CONF-76-1012--11

Lawrence Livermore Laboratory

MIRROR REACTOR STUDIES

R. W. Moir, W. L. Barr, D. J. Bender, R. J. Burleigh, G. A. Carlson,
R. S. Devoto, J. N. Doggett, J. H. Fink, G. W. Hamilton, J. D. Lee,
M. E. Rensink, C. E. Taylor, R. W. Werner, and K. R. Schultz

August 10, 1976

This paper was prepared for inclusion in the Proceedings of the Sixth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Berchtesgaden, Federal Republic of Germany, October 6-13, 1976.

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

MASTER

NOTICE
 This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

MIRROR REACTOR STUDIES*

R. W. Moir, W. L. Barr, D. J. Bender, R. J. Burleigh, G. A. Carlson,
 R. S. Devoto, J. N. Doggett, J. H. Fink[†], G. W. Hamilton, J. D. Lee,
 M. E. Rensink, C. E. Taylor, and R. W. Werner

Lawrence Livermore Laboratory, University of California

Livermore, California 94550, United States of America

K. R. Schultz

General Atomic Company

San Diego, California 81608, United States of America

ABSTRACT

Design studies of a fusion mirror reactor, a fusion-fission mirror reactor, and two small mirror reactors are summarized. The fusion reactor uses 150-keV neutral-beam injectors based on the acceleration of negative ions. The injectors provide over 1 GW of continuous power at an efficiency greater than 80%. The fusion reactor has three-stage, modularized, Venetian blind, plasma direct converter with a predicted efficiency of 59% and a new concept for removal of the lune-shaped blanket: a crane is brought between the two halves of the Yin-Yang magnet, which are separated by a float. The design has desirable features such as steady-state operation, minimal impurity problems, and low first-wall thermal stress. The major disadvantage is low Q resulting in high recirculating power and hence high cost of electrical power. However, the direct capital cost per unit of gross electrical power is reasonable [\$1000/kW(e)].

By contrast, the fusion-fission reactor design is not penalized by recirculating power and uses relatively near-term fusion technology being developed for the fusion power program. New results are presented on the Th-²³³U and the U-²³⁹Pu fuel cycles. The purpose of this hybrid is fuel production, with projected costs at \$55/g of Pu or \$127/g of ²³³U. Blanket

* This work was performed under the auspices of the U.S. Energy Research & Development Administration, under contract No. W-7405-Eng-48.

[†] On loan from Westinghouse Electric Corporation.

and cooling system designs, including an emergency cooling system, by General Atomic Company, lead us to the opinion that the reactor can meet expected safety standards for licensing.

The smallest mirror reactor having only a shield between the plasma and the coil is the 4.2-m long fusion engineering research facility (FERF) designed for material irradiation. The smallest mirror reactor having both a blanket and shield is the 7.5-m long experimental power reactor (EPR), which has both a fusion and a fusion-fission version.

FUSION MIRROR REACTOR DESIGN

The conceptual design of a mirror reactor is shown in Fig. 1; its parameters are given in Table I. The design is based on a steady-state, mirror-confined D-T plasma sustained by continuous injection of D^0 and T^0 . The magnet is of the Yin-Yang type, oriented vertically to allow for

Fig. 1. Mirror fusion reactor.

TABLE 1. PARAMETERS FOR MIRROR REACTOR DESIGNS

Parameter	2X11B	MX	FERF	EPR/fusion-fission	Fusion reactor	Fusion-fission reactor (U-Pu)
R_{plasma} , m	1.6	3.4	4.2	7.5	16.0	15.0
r_{plasma} , m	0.05	0.3	0.25	1.2	3.0	2.4
n_{divac} , l	0.6	2.0	3.75	2.3	4.0	2.5
h, conductor		7.0	9.0	8.0	15.0	6.0
R_{vac}	2.0	2.0	2.0	2.5	3.0	2.5
$\phi_{\text{injection}}$, (keV)	20	80	60	100	150	100
ϕ_{ion} , keV	10	50	80	100	190	100
n_0 , cm ⁻³	10^{14} cm ⁻³	$1 \cdot 10^{13}$	$1 \cdot 10^{14}$	$1.1 \cdot 10^{14}$	$1.6 \cdot 10^{14}$	$1.1 \cdot 10^{14}$
n_1 , cm ⁻³	0.4-1.5	0.5	0.65	0.75	0.75	0.76
n_2 , cm ⁻³	$7 \cdot 10^{10}$	10^{12}	$1 \cdot 10^{12}$	$1.2 \cdot 10^{13}$	$1.6 \cdot 10^{13}$	$1.8 \cdot 10^{13}$
$Q_{\text{classical}}$			0.1	0.7	1.1	0.7
$(\epsilon_{\text{plasma}}/\epsilon_{\text{vac}})$	20.0	5.0	6.0	8.3	4.0	8.7
L/a_1	50.0	100.0	110.0	130.0	370.0	250.0
r/a_1	3.0	9.0	8.0	21.0	70.0	47.0
Power, MW		0.3	3.4	44.0	1270.0	470.0
Electric, MW(e)				62.0	450.0	164.0
Cost, CM	10.0	100.0	300.0	500.0	2000.0	2000.0
Cost/P, electric, \$/kW(e)				5700.0	4600.	2150.0
Fuel production, kg/yr			5	190.0		2400.0
Fuel cost, \$/yr				1200		55.0

lowering the bottom half of the magnet by means of a float. Once lowered, the blanket segments can be removed by a crane. The blanket is a spherical shell, segmented in shapes called lunes (see Fig. 2). Negative-ion injectors sustain the plasma. "Venetian blind" direct converters provide direct energy conversion of plasma and losses. The reactor is enclosed in a reinforced-concrete, dome-shaped building, which is sealed to prevent escape of radionuclides (principally tritium) in case of accidental or routine releases inside the building. Not shown in Fig. 2 is the thermal conversion system consisting of a potassium primary cooling system coupled to a potassium-topped steam cycle.

Blanket and blanket replacement

The blanket and its coolant plena constitute a spherical shell inside the coil that is set with appendages near the midplane for coolant to enter and exit. The shell is divided into an arbitrary number of segments for convenience in handling. With the blanket divided as one slices a melon, the segments may be removed by a simple vertical movement (see Fig. 2).

The neutron and gamma fluxes are attenuated by the blanket and its shield to substantially eliminate radiation damage in materials located behind the shield and to allow contact maintenance outside the reactor.

Fig. 2. Blanket design, showing (a) segment of a spherical shell called a lune and (b) detail of blanket submodule.

The piping and wiring connections along with the main vacuum seal are outside the irradiated area. During blanket replacement or repair, all joints can be broken and remade in a contact mode, minimizing the need for remote manipulators.

Neutral-beam injector

We have evaluated several different types of very large injectors, ultimately concentrating on the most economical design, one which employs negative ions as a source of neutrals. Figure 3 shows two of the alternatives under investigation. Figure 3(a) shows a positive-ion system [1] in which the fast atoms are produced by charge exchange in a neutralizing duct and the energy of the un-neutralized beam is recovered by an in-line direct converter. Figure 3(b) shows a negative-ion system in which low-energy D^- ions are produced by double charge exchange in a cesium-vapor jet, accelerated to 150 keV, and then converted to fast atoms by photodetachment of the weakly bound electrons.

Plasma direct energy converter

The system uses two end-loss direct converters; a simple, one-stage unit receives 20% of the power at one end, and a three-stage, Venetian blind unit (Fig. 4) receives the other 80%. The magnetic mirror at one end is slightly stronger than the other to achieve the 80%-20% split in ion losses due to a process of selective leakage. Together, these direct converters handle 1390 MW with an efficiency of 57% to produce

Fig. 1. Neutral-beam injector with beam direct conversion, showing (a) the positive-ion system and (b) the negative-ion system. In (a), the details called out are (1) 150-keV D^+ ion source, (2) neutralizing duct, (3) cryogenic gas pumping, and (4) energy-recovery system. In (b), the details called out are (1) low-energy D^+ ion source, (2) Cs jet for double electron capture, (3) 150-keV D^- accelerator, (4) cryogenic gas pumping, (5) photo-detachment optical cavity, and (6) energy recovery system.

790 MW of electrical power. Nearly all of the 600 MW that is not directly recovered is converted to high-grade heat (helium at 1000 K) and is processed in a thermal bottoming cycle. Thus, the net efficiency of recovering end losses including thermal recovery is 74%.

The single-stage unit consists of a helium-cooled grounded grid, a water-cooled negative grid, and a helium-cooled positive collector. The efficiency of the unit is high, 52%, because of the +87-kV ambipolar potential in the plasma that allows the collector to be held at 92 kV without any of the ions being turned back.

At the other end, there is a much larger three-stage unit consisting of a helium-cooled grounded grid, a radiatively cooled negative grid, two radiatively cooled collector stages, and a final helium-cooled collector stage. The efficiency of the three-stage unit is 59%, much less than the

Fig. 4. Modules of the three-stage Venetian blind direct energy converter.

79% which is theoretically possible with three collectors and this ion energy distribution. The difference results from the massive grounded grid which not only collects all primary electrons (87 MW) but also intercepts 51 MW of ions. Another large loss is due to the interception of ions on the first two collector stages. This loss is the consequence of the angular spread in the ion trajectories, which is due to the magnetic field at the collector (0.03 T).

Parametric analysis

We characterize the mirror reactor by means of a parametric analysis that couples simplified models of the reactor components in a consistent manner. The analysis, including a cost estimate, optimizes the reactor design; i.e., it minimizes the direct capital cost per unit of net electrical power [\$/kW(e)].

The most critical physics parameter in the design is the plasma Q (fusion power output divided by injected beam power). The value of Q is

obtained from a sophisticated Fokker-Planck model [2] for classical mirror-confined plasmas that includes the effects of ambipolar potential, alpha-particle heating, and enhanced mirror ratio due to plasma diamagnetism. An enhancement factor for Q is also introduced to explore the consequences of future improvements in the physics of mirror-confined plasmas. By "enhanced Q " we mean the classical Q predicted by Fokker-Planck calculations multiplied by some constant factor. Thus, enhanced Q retains all of the functional dependences of classical Q .

The maximum β of the plasma (perpendicular kinetic pressure divided by vacuum field magnetic pressure) at the midplane is limited by the magnetohydrodynamic (MHD) "mirror-mode" stability condition [3]; and the long-thin approximation, $R = R_{vac}(1-\beta)^{-1/2}$, is used to relate the net mirror ratio to the vacuum field mirror ratio.

The effects of parametric variations are summarized in Fig. 5. Figure 5(a) shows that the $\$/kW(e)$ cost is sensitive to mirror ratio. An increase in R_{vac} from the optimum results in better confinement (higher Q), but this positive effect is more than offset by a reduction in central field strength and hence in fusion power. The effects are reversed for a decrease in R_{vac} . Figure 5(b) shows the effect of decreasing the reactor length L below the reference value of 16 m. The direct capital cost and the reactor net power are shown. Lengths less than about 8 m are impossible because the space between the coil and plasma is inadequate for the blanket and shield. Before a minimum size is reached, the cost of electricity rises steeply because the net power decreases more rapidly than the capital cost. Nevertheless, these small reactors may be attractive as experimental power reactors. Figure 5(c) shows the cost of electricity for optimized reactors (optimum mirror ratio, injection energy, and injection angle) as a function of the Q enhancement factor.

We see that the $\$/kW(e)$ decreases with both increasing magnetic field strength and Q enhancement. For Q/Q_{cl} greater than about 2.5, the cost reduction with increasing Q enhancement is slow. Also, for high Q enhancement, the relative advantage of high field strength is less than for a lower Q .

Conclusions

Because of its high power density and because plasma losses do not increase with decreasing size, the mirror reactor can be made small and at low cost relative to some other fusion concepts [Fig. 5(b)]. The operating mode is continuous rather than pulsed. Impurity control is automatic. However, the rapid particle loss out the ends makes a mirror reactor with classical end losses have a low Q value; about 75% of the gross electrical power is recirculated back to the injector. The Q value must be raised by a factor of 2 to 3 to reduce the recirculating power fraction to a reasonable value. Further increase in the Q value or major simplifications may be required for economic competitiveness with other energy options. These further increases would allow relaxation of the demands placed on various component technologies.

FUSION-FISSION REACTOR DESIGN

The goal of our fusion-fission (hybrid) design is the production of fissile fuel at minimum cost in blankets containing uranium or thorium. The hybrid reactor [4] looks much the same as the fusion reactor (Fig. 1). The energy gain in the fissioning blanket overcomes the low- Q problems of the fusion reactor, but more important than the fission energy release are

Fig. 5. Parametric variations for the mirror fusion reactor, showing (a) relationship between vacuum mirror ratio, R_{vac} , and minimum direct capital (cost) per unit net electric power, $S/W(e)$; (b) dependence of direct capital cost and net electrical power, $MW(e)$, on reactor length, L ; and (c) minimum direct capital cost per unit of electrical power, $S/W(e)$, versus Q enhancement factor.

the extra neutrons produced by the fissions induced in the highly subcritical uranium or thorium assembly by 14-MeV neutrons. These extra neutrons are used to breed fissile fuel. To be economical fuel producers, hybrids must produce fissile fuel at lower than (1) the cost of mining uranium and isotope separating ^{235}U , (2) the cost of fissile fuel bred by accelerator-produced neutrons, or (3) the cost of the fuel produced in breeder reactors. As power producers, hybrid reactors can have a higher capital cost [\$/kW(e)] than fission reactors, but only by a small percent that is proportional to fuel cycle costs. The economic conditions imposed on hybrids to be power producers seems more difficult to achieve than those required for them to be fuel producers.

Fuel Cycle ^{239}Pu and ^{233}U

Using a mirror hybrid system model, we determined the characteristics of optimized hybrid reactors containing either ^{238}U or ^{232}Th in the blanket. Both reactor designs have a thermal rating of about 4000 MW and would produce 2.5 tonnes of fissile fuel per year. The significant difference between the two reactors is that the U blanket has an energy multiplication about four times greater than the Th blanket. The U hybrid produces 1000 MW of net electrical power, while the Th hybrid just breaks even (i.e., has recirculating power fraction of one). The cost of producing ^{239}Pu was found to be about twice the cost of producing ^{239}Pu . However, this cost differential may be acceptable because ^{233}U is a better fission reactor fuel than ^{239}Pu .

Blanket design

The blanket consists of 16 replaceable segments that form a spherical shell. This shell occupies the region between the plasma and the coils and has ports for beam injection and plasma leakage. A spherical shell is used so that the fusion neutron current is nearly constant over the surface area of the blanket.

Each segment consists of a collection of submodules assembled into a monolithic structure (see Fig. 2). Each submodule consists of a common-wall pressure vessel containing fuel assemblies. The inner zone of each assembly (25 cm thick), is fueled with rods containing natural U or Th, unmoderated so as to maximize fission of ^{238}U or ^{232}Th and to minimize fission of ^{235}U , ^{239}Pu , or ^{233}U . Over 80% of the fission occurring in natural uranium is ^{238}U fission. The outer fuel zone contains Li in the form of LiAlO_2 plus graphite for tritium breeding.

For heat removal, the submodules are supplied (in parallel) with high-pressure He coolant from plena that form the back of each blanket module. Inlet He is first used to maintain the pressure vessel temperature below 400°C; it then flows through the fuel and Li zones and finally exits at 530°C. Peak power density in the fuel is $\sim 200\text{N}\cdot\text{cm}^{-3}$.

Representative nuclear performance parameters for this blanket when fueled with either U plus 7 wt.% Mo alloy or Th metal are listed in Table II.

Primary heat-transfer loop and thermal conversion system

The design of the plant is based on technology developed for gas-cooled fission reactors [5]. The He pressure and temperature parameters were set at values typical for fission reactors: 60-atm He pressure, with blanket inlet and outlet temperatures of 280°C and 530°C, respectively.

TABLE II. TIME-DEPENDENT BLANKET PARAMETERS¹

Fuel type	T	M	Net fissile
Exposure			
U-Mo			
0 MMyr/m ²	1.1	10	1.8
5 MMyr/m ²	1.7	20	1.6
Th			
0 MMyr/m ²	1.1	2.5	0.73
10 MMyr/m ²	1.2	5.0	0.65

a_T = tritium breeding ratio (atoms/fusion neutron)

M = energy multiplication (blanket energy per fusion neutron divided by 1.4 MeV)

Net fissile = fissile production minus fissile consumption (atoms/fusion neutron)

Exposure = Integrated fusion neutron energy current through the first wall (MMyr/m²)

These values permit the use of existing designs of He circulators and steam generators and result in acceptable He ducting dimensions. In general, existing gas-cooled fission reactor technology is directly applicable to the hybrid, although various parameters must be optimized.

We have also considered the safety and licensing of the plant. The hybrid appears to have an advantage over fission reactors in this area because it is possible to eliminate the potential for a criticality accident. This should ameliorate the licensing procedure. However, due to the fuel afterheat power density of up to 10 W/cm³, a total loss of forced cooling in the blanket would probably result in fuel melting, an unacceptable situation from the licensing standpoint. Thus, the major safety consideration is to develop a design in which forced cooling to the blanket can always be assured to a high degree of confidence. To help provide this confidence, the present design includes redundant He circulators and redundant auxiliary circulators of diverse types. Given the verification of this aspect of the plant, it is expected that the hybrid could be licensed.

Conclusions

The design studies show that the mirror concept with classical plasma confinement can produce fissile fuel for burner fission reactors [light-water reactor (LWR), high-temperature gas reactor (HTGR), heavy-water reactor (HWR)] at a competitive cost, (\$55/g Pu; \$127/g ²³³U). The technology required for the hybrid is less demanding than for a pure-fusion reactor. The safety systems for the fission blanket are comparable to

those required for fission reactors. The lack of criticality may off-set safety problems introduced by the more complex geometry. Further design studies are needed to improve the technical feasibility and cost projections.

SMALL MIRROR REACTORS

We studied two classes of small mirror reactors. One, called FERF, is the smallest machine that can accommodate a shield between the plasma and the superconductor. Its purpose is to irradiate many small samples in 14-MeV neutron fluxes of about $10^{14} \text{ n} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$. The second small mirror reactor, EPR, is the smallest machine that can accommodate both an energy recovery and tritium breeding blanket and a shield between the plasma and the superconductor. There are two versions of EPR: one is a fusion reactor in which breakeven is not achieved; the other is a fusion-fission reactor that produces net power and fissile fuel (see Table 1 for parameters of these machines).

Fusion energy research facility (FERF)

The purpose of FERF is to provide adequate space and 14-MeV neutron fluence to perform the extensive materials and system testing required prior to the final design of a power reactor.

A secondary but essential purpose for building and operating FERF is to gain experience in the problems associated with the practical integration of the complex subsystems of a fusion reactor into a reliable machine. The purpose of this study was to optimize FERF for the testing of materials and systems.

Fig. 6. Vertical cross section through fusion engineering research facility (FERF).

The study is based on a mirror reactor for FERF. The basic geometry and neutron yields are those reported in Ref. [6]. The magnet orientation and supporting structure have been modified to improve access and maintainability (see Fig. 6).

The features that make the mirror machine attractive for FERF are:

- Small size — a mirror machine is smaller and potentially less costly to build and operate than other confinement schemes.
- Reactor level first-wall neutron flux = $1.4 \times 10^{14} \text{ cm}^{-2}\cdot\text{s}^{-1}$.
- Maintainability — the first wall is easily replaceable.
- d.c. operation — the mirror reactor will operate at steady state for relatively long periods (weeks), providing high availability for irradiations.
- Accessibility — the unique geometry of the Yin-Yang magnet set provides excellent access to the high-flux region of the reactor.

Figure 7 shows the location of the sample tubes and system test facility in relation to the first wall. The tubes have a 60-mm inside diameter and their useful experimental length is 0.5 m. There are 12

Fig. 7. Vertical cross section through FERF mirror reactor.

tubes per coil lobe for a total of 48. The principal system test facility proposed is a large-diameter port identical to the beam ports, giving access to the central region of the reacting plasma.

A comparison of FERF capabilities to estimated needs for testing fusion reactor materials shows that FERF can provide virtually all the requested space and flux (except for very large blanket sections). However, accelerated testing at a continuous neutron flux $10^{15} \text{ cm}^{-2} \cdot \text{s}^{-1}$ is beyond the practical capability of this or probably any other reactor source.

Experimental power reactor (EPR) fusion and fusion-fission reactor

A major step in the development of engineering technology for mirror reactors, after resolution of the plasma physics in MX, will be the design and construction of a test-bed reactor that is capable of incorporating full-scale mirror reactor components. We envision this facility to be the minimum size that permits the inclusion of a blanket and shield inside the coil windings. We use the mirror reactor system as a model to determine representative parameters for this machine.

It was found that a Yin-Yang coil set of 7.5-m mirror-to-mirror length can accommodate a 1-m-thick blanket plus a coolant plenum and shield with a blanket coverage of about 74%. Below the 7.5 m, the wall area available for blanket modules rapidly goes to zero. The EPR utilizes a reactor-grade plasma (100-keV energy) contained in a magnetic field that has a maximum of 8 T at the conductor and a vacuum mirror ratio of 2.5. This results in a first-wall loading of 0.9 MW/m^2 .

Because of the low blanket coverage, coupled with the low Q of the mirror plasma, the machine must rely on significant energy multiplication in the blanket for a positive power balance. By configuring the EPR as a hybrid with ^{238}U , we can obtain 300 MW of thermal power in the blanket from 35 MW of fusion neutrons. By employing a plasma direct converter and a steam-cycle thermal conversion system, the resulting plant has a recirculating power fraction of 0.6 and produces 62 MW of net electrical output. In addition, the ^{238}U blanket breeds 200 kg of ^{239}Pu per year. Further parameters for the EPR hybrid appear in Table I.

Conclusion

Small mirror reactors having room for a shield only can be used for material testing (FERF). Somewhat larger mirror reactors having room for a blanket can be used for blanket testing (EPR). A fusion-fission EPR would produce considerable amounts of fissile fuel as well as net power.

REFERENCES

- [1] FINK, J.H., BARR, W.L., HAMILTON, G.W., Nucl. Fusion 15 (1975).
- [2] KILEEN, J., MIRN, A.A., RENSINK, M.E., "The solution of the kinetic equations for a multi-species plasma," Methods in Computational Physics, Vol. 16; Control Fusion (KILEEN, J., Ed.), Academic Press, New York (1976).
- [3] RENSINK, M.E., et al., 5th Int. Conf. Plasma Physics and Controlled Nuclear Fusion Research (Proc. Conf. Tokyo. 1974) 1, IAEA (1975) 311.
- [4] MOIR, R.W., et al., LLL Rep. UCRL-51797 (1975).
- [5] SCHULTZ, K.R., et al., General Atomic Company Rep. GA-A14021 (1976).
- [6] BATZER, T.H., et al., LLL Rep. UCRL-517617, (1974).