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TITLE MODELING AND ANALYSIS OF INERTIAL-CONFINEMENT-FUSION FACILITIES

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MODELING AND ANALYSIS OF INERTIAL-CONFINEMENT-FUSION FACILITIES

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ABSTRACT

Approximate analytic models are used to explore relations among technical and economic characteristics of Inertial Confinement Fusion (ICF) facilities. Presented are attainable pulse rates for different reactor cavities and dependencies of the unit production cost of electricity on ICF driver pulse energy and repetition rate and on the facility size and the performance of the driver-pellet combination. The results indicate that economic electricity production with ICF reactors may require repetition rates of ~15 Hz or 20 Hz but that it may be achieved with values of the driver efficiency-pellet gain product as low as ~3 or 4.

I. INTRODUCTION

The use of ICF facilities for the generation of electricity and production of special nuclear materials has been studied for a decade. Many reactor concepts have been proposed and analyzed: wetted and magnetically protected wall concepts,[1,2] the modified wetted wall concept,[3] HYLIFE,[4] SOLASE,[5] HIBALL,[6] the renewable solid wall proposed by WECo,[7] and others.[4] Although previous attempts have been made to model and deduce trends and parametric dependencies of costs and operating characteristics of ICF facilities,[8-10] these attempts did not provide a sufficiently wide overview of parameter ranges where the ICF process may be technically and economically feasible.

This paper is intended to correct the above deficiency. We employ approximate analytic performance and cost models to gain insight into the dependence of economic and technical characteristics on the relevant parameters. The objective is to exhibit relative trends and to indicate directions for most profitable research and development efforts and not to determine the absolute production costs.

The presentation is organized as follows: In Section II, we model the time required to clear the ICF reactor cavity of the fuel pellet microexplosion products and thus reestablish the interpulse ambient conditions dictated by the beam propagation and pellet injection requirements. The results of this modeling estimate the frequencies available for cavity operations. In Section III, we model the dependence of the levelized (average) life-cycle unit production cost on the driver and power plant characteristics. The driver characteristics considered are pulse energy and repetition rate; the power plant characteristics considered are plant size (gross power) and the driver-pellet performance expressed by the product of the driver efficiency and the pellet gain. In the concluding Section IV, we discuss the results.

II. REACTOR CAVITY CLEARING TIME

The reactor cavity must be cleared of the reaction products after each fuel pellet microexplosion to reestablish between successive pulses the ambient conditions compatible with satisfactory beam propagation and pellet injection. We postulate that the medium in the reactor cavity immediately after the pellet microexplosion behaves like an ideal gas with a constant ratio of specific heats, γ, and consider two mechanisms for its evacuation: exhaust through a nozzle and condensation on a cool and wet wall.

Maximum mass flow rate through a DeLaval nozzle is achieved when the nozzle operates above the critical pressure ratio; we assume this to be the case. We also assume that the initial temperature following pellet microexplosion, T_o, is much higher than the desired interpulse ambient temperature T_a, in particular that $\sqrt{T_o/T_a} >> 1$. Then the time required to exhaust fusion products and to attain the ambient temperature T_a appears to be independent of T_o and given by:

$$\tau_n = \frac{V}{A} F(\gamma) \sqrt{\frac{m}{RT_a}} \quad , \tag{1}$$

where: $$F(\gamma) = \left(\frac{1}{2}\right)^{\frac{1}{\gamma-1}} (\gamma+1)^{\frac{\gamma+1}{2(\gamma-1)}} \left(\frac{1}{\gamma-1}\right) \sqrt{\frac{2}{\gamma}} \quad ,$$

m is the molecular (atomic) weight of the cavity medium, R is the universal gas constant, V is the reactor cavity volume, and A is the nozzle throat area. For a spherical cavity and a circular nozzle $V/A = (4/3)\ R_c\ (R_c/R_n)^2$, where R_c is the reactor cavity radius and R_n the nozzle throat radius. A derivation of Eq. (1) may be found in Ref. 8 or in any standard text on gas dynamics.

The absence of an explicit dependence of τ_n on T_o is only apparent; the required ambient state is specified by the particle number density, n_a, the calculation of which requires the knowledge of the initial postexplosion conditions.

The reciprocal of the cavity clearing time, τ_n^{-1}, is the highest frequency at which the cavity can be operated. It is plotted in Fig. 1 with $\gamma = 1.2$ and $R_c = 150$ cm as a function of the ratio R_n/R_c for different values of $\sqrt{m/T_a}$. Clearly, high-frequency operation requires a low atomic weight medium; this requirement is at variance with the use of a gas for the wall protection because substantial absorption of x rays requires a high atomic weight gas.

When the cavity exhaust is through condensation on a cool and wet wall, the exhaust time τ_c is

$$\tau_c = \frac{2}{\gamma-1}\,\frac{V}{S}\left[\left(\frac{n_o}{n_a}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]\sqrt{\frac{m}{RT_o}} \quad , \qquad (2)$$

where n_o is the initial postexplosion particle density and S is the surface area of the reactor cavity on which the condensation occurs;[3,8] for a spherical cavity $V/S = R_c/3$. This expression is based on the postulate that all molecules which strike the wall adhere to it and are removed from the cavity.

The pulse frequency, τ_c^{-1}, implied by Eq. (2) is plotted in Fig. 2 for $R_c = 150$ cm as a function of T_o and of the ratio n_o/n_a.

III. ELECTRICITY PRODUCTION

In this study of the economics of the ICF process we used several cost estimates of ICF systems. Reasonable agreement was found between independently published estimates by the Electric Power Research Institute (EPRI),[11] the University of Wisconsin,[6] AVCO,[12] and the Los Alamos National Laboratory.[13] The capital costs of various ICF drivers have been estimated in terms of the pulse energy, E(MJ), delivered to the pellet. These estimates, adjusted to 1981 dollars, are: CO_2 Laser Driver, $\$1.9 \times 10^8\ E^{0.8}$; KrF Laser Driver, $\$2.5 \times 10^8\ E^{0.8}$; Heavy Ion Driver, $\$5.0 \times 10^8\ E^{0.4}$. Detailed cost estimates of CO_2 laser drivers, including the costs of circulating and cooling the lasing medium, carried out at Los Alamos National Laboratory,[13] have quantified the dependence of capital cost on pulse repetition frequency. In the range of pulse energies and pulse repetition frequencies of interest in this study, this dependence can be approximated by an exponential function included in Eq. (3).

To the capital costs of the driver must be added[6] the capital costs of the reactor cavity and blanket ($200 M); liquid metal pumps ($56 M); the pellet factory ($200 M); and miscellaneous pipes, dump tanks, and cleanup systems ($40 M); or approximately $500 M. Finally, we add the capital cost of turbines and generators.

These estimates are summarized by the following expression:

$$C = a + bE^{\alpha}e^{\phi f} + dfW \quad (\$) \quad , \tag{3}$$

where C is the total capital cost, d = 0.50 \$/watt, and ϕ = 0.026. The gross electric energy output per pulse, W, is

$$W = \left[Y(0.7\ E_x + 0.3) + E\right] \eta_t \quad (MJ) \tag{4}$$

where Y is the fuel pellet energy yield, E_x is the neutron energy multiplication, and η_t is the thermodynamic cycle efficiency. The pellet yield Y is related to the driver pulse energy, E, through the gain function G(E):

$$Y = EG(E) \quad . \tag{5}$$

In this analysis we used an optimistic approximation to the gain function derived by Bangerter, Mark, and Thiessen,[15] and given by

$$G(E) = kE^{\beta} \tag{6}$$

with k = 21.6, β = 0.76 when E is in megajoules (MJ). The coefficients a, b, and the economy of scale exponent, α, are listed in Table 1 for CO_2 laser, KrF laser, and heavy ion (HI) beam drivers.

The levelized life-cycle cost is commonly used in economic comparisons of unit production costs. It is the ratio of annual expenditures to the annual output averaged over the lifetime, L, of the plant. The levelized life-cycle cost, U, is given by the analytic expression

$$U = \frac{1}{P_E}\left(\frac{B}{XQ} C + M\right) \tag{7}$$

where $B = \sum_{j=1}^{X} (1 + i)^{X-j}$, $Q = (1 + z)^X \sum_{j=1}^{L} \left(\frac{1 + z}{1 + i}\right)^j$, X is the construction period in years, i is the annual interest rate, and z is the inflation rate. The net electricity production rate, P_E, is

$$P_E = 8.776 \times 10^6 \; f\left(W - \frac{E}{\eta_d}\right) \quad \left(\frac{\text{MWh}}{\text{year}}\right) , \tag{8}$$

where η_d is the driver efficiency (E/η_d is the circulating fraction required to operate the driver); and the maintenance and operating cost, M, is approximated with[6,14]

$$M = 16 \times 10^6 + 0.02C + 3.16 \times 10^7 \; fc_p \quad , \tag{9}$$

where c_p is the pellet cost, here assumed equal to 0.10 $/ pellet.

The unit production cost, U, given by Eq. (7) becomes a function of the pulse energy, E, and of the frequency f, when Eqs. (3)-(6) with Eqs. (8) and (9) are substituted into Eq. (7). The dependence of the cost on these two variables in the range $1 \leq E \leq 5$ MJ, $5 \leq f \leq 50$ Hz is presented in Figs. 3 and 4. The results show that at low pulse energies the unit cost is a strong function of the frequency for frequencies less than approximately 10 Hz but that the cost becomes nearly independent of the frequency beyond approximately 20 Hz. The input for these calculations is summarized in Table II. Similar results were calculated for other drivers; KrF laser and HI accelerator were chosen for presentation as representatives of low and high efficiency drivers.

Figures 3 and 4 illustrate the dependence of the production cost on the driver characteristics: pulse energy and frequency. For general systems and economics analyses it is useful and convenient to know the dependence of the production cost on integrated facility characteristics. The most relevant of these are the size of the plant and the performance of the driver-fuel pellet combination. We use the gross fusion power output, fY, as a measure of the plant size and the product of the driver efficiency with the pellet gain as a measure of the driver-pellet performance. The corresponding results are shown in Figs. 5 and 6. The plots terminate where either of the inequalities, $E \leq 5$ MJ and $f \leq 50$ Hz, is violated.

IV. DISCUSSION OF RESULTS

The results presented thus far without comments indicate the following observations and conclusions. Exhaust of the fusion products through nozzles will not admit pulse repetition rates greater than ~1 or 2 Hz unless the gas load on the exhaust system is very light. However, condensation of reaction products on cool, wet walls of ICF reactor cavities may allow pulse rates perhaps as high as 100 Hz. Therefore, efforts should be directed to develop cavity wall protection schemes compatible with the use of the condensation for cavity evacuation. One such scheme is being investigated at the Los Alamos National Laboratory.[3,16]

The dependence of the unit production cost of electricity on the ICF driver pulse energy and repetition rate shows that the cost varies rapidly with pulse energy and repetition rate at low values of these parameters, i.e., $E \lesssim 2$ MJ, $f \lesssim 10$ Hz. The sensitivity of the cost to variation in frequency decreases with increasing pulse energy and frequency and most of the potential cost reductions will be achieved at frequencies above ~20 Hz. This appears to be a general characteristic of ICF production facilities.[16]

The dependence of the unit production cost on the facility size shows that most of the economies of scale will be attained with facility sizes greater than ~500 MW of fusion power, fY. The dependence of the unit production cost on the driver-pellet performance, measured with the driver efficiency-pellet gain product, shows that economic electricity production may be possible with the values of this product as low as approximately three or four when neutron energy is multiplied and when account is taken of the fact that the pulse energy of the driver remains in the thermal cycle. Neutron energy multiplication as low as 1.5 (used in this investigation) appears sufficient; it is easily achievable even with nonfissionable (e.g., beryllium) multipliers.[16] Fissionable (e.g., ^{238}U) multipliers improve the performance by approximately a factor of ten.[16,17]

The above conclusion is very encouraging; we hope that results of more detailed and accurate results will sustain it. To a large degree it is a consequence of high gain estimates used in this study. Conservative readers may use explicit expressions presented throughout the paper to derive their own cost estimates. The trends and changes of costs with different parameters do not depend strongly on the values of constants that specify the gain function.

We conclude this presentation with a summary of the characteristics of the ICF reactor designs proposed by various groups at different times. The values of the four parameters used in this study to characterize ICF reactor systems (E, f, $\eta_d G$, fY) are listed in Table III. The table shows that the individual designs are larger than necessary to exploit the economies of scale but that the operating pulse rates are much lower than the desirable value of 20 Hz. It is necessary to point out that some of the postulated higher pulse rates are not always consistent with the results presented in Fig. 1. The high values of the product $\eta_d G$ reflect the past prevailing confidence in the ability to design and manufacture high gain fuel pellets. The results of this study indicate that the requirements on that parameter may not be as severe as previously thought.

TABLE I

DRIVER COST CHARACTERISTICS

	a	b	α	η_d
CO_2 Laser	5×10^8	1.9×10^8	0.8	0.10
KrF Laser	5×10^8	2.5×10^8	0.8	0.04
HI Beam	5×10^8	5.0×10^8	0.4	0.25

TABLE II

INPUT TO U(E,f) COMPUTATION

$i = 0.15$	$E_x = 1.5$
$z = 0.10$	$\eta_t = 0.4$
$X = 8$ years	$c_p = 0.10$ \$/pellet
$L = 30$ years	$\phi = 0.026$
$k = 21.6$	$d = 0.5$ \$/watt
$\beta = 0.78$	

TABLE III

CHARACTERISTICS OF ICF REACTOR SYSTEMS

Design	E (MJ)	f (Hz)	$\eta_d G$	fY (GW)
SNL (LIGHT ION)	12.0	35.0	5.7	3.0
LANL (MAG WALL)	1.0	10.0[a]	6.3	1.4
HYLIFE	4.5	1.5	20.0	2.7
WECo (Laser)	2.0	10.0	17.5	3.5
WECo (HI)	2.0	10.0	52.5	3.5
SOLASE	1.0	20.0	10.05	3.0
HIBALL	4.8	5.0[a]	22.0	1.992

[a] Per cavity. Reactor has four cavities.

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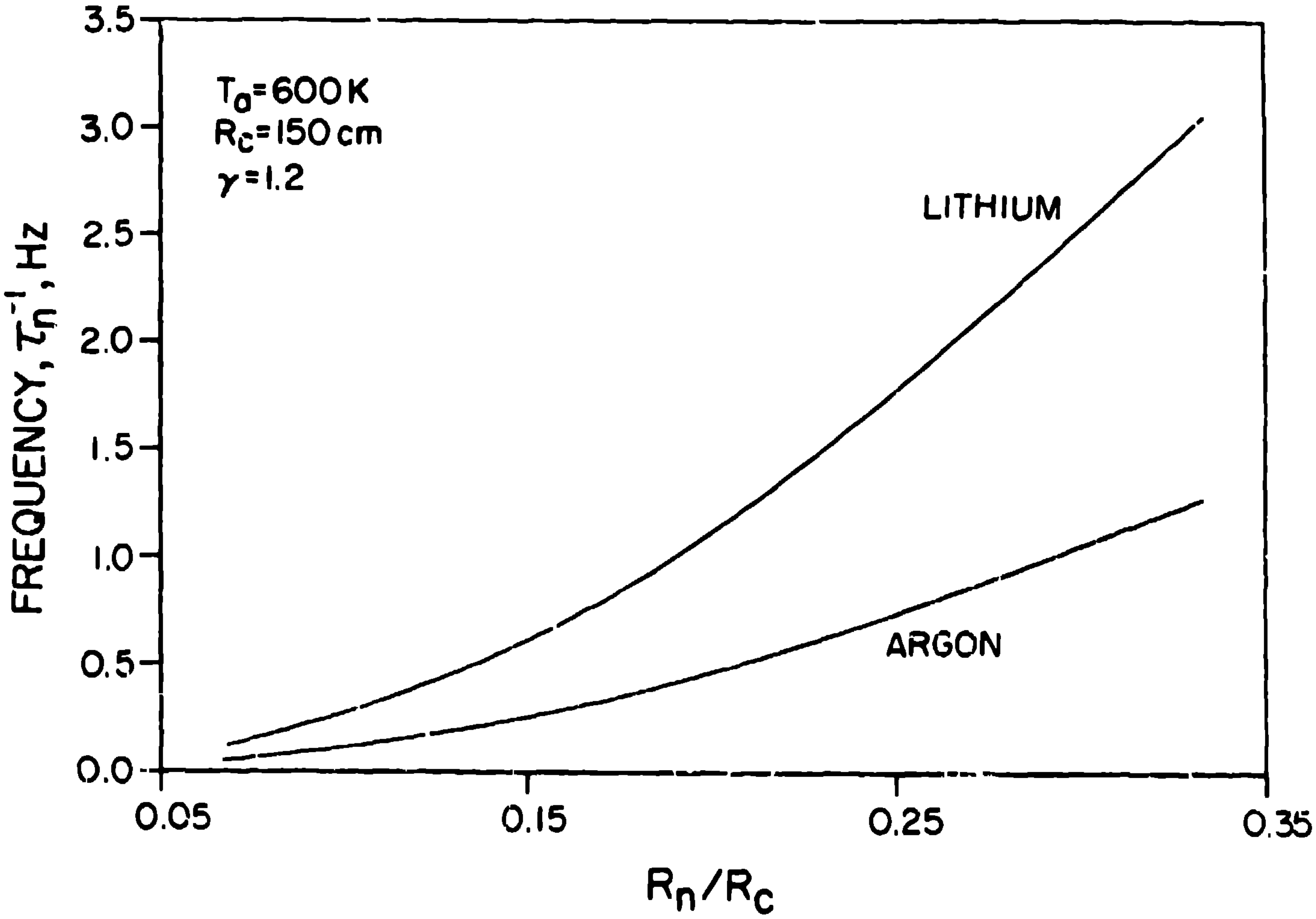

Fig. 1. Pulse repetion rate with nozzle exhaust.

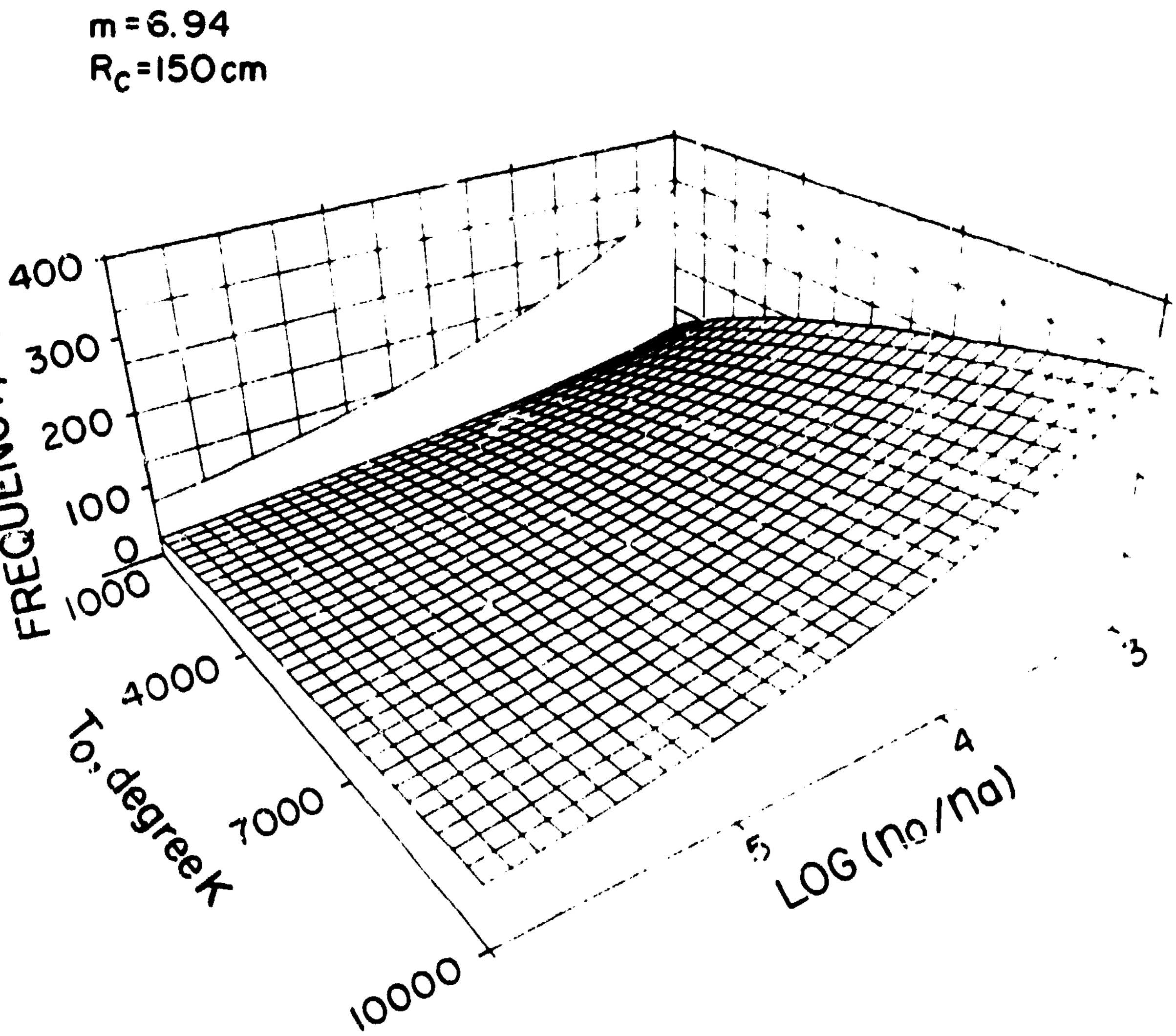

Fig. 2. Pulse repetion rate with surface condensation.

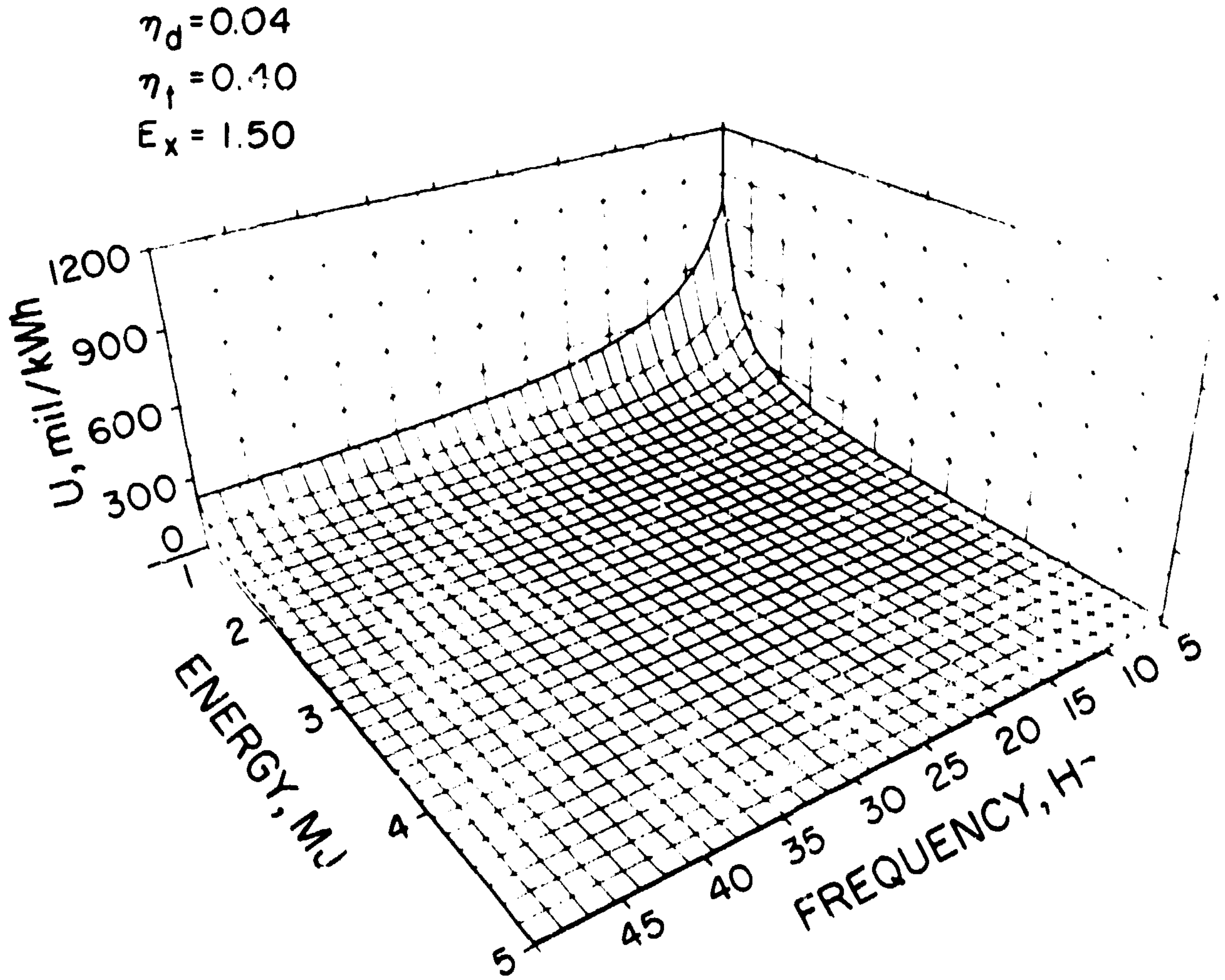

Fig. 3. Variation of the unit production cost with pulse energy, E, and repetion rate, f, for KrF laser driver.

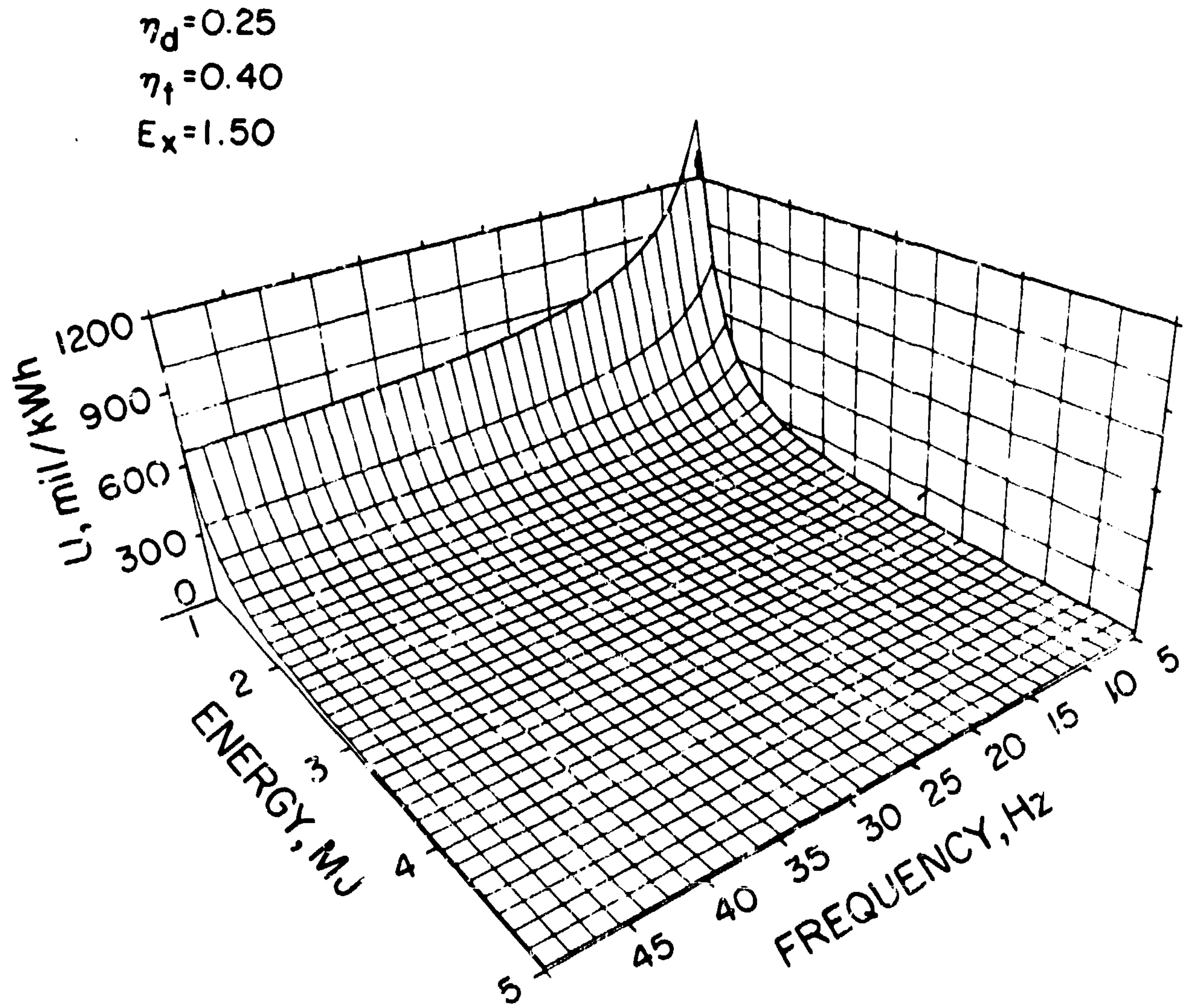

Fig. 4. Variation of the unit production cost with pulse energy, E, and repetion rate, f, for HI beam driver.

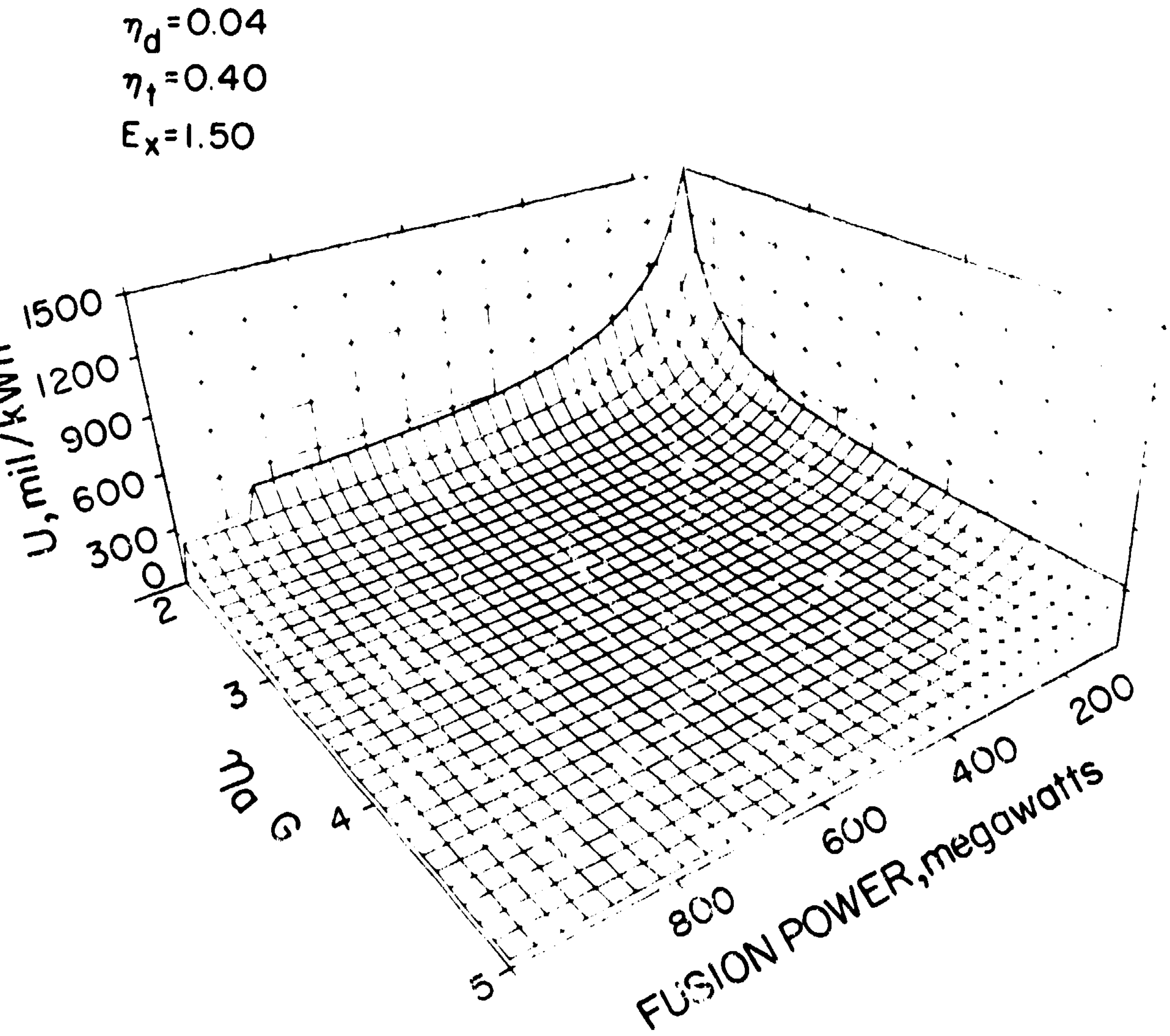

Fig. 5. Variation of the unit production cost with facility size, fY, and driver-pellet performance, $\eta_d G$, for KrF laser driver.

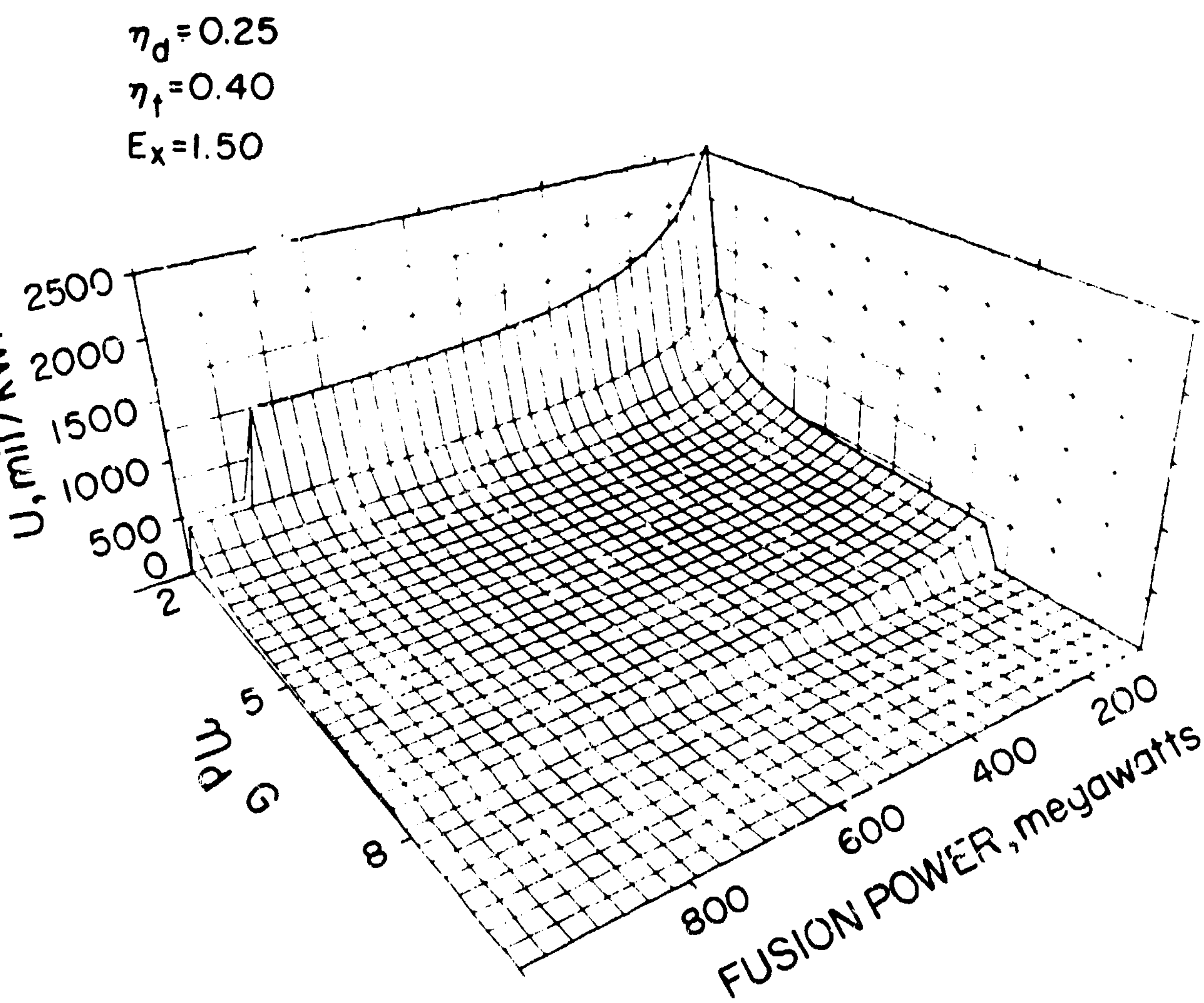

Fig. 6. Variation of the unit production cost with facility size, fY, and driver-pellet performance, $\eta_d G$, for HI beam driver.