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ICF REACTOR ECONOMICS: IDENTIFYING THE
HIGH LEVERAGE DESIGN FEATURES

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ICF REACTOR ECONOMICS: IDENTIFYING THE HIGH LEVERAGE DESIGN FEATURES*

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ABSTRACT

Parametric studies were carried out for a heavy ion beam (HIB) fusion electric power plant to investigate the effects on the cost of electricity (COE) of variations in several design parameters. In particular, we examined the effects of maximum achievable chamber pulse rate, driver cost, target gain, electric conversion efficiency, and net electric power. We find that with a combination of improvements over our base case, HIB fusion can be economically competitive with other future power sources.

INTRODUCTION

One of the primary objectives of the ICF Applications Group is to develop power plant concepts that will be economically competitive with other long-term electric power producers such as fission and coal. We are developing systems models for ICF power plants that allow us 1) to identify design features that have the highest leverage for improving ICF economics and 2) to do first order economic comparisons with other power sources.

While economic factors are not the only ones that will be considered in decision making about future power sources, other factors, such as safety, environmental impact, and public acceptance may not weigh heavily unless ICF also appears to be economically competitive. The definition of economic competitiveness is subject to much debate. A common figure of merit is the COE. Because of economies of scale, the COE decreases monotonically with increasing power plant size. Therefore, other figures of merit, which reflect the total capital investment, must also be considered. In this paper, however, we limit our discussions to the COE as the figure of merit.

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In this paper we consider a heavy ion beam fusion power plant that consists of a driver, a target factory and one or more power units. A power unit is defined as all the buildings and equipment needed to generate electric power given that the target and beams are delivered to the reaction chamber. Each power unit may have several reaction chambers where the fusion pulses occur. The maximum achievable pulse rate in a single chamber is limited. Therefore more than one reaction chamber may be required to achieve the desired output of a single power unit. We distinguish between multiple power units and multiple reaction chambers so we can examine separately the effects of increasing the number of reaction chambers at a constant net power and of increasing the power level by driving more power units with a single driver.

COSTS

The cost models we used in this study are reported in detail in Ref. 1. The essence of the models is summarized here.

Power Unit Cost

The model we have assumed for the HIB fusion power plant uses a conventional steam cycle to produce electricity. Other than the fusion reaction chamber itself, the rest of each power unit look essentially like a fission power plant outside the reactor vessel. Therefore, our cost scaling models are derived from recent estimates for future fission plants. Fission power plants recently completed and currently under construction are significantly more expensive than coal-fired power plants. United Engineers and Constructors and researchers in the Engineering Technology Division at Oak Ridge National Laboratory have, however, estimated the cost of nuclear power plants for the 1990's based on the presumed effects of licensing reform.^{2,3} The 1990's nuclear plants have direct capital costs that are essentially equal to those of coal plants. We

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assume that the fusion plant can achieve similar direct capital costs for those elements not unique to fusion. On this basis, the direct capital cost of a 1 GWe power unit is \$0.7 B.

As previously indicated, each power unit may have more than one reaction chamber. To account for this in our cost algorithms, we break down the direct capital cost into three parts, the containment building cost, the steam supply system (SSS) cost, and the remainder of the power unit cost. Reference 3 gives a detailed break-down of the cost of the PWR for the 1990's. It shows that the reactor containment building cost is 7.5% of the total direct cost, and the SSS accounts for 18.2% of the total direct cost. We allocate additional containment building space and SSS equipment for each additional fusion chamber using these same fractions. The direct capital cost of the power unit can be written as

$$C_{ud} = 0.705[0.743P_g^{0.6} + 0.075P_c^{0.5}N_c + 0.182P_c^{0.6}N_c] \$B, \quad (1)$$

where P_g is the gross electric power for one power unit, P_c is the gross electric power associated with each chamber, and N_c is the number of chambers per power unit. Hence, $P_c N_c$ is equal to P_g for each power unit. Experience has shown that there are savings in both the direct and indirect capital costs for multi-unit power plants.^{2,3,4} Typically, each additional unit has a direct capital cost equal to 80% of the first unit on the site, and an indirect capital cost equal to 60% of the indirect costs for the first unit. These factors are included in our analyses.

Driver Cost

The cost of a heavy ion beam driver have been estimated based on RF accelerator⁵ and induction linac⁶ technology. Using the results given in Ref. 6, the driver direct capital cost is given by

$$C_{dd} = 0.64E_d^{0.4} + 0.1(N_c N_u - 1) \$B, \quad (2)$$

where E_d is the driver beam energy in MJ. The second term in Eq. 2 accounts for the additional cost of transporting beams to the individual reaction chambers.

Other Factors

In addition to the driver and power unit costs, we include \$100 M for the direct capital cost of the target factory and 1¢/target for consumable materials. The total capital cost is 1.9 times the direct capital cost. This factor accounts for contingency (10%), indirect construction costs (50%), and

interest during construction (15%). Annual O + M costs equal to 2% of the total capital cost are also included. The fixed charge rate used in our constant dollar analysis is 10%, and the plant capacity factor is 70%.

RESULTS

The base case parameters used in our calculations are a net power per power unit (P_n) of 1GW_e, one power unit per plant ($N_u = 1$), maximum chamber pulse rate (ω_{cm}) of 10 Hz, and an electric conversion efficiency (η_c) of 40%.

Figure 1 shows the net power, driver power, auxiliary power, and gross electric power as a function of the driver pulse rate for the base case. The driver power requirement increases with increasing pulse rate. This follows since a higher pulse rate corresponds to a lower target gain, and, therefore, more power must be recirculated to run the driver. The gross electric power required to maintain a net output of 1.0 GW_e increases from 1.15 to 1.45 GW_e as the driver pulse rate increases from 5 to 50 Hz.

Maximum Chamber Pulse Rate as a Parameter

The COE as a function of the driver pulse rate is shown in Fig. 2 for four different maximum chamber pulse rates; $\omega_{cm} = 5, 10, 20$, and >50 Hz. The discontinuities, which occur every ω_{cm} Hz, reflect the cost of additional SSS equipment containment building space, and beam transport lines incurred each time an additional chamber is added.

Focusing on the base case with $\omega_{cm} = 10$ Hz, we see that the COE initially decreases with increasing driver pulse rate. This is due to the fact that the driver cost decreases with increasing driver pulse rate since higher pulse rates correspond to lower driver energies. The minimum COE is 7.0¢/kW_eh for the base case and occurs at 10 Hz. At this point, the driver energy is 3 MJ and the gross electric power is 1.18 GW_e.

It is interesting to note how flat the >50 Hz line is. If a chamber could be designed to operate at an unlimited pulse rate (or if there were no cost associated with increasing the number of chambers), the minimum COE would be 6.75¢/kW_eh which is realized between 25-30 Hz. Hence the 10 Hz limit on chamber pulse rate increases the COE by less than 4%. If the chamber pulse rate is limited to 5 Hz, the COE is 7.4¢/kW_eh, or less than 10% higher than the 6.75¢/kW_eh minimum. The curves also rise at high pulse rates since the cost of the power unit is increasing with increasing gross power.

Fig. 1 The gross electric power required to maintain a constant net electric power increases with increasing driver pulse rate.

Fig. 2 The COE decreases as the driver pulse rate increases until the chamber pulse limit is reached.

Driver Cost as a Parameter

Figure 3 shows the sensitivity of the COE to the cost of the driver. The three curves, from top to bottom, are the base case, the driver cost reduced by 25%, and the driver cost reduced by 50%, respectively. The cost reductions are applied to the total driver cost including the additional beam transport lines required for power units with more than one chamber. In all three cases the minimum COE occurs at 10 Hz. Since the driver cost is about half of the total capital cost, reducing the driver cost leads to significant savings in the COE. Each 25% reduction in the driver cost gives a 13% reduction in the COE.

Fig. 3 Reducing the driver cost reduces the COE.

The dashed curves show that if the chamber pulse rate is unlimited, the optimum driver pulse rate decreases with decreasing driver cost. In addition, the COE becomes less sensitive to driver pulse rate, i.e., the curves tend to flatten out.

Target Gain as a Parameter

The reference target gain corresponds to the $r^{3/2}R = 0.01$ case given in Ref. 7. It is fit by the expression,

$$G = 20 + 113 \ln (E_d/1.7) \quad (3)$$

We also investigated the effect of improving the target performance. We assume that the driver energy required to achieve a given

target gain is reduced by a factor of three. This is consistent with estimates for polarized fuel.⁸ At 10 Hz the COE is reduced by 12%. With no limit on chamber pulse rate, the COE minimum shifts toward higher pulse rates as gain improves at lower driver energy. Furthermore, in this case the COE also becomes more sensitive to pulse rate.

Conversion Efficiency as a Parameter

We examined the effect of increasing the electric conversion efficiency by assuming that the conversion efficiency can be increased without increasing the cost per kW_t . We found that increasing the conversion efficiency from 40 to 60% only reduces the COE by 12%. Remember that the net electric power is held constant, therefore, a more efficient power unit is smaller and suffers an economy of scale penalty. That is, the cost per kW_t is only the same for plants of equal thermal power.

Plant Power as a Parameter

As noted previously, there are two ways to consider net plant power as a variable. The number of units can be set equal to one and we can vary the power of the unit. On the other hand, we can keep the power of each unit constant and vary the number of power units in a plant.

First, we consider a single-unit plant. Figure 4 shows the COE for three different net power outputs, 0.5, 1.0 and 2.0 GW_e . The COE from the 0.5 GW_e plant is 66% more than the base case at 10 Hz, i.e., 11.6 versus 7.0¢/kWh. The 2.0 GW_e plant produces electricity at 4.3¢/kWh or 39% less than the base case. It is clearly advantageous, in terms of the COE, to use the driver to produce as much power as possible. Other considerations such as following load growth and minimizing total capital investment may favor smaller net powers.

We also considered the advantages of using a single driver and target factory to operate more than one power unit. At a driver pulse rate of 20 Hz, a two-unit, 2 GW_e power plant produces electricity at 4.8¢/kWh, or 31% lower than the single-unit, 1 GW_e plant. A four-unit, 4 GW_e power plant reduces the COE to 3.6¢/kWh, or 49% lower than the single-unit plant. The total capital investment, however, increases as the number of units is increased. The total capital costs for the 1, 2 and 4 unit plants are \$3.55B, \$4.81B, and \$7.35B, respectively.

We found that as the number of units increase, the COE becomes less sensitive to the driver pulse rate. In fact the four-unit

Fig. 4 The COE decreases as the net power of the plant increases.

plant could operate at a driver pulse rate of 12 Hz and still be within 5% of its minimum COE. The required chamber pulse rate in this case is only 3 Hz.

Figure 5 shows the COE as a function of the total net power for plants made up of different size units, 0.5, 1.0, and 2.0 GW_e net. The COE from a 1.0 GW_e power plant consisting of two 0.5 GW_e units and a single driver is 7.7¢/kWh. This is 10% higher than the COE from a single-unit power plant generating 1 GW_e . This higher COE is the result of the economies of scale in the power unit cost and the additional cost of beam transport lines for the two-unit plant. The COE from a 2 GW_e power plant with a single unit is 4.3¢/kWh compared to 4.8¢/kWh for a two-unit plant, and 5.8¢/kWh for a four-unit plant.

We see that at a fixed net power, the COE is lower for a single-unit plant than for a multi-unit plant. The multi-unit plant does, however, achieve most of the economy of scale benefits of a single large unit. For example, going from 0.5 to 2 GW_e in single-unit plant reduces the COE by 63%, compared to the 50% reduction achieved by a four-unit plant. An advantage of the multi-unit plant is its operational flexibility. The plant can begin to operate and produce revenues from one unit while decisions are pending on the need for

Fig. 5 For the same net power, plants with fewer, larger power units have lower COE.

additional units. Capital costs for the future units are, of course, also deferred.

Several Parameters Simultaneously

Most of the parameters considered have a modest impact on the COE. No single improvement considered is able to reduce the COE to the point where it would be competitive with coal (4.6¢/kW_eh) or nuclear (3.5¢/kW_eh) power.² Hence it is important to make advances in as many areas as possible. In Fig. 6 when we considered several simultaneous improvements, namely, a driver cost reduction of 25%, the improved target gain, an electric conversion efficiency of 50%, and two-unit power plants, we found that a 2 GW_e plant produced power for 3.6¢/kW_eh which is economically competitive with coal and nuclear power.

CONCLUSIONS

We have examined the COE of HIB fusion power plants in order to determine the economic impact of various design and system improvements. Our conclusions fall into four major areas.

Fig. 6 With several simultaneous improvements, the COE from HIB fusion power plants will be competitive with nuclear and coal.

Pulse Rate

For the single-unit, 1 GW_e power plant, the optimum pulse rate (for both driver and chamber) is 25-30 Hz, resulting in a COE of 6.75¢/kW_eh. However, the COE is not very sensitive to pulse rate. For example, if the chamber pulse rate is limited to 5 Hz, the COE increases by less than 10%. This is important because there are major uncertainties associated with predicting the maximum achievable chamber pulse rate. We also note that decreasing the driver cost or increasing the plant size results in a lower optimum pulse rate but also in less sensitivity to pulse rate (i.e., flatter curves). Improving the target gain by reducing the required driver energy for a given gain, results in a higher optimum pulse rate and a greater sensitivity. Increasing the electric conversion efficiency has little effect on the location of the optimum pulse rate.

Multiple Reaction Chambers

For the conditions examined here, using multiple reaction chambers at constant net power never improved the COE. The optimum driver pulse rate in every case was at the maximum achievable pulse rate of a single reaction chamber. This is due to the large cost (\$100M) direct of adding beam transport lines for each new chamber and to the insensitivity to pulse rate of the COE curves.

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 power units. These savings result from the fact that the driver is 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.

We note that for a given net power, a multi-unit plant achieves most of the economy of scale advantage of a single large plant. Because the difference is so small, a plant construction scenario of starting small (0.5 GW_e or less) and adding power units might be particularly attractive. In this way, revenues can be collected from the first units while the later units are constructed as needed. Other advantages of smaller units, such as reduced on-site construction costs due to increased factory fabrication and shortened construction periods, have not yet been considered in our studies. These will tend to reduce the COE penalty of plants made up of several, smaller power units.

Various Design Improvements

Reducing the HIB driver cost is important. A 25% reduction in the driver cost leads to a 13% reduction in the COE. Improving target performance is also important. If the same target gain can be achieved with a factor of 3 less driver energy, the COE can be reduced by 12%. Improving the electric conversion efficiency is not as advantageous as might be expected at first glance. Increasing the conversion efficiency from 40 to 60% reduces the COE by 12%. However, this assumes that the power unit cost per kW_e does not increase with increasing efficiency. If it does the savings will be even less.

Only a combination of improvements reduces the COE to values in the range of those forecast for future coal and fission plants. Such a combination of improvements is not unreasonable, however. For example, if the driver cost is reduced 25%, the target gain improved at low E_d and the electric conversion efficiency increased to 50%, and a two-unit plant is built (2 GW_e total), then the COE is competitive.

SUMMARY

We find that the COE from HIB fusion can be competitive with other future energy sources. Staged construction of multi-unit plants may make smaller initial plant sizes

more attractive. Chamber pulse rates of 5-10 Hz appear adequate to achieve these economic goals.

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