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Reactors**

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Power Supply Costs for  
Inertial Confinement Fusion Reactors

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## Abstract

The economic feasibility of inertial confinement fusion depends not only on the fraction of recirculating power but also on the absolute electrical efficiency of the driver and the absolute driver energy requirement. A low efficiency driver requires more power supply energy and therefore will be more expensive than high efficiency drivers at equal values of  $\eta_D G$ . The major conclusion of this analysis is that pulsed power supply technology as it relates to any of the ICF driver candidates is a critical element that demands significant innovation before commercialization of ICF will be possible. Any reliance on low efficiency drivers further strengthens this conclusion.

The economic penalty of high power supply cost is most acute when the reactor power output is small. This has an important influence on the path to commercialization of ICF. Although the full scale power plant may be economically attractive, demonstration reactors may have unrealistically high power supply costs.

In this analysis, simple scaling laws for power supply costs are developed and applied to the various ICF driver candidates to obtain the above conclusions.

## I. Introduction

The pellet physics and driver performance criterion requirements for an economically attractive inertial confinement fusion (ICF) reactor is generally taken as the product of pellet energy gain and driver efficiency. This product, called the fusion gain, governs the fraction of power,  $f_R$ , that must be recirculated to the driver:

$$f_R = \frac{1}{\eta_{th} \eta_D^e (G+1)} \quad (1)$$

where  $\eta_{th}$  is the plant thermal efficiency,  $\eta_D^e$  is the driver electrical efficiency and  $G$  is the pellet gain. The capital cost of the power generating equipment will be excessive if  $f_R$  is too large and a commonly used limit is 25%. Assuming a 40% thermal efficiency and  $G \gg 1$ , the requirement that  $f_R$  be less than 25% implies

$$\eta_D^e G \geq 10 . \quad (2)$$

It is usually assumed that this inequality can be satisfied by any combination of driver efficiency and pellet gain.

Until recently, reported pellet designs<sup>(1)</sup> for laser driven fusion (the most developed approach to ICF) were in the range of 100-200 and the estimated laser energy was 1 MJ. Such a laser must have 5-10% efficiency in order for the condition  $\eta_D^e G \geq 10$  to be satisfied. Recent advances in pellet design<sup>(2)</sup> have improved the chances of higher pellet gain.

A gain of 1000 is currently considered feasible using lasers in the mega-joule range. With these greater gains, the required laser efficiency needed

to satisfy the inequality  $\eta_D G \geq 10$  may be relaxed to only 1.2%. Since most known lasers do not have high efficiencies in short pulse operation, this relaxation permits many more lasers to fit into the category of "potential laser fusion drivers". Unfortunately, relaxing the driver electrical efficiency without simultaneously lowering the driver energy requirement implies that the power supplies will be large and expensive. This added cost is only partially offset by the lower repetition rate associated with the use of high gain targets. The relation between the incremental cost of additional power supply energy and the cost of extended power supply lifetime is basic to the economics of ICF reactors. It is this relationship that is examined in this report.

## II. General Power Supply Cost Analysis

The electrical power generated in an ICF reactor is

$$P_e = y \omega \eta_{th} \quad (3)$$

where  $y$  is the pellet yield,  $\omega$  is the repetition rate and  $P_e$  is the gross electrical power output. Eqn. (3) can be expressed in terms of the pellet gain and driver electrical efficiency as

$$P_e = (G E_{ps} \eta_D^e) \omega \eta_{th} \quad (4)$$

where  $E_{ps}$  is the power supply energy.

Power supply costs are only known for relatively short lifetime systems ( $10^6 - 10^7$  shots). We will therefore assume the general relationship

$$C = [C_0 \left(\frac{\omega}{\omega_0}\right)^n] E_{ps} \quad (5)$$

where  $C$  is the power supply cost,  $C_0$  is the power supply cost per unit energy

at a reference lifetime (or repetition rate  $\omega_0$ ) and  $n$  is a free parameter determined by power supply design. The power supply energy can then be written as

$$E_{ps} = \frac{C}{C_0} \left(\frac{\omega}{\omega_0}\right)^n \quad (6)$$

and hence,

$$P_e = G \frac{C}{C_0} \left(\frac{\omega}{\omega_0}\right)^n \eta_D^e \omega \eta_{th} \quad (7)$$

so that the final expression for power supply costs is

$$\text{Cost } (\$/kW_e \text{ (net)}) = \frac{C}{P_e (1-f_R)} = \frac{2000 C_0 \omega^{n-1}}{\omega_0^n [\eta_{th} (G \eta_D^e) - 1]} \quad (8)$$

where  $C_0$  is in  $\$/\text{Joule}$  and  $\omega$  is in  $\text{sec}^{-1}$ . A factor of two has been included to account for indirect costs. The repetition rate can be eliminated in favor of the driver efficiency if we fix the electrical power and fusion gain. Then

$$\omega = \omega_0 \left(\frac{\eta_D^e}{\eta_{D0}^e}\right) \quad (9)$$

where the zero subscript denotes a reference system. The cost formula is now

$$\text{Cost } (\$/kW_e \text{ (net)}) = \frac{2000 C_0 (\eta_{D0}^e)^{1-n} (\eta_D^e)^{n-1}}{\omega_0 \eta_{th} (G \eta_D^e) - \omega_0} \quad (10)$$

The product  $G \eta_D^e$  is, therefore, the power supply cost proportional to  $(\eta_D^e)^{n-1}$ . For  $n = 1$ , there is no dependence of power supply capital costs on driver efficiency. For  $n < 1$ , the capital cost would favor high repetition rate systems (lifetime is cheap, energy is expensive) while  $n > 1$  would favor low repetition rates (energy is cheap, lifetime is expensive).



It has been determined empirically for high voltage capacitive power supplies that derating the voltage by  $1/\ell$  increases the lifetime by  $\ell^{8(3)}$ . On the other hand, the volume of a power supply in which the same amount of energy is stored at a lower voltage is proportional to  $\ell^2$ . If the cost of the power supply is assumed to be linearly proportional to the volume, then

$$C = [C_0 \left(\frac{\omega}{\omega_0}\right)^{1/4}] E_{ps} . \quad (11)$$

Hence the cost exponential,  $n$ , is  $1/4$  for derated capacitive power supplies. This scaling clearly favors high repetition rate, high driver efficiency systems.

### III. Results

The analysis described in Section II can be used to study the dependence of power supply cost on driver electrical efficiency. A reference set of power supply parameters are given in Table 1. With these parameters, a  $1000 \text{ MW}_e$  reactor with a 40% thermal efficiency and  $G \eta_D^e = 10$  would have a capital cost for power supplies of  $\$167/\text{kW}_e$ . We will assume an acceptable total capital cost for the plant is  $\$1500\text{-}2000/\text{kW}_e$ . Thus,  $\$167/\text{kW}_e$  represents approximately 10% of the total cost and is a convenient reference for the arguments presented here.

We show in Fig. 1 the power supply capital cost as a function of driver efficiency for the  $1000 \text{ MW}_e$  reference reactor and a  $100 \text{ MW}_e$  demonstration reactor. In the latter case the repetition rate is scaled down by a factor of ten such that the power supply unit cost is  $\$2.10/\text{joule}$ . Note again that

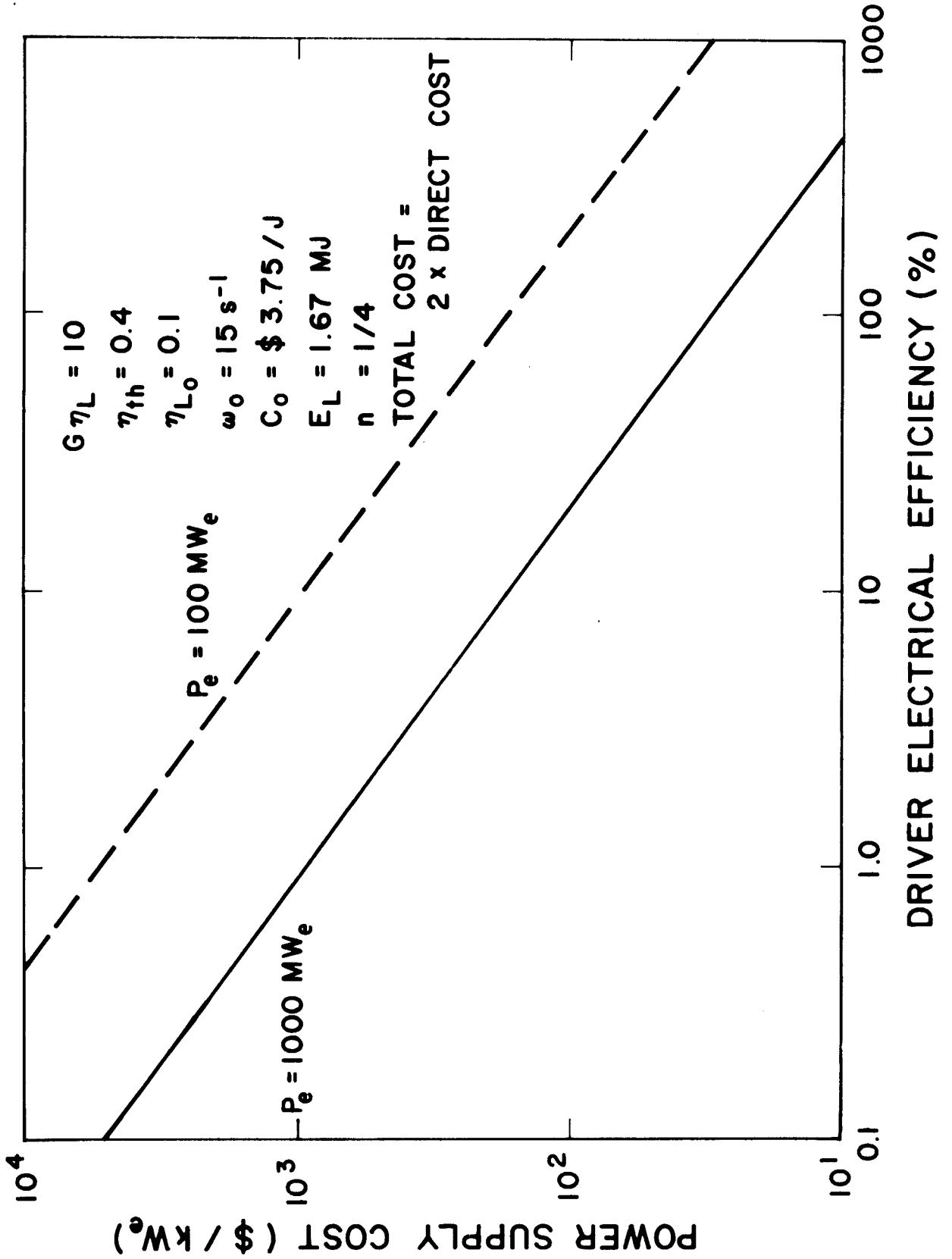
Table 1  
Reference Power Supply Parameters

Unit cost	\$3.75/J
Repetition rate	15 Hz
Lifetime*	$10^{10}$ shots
Driver energy**	1.67 MJ
Driver efficiency	10%
Power supply energy	16.7 MJ

\*Corresponds to 30 year life at 70% plant factor

\*\*Assumed to be necessary for adequate pellet gain

# POWER SUPPLY COSTS (DIRECT + INDIRECT) vs. DRIVER EFFICIENCY FOR DIFFERENT POWER LEVELS



the driver energy in all the examples discussed is 1.67 MJ to be consistent with several pellet physics analyses that indicate a target gain in the range 100-1000 is unlikely if the driver energy is below 1-2 MJ.

Let us now consider several specific cases. A 2% efficient laser driver such as rare gas eximer systems would imply a power supply capital cost of \$550/kW<sub>e</sub> for a 1000 MW<sub>e</sub> reactor and \$3200/kW<sub>e</sub> in a 100 MW<sub>e</sub> reactor. A 30% efficient driver, such as a relativistic electron beam (REB), would involve a cost of \$75/kW<sub>e</sub> at 1000 MW<sub>e</sub> and \$420/kW<sub>e</sub> at 100 MW<sub>e</sub>. The power supply cost for even this high efficiency driver is excessively large for a 100 MW<sub>e</sub> unit. Other examples are:

- (a) The iodine laser at 1% efficiency would have power supply costs of \$940/kW<sub>e</sub> at 1000 MW<sub>e</sub> and \$5300/kW<sub>e</sub> at 100 MW<sub>e</sub>;
- (b) A 10% efficient CO<sub>2</sub> laser would have power supply costs of \$167/kW<sub>e</sub> at 1000 MW<sub>e</sub> and \$940/kW<sub>e</sub> at 100 MW<sub>e</sub> and
- (c) The 100% electrically efficient HF laser would have power supply costs of \$31/kW<sub>e</sub> at 1000 MW<sub>e</sub> and \$170/kW<sub>e</sub> at 100 MW<sub>e</sub>.

The Nd glass laser has a very low efficiency (less than 1%) and has problems at high repetition rates because it is a solid state laser. However, it can be pumped over long times (milliseconds) which might allow the use of inductive rather than capacitive energy storage. The cost of superconducting homopolar generators has been estimated to be as low as \$0.055/joule, very small by comparison with capacitive storage.<sup>(4)</sup> The minimum discharge time is 1-3 ms and is limited by the machine internal inductance and high surface stresses on the rotors.<sup>(4)</sup> This large cost difference between capacitive and inductive energy storage indicates that the

most desirable laser is one which can be pumped on a time scale of milliseconds even if its efficiency is just 1-2%.

One remedy for the power supply cost problem is to increase the fusion gain since the capital cost of the power supplies is inversely proportional to this quantity; see Eqn. (10). In Table 2 the fusion gain,  $\eta_D G$ , that is needed to bring the power supply costs down to \$167/kW<sub>e</sub> is given for a range of values of driver efficiency associated with different prospective ICF drivers. Costs for both a 1000 MW<sub>e</sub> power reactor and 100 MW<sub>e</sub> experimental unit are shown. In addition we include the implied gain and repetition rate. For the 100 MW<sub>e</sub> unit, the required value of  $\eta_D G$  is probably too large to be realistic if the driver efficiency is below about 10%. At 10% efficiency the needed fusion gain is 45. In addition, a reactor cavity designed to accommodate more than 1000 MJ per explosion in a reactor that only produces 100 MW<sub>e</sub> would be very unattractive.

On the other hand, there is a broad range of acceptable parameters for the 1000 MW<sub>e</sub> reactor. For instance, a system with a 3.2% efficient laser, a pellet gain of 613, and a repetition rate of 2.44 Hz would have the same power supply cost (\$167/kW<sub>e</sub>) as one with a 10% efficient driver, a pellet gain of 100, and a repetition rate of 15 Hz. We should also point out that this comparative analysis does not account for the wavelength dependence of the pellet performance (gain). That is, a 0.489  $\mu\text{m}$  wavelength, 1.67 MJ, 3.2% efficient selenium laser might in fact produce pellet gains of 613, while a 10  $\mu\text{m}$ , 1.67 MJ, 10% efficient CO<sub>2</sub> laser may only produce pellet gains of 100. This remains an unresolved pellet physics question, which we do not address in this analysis.

Table 2

Potential ICF Drivers and the Performance Required Such That The Power Supply Costs Will Be No More Than 10% Of The Total Plant Cost

<u>Driver</u>	<u>Wavelength</u>	<u>Efficiency</u>	<u>Energy</u>	<u>Performance Requirements</u>					
				<u>1000 MWe</u>		<u>100 MWe</u>			
				$\frac{G}{D}$	$\frac{G}{D}$	$\omega$	$\omega$		
Iodine	1.3 $\mu\text{m}$	~ 1%	1.67 MJ	44.7	4470	0.33	240	24000	0.0062
Selenium	.489 $\mu\text{m}$	~ 3.2%	1.67 MJ	19.6	613	2.44	101	3156	0.047
CO <sub>2</sub>	10.6 $\mu\text{m}$	10%	1.67 MJ	10	100	15	45	450	0.33
REB	-	30%	1.67 MJ	5.78	19.3	78	21	71	2.1
HF	2.7-3.5 $\mu\text{m}$	100%	1.67 MJ	3.83	3.83	391	10	10	15

Another solution to the cost dilemma is to reduce the basic unit cost of the power supplies. The power supply cost for the ANTARES CO<sub>2</sub> laser<sup>(5)</sup> is \$0.50/joule. The expected lifetime is about 10<sup>6</sup> shots. Scaling up to 10<sup>10</sup> shots using  $n = 1/4$  in Eqn. (10) gives a unit cost of \$5.00/joule. We have used \$3.75/joule which might therefore be considered optimistic. Nevertheless, using \$3.75/joule and a 10% efficient driver as a reference, we show in Table 3, as a function of efficiency, the unit cost necessary to lower the power supply capital cost to \$167/kW<sub>e</sub>. Note that for the 100 MW<sub>e</sub> reactor the driver electrical efficiency must be about 100% in order to bring the power supply unit costs down to \$3.75/joule. The only driver with this efficiency is the HF laser.

If the cost scaling parameter is not equal to 1/4, then the above results will of course change. The cost of power supplies for the reference 1000 MW<sub>e</sub> reactor is shown on Fig. 2 as a function of driver efficiency for different values of  $n$ . There are significant changes when the driver efficiency is low but the general conclusions remain the same for values of  $n$  as large as 1/2.

Table 3  
Adjustment of Power Supply Cost Per Joule Required  
To Achieve Comparable Capital Costs of \$167/kW<sub>e</sub>

$$P_e = 1000 \text{ MW}_e$$

$$E_L = 1.67 \text{ MJ}$$

$$G\eta_L = 10$$

<u><math>\eta_L</math></u>	<u>Cost Per Joule</u>	<u><math>\eta_L</math></u>	<u>Cost Per Joule</u>
0.01	\$0.67	0.30	8.35
0.032	\$1.65	1.0	20.20
0.05	\$2.24	2.0	34.79
0.1	\$3.75		

$$P_e = 100 \text{ MW}_e$$

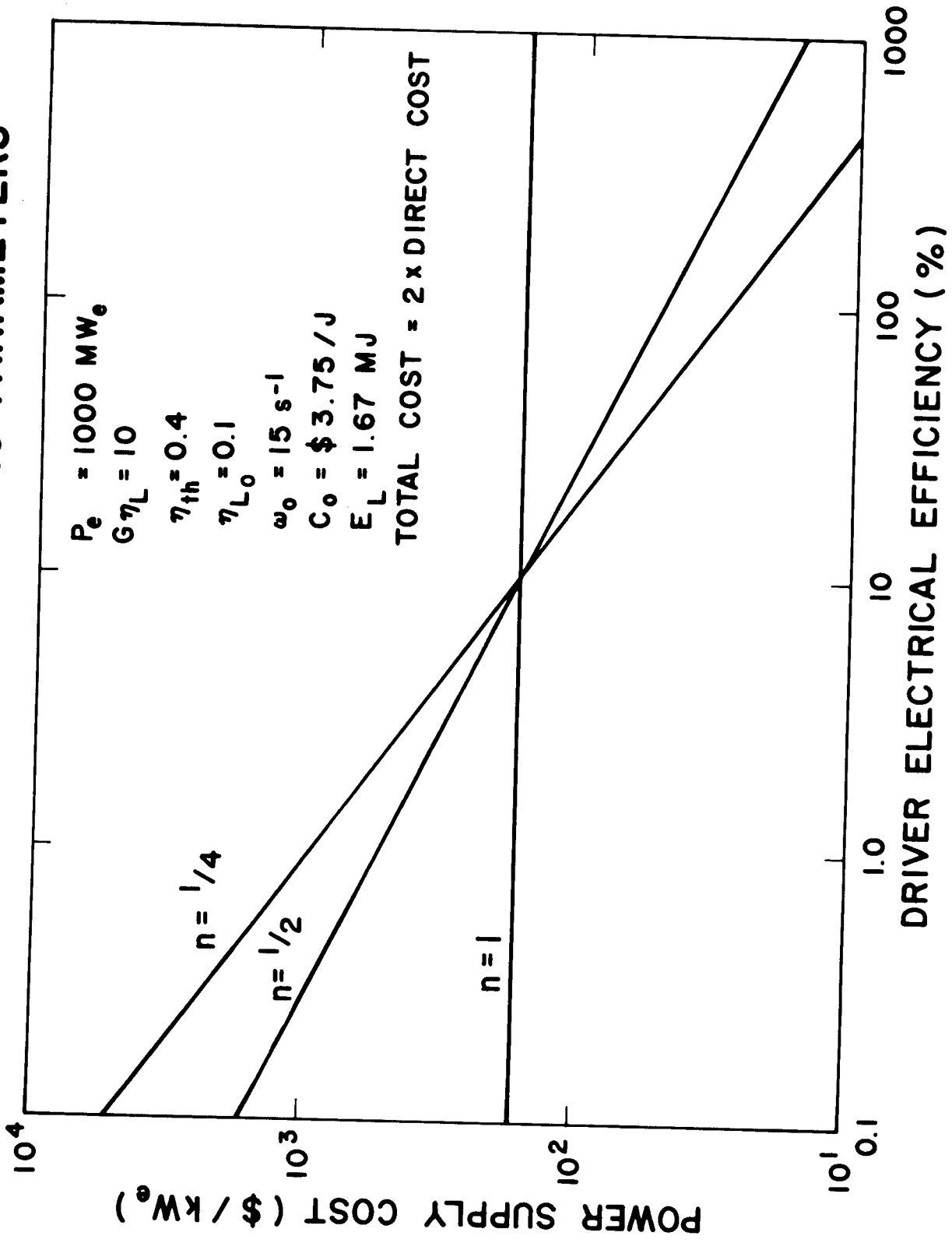
$$E_L = 1.67 \text{ MJ}$$

$$G\eta_L = 10$$

<u><math>\eta_L</math></u>	<u>Cost Per Joule</u>	<u><math>\eta_L</math></u>	<u>Cost Per Joule</u>
0.01	\$0.12	0.30	1.49
0.032	3.28	1.0	3.68
0.05	0.39	2.0	6.26
0.1	0.66		



# POWER SUPPLY COSTS (DIRECT + INDIRECT) vs. DRIVER EFFICIENCY FOR DIFFERENT COST SCALING PARAMETERS



#### IV. Summary and Conclusions

1. The economic feasibility of ICF depends not only on the fraction of recirculating power as dictated by the inequality  $\eta_D G \geq 10$  but also on the absolute electrical efficiency of the driver and the absolute driver energy requirement. The reason is that the increase in capacitive power supply cost with energy is greater than the cost reduction associated with lowering the repetition rate. A low efficiency driver requires more power supply energy and therefore will be more expensive than high efficiency drivers at equal values of  $\eta_D G$ . The major conclusion of this analysis is that pulsed power supply technology, as it relates to any of the ICF driver candidates, is a critical element that demands significant innovation before commercialization of ICF will be possible. Any reliance on low efficiency drivers further strengthens this conclusion.

2. The economic penalty of high power supply cost is most acute when the reactor power output is small. Power supplies are a dominant cost for a 100 MW<sub>e</sub> unit even when the driver efficiency is as high as 30%. This has an important influence on the path to commercialization of inertial confinement fusion. Although the full scale power plant may be economically attractive, demonstration reactors may have unrealistically high power supply costs. The driver energy needed to achieve a pellet gain in the range 100-1000 will probably be 1 MJ or more so that one cannot lower  $E_D$  and increase the repetition rate to alleviate this problem. In addition, this result is contrary to the argument that ICF is attractive because it can be implemented in small units.

3. The power supply cost problem can be alleviated at 1000 MW<sub>e</sub> by demanding a greater fusion gain,  $\eta_D G$ , with low efficiency drivers. A 2-3%

efficient, 1.67 MJ driver must achieve a pellet gain of 600-700, thus a fusion gain of 14-18, to bring the power supply cost down to an acceptable fraction, 10%, of the plant cost. For 100 MW<sub>e</sub> units the necessary increase in fusion gain is beyond reasonable limits for all but very high efficiency drivers, such as the HF laser. This result places the HF laser in a very attractive position for use in early demonstration plants or hybrid reactors where the power output need not be very large.

4. The problem can also be solved by development of low cost, long lifetime, short pulse, power supplies. However, it is doubtful that the cost of current capacitive energy storage can be sufficiently reduced to meet the requirements of low efficiency drivers. Inductive storage is not suitable in its present form for most ICF driver candidates.

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