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THE ECONOMIC SIGNIFICANCE OF Q FOR MIRROR REACTORS - COMBINATIONS OF Q AND M WHICH LOOK PROMISING

MASTER

Richard W. Werner

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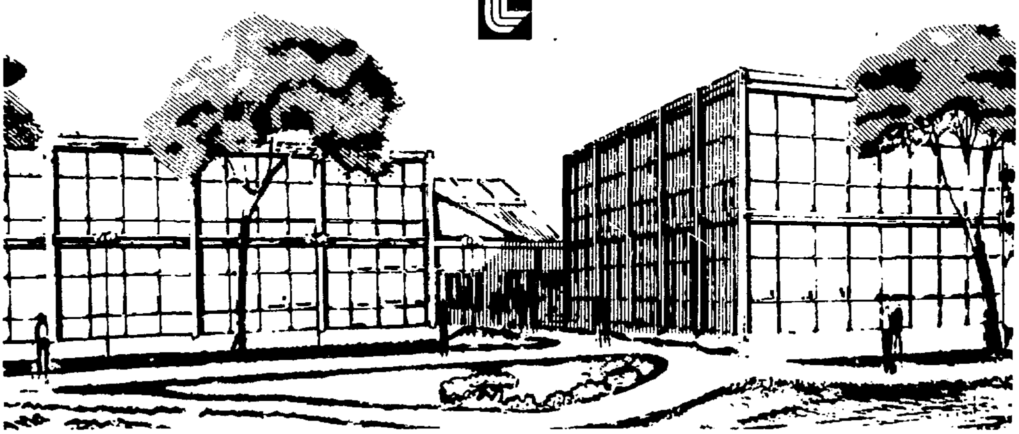

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Summary

The mirror machine as a potential power producing fusion reactor has many inherent features and advantages not generally available to the mainline tokamak. It is a steady state, high β, constant B field, linear machine with established fueling and automatic "ash" removal. There are other advantages such as the absence of cyclic fatigue problems and a positive plasma potential. Notwithstanding its virtues, the mirror reactor is suspect as an economic power producer because of one of its principal parameters called Q. This term Q is the ratio of the fusion power produced to the power input. It is a driven device. Q is truly the success parameter for mirrors - widely discussed but not succinctly specified as to required value. The problem is that Q can be treated as a subjective parameter - there are many milestone Qs; for scientific demonstration, for breakeven power, etc. Yet for a successful reactor, there is only one Q and that is the Q which produces mirror fusion power at the busbar that is less than the cost of delivered power in mills/kwhr by other means. We call this $Q_{PRACTICAL}$ and believe there is a convincing argument that says this $Q_{PRACTICAL}$ can be about 5.0 even assuming modest efficiencies for system components. A direct convertor is necessary. If the direct convertor were deleted, a $Q_{PRACTICAL}$ of ~ 7.5 would be required. If we wish to soften the value of Q further, then the technical logic for the fusion fission hybrid is very powerful. With the hybrid a $Q_{PRACTICAL}$ of 1.5 - 2.0 appears to be a very reasonable value. The key in being able to specify values of $Q_{PRACTICAL}$ lies in economically comparing the capital cost of fusion power to the sum of the capital cost and the present value of all the fuel costs for the competitive fuel intensive plants.

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The Strong Engineering Case for Mirror Reactors:

From an engineering viewpoint it is difficult to understate the advantages of the mirror reactor, open system concept. Some of these advantages are:

1) steady state operation
2) an established fueling method
3) an automatic "ash" disposal method
4) a positive plasma potential which minimizes wall ion - plasma interaction for impurity control
5) a characteristic plasma-ion loss mechanism into the loss cone that further minimizes plasma-wall interaction for impurity control
6) a high β
7) a programmable plasma heating, sustaining, and cooling sequence -- in essence an ability for load following and power control
8) an enhanced plant life due to the absence of cyclic fatigue
9) constant B fields -- no poloidal -- toroidal field interaction.

None of these advantages is available to the mainline Tokamak systems. Furthermore, the prospects for a two-component tandem mirror reactor are highly encouraging. If this proves to be the case, then two additional very strong advantages are acquired:

10) The reactor is linear and remote maintenance of the power-producing mid-section need not be unduly complicated
11) The length of the power-producing mid-section can be sized, within limits, to fit the application -- short and less capital intensive for DEMO, long and lower on cost per kilowatt for commercial power. This is true because the mid-section not only governs its own cost but controls the balance of plant cost in proportion to power out. Very roughly, costs are ~30% for the nuclear island and ~70% for BOP.

Finally, if the physics for field reversal bears fruit then the size of a reactor, the number of megawatts output, will be a comfortably small value -- perhaps 25 MWe or higher allowing entry into the marketplace at a price where risk capital can come from the private sector instead of government financing.

Some Background on Q - The Success Parameter for Mirrors:

These advantages for the mirror machine, although very persuasive, are always in the shadow of Q, perhaps the mirrors most important parameter. Certainly it is the most widely discussed. Unless Q has certain minimum values or unless promising combinations of Q and M are available, the advantages of mirror reactors are academic. By Q we mean the fusion power output divided by the power input. The term M is the blanket energy multiplication.

The scientific community has been talking about Q and the program scientists have been trying to increase its value since the inception of the mirror program. The engineering community has factored Q into reactor studies since 1969. The studies group has been instrumental in forcing attention on methods for increasing Q. Recently the Open Systems Technical Review Panel, convened in September 1976, was charged with suggesting guidelines on Q values for reactors and to search out and evaluate Q enhancement methods. Their conclusions were less than rigorous. They stated on page 81 of their report:[1]

"2. To be attractive a pure fusion mirror reactor should have a Q greater than the Q ≅ 1 presently estimated. Q of 2-3 is the threshold for reactor interest; higher Q's would considerably ease the engineering problems of achieving high subsystem efficiencies. Although difficult, there is reason to hope that methods can be developed to provide enhancement of Q. Q of 2-3 can probably be achieved by relatively minor modification of present mirror concepts; higher Q's will require more radical concepts, e.g., field reversal;"

"5. Fusion/Fission hybrid systems require lower Q than pure fusion power plants and may provide a nearer-term feasible alternative to pure fusion;"

On pages 7-8 in the body of the report, the panel states:

"The absolute Q-value needed for a reactor is a matter of subjective judgment, and is not easily inferred from the curves in Figure 1. (Reproduced here.) Factors which enter into this judgment include the increased probability of being able to achieve lesser efficiencies, the uncertainty of actual reactor costs, and the ability to reach the classical Q-values without enhancement. The reactor community will not agree on the required Q, given these uncertainties, but the Mirror Senior Review Panel has identified Q's of 2-3 as being the threshold for reactor interest for a pure fusion mirror reactor, and values ranging as high as 10 have been suggested. While the quantification of the absolute value of Q required for a practical reactor has not been established, one should note that the presently optimized classical Q value of 1.1 is below the range of interest for 'modest technology,' and therefore, some enchancement seems necessary. Only the magnitude of Q-enhancement is in question, and while modest increases (order of factor of 2) may be sufficient, the goal should remain one of even larger gains. As long as the absolute Q is less than 4-5, both high efficiency direct converter modules and injectors appear necessary."

Lessening the Subjective-Judgment on Q:

It is the intent of this paper to discuss two interrelated arguments: (1) Q as seen from an engineering viewpoint and (2) the relationship of fuel costs and capital costs in systems competitive to fusion; that is, the establishment of a logical comparison between capital intensive systems and fuel intensive systems. Taking the latter into account we propose to show how critical a parameter Q will be as seen from a utility engineers perspective. We will attempt to develop a range of values for $Q_{practical}$.

The Basis for Q:

The term Q is a plasma quantity defined as the fusion power produced/ power in.

For mirrors
$$Q = \frac{1/4 n^2 \langle\sigma v\rangle E_{fus}}{\frac{n E_{injected}}{\tau}} \qquad (1)$$

Or in terms of the containment parameter n :

$$Q = \frac{1/4 n\tau \langle\sigma v\rangle E_{fus}}{E_{injected}} \qquad (2)$$

This physics based term, in a sense, represents the gain in the first stage of a fusion machine that resembles a two-stage power amplifier. Another term which we call M, determined substantially by engineering considerations, represents the gain in the second stage of the power amplifier. The second stage is the blanket. The product of the two is highly important to mirror reactor success and we are concerned with combinations of Q and M that can lead to a competitive, economic, practical reactor. We know with reasonable certainty the expectations for M, but are less certain of Q. How large must Q be in a practical sense? The Q required for break-even (no net power out), called Q_{crit}, or the Q required to produce only a demonstration amount of net power -Q_{token}, or the Q derived from very low duty cycles -$Q_{transient}$, are of passing interest. They are vital to progress but not sufficient for economic success. As designers of commercial fusion reactors, the Q on which we must focus is $Q_{practical}$. As others have indicated, it seems difficult to quantify this Q, but we hope to do so in a economic or competitive sense. We start with the general energy balance shown in Figure 2 which is for a mirror machine with a direct convertor. From the figure and assuming D-T as the fuel, we may write:

$$A = 0.8\, P_{inj} \eta_A Q = \text{(the neutron fraction)}$$

$$B = 0.2\, P_{inj} \eta_A Q + P_{inj} \eta_A = \text{(the d and c.p. fraction)}$$

$$C = P_{inj}\, (1 - \eta_A) = \text{(the neutral fraction)}$$

Thus: $P_{gross} = AM\eta_{th1} + B\eta_{DC} + B(1 - \eta_{DC})\, \eta_{TH2} + C\eta_{TH1}$

and $P_{net} = P_{Gross} - P_{aux} - P_{circ}$ (2)

By definition

$$P_{circ} = P_{inj} / \eta_{inj} \quad . \qquad (3)$$

The value of P_{aux}, the power required for pumps, refrigeration and other plant needs, may be specified as some fraction, f, of the thermal and DC energy before conversion

$$P_{aux} = f(B + AM + C) \quad (4)$$

$$P_{NET} = \left[AM\eta_{TH1} + B\eta_{DC} + B(1 - \eta_{DC})\,\eta_{TH2} + C\eta_{TH1}\right] - \left[f(B + AM + C) + P_{inj}/\eta_{inj}\right] \quad (5)$$

It is convenient to set $P_{inj} = 1.0$ and solve (5) for P_{NET} and (1) for P_{GROSS} using Q as a variable.

We will illustrate by using two boundary condition examples:

1. A somewhat "idealized" case where all parameters are maximized. Roughly the best one can hope to do. This we term the physics case.
2. A "realists" case where all parameters are set at modest levels. No breakthroughs required (almost) - the engineering case and because of the parenthetical "almost" a third example where
3. Not only are all parameters set at proven levels but the direct convertor is not used.

The values are given in the following table.

The economic need for reasonable values of $Q_{practical}$ may be quantified or at last logically presented using the ratio of P_{gross}/P_{net}. This ratio is, in essence, the cost multiplier with which machines, such as mirrors and two component Tokamaks, are burdened because they are driven machines with substantial fractions of circulating power. The ratio is the cost multiplier because the net power is the salable commodity and the gross power is a measure of the cost of doing business. The reactor clearly must be sized to handle the gross power. We have seen that

$$P_{gross} = P_{net} + P_{circ} + P_{aux} .$$

If ones background is the fuel intensive power producing plants, it is then helpful to think of the P_{circ} term as a form of fueling cost so that circulating power is to a mirror machine as fueling is to a coal plant. The important difference is that circulating power increases capital expenditures whereas fueling is part of the running expense.

Using the values specified in the table, we may plot P_{gross}/P_{net} versus Q. This is shown on Figures 3 for the three different models. We state with reasonable precision that a coal plant or a fission plant, etc., has substantially zero circulating power, and P_{gross}/P_{net} is very nearly equal to one. This then gages the relative capital cost for competitive systems indicated as the baseline on the figure.

The implications of the data presented may be initially disconcerting to mirror reactor advocates since the capital costs only approach the direct capital cost of the competitive systems asymptotically, with increasing Q. However, there is a major correction to be included that will place fusion in a much more favorable light. This correction accounts for the fact that fusion will be a capital intensive effort with minimal fuel costs whereas coal plants, fission plants, oil from oil shale plants, etc., are about equally balanced between fuel costs and capital costs. That is, busbar costs are arrived at by both fuel costs and capital costs. It would seem evident that the fuel costs over the life of the plant which these fuel intensive plants must unavoidably pay must be credited to fusion in terms of increased allowance for capital costs. In the final analysis, from a competitive viewpoint, what counts is the cost of electricity at the busbar in mills/kWh and it should not matter to first order how the costs happen to come about. Figure 4 taken from the EPRI Journal of October, 1977, shows these busbar costs for coal and nuclear. If we use coal as a reference, it is indicated that fusion as a new base load technology would be allowed total busbar costs of ~ 40-50 mills/kWh in <u>1976</u> dollars to compete on an economic basis. For nuclear fission as a reference the competitive busbar costs for fusion would be ~ 40 mills/kWh.

We may relate this allowable busbar cost to <u>allowable capital investment</u> for fusion by translating lifetime fuel costs to capital money.

<u>The Economic Leverage for Fusion</u>:

The economic studies of fusion, to this date, have almost universally tended to compare <u>capital costs with capital costs</u>. The fusion advocates and detractors alike (see the \$/kW abscissa chosen by the Mirror Review Panel in Fig. 1 for instance) respond to the typical question, "CAN FUSION COMPETE WITH COAL?" (for example), and then proceed to prove that in all likelihood we <u>cannot</u> compete because capital costs for fusion will always be higher than capital costs for coal. The comparison is unfair and the question that must be asked is: Can a fusion reactor produce electricity cheaper, or as cheaply, as a coal plant or other competition. The answer lies in recognizing two vital points: that fuel costs for fusion appear to be negligible, and that coal plants, fission plants, plants of the future using oil from oil shale rather than being capital intensive, are fuel intensive. What must be equated to make a proper comparison is the capital cost of a fusion plant to the sum of the capital cost for a fuel intensive plant and the present value P(R) of all the fuel that will be used by the plant during its lifetime; that is,

$$CC_F = CC_C + P(R) \qquad (6)$$

Here we will consider coal as the prime competitor because in the United States the present national policy is to have a resurgence of coal usage so that it may be a replacement fuel for a diminishing oil supply. From a resource and reserve standpoint this makes eminently good sense because U.S. supplies are adequate for several hundred years. The implementation of this policy is not as clear. There will be many constraints -- social, political, environmental, CO_2, engineering, geographical, etc., all of which will slow the time scale for coal to be a prime energy source and certainly will raise the price of coal. Again in terms of national policy we observe the diminution of effort on the fission breeder -- once thought to be fusions principal competitor, since it was likely to be commercialized sooner in the U.S. than fusion. As a possible runnerup to coal, the recovery of oil from oil shales or tar sands could play a vital role in meeting future energy needs both for the U.S. and the world. Resources are enormous. Oil shale fired plants, even more than coal are fuel intensive.

The basic equation for the present value, P(R), of a series of annual payments R is:

$$P(R) = \left[\left(\frac{1. - (1 + i)^{-m}}{i}\right)\right] R \qquad (7)$$

where

n = life of the plant
i = cost of capital
R = in this case is the annual payment for fuel.

The value of R is time varying because of inflation. What is needed is a levelized value of R to use in equation 7. By definition, the levelized value of a time varying series of expenditures is the constant (or level) series of expenditures with the same present value as the time varying series.[1] If all escalation rates, cost of capital and expenditures are constant from the base year to the end of the project life, then Le can be solved for directly using the relation:

$$Le = R(1+e)^m \frac{\left[1-\left(\frac{1+e}{1+i}\right)^n\right]\left[1-\frac{1}{1+i}\right]}{\left[1-\left(\frac{1+e}{1+i}\right)\right]\left[1-\frac{1}{(1+i)^n}\right]} \qquad)8)$$

where the new terms are:

e = escalation rate
m = number of years between some reference date and when the plant is built.

The levelized costs include the effect of inflation on both expenditures and cost of capital: Example - a 35 year economic life coal plant operational in 1977, 1990 or 2000. (Table II)

In 1977 as a ref data fuel (coal) costs for a representative 1000 MWe plant were R = \$100 M/annum. The average capital cost for a 1977 1000 MWe coal plant was C_c = \$650 M. If we select 1990 as a possible entry date for fusion we can calculate the apparent cost of the competiting coal plant

$$C_{APP} = [\text{1990 CAP COST}] + \text{PRES VALUE OF FUEL}$$

$$= [650\ M\ (1+e)^{13}] + \left[\frac{1-(1.11)^{-35}}{0.11}\right] [100\ M \times 3.857]$$

$= 1336\ M + 3415\ M$

$= \$4751\ M$

The fuel costs are dominant. We are approaching the allowable capital expenditure for fusion. However, there is a further correction to be made since the apparent cost for coal plants cannot be used directly. There is also involved, to make this comparison valid, the annual charge rate on invested capital. This annual charge rate includes cost of capital, capital recovery, taxes and insurance. For this, a value of 16% is representative.

To do this we consider the lifetime cash flow and may then equate:

$$(\text{ALLOW. CAP.})_{\text{FUSION}} \bullet a \bullet n$$
$$= (\text{CAP COST})_{\text{COAL}} \bullet a \bullet n$$
$$+ (\text{FUEL COST})_{\text{COAL}} \bullet n$$

Using the values previously established we may write

$$(\text{ALLOW CAP})_{\text{FUSION}} = \frac{\$1336 \cdot 0.16 + 385.7}{0.16}$$

$$= \$3747\ M$$

The ratio \$3747/1336 = 2.8 is impressive! A \$3747 M fusion plant produces power at the same busbar cost as a \$1336 M coal plant. For overall perspective we look at a series of dates from 1980 to 2020. The data are plotted in the next figure. O & M has been purposely ommitted: it is a 5% effect; the difference in O & M between coal and fusion should not be great; the difference in fact may favor fusion as it does fission over coal.

Similar comparisons could have been made between fission and fusion or oil shale derived oil and fusion. The ratio would not be as high in the case of fusion and would be substantially higher for oil.

The question will arise - without inflation (e = 0) is there still leverage for fusion? The calculation is straightforward. We again balance lifetime cash flow

Example

$$(\text{ALLOW CAP})_{\text{FUSION}} = \frac{650 \cdot 0.16 + 100}{0.16}$$
$$= 1275\ M$$

The allowable capital cost for fusion is still 1275/650 ≅ 2 times the capital cost for coal.

We may relate these two values of 2.8 and 2 to Q and mirror machines by returning to a previous figure. Notice in this figure that when we use the engineering case where modest, credible efficiencies are involved a Q of about 5 is required. If the direct convertor were to be deleted a Q of ~7+ would be necessary. If we wish to soften further the value of $Q_{PRACTICAL}$, or if we are neutron economists instead of fusion purists, then the technical logic for the hybrid is very powerful for mirror machines, and the hybrid reduces the requirements on Q substantially. We may replot the original figure of P_{GROSS}/P_{NET} vs. Q, this time using a blanket M = 10. Here we see that required Q values are as low as 1 or 2 essentially independent of the model chosen. The criteria here is to stay off the steep part of the slope. How the hybrid interfaces into the energy economy is discussed in a companion paper.

References

1. Discussion of Levelizing and Constant Dollar Economic Analysis, R. B. Fincher, J. H. Malinowski, June 22, 1977, Pacific Gas & Electric Company note.

MIRROR POWER BAI ANCE

PARAMETER	PHYSICS CASE	ENGIN CASE	CONSERVATIVE CASE
TRAPPING EFF η_A	0.95	0.95	0.95
BLANKET MULT M	1.4	1.2	1.2
THERMAL EFF η_T	0.40	0.32	0.32
INJECTOR EFF η_I	0.80	0.60	0.60
AUX POWER FRACT f	0.02	0.02	0.02
DIR CONV EFF η_{DC}	0.60	0.45	0

TABLE I

TABLE II

ESCALATION FACTORS - 77 REF

	1977	1990	2000	LEVELIZED 1977	LEVELIZED 1990	LEVELIZED 2000
CAPITAL (5.7)	1.0	2.056	3.579	1.0	2.056	3.579*
O & M (5.4)	1.0	1.981	3.352	1.687	3.343	5.656
COAL FUEL (6.0)	1.0	2.133	3.820	1.809	3.857	6.908Δ

NOTICE: *CAPITAL ESCALATION FACTORS STOP ONCE THE PLANT IS BUILD WHILE

ΔFUEL ESCALATION CONTINUES

DIRECT CAPITAL COST OF OPTIMIZED DESIGNS AS A FUNCTION OF Q

	ADVANCED TECHNOLOGY	MODEST TECHNOLOGY
1. BLANKET	BERYLLIUM (M = 1.7)	NO BERYLLIUM (M = 1.2)
2. STRUCTURE	REFRACTORY METAL (η_{TH} = 0.50)	STAINLESS STEEL (η_{TH} = 0.35)
3. THERMAL CONVERTER	POTASSIUM TOPPING CYCLE	STEAM CYCLE ONLY
4. DIRECT CONVERTER	3-STAGE (η_{DC} = 0.60)	1 STAGE (η_{DC} = 0.5)
5. INJECTOR	η_{INJ} = 0.80	η_{INJ} = 0.80

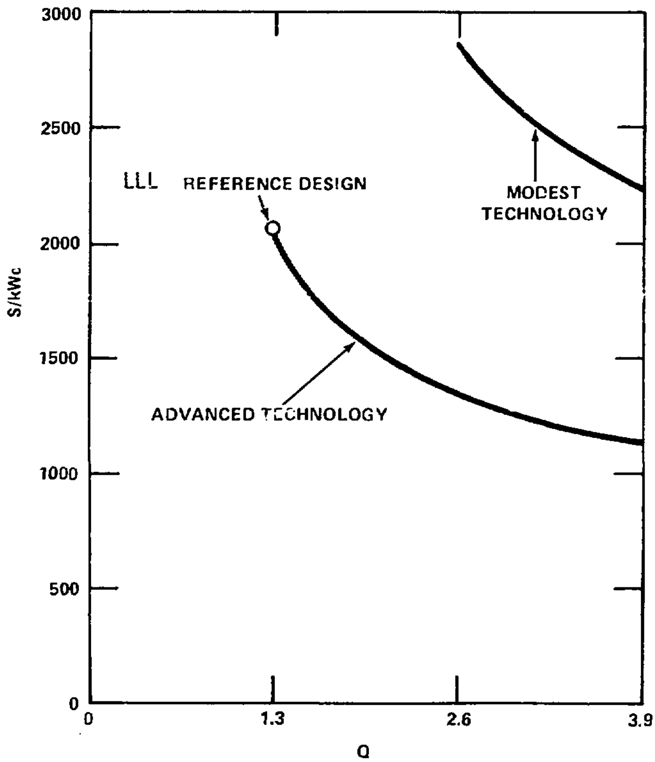

FIGURE 1

POWER BALANCE-MIRROR REACTOR
WITH DIRECT CONVERSION RW

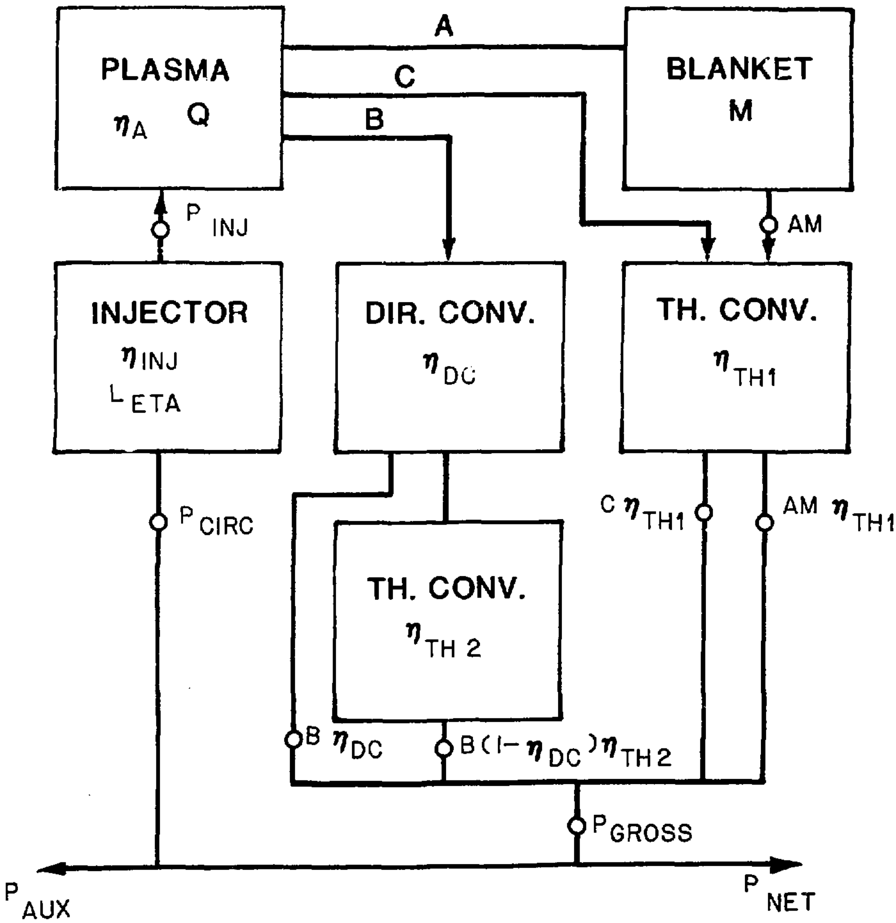

FIGURE 2

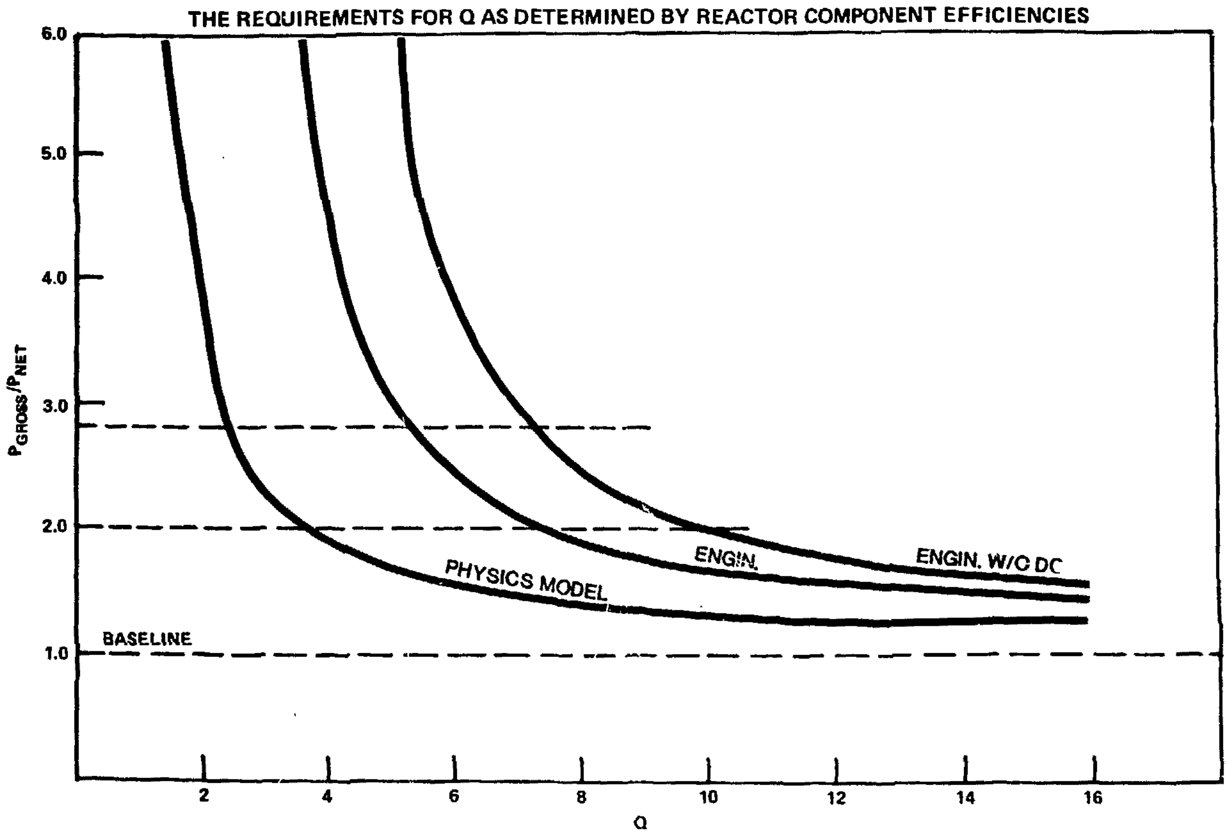
THE REQUIREMENTS FOR Q AS DETERMINED BY REACTOR COMPONENT EFFICIENCIES
6.0
5.0
4.0
3.0
2.0
1.0
P GROSS/P NET
BASELINE
PHYSICS MODEL
ENGIN.
ENGIN. W/O DC
2
4
6
8
10
12
14
16
Q

FIGURE 3

BREAKDOWN OF LEVELIZED BUSBAR COSTS FOR A TYPICAL REGION SHOWS CAPITAL COSTS, FUEL COSTS, AND OPERATION AND MAINTENANCE COSTS (1976$). THE SLOPING TOPS SHOW RANGES OF THE ESTIMATES. (FROM E P R I JOURNAL OCT.77)

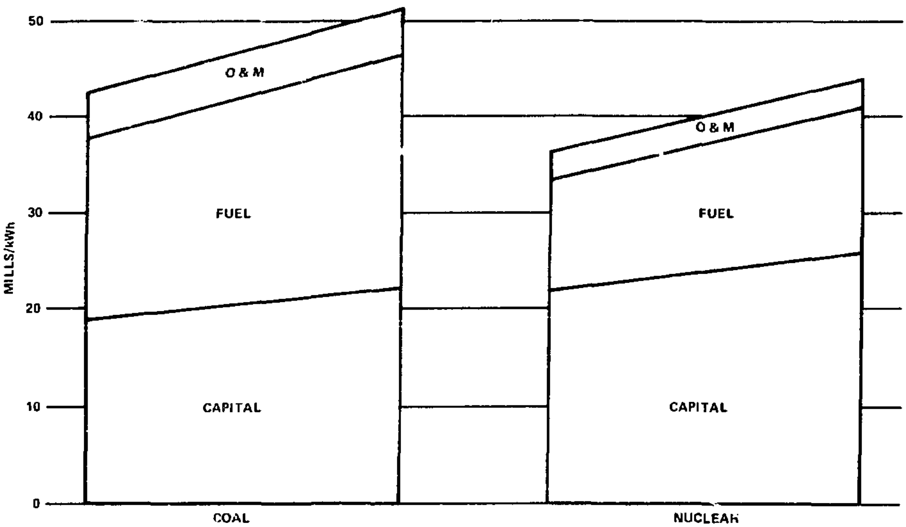

FIGURE 4

COMPARATIVE COSTS FOR 100 MWe FUSION AND COAL FIRED PLANTS DELIVERING ELECTRICITY AT EQUAL BUS BAR COSTS.

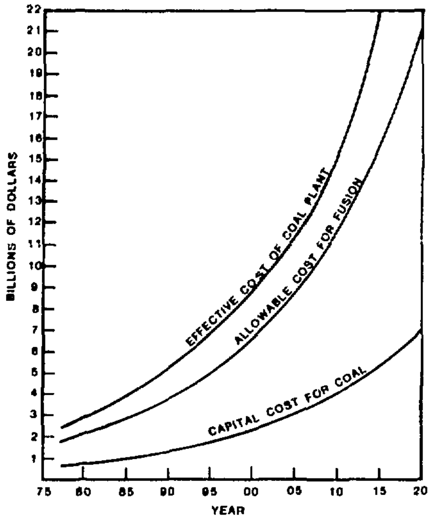

FIGURE 5