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AUTHOR(S): R. O. Bangerter

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Los Alamos Los Alamos National Laboratory Los Alamos, New Mexico 87545

HEAVY ION FUSION PHYSICS ISSUES

R. O. Bangerter
University of California
Los Alamos National Laboratory
Los Alamos, NM 87545

I. INTRODUCTION

Two years ago at GSI, we presented a list of six statements or assumptions on which the promise of heavy ion fusion (HIF) rests.[1] For this paper, we rephrase the six statements as questions (or issues):

1. Can, at reasonable cost, an accelerator be built that puts more than 1 MJ of energy into a small 6-D phase space volume?

2. Can the beam be focused over a distance of several meters onto a small target in a reaction chamber?

3. Do present calculations adequately describe ion energy deposition?

4. Do current numerical simulations adequately describe the hydrodynamic and thermonuclear behavior of targets?

5. Can targets be cheaply mass produced?

6. Can an economical, tritium-breeding reactor be built?

We have used these six questions as a framework for the U.S. Heavy Ion Fusion Program.[2]

There are two principal difficulties with the six questions as formulated above. They are not sufficiently quantitative. Moreover not everyone agrees that all of them are truly concerns.

In this paper we state the questions more quantitatively and determine the extent to which they questions are truly concerns.

II. CONSIDERATIONS FOR POWER PRODUCTION

Two important parameters for commercial power production are the cost of electricity, r_e, and the total capital cost of the power plant, C. It is obvious that r_e is an important parameter. If HIF can not produce electricity at a cost that is competitive with other sources, it will not be implemented.

Total capital cost is also important. In the U.S., where utilities are privately owned and financed, plants costing several times 10^9 dollars severely train the capital assets of even large utilities. Furthermore, high costs are usually associated with long construction times leading to excessive financing costs and expensive power. From a utility standpoint, plants with large electrical capacity are undesirable in terms of siting, power transmission costs (or market size), flexibility, and reliability. If a very large plant goes off-line it creates an unacceptable perturbation on the power grid. Finally, and perhaps most importantly, low capital costs facilitate the development and introduction of any new energy technology. This last point is currently being discussed in the popular media. The New York Times of 10 January 1984 quotes T. P. Heuchling of Arthur D. Little, Inc., "...studies indicating nuclear is cheaper than coal are empty exercises. 'No one wants to see if they're right, because it's too expensive to find out they're wrong.'" We conclude that it is advantageous to demonstrate feasibility and gain operating experience at low capital cost. Then, if the economics dictate, the cost and capacity of the power plants can increase.

It is useful to place these considerations in the context of fusion research in general and HIF in particular. Thanks to the remarkable productivity of the German HIBALL program, the current status of HIF research has been well documented.[3] We choose HIBALL I as the "standard" HIF scenario. In Fig. 1 HIBALL is represented by a point in a two dimensional space having axes C and r_e. NUWMAK and WITAMIR, two magnetic fusion scenarios, are also plotted in Fig. 1. NUWMAK and WITAMIR have been chosen since the cost accounting is consistent with HIBALL. It must be emphasized that accurate cost estimates cannot be made at this time. All three systems depend strongly on untested physics and engineering assumptions. Furthermore the costs are not in current (1984) dollars so at best only relative meaning can be assigned to the estimates. All three systems produce electricity for roughly the same rate ($r_e \approx 40$ mills/kWh), but some concern has been expressed that HIBALL is too expensive. It is not productive to argue this point in an absolute sense. By the time fusion power becomes a reality, 4-5 G$ may be an acceptable price. It is true however that lower r_e and/or C are better. Similarly higher r_e and/or C are worse. This is illustrated in Fig. 1. The extent to which one is willing to trade lower capital costs for more expensive power or vice versa depends on the situation. The areas in which these trade-offs occur are indicated by question marks. In the remainder of this paper we consider two possible goals.

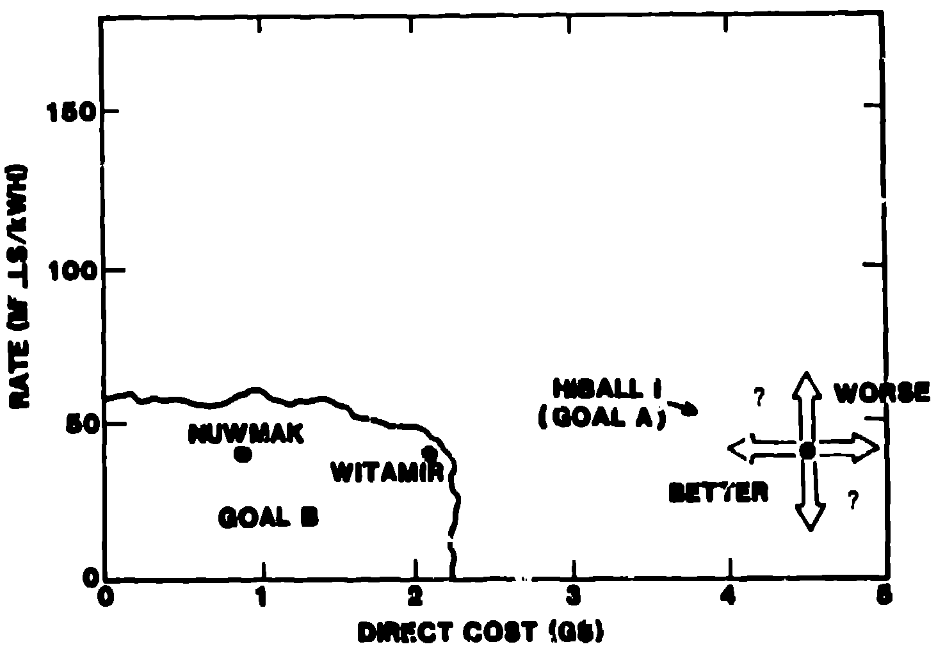

Fig. 1 Diagram showing current status of three fusion energy scenarios. The area inside of the wavy line and denoted Goal B represents a reasonable goal for HIF.

GOAL A - The HIBALL point

GOAL B - A different (B for better) goal indicated in Fig. 1

A very simple model is used to obtain rough, quantitative conditions that are necessary to achieve these goals. Specifically, we assume that the cost of the power plant is the sum of four terms

$$C = C_D + C_R + C_T + C_B$$

where C_D, C_R, C_T, and C_B are the cost of the driver, reaction chamber(s), target factory, and balance of plant.

For HIBALL I the driver cost (exclusive of final beam lines) is about 1.4 G\$ at a total beam energy of $E = 4.8$ MJ. It is widely assumed that accelerator cost scales roughly as $E^{0.4}$. Therefore we set $C_D = A_D E^{0.4}$ G\$, where $A_D = 0.75$.

The cost of a HIBALL reaction chamber is 0.196 G\$, but each chamber requires beam lines and focusing systems costing about 0.12 G\$. Thus, the total cost per chamber is 0.316 G\$. We assume that the amount of material in the chamber, and therefore its cost, is roughly proportional to the target yield Y. Specifically we assume that

$$C_R = N_R(B_R + A_R Y)$$

where N_R is the number of reaction chambers and B_R is a small threshold term arbitrarily set to 0.02 G\$. Normalizing to the HIBALL yield, $Y = 400$ MJ, we obtain $A_R = 7.4 \times 10^{-4}$. We also use HIBALL numbers $C_T = 0.2$ G\$ and $C_B = 0.35\ W_G$(G\$) where W_G is the gross electrical output in GW.

The gross electrical output is given by $W_G = E\nu GM\epsilon$ where ν, G, M, and ϵ are pulse repetition rate, target gain, blanket energy multiplication factor, and thermal-to-electrical conversion efficiency. The power required by the driver is $E\nu/\eta_D$ where η_D is driver efficiency. Ignoring recirculating power other than for the driver, the net electrical output is given by $W = E\nu(GM\eta - 1/\eta_D)$. We use HIBALL values $\epsilon = 0.42$, $M = 1.274$, and $\eta_D = 0.267$. In principal η_D depends on pulse repetition rate. In particular η_D decreases rapidly as ν approaches zero, we will show that high ν is advantageous. For high ν, η_D in not strongly dependent on ν and the assumption of constant η_D is reasonable.

In the HIBALL study, the target factory was not included in the total capital cost. Instead a price was assessed for each target. For simplicity, we include the target factory as part of the capital cost and assume that all costs are proportional to the total capital cost. We obtain $r_e = 35.5$ C/W mills/kwh where the factor 35.5 has been chosen to give the r_e for HIBALL. Net electrical output is expressed in GW.

One guesses that the reaction chambers could operate at a higher repetition rate if the yield of an individual target were reduced. If the wall loading is to remain constant the linear dimensions of the cavity scale as $Y^{-1/2}$. Smaller size should result in shorter time scales for some reactor phenomena. Moreover if the reactor is smaller, shorter beam focal lengths are needed and higher residual pressures are tolerable. We assume the allowable repetition rate scales as $Y^{-1/2}$ up to a maximum value of 20Hz i.e. $\nu_{reactor} = \min[5(400/Y)^{1/2}, 20]$ where Y is in MJ.

Finally we examine the question of target performance. We consider only single-shell targets. More complicated double-shell targets might offer better performance, but the physics uncertainties appear to be larger and fabrication appears to be more difficult. In general both target gain and peak power requirement are given by $G = G(E,r,R)$ and $P_{max} = P_{max}(E,r,R)$ where r and R are focal spot radius and ion range. The Livermore group has shown that to a reasonable approximation G and P_{max} depend only on E and $r^{3/2}R$.[4] The original value of r assumed for HIBALL I is 0.3 cm. With this radius it is necessary to multiply the 1982 Livermore gain function by about 2.3 and the power by about 0.75 to obtain the HIBALL gain and power values. Thus both the gain and power values for HIBALL are substantially more optimistic than the 1982 Livermore results. However the new Livermore results presented at this conference approach the HIBALL gain. It therefore appears that there is some concensus that the HIBALL gain is possible within the uncertainty of our current knowledge of target performance. We normalize to HIBALL by multiplying the 1982 Livermore values of G and P_{max} by 2.3 and 0.75 respectively but retain the Livermore dependence on $r^{3/2}R$.

It is interesting to determine how power plant performance depends on uncertainties in accelerator physics and engineering. In 1978, D. Judd defined a single quantity, usually denoted F_{TI}, that is proportional to the 6-D phase-space volume per particle available to the beam emerging from the accelerator.[5] The quantity F_{TI} is determined by the target requirements and the properties of final lens systems. In the 1978 analysis Judd ignored some effects such as 3rd order aberrations. He has subsequently included these effects.[6] For the purposes of this paper, we adopt the simple 1978 model. The expression for F_{TI} is given by

$$F_{TI} = \frac{1000fT}{P_{max}} \left[\frac{2\pi r^3 T}{A}\right]^{3/2}$$

where f is the fraction of the beams available to deliver the portion of the pulse at P_{max}, T is ion kinetic energy, and A is ion mass. For a typical target the value of f is about 0.6. The factors of 1000 and 2π are historical and have been retained to allow us to obtain values of F_{TI} consistent with earlier values when P_{max} is expressed in TW, r in cm, T in GeV, and A in atomic mass units. The HIBALL parameters give $F_{TI} = 0.11$.

At $T \sim 10$ GeV, R is approximately proportional to $T^{5/4}$ so that constant $r^{3/2}R$ nearly corresponds to constant $r^3T^{5/2}$ and therefore constant F_{TI} for constant E and A. Thus G and P_{max} can be considered functions of E and

F_{TI}. This gives accelerator designers the flexibility (within limits) to choose r or T to satisfy other constraints while retaining the same 6-D phase space density.

We have now developed a number of scaling laws, all normalized to HIBALL I, that enable us to vary the cost and capacity of HIBALL-like power plants. In the following analysis we choose C and F_{TI} as independent parameters. Quantities E and N_R are varied to minimize r_e. The results are given as curve A in Fig. 2. This curve goes through the HIBALL I point. It represents a reasonable developmental path that one might follow to arrive at goal A. Below C $\simeq$ 2G\$, r_e increases very rapidly so that ~2G\$ is the "buy-in" price for an integrated plant leading to goal A. We emphasize again that C has relative meaning only. It should not be taken as an accurate cost estimate in current dollars. Note that with this model, constant plant capacity corresponds to straight lines emanating from the origin because r_e = 35.5 C/W. Curves B and C correspond to reasonable physics uncertainties. Curve B uses the 1982 Livermore gain results but retains F_{TI} = 0.11. Curve C uses the 1982 results with F_{TI} increased by about $\sqrt{10}$. This value corresponds to

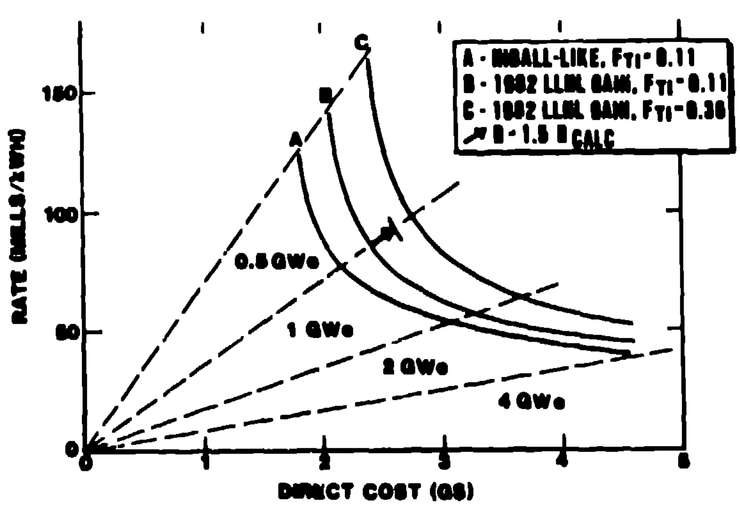

Fig. 2 Cost of electricity as a function of the total direct cost of the power plant for different physics assumptions. The driver energy and number of reactors have been chosen to minimize the cost of electricity. Since the number of reactors is an integer the curves are not truly smooth. The curves shown are smooth approximations to the actual numerical results.

the value of the F_{TI} that would be required if the emittance dilution were about a factor of 1.5 times worse (in each of the three planes) than the dilution assumed for HIBALL. If the ion range were 1.5 times larger than calculated, curve B would move by the amount indicated by the arrow.

It is not possible to reach goal B along curves A, B, or C. However reasonable improvements might allow us to reach it. In 1981, Faltens, Hoyer, and Keefe published a paper entitled "A 3 Megajoule Heavy Ion Fusion Driver" in which they stated that a concerted developmental effort might eventually yield a 0.5 G$ machine.[6] Assuming $C_D \propto E^{0.4}$ we set $C_D = 0.325\ E^{0.4}$ G$. Perhaps it might also be possible to develop improved reactors that could pulse at higher repetition rates, maybe twice as fast as HIBALL or $\nu_{reac} = \min[10(400/Y)^{1/2},20]$. Finally, it might be possible to reduce F_{TI} by an order of magnitude by reducing the emittance growth by about a factor of two in each plane. Results corresponding to these improved conditions are shown in Fig. 3. These systems achieve goal B. Curves B, C, and D assume a maximum driver repetition rate of 40 Hz in order to exploit the advantages of low-yield targets. This high driver repetition rate is important, but the results are quite insensitive to the assumed factor of two increase in reactor repetition rate. The reactors that optimize the system typically represent a small fraction ($\lesssim$10 percent) of the total cost of the power plant so that the number of reactors could be doubled at a penalty of $\lesssim$10 percent in r_e. Note that a pessimistic assumption about target gain (0.5 times the 1982 LLNL results) still gives the acceptable results illustrated in curve B.

III. CONCLUSIONS

A simple systems model has been used to determine the sensitivity of the cost of electricity and the total cost of a power plant to the various uncertainties expressed in the six issues at the beginning of this paper Thus, the issues have been given quantitative meaning.

Accelerator and Focusing - The cost of the driver is a particularly important quantity. This is nearly obvious. If the cost of the driver is reduced by a factor of two, the cost of the other components of a HIBALL-like power plant

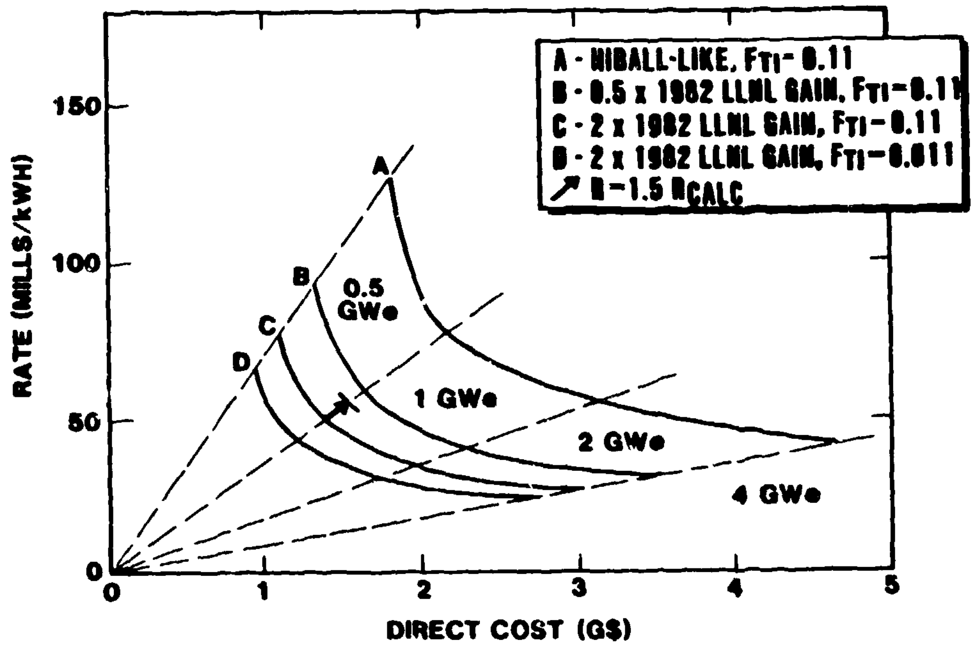

Fig. 3 Cost of electricity as a function of the total direct cost of the power plant. The assumptions are more optimistic than those used to generate Fig. 2.

(except the land and target factory) can be reduced by about a factor of two simply by constructing only two of the four HIBALL reaction chambers. The cost of electricity would increase only slightly. Moreover low driver cost allows relatively poor target performance (See Fig. 3 curve B) since E can be increased to provide adequate target gain without incurring a large cost penalty.

High 6-D phase-space density is also important. Substantial, but perhaps not decisive, changes occur for changes of about a factor of three in phase space density. Since the minimum allowable phase space density is partly determined by the final focusing system, this accelerator issue is closely coupled to the focusing issue (issue 2) given in the introduction. At the present time, there is no design for a focusing system that achieves the assumed 0.3 cm focal spot radius with the HIBALL phase space volume. There has been substantial progress since HIBALL I, but more work is needed. It may be possible to design systems that are corrected for chromatic and/or geometric aberrations. Corrected systems would accept larger phase space volume. Neutralization and pinched beams have been suggested and should also be studied.

Beam-Target Interaction Issues - The feasibility of HIF is not strongly dependent on reasonable uncertainties in ion range. An ion range less than about 1.5 times the currently calculated range is acceptable. Nevertheless an improved understanding of ion energy deposition is important for detailed target design work. Some recent work in this area has been reported at this symposium. This work should be encourged. Although it appears unlikely that there will be serious problems with beam-plasma instabilities some additional work is needed in this area.

Target - It is important to verify that target gains within roughly a factor of 2 of the 1982 LLNL results can be achieved. It would be very useful if targets could be desiged that allow higher F_{TI} at fixed energy and gain. Such targets may be possible.

Target Factory - Almost no work has been done on the mass production of targets. Therefore the 0.2G$ price for a target factory is largely a guess. Some work in this area would be very useful.

Reaction Chambers - Experiments and additional design and analysis are needed to verify current concepts. Low-yield, high-repetition-rate chambers could have a favorable economic impact.

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