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DESIGN STUDIES OF MIRROR MACHINE REACTORS[*]

by

R. W. Werner, G. A. Carlson, Jack Hovingh
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The purpose of this paper is to provide an overview of the mirror fusion reactor design study elucidated in our comprehensive report, "Progress Report #2 on the Design Considerations for a Low Power Experimental Mirror Fusion Reactor".[1] The general methodology used in the study will be discussed, the reactor will be described and some design alternatives to the present approach enumerated.

The system chosen for this design study is a mirror machine with direct conversion using D-T fuel. The nominal power output is 200 megawatts. The coil geometry is the Yin Yang, minimum $|B|$ with a vacuum mirror ratio of 3.[2] The coil is of particular utility because of its simple conductor shapes and because the two separate conductors, by proper B field biasing, allow the charged particles to escape preferentially through one mirror only and through a relatively small "window" of that mirror. This is necessary for direct converter economy. Figure 1 shows a view of the Yin Yang coils, the plasma contained therein and some representative field lines.

POWER LEVELS IN THE SYSTEM

Typical power levels in the system are indicated in Figure 2 which shows schematically the major system components, the power flow and the energy balance. Starting at the injector, energetic deuterons and tritons in the form of neutral particles are injected into the reactor where they are ionized and trapped in the plasma. From this plasma as a consequence of the D-T reactions, 14.1 MeV neutrons and 3.5 MeV alpha particles are produced as fusion power. This is what we term the first stage of energy amplification in the reactor and we define this amplification for our purposes as: Q = Fusion Power/Trapped Injected Power. The neutrons that are produced enter the enveloping blanket which may be imagined to be the second stage of a two stage amplifier and which has an energy multiplication of value m. This m value in conjunction with Q, the energy amplification of the plasma itself, is a parameter of utmost significance for mirror machines. Other authors use this $Q \cdot m$ produce and call it Q. We shall keep the two quantities separated because they may be independently varied and m is a blanket design parameter while Q is a plasma physics parameter. The blanket, in addition to its amplifier role, converts neutron kinetic energy to thermal energy and concurrently

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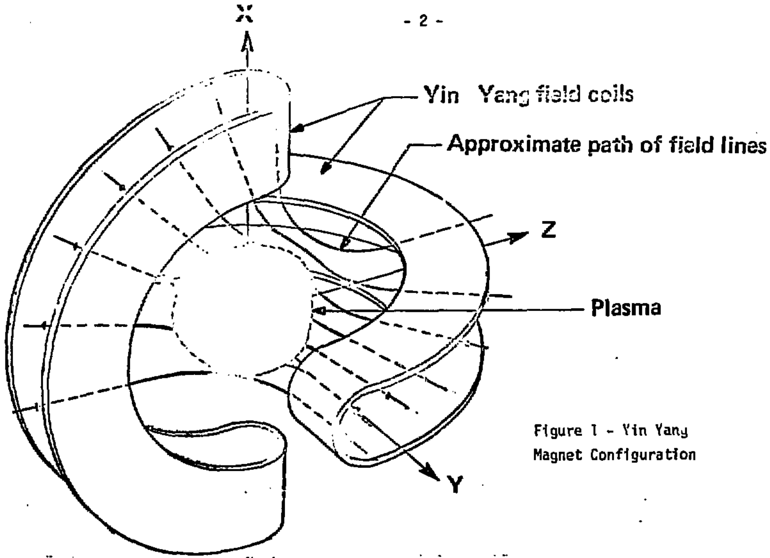

Figure 1 - Yin Yang Magnet Configuration

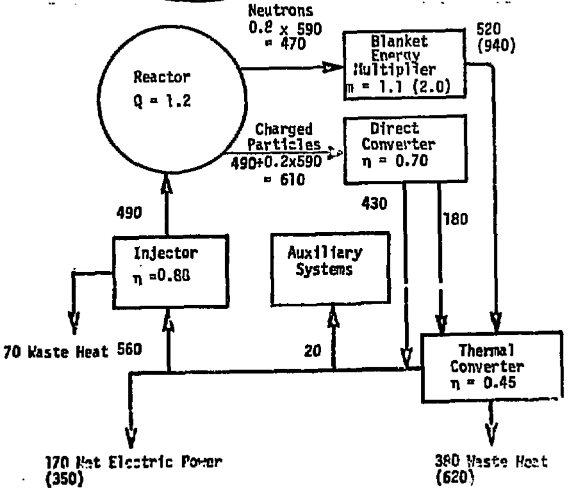

Figure 2 - Power Flow Diagram for a Mirror Machine with Direct Conversion (All powers are in MW, Parenthetical entries are for a blanket energy multiplier m = 2.0)

breeds tritium. The thermal energy from the blanket is converted to electricity in an external converter. Charged particles, as the other energetic source (either as alphas from the D-T reaction, or as unreacted D's and T's) are converted to useful energy in the direct converter where again, kinetic energy is changed in form - this time to high voltage D.C. This direct conversion of charged particle energy is a feature at present unique to mirror machine designs but applicable to other reactors also. The thermal energy from both the direct converter and the injector caused by D.C. inefficiency is also thermally converted to electricity. The power numbers of Figure 2 are presented as an example to demonstrate a net power output of ~ 170 MW. The actual component efficiencies, the Q, and the blanket energy multiplication, m, play a large role in success or failure of mirror machines. For instance, if the parameter m is increased from 1.1 to (2.0) the net electrical power output is more than doubled - from 170 to 350 MW. This will be discussed subsequently.

THE PLASMA

In our calculations for mirror machine reactor studies, we start with the previously defined quantity, Q, which provides the physics base for the subsequent engineering calculations. We have determined Q to have a value of 1.2 for this particular study. The Q is calculated by starting with the dimensionless ratio β defined by:

$$\beta \equiv \frac{p}{B^2_{o,vac}/2\mu_o} = \frac{\sum_i n_i kT_i}{B^2_{o,vac}/2\mu_o} \qquad (1)$$

This β is less than or equal to unity by definition any may be further limited by plasma stability requirements. We elect to use a Yin Yang containment configuration which has a nearly spherical minimum |B| plasma volume. We assume that for this configuration β may be as large as 0.85.

Next, a somewhat arbitrary decision was made to provide a vacuum mirror ratio R_{vac} = 3.0. This is a compromise value based on the considerations: (1) At constant β, the fusion power density increases with the fourth power of $B_{o,vac}$, thus decreasing size and cost per unit power, (2) The containment parameter, Q, increases with the log of the mirror ratio, but (3) B_{max} is limited by superconducting technology and the strength of structural materials. Then, from an approximate equation for the plasma mirror ratio,'

$$R \approx \frac{R_{vac}}{\sqrt{1-\beta}} \qquad (2)$$

We calculate R = 7.7.

Futch, Holdren, Killeen and Mirin[4] present results of Fokker-Planck calculations for Q values of DT systems as a function of R and injection energy. An extension of their reported results[5] yields Figure 3 for R = 7.7. The Q values of Figure 3 include Futch, et al's estimated 40% containment enhancement for a narrow angle source injecting perpendicular to the magnetic field. Although Q maximizes at an injection energy near 200 KeV, operation at this low an energy would require a prohibitively large direct converter for this particular concept. After several iterations, we choose a D and T injection energy of 550 KeV. Then from Figure 3, we have Q = 1.2.

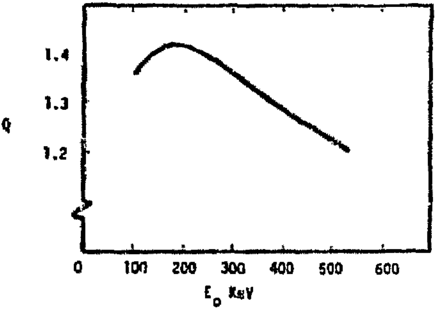

Figure 3 - Q as a Function of Injection Energy for R = 7.7

It must be emphasized that the value of β and Q used in this study cannot be viewed as final plasma parameters. Investigations of plasma stability (achievable β) and more sophisticated containment analyses (achievable Q) are major ongoing projects in the mirror machine program. Cordey and Watson[7] and Hall[2] are somewhat more pessimistic than us concerning achievable β and plasma mirror ratio. For a long plasma and R_{vac} = 3.0, Cordey and Watson predict a maximum β = 0.75 at the boundary of MHD instability and then calculate (from Eq. (2)) a maximum plasma mirror ratio R = 5.0. For a spherical plasma and the same R_{vac} = 3.0, Hall predicts a maximum β = 4.2 (Hall does not use Equation 2).

Since Q scales with log R, Ball's prediction would result in a 30% reduction in Q. On the other hand, recent consideration of anisotropic effects in the Fokker-Planck equations indicates that the Q values calculated by Futch, et al may be low by a factor of 2.[6]

In this study we use the value Q = 1.2 with the recognition that the final value may be either higher or lower. If it is much lower our reactor system may be unacceptable because of low system efficiency. If it is higher, we will have a welcomed increase in reactor system efficiency and a reduction in circulating power.

We use the results of the Fokker-Planck calculations by Futch et al to specify the relative densities and mean energies of the plasma species. Fuel is injected at the relative rate D/T = 1.6/1.0 in order to achieve equal D and T plasma densities. For the chosen injection energy of 550 KeV, the plasma density ratios at steady state are D/T/α/e = 1/1/0.06/2.12. The mean energies of the various plasma components are:

E_D = 580 KeV $\qquad E_T$ = 640 $\qquad E_\alpha$ = 1600

Approximately 6% of the injected D and 10% of the injected T undergoes thermonuclear burn. The mean energies of the escaping charged particles (after passing through the plasma ambipolar potential of 280 KeV) are:

$E_{exit,D}$ = 550 KeV $\qquad E_{exit,T}$ = 580

$E_{exit,e}$ = 58 $\qquad E_{exit,\alpha}$ = 1200

The escaping D and T ions have a minimum energy equal to the plasma potential; the escaping alpha particles have a minimum energy equal to twice the plasma potential.

For plasma mirror ratios between 5 and 10, Moir[7] estimates the mean plasma energies E to be related to kT by:

E = 1.8 kT (A Maxwellian distribution would have E = 1.5 kT) (3)

We set $B_{o,vac}$ = 50 kG to limit the maximum field at the conductor nearest the mirror to something less than 200 kG. Then, from Equation (1) the plasma component densities are:

$n_D = n_T = 0.6 \times 10^{14}\ cm^{-3}$

$$n_\alpha = 0.04 \times 10^{14}$$

$$n_e = 1.3 \times 10^{14}$$

Using these component densities and the $\overline{\sigma v}$ values calculated by Futch, et al, we find that the plasma has a fusion power density of ~ 4.5 MW/m^3.

The Yin Yang containment magnet was sized to provide the containment volume necessary for the desired fusion power, 590 MW. The resulting magnet has a radius to the center of the fan coils of 10 m, a fan midplane separation of 4.1 m, and a fan width of 6.6 m as shown in Figure 4.

The computer code MAFCO was used to calculate the magnet fields.[14] Figure 5 shows the magnetic field lines (solid lines) and the closed constant |B| contours (dashed lines) of the magnetic well. The vacuum mirror ratio is 3.0 and B_o is 50 kG. Each coil requires a total of 1.4 x 10^8 ampere turns.

The nearly ellipsoidal volume inside the last closed contour of |B| is 130 m^3. Taking this to be the volume of the dense plasma (with the previously calculated fusion power density) we calculate the total fusion power of 590 MW.

A separate MAFCO calculation yielded a maximum field within the conductor region of 165 kG, or 10% greater than the mirror field.

The coil superconductor materials are assumed to be niobium-titanium (used in the lower field strength regions $\lesssim$ 50 kG) and niobium-tin, both in a copper matrix.

With these calculations completed we compile Table 1 which sums up those quantities which may be considered to be basically physics in origin. Table 2 sums up other quantities which are (subsequently) calculated using data from Table 1. These latter quantities are more engineering dominated although there is a strong physics-engineering interaction involved in all of our calculations. It should be pointed out that all the quantities we specify are the result of a large number of iterations, both for the design of a single component and for the entire system design. We have not yet brought reactor system analysis to a point of optimization by computer since we feel this to be premature. But implicit in all of our calculations is a search for consistency and a strong attempt to take into account all relevant effects. For instance, diameters, wall thicknesses and material choice for coolant tubes are selected on the basis of neutronics,

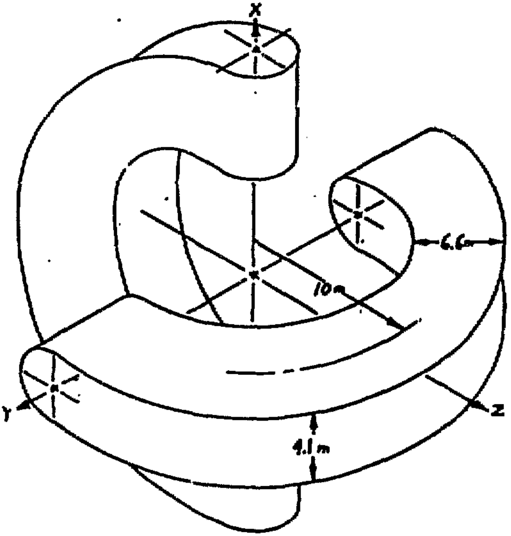

Figure 4 - Yin Yang Coil

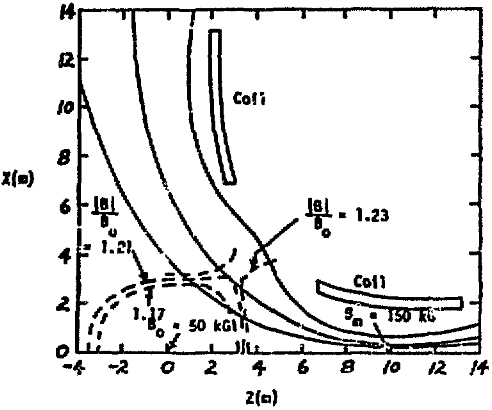

Figure 5 - Field Configuration

TABLE 1

SYSTEM DIMENSION AND CHARACTERISTICS OF A 200 MWe DT MIRROR REACTOR WITH DIRECT CONVERSION

POWER HANDLING COMPONENTS

Plasma

Shape - Ellipsoidal (Minimum B Volume)
Z Axis Intercept = 3.5 m
Q = 1.2
Volume = 130 m^3
Density n = 1.2 x 10^{14}
β = .85

Magnet Coil

R = 10 m
w = 6.6 m
2h = 4.2 m
Central Field = 50 kG
Mirror Field = 150 kG

First Wall

Wall Loading = 1.7 MW/m^2
Synchrotron Radiation = 2.5 x 10^{-2} MW/m^2
Bremsstrahlung = 2.5 x 10^{-2} MW/m^2

Power Distribution

P_{Fusion} = 590 MW
$P_{Injection}$ = 490 MW
$P_{Neutron}$ = 470 MW
P_{Ion} = 610 MW
P_{Elec} = 170 MW

TABLE 2

SYSTEM DIMENSION AND CHARACTERISTICS OF A 200 MWe DT MIRROR REACTOR WITH DIRECT CONVERSION

GENERAL SIZES

Blanket

Thickness = 1. m ave.
Individual Tube Diam. = .06 m
Shape = Conform to Field Lines
Composition = Li-C-Fe-Ni
Energy Multiplication = 1.1-1.2
Tritium Breeding Ratio = 1.0-1.4

Expander

Expansion Ratio = 100
Expander Angle θ = 240°
F @ Expander = 670 KeV
Beam Height at Mirror Exit = 0.74 m
Beam Area at Mirror = 1.5 m^2
Beam Height @ Expander Exit = 0.87 m
Radius = 76 m

Injector

Injected Power = 490 MW
Ave. Injection Energy = 550 KeV
Total Injection Current = 890 a
Max. Current Density = 20 ma/cm^2
Injection Area Required = 5 m^2
Type = Neutral Beam
No. Injectors = Unknown
No. of Accelerating Stages = Unknown

Collector

Depth = 22 m
Number of Elements = 20
Focusing = Electrostatic
Ion Power = 610 MW

heat transfer, sputtering, spalling, wall loading, availability, chemistry, corrosion, allowable creep stress, etc. These considerations are not necessarily detailed in our Progress Report #2, but may be found in our reference material.[11] With the basic groundwork established we can briefly discuss the individual components.

THE INJECTOR SYSTEM

The mirror machine reactor requires the continuous injection of high energy particles to maintain the plasma against end losses. This particular design requires the injection and trapping of 550 amps of 550 KeV deuterium atoms and 340 amps of 550 KeV tritium atoms into a nearly spherical plasma. The total power of the trapped injected beam is 490 MW. The efficiency of the injection system has a strong influence on the overall reactor system efficiency.

The injection system is shown in Figure 6. Positive ions are produced in a source and accelerated to an energy of E^+. These ions are passed through an alkali metal vapor cell which produces negative ions from the positive ions entering the cell. We are interested in negative ions because at energies greater than 100 KeV the efficiencies of neutralization of D^- is ~ 65-90% whereas for D^+ it is ~ 20%. Negative ions can be produced directly by an ion source or by electron capture by a positive ion beam in a gas or vapor cell. The negative ions are accelerated to the desired injection energy, neutralized, and the neutral atoms are injected into the plasma. The ions not neutralized are magnetically separated from the neutrals and guided into a direct converter where a fraction of their energy is recovered. Some of the injected neutrals charge exchange with the trapped reactor plasma ions such that the neutrals formed deposit their energy over the reactor first wall. The portion of the injected beam which passes completely through the reactor plasma may be stripped of an electron and the energy partially recovered in a second direct converter.

As suggested by this figure with its numerous stages, we studied an "in principle" injector as a complete sub-system starting with the ion source and ending with the trapping efficiency of neutrals entering the plasma. To our knowledge this study is the first of its kind. Our findings indicate that injector efficiencies of 88% are possible provided that very close attention be given to thermal recovery of the kinetic energy losses. Figure 7 indicates the injector system elements and their individual effect on overall injection efficiency.

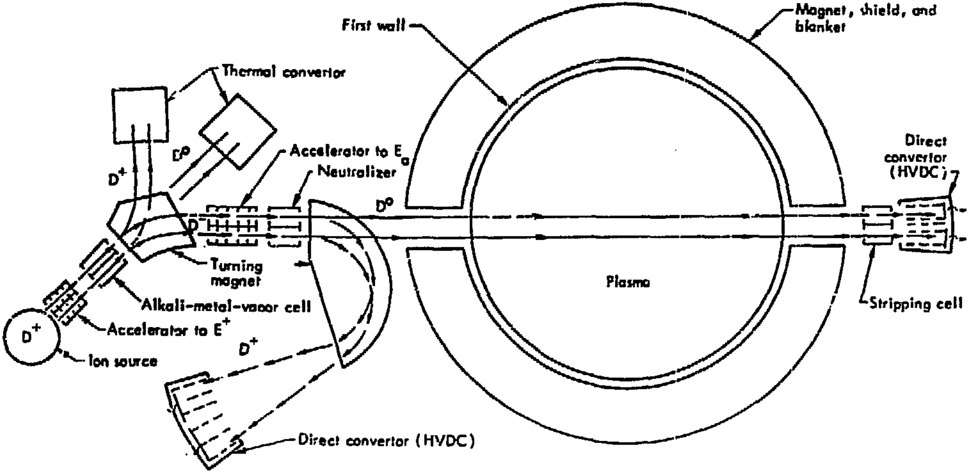
Thermal convertor
First wall
Magnet, shield, and blanket
D⁰
D⁺
Accelerator to E_a
Neutralizer
D⁰
D⁻
Direct convertor (HVDC)
Turning magnet
Alkali-metal-vapor cell
Accelerator to E⁺
D⁺
Ion source
D⁺
Plasma
Stripping cell
Direct convertor (HVDC)

Figure 6

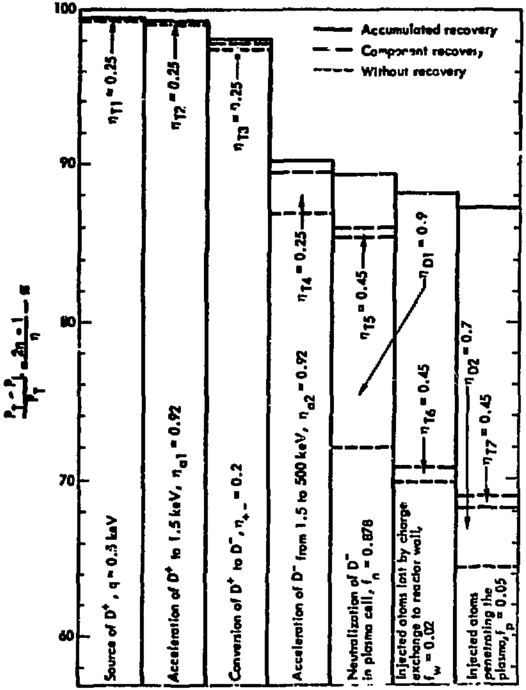

Fig. 7 Ratio of trapped power minus losses to trapped power of a particle passing through the injection system.

Notice that the D^+ to D^- conversion loss is greater than the sum of all other losses.

NEUTRONICS

The blanket concept chosen for this design study employs liquid lithium to perform the three functions of tritium breeding, heat transfer, and neutron moderation. The coolant tubes containing flowing lithium follow the magnetic field lines as closely as possible. A large number of such tubes surround the plasma to intercept the D-T neutrons. In this blanket thermal-hydraulic design, we found that tube routing on a path comprised of circular arcs is sufficiently close to the path of the actual magnetic field lines so that pressure drop penalties associated with MHD effects of flowing lithium in B fields are acceptably low. This we had previously postulated but now we have a specific design. Figure 8 is a general view of a blanket which conforms to field lines. We found that the bulge shown in the blanket in the vicinity of the plasma is actually not necessary. In our neutronics calculations, we have taken into account the real blanket geometry, the effects of voids and coupled neutron-gamma effects. We have found that voids of approximately 20% which are a consequence of using individual tubes in a square pack array for our blanket, have negligible effect on tritium generation or energy generation. The investigation of the effects caused by the blanket geometry dictated by the Yin Yang coil showed minor differences between "real" geometry and our original assumption of a blanket representation by a series of spherical shells. For this current study we chose a blanket whose composition was very simple. Simplicity has its attributes but a very important outcome is that the price we paid for simplicity was a low value for m, the blanket energy multiplication. The value of m was 1.1. The importance of this parameter can be seen in the following table where we compared the "simple" blanket with a blanket in which the multiplication is 2.0. The most significant effect of increasing m is the factor of two decrease in circulating power shown in Table 3 as injector power/net electrical. The means for increasing m are straightforward. We can trade the excess tritium generation for energy production by making compositional changes in the blanket; e.g., substitute sodium for some of the lithium and add materials with high (n,2n) characteristics such as beryllium or lead. The limit of m is not clear. In a blanket study for Astron[12] we were able to obtain values of m of ~1.85 with tritium breeding of 1.2. If the tritium breeding were allowed to approach unity, then an m of

BLANKET CONFIGURATION

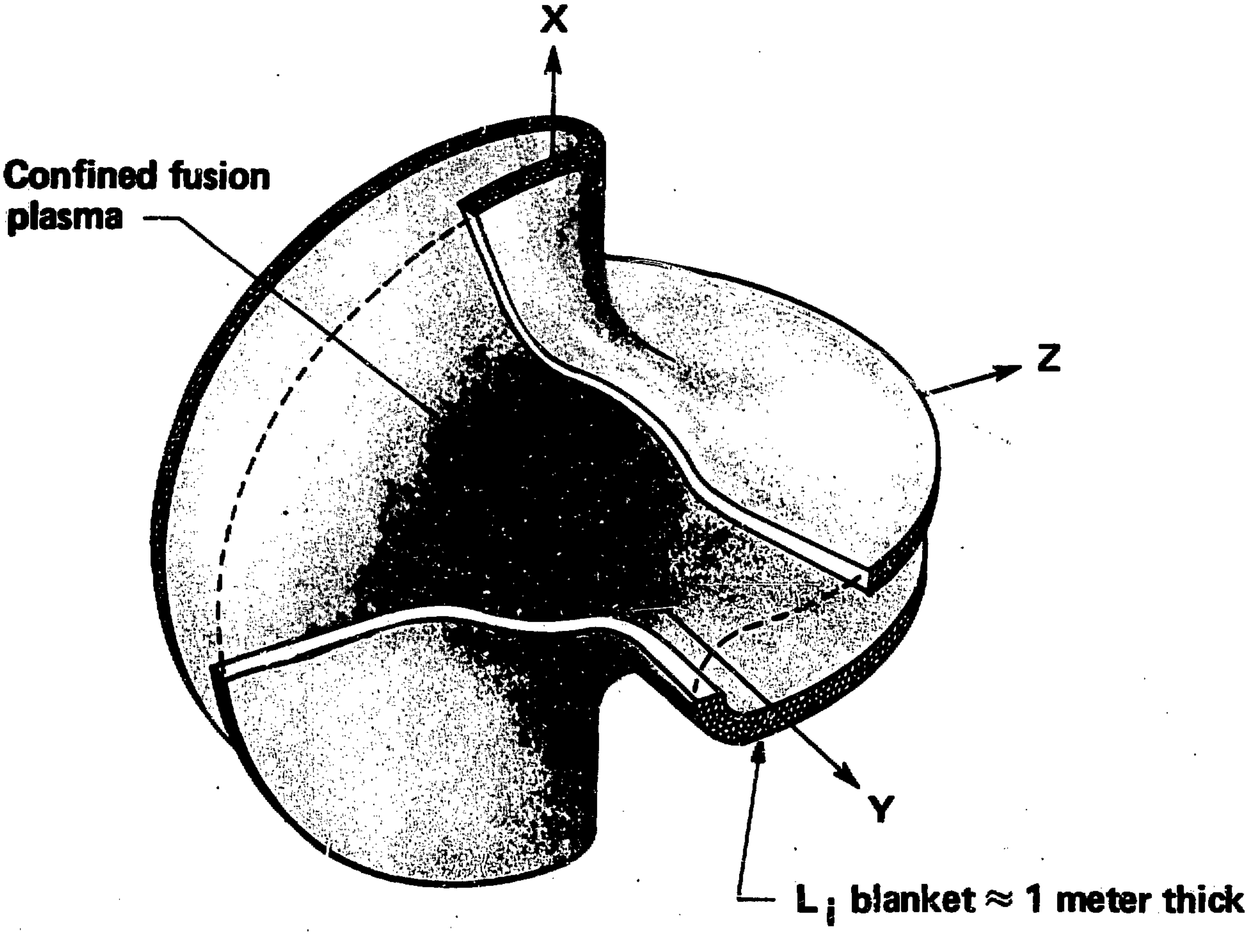

Figure 8

TABLE 3

	Simple Blanket	Better Blanket	Better Blanket & Higher η_{DC}
Q	1.2	1.2	1.2
M	1.1	2.0	2.0
η_{DC}	0.70	0.70	0.85
η_T	0.45	0.45	0.45
η_I	0.88	0.88	0.88
Aux Power	20 MW	20 MW	20 MW
η_{sys}	27%	33%	38%
$\frac{\text{Injector power}}{\text{Net elec. power}}$	3.3	1.6	1.4

2 seems in order for a conventional blanket. Values of m greater than 2 can be obtained via a fissioning blanket in which case values may be as high as ~ 30. This hybridization of fusion and fission warrants serious consideration for all reactor concepts. It is simply not sufficient to stay with the "purist" attitude of "fusion only" and ignore a clearly viable means of utilizing the energetic 14 MeV neutrons to the maximum extent.

This is illustrated in the following summary of a parametric study which compares direct conversion with a fissioning blanket.[13] For the direct conversion case we set $m = 2.0$. For the fission blanket case there is no direct converter and ion energy is thermally converted at 45%. Figures 9 and 10 show system efficiency and the important quantity, the ratio of injected power to net power as a function of Q for an η_{DC} of 70 and 90% for the direct converter and $m = 5$ and 30 for the fissioning blanket.

We have used in our study the direct converter of Post which he first discussed at the 1969 Culham Conference.[14] An interesting alternate design is one proposed by Moir which he calls the "Venetian Blind" concept[15] This design may be an attractive possibility to use with a fission blanket. Direct conversion efficiencies are lower (~ 65% for 4 collectors, 59% for 2 and 48% for 1) but the system is physically smaller and utilizes ion energies that are lower with a consequent increase in Q (recall Figure 3). Since direct conversion is in essence a "topping cycle" i.e.,

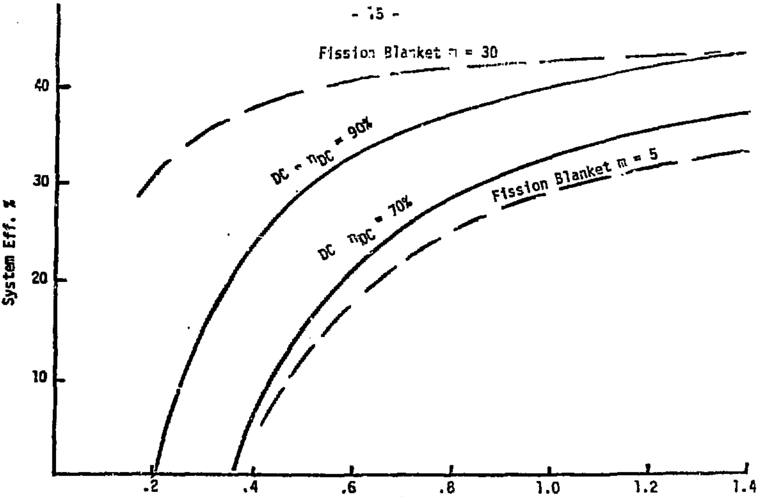

Figure 9

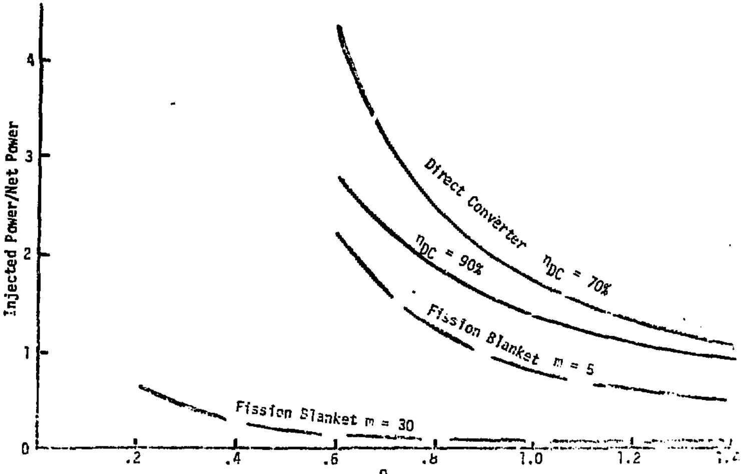

Figure 10

$$\eta_{net} = \eta_{DC} + (1-\eta_{DC})\,\eta_{Thermal}$$

we would be remiss in examining systems if we did not consider direct conversion of the ion energy in parallel with a fissioning blanket. Figure 11 shows the consequence of usin both the Moir direct converter at 65% for η_{DC} and the fissioning blanket for m = 5, 30. The fissioning blanket in which the ions are only thermally converted is shown for comparison. As either Q or m decreases the value of direct conversion is apparent in decreasing circulating power.

We have been asked why we chose ~ 200 MWe for the reactor size in this study as opposed to 1000 MWe since the latter is representative of commercial power plants. There are several reasons. First, we are not designing a commercial reactor. There are many steps to be taken before anyone in the fusion reactor area can credibly get to this point. We do not choose to call this a reference study for a commercial design but more appropriately a detailed study to determine what it is that needs attention, both scientifically and technologically, to make mirror machines attractive reactors. Secondly, we wished to make a point that mirror machines may be uniquely qualified to be small reactors if that is desired. In support of this smallness capability, Figure 12 is reproduced from our Wisconsin paper.[18] Notice that at ~ 200 MWe and higher, the cost of a mirror reactor with direct conversion is a weak function of power output. Roughly, for that particular study, capital costs are only about 35% more per KW at 200 MW than at 1000 MW. This result, that mirror reactors can be constructed relatively economically at power levels lower than the "norm" is in rather striking contrast to the predictions for other fusion reactors. The addition of a fissioning blanket to this reactor with a Post converter or a Moir converter would allow electrical output to be increased to values of commercial interest at probably small incremental costs. Finally, if this study is accepted as one dealing with an "experimental" reactor, (one presumably preceding a commercial plant), then from a funding standpoing, we must be concerned not with dollars per kilowatt as our principal criteria but in the total dollars involved. For equal risk, and certainly there will be risk involved, the Congress of the United States or any funding agency, would be more receptive to funding, for example, a hundred million dollar venture than one costing a billion.

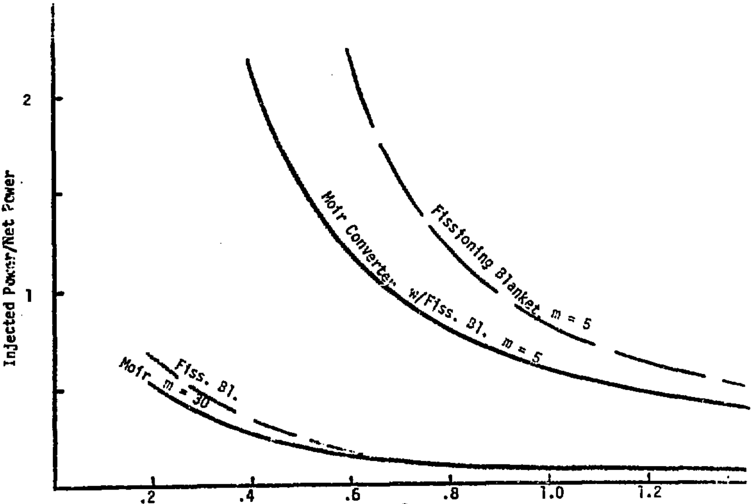

Figure 11

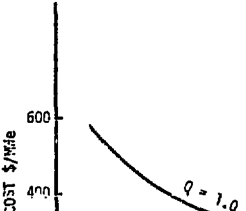

Figure 12 - System Cost as a Function of Power Output for Mirror Reactor with DT Cycle, and Nominal Component Performance

In retrospect, Progress Report #2 was an extremely valuable exercise - not *only in its explicit determinations but also in its implicit findings. Explicitly* we found:

1. Multitubular blankets of rather simple shapes (circular arcs) can have adequate conformity to the magnetic field lines to permit the use of flowing lithium coolant.
2. Gamma ray transport in the blanket can have a large effect on local energy depositions.
3. The heterogenity of this multitubular blanket has a negligible effect on neutronic performance.
4. "In principle" injection efficiencies of ~ 88% can be achieved.
5. Selective leakage can be achieved with an "in principle" efficiency of 95%. Selective leakage means that by local biasing of the B field in the mirror region escaping charged particles do so through a small "window". The area *of the window sizes the expander.*

Implicitly, we found:

1. As presently envisioned the "standard" mirror machine with a Post-type direct converter is a marginal performer. Acceptable plant efficiency will require the attainment of classically predicted containment and careful attention to the design of the injection and direct conversion systems.
2. The circulating power (and hence the required efficiency of the injection and conversion systems) can be considerably reduced by designing blankets with high energy multiplication.
3. Design of the hardware; e.g. main coil perturbation, auxiliary coils, electrostatic stopper grids to accomplish selective leakage should proceed.
4. A design and test program for injector systems should be initiated with the object of maximizing performance.
5. Superconductor development should be accelerated to produce fields > 150 kG.
6. Model tests on flowing lithium in B fields should be continued.

REFERENCES:

1. Werner, R. W., et al, "Progress Report #2 on the Design Considerations for a Low Power Experimental Mirror Fusion Reactor", UCRL-74054-2, Sept. 14, 1973.

2. Moir, R. W., R. F. Post, "Yin-Yang Minimum - |B| Magnetic-Field Coil", Nuclear Fusion, 9; pp. 253-258, (1969).

3. Werner, R. W., et al, "Progress Report #1 on the Design Considerations for a Low Power Experimental Mirror Fusion Reactor," UCRL-74054-1, Nov. 22, 1972.

4. Futch, A. H., J. P. Holdren, J. Killeen, A. A. Mirin, "Multi-Species Fokker-Planck Calculations for D-T and D-He^3 Mirror Reactors", UCRL-73226, 1972.

5. Personal communication with A. H. Futch of Lawrence Livermore Laboratory

6. Cordey, J. G. and C. J. H. Watson, "Optimized Magnetic Field Profiles and a β-Limitation in Minimum-B Mirror Reactors", Nuclear Fusion, 12; pp. 287-296, (1972).

7. Hall, Laurence S, "Magnetostatis Equilibria of Finite-Pressure Minimum-B Plasma Configurations", The Physics of Fluids, Vol. 15, No. 5; pp. 882-890, (1972).

8. Personal communication with Christopher Watson of Culham Laboratory, England

9. Moir, R. W., "Warm Plasma Stabilization of the Convective Loss Cone Mode," Plasma Physics, Vol. II; pp. 169-174, (1969).

10. Perkins, W. A., & J. C. Brown, "MAFCO - A Magnetic Field Code for Handling General Current Elements in Three Dimensions", UCRL-7744-Rev. II, Nov. 9, 1966.

11. To dig deeper see:
    - A. Thermonuclear Reactor Memos (TRM's) 1 through 49 - A continuing series of informal technical documents.
    - B. Approximately 35 UCRL's, formal technical papers on technology, and
    - C. Approximately 5 UCID's, formal limited distribution papers on technology. Listing of these papers is available on request.

12. Werner, R. W., B. Myers, P. Mohr, J. D. Lee, N. Christofilos, "Preliminary Design Considerations for an Astron Power Reactor System", UCRL-71768, (1969).

13. TRM #41 - "A Parametric Study of DT Mirror Machine Power Cycles - Direct Conversion and Fission Blankets," G. A. Carlson, May 4, 1973.

14. Post, R. F., "Mirror Systems: Fuel Cycles, Loss Reduction and Energy Recovery", UCRL-71753, Sept. 1969.

15. Barr, W. L., R. J. Burleigh, W. L. Dexter, R. W. Moir, R. R. Smith, "A Preliminary Engineering Design of a "Venetian Blind" Direct Energy Converter for Fusion Reactors", UCRL-74636, June 4, 1973.

16. Werner, R. W., G. A. Carlson, J. D. Lee, R. W. Moir, R. F. Post, and C. E. Taylor, "Engineering and Economic Aspects of Mirror Machine Reactors with Direct Conversion", UCRL-72883, June, 1971.