to the public larger than 25 rem. [2, 25] In the HYLIFE-II safety analysis[2] performed by INEL, there was no mechanism found to spread enough radioactive Flibe, steel, or tritium beyond the site boundary to give such a dose even if the HYLIFE-II chamber integrity failed. We consider only the tritium management system and the target factory (which has to fabricate targets containing tritium) to be nuclear grade, so that the costs of those systems are increased by factor of 1.5. The 304-stainless steel for the chamber and piping is assumed to have adequate corrosion resistance to be used in place of the much more expensive Hastelloy-N. [26]

Three additional new improvements to the HYLIFE-II model are included in this paper which exert important influence on the optimum driver energy and rep-rate which minimizes CoE, and which are especially important to the optimization of multi-unit plants at higher driver energies and target yields: (1) the dependence of fusion chamber costs with target yield in addition to chamber thermal power; (2) the stronger dependence of the cost of the bypass pumps with rep-rate, through the stronger dependence of the bypass pump power with rep-rate in Eq.4; and (3) the inclusion of extra operating and maintenance (O&M) charges for the target factory, above the 3% of direct costs included in the CoE calculation. The new relationship we use for the fusion chamber cost scaling is:

$$C_{FC} = 15.3\left[\left(\frac{P_{th}}{2500}\right)^{0.855} + \frac{Y}{350}\right] cd(N_u) \ , \quad (16)$$

where the second term has been added to account for the increasing size required for the chamber with increasing yield, for a given thermal power P_{th} per unit. This second term is based on a very conservative "virial theorem" coefficient of 750 kg of steel per MJ of yield to handle the pulsed stresses associated with the PV-expansion energy of the target debris and Flibe vapor/liquid (~ 25 to 30 % of the yield). This coefficient is 10 times that derived from an earlier high-yield IFE concept,[27] to insure a cyclic-fatigue lifetime for the HYLIFE-II chamber much longer than its designed 30 year radiation damage lifetime. Figure 6 plots the fusion chamber costs from Eq. 16 as a function of the driver beam energy for the same reference electric and hydrogen plants as used in Fig. 5.

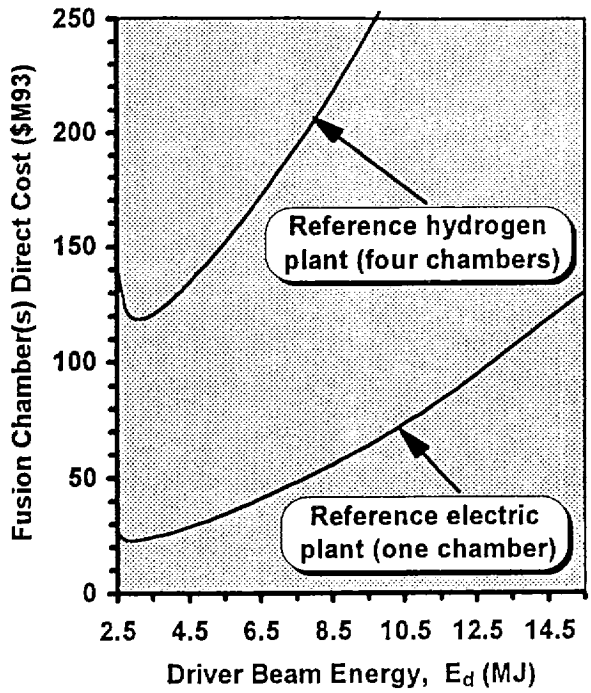


Fig. 6 : Direct cost of fusion chamber(s) as a function of driver beam energy. The upturn in costs at very low E_d reflects the effect of P_{th} increasing at lower E_d in order to keep P_{net} constant for each case.

Eq. 16 gives a chamber cost proportional to P_{th} in the limit of small yield, with the yield-dependent term becoming comparable to the power dependent term at a yield of 350 MJ.The crude scaling with yield in Eq. 16 implies a chamber radius increasing with yield, an effect not yet included self-consistently in the bypass pump power (Eq. 4). Improving this consistency is left for future work. For now, Eq. 16 captures a reasonable penalty for yields much higher than 350 MJ, which is important for multi-unit cases which would otherwise optimize to much higher driver energies and yields.

The second important new cost scaling compared to reference 2 is the cost of the bypass pumps:

$$C_{BPP} = 58.4\left(\frac{P_{BPP}}{24.8}\right)^{1.0} cd(N_u) \quad , \qquad (17)$$

where P_{BPP} is given by Eq. 4. Figure 7 plots the bypass pump costs from Eq. 17 as a function of driver energy, for the reference electric and hydrogen plants. The very steep rise in bypass pump power costs at low E_d in Fig. 7 is a result of the P_{BPP} scaling of Eq. 4, and the fact that RR_{ch} also increases sharply to maintain constant net power at low E_d (See Fig. 4). The scaling of Eq.4 is an empirical fit

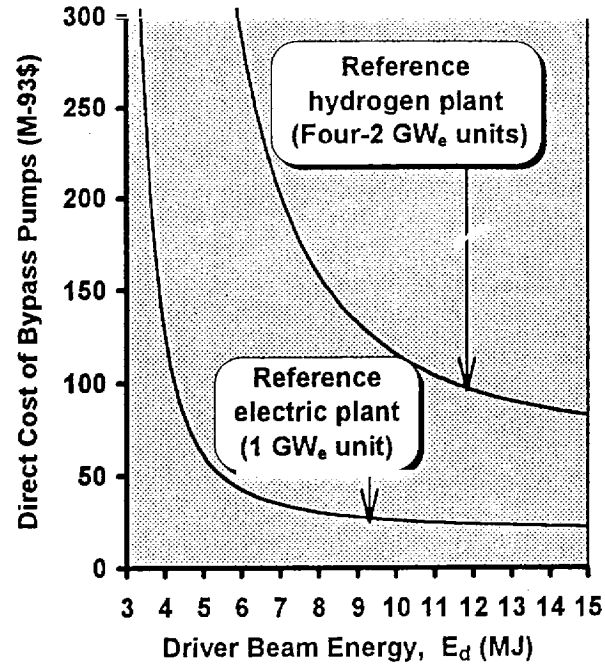


Fig. 7: The direct cost of the bypass pumps (Eq.16) as a function of driver beam energy, for the reference electric and hydrogen plants as in Fig.5.

to detailed calculations which maintain constant 0.5 m thickness of the jets. The pumping head model includes gravity contribution and friction losses. The velocity in the bypass pipes is limited to 6 m/s, so the number of 1 m diameter pipes increases with RR_{ch}.

The third important new cost scaling is the cost of target fabrication, which includes the capital cost of the target factory equipment due to Woodworth[28] :

$$C_{TFE} = \left[4.65 + 24.2\left(\frac{N_u RR_{ch}}{5}\right)^{0.7} + 4.32\left(\frac{N_u P_{th}\eta_{spp}}{1000}\right)^{0.67}\right] CF_{NS} \, , \qquad (18)$$

where CF_{NS} =1.5 is an explicit cost multiplier for nuclear grade construction. We include an extra O&M annual cost for target fabrication, above the 3 % of total direct capital:

$$OM_{TF} = 12\left(\frac{N_u RR_{ch}}{5}\right)^{0.3} \quad \text{(\$M per year expense).} \qquad (19)$$

This extra O&M charge for target factory operation reflects skilled staff levels expected to be needed for the sophisticated target fabrication and quality assurance. This contributes about as much to the total expenses per target as the annual charges on the target factory capital equipment given in Eq. 18. Figure 8 plots both the target factory direct capital from Eq. 18 and the total cost per target from both

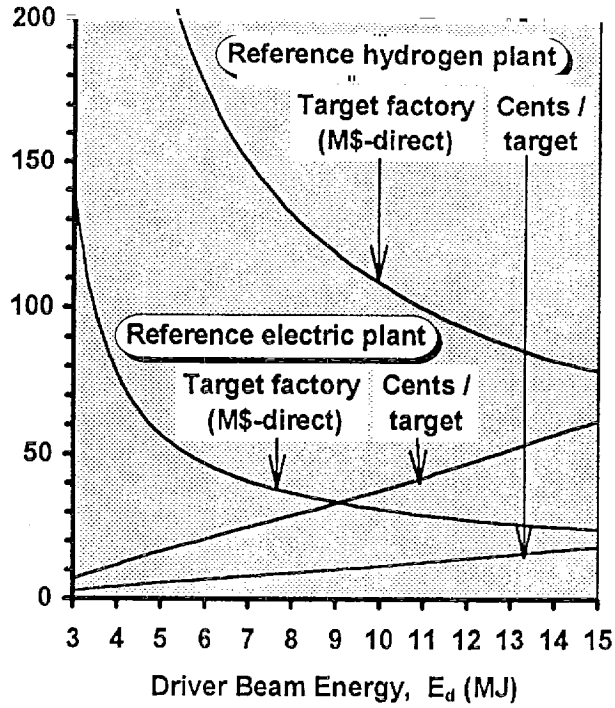


Fig. 8: Direct capital cost of the target factory equipment, and the total cost per target including capital and O&M charges, as a function of driver beam energy.

Eq. 18 and Eq 19, as functions of the driver beam energy, for the reference electric and hydrogen plants. While the target factory costs decrease with increasing driver energy because fewer targets are produced at constant power with higher yields, the costs per target increase with E_d because of the economy-of-scale in number of targets in Eq. 18. For the reference electric plant case shown in Fig. 8, about 126 million targets per year are produced. The costs per target are derived from adding up the capital cost of several target factory equipment items[28] sized to produce targets at the required rate, adding an annual operating cost for the target factory itself to the annual charge on the target factory capital, and then dividing by the number of targets produced. The target factory equipment cost was estimated from the cost of similar industrial equipment items that produce similar numbers of small precision items[28] .

The cost of Flibe (Li_2BeF_4) is a significant item within the fusion chamber group, primarily because of the cost of beryllium it contains. Since such large uses of an expensive bulk material do not have an analogue in fission plants from which the indirect cost multiplier IDC = 1.936 we use was derived, and since such a commodity does not require comparable fractions of field engineering as does average construction, and since such a commodity can be delivered near the end of construction, avoiding interest cost during construction, we have reduced the effective indirect cost factor for Flibe from 1.936 down to 1.22. This keeps the contingency. We then artificially reduce the explicit direct cost of Flibe from the $45 /kg used in ref. 2, escalated to 93 dollars, down to (45)(1.22)/1.936 = $28 /kg. Thus, when the total plant direct costs (including these Flibe costs) are later multiplied by IDC = 1.936, the total unit cost of Flibe will be $55 /kg. More recent cost estimates for beryllium floride (the most costly ingredient in Flibe) from Brush Wellman[29] leads to 34 $/kg of Flibe (in1994 $), which is less than we assumed in this study. We estimate the total cost of Flibe based on the actual volume of Flibe we calculate in the various parts of the system, which does not scale linearly with the thermal power.

4. *Steam plant group.* The Steam Power Plant Group (SPG) consists of the land (Cost Account 20), the buildings to house each steam power plant (SPP) (part of Cost Account 21) and the four SPP subsystems: the turbine plant equipment,(Account 23), the electric plant equipment (Account 24), the miscellaneous plant equipment (Account 25) and the main heat rejection system (Account 26). For multi-unit power plants, it is assumed that there is a separate SPP for each unit, to facilitate the possibility that a utility could deploy each fusion chamber unit in separate stages, if desired. We did consider the possibility of several fusion chambers per SPP, and the possibility of cross-connecting the Flibe loops and steam generators for all units, as a way to increase redundancy and to further improve overall plant availability. However, we dropped the idea because (a), the cost of cross-connecting all the Flibe and steam loops appeared to be very high, (b), the plant availability using all-liquid HYLIFE-II fusion chambers was already high (0.85), and (c), the need to keep the cross-connect piping runs short would so constrain the spacing of the separate units that a stageable plant deployment would be made more difficult.

Since a single SPP has been limited to about 1300 MWe up to the present time, there will be more than one SPP when the unit size (per fusion chamber) exceeds a gross power output of 1300 MWe. For one SPP per fusion chamber, the multiple SPP's also realize the cost savings for multiple units according to Eq. 10. When each fusion chamber unit is large enough to require two SPP's per unit, an additional cost savings factor of 0.88 multiplies the direct cost of each SPP, to reflect the greater number of SPP's on which to base learning curve reductions.[30] We scale the cost as two equal size SPP's, when there are two SPP's per unit. The cost of the SPP's are derived from adding the costs of several subsystems of the SPP, each of which scales differently with power. Consequently, when

we add them up, the total SPP cost does not scale simply as P_e to some constant exponent.

For this study, the modern supercritical steam power plant used for the HYLIFE-II Reference Case study[2] has been retained. This 31 MPa (4500 psi) supercritical SPP cycle chosen has a thermal efficiency of about 47%. After all the internal auxiliary power requirements of the SPP are subtracted, the resulting "net station" efficiency is about 43%; this is the correct efficiency we use in the power balance equations 1 and 2.

This modern supercritical SPP is clearly superior to the original subcritical SPP used in the earlier HYLIFE-II studies, which had a net station efficiency of only about 38%. Recent large supercritical steam power plants around the world now have high reliability and availability, in contrast to the performance records of the very early supercritical SPP's. The HYLIFE-II heat transport system is fully capable of supplying the heat at the high temperatures required to utilize a high-efficiency supercritical steam cycle; i.e., the Flibe at 923 K can produce steam at 867 K (1100 F), which is close to the upper limit considered for the near future. Since the CoE is approximately inversely proportional to the net station efficiency, it can be seen that the ability to use a supercritical SPP instead of a subcritical one reduces the COE by about 16%. As a result, all recent fusion studies have opted for the supercritical cycle where possible.

C. Minimization of Cost of Electricity

The CoE is obtained from the following equation:

$$CoE = \frac{C_{tot}(IDC \cdot FCR + \mathrm{OMSCR}) + OM_{TF}}{0.0876\, F_a P_{e(net)tot}} + CoE_{fuel} + CoE_{decom} \quad (\text{Cents/kW}_e\text{h}), \quad (20)$$

where $C_{tot} = C_{DRG} + C_{FCG} + C_{SPG}$ is the sum of the direct capital costs of the driver, fusion chamber, and steam plant groups C_{DRG}, C_{FCG}, and C_{SPG}, respectively, the indirect cost multiplier IDC = 1.936, the fixed charge rate FCR = 0.0966, the factor for operations, maintenance and scheduled component replacement OMSCR = 0.03, and the plant availability factor F_a = 0.85. The plant availability is higher than the 0.75 usually assumed for fusion concepts using solid first wall materials that require regularly replacement. Also, the OMSCR is lower than the 6 % of direct costs usually assumed for the same type of plants, since HYLIFE-II has renewable liquid fusion chamber walls that do not require regular shutdowns for replacement. An availability of 0.85 has been achieved with modern fossil and nuclear plant operation. We assume that the heavy-ion driver is a very reliable system as is the case for modern large accelerator facilities, so that the driver does not contribute significantly to plant unavailability. The OMSCR of 3% is comparable to non-nuclear plants because the safety study of HYLIFE-II done by INEL (Longhurst and Dolan, 1993)[25] indicates that the entire plant can be non-nuclear grade except for the tritium management system and the target factory, as we have assumed. The operations and maintenance costs of the target factory are expected to be higher than the 3 % for the rest of the plant, so the additional OM_{TF} as given by Eq. 19 is included. The small additional contributions to CoE for fuel (makeup lithium-6, primarily), and for decommissioning have been estimated to be 0.003 and 0.10 cents/kW$_e$h, respectively.

The IFEFUEL5 systems code minimizes the CoE given by Eq. 20 with respect to the driver beam energy as the primary independent variable. The following Section III describes the resulting optimized parameters for the reference electric and hydrogen plants defined in Fig. 5 in detail, and then the optimum CoE and CoH are surveyed for a matrix of 4 x 4 cases with 1, 2, 4 and 8 units, and net powers per unit of 250, 500, 1000, and 2000 MW$_e$.

III. MULTI-UNIT ECONOMIC SURVEY RESULTS

A. Reference Electric and Hydrogen Plants

For comparison of the model improvements with the previous HYLIFE-II reference case in ref. 2, we selected a single-unit, 1000 MW$_e$ case as the reference electric plant. For the reference hydrogen case, we selected an 8 GW$_e$ plant with four- 2 GW$_e$ units to have an energy scale comparable to a typical oil refinery, and to be the same size scale at which the competitive hydrogen cost requirements for generic fusion plants were derived in ref. 10. The parameters for each case are determined for the driver energy which minimized CoE. To see the cost variations in the neighborhood of where these reference cases are selected within the range of driver energies, Figures 9(a) and 9(b) shows the contributions of the three subsystem groups to the total CoE as a function of the driver beam energy for the reference electric and hydrogen plants, respectively.

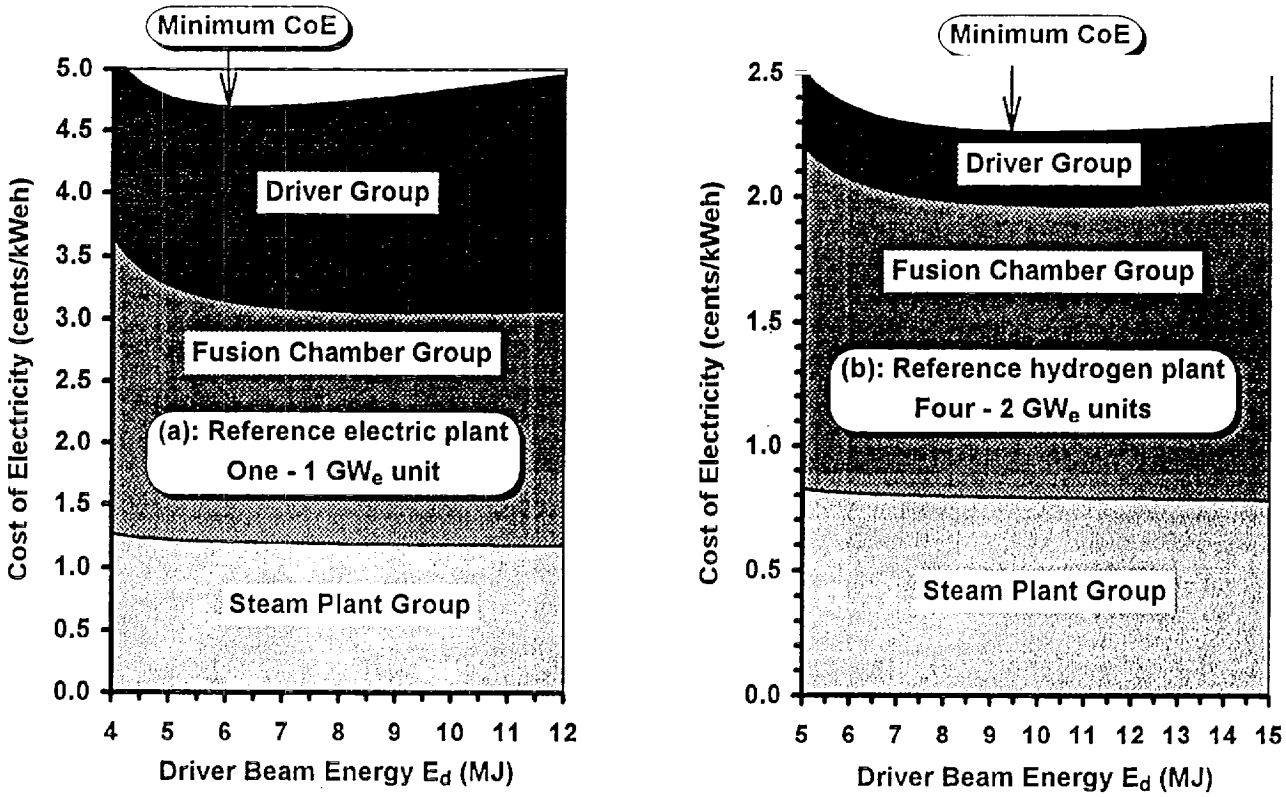


Fig. 9: The contributions of the driver, fusion chamber, and steam plant groups to the CoE as a function of the driver energy, for the reference electric (a) and hydrogen (b) plants at 1 GWe and 8 GWe (four-2 GWe units), respectively.

Figs. 9(a) and 9(b) exhibit fairly broad minima in CoE versus driver energy, because opposing cost dependencies with E_d in the different subsystem groups approximately cancel over a significant range in E_d. As the IFEFUEL5 systems code calculates CoE on a discrete grid of E_d points, it selects the point that is within 0.1 % of the interpolated true minimum, on the smaller E_d side. All plant subsystem costs depend on E_d either directly, or indirectly with P_{th} or RR_{ch}, which depend on E_d through the power balance relations (Eqs. 1 to 9). It is important to note that to keep the net power constant, the thermal power P_{th} increases monotonically as E_d decreases, as does most of the subsystem costs that depend on P_{th} in the fusion chamber and steam plant groups. In fact, all plant subsystem costs, including the particular ones discussed in the preceding subsystem cost scalings depicted in Figs. 5 to 8, increase in going to very low E_d, as a consequence of having to keep the net power constant. On the other hand, only two subsystems increase in cost with E_d at large E_d, however, those two being the driver and the fusion chamber, the latter only because of the inclusion of a yield dependence.

1. *Target and fusion chamber costs and risks.* A key finding from Fig. 9(a) is that the CoE minimum for the reference 1 GW_e electric plant occurs at a higher Ed = 6 MJ, and at a significantly higher yield Y = 508 MJ (using Fig. 4), compared to Ed = 5 MJ and Y = 350 MJ of the previous HYLIFE-II reference case,[2] in spite of the added cost of the fusion chamber with higher yield now included in Eq. 16. This is a combined result of: (1) a flatter driver cost with driver energy (see Fig. 5) due to the proper inclusion of average power costs, (2) a much stronger increase of bypass pump power and cost with higher rep-rates at low E_d (see Fig. 7), and (3), a proper scaling (Eq. 9) of driver efficiency η_{HI} increasing with E_d. Comparing Fig. 9 (b) with 9 (a), we see that the larger multi-unit hydrogen plant has a minimum CoE occuring at an even higher E_d = 9.5 MJ and yield Y = 1.12 GJ than for the reference electric plant. Thus our higher fidelity model improvements, and multi-unit optimization, leads us back to considering future IFE chamber designs at yields above 1 GJ, approaching the 1.8 GJ yield of the original High Yield Lithium Injection Fusion Energy (HYLIFE) concept.[17]

There is proper concern for our lack of experience in containing GJ-scale fusion yields with affordable and long-lasting chambers, despite our optimism based on the shock-absorbing capabilities of the liquid jets in the HYLIFE and HYLIFE-II concepts. We have included a crude, but conservative accounting for the expected larger vessel sizes and costs to contain the impulses arising from the larger fusion yields we find for minimum CoE. However, until these fusion chamber concepts are actually tested, uncertainty in our cost model remains. Since the variation of CoE with driver energy exhibited in Fig. 9 is so weak in the vicinity of the minimum CoE, one may ask why not just pick a reference case at a lower driver energy than at the CoE minimum, and pay a small calculated CoE penalty in return for less risk of chamber cost escalation at lower yields. The answer is that there is another equally critical yet uncertain issue that could impact IFE economics as much as yield containment and driver cost with energy, namely, the potential fabrication cost of high-precision IFE targets, per unit of fusion energy produced. IFE targets are so small that the cost of raw materials (assuming lead or mercury can be substituted for gold), and aside from the recovery cost of tritium used in the targets which is bred in the Flibe, is insignificant compared to cost of their fabrication. The cost of targets for today's inertial fusion experiments (of order $10,000 per target) depends not on the target's physical size (if anything, that dependence is inverse), as much as on the degree of precision required. While costs per target are expected to drop dramatically with large-scale mass production as appropriate for an IFE power plant, the required extrapolation to < 30 cents/target for reasonable IFE economics is long and uncertain. Higher yields per target can reduce exposure to this cost uncertainty, since the expected cost for a target designed to produce, say, 1000 MJ yield, may actually turn out to be *less* than for one designed to produce 100 MJ (for the same number of targets produced): the 100 MJ target has to work with a low ~ 3 MJ driver energy in the steep region of the gain curve of Fig. 4, and thus requires a higher degree of perfection than that which can be tolerated with a 1000 MJ target driven by a 10 MJ driver.

The target factory cost model of Woodworth[28] given by Eq. 18 reflects target factory "economy-with-number-of targets", such that the target factory equipment costs drop with E_d, even though the cost per target goes up with E_d due to the fewer number of targets needed (see Fig. 8). It is in fact fortunate that the CoE has such a broad minimum with driver energy as shown in Fig. 9, because if either fusion chambers or fusion targets turned out to be much more expensive than we estimate in these models, competitive CoE might still be achievable by appropriate adjustment of the driver energy and rep-rate. Based on our best current information as captured in these models, the CoE minimum is our best guide to selection of parameters for the reference electric and hydrogen plants. The sensitivity of the minimum CoE to variation of target factory, fusion chamber, driver, beam switchyard, and Flibe costs are also explored and presented in Table 4.

Table 2: Plant Parameters (Optimized)

Parameter	Reference Electric Plant	Reference Hydrogen Plant
Total plant net output (GW_e)	1	8
Number of chamber units	1	4
Number of steam power plants	1	8
Number of Flibe loops (total)	3	24
Driver beam energy (MJ)	6	9.5
Target fusion energy gain	84	118
Target fusion yield (MJ)	508	1119
Fusion chamber rep-rate (Hz)	4.3	3.8
Driver rep-rate (Hz)	4.3	15.2
Thermal power / unit (MW_{th})	2592	5017
Bypass pump power (total, MW_e)	18	65
Driver input power (MW_e)	67	330
Driver efficiency (%)	38.7	43.5
Recirculating power fraction (%)	10.3	7.3
Plant efficiency (%)	38.6	39.9

Common parameters: plant availability = 85%, pump efficiency η_p = 80%, blanket energy multiplication M_t =1.18, thermal efficiency η_{spp} = 43%, auxiliary power = 0.0072 P_{th}.

Table 2 lists the plant performance parameters obtained at the indicated CoE minima in Fig. 9 for the reference electric and hydrogen plant cases, and Table 3 on the following page lists the 23 subsystem costs by the standard cost account, and segregated into the driver, fusion chamber, and steam plant groups, that correspond to those cases. Note in Table 2 that the eight-fold increase in power output of the hydrogen plant compared to the electric plant is achieved for minimum CoE by a combination of increasing the driver energy and rep-rate, such that the individual fusion chamber rep-rate is lowered. This allows both the average driver power and the bypass power consumption to increase by much smaller factors than eight times, reducing the recirculating power fraction. The minimum CoE = 4.69 cents/kW_ehr for the reference electric case consists of 3.81 cents/kW_ehr for annual capital charges, 0.77 cents/kW_ehr for O&M, 0.0042 cents/kW_ehr for fuel (lithium 6 makeup), and 0.11 cents/kW_ehr for decommissioning. The minimum CoE = 4.69 cents/kW_ehr for the reference hydrogen case consists of 1.83 cents/kW_ehr for annual capital charges, 0.32 cents/kW_ehr

for O&M, 0.0042 cents/kW$_e$hr for fuel (lithium 6 makeup), and 0.11 cents/kW$_e$hr for decommissioning.

2. *Reference electric plant CoE.* The CoE for the reference electric case shown in Fig. 9a and Table 3 of 4.69 cents/KW$_e$h is lower than the 6.5 cents/kW$_e$h quoted for the reference HYLIFE-II case in ref. 2, primarily because we wanted to credit the changes in higher availability and lower O&M costs accruing to the HYLIFE-II chamber's long expected lifetime that were discussed in ref. 2. This should properly put the focus of attention on the specific HYLIFE-II chamber design issues that are discussed in ref. 2, rather than on the generic fusion availability and O&M rates from which those rate differentials were estimated. The reference electric plant CoE of 4.69 cents/kW$_e$h found here is still lower than the 5 cents/kW$_e$h quoted in ref. 2 after taking into account those availability and O&M credits, because (a), the RIA driver is now a slightly lower cost, more optimum design, (b), the effective indirect costs for Flibe is reduced as a commodity, and (c), the remote maintenance equipment cost is reduced to credit the fact that there is no need for regular blanket replacement in the HYLIFE-II fusion chambers.

3. *Reference hydrogen plant CoE.* The CoE for the reference hydrogen case is 2.26 cents/kWehr (see Fig. 9 b and Table 3), 25 % less than the 3 cents/kWehr required to meet the initial target CoH = 13.4 $/GJ, no tax (see Fig. 2), and just low enough to meet the final competitive CoH goal of 19.4 $/GJ for equal consumer fuel cost per mile with equal taxes at the station.[10] Thus, this reference hydrogen plant case has a 25% CoE margin to meet the initial CoH goal of 13.4 $/GJ (no tax), and can tolerate higher costs for those subsystems which have a significant uncertainty and still meet that initial goal.

4. **Cost sensitivity survey.** We have considered the possible impact on CoE for the reference hydrogen case from increases in costs of the heavy-ion accelerator (first term in Eq. 11), the beam switchyard, the Flibe coolant, the fusion chambers, and the target factory equipment. One way to look at the CoE sensitivity to changes in these costs is to ask by what factor those selected subsystem costs would have to increase, either individually or collectively, to raise the reference hydrogen case CoE by 25%. This approach allows comparisons of the sensitivities of CoE to those various subsystems, while at the same time estimating the absolute magnitude each could increase and still allow the reference hydrogen case to meet the first CoH target with a CoE = 3 cents/kW$_e$h. Table 4 lists cost factors (multipliers of the coefficients in the cost formulas) for the above selected items that are required to increase CoE from the reference hydrogen value of 2.26 to 3 cents/kW$_e$h. Since each case is reoptimized to minimize CoE, the reoptimized subsystem costs are also listed in Table 4. Note that the reoptimized subsystem costs do not increase as much as the cost factors, except for Flibe, which increases linearly with the cost factor. Also indicated in Table 4 are the reoptimized values of E_d and RR_{ch}. Note that Ed decreases and RRch increases, as expected, when the HI accelerator or fusion chamber costs are escalated, with the opposite changes occuring when the target factory costs escalate. We neglect the beam switchyard cost variation by itself, since its impact is so small (we found that a four fold increase in beam switchyard costs, to 100 M$ direct per unit, raised the reference hydrogen plant CoE by only 3.5%). The fifth case in Table 4 multiplies all five items by 2.5 times. The results in Table 4 indicate that relatively large cost increases can be tolerated for some subsystems and still meet the first CoH target of 13.4 $/GJ at a CoE = 3 cents/kW$_e$h.

B. Economy-of-Scale Surveys.

1. *CoE and RR_{ch} versus N_u and P_{net}/unit.* Figure 10(a) displays the optimized CoE and Fig. 10(b) the chamber rep-rate for a 4 x 4 matrix of multi-unit plants with 1, 2, 4 and 8 units, and with 250, 500, 1000, and 2000 MW$_e$ net powers per unit, both graphically and tabularly. Note that the net power per unit axis is reversed between Figs. 10(a) and 10(b) to facilitate the three-dimensional view of the data. Remember that the driver rep-rates are N_u times larger than the chamber rep-rates shown in Fig. 10(b). The key feature exhibited in Fig. 10(a) is that cases with the same total plant output power (along diagonals in the matrix) have weaker CoE variation than cases which vary the total plant output by either net power per unit or number of units (cases along a row or column in the matrix, respectively). Thus, total plant output is the most important variable affecting the economy-of-scale of CoE. Comparing cases with the same total plant output, CoE is always lowest for a single unit (with highest RR_{ch}), in agreement with the simple multi-unit cost model used earlier by Meier and Hogan.[4] Fig. 10(b) shows that optimized RR_{ch} decreases with decreasing net power per unit and with increasing number of units (along rows and columns of the matrix, respectively), and decreases with increasing number of units for constant total power (along diagonals of the matrix). Thus, if chamber clearing should ultimately require a lower rep-rate than our model calculates, cases with nearly the same CoE can be recovered through the use of more units.

Table 3: Plant Cost Breakdown (in millions of 1993 dollars)

Account	Item	Reference Electric Plant [One - 1 GW_e unit]			Reference Hydrogen Plant [Four - 2 GW_e units]		
		Driver	Fusion Chamber	Steam Plant	Driver	Fusion Chamber	Steam Plant
20	Land and land rights			11.7			37.4
21	Structures and improvements						
21.1	Driver building	36.4			45.8		
21.2	Fusion chamber buildings		33.2			206.2	
21.3	Target factory building		13.5			19.7	
21.4	Steam plant buildings			76.5			341.7
22	Fusion plant equipment						
22.1	Fusion chamber equipment						
22.1.1	Fusion chamber		37.9			245.6	
22.1.2	Bypass pumps		42.5			123.7	
22.1.3	Bypass pipes		10			50.6	
22.2	Flibe coolant		68.9			341.3	
22.3	Vacuum system (in Acc. 22.5)						
22.4	Target factory equipment		46.5			113.1	
22.5	Tritium management system		97.5			544.2	
22.6	Shielding (in Acc. 21.2)						
22.7	Heat transport system						
22.7.1	Coolant piping		11.6			74.2	
22.7.2	Coolant valves&bellows		20.2			129.7	
22.7.3	Pumps and motors		40.3			252.8	
22.7.4	Coolant cleanup plant		16.5			102.5	
22.7.5	Steam separators		10			62	
22.7.6	Water loop piping		0.2			0.7	
22.7.7	Steam generators		72.4			458.7	
22.8	Remote maintenance equipment		53			115.9	
23	Turbine plant equipment			194.3			1069.5
24	Electric plant equipment			65.2			363.4
25	Miscellaneous plant equipment			25.4			142.2
26	Main heat rejection system			39.4			217.1
27	Driver equipment						
27.1	Driver	468.7			675.8		
27.2	Beam switchyard	22.6			72.6		
27.3	Target injector system	4.6			13.4		
	Subtotals of subsystem group costs	532	574	413	808	2841	2171
	Total direct cost		1519			5820	
	Unit direct cost ($/ W_e)		1.519			0.728	
	Indirect cost factor		1.936			1.936	
	Total capital cost		2941			11268	
	Levelized Cost of Electricity [a] (Cents/kW_eh)		4.69			2.26	
	Cost of Hydrogen ($/GJ, no tax)		19.1			10.8	

[a] The fixed charge rate for noninflating dollars = 9.66%; the indirect cost factor = 1.936 includes contingency and interest for 6 year construction. Because of long-lived, all-liquid-protected HYLIFE-II chambers, availability of 85% versus 75%, and annual O&M /scheduled component replacement charges of 3% of direct costs, instead of 6%, is assumed.

Table 4: Cost sensitivity of reference hydrogen plant CoE to selected subsystems: cost increase factors raising CoE to 3 cents/ kW_eh (25 % increase in CoE from baseline).

Subsystem	Baseline (Table 2)	Cost Factor	New Cost
a) HI accelerator (first term in Eq. 11)	Acc 27.1 676	6	Acc 27.1 2742 *
b) Flibe coolant (42 $/ kg)*1.22/ 1.96	Acc 22.2 341	7.2	Acc 22.2 2430
c) Fusion chambers (Eq. 16)	Acc 22.1.1 246	12	Acc 22.1.1 1946 **
d) Target factory equip (Eq. 18)	Acc 22.4 113	24	Acc 22.4 1812 ***
All a, b, c, d plus beam switchyard	Total direct 5820	2.5	New total 7674

*Optimum E_d decreases to 6.5 MJ; RR_{ch} up to 7.4 Hz

**Optimum E_d decreases to 6.0 MJ; RR_{ch} up to 8.6 Hz

***Optimum E_d = 16 MJ; RR_{ch} = 1.5 Hz, cost / target = $1.2

Fig.10 (b): Optimized Rep-Rate (Hz)

# units \ Pnet / unit	250	500	1000	2000
1	2.3	3.2	4.3	5.4
2	1.8	2.6	3.5	4.4
4	1.6	2.2	2.9	3.8
8	1.4	2.0	2.7	3.6

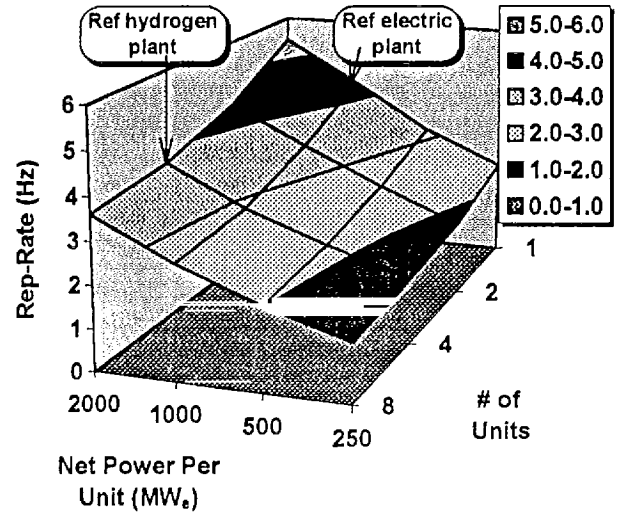
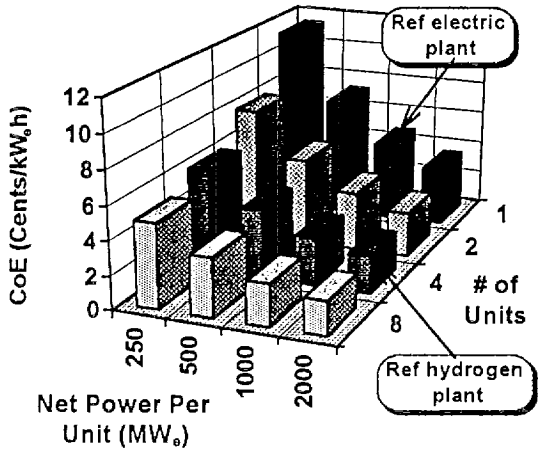


Fig.10(a):Optimized CoE (cents/kW_eh)

# units \ Pnet / unit	250	500	1000	2000
1	11.33	7.18	4.69	3.47
2	7.90	5.18	3.50	2.69
4	6.03	4.09	2.84	2.26
8	5.00	3.47	2.46	2.01



The earlier multi-unit study by Meier and Hogan concluded that for most cases, minimum CoE was obtained at the highest chamber pulse rate set by a specified limit of 10 Hz.[4] Here, however, we impose no arbitrary limit on the chamber pulse rate, allowing the minimization of CoE to determine the optimum pulse rate with the bypass pumping power according to Eq. 4 . We find that rapidly increasing bypass pump power with rep-rate always causes the minimum CoE to occur at rep rates well below 10 Hz [see Fig. 10(b)], because the lower-cost RIA driver we have adopted allows the optimum to occur at higher driver energy and yield for lower rep-rates. When we consider arbitrarily raising the driver cost several-fold, as we did in case (a) of Table 4, we then do find cases in which optimum rep-rates and bypass pump powers are sufficiently large that multi-unit plants have lower CoE than single units at the same total power output. For example, with a six-fold more expensive accelerator as in Table 4, we find a two-unit, 1000 MW_e/unit plant has a minimum CoE = 6.32 cents/kW_ehr with E_d = 4.8 MJ and RR_{ch} = 7.1 Hz, compared to a 2000 MW_e single unit with a higher minimum CoE = 6.43 cents/kW_ehr, with E_d = 5.3 MJ and RR_{ch} = 11.4 Hz.

2. *Capital cost variation with plant output power.* To investigate the economy-of-scale effect on CoE over a large range of plant output powers, we consider the sequence of cases along the top row in the matrix of Fig.10(a) for single units increasing in net power up to 2000 MW_e, followed by multiple-units of 2000 MW_e going down the last column on the right. This particular sequence includes both the reference electric and hydrogen plant cases, and follows the optimum with respect to minimum CoE with total plant output. The break-point in going from single units to multi-units at 2000 MWe/unit is at the optimum for minimum CoE since going to 4000 MWe units would incur much higher rep-rates (approaching 10 Hz) where the higher bypass pumping power would negate further savings in fusion chamber costs.

Figure 11 displays both the direct capital costs and the relative fractions of the driver, fusion chamber, and steam plant groups costs for the above sequence of cases with increasing plant output power.

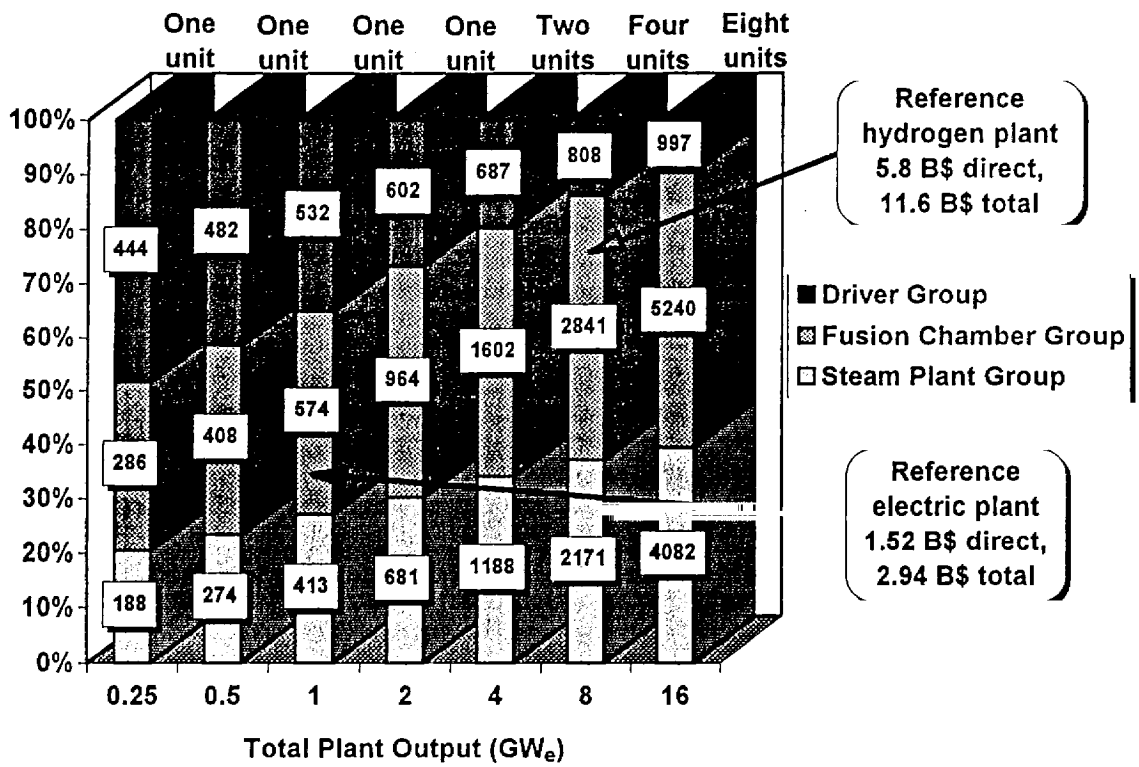


Fig. 11: The fractions of plant direct costs for the driver, fusion chamber, and steam plant groups as a function of total plant output power. The absolute direct costs (M-93$) for each group are labeled on each power output case.

The major feature shown in Fig. 11 is the consistent shrinking of the fraction of plant capital cost for the driver as the plant output increases, in spite of the absolute driver costs increasing with plant output power. Thus the driver group is a major factor contributing to the economy-of-scale, and multi-units with a shared driver allows dimunition of relative driver costs to continue to plant outputs well beyond those achievable with single fusion chambers. Note that the reference hydrogen plant indicated in Fig. 11 costs less than four times the reference electric plant case, yet produces eight times as much power.

The direct capital cost for the Steam Plant Group of $413 M indicated in Fig. 11 for the reference 1 GW_e electric plant is consistent with the costs of modern steam turbine generator plants for coal-fired power plants. This direct cost may be lower than the direct costs quoted for the balance-of-plant (BoP) in other fusion studies, because they often include the steam generators and the main heat transport systems which we include in the fusion chamber group. In addition, a BoP including the main heat transport system can be much more expensive if the heat transport system must be nuclear grade as in a fission power plant. For the HYLIFE-II design where the heat transport system does not have to be nuclear grade, a BoP cost including the

heat transport system and steam generators would be about 30% higher than that for the Steam Plant Group alone.

3. *CoE variation with plant ouptut, and comparison of economy-of scale with future fission plants.* Typically, fusion designs are compared with fission power plants of similar power output, as advanced fission is often expected to be one of the primary future competitors to fusion. Fission plants have exhibited an economy-of-scale also, and while single fission cores may be limited to well below 2000 MW_e size due to safety design such as for emergency afterheat removal, larger fission plants with multiple units and learning curve cost credits could also be considered in principle for future hydrogen production by electrolysis. Eight-unit fission plants such as the Pickering plant have been built,[31] although not as large as the 8 GW_e reference hydrogen plant we have considered (Pickering uses 600 MW_e-size units). To compare the economy-of-scale of our multi-unit IFE-HYLIFE-II plants with future fission, we adopt the following simple model for the fission case: Delene[32] implies that the CoE for a standard 1000 MW_e advanced future fission plant will be about 4 cents/kW_eh, consisting of 3.3 cents for capital and O&M annual costs, plus 0.7 cents/kW_eh annual fuel costs. For single units smaller than 1000 MW_e, we take the non-fuel CoE scaling with power output to the - 0.45 exponent,[33] as:

$$CoE_{fission(<1\,GW_e)} = 3.3\,(P_{enet}/1000)^{-0.45} + 0.7, \quad (21)$$

(cents/kW_eh), while for fission plants greater than 1 GW_e assumed to be built of multiple-1 GW_e units, we apply the same learning curve cost credits given by Eq. 10 to the non-fuel annual costs as a simple first approximation (O&M gets multi-unit credits as a fixed percentage of costs, as in Eq.20):

$$CoE_{fission(N_u\,GW_e)} = 3.3\,cd(N_u)/N_u + 0.7\,. \quad (22)$$

Using Eqs. 21 and 22 for future fission CoE, and Fig. 10(a) for IFE-HYLIFE-II CoE, Figure 12 compares the economy-of-scale in CoE over the same range of plant outputs as in Fig. 11.

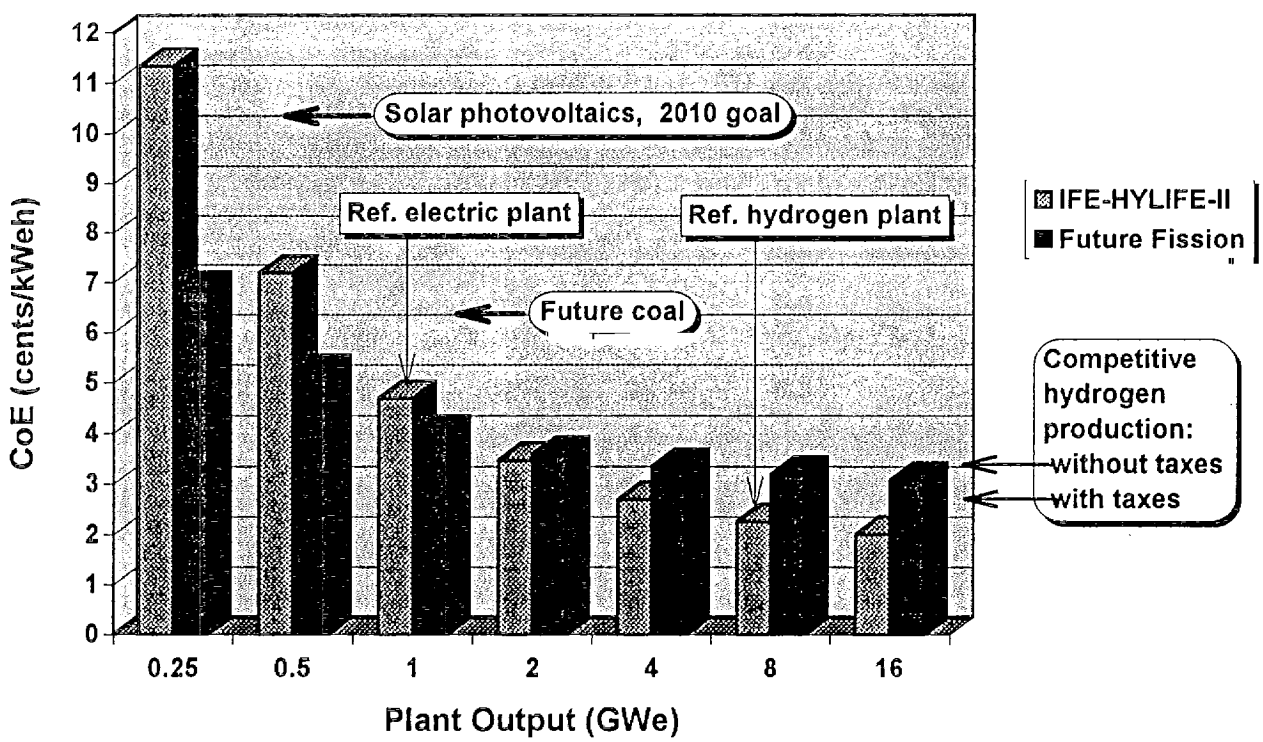


Fig. 12: The economy-of-scale variation of cost of electricity as a function of plant output, comparing inertial fusion energy based on HYLIFE-II (IFE-HYLIFE-II) and future fission plants (based on model in Eqs. 21 and 22). The fission cases assume single units up to 1 GW_e, then multiple- 1 GW_e units for outputs above 1 GW_e. The IFE-HYLIFE-II cases assume multiple 2 GW_e units for outputs above 2 GW_e. Typical oil refinery outputs are equivalent to hydrogen electrolysis plants of 8 to 16 GW_e output.

The fission cases in Fig. 12 are single units up to 1 GW_e output, and then multiple-1 GW_e units above 1 GW_e plant output. The IFE-HYLIFE-II cases are single units up to 2 GW_e, switching to multiple-2 GW_e units for power outputs above 2 GW_e. The results in Fig. 12 show that the IFE-HYLIFE-II CoE has a much stronger economy-of-scale than for fission, so that while fission has a lower CoE for small plant outputs < 2 GW_e, a result typically found in fusion studies, the HYLIFE-II CoE falls below that of fission for plant outputs of 2 GW_e and higher. The stronger economy-of-scale for HYLIFE-II compared to fission is due primarily to the economy-of-shared-equipment of the driver and target factory, as would be the case for other IFE designs with similar driver costs and ability to use a beam switchyard.Also indicated in Fig.12 are the CoE values of 3 and 2.3 cents/kWeh required to produce hydrogen fuel by electrolysis meeting equal consumer fuel cost per mile without and with equal taxes, respectively, as for gasoline powered vehicles.

Fig. 12 shows that IFE-HYLIFE-II plants have the potential, assuming the technical requirements discussed in the next section are met, to meet these stringent CoE goals at plant outputs of 8 GW_e comparable to the equivalent energy output of typical oil refineries. Two of the key reasons multi-unit HYLIFE-II plants can reach lower CoE than fission at these plant sizes are: (1) fusion fuel costs are negligible, while the optimized RIA driver, shared among several units, contributes only 0.3 cents/kW_eh to CoE [see Fig. 9(b)], less than the 0.7 cents/kW_eh that fission fuel costs contribute to the fission CoE; and (2), the HYLIFE-II radioactive inventories, including tritium, are sufficiently low that the HYLIFE-II fusion chamber and heat transport systems can be built non-nuclear-grade with 33% cost savings, whereas the corresponding fission systems must be nuclear grade. Also shown in Fig. 12 are the approximate CoE levels expected for future solar[34] and fossil-fired[32] plants. Solar, already mass-produced in modules, and coal, with high fuel costs, are not expected to have very strong economies-of-scale, and so are less likely to benefit from large plant sizes.

IV. SUMMARY AND CONCLUSIONS

A. Conclusions

Following are the principle conclusions of this work. These conclusions depend on successful development resolving critical issues listed in the next section IV B.

1. ***CoE/CoH goals for hydrogen production can be met.*** Multi-unit IFE plants with HYLIFE-II fusion chambers and a shared heavy-ion RIA driver and target factory, can potentially meet the CoE targets of < 3 cents/kW_eh and < 2.3 cents/kW_eh at 4 and 8 GW_e plant sizes, respectively, for competitive hydrogen fuel production by electrolysis assuming no hydrogen taxes as an initial subsidy, and assuming equal taxes as on gasoline, respectively. Other IFE concepts with similar cost drivers capable of beam switching to multiple fusion chamber units with equivalently-low maintenance costs could in principle achieve these same goals. The 8 GW_e plant size required for the latter goal is similar in energy scale to 200,000 bbl/day modern oil refineries. The total capital requirement (direct +indirect) of $ 11.3 B found for the reference 8 GW_e IFE hydrogen plant (see Table 3) is much higher than the ~ $3 B cost of a new 200,000 bbl/day oil refinery, but the annual (levelized) charge on the IFE plant capital of 0.0966 x 11.3 = $1.1 B/yr is less than the annual cost of imported oil at 20$/bbl for the refinery case: 200,000bbl/d x 365d/yr x 0.85(capacityfactor) x 20$/bbl = $1.2 B/yr.[10] By implication, future American motorists could pay those annual costs either to U.S. banks or U.S. oil company investors for such a hydrogen fuel plant, or, as they do now, to foreign oil producers, assuming air pollution restrictions don't constrain future gasoline use. We point out this comparison with current capital outflows for foreign oil just to dramatize the fact that the cost of capital for an 11.3 B$ IFE hydrogen plant is not unreasonable for the U.S. domestic transportation fuels market, provided the plant's CoH is low enough to maintain the consumer's fuel cost per mile. In Appendix I , we discuss how such a multi-unit plant could be built in stages to prove the economic scaling with a smaller initial capital-at-risk.

2. ***IFE may beat fission CoE above 1 GW_e outputs.*** If requirements for item 1 above are met, then IFE may also produce electricity at lower cost than all future electricity competitors at plant sizes of 2 GW_e or larger, making these large IFE plants a prime candidate for large independent central electric producers, selling electricity to many neighboring utility districts in the new deregulated electricity markets of the future. Such large electric plants would also be appropriate if electric battery-powered cars replaced gasoline cars, rather than hydrogen-powered engines. The conservative choice of thermal conversion to electricity followed by water electrolysis, allows this approach to support either or both future technologies for low-emission vehicles.

3. ***Multi-unit IFE plants are robust with respect to fusion subsystem cost uncertainties.*** With a shared driver and target factory, the costs of the major fusion-specific equipment (i.e., the driver and target factory) do not increase strongly with plant output power, making

the economy-of-scale for such IFE plants stronger than for fission plants. This favors IFE for the larger plant sizes required for the alternative fuels market. Furthermore, the CoE for such large plants becomes less sensitive to uncertainties in the cost of these less-conventional fusion subsystems. The reference hydrogen plant, for example, is found to tolerate cost increases of 250% in the driver (HI accelerator), beam switchyard, fusion chambers, target chamber, and Flibe coolant costs, and still meet CoE < 3 cents/kW$_e$h. Individually, larger cost increases (6 fold) can be tolerated for the driver accelerator; and in costs per target (up to $1.2 per target).

4. ***Model improvements lead to lower optimum chamber rep-rates.*** Several improvements to the previous HYLIFE-II model, particularly, in the bypass pump power dependence on chamber rep-rate, the inclusion of average-driver-power-cost dependence on driver rep-rate, and scaling of driver efficiency with driver beam energy, are found to lead to significantly lower optimum chamber rep-rates (even for single-unit plants) and to higher optimum driver energies and target fusion yields, in spite of a new fusion chamber cost scaling including a conservative dependence on target fusion yield as well as thermal power. The higher fusion yields will be important to take into account in the future evolution of HYLIFE-II chamber designs.

The above findings are supported by extensive previous work in the many references for the RIA driver design, target factory, HYLIFE-II chamber and balance-of-plant, and on multi-unit plant and hydrogen plant economics. This paper is the first time these specific elements have been synthesized and optimized for such a large range of plant outputs. We realize the difficulty many of our fusion colleagues will have in accepting our conclusions pointing to larger plant sizes than have heretofore been contemplated, especially since many U.S. electric utility executives have been advising us to seek fusion plant designs much smaller than the 1 GW$_e$-size typical of previous nuclear plants. However, no recent study of MFE or IFE power plants, including this one, has been able to show, with reasonable assumptions, a potential CoE for fusion lower than for future fission (as shown in Fig. 12) at 1 GW$_e$ size, and the projected fusion CoE gap generally widens rapidly for plant outputs below 1 GW$_e$. Ref. 32 does allow for several improvements and reasonably-favorable assumptions regarding future fission, but so also do fusion studies in general. Meanwhile, the ongoing deregulation of the U.S. electricity market is expected to lower average electricity selling prices (wholesale, "at the plant busbar", as we typically assume in our CoE calculations), intensifying the competition for lowest CoE.

We also recognize the importance that low radioactive inventories, potential for passive safety, and lower-level waste will have for fusion success, and we have striven to exploit these potential advantages in HYLIFE-II as well. A CoE advantage for fusion in addition could be very important in more competitive future markets. A strong economy-of-scale has long been a recognized hallmark of fusion.[35] We did this study to support our suggestion that, in addition to electric plants, attention be given fusion for larger synthetic fuel plants (or for electric transportation energy for electric cars) where fusion's economy-of-scale can be better exploited, and we urge our fusion colleagues to consider similar studies for other types of fusion designs. We turn next to the important IFE development requirements and assumptions which underpin our results. Critical areas deserving further work are discussed in Appendix I

B. Development Requirements

Following is a list of several critical developments identified as essential for success for the multi-unit HYLIFE-II plants considered in this study. Where possible, we have tried to provide quantitaive *minimum* requirements specific to the reference hydrogen case.

1. ***Target physics.*** Laboratory inertial fusion ignition must be demonstrated, and indirect-drive targets appropriate to heavy-ion drivers must be tested and understood well enough to predict gains of ~100 at HI beam energies of ~ 10 MJ, with low uncertainty (say, within 20 %). Targets meeting this requirement with single-sided illumination are desirable but not essential. Ref. 36 describes possible target tests simulating heavy-ion-type targets that could be carried out in a laser ignition facility based on the facility capabilities described in the recently completed Conceptual Design Report for the National Ignition Facility.

2. ***Driver.*** The feasibility of reliable (>95% availability), efficient (> 20 %) heavy-ion or medium-mass ion drivers capable of switching between several target chambers must be demonstrated by accelerating, transporting (switching) and focusing relevantly-space-charge-dominated beams with a sufficiently-low emittance that the beams can be focused to spot sizes of less than 3 mm radius appropriate for 10 MJ targets. Ion driver technology must be demonstrated capable of shot repetition rates of 15 to 20 Hz, at costs that

extrapolate to a total driver capital cost less than $5 B (direct +indirect), at a beam energy of 10 MJ. A driver architecture allowing efficient construction in two stages with intermediate operation (e.g. at 4 to 5 MJ initially, then upgraded to 10 MJ) is highly desirable for staged plant deployment (see future work, next section). Added thermal loads on the accelerator switches and metglass cores need to be specifically considered in driver designs for the higher rep-rates considered here. A recirculating induction accelerator driver is a good approach to meet these requirements, but is not the only possible ion driver architecture.

3. ***Driver-target interface.*** Fusion chambers and compatible targets must be developed with an illumination geometry simple enough to permit a practical and affordable multi-unit beam switchyard and final focus system for less than 100 M$ direct cost per target chamber. For example, this would be easiest to meet with targets capable of single-sided illumination, (each "end" implying a cluster of 4 to 12 beamlet cluster within a 10 degree cone), reasonably possible with double-sided illumination targets, and may not be likely practical, in our opinion, with targets requiring spherically-distributed illumination from 10 or more directions.

4. ***Fusion chambers.*** Until low cost, long lasting, low activation structural materials are validated, target chambers with renewable fluid walls such as HYLIFE-II,[2] or possibly chambers with minimal use of solid structures such as OSIRIS[15] and CASCADE,[16] must be developed if IFE maintenance and materials replacement costs are to be much lower than fission fuel costs. Lower optimum pulse repetition rates that result with multi-unit IFE plants will assist chamber splash clearing, increasing the likelihood fluid-wall target chambers can be successfully developed. Target chamber concepts must be tested to benchmark model code calculations well enough to extrapolate to a 3×10^9 shots of 1 GJ yield without cyclic fatigue. Use of liquid jets to attenuate shocks reaching the walls as in HYLIFE-II are a good candidate approach, and there may be ways to improve on the scheme. Scaled laboratory experiments addressing the feasibility of these schemes are essential.

5. ***Target fabrication and injection.*** Injectable, mass-produced targets must be developed with recoverable and recyclable materials, for costs of less than $0.3 to $1.2 /target for 6 to 16 MJ driver energy, respectively. Sharing a target fabrication facility among multiple target chambers will increase the total production rate of targets, which will lower the cost per target for multi-unit IFE plants. Target injector systems must be developed capable of injecting cryogenic targets at 3 to 4 Hz, with an accuracy such that the beams can hit the targets arriving in the center with an error at least 5 times smaller than the spot size.

6. ***Low-emission vehicles that people will buy.*** Since the markets for the reference 8 GW_e plant are predicated on the future growth in demand for either hydrogen or electric-battery powered vehicles, the deployment of such plants depends on the successful development of such advanced cars meeting consumer's expectations of cost, performance, and durability. The motivation to develop these cars is intense and focused to near term goals. Fusion development can be seen to provide an ultimate and inexhaustible energy source to help justify the enormous infrastructure investments that will be required to ween us from an oil based transportation economy. Low emission cars and electric trains will be dominant transportation modes sooner or later; the questions are only when and at what price. A good guess is that such cars, and the electricity demand to power them, will arise before we have completed all the fusion developments in this list.

APPENDIX I: CRITICAL AREAS FOR FUTURE WORK

The preceeding list of development requirements can be viewed as the most important critical areas that largely need experimental development and demonstration. Here we list those critical design areas which can profit from more data obtained from these ongoing developments, so that folding in the new information can better define the further experimental developments, resolve remaining uncertainties in subsystem interactions, further optimize the systems within a larger variable space, and finally, improve the projected cost and performance estimates for the power plants.

1. ***Integrated driver and target optimization.*** With the recent de-classification of IFE last Dec. 1993 by DOE, there are new opportunities to explore the optimization of driver parameters, beam transport and focusing, and optimum target design, in a larger variable space than has been done before. New beam transport codes are being developed which should permit us to better define chamber vacuum recovery, or, as the case may be, required background gas pressures for beam neutralization. Three-dimensional IFE implosion codes under development will allow us to accurately calculate

the gain penalty for single-sided versus double-sided target illuminations, for example, confirming the viability of new targets with total line-of-sight neutron shielding.[12] An integrated "source-to-target" modeling should reduce uncertainties about target performance in a "real chamber environment" accounting for finite gas effects and finite target positioning errors. A series of 3D code calculations varying the precision in various target parameters, coupled with a more detailed target factory fabrication study, may be useful to identify ways to reduce candidate target fabrication costs with acceptable gain performance. As beam transport models improve, the optimum ion mass and energy could be reexamined with an improved, flexible, ion driver systems code, and new ion driver architectures exploiting these improved transport models could be explored. As information is obtained from experiments in beam transport, beam-combining, and beam circulation in small recirculating induction accelerator experiments, the design, optimization and cost estimates for power plant drivers can be improved.

2. ***Improved HYLIFE-II chamber design.*** Small working models of the liquid jets used in the HYLIFE-II concept could be developed to improve the computational models predicting the chamber recovery rates, and to measure the shock attenuation factors and cyclic stresses on the chamber walls. This could lead to better understanding of how the chamber size and cost should scale with fusion yield, in turn allowing better estimates of the important bypass-pumping power with rep-rate.

3. ***More detailed beam switchyard designs.*** More detailed designs of candidate beam switchyard concepts are needed to better define the cost of beam switching with the number of units in a multi-unit plant. Three-D particle simulation code calculations should then be done to check for possible beam-emittance growth problems that may arise.

4. ***Staged plant deployment.*** Multi-unit plants could be greatly facilitated with staged deployment of units, by allowing revenues from the first units to be used to pay for the subsequent completion of the remaining units, an idea first suggested by Meier and Hogan.[4] Electricity returns would be initially higher than for hydrogen, so such plants may start out selling mostly electricity at smaller ouputs to pay for subsequent plant expansions. Then, when electricity sale prices decline at larger outputs (due to market elasticity for electricity prices), such plants could end up selling mostly hydrogen. The operation of the first units would also calibrate the economic projections as a function of the number of units, to allow investors to make informed decisions on how many units to add and at what intervals as the electricity and hydrogen markets evolves. Driver upgrades in energy and rep-rate could also defer some of the initial driver costs in such a sequence. A detailed financial "business plan" for such a staged deployment could provide a rationale plan for financing large hydrogen synfuel plants with minimal investor risk.

5. ***Advanced targets.*** For IFE, the possible impact of a dramatically-reduced driver energy requirement resulting from advanced targets such as the Fast Ignitor,[37] may lower the plant size for a given CoE target by a factor of about two[1] (i.e., the IFE bars in Fig. 12 would shift to the left by one power output level). Since the Fast Ignitor concept separates the functions of fuel compression and ignition heating, a heavy-ion driver could be used to supply the majority fuel compression energy, together with a relatively small short pulse laser for the ignitor. A solution for the protection of the final optic for the ignitor laser beam remains to be found. While not essential to meeting the CoE and CoH goals for competitive hydrogen production, such advanced targets could reduce the initial size of the driver and capital cost required for the first demonstration plant.

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