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ECONOMIC ASPECTS OF HEAVY ION FUSION*

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ABSTRACT

The usual parameter space for examining scenarios for heavy ion fusion power plants has generally been based on large, slow cycling, reactor chambers which are only marginally different from chambers proposed for laser drivers. This paper will examine the economic implications of assuming that an inexpensive, low gain pellet is available and that a suitable high-repetition rate reactor has been devised. Interesting scenarios are found that generate economically feasible power from a system with a minimum net capacity of $\sim$ 1 GWe compared to the larger $\sim$ 4 GWe required in previous studies.

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1. INTRODUCTION

The capital cost of a fusion power plant, even a low power demonstration plant, is likely to be so great as to seriously reduce the likelyhood that any such plant can be funded. This risk is well known to the magnetic fusion community and is at least partially the cause for such papers as the recent ones by Miley1) and by Lidsky.2) Heavy Ion Fusion is especially vulnerable to this risk because it has already gained a reputation as having the expensive driver with the "high buy-in cost". Utilities are known to be sensitive to the prospect that fusion might only be economic if constructed on a scale of very large, multigigawatt power parks. The purpose of this paper is to question the systems assumptions that lead to the conclusions as found, for example, in the HIBALL3) study, that an economic HIF power plant would comprise several large ($\sim$ 1 GWe) reactors and would have a total cost of $5-10 B. It is this author's personal opinion that, by using reactor systems proposed for laser drivers, HIF has stumbled onto the single most expensive spot in the available parameter space. If this view is correct, it follows that HIF is not necessarily the expensive fusion option that it has been held to be.

The material in the tables and figures of this paper are preliminary versions of material planned for inclusion in the forthcoming book being edited by Beynon.4) By publishing this material at this time I hope to get reactions from the HIF community that will be useful in developing the chapter for the book. Some of the ideas and methods I have used are due to the work of Bohachevksy. This especially true of the scaling rules for cavity pumping5) that lead to the possibility of small, high-repetition rate reactors. The logic is very simple; if pellet yields are small enough, the reactor cavity can be small. The time needed for pumping must be a function of the ratio of cavity volume to the surface area. If the volume is reduced, repetition rate can be increased. Without concerning ourselves with the details of such a reactor, which is not the subject of this paper, it is nevertheless useful to explore the implications of having a small, rapid cycling chamber.

2. THE ALGORITHMS

It will be our objective in this section to suggest reasonable, simple algorithms to be used to find the optimum parameters for a heavy ion fusion power plant. A complete treatment of this subject is not appropriate for this paper where we only seek to use economic arguments to suggest the direction for profitable R and D. A much more complete treatment of the way in which the size and cost of the optimized reactor could be found was developed by Bohachevsky.6)

2.1 POWER PRODUCTION

To find the dependence of power cost on frequency, we will first find the net power as a function of frequency. The gross power produced is

$$Pgross = f \cdot E \cdot (G+1) \cdot \eta_t$$

where f is the pulse repetition frequency, s^{-1},

E is the driver pulse energy, MJ,

G is the pellet gain, and

η_t is the thermal fusion energy-to-electric conversion efficiency.

Since the power used by the driver is f $\cdot E/\eta_d$, where η_d is the driver wall plug efficiency, the net power available for sale is

$$Pnet = f \cdot E \cdot ((G+1)\eta_t - 1/\eta_d).$$

We have included the initial driver energy in the expression $(G+1)$ because, for the small gains that are economically interesting, the "+1" is significant. We have not explicity included neutron multiplication and thermal gain in the reactor blanket because these effects can be easily included in the thermal-to-electric conversion efficiency. In the plots that will follow this discussion, we will use 40% for this efficiency, which is only conservative if such effects are included. Unless a direct conversion system is developed, as suggested by Lasche,$^{7)}$ the only way to significantly increase the conversion efficiency beyond 40% is with higher temperatures. Conventional fission reactors do not operate at much over 700° K because of corrosion problems. If there is any liquid lithium in the reactor, higher temperatures are probably ruled out both because of corrosion and because the vapor pressure may interfere with beam transport.

2.2 YIELD

It is customary to use the gain curves published by Bangerter et al.,$^{8)}$ to find the functional dependence for G. We are interested in the gain at the low end of the gain curves. Examination of these curves, shown elsewhere in this proceedings, shows that they can be represented by the simple function

$$G = A \cdot E,$$

where $A = 10$ is conservative and $A = 20$ is being predicted by recent target design calculations. This function is reasonably valid for the single shell curves in the range 1.0

$< E(MJ) < 4.0$. Note that this means that pellet fusion yield is proportional to E-squared, a much steeper function than usually considered because of the flattening that occurs at higher driver energy. The steepness of the gain curve means that, in effect, the uncertainty is greater and the threshold for ignition may not be as low as one megajoule.

2.3 DRIVER EFFICIENCY

The driver efficiency, η_d, will have a dependence on pulse repetition rate. This is because some systems operate continuously even for a low duty cycle machine. The usual estimate of 25% efficiency for a heavy ion accelerator applies at full design pulse rate. The maximum pulse rate for heavy ion accelerators is probably in the 50-100 pps range unless special provision is made. The power delivered is proportional to the pulse rate and the power used by the driver is given by the base power, P, added to the power that depends on pulse rate. Typical HIF scenarios have claimed about 25% efficiency for the accelerator system (the original HIBALL study had 26.7%). If 25% is assumed as the ultimate efficiency for unlimited repetition rate, and the base power is assumed to equal the pulse energy per second (i.e., 3 MW for a 3 MJ driver), then

$$\eta_d = f / (1.0 + 4.0 \cdot f).$$

2.4 DRIVER COSTS

It has generally been found that cost estimates for heavy ion induction linacs have been lower than those for rf linac/storage ring systems with similar specifications. In a paper presented by the LBL group at Palaiseau,[9] a four-beam magnetically focused linac was described. The total cost given was about $1000 million. Principal parameters were;

3 MJ 150 TW 10 GeV 300 uC Hg+1 $8.3\ 10^{-6}$ m-rad

This design used magnetic focusing for the entire linac and used only 0.4 for the space charge tune shift factor, i.e., 60-degrees tune shift at zero current and 24-degrees at full current. This focusing scenario, and several other similarly conservative assumptions, mark this design as the sort of conservative machine that would be constructed as a "one-of-a-kind" research machine, but not for a "power plant" driver. The LBL paper goes on to suggest a list of innovations that need to be demonstrated, but that all put together, could reduce the cost by 50%. The list of innovations included more multiple beams, electrostatic focusing in the low-energy part of the linac, higher tune shift (60° to 12°), increased emittance, etc.

It is noteworthy that preliminary experimental results have confirmed that it is possible to transport a beam with the space charge tune shift from 60° to 12°, and tests are progressing to extend this limit as low as possible. Also, current thinking for the High Temperature Experiment suggests that a 16-beam system could be used. This would make it possible to transport the pulse in 16 separate beam lines all the way to the target without ever splitting or combining beamlets. The LBL estimate was in 1979 dollars, and included only the linac and not the final transport and the "injector", i.e., zero to 50 MeV.

Escalation can be estimated using the "official" high energy physics construction experience. These are: 1980; 10.5%, 1981; 9.1%, 1982; 6.8% and 1983; 6% (estimated). Compounded, this becomes 36% for 1979 thru 1983.

An estimate for the 50 MeV injector, obtained privately from LBL, using the same conservative technology, came to $300 million. This cost is a direct consequence of the difficulty encountered in trying to get an intense heavy ion beam started using conventional accelerator technology. There are several proposals for lower cost injectors, including; electrostatic focused multiple beamlets (similar conceptually to Maschke's MEQALAC), Pulselac, very high voltage ion sources, and rf/storage ring hybrid injectors. Evaluating some of the most promising low energy systems is the main part of the accelerator R and D work proposed for the National Plan for Accelerator Inertial Fusion.10)

The final transport system has been estimated by LBL at $100 million for one reactor. For multiple reactors, as for instance the four chamber design of HIBALL, part of the final transport system would be used in common for all chambers, and part, the final focusing elements, would necessarily have to be replicated for each chamber.

We can now try to tabulate the total of all these estimates. In the first column below, I list the estimates for present technology. In the second column, I give my best guess, based on the above arguments, for how much a driver for a power plant will cost.

3 MJ Case	Present Technology $M	Power Plant $M
Injector	300	100
Linac	1000	600
Final Transport (one line)	100	80
Totals	1400	780
Escalation (thru '83)	500	280
Totals	1900	1060

The cost scaling of heavy ion linacs has been well established by the many examples tested with LIACEP,$^{11)}$ the LBL program for optimizing and calculating linac costs. Assuming the same technology and the same set of constraints, the linacs scale in cost as energy (joules) to the 0.4 power. The examples used to determine scaling do not usually include injectors or final transport systems, but it seems reasonable to expect a similar scaling to apply to these subsystems. We note that since injectors and final transport systems are much less costly than the main linac, the error that will result if the scaling exponent is wrong for these subsystems, is probably not very significant.

The examples in the table can be used to solve for the coefficient A in a costing expression;

$$\text{Cost} = \text{A} \cdot \text{E (megajoules)}^{0.4}$$

$$\begin{aligned} \text{A (present technology)} &= 1225 \text{ mega dollars} \\ \text{A (power plant)} &= 680 \end{aligned}$$

2.5 REACTOR COSTS

Each reactor requires a beam transport system. In the absence of any kind of design, it is impossible to estimate how much such a system might cost and, especially, if it can make use of part of the system installed for the first chamber. I have included \$100 M in the cost algorithm for beam transport for each reactor after the first one.

The cost scaling for reactors was estimated by Bohachevsky$^{12)}$ to be proportional to the 3/2 power of the pellet yield. This is a very steep dependence and again, in the absence of even a conceptual design, one cannot estimate how valid it might be. Scaling from the HIBALL reactors, about \$250 M each, including some inflation, for 400 MJ, the 3/2 rule results in \$1 M for 10 MJ and \$32 M for 100 MJ. These numbers do not include pumps, heat exchangers and other auxilliary subsystems. Thus, even though they may be very wrong, they do not account for a large fraction of a system's cost.

2.6 TOTAL COST

All the rest of the capital costs beyond the nuclear island of a fission reactor might be the same for a fusion plant. Different authors typically use \$0.5-0.6/watt for this, where the power figure used must be the gross power including recirculating power. We will use \$0.5/watt, but with the warning in advance that at higher net power levels, this balance of plant (BOP) component will dominate the total cost of the plant.

The cost of the pellet factory can either be included in the cost of the pellets, as if it was a facility needed to generate fuel, like a coal mine, or it can be included in the total capital cost of the power plant. Unfortunately, no one has any idea of what a pellet factory might cost, though it has become customary to put in \$200 M. We will also include \$200 M for a pellet factory and will add an additional cost of \$0.1 per pellet. For comparison, the HIBALL cost analysis used \$0.15 per pellet, including amortization of a \$200 M facility, but allowed only about \$0.035 per pellet for materials and operating costs.

Indirect costs are a major item for which there is no well established methodology. In the HIBALL study, which used the standard guide rules for estimating the cost of a fusion power plant,[13)] indirect costs amounted to almost 60% of the total direct cost. This is not so great compared to indirect costs facing a government funded project, such as an accelerator facility, but the reasons are very different. The government funded project must include engineering and supervision cost, construction facilities and escalation. An investor-owned utility must include the engineering, supervision and construction facility costs, but in addition there are owner's costs and the cost of money during construction. However, because we are interested in the total cost, and the cost of electricity, in current dollars, the utility costs do not include inflation. The only need for inflation factors is to adjust an old cost estimate to current dollars, as was done earlier for LIA costs. In the HIBALL study, the indirect costs directly related to construction (engineering, supervision and owner's costs) were allocated a total of 35% of the direct costs. For consistancy, we will also use 35% for these indirects.

The cost of money, or allowance for funds during construction (AFDC), depends on the construction time, the interest rates and the work rate, i. e., percent of construction completed per year. Government funded projects try to peak in the early years in order to reduce the impact of inflation while an investor-owned utility would try to delay the costs until the end of the construction period in order to reduce the cost of money. It is, course, customary in these estimates to assume a linear construction rate. The construction time presumably depends on the total size of the project. For a HIF power plant, I would expect the largest component of construction, the accelerator, to determine the construction time. In my algorithms, I have set construction time to be a minimum of five years and have added a year for every \$500 M over \$1000 M for the accelerator direct costs. This results in about eight years for a HIBALL-sized project, which agrees with the period used in that study. The interest rates used to estimate the AFDC rate should be the "deflated" rate, essentially the current rate minus the inflation rate. HIBALL used 5% for this "deflated" rate. In my algorithms, after consultation with utility experts at the Electric Power Research Institute (EPRI), I have used a model which allows for procurement of funds from three sources (equities, bonds and preferred stocks) in fractions and at rates that have become standards for current utility estimates. The overall effect of this is that my rates for AFDC are about 75% of the effective rate used for the HIBALL study. A complete development of this methodology for estimating is too long for this report, but is planned for inclusion in the book chapter referred to earlier.

From all of the above, the total investment is given by

$$CT = (1.35) \cdot (1 + AFDC) \cdot (CD + CR + BOP + 200) \text{ (\$ millions)}$$

where (1.35) is the allowance for indirect costs,
AFDC is the allowance for funds during construction,
CD is the direct cost of the driver,
CR is the direct cost of the reactor,
BOP is the direct cost of the balance-of-plant at $0.5/watt,
and
$200 M is the direct cost of the pellet factory.

2.7 THE COST OF ELECTRICITY

The utility industry uses a "levelized annual revenue" to calculate a cost of electricity for the purpose of comparing alternative generating schemes. The purpose of a levelized quantity is to find a single value which has the same effect as a string of varying values. In this case, the string of varying numbers is essentially the annual revenue required to pay back the funds borrowed to build the power plant. The effect which is to be made the same is the rate of return to common equity. The cost of power in current year dollars, meaning after inflation has been discounted, is only equivalent to ignoring inflation if the inflation rate is constant. Since we are interested in a future project for which construction is not even proposed, and lifetime is 30 years, it is necessary to make all possible simplifying assumptions, including constant inflation and constant annual capacity factor. We will use 30 years lifetime and 70% annual capacity factor.

The formalism for deriving the levelized annual revenue is too involved for this paper but, as in the case of the calculation for the AFDC, is planned for inclusion in the forthcoming book. Using the same funding assumptions that were used to find the AFDC, and including an assumed 50% rate for income tax and 3% for property tax and insurance, we find a fixed charge rate (FCR) of 10.54%. This compares to the 10% FCR used in the HIBALL study with quite different assumptions.

The levelized annual revenue is given by

$$RL = FCR \cdot CT + M$$

where M is all annual operating, maintenance, fuel costs, etc., in current year dollars.

As discussed above, we allocate $0.1 per pellet. The other terms in M are an arbitrary amount for fixed operating costs (only $16M in our case) and an amount equal to 2% of the total cost, CT.

Since there are 8760 hours per year, the total power sold is 8760*ACF*Pnet(kW), and the cost of electricity is

$$U(mils/kWh) = (10^9) \cdot RL/(8760 \cdot ACF \cdot Pnet).$$

3. CONCLUSIONS

We have not gone into much detail on the calculations that result only in a general multiplicative factor on total cost, CT. The cost of power is clearly dominated by the capital cost in our model, although the cost of pellets is significant at higher repetition rates. To show the relative costs of various components, we show a sample case from computer results based on these algorithms. Figure 1 shows the cost breakdown for a 3 MJ Linear Induction Accelerator (LIA) driven power plant as a function of repetition rate. Although the driver capital cost does not depend on repetition rate (it is assumed to be designed to run up to 50 pps), all of the other elements of the system do depend on pulse rate, or on total power generated, which is equivalent. The steps occur when another reactor is added (every 20 pps). The dashed lines in Fig. 1 show the operating costs divided by the FCR to normalize them to the same scale as the fraction of the capital costs that contribute to the cost of electricity. In this way one can see that, for instance, at low repetition rate the cost of power is dominated by the charges for the capital cost of the driver, which is no surprise. However, the fact that the driver cost becomes a small fraction of the total cost as early as 20 pps is interesting.

In Fig. 2, we show the function for driver efficiency and the quantity $\eta_d G$ for pellets of gain 30 and 60, respectively. This plot also shows the cost of electricity for these two cases. In Fig. 3, we plot the capital cost of a 1 gigawatt power plant for the two gain curves given earlier. This shows a minimum for a driver of 2.5-3.0 MJ. In Fig. 4, we show several curves for power cost for each pellet gain. The significant result here is that most of the benefit of high repetition rate is realized as low as 20 pps for the higher gain pellets, and by 40 pps for lower gain pellets with mid-range driver energies ($\sim$ 3 MJ). Note that, from Fig. 2, this means $\eta_d G$ is less than 7.5, which is well below the 10-12 value previously felt necessary for economic feasibility. Thus it appears that high repetition rate may somewhat ease the requirement on the $\eta_d G$ product.

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FIGURE CAPTIONS

1. The costs of various systems components are plotted against pulse repetition rate. Reactors are limited to 20 pps each. Operating costs are plotted on a scale proportional to their impact on power costs.
2. The power cost and $\eta_d G$ product is shown for two pellet gains for a 3 MJ LIA driver.
3. The capital cost is plotted as a function of driver energy for two different pellet gain curves.
4. Power costs are shown as a function of repetition rate for two different gain curves.

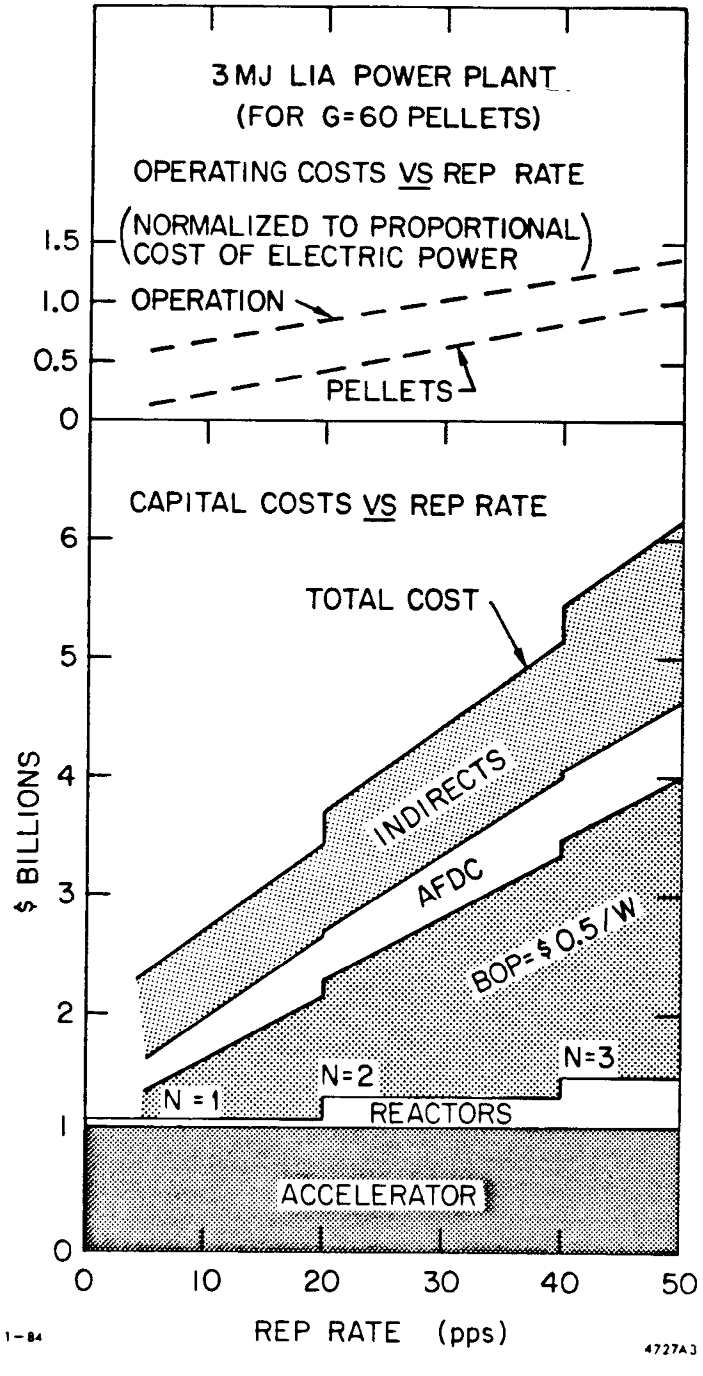
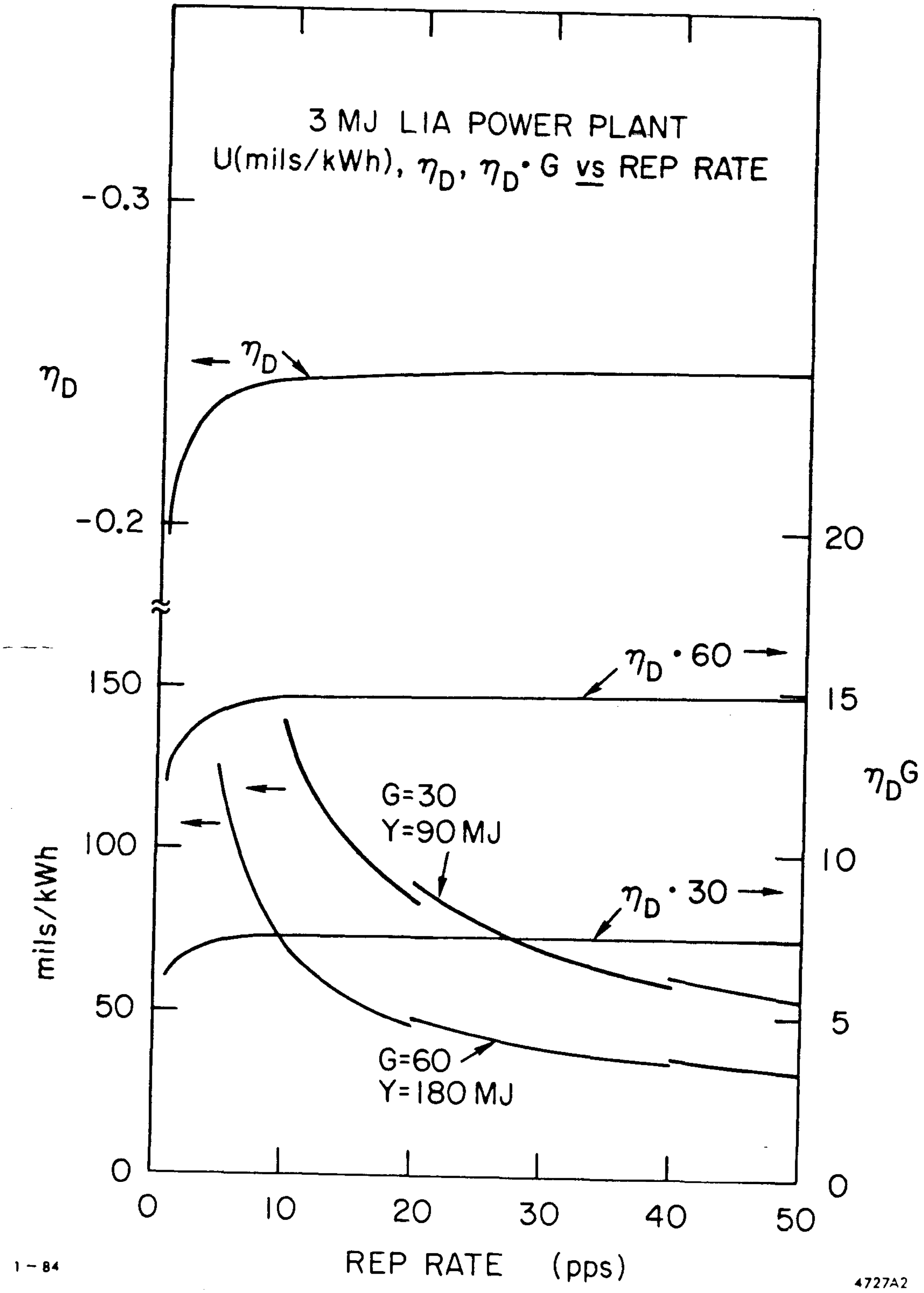

3 MJ LIA POWER PLANT
(FOR G=60 PELLETS)
OPERATING COSTS VS REP RATE
(NORMALIZED TO PROPORTIONAL COST OF ELECTRIC POWER)
1.5
1.0
0.5
0
OPERATION
PELLETS
CAPITAL COSTS VS REP RATE
6
5
4
3
2
1
0
$ BILLIONS
TOTAL COST
INDIRECTS
AFDC
BOP=$0.5/W
N=1
N=2
N=3
REACTORS
ACCELERATOR
0
10
20
30
40
50
REP RATE (pps)
1-84
4727A3

Fig. 1



3 MJ LIA POWER PLANT
U(mils/kWh), η_D, $\eta_D \cdot G$ vs REP RATE
-0.3
η_D
-0.2
150
100
50
0
mils/kWh
η_D
$\eta_D \cdot 60$
$\eta_D \cdot 30$
G=30
Y=90 MJ
G=60
Y=180 MJ
20
15
10
5
0
$\eta_D G$
0
10
20
30
40
50
REP RATE (pps)
1-84
4727A2

Fig. 2

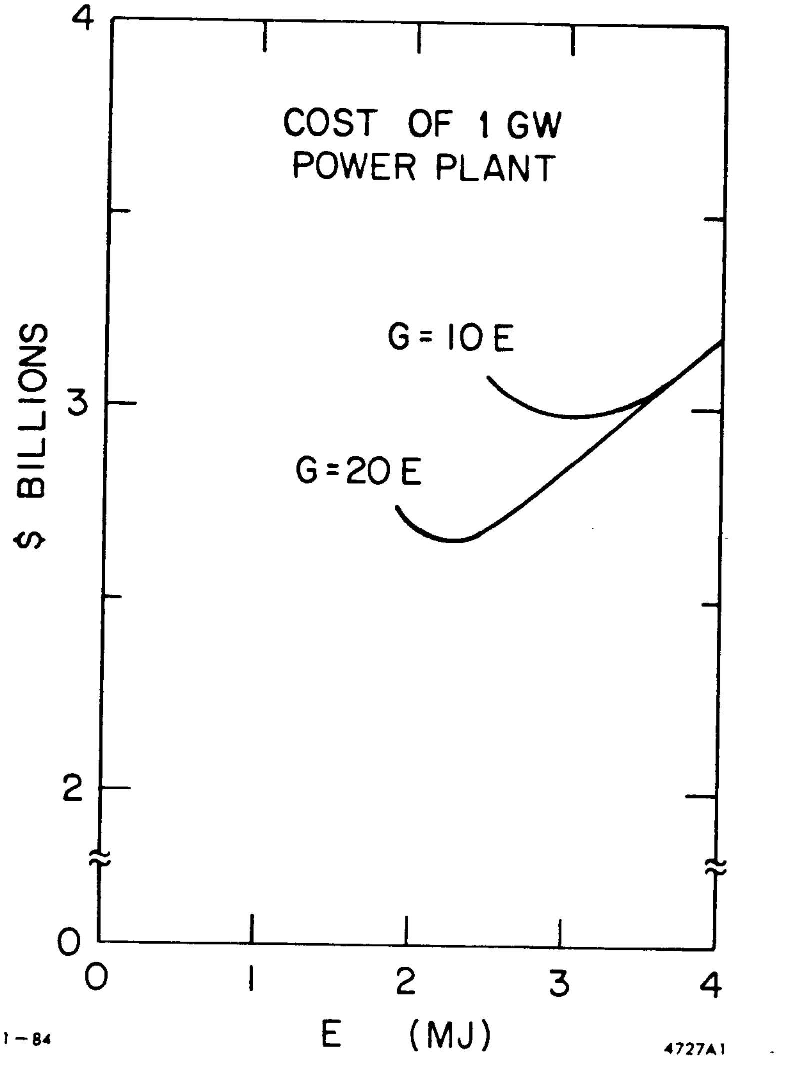

COST OF 1 GW POWER PLANT
G = 10 E
G = 20 E
$ BILLIONS
4
3
2
0
0
1
2
3
4
E (MJ)
1-84
4727A1

Fig. 3

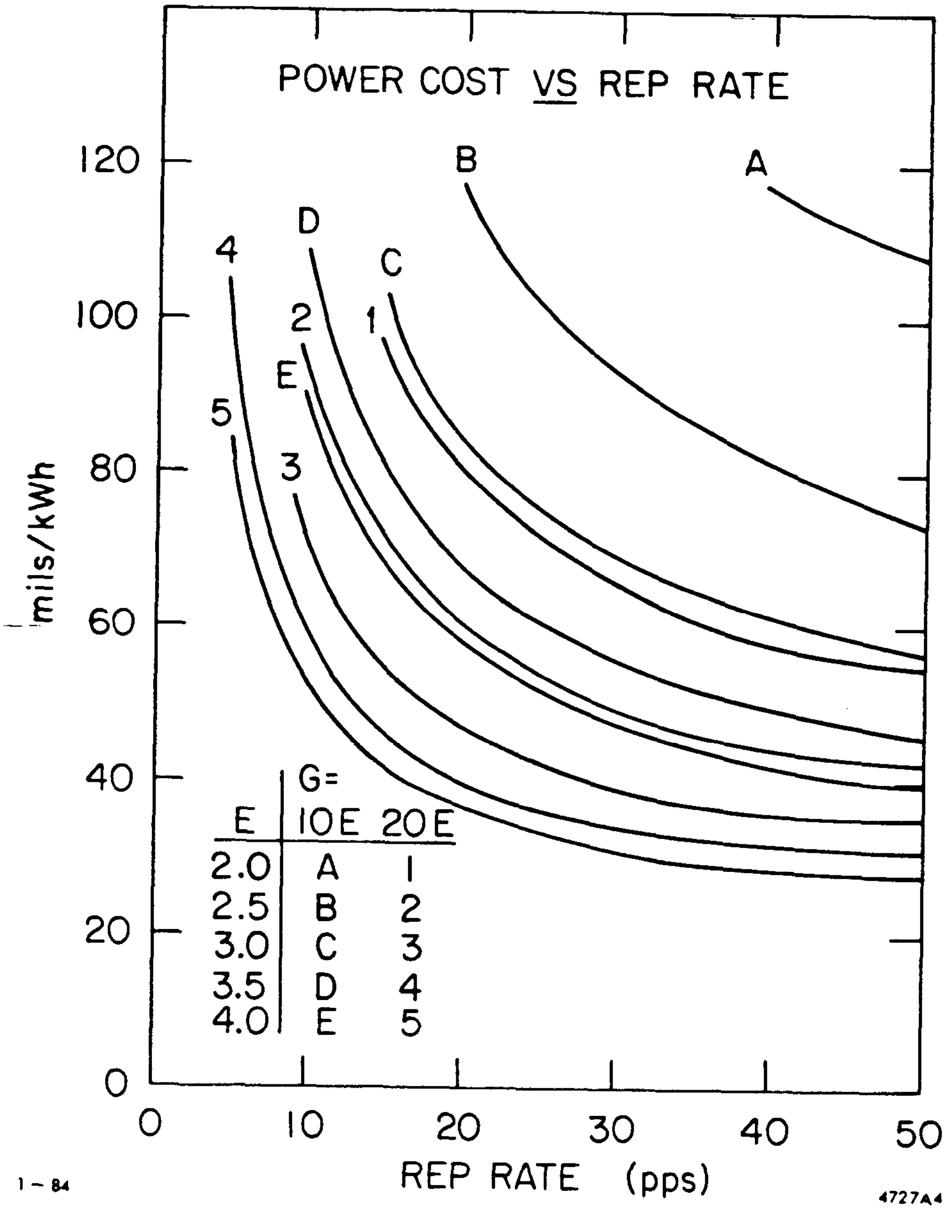

POWER COST VS REP RATE
mils/kWh
REP RATE (pps)
0
20
40
60
80
100
120
0
10
20
30
40
50
A
B
C
D
E
1
2
3
4
5
E
G=
10E
20E
2.0 A 1
2.5 B 2
3.0 C 3
3.5 D 4
4.0 E 5
1 – 84
4727A4

Fig. 4