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ELECTRIC POWER PLANTS

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ECONOMIC STUDIES FOR HEAVY-ION-FUSION ELECTRIC POWER PLANTS*

MASTER

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ABSTRACT

We have conducted parametric economic studies for heavy-ion-fusion electric power plants. We examined the effects on the cost of electricity of several design parameters: cost and cost scaling for the reactor, driver, and target factory; maximum achievable chamber pulse rate; target gain; electric conversion efficiency; and net electric power. Using the most recent estimates for the heavy-ion-driver cost along with the Cascade reactor cost and efficiency, we found that a 1.5 to 3 GWe heavy-ion-fusion power plant, with a pulse rate of 5-10 Hz, can be competitive with nuclear and coal power plants.

INTRODUCTION

The Heavy-ion-fusion Systems Assessment Project has produced new estimates of the capital cost and performance of an induction linac accelerator for inertial fusion.¹ These estimates have been incorporated in an economic model of a heavy-ion-fusion (HIF) electric power plant. This model has been used to do parametric studies to identify the features of the plant that have the highest leverage for improving HIF economics. One of the factors that will be used to judge the desirability of an ICF power plant is its economic competitiveness compared to other power sources, and one of the several figures of merit for economic competitiveness is the projected cost of electricity (COE). While we caution against using any of the COEs calculated in this paper in an absolute sense, we believe the results are useful in relative comparisons. The model should primarily be used to identify the technical developments that would lead to the greatest reduction in COE. The model can also be used (if a great deal of care is taken) to grossly compare HIF to other future power sources. The same economic assumptions must be used in the comparison. This paper updates our previous analyses of HIF economics.^{2,3}

COST AND PERFORMANCE MODELS

The COE in ¢/kWh is given by

$$\text{COE} = (\text{RC}_T + \text{M} + \text{F}) / (0.0876 \text{aP}_n) \quad , \quad (1)$$

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where R = annual fixed charge rate (yr^{-1}),
 C_T = total capital cost of the plant (\$B),
 M = annual operation and maintenance cost (\$B),
 F = annual fuel cycle cost (\$B),
 α = plant availability factor, and
 P_n = net electric power (GW_e).

The evaluation of this expression for future fission and coal plants is discussed at length in the Nuclear Energy Cost Data Base.⁴ Based on the methods and financial parameters given in Ref. 4, the constant dollar fixed charge rate we use is 8.3%. We assume that the annual fuel cost is negligible, and that the O&M cost is 3% of C_T . Thus, the numerator of Eq. 1 is equal to $0.113C_T$. The total capital cost is 1.83 times the direct capital cost. This factor includes home and field office construction and engineering services, owner's cost, a project contingency, and interest during construction in constant dollars. The ratio of total capital cost to direct capital cost (1.83) is midway between the value for coal plants (1.53) and the value for nuclear plants with the best experience in holding down costs (2.07). (The average ratio for fission plants is significantly higher at 2.75)

The capital cost of the power plant is broken into three items; the reactor, the driver and the target factory.

$$C_T = 1.83 (C_{Td} + C_{dd} + C_{tfd}) \quad (2)$$

where C_{Td} , C_{dd} , and C_{tfd} are the direct capital costs of the reactor, driver and target factory, respectively.

Reactor Cost

The cost of the reactor, which includes the the fusion chamber and balance of plant, is based on the recent cost estimate for the Cascade reactor.⁵ The Cascade reference design has an estimated direct capital cost of \$0.66 B at a plant thermal power of 1.67 GW_t and a gross electric power of 0.905 GW_e . The auxiliary power requirement of the Cascade plant are 1.7% of the gross electric power. The direct capital cost can be scaled to other sizes by

$$C_{Td} = C_T (P_t/1.67)^a (0.72N_u + 0.28) \quad \$B \quad (3)$$

where C_T is reactor cost coefficient (\$B), P_t is thermal power (GW_t), a is the power scaling exponent, and N_u is the number of reactor units (i.e., chamber, structures, and associated balance of plant equipment) in the plant. The reference case scaling exponent is 0.49. The last term accounts for savings in both direct and indirect costs when more than one unit is built at a single site.

Target Factory Cost

The direct capital cost of the target factory is given by

$$C_{tfd} = C_{tf} v^f, \quad (4)$$

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where C_{tf} is the target factory cost coefficient, ν is the pulse rate (Hz), and f is the scaling exponent. The base case parameters are $C_{tf} = \$0.1 \text{ B}$ and $f = 0$. That is, we assume a constant direct capital cost of $\$0.1 \text{ B}$. The effects of scaling with pulse rate are examined in the sensitivity studies describe later. There are currently no definitive studies on target factory costs; Eq. 4 is simply an estimate based on analogies to current facilities that mass produce precision products; e.g., semiconductor micro-chips.

Driver Cost

The cost of the heavy ion driver is based on an accelerator with the following characteristics: charge state = +3; ion mass = 210 amu; emittance = 30 $\mu\text{m-rad}$; ion kinetic energy = 10 GeV; number of beamlets = 8; initial tune = 850. The direct capital cost of the driver is given by

$$C_{dd} = (0.32 + 0.088E_d)(1.25 + 0.05N_c)(1 + 0.0088(\nu - 5)) \quad \$\text{B} \quad (5)$$

where E_d is the driver energy (MJ), N_c is the number of chambers, and ν is driver pulse rate (Hz). The first term is the cost of the high energy part of the accelerator, which increases linearly with driver energy. The second term includes additional costs for the low energy front end (25%) and for the beam transport and final focusing (5% per chamber). The last term accounts for the scaling of the cost with pulse rate. The cost increases by 4.4% for each 5 Hz above the base case pulse rate of 5 Hz. Equation 5 gives driver costs that are consistent with the more detailed driver cost model developed by McDonnell Douglas.⁶

Driver Efficiency

The efficiency of the driver is a function of both its energy and its pulse rate. Hovingh's data⁷ (converted to charge state +3) is fit by the following expressions at $\nu = 5$ and 10 Hz:

$$\eta(E_d, 5) = 0.208 + 0.0284 \ln(E_d - 1.7) \quad , \quad \text{and} \quad (6)$$

$$\eta(E_d, 10) = 0.221 + 0.0273 \ln(E_d - 1.7) \quad , \quad (7)$$

where E_d is in MJ. At 10 Hz the efficiency is slightly higher. To scale to other pulse rates, the above equations are used in the following expression.⁸

$$\eta(E_d, \nu) = \frac{(1.55) (5\nu) \eta(E_d, 5) \eta(E_d, 10)}{[10 \eta(E_d, 5)(\nu - 5)] - [5 \eta(E_d, 10)(\nu - 10)]} \quad (8)$$

The factor of 1.55 converts the charge state +1 results to the charge state +3 case. That is, the $Q = 3$ driver is a factor of 1.55 times more efficient than the $Q = 1$ driver.

Target Gain

The target gain versus driver energy relationship used in our analysis is taken from Ref. 8. The following expression is used for

the gain curve for single-shelled, cryogenic targets with a $r^{3/2}R$ parameter of 0.02. [r is the focal radius (cm) of the beam and R is the range (g/cm²) of the ions.]

$$G = 20 + 157 \ln(E_d/3.0) \quad , \quad (9)$$

where E_d is in MJ. In our parametric studies, we looked at the effects of an advanced target design with improved performance. The advanced gain is given by a multiplier times G from Eq. 9.

$$G_{adv} = 2.56 G \exp(0.36/E_d) \quad . \quad (10)$$

RESULTS OF PARAMETRIC STUDIES

Parametric studies were carried out to examine the COE as a function of the driver pulse rate. We also examined the sensitivity of the results to variations from the reference case in the cost and performance models. The reference case was a single-unit plant with a constant net electric power of 1.0 GW_e. (Other reference case parameters are indicated in Table II.)

Economy of Scale

The COE as a function of the driver pulse rate is shown in Fig. 1 for the reference case power of 1.0 GW_e as well as for 0.5 and 1.5 GW_e plant. There are several things to note. First, and

Fig. 1. Cost of electricity as a function of driver pulse rate for plants with net electric powers of 0.5, 1.0 and 1.5 GW_e.

most striking, is the strong economy of scale with increasing net electric power. The COE at 5 Hz is reduced by 41% (from 9.8 to 5.8 ¢/kWh) when the net power is increased from 0.5 to 1.0 GW_e. All of the curves show the same general shape; the COE initially decreases with increasing pulse rate and then goes through a broad, shallow minimum. The COE is insensitive to pulse rate above about 4 Hz. For the 1.0 GW_e case, the optimum pulse rate is about 10 Hz. The COE at 4 Hz, however, is within 5% of the minimum. At 1.5 GW_e, the COE is competitive with the projected COE from a coal-fired power plant (4.4 ¢/kWh).⁴

Multi-unit Power Plants

Figure 2 shows the COE as a function of the total net power for plants made up of different size units: 0.5, 1.0, and 1.5 GW_e net. A multi-unit power plant consists of a single driver and target factory associated with more than one complete reactor units (i.e., chamber, structures, and balance of plant equipment). As indicated the COE decreases with increasing net power and with increasing unit size. The results shown here are all at a driver pulse rate of 5 Hz per unit.

The COE from a 1.0-GW_e power plant consisting of two 0.5-GW_e units is 6.4 ¢/kWh. This is 10% higher than the COE from a single-unit power plant generating 1.0 GW_e. Hence the

Fig. 2. Cost of electricity versus total net power for plants made up of different size units.

multi-unit plant achieves most of the economy of scale benefits of the single unit plant. This is important since there may be other reasons for choosing a multi-unit plant (e.g., phased construction could more closely match load growth and spread out capital requirements). The single-unit plant has a reactor that is less expensive than the sum of the two smaller reactors due to the scaling given in Eq. 3. Also the two-unit plant has additional costs for beam transport and focusing. The COE for a four-unit, 2-GW_e plant is 4.7 ¢/kW_{eh} while a two-unit, 2 GW_e plant results in a COE of 3.9 ¢/kW_{eh}. The 3 GW_e plants at 3.0 and 3.3 ¢/kW_{eh} are competitive with the COE from future 1-GW_e nuclear power plants (3.5 ¢/kW_{eh}).⁴

The COE from the HIF plant is compared to other fusion reactor studies in Table I. The costs from the other studies⁹⁻¹¹ were inflated to January 1985 dollars, and the economic assumptions previously described were applied in all cases. That is, we used the same contingency, indirect cost factors, time-related cost factor, fixed charge rate, capacity factor, etc. As indicated, the COE projected for the 1200 MW_e HIF plant using the Cascade reactor is 16 to 19% less than the COE for STARFIRE and MARS, respectively. Compared to HIBALL-II at 3784 MW_e, the HIF/Cascade plant has a COE that is 33% lower.

Table I. Comparison of results with other fusion reactor studies. All cost are in constant 1985 dollars.

	Net Power = 1200 MW _e			Net Power = 3784 MW _e	
	STARFIRE	MARS	HIF/CAS	HIBALL-II	HIF/CAS
Direct cost (\$B)	2.07	2.24	1.83	4.80	3.43
Total cost (\$B)	3.78	4.10	3.34	8.78	6.30
COE (¢/kW _{eh})	6.13	6.33	5.14	4.59	3.07

Other Parameter Studies

The results of a sensitivity study, where we varied several parameters, are summarized in Table II. A 25% change in the driver cost results in a 13% change in the COE. A 25% change in the reactor cost leads to a 11% change in the COE. The COE is insensitive to the reactor scaling exponent in Eq. 3. If the target factory cost increases moderately with increasing pulse rate, the COE increases by 10% at 5 Hz. (The selected normalization pulse rate of 1 Hz is, of course, arbitrary. If we had selected a higher pulse rate to normalize to, the sensitivity would be less.) Reducing the conversion efficiency to 35% increases the COE by 15%. The advanced target gain curve, which at 4 MJ gives a gain of 182 compared to 65 with the reference gain curve, leads to a 8% reduction in the COE. The economy of scale effects previously discussed are also indicated in the table and are seen to cause the largest effects.

Table II. Changes in the COE ($\text{¢/kW}_e\text{h}$) resulting from changes in the reference case parameters. The reference case COE is $5.84 \text{ ¢/kW}_e\text{h}$. The reference case parameters are given in square brackets. Fractional changes are given in parenthesis.

Parameter	COE	Parameter	COE
Pulse rate		T. F. scaling	
[5 Hz]		[0]	
2 Hz	6.5 (+ 11%)	0.6	6.4 (+ 10%)
10 Hz	5.7 (- 2%)	Conversion eff.	
Driver cost		[54%]	
[C_d]		45%	6.2 (+ 6%)
0.75 C_d	5.1 (- 13%)	35%	6.7 (+ 15%)
1.25 C_d	6.6 (+ 13%)	Target gain curve	
Reactor cost		[G]	
[C_r]		G_{adv}	5.4 (- 8%)
0.75 C_r	5.2 (- 11%)	Net electric power	
1.25 C_r	6.5 (+ 11%)	[1.0 GW_e]	
Reactor scaling		0.5	9.8 (+ 68%)
[0.49]		1.5	4.4 (- 25%)
0.70	5.9 (+ 2%)	Units per plant	
0.90	6.0 (+ 3%)	[1]	
		2	3.9 (- 33%)
		3	3.3 (- 43%)

CONCLUSIONS

We have examined the COE of HIF power plants in order to determine the economic impact of various design and system improvements. Our conclusions fall into three major areas: (1) optimum pulse rate, (2) economy of scale, and (3) various design improvements.

Optimum Pulse Rate

For the single-unit, 1- GW_e power plant, the optimum pulse rate (for both driver and chamber) is about 10 Hz, resulting in a COE of $5.7\text{ ¢/kW}_e\text{h}$. However, the COE is not very sensitive to pulse rate. For example, if the chamber pulse rate is limited to 4 Hz, the COE increases by less than 5%. This weak dependence of COE on pulse rate is important because major technological uncertainties are associated with predicting the maximum achievable chamber pulse rate.

Economy of Scale

As expected, the COE decreases with increasing net electric power. The reduction is significant, whether the power is increased by increasing the power of a single unit, or by using a single driver to operate several units. For a given net power, a multi-unit plant achieves most of the economy-of-scale advantage of a

single large plant. These savings result from the driver being such a large fraction of the plant cost. Only if the cost of the driver is significantly reduced will the penalty for small power units be significantly affected. The HIF power plant can be competitive with coal or nuclear with a single unit 1.5 GW_e plant or with multi-unit, 2-3 GW_e plants. The COE projected in these studies indicate that the COE is 16 to 19% lower than from STARFIRE and MARS, and 33% lower than from HIBALL-II.

Various Design Improvements

Other than changing the net power of the plant, each of the variations we considered resulted in a change in the COE on the order of 10%. To make dramatic improvements in the COEs reported here will require a combination of success in reducing costs and improving performance in a variety of areas.

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