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Lawrence Livermore Laboratory

MIRROR HYBRID REACTOR STUDIES

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Prepared for the Proceedings of the 2nd DMFE Hybrid Reactor Meeting
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1. Review of Past Studies

The reactor studies group at Livermore has been involved in the conceptual design and analysis of the hybrid reactor, based on mirror confinement of the plasma, for over five years. Prior to 1975, some preliminary engineering analysis was performed (1,2,3), but a great deal of the work was concentrated on blanket neutronic studies, determining interaction of the 14 MeV neutrons with various assemblies of fertile materials, coolant and structural material.(4,5)

In 1975, our first point design study was completed (6). It was a conceptul design on which we could build and begin to understand the way in which one would perform the different functions that were necessary in the reactor.

We devoted 1976, at Livermore, to optimization of our point design (7,8,9,10,11) and, at that time, General Atomic joined us, applying their expertise in gas-cooled reactor technology to our point design (10,11,12). In this past year, we have concentrated our effort on a reference design, which will present a good illustration of the capability of the classical mirror hybrid reactor.

Our interest in the mirror hybrid has evolved to optimizing the reactor for fissile fuel production, the hybrid being part of a nuclear power system where it supplies makeup fissile fuel for five to ten fission converter reactors. Our interest in the fissile fuel producer has come from our economic analyses that have indicated that this is the most attractive hybrid system (9).

To summarize the status of our work, we've devoted a good deal of effort to the nuclear analysis of fast spectrum blankets, and at this point, we have established the nuclear performance of these types of assemblies (blanket multiplications and fissile production rates). Our systems studies work has evolved a set of "necessary conditions" for an attractive fissile fuel producing hybrid reactor. These conditions are (i) a plasma Q of 1-2, and (ii) a first wall fusion neutron loading of 1-2 MW/m^2. The hybrid reactors we've studied to date have been based on fuel cycles which employ reprocessing, and our optimization studies have indicated to us that these are low burnup fuel cycles (in the hybrid) and we, therefore, have been able to use metallic fuels. And, finally, we've gained some appreciation for the implications of fusion reactor geometry on the mechanical design of the machine.

2. Reference Design Study

We are completing our reference design (13,14) this year, based on classical or minimum-B mirror confinement and a fast fission U-238 blanket. The reactor Q is ~ 0.6, and it achieves a first wall loading of about 1.7 megawatts per square meter of 14 MeV neutrons. The design appears feasible in the sense that we have not encountered any engineering constraints which we have not been able to meet. The economics could be improved in that the rather low plasma Q of this reactor requires recirculation of about 65% of the gross electrical power production to run the injector system, and this is an economic penalty. The spherical geometry of this reactor appears to be workable, but it is more complex than the right circular cylinder geometry of a fission reactor.

The physics demonstration for the plasma that we've used in the reference design will occur with successful operation of a machine called MFTF, the Mirror Fusion Test Facility, which is now under construction at Livermore and will begin operation in 1981. Thus the necessary physics demonstration will occur within the next five years and we can consider a technology development phase after that time.

We have constrained ourselves to a minimum extrapolation of the fusion technology which is now being employed in the experimental plasma physics program. We also used fission reactor technology which is now in use in the fission reactor industry, or is the subject of active development. Our design, then, is best described as an early commercial facility.

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Figure 1 is an illustration of classical mirror confinement geometry. We use a Yin-Yang coil which creates a spherical region for plasma confinement *inside of the magnet windings.* In this confinement scheme, energetic plasma continually streams out through the "ends" of the machine, (the two fans on either end of the figure). To compensate for this loss of fuel and energy, the plasma must be continuously supplied with energetic neutral particles. When the injected neutral particles enter the plasma, they are ionized by collisions and trapped in the magnetic field.

It is these plasma constraints around which the reactor must be designed: the spherical geometry, energetic neutral particle injection into the plasma and the streaming of energetic plasma out the ends of the machine.

2.1 Summary

To summarize the reference mirror hybrid design, we list the major design choices that have been made for the reactor.

- Minimum-B mirror confinement
- Yin-Yang coil design, NbTi superconductor
- positive ion injectors with direct recovery
- fast spectrum blanket neutronics
- single-stage plasma direct converter
- cryocondensation vacuum pumping
- blanket
  - U_3Si fuel (depleted U)
  - LiH tritium breeder (natural Li)
  - Inconel 718 structural material
- He primary heat transfer loop (PHTL)
- Prestressed Concrete Reactor Vessel (PCRV)
  - magnet restraint
  - PHTL restraint
  - blanket support and restraint
- steam thermal conversion system

Characteristics for the reactor are listed in Table 1.

half and third energy components in the beam, the average beam energies are 104 and 156 keV, respectively, for D^0 and T^0. Our analysis predicts an *efficiency for the injectors of 60%.*

Outboard of the coils, end tanks must be provided to receive the plasma leakage. In the end tanks, we perform direct conversion, converting some of the kinetic energy of the ion flow directly into electricity. The remaining kinetic energy is deposited as thermal energy in the direct converter electrodes and must be removed by active cooling. Upon strikig the direct converter electrodes, the plasma flow is neutralized and the end tank must contain vacuum pumping equipment to remove the resulting gas load.

To provide access to the blanket from outside the machine, it is a convenient design feature to have one of the end tanks as small as possible. We implement the small end tank by designing the magnet such that one of the mirror fields is 5% stronger than the other. This field perturbation causes approximately 90% of the plasma leakage to flow out through the weak mirror and the remaining 10% to exit through the strong mirror. Since the size of the end tank is proportional to the amount of plasma flow, we can use a small end tank on the strong mirror. To keep this tank as simple as possible, we do not perform any direct conversion but design for the plasma energy to be deposited as thermal energy, with provisions for active cooling and vacuum pumping with cryopanels. The large end tank, which receives the 90% end leakage flow, is designed with a simple single-stage direct converter unit, having an efficiency of about 40%. This end tank must also have provisions for active cooling and vacuum pumping.

2.3 Blanket Nuclear Design

In the past, we have examined the use of primarily three fertile fuels in the blanket: UC, U-Mo alloy and thorium (8). In our present hybrid design we are advocating the use of U_3Si, a fuel being developed in the Canadian nuclear power program for the CANDU reactor. Our reasons for this choice are (1) high uranium density (U_3Si is a metallic alloy), (2) ease of fabricability, and (3) a comparatively high burnup capability (for a metallic fuel), on the order of 3%. Economic optimization of the fuel cycle for this reactor dictates a total fuel exposure of about 6 MW-yr/m^2 of 14 MeV neutron energy through the first wall. In Table 2, the initial (beginning of life) and final (end of life) neutronic parameters for the U_3Si blanket are listed.

accident, and the design therefore had to be one in which the maintenance of forced cooling to the blanket could be assured to a high level of confidence.

The design approach we have selected is to mount the magnet, blanket and *primary heat transfer loop all within a prestressed concrete reactor vessel* (PCRV), of the type developed for gas-cooled fission reactors. This is shown in Figure 3. In the center of the PCRV is the magnet and blanket, and the steam generators and He circulators are located around the periphery. The blanket is a spherical shell inside the magnet. In this way, the blanket and its cooling system are locked together so that no relative motion between them can occur, thus precluding the possibility of rupturing any of the coolant ducts.

The PCRV also serves a second function. It provides the main restraining forces for the magnet. Since the PCRV operates at room temperature, a way had to be found to transmit the forces from the magnet (at 4 ^{0}K) out to the concrete. Our design solution has been to use a high-compressive-strength thermal insulation (Masrock, a silicate refractory), capable of sustaining about 5,000 psi. Our calculations have shown that an insulation thickness of about 50 cm is adequate to reduce the heat leak from the concrete to the magnet to an acceptable level.

The blanket design concept is one which avoids any major disassembly of the reactor during the blanket change operation but instead relies on remote operations to assemble and disassemble the blanket inside the PCRV. The blanket is made up of small cylindrical modules, approximately 50 cm in diameter, with the blanket structure being suspended directly from the inside wall of the PCRV as shown in Figure 4. Removal and replacement of blanket modules is accomplished with refueling machine shown in Figure 5, which consists of a post which is inserted down through the center of the machine and has a pivoting arm to operate on the modules. The maintenance operation consists of a series of manipulations of each of the several hundred modules.

The module, as shown in Figure 6, consists of a cylindrical pressure vessel with a hexagonal base. One of the more challenging aspects of the module design has been to devise a fast, reliable method of making up the seal that isolates the high pressure He coolant from the vacuum region that contains the plasma. We have discarded a welded joint, since remote grinding (i.e., at the first wall) at beginning-of-life of about 230 watts/cm^3 and an end-of-life value of 410 watts/cm^3. The fuel pins are 0.7 cm in diameter with 0.15 mm thick Inconel 718 clad on a pitch-to-diameter ratio of 1.05. The maximum mid-wall clad temperature (hot channel) is limited to 700°C.

5. Future Directions

In the future, we are going to examine hybrid reactors based on new mirror confinement concepts. As was mentioned previously one area of the mirror hybrid design that could be improved is to use a plasma confinement concept that has a higher Q than the classical mirror. Also, the classical mirror geometry is workable but a cylindrical confinement geometry would be more attractive.

One of the reactors which we're going to examine is based on the tandem mirror confinement concept, which is a modification of classical mirror confinement. There is currently a machine under construction at Livermore, called the Tandem Mirror Experiment, which will begin to investigate this type of confinement concept. Our present understanding of tandem mirror confinement is based on theoretical considerations.

There are several reasons that we find this type of reactor attractive. We have developed a low technology (8T magnet, 125 keV injectors) version of this particular confinement concept which exhibits a plasma Q of about 2 and a first wall neutron loading of 3 megawatts per square meter. The results of a preliminary analysis of the reactor are listed on Table 3. It produces a fusion power of 260 megawatts, would have a net electrical output of 500 megawatts, an acceptable recirculating power faction of about 30 percent and, with a U-233 producing blanket, would generate about one tonne of U-233 per year. A schematic of the reactor is shown in Figure 7. The fusioning plasma is located in the central cylindrical volume 27 meters in length, 7 meters in diameter. Plasma confinement is provided in the end regions by classical mirror plasmas, but no fusioning occurs in these "plugs."

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Figure 1

FUSION-FISSION MIRROR HYBRID REACTOR

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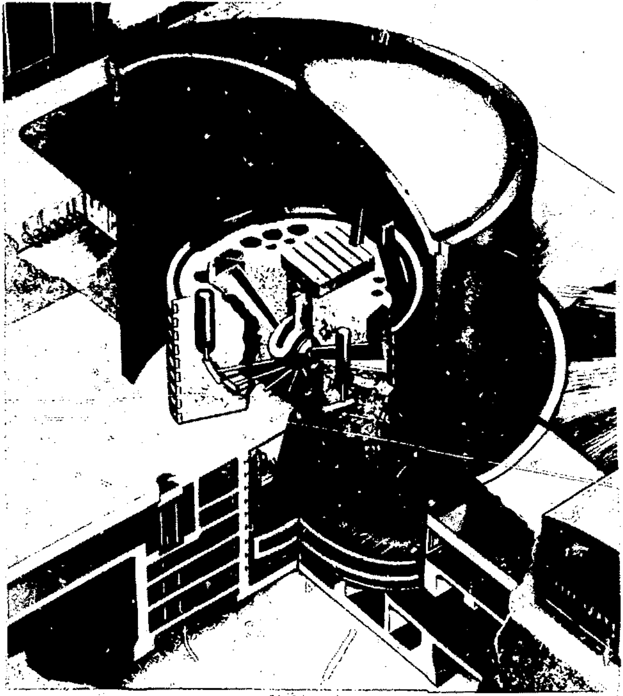
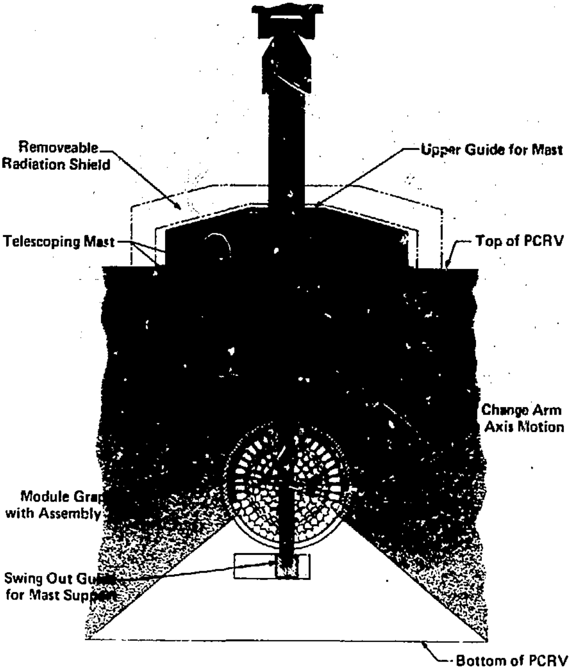


Figure 3

FUSION-FISSION MIRROR HYBRID REACTOR



FUEL MODULE CHANGE TOOL

Figure 5

TANDEM MIRROR HYBRID REACTOR

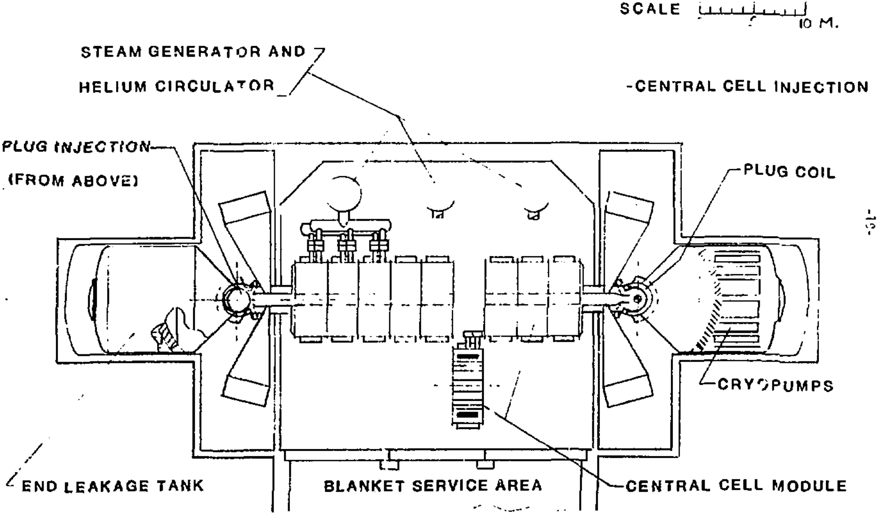


Figure 7

REFERENCE MIRROR HYBRID REACTOR PARAMETERS

TABLE 1

Fusion Power	400 MW
Thermal Power (Avg.)	3350 MW
Injected Neutral Power	625 MW
Net Electric Output Power	600 MW
First Wall 14 MeV Neutron Current	1.7 MW/m^2
Annual Fissile Production	2020 kg
Recirculating Power Fraction	0.65
Q	0.63

2.2 Fusion Core Design

The variation of the basic Yin-Yang magnet, developed for reactor applications, is shown in Figure 2. The magnet has an outside diameter of amout 22 meters, and a distance of 13 meters between mirror points. It is designed with a maximum field at the conductor of 8.5 Telsa, dictated by the use of NbTi superconductor. The maximum current density is about 1000 A/cm^2 in the bundle cross-section and the resulting coil-case pressure is about 2000 psi. These conditions imply comparatively modest magnet technology, although the magnet is quite large, about 3000 tonnes for each magnet half (including the stainless steel coil case).

The injector design developed for the reference hybrid is based on the positive-ion LBL injector. The reactor requires deuterium injectors with acceleration to 125 keV and tritium to 188 keV. When account is taken of the

TIME-DEPENDENT U_3Si BLANKET NEUTRONIC PARAMETERS
TABLE 2

Exposure (MW-yr/m^2)	M	Pu/n	% PU	Burnup %	T/n
0	9.1	1.85	0	0	0.99
6.6	16.2	1.65	2.4	1.0	1.35

In this design we are examining a new approach to tritium breeding, that of holding up all of the bred T_2 in the blanket and recovering it by processing the T_2 pins outside the reactor, in much the same manner as is done to recover the bred fissile material. This scheme has the disadvantages of a large blanket inventory and a large inventory to start the reactor, but the inherent simplicty (which implies good safety characteristics) makes this design option worthy of examination. We are presently considering LiH + Li as a candidate breeding material. With the He coolant temperatures being used in the hybrid (280°C in, 530°C out) this material will have a reasonably low T_2 vapor pressure. By encapsulating this material in pins with a cladding that is a modestly good T_2 diffusion barrier (an Al alloy) we hope to maintain the release rate of T_2 to the coolant below 10 curies/day. The tritium will then be recovered at the end of the blanket life, when the blanket segments are removed from the reactor. Recovery is accomplished by removing the pins from the disassembled blanket and heating them to a high enough temperature in an oven to drive off the T_2. This is basically the procedure that is presently used for T_2 production in fission reactors. The average of the tritium breeding ratios (T/n) quoted in Table 2 is greater than one to compensate for 14 MeV neutrons lost through holes in the blanket and decay of the tritium inventory.

3. Mechanical Design

One of our primary concerns in the mechanical design of the reactor was to provide highly reliable support and containment of the blanket and primary heat transfer loop components. The basis of our concern was the conclusion that the primary safety consideration for the reactor was a loss of flow and welding are time consuming operations and we have serious doubts about the ability to consistently generate remote vacuum-tight welds. We hve therefore adopted a bolted joint using a double knife-edge (Varian type) seal with differential pumping between the two knife-edges. The pressure vessel is bolted in place with 6 bolts, one at each corner of the hex-shaped base. The internals of the module are fabricated as a single unit, containing the U_3Si pins, the tritium breeding pins and internal flow ducting. Thus, to renew a module the pressure vessel is unbolted and removed, the pin assembly is removed, a new pin assembly is inserted and a new pressure vessel is bolted in place. The coolant flow is re-entrant, with the tritium pins being cooled by the inlet flow and the coolant then proceeding down to the first wall, turning, and cooling the uranium pins on its exit path out through the module.

4. Power Conversion Loop

The primary heat transfer loop is designed to operate with helium as the working fluid. The coolant pressure is 60 atm., with an inlet temperature to the blanket of 280°C and an outlet temperature of 530°C. The flow path is designed to maintain the relative pressure drop, $\Delta p/p$, to about 3% through the entire loop (blanket, ducting and steam generator). This combination of conditions permits the use of existing gas-cooled fission reactor technology for the design of the He circulators and steam generators.

The local blanket multiplication and therefore local blanket power density increases by about a factor of almost two over the life of the fuel (See Table 2). By devising an appropriate fuel management scheme for the blanket, we are able to limit the peak-to-average variation in the total blanket thermal power to about 7% (3350 MW average; 3600 MW peak) and the primary heat transfer and power conversion loop capacity are designed to accommodate this power variation. The blanket modules are grouped into four quadrants and at time intervals of one quarter of the blanket life, the reactor is shut down and one quadrant of the blanket is refurbished with new fuel assemblies. In this way we are able to establish an equilibrium fuel cycle where the four quadrants are each at a differenct exposure.

The thermal-hydraulic design for the fuel, on the other hand, must provide adequate cooling of the fuel pins during the lifetime power density variation of 16.2/9.1 = 1.8. Our present design specifies a peak fuel power density

PARAMETERS OF A TANDEM MIRROR HYBRID REACTOR

TABLE 3

Fissile-Fuel-Breeding Central Cell:
Cylindrical shape length = 27 m
outside Radius = 3.5 m
Magnetic field strength = 3 T
Neutal beam injection of D & T = 1070 A @ 125 keV
First Wall Neutron Loading = 2.8 MW/m^2
Fusion power = 260 MW
Blanket thermal power = 1700 MW

End Plugs:
Spherical shape outside coil radius = 2.0 m
Magnetic field strength = 8 T
Neutral beam injection of D into each plug = 42 A @ 125 keV

Performance:
Overall plasma Q = 1.8
Recirculating power fraction = 0.29
Net electrical output = 500 MWe
Annual fissile production = 1000 kg ^{233}U

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MAGNET CONDUCTOR CONFIGURATION

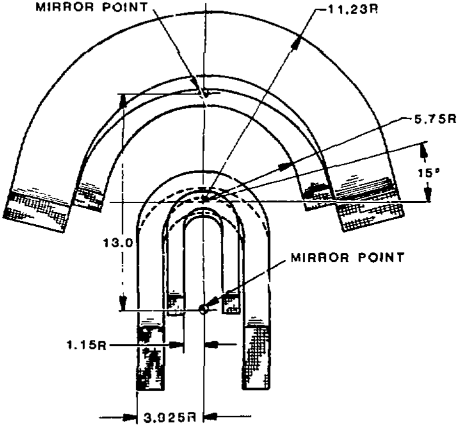


Figure 2

BLANKET/SHIELD CUTAWAY-HYBRID REACTOR

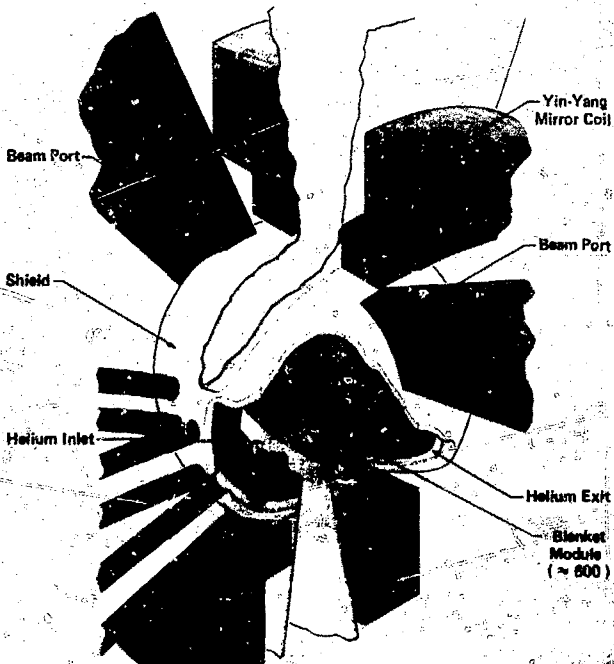
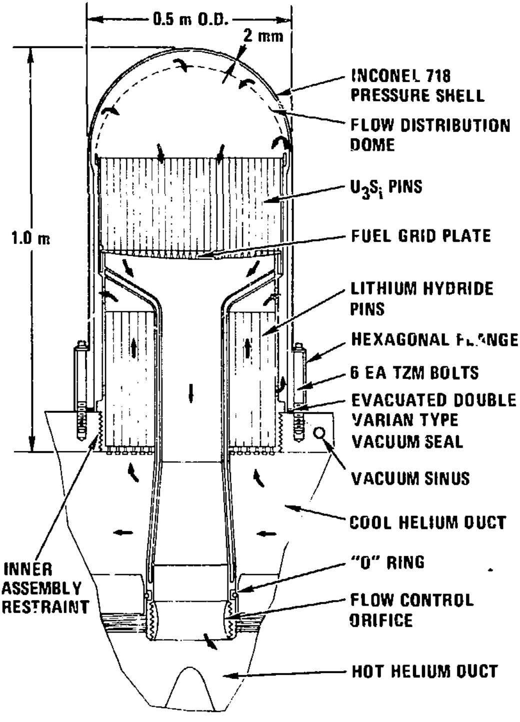


Figure 4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2 mm
1.0 m
INCONEL 718 PRESSURE SHELL
FLOW DISTRIBUTION DOME
U_3Si PINS
FUEL GRID PLATE
LITHIUM HYDRIDE PINS
HEXAGONAL FLANGE
6 EA TZM BOLTS
EVACUATED DOUBLE VARIAN TYPE VACUUM SEAL
VACUUM SINUS
COOL HELIUM DUCT
"O" RING
FLOW CONTROL ORIFICE
HOT HELIUM DUCT
INNER ASSEMBLY RESTRAINT

Figure 6