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Mechanical Design of a Magnetic Fusion Production Reactor[1]

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The mechanical aspects of tandem mirror and tokamak concepts for the tritium production mission are compared and a proposed breeding blanket configuration for each type of reactor is presented in detail, along with a design outline of the complete fusion reactor system. In both cases, the reactor design is developed sufficiently to permit preliminary cost estimates of all components. A qualitative comparison is drawn between both concepts from the view of mechanical design and serviceability, and suggestions are made for technology proof tests on unique mechanical features. Detailed cost breakdowns indicate less than 10% difference in the overall costs of the two reactors.

KEY WORDS: magnetic fusion production reactor; tritium production; fusion breeder.

1. GENERAL DESCRIPTION OF TWO FUSION PRODUCTION REACTOR DESIGNS

Two distinctly different and competitive reactor designs are presented in this report. The tandem mirror reactor employs open-field line geometry for plasma confinement, while the tokamak is a closed-field line torus. A fusion power of 400 MW was chosen for the tandem mirror. For comparison, a 450-MW tokamak design was chosen from a family of TORFA reactor concepts being studied at the FED Design Center at Oak Ridge, Tennessee. Figure 1 shows, to the same scale, the two reactor concepts. Important design parameters for both reactors are given in Table I.

One especially significant difference between the two reactors—their use of magnets—should be emphasized. The tandem mirror, with one exception, uses superconducting magnets for its magnetic fields. A copper insert forms the inner section of the first barrier coil at each end of the reactor. Together, these two inserts consume about 20 MW of power.

This particular tokamak (TORFA) design uses normal copper magnets for most of its coils. The magnet power consumed is estimated to be 240 MW. Because two poloidal field coils are to be superconducting, a cryogenic plant will still be required.

Locating the poloidal field (PF) coils outside the outer leg of the toroidal field (TF) coils greatly simplifies reactor and blanket assembly and servicing operations. Their greater distance from the plasma calls for large circulating current. Rather than pay the price of large resistive power loss, it was deemed better to use a superconductor for those two coils only.

The bred product can be extracted from the tandem mirror by a service machine traveling in a gallery beneath the central cell. New breeding slugs are provided by a similar machine moving in the

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[1] This paper represents work carried out from 1980 to 1982 and was in draft form in 1982. It was received for publication with only minor editing of its 1982 version, explaining the fact that some of the material is dated.

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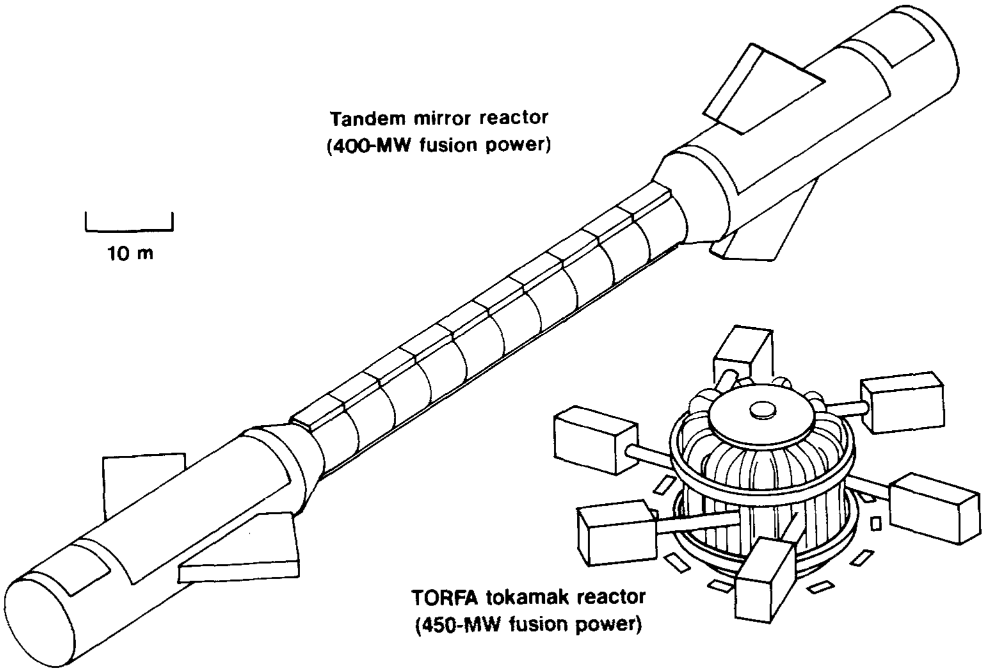

Fig. 1. Comparative geometry of tandem mirror and tokamak (TORFA-D2) reactors (shown to the same scale).

unobstructed space above the modules of the central cell.

The tokamak reactor has six neutral beam lines surrounding the torus. Bred product can be extracted by dropping a service machine into position between a pair of TF field coils. One neutral beam source will have to be decoupled and parked to allow the service machine access to any segment of the breeding blanket. Movement between blanket segments will require crane operation on the service machine. Bred product is discharged by the servicing machine through a floor "chute" to a conveyor belt under the reactor.

1.1. Scope of Paper

We have addressed the technical issues that will ultimately determine whether fusion reactors are a

Table I. Reactor Parameters

Tandem mirror		Tokamak (TORFA-D2)	
Plasma radius in central cell (m)	0.46	Plasma major radius (m)	3.9
First-wall radius (m)	0.67	Plasma minor radius (ellipse-like)	
Magnetic field in central cell (T)	4.0	Half-height (m)	1.5
Fusion power (MW)	400	Half-width (m)	1.0
Length of central cell (m)	50	Toroidal field strength at plasma centerline (T)	5.0
		Fusion power (MW)	450
Plasma $Q = \frac{\text{Fusion power}}{\text{Injected power}}$	~10	Plasma $Q = \frac{\text{Fusion power}}{\text{Injected power}}$	3.0
(first-wall neutron loading)	1.0	Blanket energy multiplication	1.5
Blanket energy multiplication	1.35	Power to drive toroidal field coils (MW)	200
Barrier-cell length (m)	7.0	Power to drive poloidal field coils (MW)	40
Maximum field at barrier (T)	24	Overall diameter of reactor (m)	36
Barrier-field power requirement (MW)	~ 20		
Quadrupole anchor field (T)	2.3		
Overall reactor length (m)	115		

viable option for the production of critical weapon-grade material. Two of the most important approaches to fusion reactor design—tandem mirrors and tokamaks—are examined and compared to determine if a clear choice can be made at this time.

The issues discussed here are related to blanket engineering and cost. We assume that the physics to be demonstrated in the MFTF-B tandem mirror at Livermore, TFTR at Princeton, JET at Culham, and Big-Dee at General Atomic will prove satisfactory for the plasma containment quality specified herein.

A blanket design that permits plutonium or tritium production by a flow-through process is proposed. Whether the flow of material is by batch or continuous depends on the design details of the remote fueling machines. This design employs the less-costly batch process. The same blanket design can be used for a continuous-flow process.

1.2. Purpose of Breeding-Blanket Design

The design of the cold-water-cooled blanket was instigated in recognition of two important situations. First, the equipment used by the United States to manufacture nuclear-weapon-grade plutonium and tritium for weapon applications uses a similar low-temperature breeding system. Second, the technology of fusion-power reactors has reached significant milestones in areas other than blankets.

The operation of large superconducting magnet systems has been convincingly demonstrated. Neutral beam injection has, for brief periods, augmented plasma operation to the temperature required for sustained reactor operation. Steady operation of these high-voltage injectors at high power remains to be demonstrated. Current progress suggests that continuous operation will be achieved within 5 years.

For tandem mirror reactors, the technology of directly converting the power of end-loss ions to electricity has been demonstrated in laboratory scale experiments.

The largest tandem mirror experimental reactor is MFTF-B at Livermore. Figure 2 compares the tandem mirror production reactor to MFTF-B to show that current experimental hardware is as large as the facility proposed here, although the central cell is not as long.

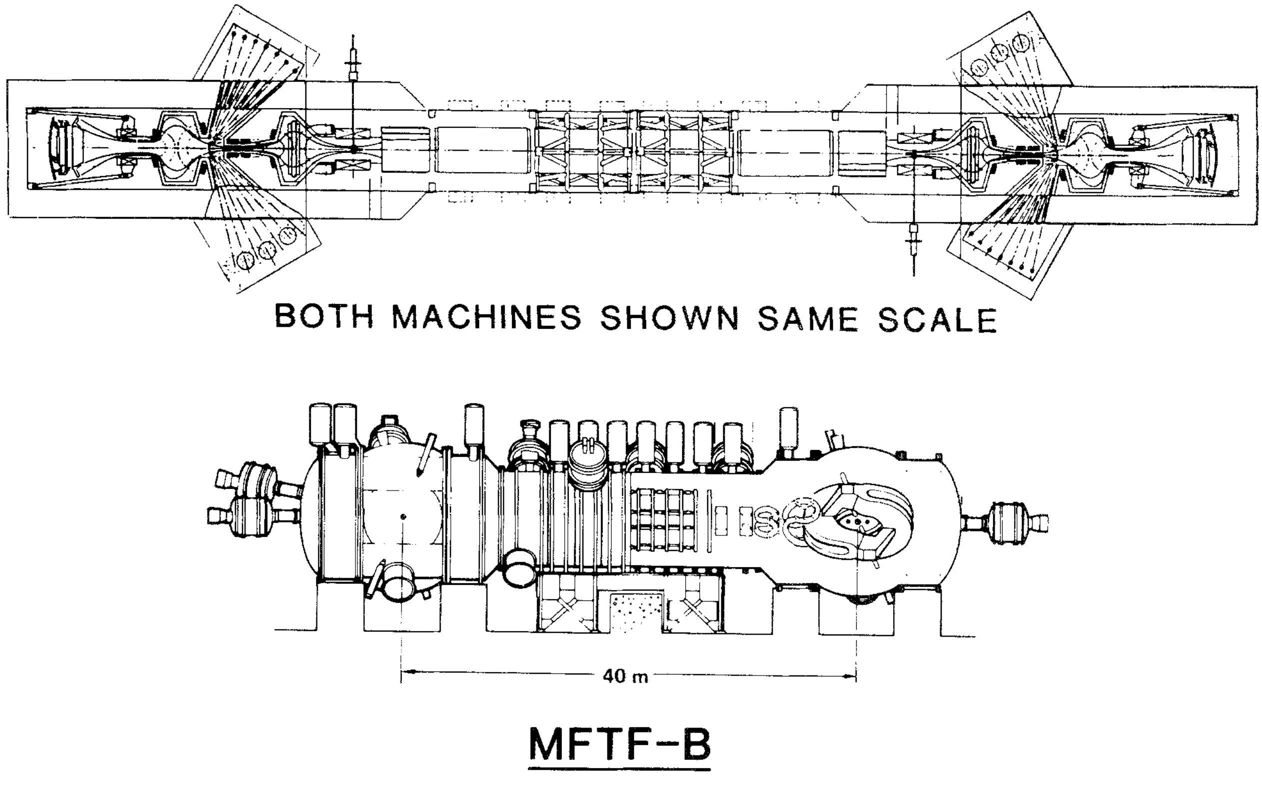

Fig. 2. Comparative size of the tandem mirror reactor and the MFTF-B.

In a parallel achievement, the tokamak reactor has demonstrated the ability of a poloidal divertor to maintain the clean vacuum environment required for deuterium–tritium (D–T) plasma.

The cold-water-cooled blanket design shows that the low-temperature coolant system employed for the past several decades in weapon-grade material production can be applied directly to a fusion driver. We believe that blanket technology needs no further development for this application.

2. TANDEM MIRROR PRODUCTION REACTOR WITH COLD-WATER-COOLED BLANKET

2.1. Blanket Configuration

For the production of tritium, our first blanket design stays close to the low-temperature technology currently employed in Savannah River fission breeders. A tandem mirror fusion reactor is proposed, with an end-plug design following current axicell Livermore physics. The blanket of such a reactor is confined to the cylindrical central cell, which for this application is 50 m long. Four hundred megawatts of fusion power is generated in that central cell. The blanket, having no high-temperature coolants, will produce no electricity.

The accepted practice is to subdivide tandem mirror blankets into short cylindrical modules that can be easily fabricated near the reactor and that can be installed or replaced by remote servicing tools. The final choice of module length will be made after a cost study. We chose a length of 2 m because previous studies have shown that modules of much more than 2 m in length are quite heavy and present transportation problems. However, the length chosen has negligible impact on the details of the blanket design.

Our philosophy is to design a system that allows us to add to or remove breeding material from the blanket without removing the central-cell modules. We have a design that permits batch replacement of breeding material. The reactor must be shut down to allow cooling water interruption in the desired modules. Access for fuel change depends on opening the coolant circuit. The fuel-change machinery required for this batch processing provides for multiple channel changeout simultaneously.

We recognize the advantages of replacing breeding material without reactor shutdown. To accomplish this, one must maintain the coolant flow to the region where material exchange is occurring, which would require a much more complex and costly fuel-change machine. Instead, we have elected to postpone our detailed analysis of such a method to a possible continuation of this study. The blanket configuration would not be fundamentally altered, just the mechanical and hydraulic details of the entrance and exit ports.

2.1.1. Tritium Breeding Slugs

Tritium breeding is accomplished in the same lithium–aluminum (Li–Al) alloy currently used for that purpose at Savannah River. A thin aluminum capsule is deep drawn so it can be closed by welds at one end only. The shell, along with the slug end cap, serves as a permeation barrier to prevent tritium from leaving the Li–Al alloy where it is born. Aluminum at low temperature is a very effective permeation barrier. Contamination of the cooling water with tritium can be virtually eliminated by employing this aluminum jacket. Figure 3 shows the fuel-slug assembly. (The purpose of the small on-axis hole will be discussed later.) The simple fuel slug—basically a cylinder with a hole in the center—can be dropped into the aluminum capsule. Next, the end cover is welded on, using electron beams on both the outer and inner weld rings.

Should one wish to breed plutonium in this blanket, the same design can be employed. A depleted uranium "slug" would replace the Li–Al alloy. The same aluminum protective jacket could be used so that the frictional properties of the string in the tube would not be changed. Of course, both types of breeding slugs could be on one chain.

The radii at the end of the slug are used to permit close stacking in a conduit. The hole in the center of each slug allows the slugs to be strung on a small cable, like pearls on a string. At this string is pulled through the curved channel, the slugs must move angularly with respect to adjacent slugs in order to negotiate the turns. The convex nose and concave tail provide for efficient use of the volume of this conduit.

It is also possible that a pull cable is unnecessary. Fuel slugs without the center hole may be pushed through the guide tubes. Our concern with that design is the greater likelihood of cocking and jamming of one or more slugs in some remote part of a guide tube. Simple engineering tests will help us

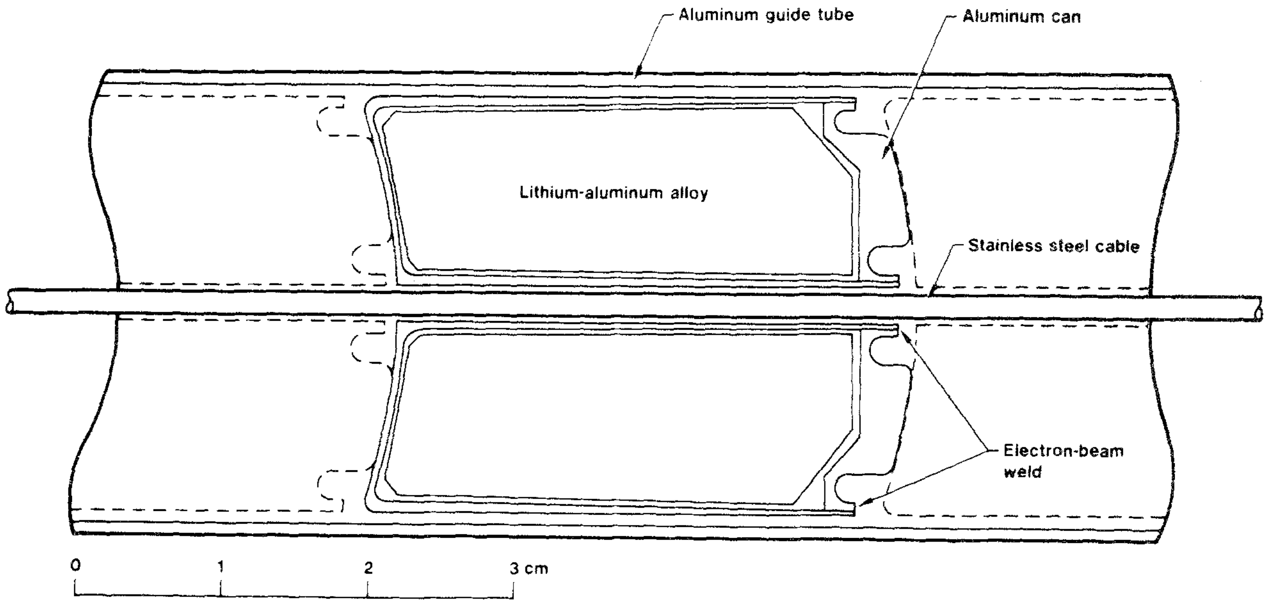

Fig. 3. Tritium breeding slug.

- Water cooling (< 100°C)
- *Aluminum structures*
- Li Al breeding material
- Beryllium neutron multiplier

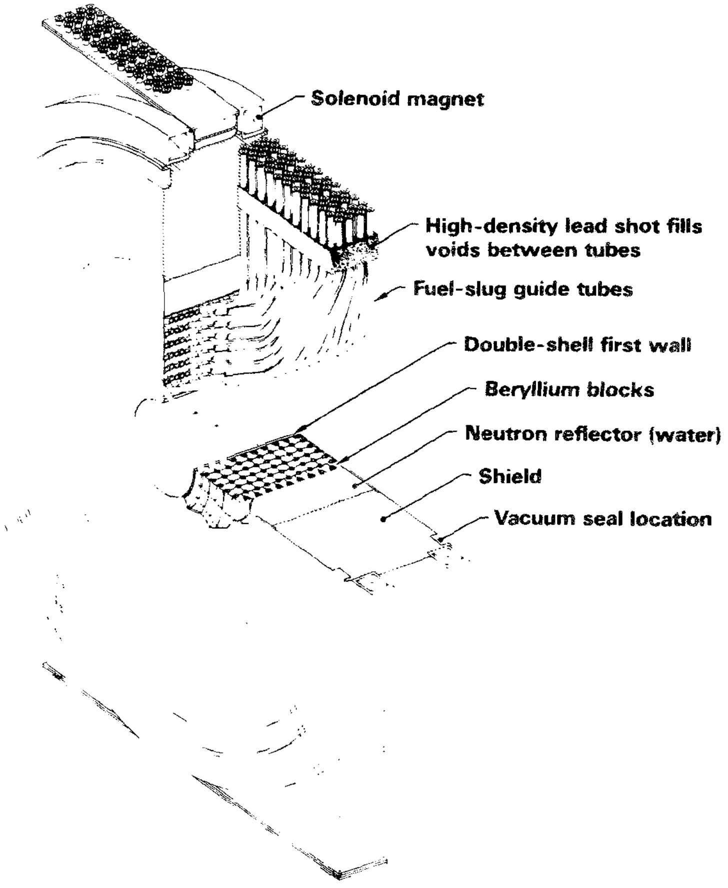

Fig. 4. Cross section of breeding blanket for tandem mirror production reactor.

select the optimum slug configuration and means of locomotion.

Nominally, there will be a 2-mm-diameter clearance between the outside of the fuel slug and the inside wall of the guiding conduit.

Aluminum tubes will guide the strings of Li–Al fuel slugs through the body of the blanket. These conduits will be spaced on 10-cm × 10-cm grid centers. Figures 4 and 5 show perpendicular cross-sectional views of the blanket internals. Notice that fuel slugs enter the reactor at the top, move around the curve of the first wall, and exit the reactor at the bottom. Left- and right-hand groups of conduits interlace at the crossover regions, like the fingers of folded hands. These conduits are spaced on about 10-cm centerline spacing. The radial spacing may be further optimized to allow for decreasing neutron penetration at the larger radii. That optimization will require three-dimensional neutronics analysis.

The optimum length of the breeding slug relative to its diameter is not clear at this time. The maximum angle one slug can assume relative to its neighboring slugs is Δ/L, where Δ is the diametrical clearance (cable hole to cable) and L is the slug

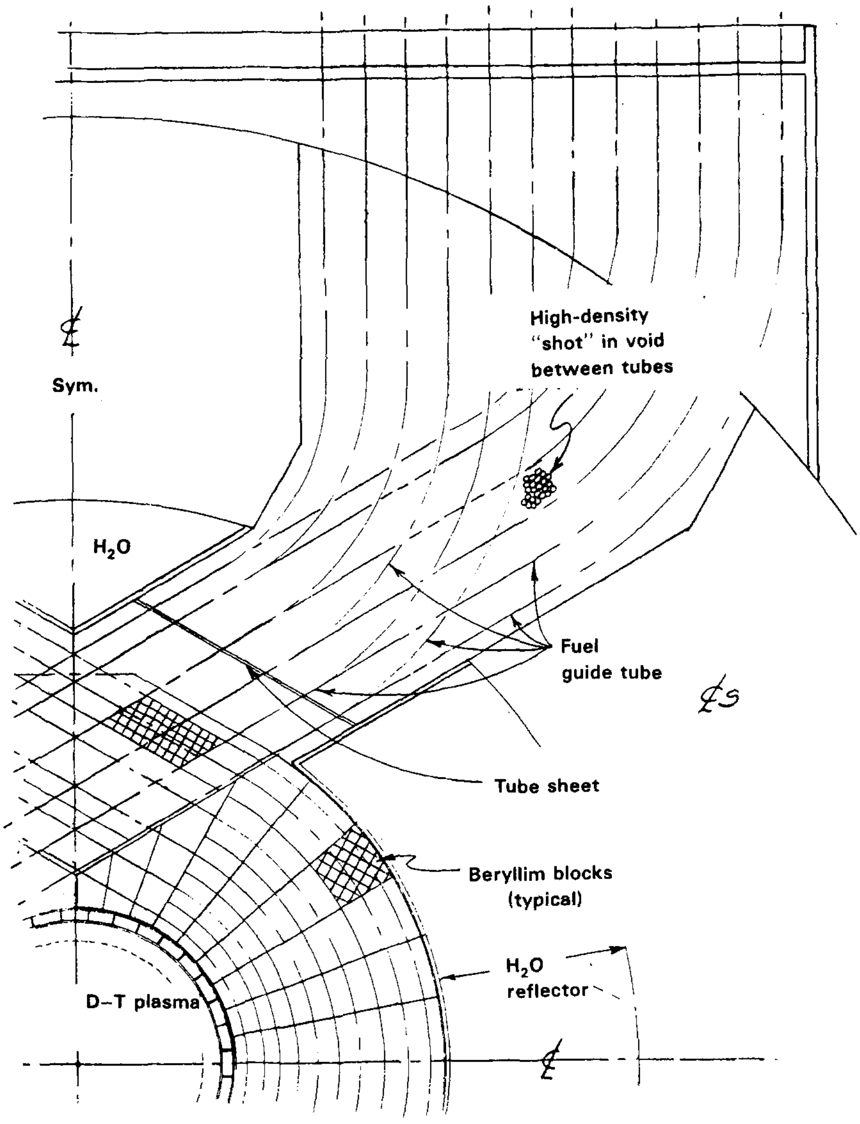

Fig. 5. Perpendicular cross-section view of blanket internals.

length. Both parameters can be very small, which implies close tolerances and a very large number of slugs and, hence, a high manufacturing cost.

If L is large, the inside diameter of the guide tube must be large to provide clearance for the ends of the slug as it negotiates a tube bend. That implies too much void space in the blanket and a costly sacrifice in breeding efficiency. The voids could be occupied with either neutron multiplier or more breeding material.

We believe the optimum lies close to a design where length, diameter, and spherical end radius are all equal.

Entering this complex relationship is the cable diameter, which we would like to be as small as possible, consistent with the strength needed to pull the chain of slugs around the several bends. The clearance between the cable and slug should also be small so as to not waste breeding volume.

Experiments with the frictional aspects of this design will allow slug length, cable diameter, cable-hole clearance, and guide-tube inside diameter to be selected.

2.1.2. Neutron Multiplier

The space between conduits must be occupied by a good neutron multiplier. Beryllium is the logical choice. Experience at the Advanced Test Reactor (ATR) at Idaho Falls has shown that, at low-water temperature, the corrosion of beryllium is very slow —about 0.006 in/year at 100°C. Workers at ATR have operated unprotected beryllium reflectors around their reactor core for about 5 years. Replacement was the result of crack development thought to be due to helium gas formation within the beryllium.

Our configuration, shown in Fig. 6, consists of a large number of small blocks, rather than the massive pieces used in the ATR reflector. We do not anticipate serious cracking because the dimensions of our blocks are about 10 cm maximum. Should cracks develop or spallation occur, the blanket can continue to function. The migration of a large quantity of small "chips" from the blocks must be prevented by the filters protecting the coolant pumps.

The surface area of our small-block neutron-multiplier matrix is quite large. If we experienced corrosion of 0.006 in/year, 1600 kg/year of beryllium would disappear from the blanket! Although that is a small percentage of overall blanket volume (0.45%), we do not know where in the cooling system it would redeposit. It seems prudent to inhibit corrosion to reduce potential mass transport. The least objectionable coating material from the standpoint of neutronics considerations is aluminum. We recommend a light film of aluminum; about 0.005 in or less will satisfactorily arrest beryllium corrosion and be present as only 0.35% of the blanket's volume.

The geometry of the blanket permits several beryllium block shapes to be duplicated many times. Even so, there are about 100 conduits/m, and many different block shapes will be required to fill all the space between conduits. These beryllium blocks will require cooling and will have several surface grooves to allow water flow in the circumferential direction, i.e., parallel to the conduits.

Notice that each central cell module contains two solenoid magnets. Those magnet coils are mounted outboard of the tube-loading region to permit easy assembly. If the magnet coil were in the center of the module, it would have to be wound directly on the module since it would be trapped by those features of the structure related to conduit access and fuel change.

The presence of the magnet coils and associated shielding creates an access problem. The breeding-material conduits directly below the coils must be routed toward the center of the module as they enter and leave the module. Bending such conduit shapes is not a problem. However, the warpage of conduit toward the center of the module should be confined to a radial location outside the tube-crossover region. The space just behind the breeding zone is a water reflector to improve breeding. That space between the conduits is simply filled with water. No complex beryllium parts are needed to accommodate out-of-plane conduit curvature.

As the conduits exit through the shield, a large void is left in the shield to accommodate them. This void must be filled to control neutron leakage and the resultant heating of the superconducting solenoids. We propose filling that space with lead shot and/or steel shot in appropriate combination. The space would be filled by pouring in shot so no complex parts have to be manufactured. The conduits themselves are also a neutron leakage path. If the portion of the breeding slug chain that is in the shield space had "dummy" slugs made of heavy metal, they would effectively block neutrons and could easily be separated from the breeding slugs after extraction of the string.

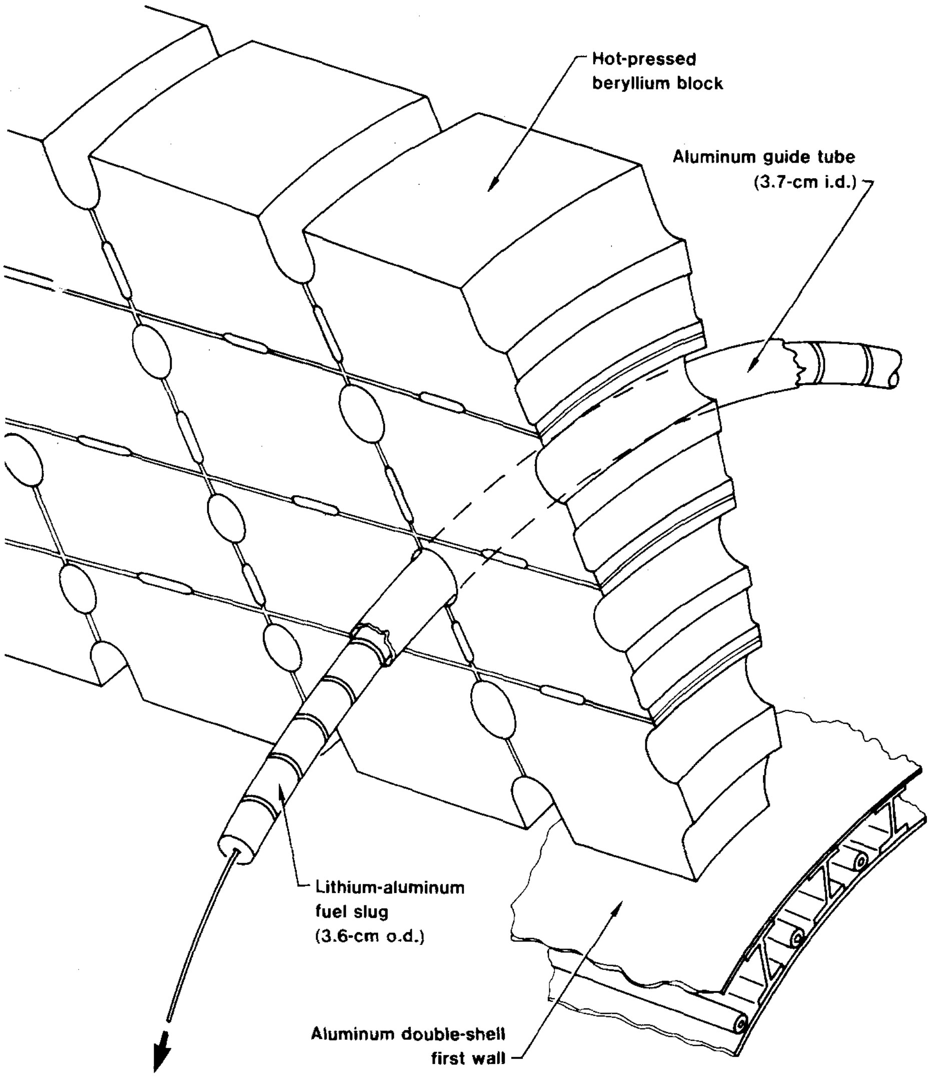

Fig. 6. Proposed production blanket, showing internal details.

2.1.3. Cooling the Low-Temperature Blanket

2.1.3.1. First-Wall Cooling. The energy deposition in the first wall is estimated to be 10.6 $W \cdot cm^{-3}$, which is 4% of the neutron energy incident on that wall. Figure 7 shows a typical cross section of the first wall, with two concentric shells spaced apart by I-beam-shaped stringers. Two cooling tubes are needed between each pair of stringers. They limit the thermal gradient in the aluminum shell to about 35°C from the "hot spot" most remote from the coolant to the inside surface of the water tubes.

The coolant flow rate was chosen to limit the water temperature to 85°C at the first wall and blanket exit. The drop in film temperature is estimated at 10 °C. This leads to a hot-spot temperature of 130 °C. The yield point of 7075-T6 aluminum is 50,000 psi at that temperature.

If the cooling tubes are 1 cm in diameter, the pressure drop along a 2-m-long run of tube is less than 1 psi for the necessary coolant flow rate of 1020 $cm^2 \cdot s^{-1}$ for the complete first wall. The coolant is supplied by radial flow tubes incorporated in the blanket end plates. This radial flow enters a ring manifold that serves to close one end of the first-wall annulus. The first-wall coolant tubes are fed from that ring manifold. An identical ring manifold at the other end of the blanket module serves as a coolant

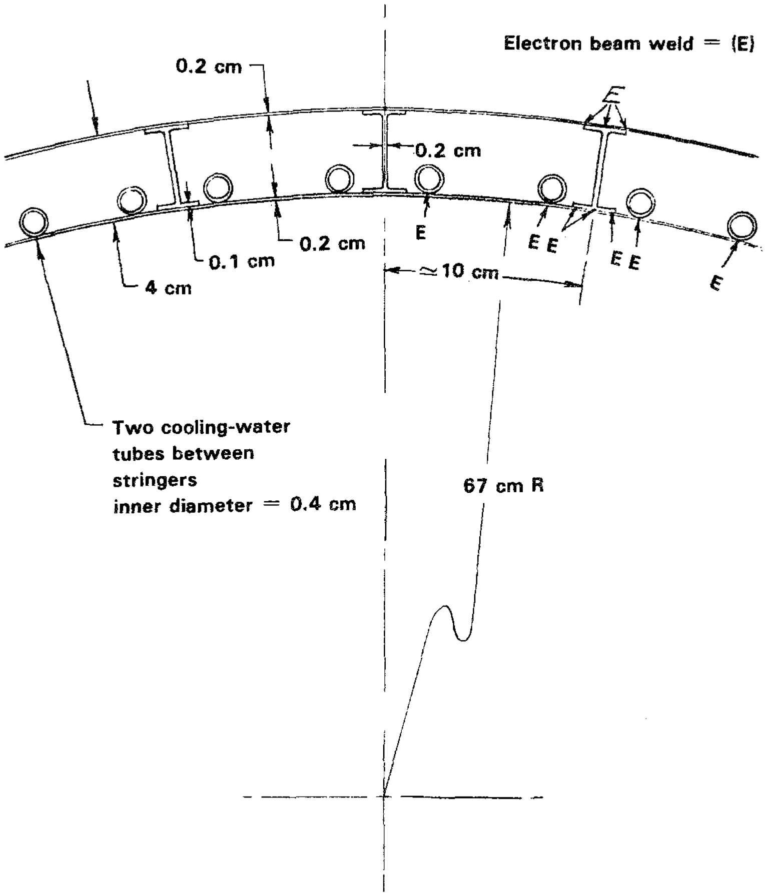

Fig. 7. Production tandem mirror reactor, showing first-wall aluminum structure.

collector. Radial flow in the end plate returns the water to the main coolant-return pipe.

2.1.3.2. Blanket Cooling. The blanket absorbs 6.1 MW of neutron energy for every meter of its length. The blanket energy-multiplication factor (M) is 1.35, so we must remove 8.24 MW of heat from every meter of blanket length.

Coolant flow is from the top to the bottom of the module. Flow enters both the fuel guide tubes and surrounding neutron-multiplier region. The two parallel flow paths are not totally separated. Holes in the walls of the guide tubes allow communication between coolant paths, which eliminates any possibility of a guide tube becoming obstructed and preventing "downstream" slugs from receiving coolant flow.

Hence, we have coolant flow in and around the neutron multipler and flow in the annular space between the fuel slugs and the guide-tube walls. For a 2-m-long blanket module, the total flow rate required is $56.31 \cdot s^{-1}$. The Reynolds number is about 18,000, which ensures turbulent flow. The pressure drop from the top coolant inlet (where the tube bundle emerges from the blanket) to the bottom coolant exit (where the lower end of the tubes emerge from the blanket) is calculated to be 19 psi at that flow rate. With other pressure drops in a closed-loop system taken into account, especially that of the tube side of a shell and tube heat-exchanger, the pump delivery pressure can be estimated at 40 psi. The pump can be just ahead of the heat-exchanger to keep the blanket water pressure as low as possible. The external pressure on the cylindrical first wall will not exceed 30 psi.

Calculation of the critical buckling pressure for our double-shell first-wall design shows that, at 130 °C with the yield point at 50,000 psi, the critical pressure exceeds 550 psi—a generous margin of safety. Indeed, it is apparent that optimization of the first-wall design to give a smaller safety factor would improve blanket breeding. The gain would be small since only 4% of the neutrons give up their energy to the first wall. For now we will settle for a very conservative first-wall design.

2.1.3.3. Beryllium Block Temperature. The thermal conductivity of beryllium is 2 W·cm K. The blocks can be approximated by a short cylinder of equivalent volume to help analyze the temperature differential within the beryllium.

A cylinder of radius R, with a uniformly distributed heat source and constant thermal conductivity, has a center-to-surface temperature difference expressed by

$$T_0 - T_w = 9R^2/4k$$

where q is volumetric heat deposition.

Our neutrons deposit about 7 $\mathrm{W \cdot cm^{-3}}$ in the beryllium. The resulting temperature difference is 44 °C. Since our wall temperature should not exceed 90 °C, the "hot spot" is only 134 °C, not a concern for corrosion.

2.1.3.4. Lithium–Aluminum Breeding-Slug Temperature. The energy deposition in the tritium breeding slugs is about 20 times the average blanket power density of 5 $\mathrm{W \cdot cm^{-3}}$. The radius of a slug is 1.8 cm, and the conductivity is 2.2 $\mathrm{W \cdot cm^{-1}\ K^{-1}}$. Therefore, the core temperature of a slug whose surface is at 90°C is only 127°C. There will be some additional difference in temperature because of the interface at the slug jacket. The jacket must have the equivalent of a light press fit over the Li–Al core to minimize that temperature differential.

2.1.4. First-Wall Design

The first wall of the reactor is an annular, hollow structure cooled by water-cooling tubes that run axially and are spaced about 4 cm apart.

The first wall is attached, at its two ends, to the end plates of the blanket module. The water that cools the blanket is slightly pressurized; this pressure is exerted on the outside of the first-wall assembly. Because a classical cylinder-collapse condition exists, our analysis tests the planned design for structural stability under such loading.

The major components of the blanket are made of aluminum because of the low temperature. We plan to change the water temperature from 25 to 85°C to extract energy deposited in the blanket.

To increase the buckling stiffness of the shell, the effective moment of inertia of the shell had to be increased. Neutronics considerations call for minimization of mass in the first wall. We have tried to limit the actual metal thickness to about 0.5–0.6 cm of aluminum.

Another advantage of this concentric wall construction is the redundancy provided. The wall facing the plasma can develop minor cracks or other flaws with no immediate effect on the plasma. The space between the concentric aluminum cylinders is also evacuated. A separate vacuum pump will be used for that annular space to ensure that a coolant leak will not ruin the plasma vacuum.

The inner cylinder, adjacent to the plasma, can suffer arcing damage or neutron-induced embrittlement leading to cracks without developing a vacuum leak and resulting plasma quench. Cooling-water tubes on the back of the cylinder, rather than on the front, give added assurance that the coolant tubes will not be damaged by arcs.

2.1.4.1. Buckling of First Wall. As a reference for cylinder collapse calculations, we have used the work of A. Blake at Lawrence Livermore National Laboratory. Important parameters are:

1. Wall thickness
2. Length of cylinder between stiffeners
3. Mean radius
4. Radial amount of out-of-roundness
5. Modules of elasticity
6. Yield strength

For neutronics reasons, the wall thickness should be 0.5–0.6 cm. The module can be 1–2 m in length; because some advantages accrue to larger modules, we chose a length of 2 m. It is readily shown that a single-thickness (i.e., a one-piece) cylinder meeting these criteria cannot sustain significant external cooling pressure. Additional wall stiffness, with no added material, is required.

We chose to use two concentric shells, each 0.08 in thick, spaced apart by I-beam-shaped stringers that can be welded to the cylinders by electron-beam methods, thereby increasing the effective thickness of the shells by increasing their stiffness. Our method was to calculate the moment of inertia of a segment of the double cylinder, including the contribution by the stringer spaces. A second calculation yields the single-thickness shell, which would produce the same moment of enertia. That thickness is then used in Blake's formulas for cylinder collapse to check the critical buckling pressure. If that pressure is sufficiently higher than the hydraulic pressure needed for adequate blanket coolant flow, a solution has been reached.

The wall design shown in Fig. 7 will have a critical buckling pressure of 559 psi if constructed of 7075-T6 aluminum sheet with a yield point of 50,000 psi. This compares favorably with the hydraulic pressure of 40 psi shown to be required for water flow through the blanket cooling circuit.

Shell buckling is not the only possible mode of failure. The short arc of the outer cylinder, between the cylinder separators, can fail as a beam with a uniformly distributed load. To evaluate this failure mode, we resorted to finite-element stress analysis, using the NIKE 2D computer code. The results showed lower failure pressure. We conclude that the local "oil-canning" demonstrated by the finite-element technique will be the controlling failure mode.

The finite-element model used for this analysis was composed of two thin sections connected by an I-beam. The I-beam was modeled as being rigidly attached (bonded) to the outer and inner shells. The motion of the segment midplane, represented by the ends of the thin pieces, was confined to radial surfaces that intersect at a line representing the centerline of the reactor's vacuum cylinder (see Fig. 8).

All of the structures was assigned the properties of 7075-T6 aluminum, and pressure was applied uniformly along the outer surface of the upper shell. One code run (using NIKE 2D) was run for each of a series of applied pressures in 5-psi increments. As nonlinear behavior-representing incipient buckling —was observed, the increments were decreased.

We determined the failure pressure by local buckling of the outer shell to be only 40 psi. This failure is similar to "oil-can" failures, where sudden large deflections occur at a "critical pressure."

As a second test, we assigned the properties of stainless steel to the shells and stringers. This time failure occurred at an external pressure of 70 psi.

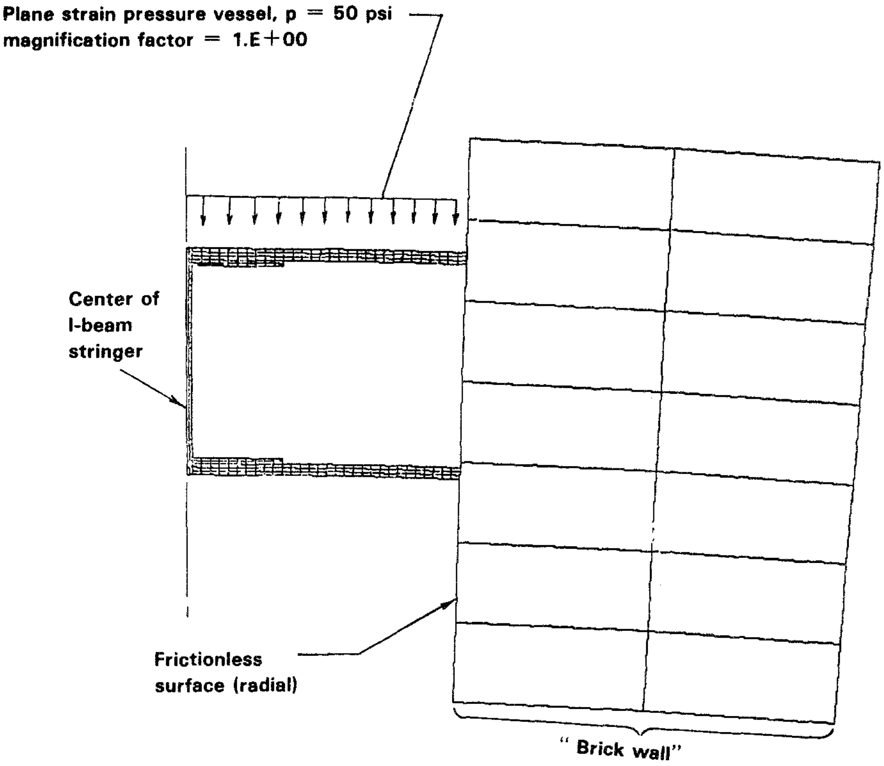

Fig. 8. Tandem mirror first wall, showing finite-element analysis grid and boundaries.

Table II. Volume Fractions of First Wall and Blanket

First wall		Blanket	
Outside radius (cm)	72.0	Outside radius (cm)	112.0
Inside radius (cm)	67.0	Inside radius (cm)	72.0
Volume fraction (%) of		Volume fraction (%) of	
Aluminum	11.0	Aluminum guide tubes	0.8
Cooling water	5.0	Covering on "fuel" pellet	0.9
Internal vacuum	84.0	Li–Al alloy pellet	10.0
		Beryllium	81.0
		Aluminum end plate	3.0
		Cooling water	4.2
		Pellet pull cables (steel)	0.1

Again, the "oil-can" mode of failure was demonstrated.

2.1.5. Volume Fractions of First Wall and Blanket

To evaluate the breeding capability of the low-temperature blanket design, the material fractions in the first wall and blanket must be calculated. A neutronics code can then be used to test blanket performance.

Our design has an aluminum first-wall structure, a double shell with axial stringers to maintain the wall spacing. This design evolved from two considerations. First, we needed a shell capable of withstanding external cooling water pressure. Second, we wanted a structure tolerant of small flaws in the material wall facing the plasma. Figure 7 illustrates the design developed.

The material that intercepts neutrons is about 0.55 cm thick. The double-wall construction leads to an actual thickness of 5.0 cm. The moment of inertia of this hollow wall can be converted to an "effective" wall thickness for external buckling calculations. Section 2.1.4. of this report reviews those calculations. The design-yield first-wall volume fractions are listed in Table II.

The next 40 cm in radius, behind the first wall, is the blanket. It consists of aluminum guide tubes for the breeding material, the breeding slugs within the tubes, the beryllium neutron multiplier surrounding the tubes, and cooling water. Material fractions calculated for that zone are also listed in Table II.

2.1.6. Module Assembly

We believe that the best assembly method will be to construct the module face up on a floor jig. The shield, blanket, and first wall can be assembled in that position. This assembly would be lifted by temporary stub-axles bolted to the shield, rotated 90°, then lowered on and attached to a permanent support cradle.

Coolant plumbing manifolds can be added after the blanket shield is attached to the cradle. At this point, the superconducting solenoid coils can be slipped over each end, shimmed, and locked in place.

The design is only conceptual now, but depends on progressive layers of neutron multiplier and guide tubes starting at the bottom of the blanket annulus. Possible assembly steps are listed below in order of execution:

1. Lay the blanket side-wall plate on the bottom level of the assembly jig.
2. Construct the entire shield around the perimeter of the side-wall plate and weld the plate to the shield.
3. Lower the first-wall subassembly into the center and weld it to the inner edge of the face plate.
4. Lay the first row of beryllium blocks. (The left side of the assembly will differ from the right because of the necessary interlacing of tube rows.)
5. Lay in the first row of guide tubes. Shim to establish alignment with the plenum-chamber position template, using thin aluminum plates and tube collars machined as required.
6. Lay in the second layer of beryllium blocks, followed by the second row of guide tubes. Continue to shim as required for accurate alignment with the plenum-chamber template. Continue this layering until the "top" of the blanket annulus is reached.

7. Weld the "top" side-wall plate on the assembly after inserting the shims so the entire 2-m-thick assembly has less than a 0.5-mm clearance between the block and tube stack and the inside surface of the end-wall plates. Spring washers in that clearance space serve to restrict blanket vibrations excited by hydraulic vortices.

2.2. Fueling Scenario

2.2.1. Installing and Removing Fuel Chains

All conduits open into cooling-water plenum boxes. Each module of the central cell is supplied by one water circuit. One large pipe enters each water plenum above the reactor, and one large pipe leaves each plenum below the reactor. Access to change breeding material is obtained with two automatic machines. One machine above the reactor travels on the gantry crane rails and is positioned over the module to be changed. The second, moving in a gallery below the central cell, positions itself below the desired module. The first task of each machine is to remove the rectangular bolted flange cover of the water plenum it faces. After that cover plate is removed and temporarily stored, the open ends of all fuel conduits are exposed.

The machine above the reactor has been preloaded with reels of breeding slugs, active in the center, dummy at both ends of each string. The top machine attaches its new fuel strings to the exposed top cable ends of the enriched strings. We estimate that about 50 reels of fuel can be changed simultaneously.

The lower machine pulls the enriched strings out of the bottom of the blanket module. While dong so, it pulls the recharge string into the blanket, since the two strings are attached. After winding the correct length of string on its take-up reels, it stops and decouples the old string from the new string just drawn into place. The lower machine then moves to a central discharge door and lowers its enriched fuel strings into a water pool covering a long conveyor belt. This conveyor belt transports radioactive slugs, with 6 m of water cover, to the chemical processing facility designed to harvest and store tritium. Then the machine returns to the module being serviced for the next load of slug strings.

The process is repeated a second time to changeout one blanket module. Reindexing of the two machines will be necessary to permit work on similar, but slightly displaced, tube patterns as the total number of about 100 tubes per module is serviced.

2.2.2. Fueling Machines

To replace the bred material in the blanket, two remotely operated service machines will be needed. The one above the central cell will bring new material to be exposed to fusion neutrons and the one below the central cell will extract material that has reached the desired level of enrichment for chemical processing to other forms.

The top machine will receive newly assembled strings of slugs from racks on the walls of the delivery corridor (see Figs. 9 and 10 for general plant layout). The delivery corridor runs from the reactor containment building to the fuel-preparation facility, a building several hundreds of meters removed. The top machine resides in a parking area at one end of the reactor bay and rolls on the same rails used by a service gantry crane. A small shuttle car transfers fuel strings from the corridor-wall storage shelves to transfer reels (about 50 reels) in the top machine. The reels will be about 2 m in diameter, so one complete 6-m fuel string is held on one reel in a little less than 360° of its circumference. All reels will operate simultaneously while loading the blanket. Once loaded, this top machine can move along the central cell to a position directly over the cell module to be changed.

As described in Section 2.2.1, the first operation required is to remove the cover plate of the cooling-water plenum box. Quick-operating motorized clamps are used to seal that cover so that removal and storage can be accomplished in about 30 min.

The ends of the slug strings of all 50 reels are automatically coupled to the exposed cable ends of the strings currently residing in the blanket. All 50 reels would be powered to pull the blanket slugs onto the storage reels, while simultaneously pulling the new strings into the blanket. The connections to the new strings would then be opened both above and below the reactor. Then, both plenum covers would be restored and leak-tested.

The bottom machine, with its load of radioactive enriched slugs, is then caused to move to a central position in its gallery. A transfer canal terminates directly below the gallery at that location. At the bottom of this canal, under 6 m of water, runs a

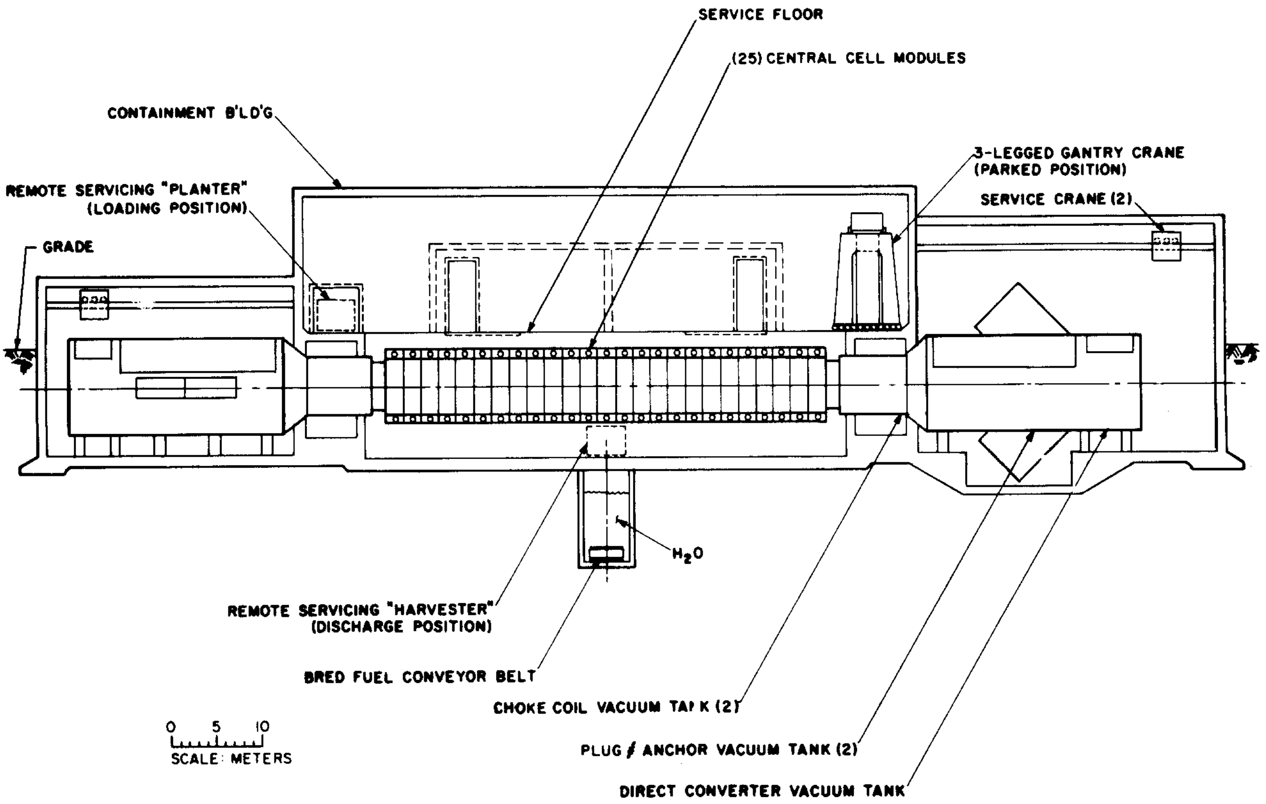

Fig. 9. Elevation view of containment building with production tandem mirror reactor.

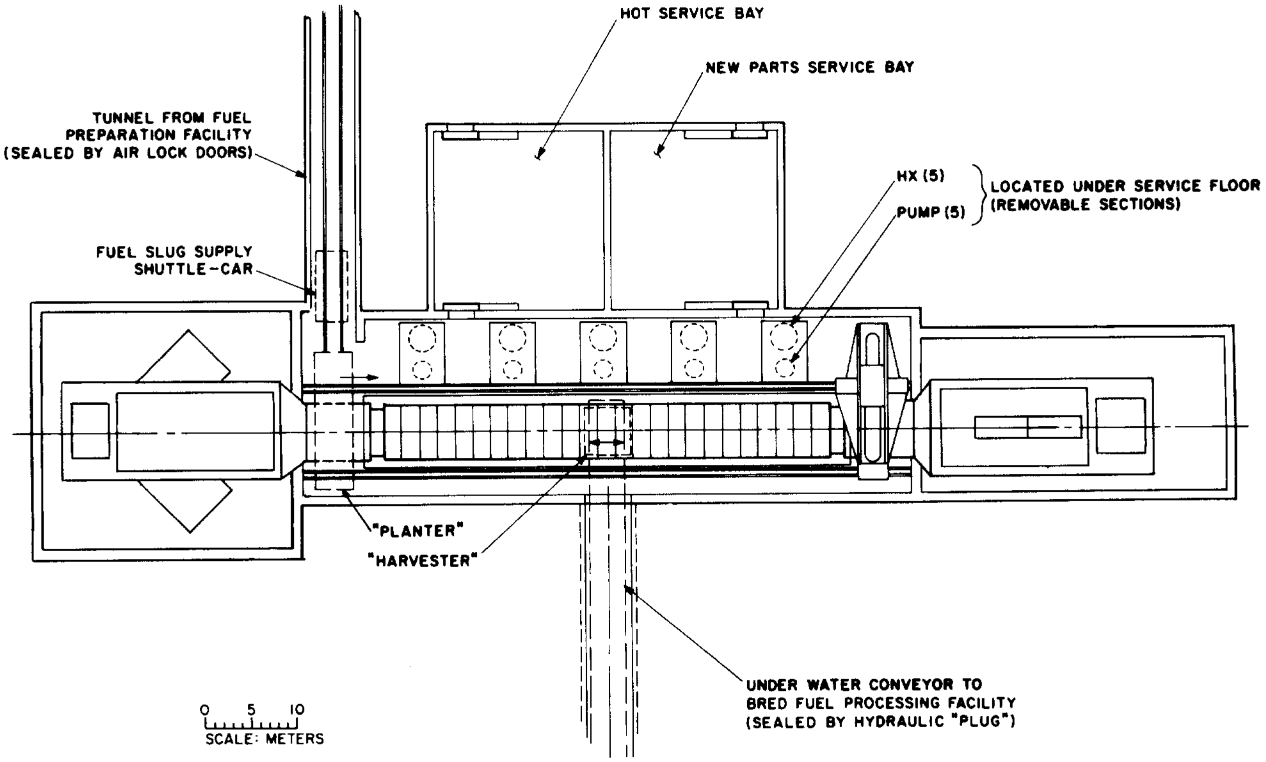

Fig. 10. Top view of containment building with production tandem mirror reactor.

Table III. Time (h) to Replace Breeding Slugs in One Blanket Module

Shut down reactor	1.0
Move both service machines to position	0.5
Remove plenum covers	0.5
Attach 50 new strings	0.25
Pull out bred slugs; pull in new ones	1.0
Deliver bred slugs to canal	1.0
Return to module	0.5
Repeat steps 4 through 7 three times	8.25
Replace covers and leak test	1.0
Return to park position	0.5
Start up machine	0.5
	15.0[a]

[a] Conclusion: Allow 16 h or two shifts for this procedure.

conveyor. The 50 reels of "hot" slugs are lowered from the bottom changeout machine onto the submerged conveyor belt, which moves the slugs to a nearby chemical processing plant, a distance of several hundred meters from the reactor hall.

We are unable to present a design for the two fueling machines at this time. An extension of this design study will include extensive planning of these two remotely operated robot fuel changers.

We have developed a design target scenario for fuel-change time; it is shown in Table III. A key assumption is that the magnetic field is not shut off. The robot machines must be capable of functioning in a fringe-field environment of about 100 G.

2.3. Reactor Description

2.3.1. Nuclear Island Arrangement

The tandem mirror reactor, to which this blanket design is applied, has the axicell end-plug configuration shown in Fig. 9. At each end of the 50-m-long central cell is a barrier cell characterized by a very high field solenoid—about 24-T field strength—that requires a water-cooled copper insert. This solenoid also has Nb_3Sn and NbTi superconducting portions that contribute to the total field but are located in regions where only fields tolerable to the superconductor are felt.

This highest field solenoid is closest to the central cell. Seven meters beyond it is another solenoid having a lower field strength. The low-field region of this barrier mirror forms the electron barrier that separates central-cell electrons from those in the quadrupole end plug.

A C-shaped transition coil follows the barrier solenoid to assist the flux transition from a circular to a quadrupole "fan" shape. The quadrupole is provided by a Yin–Yang coil pair at the extreme end of the reactor. This quadrupole provides magnetohydrodynamic anchoring of the flux lines.

The central-cell solenoidal field is provided by simple superconducting coils, two of which are mounted near the ends of each central-cell module. The exposed upper and lower ends of the blanket guide tubes are grouped in the middle of each module to permit coil replacement with no interference. (The alternative is a single, centrally located coil on each module. It would be trapped by the ends of the guide tubes. The magnet conductor would have to be wound directly on the shield exterior and could not be removed except by costly unwinding.)

At both ends of the reactor the escaping ions and electrons enter a region called a direct converter. Included with the direct converter is a "halo dump" where pumping of escaped ion occurs. Most particles confined within plasma-boundary magnetic-flux lines are electrons. They strike water-cooled end plates that are maintained at voltages closely matching the escaping electrons' energy level.

Ions are lost to the "halo" or cold plasma immediately surrounding the burning plasma. This loss is a radial diffusion process encouraged by drift pump coils located in the thermal barrier regions. (See Ref. 1 for a complete description of drift pumping.) The pumped ions (He^+, D^+, T^+, and high Z^+) exit in the halo annulus and are disposed of in a vacuum pumping annulus at a pressure of several torr. The ions find the pumping annulus by following magnetic field lines, so this annulus must be shaped to conform to the plasma fan. Recircularizing coils can be employed to reduce the ellipticity of the end plasma, thus making the direct converter and halo dump fit into a vacuum tank of smaller size and cost.

2.3.2. Beam and Microwave Heating

Each of the two end plugs requires three types of beam injection:

1. The barrier cell "sloshing" ions are injected perpendicular to the reactor axis near one of the mirror reflection points in that cell. The injection energy must be 475 keV, and the total power required is 1.37 MW.
2. Drift pumps(1) are needed to clear the bar-

Table IV. Vacuum Pumping Requirements

	Gas input (Torr l·s)	Area of active cryopanels (m^2)	Total cryopanel area (m^2)
Electron dump	7	9	14
Halo pump	17	21	32
Plasma direct converter	28	35	53

rier cell of accumulated trapped positive ions. This method of ash and trapped-ion removal is dependent on small, perpendicular, alternating magnetic fields superimposed on the background magnetic field. By tuning these $B_\perp$ coils to the sloshing frequency of trapped ions, the ions can be given small additive "kicks" that cause radial drift and lead to final removal by halo pumping. The "drift" carries the particles to field lines outside those that are plugged by ambipolar potential, hence axial loss is permitted. This innovative design is described thoroughly in the referenced report on the Mirror Advanced Reactor Study.(1)

The end-plug magnets are to be mounted inside cylindrical vacuum tanks (similar to the MFTF-B configuration). The various beam sources will be mounted on the cylindrical walls of these tanks or, in the case of certain pumping beams, may be attached as appendages to structural supports for the transition magnet. The latter location implies the use of sizable ducts from the beam-source box to the tank wall to expel the excess gas that always results from the production of neutral beams.

All the microwave power is injected into the barrier cell. Some power (5.5 MW total for both ends of the reactor) is focused at the potential peak in the barrier region. The balance (13.1 MW total for both ends of the reactor) is focused on the negative thermal barrier, which is at a different location in the same barrier region. Each gyrotron is to be rated at 1.0 MW, so about 20 waveguides will be needed.

The large microwave power tubes will be located outside the barrier cell's vacuum vessel. Waveguides with a minimum number of turns, and including a vacuum window, will transport the ECRH power the 3- to 4-m distance to the plasma surface.

Previous studies have shown that wave guides can be interspersed, without interference, between sloshing beam-injection lines.

2.3.3. Direct Converter,[4] Halo Plasma, Cryopumping

The location of the direct converter and electron energy dump has been discussed in Section 2.3.1. The plasma fan at the end of the reactor has a wide divergence angle. The included angle for hot plasma ions will be about 80°, and the included angle for the halo-plasma ions will be about 90°. So that a tolerable power density of 250 W·cm^{-2} can be reached at the direct converter, it will be on a circular arc of about 10 m radius. The center of that arc is near the center of the anchor-plug plasma.

We have chosen to house the direct converter within a half-circular appendage tank attached to the vacuum vessel that enclosed the Yin–Yang anchor coils. The outer surface of that appendage tank—both top and bottom, as well as the circular arc wall—has a corrugated appearance. Thus, the surface area available to mount cryopumps is larger. Also, structural benefits accrue to the elimination of large, flat surfaces carrying 15-psi differential pressure.

The total estimated gas load for this reactor system is 52 Torr l·s^{-1}.

We allow about one-third of the total cryopumping surface to be warming and outgassing at any one time. We assume a pumping speed of 4 L·s^{-1} cm^{-2} for liquid helium cryopanels properly baffled against thermal loss and equipped with argon sprays to pump helium gas. Table IV shows the surface area required in various reactor locations.

The halo plasma is pumped at both ends of the reactor. An annular elliptical "skimmer" is provided

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[4] Since this was written there have been several developments that have simplified the direct converter. In the MINIMARS design (see Ref. 2), drift pumping removes ions radially in order to sweep out the alpha ash. This separates the ions from electrons and simplifies the direct converter. Recircularizer coils are now used to allow cylindrical symmetry at the direct converter. Another very important change is the enhanced halo plasma that pumps gas very efficiently and eliminates the need for cryopumps.

close to the anchor magnets because the ion energy is very low. An annular cavity containing cryopanels surrounds this skimmer, and all halo ions that escape confinement are pumped in that cavity. (This is analogous to the tokamak's pumped limiter, a key feature of the STARFIRE[3] design.) The elliptical skimmer defines the plasma end-loss ellipse. Its shape is determined by field line plots so that hot ions and electrons pass unimpeded either to the direct converter at one end of the reactor or to the electron dump at the other end.

The halo pump cavity is enclosed by the main vacuum housing. Several ducts must connect that cavity to the outer vacuum wall. Those ducts will transport collected gas that is cyclically discharged by the cryopanels.

2.3.4. Containment Building

The "nuclear island" represented by the complete tandem mirror reactor must be housed in a structure capable of retaining full structural integrity and gas tightness under conditions of a "worst possible accident" scenario. The requirements posed by the low-temperature blanket are less demanding than those for previous designs, which included a high-temperature thermal transport system. Since our cooling system will not reach a maximum water temperature of 100 °C, we will not be forced to design for building pressurization beyond a few pounds per square inch. The shape of the building can conform fairly closely to that of the reactor, leaving adequate space for the movement of cranes and other service machinery between the reactor outer surfaces and the containment building walls.

The part of our operation that raises important containment questions is our frequent replacement of blanket breeding material, which requires ready and frequent access to the reactor vault from a breeding material preparation building. At the same time, ready and frequent access to a bred-material processing facility must also be provided.

Two fuel-change machines are needed: one that moves above the central cell of the reactor, and one that moves in a gallery beneath the central cell. Reference to Figs. 9 and 10 will clarify these relationships.

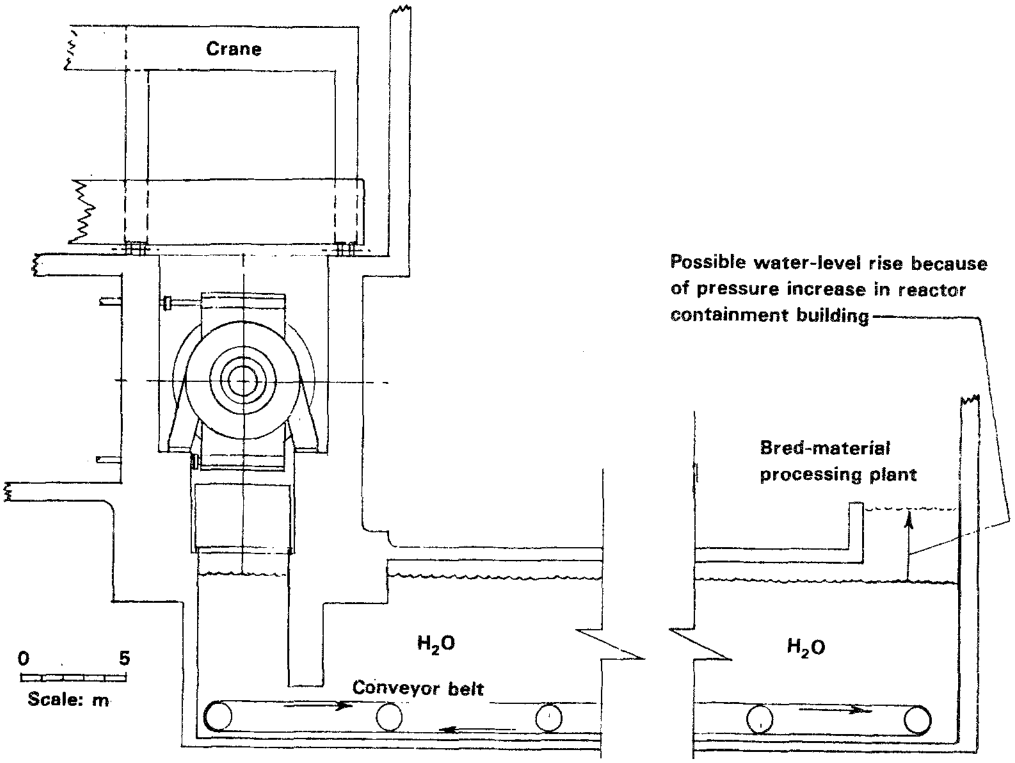


Fig. 11. Containment water seal for production tandem mirror reactor.

An above-grade corridor leads from the reactor vault near the parked location of the top blanket-change machine to the factory, where slugs of breeding material are manufactured and stored for installation. This corridor can be provided with a rolling shield door having inflatable gas seals. Common elastomers can probably be used in these seals because radiation levels at the door are low enough to permit them to be used for many years before they become embrittled and must be replaced.

The situation at the bred-material discharge port, where radiation levels are high, is very different. We have chosen a conveyor belt that runs under 6 m of water as our means of egress to the bred-material processing facility. The lower blanket-change machine receives its load while positioned directly beneath the module being serviced. It then proceeds, together with its load, to the central dump station located mid-gallery. The reels of radioactive slug chains are lowered onto a moving conveyor at the bottom of a water channel. This underground channel or "canal" is sealed by a foundation wall of the containment building, which forms a concrete curtain down to about 1 m from the moving conveyor belt (see Fig. 11). An increase in building pressure will cause the water level to rise in the channel outside the curtain. If a pressure change of 5 psi were to occur, the change in water level would be 3.52 m. Allowances for such a "surge" can easily be accommodated by properly elevating the bred-material process equipment.

If preferable, a sliding "trap door" can be provided at the point where the blanket-change machine drops its load onto the conveyor. Although this door seal would not be in a low-radiation environment, it would be somewhat protected by water if the door were positioned about 3 m deep in the canal. The protection afforded by 3 m of water should permit elastomer seals to be used.

2.4. Plant Layout

2.4.1. Reactor Containment

We have housed the fusion tandem mirror reactor and its module service bays in a reinforced concrete building 1.5-m-thick walls. The pressure containment requirements will be relatively low, probably less than 1 atm gauge, since we are using a low-temperature, low-pressure cooling system. The biological shielding afforded is ample, and tritium permeation will be controlled by a thin steel shell inside the reinforced concrete structure. The standoff space between the shell and concrete will be vacuum-pumped to further reduce tritium loss to the environment.

To reduce costs, the building is sized for normal service activities on central-cell modules and barrier-cell magnets. The central-cell module assembly bay would be used for that activity. Abnormal service, such as a transition or anchor Yin–Yang coil failure, cannot be accomplished inside the containment shell. The wall of the building at the electron-dump end or at the direct converter end would have to be removed to extricate an anchor coil and would have to be rebuilt after magnet replacement. Such a process could require as much as 2 years of reactor downtime.

William Allen of the Bechtel Group, in reviewing our layout, advised that the containment structure did not allow sufficient maintenance space around the reactor. We believe that more-detailed studies are necessary to define certain special maintenance scenarios. Although enlarging the building may prove advantageous, we chose to stay with our initial sizing for this first design.

2.4.2. Heat Transport

The blanket is cooled by a flowing water system designed for an exit temperature of about 90 °C. This water is pumped to nearby heat exchangers, where its temperature is lowered to 30 °C. The secondary coolant is also water and it is pumped to a row of "wet" cooling towers for energy rejection to the atmosphere. If the plant were sited on a river, cooling water could be pumped from the river into the secondary loop.

The tritium loss to coolant will be minimized by an aluminum oxide barrier on the breeding slugs. A backup barrier is provided by double-walled heat-exchanger tubes, where the space between tubes is swept continually by high-pressure helium to purge any lost tritium into a trap and removal system. This loss would be due to permeation through the inside tube wall from the primary loop cooling water.

2.4.3. Facility Power

The plant requires 312 MW of power for continuous operation. A small substation is required to supply this power from a local utility grid.

2.4.4. *Auxiliary Buildings*

We made a very preliminary study and layout plan for the support buildings and are confident that no major structure has been overlooked. However, the Bechtel Group commented that the buildings would be extremely compact and recommends that future studies consider more generous space allocations for equipment areas (more laydown area).

The preliminary layout appears to us to be consistent with that provided for a tokamak reactor with an identical purpose and similar size (see Section 3.4.). Any error due to space allocations will probably be less than 10% of the overall cost of such a production facility when extraction and processing plants are included.

2.5. Cost of Plant

Estimates were made to determine the cost of a tandem mirror reactor having a 50-m-long central cell. The end-plug magnet set was assumed to be a scaled-down axicell design chosen in a 1981 economic study of possible end-plug magnet configurations.[4] Building costs were obtained with the help of William Allen of the Bechtel Group. The estimates are summarized in Table V. The costs of fuel preparation and bred-material processing facilities are not included in the table.

2.5.1. *Magnets, Shielding, Coil Force Structure*

The cost of the end-plug magnet set is a major fraction of the cost of the nuclear island. Our most recent detailed cost estimate for an axicell magnet array was done in FY 1984 for the study reported in Ref. 5. In that study, we developed a cost algorithm based on current construction experience with MFTF-B magnets. We also employed a new estimate of the cost of a Nb_3Sn superconductor.

The cost of vacuum-vessel enclosures for this magnet coil set is calculated in Section 2.5.5.

Table V. Cost Estimate ($Millions) for Production Tandem Mirror Reactor

Magnet systems for end slugs, including magnet shields and structure	200.8	Central-cell shield	25.0
Choke coils	55.3	Instrumentation and control	70.0
Plug coils	38.1	Remote maintenance	64.0
Transition coils	19.7		
Yin–Yang anchors	34.4	Breeding-slug changeout machines	22.0
Recircularizer coil	14.2	Top "planter"	16.5
Shields	39.0	Bottom "harvester"	5.5
Central-cell magnets	60.5		
Neutral beams and power supplies	10.0	Cooling systems	60.0
Microwaves	50.0	Heat-transfer system	33.0
		Heat-rejection system	27.0
Direct converter with power conditioning	6.0		
		Balance of plant	167.0
Copper insert-coil power supplies	10.0	Reactor containment building	30.0
		Reactor auxiliaries (service)	28.0
Vacuum-system vessels	30.0	Radiation waste building	6.0
		Tritium building	12.0
Tritium handling and pellet injection	150.0	Ventilation building	8.0
		Cryogenics building	5.0
Drift pumps	5.0	Electrical building	8.0
		Electrical bulks (wire, cable conduit, etc.)	38.0
Blanket	86.0	Administration building	4.0
Neutron multiplier (Be)	84.0	Mockup and shop building	11.0
Structure	2.0	Fuel-fabrication building	5.0
		Site improvements	12.0
		Total direct cost	1016.3

2.5.2. *Neutral Beams*

Estimates of total beam power result from a computer calculation of equilibrium plasma performance. Sloshing ion injection into barrier cell will be 13.4 MW.

Our most recent estimate of neutral beam injector cost is \$2/W. The standard unit-cost guide for fusion reactor design, prepared by Battelle, recommends \$1.50/W in 1979 dollars. Some contingency is not inappropriate, and so we estimate \$10 million as the cost of neutral beams for the complete reactor when power supplies are included.

2.5.3. *Microwaves*

The plasma performance calculation also yields an estimate of total electron–cyclotron resonance heating (ECRH) and ion–cyclotron resonance heating (ICRH).

1.	ICRH directed into MHD anchor cell (MW)	0.3
2.	ECRH directed at potential peak in barrier (MW)	0.5
3.	ECRH directed at thermal barrier (MW)	11.1
	Total resonance heating (MW)	11.9

Battelle's recommended cost estimate for ECRH was \$5/W in 1979 dollars. Our recent experience in purchasing equipment for the MFTF-B experiment indicates that \$5/W is still a good estimate in 1982 dollars. (This is in contrast to the WITAMIR-1 study at the University of Wisconsin, which used \$2/W, and the STARFIRE study at ANL, which used \$1.20/W.)

With a small contingency allowance, we assign \$50 million as the cost of ECRH power.

2.5.4. *Cost of Direct Converter, Power Conditioning, and Cryopumps*

Again we refer to Ref. 5. The amount of power to the direct converters in FPD is only 40% of the amount in this production reactor design. Since the FPD costs for direct conversion totalled \$4.7 million, which included the cost of inverters, we believe \$11 million will cover those same items in this design. The slightly larger direct converter plates have some effect on the vacuum vessel cost, and that was included in our vessel estimates.

Two possible methods of pumping the halo plasma are being considered. One involves a large number of cryopumps, all pumping on the region separated from the main end vessel by the "halo scraper." The second method establishes a much higher pressure at the two ends of the halo by refluxing particles from the pump annulus into the region of the halo near the pumps. This method has not been demonstrated yet in fusion experiments. Even though the high pressure method promises to be economical, we present here estimates for the cryogenic method. Cryopaneling should cost less than \$1 million. The 4.2-K and 78-K refrigeration system is the expensive part of the vacuum pumping, and its cost is estimated to be \$5 million.

2.5.5. *End Vacuum Tanks*

One large cylindrical vacuum vessel is required at each end of the reactor. They house transition magnets, the Yin–Yang anchor-magnet pair, and the Yin–Yang plug-magnet pair with their attendant shields and force-restraining structures. Also housed is the direct converter.

We performed buckling calculations on simple shell designs to establish the wall thickness required. Our current cost estimate for type-316 stainless steel fabrications of this quality is \$19.5/kg.

The costs of the direct converter and electron-dump housings are not included in these estimates. They are covered in Section 2.5.4.

Since there are two tanks, we calculate a total cost for end-plug vacuum vessels of \$25.2 million.

2.5.6. *Blanket and Shield*

The most significant cost element of the central-cell design is the beryllium neutron multiplier. The cost estimates are consistent with previous estimates of central-cell costs for pure fusion machines when the added cost of beryllium is taken into account.

2.5.6.1. First Wall. The mass of aluminum in the 50-m-long first-wall structure is 3240 kg. We believe that the quality of workmanship, degree of inspection, and assembly procedures will drive the cost to the equivalent of commercial jet aircraft construction, or to about \$210/kg in 1982 dollars. Therefore, the first-wall assembly with its cooling tubes will cost about \$680,000.

2.5.6.2. Beryllium. The beryllium in our blanket will probably be formed by "pressureless sintering," a new process being developed by the Brush-Wellman Co. Our roughly 10-cm^3 blocks of material are well-suited in size and shape to this new process, which produces parts of approximately 98% theoretical density.

The costs estimated by Brush-Wellman Co., the only domestic supplier of beryllium parts, are:

1. \$110/lb for Be powder.
2. \$100/lb for pressing and sintering.
3. \$10/lb for machining.

No protective coating was assumed. We believe that a 100-μm coating of aluminum will be desirable to retard the corrosion that might plug coolant paths and estimate the cost of this processing at \$5/lb, giving us a total cost of \$225/lb, or \$495/kg. Our 50+ m of blanket requires 170,000 kg of beryllium-machined blocks at an estimated cost of \$84 million.

2.5.6.3. Guide Tubes and Structure. The aluminum guide tubes have a volume fraction of 0.8%, and the module end plates occupy 3% of the total blanket volume of 1.156×10^8 cm^3. Thus, these aluminum parts have a mass of 11,862 kg. The unit cost for curved tubes with accurate contours and good surface finish will probably be comparable to the first-wall cost. The remaining welded-plate structure will cost about half as much. We therefore estimate the cost at \$125/kg for a total of \$1.5 million.

2.5.6.4. Shield and Solenoid. The total shield volume is about 7×10^8 cm^3. Table VI shows our estimate of the volume percent and cost of various shield components.

The cost of the solenoid magnet was estimated from these requirements and known costs:

Required central-cell magnetic field (T)	4.0
MFTF-B solenoid (\$/kg)	27.5
Shield o.d. (m)	2.54
Case structure (\$/kg)	18.5

Each meter of central-cell length has one coil costing \$595,000. The total cost of magnets for a 50-m-long central cell is, therefore, \$29.75 million.

2.5.6.5. Total Central-Cell Cost. The total central-cell cost can now be summarized. It represents the basic "empty" structure; that is, the cost of breeding slugs and their pull cables is not included.

	Cost (\$M)
First wall	0.7
Beryllium blocks	84.0
Guide tubes and structure	1.5
Shield	54.2
Solenoid coils and cases	29.8
Subtotal	170.2
15% contingency	25.5
Total	195.7

This represents a cost of \$3.9 million/m for a 50-m-long blanket. Other blanket designs that do not employ beryllium as a neutron multiplier range in cost from \$2 million to \$3 million/m. Consider the cost of fabricated beryllium, we believe this estimate to be consistent with previous efforts on tandem mirror reactors and reasonable for this special application.

2.5.7. Building Cost

This cost estimate was based on very preliminary layouts of the reactor building and on a site layout comparable to the one proposed by the fusion Engineering Device design group at Oak Ridge, Tennessee, for a tokamak of similar complexity.(6)

The Bechtel Group Inc. assisted us and was critical of the preliminary design presented. Bechtel Group comments that the space allotted around the reactor to perform some maintenance operations was

Table VI. Cost of Shield Components

Material	Volume (%)	Density (g/cm^3)	Mass (kg)	Cost (\$/kg)	Cost (\$M)
Lead-cement	50.0	9.6	3.35×10^6	2.5	8.4
Steel	30.0	7.85	1.65×10^6	19.5	32.2
Lead	10.0	11.35	0.79×10^6	10	7.9
B_4C	0.5	2.5	8,750	600	5.3
Borated H_2O	5.0	1.1	38,500	10	0.4
Cooling H_2O	4.5				
Total					54.2

insufficient. We replied that all maintenance, except disaster repair, would be performed in adjacent hot cells in the reactor auxiliary buildings. Since a very low-temperature blanket will be used, the benefits accruing to the large building volume around a PWR or a breeder do not apply. A loss-of-cooling accident will not vent high-pressure, high-temperature steam into the containment structure.

Costs were estimated on the basis of the original LLNL layout. The costs of all buildings were estimated using unit costs based on building volumes. In 1982 dollars, the estimate covered four general classes of buildings:

1. Reactor containment buildings = $\$6600(V)^{0.8}$
2. Reactor service buildings = $\$3300(V)^{0.8}$
3. Steam generator buildings = $\$2200(V)^{0.8}$
4. General maintenance and electrical equipment buildings = $\$1100(V)^{0.8}$.

The volume is based on external dimensions and is expressed in cubic meters.

The above costs were derived from a recent fission breeder plant design and may be higher than necessary since our criticality problems and accident scenarios are less severe.

2.5.7.1. Containment. Bechtel Group estimated the cost of a complex, including reactor containment, reactor service hot-cell bays, and fuel-transfer tunnel, at $82 million.

2.5.7.2. Auxiliary Buildings. Estimates of the cost for radioactive waste, tritium processing, ventilation, cryogenics, and power supply buildings totaled $43 million.

2.5.7.3. Cooling System. The cost of two cooling loops was estimated. The primary hot-water loop with all pumps, piping, and heat-exchangers is estimated at $33 million. The secondary loop or heat-rejection system, which also has pumps and several "wet" cooling towers, will cost about $27 million.

2.5.7.4. Electrical. The cost for electrical equipment related to reactor system control, building functions, environment in the buildings, and power to run this material-producing reactor will total about $15 million. Electrical "bulks" such as wire, cable, cable trays, conduit, etc. for all buildings will cost about $65 million.

2.5.7.5. Tandem Mirror Refueling Machines. There are two track-mounted refueling machines, one above and one below the central cell. In Table VII, we have estimated their size and mean density, as well as cost per unit mass, which is the only way to estimate cost without specific design information.

Table VII. Size, Mean Density, and Cost of Tandem Mirror Refueling Machines

	Top	Bottom
Size, rectangular prism (m)	3.5 × 4 × 15	3.5 × 4 × 4.8
Approximate mean density, 20% × solid steel (tonnes/m^3)	1.57	1.57
Unit cost ($/kg)	50	50
Total cost ($M)	16.5	5.3

The total cost of the blanket changeout machines is estimated at $22 million.

2.6. Fusion Component Replacement

The reactor parts that we expect to replace during the operating lifetime of the facility are readily accessible.

The central cell, which is composed of 25 modules (each 2 m long), is serviced by a large gantry crane that spans the reactor. Each module is separated from every other module by a pressurized metal-cushion vacuum seal. Depressurization of the seal elements and retraction by evacuating the seal housing provides the removal clearance needed to lift a module assembly from its operating position. A crane lowers the module to a transport truck that rolls through a doorway into the hot-cell service bay. This door is a massive concrete shield panel that normally separates the reactor bay from the hot cell. Figure 12 shows the module service path.

Direct converter elements and cryopanels are mounted in the end-cell vacuum tanks. The corrugated end wall (a 180° arc) of the direct converter tank has many separate rectangular end panels, each of which has cryopump sections mounted on it. One or more of these panels can be removed to provide access to the back of the direct converter array. Remote disassembly tools will be needed to detach a direct converter unit. The unit that needs replacement will be moved out of the reactor building through an airlock located in the end of the containment building. A similar airlock will be provided at the electron dump end. Cryopanels may have to be replaced at that end.

Each end cell has two high-field copper insert magnets located at either end of the barrier coils, one

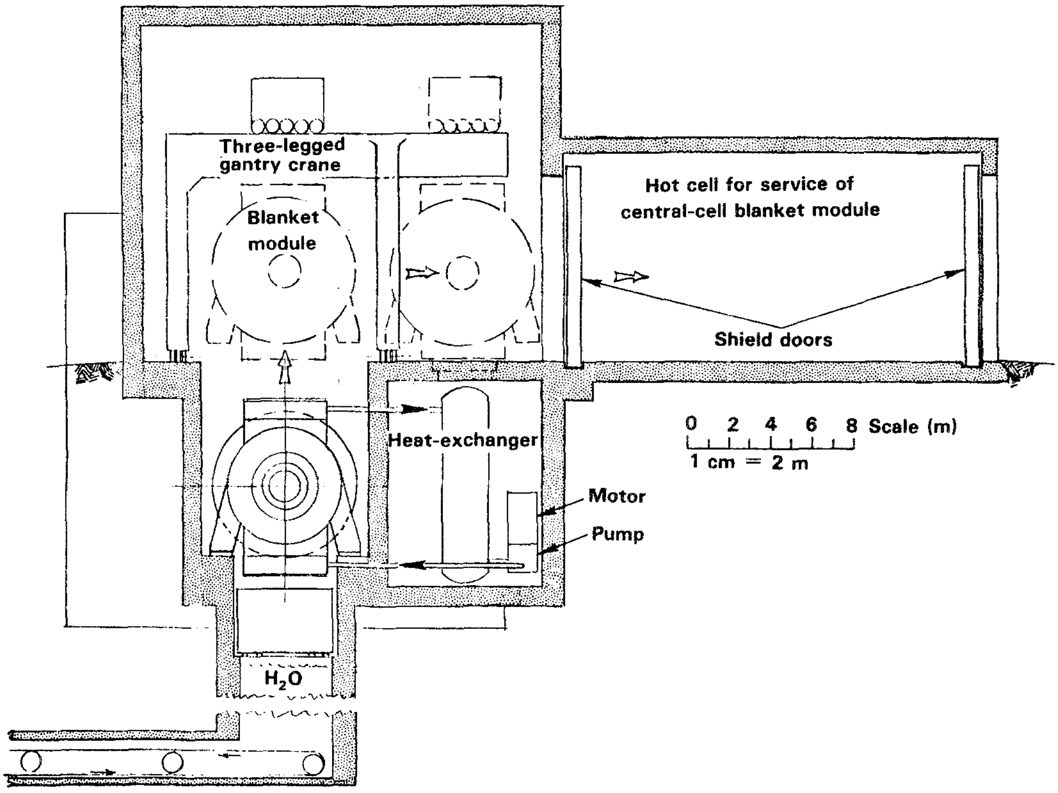


Fig. 12. Cross section at middle of production tandem mirror reactor.

of which is located at each end of the central cell. We expect that these "normal" coils will have to be removed and replaced as often as once every two years of reactor operation. The inboard magnet insert is readily accessible if two central-cell modules are temporarily moved to provide a path for coil removal. The removal path would then be identical to the end module of the central cell.

Access to the second barrier coil is more difficult. The most probable scenario is to remove the inboard "normal" coil first and then move the outboard coil through the hole vacated by the inboard coil. Both copper coils will have elaborate cooling systems and flow distributors. The water supply and return ducts may also have to be replaced because of neutron damage. The primary design criteria for these copper coil assemblies must be ease of replacement. Studies for the MARS PROGRAM[1] by General Dynamics Corporation addressed the detail design of the two magnets, using a larger scale version of this same axicell end-plug design.

Previous reactor design studies have discussed replacement scenarios for reactor components. The only major difference between this reactor and previous designs is the "normal" barrier-coil inserts described above. The barrier coils, themselves, are not peculiar to this design. All future tandem mirror reactors will have the axicell end plug.

2.7. Blanket Replacement

2.7.1. Bred-Material Replacement Time

The production material in this reactor is in the form of 3.6-cm-diameter by 3.6-cm-long cylinders (slugs) strung on a cable, much like pearls on a necklace. These strings of slugs must be pulled out of their blanket guide tubes and new strings must be inserted. Our means of accomplishing this is to use the two servicing machines described in Section 2.2.1. The time required to replace all of the chains in one central-cell module has been estimated at 16 h. Since there are 25 modules, changeout of the entire blanket would require a continuous, three-workshifts-per-day operation over a period of 17 days. With reasonable allowance for unplanned interruption, three weeks should be allowed for a complete changeout.

We have studied another method of fuel change that allows continued reactor operation during fuel replacement. This method requires that each guide tube have a separate access port in the cover plate over the coolant plenum chamber and that each access port be provided with a ball valve. The ball-valve hole must be about 4 cm in diameter to allow fuel slugs to pass through.

An extraction machine couples to the ball-valve flange. This device is filled with water so that opening the ball valve does not change the flow path of the blanket cooling water. After valve opening, a cable probe coupler is inserted through the valve to attach to the bred-fuel cable.

At the top of the reactor, a similar machine will have attached a new fuel string to the tail of the bred string that is about to be extracted. The extracted string of slugs is wound on a storage reel within the water-filled body of the service machine. The ball valve is closed after the new string of slugs is released. The service machine releases its seal to the lower ball-valve flange and is then transported to the "canal" discharge location, where the machine is upended and the collected string of slugs is allowed to sink through the shielding water to the submerged conveyor belt.

This operation on one guide tube will consume about 1 h. There are roughly 6000 guide tubes in the complete reactor. If four pairs of change machines work simultaneously, they can completely replace all breeding slugs in about 63 days.

If no routine maintenance were required, this scenario would permit continuous reactor operation for many months. Fuel could be bred and extracted in a nearly continuous process, with about 200 slugs/h arriving at the fuel-processing end of the conveyor.

3. TOKAMAK PRODUCTION REACTOR WITH COLD-WATER-COOLED BLANKET

3.1. Blanket Configuration

We took the same blanket concept developed for the tandem mirror reactor and applied it to a TORFA-type tokamak fusion reactor.[7] The extreme difference in geometry led to a system of "ducts," as

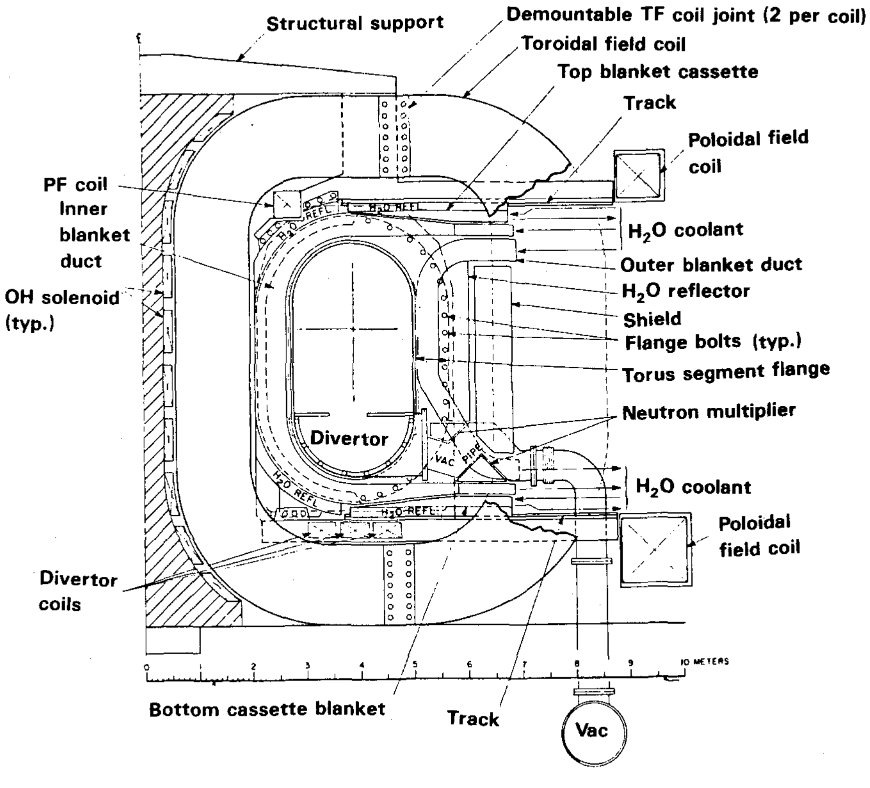


Fig. 13. Tokamak TORFA-D2 without neutral beam port.

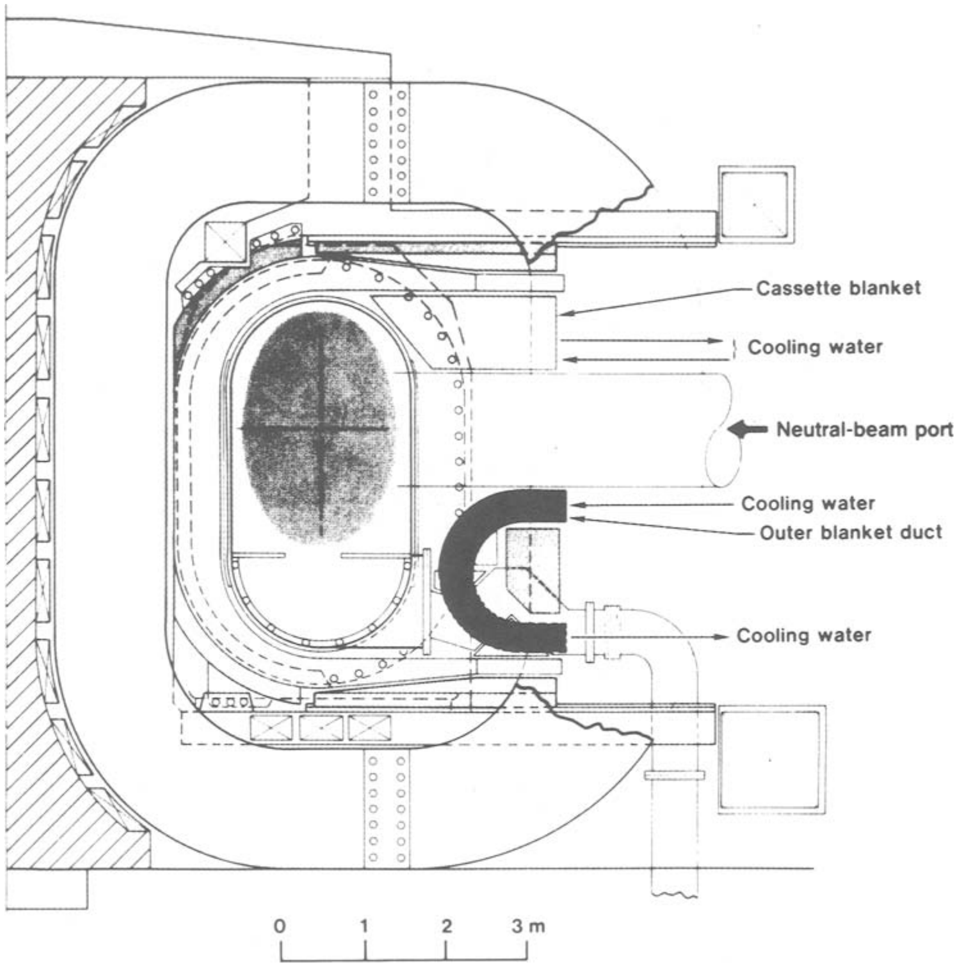


Fig. 14. Tokamak TORFA-D2 with neutral beam port.

illustrated in Figs. 13–16. The ducts are so named because an array of breeding-slug guide tubes runs lengthwise in a duct. The guide tubes are at about 10-cm centerline spacing. The space between guide tubes is filled with a neutron multiplier (such as beryllium) and cooling water. In the guide tubes are strings of cylindrical slugs placed on a 3-mm-diameter pull cable, like pearls on a necklace. The strings of breeding material are pulled through the guide tubes in batches (or possibly in a slow, continuous changeout). As one enriched string is pulled out of the blanket duct, its replacement is attached to the tail end of the string and is pulled into the blanket.

The C-shaped ducts on the outside of the torus are subjected to the most neutrons. The breeding zone is about 40 cm thick; behind that zone is a 40-cm thick water reflector. The width of the duct is controlled by the gap available between adjacent toroidal field coils. The coil cross section has been shaped to permit the widest possible duct consistent with mechanical support for the plasma vacuum and poloidal divertor chamber.

The inboard side of the torus also requires a blanket. The duct in that area is 40 cm thick. The vertical portion of the duct does not need a water reflector. The TF coil copper leg in that region provides all the neutron reflection required. Access to the ends of the inboard duct can be achieved only by curving the duct radially outward both top and bottom, which also provides blanket coverage to the top and bottom of the plasma chamber. However, as reference to the top view reveals, this duct must widen as it moves out radially. Since the number of guide tubes in a duct remains constant, we compensate for the increased duct width by decreasing its thickness. This permits the ratio of breeding-slug

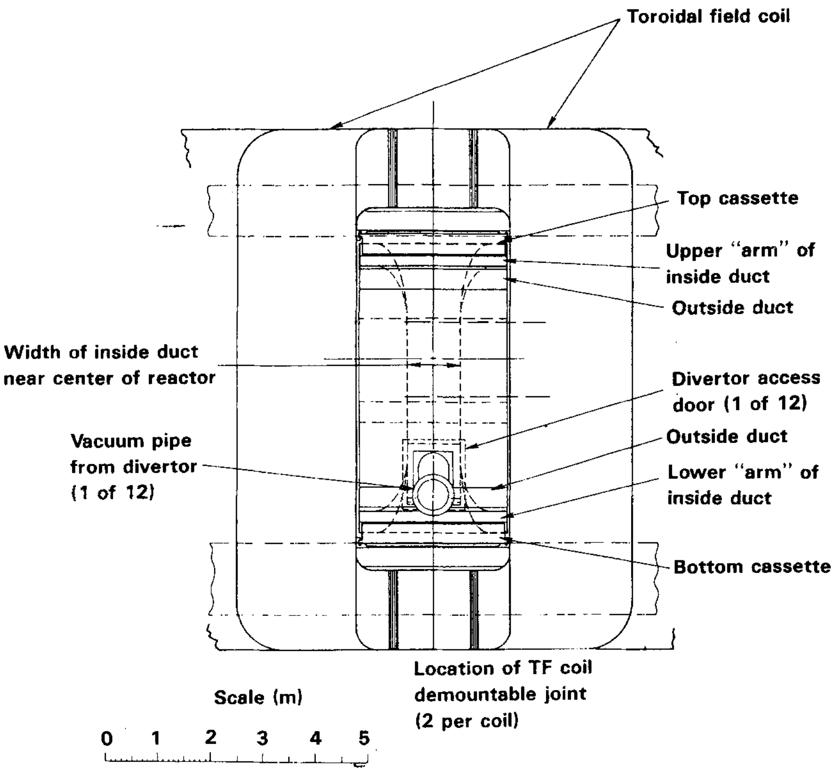


Fig. 15. Tokamak TORFA-D2. Elevation viewed from between toroidal field coils.

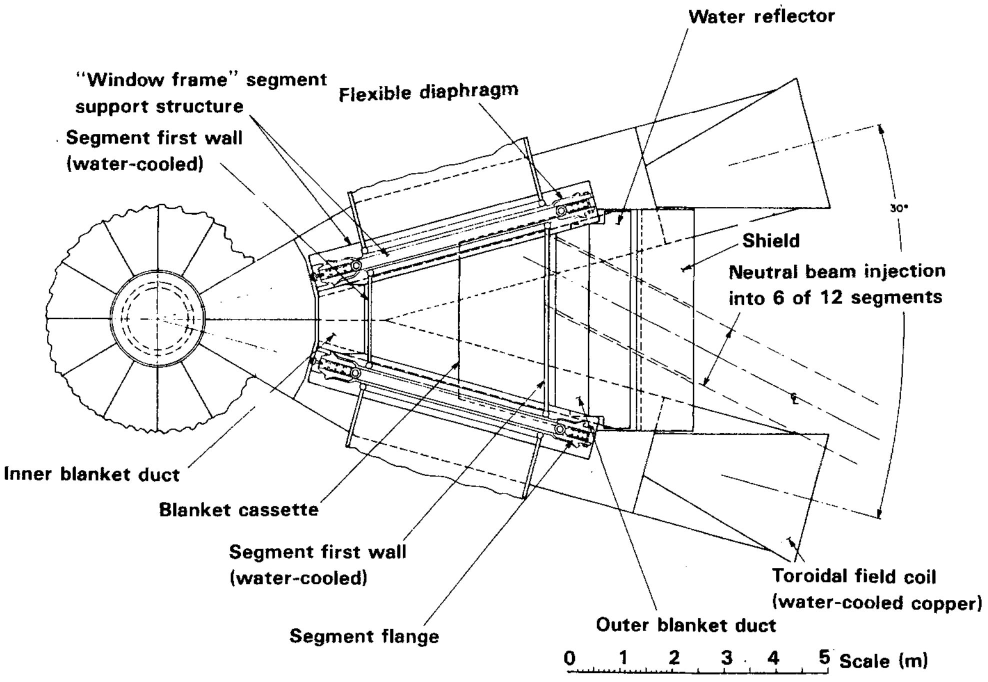


Fig. 16. One of 12 tokamak TORFA-D2 reactor segments. Top view through plasma center.

volume to neutron-multiplier volume to remain constant.

The thinner duct will not utilize neutrons as efficiently. This suggests that two special blanket cassettes will probably be needed, one above and one below each inboard-duct arm. The breeding zone of the cassette can be tapered to match the reverse taper of the duct. Included as part of the cassette is the water-reflector region for the top (or bottom) of the blanket. The breeding material in the cassettes will not be handled in the same way as the "flow-strings" of slugs in the duct guide tubes. We imagine long, rigid rods of material, spaced in an array identical to guide-tube spacing. Those rods can be extracted with the cassettes in situ, or the cassette assemblies can be removed to a hot cell for replacement of the breeding material.

3.1.1. Breeding Slugs

The tritium breeding alloy of aluminum and lithium is machined into a cylinder about 3.6 cm in diameter with a 3-mm-diameter hole through the center. That cylinder is encased in a jacket of high-purity aluminum that provides a very effective diffusion barrier against the escape of tritium from the alloy.

The tokamak slugs can be identical to those described in Section 2.1.1. for a tandem mirror reactor.

3.1.2. Neutron Multiplier

Beryllium was chosen to serve as a neutron multiplier. It will be manufactured in the same manner as described previously in Section 2.1.2. for the tandem mirror reactor.

The length, width, and thickness of a nominal beryllium block will be about 10 cm. A thin coat of aluminum will also be used to retard corrosion by the 85 °C water coolant. As in the tandem mirror reactor, the 0.015-cm/year corrosion from the surface is not devastating to breeding. Our concern for the whereabouts of more than 1000 kg of beryllium in the cooling-system plumbing, as well as beryllium-produced tritium, drives the decision to add a coating to the beryllium. We estimate that the cost of coating will have only a 2% effect on the cost of the beryllium.

3.1.3. Tokamak Thermal Hydraulics

Each duct and cassette will operate in parallel with all other ducts and cassettes. Master supply and return manifolds will encircle the reactor with throttling valves on the supply side to control flow rate so that exit flow temperatures are nearly the same for all circuits.

Each segment of the reactor (30° between toroidal field coils) has two major ducts and two cassettes. Where beam ports are present, the outside duct is shorter and partially replaced by a cassette. The outer duct intercepts only about 40% of the neutrons leaving the plasma. Its large cross-sectional area (0.96 m^2) provides 480 cm^2 of coolant flow area. The Reynolds number for water flow, allowing a 60°C temperature rise, is 11,000. This translates to a pressure loss of less than 5 psi through the duct.

The inside duct, which also partially covers the wedge-shaped top and bottom of a segment, is about twice the length of the outside duct. Because of its large area of coverage, it intercepts about 35% of the plasma neutron power. To keep the duct coolant pressure as low as possible, we allow 10% coolant flow area instead of 5%, which was sufficient for the outer duct. This converts to about a 20-psi pressure drop in the 12.5-m-long duct.

The very wide and thin-walled duct with that much internal water pressure will not be able to hold its shape without internal vanes, which serve as tie rods between the flat sides. The presence of such vanes will detract somewhat from the percentage of neutron multiplier and add some undesirable parasitic capture by additional structural fraction. The possibility of these vanes being made of zircaloy will be considered during further refinement of this design.

The remaining 25% of the neutron energy will be deposited in the torus support frames, in the first-wall structure, and in the top and bottom cassettes. There are also losses up the beam injection ports that require extra cooling of neutral beam-line components. As a first guess, prior to neutronic analysis, we assign 10% to the structure, 5% to each of the two cassettes, and 5% to beam-line losses. The divertor hardware at the bottom of the torus will moderate fast neutrons so they will be incapable of (n, 2n) reactions in beryllium. However, attenuation of the total neutron flux passing through the divertor region can be kept relatively small so that the number of tritons bred in the blanket regions under the divertor will be almost equal to the number of fusion neutrons incident on the divertor.

The cooling circuit in a cassette will be different than in the ducts. Water will make a one-way pass through the cassette by piping it directly to the "blind" end of the cassette and allowing it to be heated by the breeding rods and incidental structure as it returns through the body of the cassette.

3.1.4. First-Wall Design

Where the tandem mirror blanket has an integrated first wall forming part of each blanket module, the tokamak design uses a separate, stand-alone first-wall torus that has its own independent cooling system.

The method of fabricating and assembling the first wall is crucial to this whole concept of blanket ducts.

On the center plane of each of the 12 TF coils, but mounted on a rigid horizontal platform just above the lower legs of those coils, will be 12 "window-frame" structures with oval apertures. These "window frames" are a permanent part of the machine structure and serve as anchor points for the vacuum chamber segments. The lower semicircular portion of the oval torus cross section is used as the poloidal divertor pumping cavity. All of the torus volume above the divertor cavity is assumed to be occupied by the reacting plasma.

This design has 12 torus segments. Each segment has a wide (about 20-cm) oval-shaped flange on each end. Radial inward translation of a torus segment between a pair of TF coils allows the end flanges to mate with the stationary "window frames." The wide flange permits an unusual vacuum-sealing technique.

A differentially pumped multistage seal is employed. It consists of thin sheet-metal diaphragms welded over 5-cm-wide shallow oval grooves on both sides of the "window frames." There will probably be three concentric oval seals. The two spaces between the grooves will be differentially pumped. When the segment flanges are joined to the frames, the diaphragms are inflated to a pressure of about 500 psi.

The flange clamping is designed as follows: The inboard half of the "window frames" is completely inaccessible for welding or bolting. That half of the frames is provided with wedge-shaped female grooves that capture the leading edge of the torus-segment flanges during assembly. The outboard half is accessible; we suggest using either closely spaced bolts or clamps for flange joining. Pressurization of the seal diaphragms will impose reaction forces on the bolts in the outer half of the frame and on the wedge walls that are welded (or bolted) to the inner half of the frame.

No structure of this size and weight can be manufactured to the tolerance required for these vacuum seals unless some intentional flexibility is designed into the structure. We provide that flexibility by using special sheet-metal diaphragms between the two wide oval flanges and water-cooled spool that forms the oval first wall. These diaphragms are similar to the individual thin sheets that are welded at the inside and outside edges to form very flexible metal bellows. Figure 16 shows this feature.

3.1.5. Fabrication and Assembly Procedure

3.1.5.1. Ducts. Because there are many evenly distributed breeding-slug guide tubes in the neutron multiplier, each duct must be built up progressively in layers. The beryllium will be formed into approximately 10-cm cubes that, except for intentionally machined (or molded) grooves on the block surfaces that provide the necessary coolant passage area, are shaped to completely fill the void space between guide tubes.

Once assembled and pressure-tested, these ducts should serve for the life of the plant. If beryllium cracking occurs, the larger pieces cannot escape because of their geometry. Any small fragments will be captured in a filter or may block a local flow channel. A sufficient redundancy of blanket flow channels will be provided to make this occurrence unimportant.

3.1.5.2. Cassettes. The breeding material will be inserted into the neutron-multiplier matrix of a cassette as rigid rods in straight cylindrical holds. The absence of curved guide tubes will simplify assembly. To keep thermal stresses low and minimize the tendency for cracks to develop in the beryllium, these neutron multiplier blocks will also be kept small (probably around 10 cm). There is virtually no difference between a cassette and a duct except for their overall dimensions and the use of straight breeding tubes instead of curved ones. The overall mass of the cassettes will be considerably less than the mass of the duct assemblies.

3.1.5.3. Order of Assembly. The outline presented here is not complete. Its purpose is to show the necessary order of operations and to mention certain structural requirements that must be satisfied during assembly. The steps listed here must be repeated for each of the 12 reactor segments:

1. Install the center post and TF coil inner half.
2. Install the lower PF coils and the torus-support floor that bridges over the bottom legs of the TF coils.
3. Erect 12 torus frame supports on the torus-support floor, one at each TF coil center plane.
4. Attach the "roof" platform that supports the top PF coils to either the center post or the inner TF coil legs (or both, depending on final shape and joint location in the TF coil). This platform must also support the weight of a portion of the inboard blanket duct.
5. Install the inboard blanket with its vertical leg bolted to a vertical leg of a TF coil. The torus support floor must support the horizontal lower portion of this duct. The horizontal upper portion is supported by the "roof" platform (see 4 above).
6. Install the torus segment by translating it radially inward between the TF coils and into contact with the fixed frames at the TF coil center plane. The inboard edge of the flanges enters wedge receptables on the inboard side of the frame. The outboard edge of the flanges must register properly so bolts can be installed along the accessible half of the flange perimeter. The seal is accomplished by inflating differentially pumped diaphragms of metal (described in Section 3.1.4.).
7. Install the outer duct. It will be mounted to vertical plates that are part of the fixed "window frames."
8. Lower the one-piece PF coils into place outside the TF coils.
9. Insert the upper and lower cassettes any time after step 5.

3.1.6. Provisions for Beam Ports

Six neutral beam injectors will be used for plasma heating, current drive, and partial fueling.[8] These beams will be injected at the plasma vertical center plane. Six of the twelve torus segments must have beam ports, so the outer blanket duct must be drastically altered to provide that space.

There is enough space below the beam ports to install a short C-shaped duct (no vertical straight section) that retains the guide-tube "flow-through" feature. Above the beam port, the tube bend radius would be too small (high friction). Instead, we will provide a cassette with a water reflector. It will have rod breeding material, rather than slugs like the top and bottom cassettes described in Section 3.1. All the rods will be short and of the same length, approaching the plasma approximately radially.

3.2. Fueling Scenario

3.2.1. Procedure for Installing and Removing Breeding Material

The ducts that enclose the breeding material guide tubes and neutron multiplier also serve to channel the blanket coolant flow. A plenum chamber at the inlet end of a duct supplies water to each guide tube and to the passages through the neutron multiplier. That plenum chamber has a single inlet pipe fed by a large ring supply manifold that encircles the reactor. The exit-end plenum acts also as a common collector and returns water to a ring return manifold. To gain access to the open ends of breeding guide tubes, it is necessary to remove the cover plate that forms the end wall of the plenum chamber. Both plenum chambers can be opened by the "refueling" machine for removal and replacement of breeding material.

The neutral beam injector boxes around the periphery of the tokamak reactor are obstacles to the movement of a service or fuel-change machine that might otherwise travel on a circular track. Instead, we are proposing that a crane be used to lift the service machine into a position defined by floor-mounted dowels. Twelve such floor stations are required to serve twelve 30° reactor segments. In every case, it will be necessary to uncouple a neutral-beam injector line and move one beam-source box back to a parking location to clear the space needed to land the service machine for work on the blanket in a given segment. The machine requires a floor area that is about 4 m wide by 7 m long.

As with the tandem mirror reactor, we plan to use a string of fuel slugs on a cable (see Section 3.1.1.). When one string is removed, its replacement is pulled into position by being attached to the tail end of the string being removed. The "new" strings

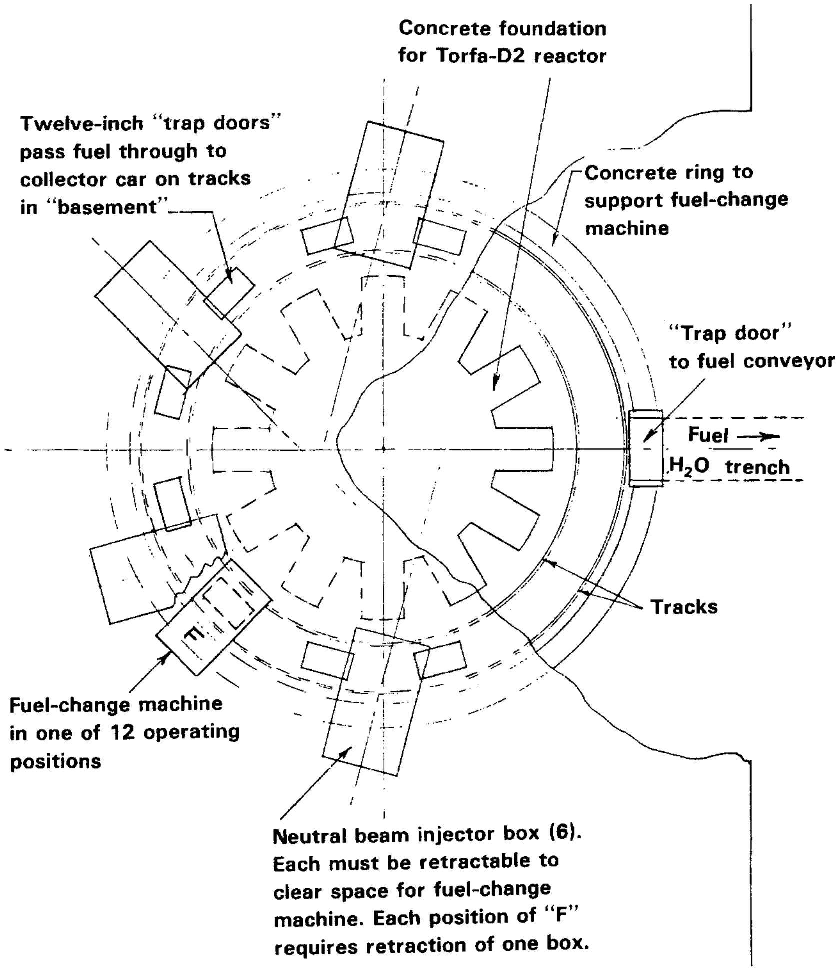


Fig. 17. Tokamak features affecting bred-fuel handling from blanket.

of breeding slugs will probably be held on circular reels in the fueling machine. As many as 50 strings may be changed simultaneously.

The strings being removed must be transferred to a reprocessing plant. This requires that the bred slugs be moved to a conveyor (or several conveyors) that runs a well-shielded path to the reprocessing building. One scenario requires a "trap door" and chute at each of the 12 service locations. Bred-fuel slugs can be fed (as strings or individually) into these discharge chutes that, like spokes of a wheel, carry the slugs to a single station for loading onto a conveyor belt. A plan view of the TORFA-D2 foundation is shown in Fig. 17. Since gravity plays a role, the central collection station will be several meters below the bottom of the lower TF coil legs. The chutes can be water-filled for shielding and could lead to an underwater conveyor similar to the one described in Section 2.2.1.

To get a new supply of breeding-slug strings, the service machine must be returned by crane to its parking location in a well-shielded corner of the main reactor bay. New breeding material is delivered from the fuel-fabrication building to this parking/loading station through an air-locked passageway. This passage is pressure sealed and shielded during reactor operation.

3.2.2. General Description of Fueling Machine

The blanket service machine must be capable of changing the strings of breeding material in the inner and outer duct, as well as the breeding rods used by the cassettes.

The inner duct will have about 30 guide tubes, each 12.5 m long. Each tube will be supplied from a 4-m diameter reel. The 30 reels can be on a common axle and will occupy a width of about 3 m.

The outer duct will contain more than 125 guide tubes, each about 6 m long. Space limitations will require the bred material to be replaced in three batches. If 50 storage reels are used, each will be 2 m in diameter. Two axles can be used to mount 25 reels each in a width of 3 m.

When the short external duct below the beam port is to be serviced, the 50 supply reels must be lowered 2.5 m so they line up with the upper arm of that short duct. This automatic realignment can be provided in the design of the service machine. The fuel-rod replacement required in the cassettes can be supplied at three required locations (top cassette, bottom cassette, and above-beam cassette) by turning the machine 180° and using the other half of the machine solely for rod replacement.

In this way, the two modes of slug or rod replacement can be performed by different parts of the same assembly. Since the mechanisms will occupy opposite ends of the same machine frame, there will be no interference between them. The only obvious limitation to this service-machine layout is that the ducts must be changed at different times than the cassettes. Machine turnaround would require about 1 h of crane operation. The total machine length of 7 m is divided approximately equally between the two types of change functions.

3.3. Reactor Description

3.3.1. Nuclear Island

The tokamak reactor for this material-production application has 360 MW of fusion neutron power and occupies a circular space 20 m in diameter to the outside of the external PF coil-support structure. An additional annular area 8 m wide is occupied by neutral beam injector source boxes. These sources must be moved radially outward during blanket service operations on adjacent blanket segments. They can be turned as they move outward to conserve overall radial dimensions. The total space occupied by the reactor and its support hardware is a circle 45 m in diameter.

For comparison, Fig. 18 shows the outline of this production reactor tokamak and the TFTR tokamak presently under construction at Princeton Plasma Physics Laboratory.[9]

The overall height of the reactor depends on certain TF coil structural details yet to be determined. Present estimates place its height as 14 m from the TF coil support surface. Vacuum equipment, electrical bus bars, major and minor coolant ducts, etc. will be in a basement area directly below the torus. Because of the enormous weight of the TF coils, the floor of the reactor immediately beneath the TF coils will extend "to bed rock," so the "basement" will be an annular space extending from about 5 m from the reactor's vertical axis to a radius of about 23 m. The outer boundary of this space need not be circular, but can conform to the overall rectangular shape chosen for the containment building. The inner boundary will be less than 9 m only in the 12 wedge-shaped spaces between the TF coils (see Fig. 17).

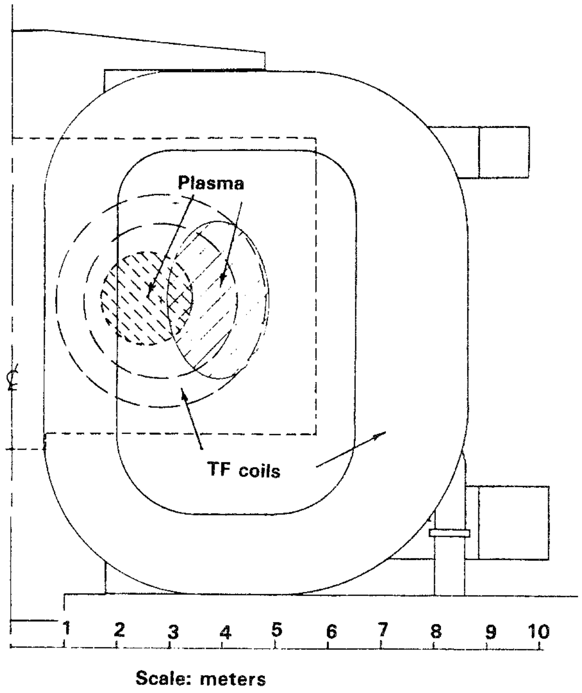


Fig. 18. Size comparison of the TORFA-D2 (solid lines) and TFTR (dashed lines) at Princeton Plasma Physics Laboratory.

3.3.2. Divertor

A poloidal divertor is planned as part of the plasma containment torus. Each of the 12 torus segments described in Section 3.1.4. has a divertor segment as an integral part. The cross section of the plasma chamber is oval or "race-track"-shaped. The lower third of this chamber is reserved for the divertor.

The walls of the divertor will be water-cooled. The directed magnetic field lines impinge on sacrificial water-cooled plates that will have to be replaced periodically before they erode enough to uncover a coolant channel. Each divertor segment has an access door to the divertor's interior. This door is about 1 m^2 and utilizes differentially pumped, concentric metal gaskets. A special divertor service machine, located on the same reference dowels that position the blanket service machine, will work through that door to extract and replace wornout divertor armor.

Each of the 12 divertor service doors has a large circular pipe attached to provide continuous vacuum pumping of material entering the divertor. These vacuum pipes all connect to a master ring manifold under the reactor. The main vacuum pumps operate on the ring manifold and must produce a pressure estimated at 5×10^{-8} Torr in that manifold. This means that the divertor pressure can be about 10^{-7} Torr and that the plasma background pressure can be near 10^{-6} Torr.

The poloidal coils that produce the field separatrix are below the torus. The separatrix leads ions through slot-like apertures into the 12 divertor chambers. Because the coils in that location would be very hard to replace, two or more redundant coils will be provided. Should the primary divertor coil malfunction, it can be replaced by two adjacent coils that have appropriate current sharing to keep the field separatrix in the same location.

3.3.3. *Neutral Beams and Microwaves*

Steady-state operation of TORFA-D2 is achieved by continuous injection of 150 MW of 250-keV neutral beams, which maintain the plasma temperature against transport and radiation losses and drive the plasma current required for equilibrium.(8) The characteristics of the neutral beam injectors are shown below:

Beam energy (keV)	250
Injected power (MW)	150
Ion species (% D^-)	100
Overall electrical efficiency (%)	0.55
Number of injectors	6
Angles of injection	
At 45° to normal	4
At 20° to normal	2
Duct cross section (cm)	80×120

An overall efficiency of at least 55% is expected to be achievable using the Lawrence Berkeley Laboratory concept now under development, namely the Ehlers D^- ion source coupled to a transverse-field focusing accelerator. The ion beam is to be neutralized by the photodetachment method, using an oxygen-iodine laser now being developed at the Air Force Weapons Laboratory and TRW.

Startup of the plasma current is accomplished over a 20-s period by three steps: (1) Two MW of RF energy at the electron cyclotron frequency (~100 GHz) ionizes the low-pressure filling gas in the torus and increases T_e to about 10 eV. (2) The 10-Vs OH (ohmic heating) transformer establishes a current of approximately 500 kA at $n_e \sim 10^{13}$ cm^{-3}. (3) While the density is increased, neutral beams are, with the assistance of the increasing equilibrium field, injected to raise the current to its final value of 5.0 MA.

Only four neutral beam injectors are needed to sustain the plasma current. The OH transformer is not used after startup.

3.4. Plant Layout

The facilities required for operation of TORFA-D2 are listed in Table VIII (See Figs. 19 and 20). The general site arrangement is shown in Fig. 19.

3.4.1. *Reactor Building and Hot Cell*

Sections of the reactor building and hot cell are illustrated in Fig. 19. The reactor building holds TORFA-D2; it also serves as part of the radiation shielding system to protect operations in the rest of the plant. The walls and roof of this building are constructed of 2-m-thick concrete. The building also forms an integral part of the radioactivity confinement system (e.g., in the event of a tritium release). The building must be resistant to earthquakes and to wind-generated and accident-caused missiles.

The hot-cell facilities are provided so that major maintenance of reactor components can be carried out while the reactor itself is operating. Components are transported from the reactor building into the hot cell by overhead crane or by such surface transport as rails.

The reactor building is 60 m long, 50 m wide, and 40 m high. These dimensions are determined by the space need for the tokamak and neutral beam lines, component transport, lay-down areas for the PF coils, crane operations, and the maneuvering of

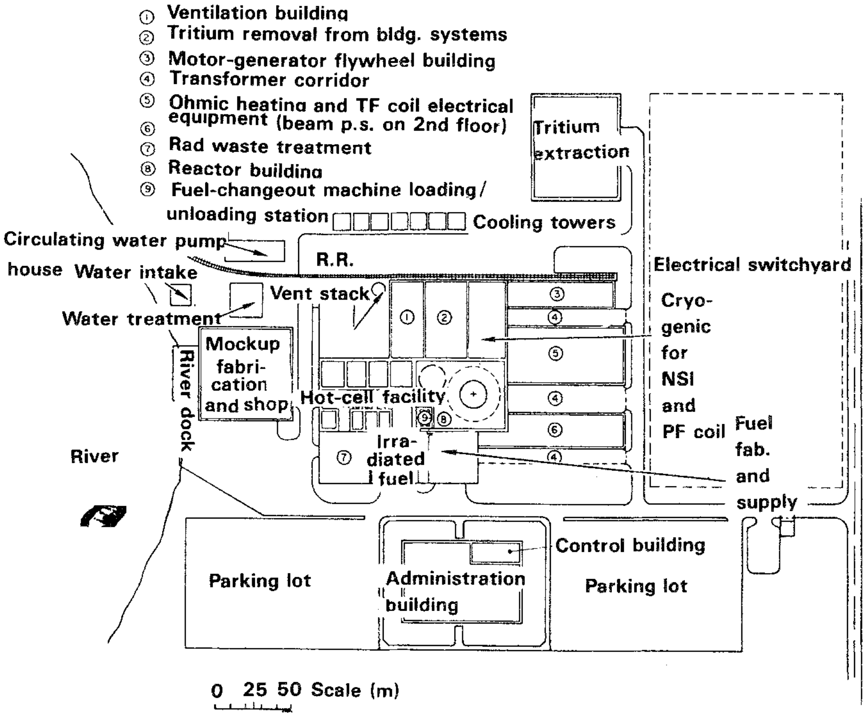


Fig. 19. Plant layout for tokamak TORFA-D2.

maintenance and blanket fueling equipment. The building height allows for clearance of the bucking cylinder and OH solenoid over the top of the reactor.

The basement area houses the vacuum pumps and heat exchangers for the plasma vessel and blanket ducts. This arrangement permits the potentially radioactive coolant systems to remain within the reactor building confinement boundary. Much of the piping and cables needed to operate TORFA-D2 will also come through the basement area.

The hot cell is a large general-purpose facility for the disassembly and repair of reactor components. It also contains smaller cells for decontamination and for storage of radioactive but reusable components. In overall dimensions, the hot cell is 75 m long, 50 m wide, and 30 m high. The walls and roof of the hot cell are constructed of 2-m-thick concrete, and the building is resistant to earthquakes and missiles. Both the reactor room and hot cell have controlled ventilation.

3.4.2. Heat Transport

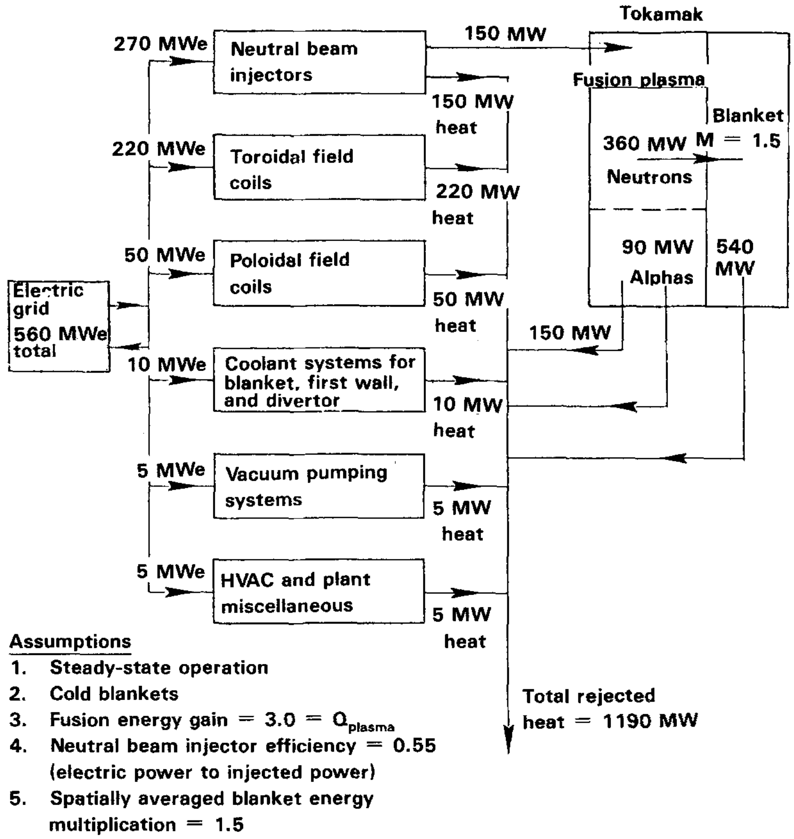
The magnets, blankets, vacuum vessel, and neutral beam injectors of TORFA-D2 are cooled directly by recirculating water. The total peak thermal power to be removed is 1190 MW.

Figure 20 shows an estimated power flow diagram for the TORFA-D2 reactor. This low-temperature blanket is not capable of producing electrical power with acceptable efficiency. (Further studies are planned with a higher coolant exit temperature. Electricity production, as a byproduct, may prove economically interesting.)

Figure 21 shows an estimated power flow diagram for the TMR for comparison purposes.

The primary purposes of the cooling-system structures are to house the circulating water system and to provide adequate heat-removal capacity. The cooling system consists of compressors, pumps, pipes, valves, heat exchangers, and cooling towers. (Heat conversion to electricity is an option recommended for consideration in a follow-on study.) The facilities required to support the cooling system include a water treatment building for purification, a water pump house, and cooling towers (see Fig. 19). Natural draft cooling towers, each of 100-MW capacity, are recommended to minimize operating and maintenance costs.

A water-intake structure obtains water from a nearby river for cooling-tower makeup. A water



Assumptions

1. Steady-state operation
2. Cold blankets
3. Fusion energy gain = 3.0 = Q_{plasma}
4. Neutral beam injector efficiency = 0.55 (electric power to injected power)
5. Spatially averaged blanket energy multiplication = 1.5

Fig. 20. Power-flow diagram for tokamak TORFA-D2.

treatment plant purifies the water according to its intended use; for example, the cooling water for the magnets must be deionized.

3.4.3. Facility Power

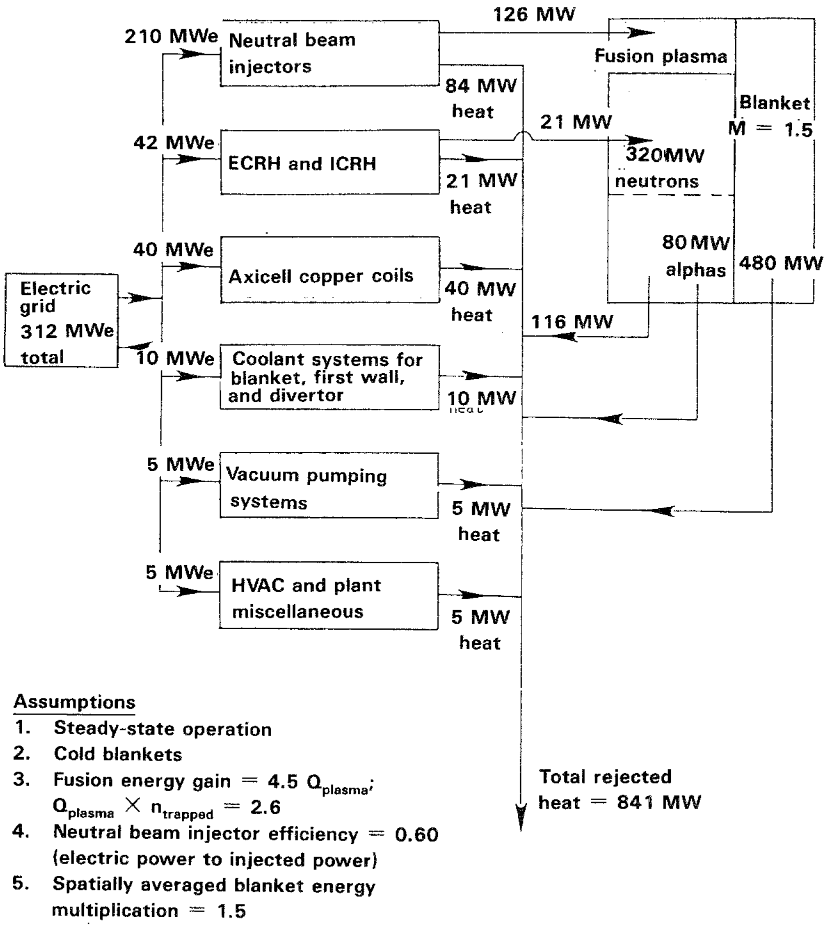
The steady-state power of 560 MW required to operate the magnets, neutral-beam injectors, and coolant and pumping systems is taken directly from the utility grid via transformer-rectifier systems (see Fig. 20). Pulsed dc power is also required during startup for the OH and EF systems and is obtained from 2 MGF sets delivering a total of 4 GJ. Following startup, the EF and divertor coils are operated directly off the grid, while the OH coils are deactivated.

Five buildings house the power-conversion systems:

1. TF coil electric equipment building.
2. OH and PF coil electrical equipment building.
3. Neutral beam injector power supply building.
4. MGF building, containing 2 MGF sets mounted in pits in the floor.
5. Diesel generator building, for emergency power.

The transformer corridors shown in Fig. 19 are required to bring ac power from the transformers mounted in the electrical switchyard to air-cooled rectifiers that may be mounted on the roofs of the buildings listed above.

The TF coils are fed by a 500-kA buswork system. Water-cooled copper buses are used inside the reactor building while large air-cooled aluminum slabs are used outside. To minimize bus separation forces, each copper bus has a concentric return while alternate aluminum slabs carry current in opposite directions.



Assumptions

1. Steady-state operation
2. Cold blankets
3. Fusion energy gain = 4.5 Q_{plasma}; $Q_{plasma} \times n_{trapped} = 2.6$
4. Neutral beam injector efficiency = 0.60 (electric power to injected power)
5. Spatially averaged blanket energy multiplication = 1.5

Fig. 21. Power-flow diagram for TMR.

3.4.4. Auxiliary Buildings

The auxiliary buildings are listed in Table VIII and include the electrical power buildings discussed in the previous section. The radioactive waste building houses the processing and packaging systems for disposal of the low-level radioactive wastes produced within the plant. The control room, which is part of the administration building, houses the plant operators. The mockup and shops building provides space for full-scale mockups of reactor sectors, as well as electrical, mechanical, and vacuum shops. The small cryogenic building supplies liquid helium for the super-conducting PF coils and for some vacuum pumping systems.

The ventilation building holds the voluminous equipment needed to control the air flow and also provides for tritium cleanup within the reactor building, hot-cell facility, and adjacent areas.

3.5. Cost of Plant

The following guidelines were used to develop cost estimates:

1. All costs are in 1982 dollars.
2. Direct capital costs include procurement, fabrication, and shipping.
3. Indirect costs include (a) engineering, design, and management (30%); (b) inspection, installation, and assembly (10%).
4. R&D costs are omitted.

Table VIII gives the estimated direct costs of the major components of TORFA-D2. Adding a 300% overall contingency to the sum of the direct and indirect costs gives a total capital cost of $2060 million.

Table VIII. Cost Estimates ($Millions) for TORFA-D2

Magnet systems		148
TF coils	113	
PF coils	22	
Bucking cylinder	2	
Intercoil structure	8	
OH solenoid	3	
Shielding (excludes blankets)		45
Cooling systems excludes blankets)		34
Refrigeration	3	
Heat-transport loops	16	
Cooling tower	15	
Tritium handling and pellet injection		45
Primary fuel cycle	13	
Detritiation systems	18	
Cleanup systems	14	
Plasma heating		315
Neutral beam systems	300	
RF systems (ECRH)	15	
Electrical systems		86
PF electrical	38	
TF electrical	12	
AC power conversion	36	
Vacuum system		43
Vacuum vessel	22	
Divertor modules and ducts	18	
Vacuum pumps	1	
Torus support	2	
Blanket		103
Neutron multiplier ducts and cases and miscellaneous	100	
Structure	3	
Blanket cooling system		45
Heat-transport loops	25	
Cooling tower	20	
Instrumentation and control		67
Plasma and blanket diagnostics	32	
Information and control systems	35	
Remote maintenance equipment		60
In reactor building	33	
In hot cell	27	
Blanket fuel-changeout machine		12
Facilities		175
Reactor building	44	
Hot cell	41	
Electrical equipment building	8	
Mockup and shop building	11	
Tritium processing building	14	
Ventilation building	12	
Radioactive waste building	6	
Administration building	4	
Fuel-fabrication building	5	
Site improvements	12	
Cryogenics building	3	
Electrical equipment building	15	
Total		1178

Some additional cost information is included in the following subsections.

3.5.1. *Magnets*

The cost of the copper magnets is taken as \$35/kg fabricated. That of the stainless steel support structure for the TF coils is taken as \$22/kg fabricated.

3.5.2. *Neutral Beam Injectors*

The actual cost of neutral beam injectors for the TFTR and the estimated cost for future test reactors is about \$2/W of injected beam. We use this value in our costing studies.

3.5.3. *Microwaves*

Radiofrequency sources providing 200 kW for 10-ms pulses at 60 GHz exist today. High-pulsed sources in the frequency range 90–100 GHz are presently under development and are projected to cost \$7/W.

3.5.4. *Electrical Systems*

The cost of transformer-rectifier systems is taken as \$100/kW and that of MGF sets is taken as \$1500/MJ. See Fig. 20 for the power requirements of the reactor subsystems. The cost of the neutral beam power supplies is included in the \$2/W quoted above.

3.5.5. Shielding

Enough shielding is included around the breeding modules and such penetrations as neutral beam ducts that the radiation dose level at the outside of the shielding is no more than 5 mrem/h at 48 h after reactor shutdown. The shielding pieces are constructed of water-cooled stainless steel and borated concrete.

3.5.6. Tritium Handling

The tritium handling systems include:

1. Primary fuel-cycle systems ($13 million)—to process the pumping efflux, separate the tritium from deuterium and impurities, and reinject the tritium as pellets or as gas-feeding neutral beam injectors.
2. Secondary systems ($18 million)—for detritiation of water and low-level wastes.
3. Cleanup systems ($14 million)—to clean the reactor and hot-cell buildings.

3.5.7. Heat-Transport System

The cost of 300-psi water-pumping systems is taken as $20 per gal/min. The cost of cooling towers is taken as $20/kW.

3.5.8. Buildings

The cost of each building is essentially proportional to its volume, which is given in Table IX.

3.5.9. Cost of Blanket

Blanket costs are totaled for both breeding ducts and cassettes and represent the blanket when "empty." That is, no breeding material in the form of

Table IX. Buildings and Site Facilities

Building or Facility	Approximate volume (m^3)	Approximate floor area (m^2)
Reactor building and hot-cell facility		
Reactor building	145,000	3,280
Hot-cell facility	130,000	4,060
Power-supply and energy-storage building		
TF coil electrical equipment building	40,000	4,000
OH and PF electrical equipment building	37,840	3,784
Bulk heating electrical equipment building	8,000	800
Motor generator flywheel building	26,000	1,300
Miscellaneous buildings		
Cryogenic building	7,000	700
Tritium recirculation building	52,200	1,740
Ventilation building	43,500	1,450
Radioactive waste building	16,000	1,600
Control room building	(4,500)	(450)
Diesel generator building	5,120	512
Administration building	54,000	5,400
Service building		
Mockup and shop building	196,000	4,900
Fuels buildings		
Fuel-fabrication building		
Irradiated fuel building		
Cooling system structures (recirculating water)		
Intake structures (river)	1,350	225
Discharge structures		
Intake and discharge conduits		
Recirculating structures	6,750	675
Cooling towers		

Table X. Volume Fraction (%) of Blanket Components

Aluminum guide tubes	1.0
Fuel slugs	11.0
Neutron multiplier	79.4
Structure	3.5
Coolant	5.0
Pull cables	0.1

slugs or rods is included. The gross volume of the blanket costed here is 1.44×10^8 cm^3.

The structure enclosing the ducts and cassettes is assumed to be stainless steel and worth \$19.50/kg as fabricated and assembled. The guide tubes are aluminum and will average about \$210/kg, considering accurate forming, good surface finish, and special packaging for shipment. The beryllium cost is the same as for the TMR blanket on a unit-cost basis. The material fractions present are shown in Table X.

The cost summary is given in Table XI. Section 2.5.6. substantiates the unit costs in Table XI.

3.5.9.1. Beryllium Cost. As with the tandem mirror reactor blanket (see Section 2.5.6.2.), the beryllium neutron multiplier will probably be cold pressed from powder and then sintered to about 98% theoretical density. The parts will be similar to those used in the TMR and will have maximum dimensions of about 10 cm.

The same cost estimates apply and, with a thin coat of aluminum for corrosion protection, the unit mass price is estimated at \$495/kg. This totals \$99.5 million for all the TORFA-D2 blanket sections.

3.5.9.2. Guide-Tube Cost. The aluminum guide tubes will have the same total mass as the jackets on the breeding slugs. Fabrication costs per unit mass are about the same, but handling and packaging for shipment are much more difficult. The reactor requires about 2500 tubes, many as long as 13 m, bent in a U-shape. We estimate the cost per tube at \$500 and the total at \$1.3 million.

3.5.9.3. Duct Cost and Cassette Case Coat. The duct and cassette structure represents about 4% of the gross volume of the breeding blanket zone. Also required is a water reflector at the back of the breeding zone; the container for that water is costed as part of the ducts.

The total volume of the breeding zone is 1.44×10^8 cm^3. The duct structure is aluminum. The water reflector casings add about 60% to the blanket volume (some duct regions are not backed by water reflectors). We estimate the 15,500 kg of blanket duct structure will increase to 25,000 kg when reflectors are added.

Unit cost is estimated at \$50/kg for aluminum structures of that size and shape. The casings for the entire blanket consist of the following:

1. 12 inner blanket ducts
2. 6 outer blanket "long" ducts
3. 6 outer blanket "short" ducts
4. 6 outer blanket cassettes
5. 12 top blanket cassettes
6. 12 bottom blanket cassettes

The total cost for the empty structures is estimated at \$1.25 million.

3.5.10. Tokamak Refueling Machine

With no specific design, there is only one way besides by comparison to estimate the cost of the refueling machine—by its size and shape and material density. The overall size of the machine is known approximately. A reasonable estimate of material density can be deduced from the type of construction required. We can also compare this type of machinery to similar machinery whose unit cost is known (\$/unit mass).

1. Size and shape: 10 m high × 3 m wide × 5 m long = 150 m^3.

Table XI. Blanket Costs

Material	Volume (%)	Density (g/cm^3)	Mass (kg)	Unit cost (\$/kg)	Cost (\$M)
Aluminum	1.0	2.7	3,888	50.0	0.2
Beryllium	79.4[a]	1.81	207,000	495.0	102.0
Stainless steel	3.5	7.85	39,564	19.5	0.8
Total					103

[a] 98% full density.

2. Approximate material density 20% that of solid steel = 1.57 tonne/m^3.
3. Unit cost = \$50/kg.

The total cost of the refueling machine is then estimated to be about \$12 million.

3.6. Fusion Reactor Component Replacement

3.6.1. *Guidelines*

The maintainability guidelines for TORFA-D2 are as follows:

1. Shielding must be segmented so individual reactor components such as breeding modules or loops can be removed singly. Shield segments should be removable by straight vertical or radial motion.
2. Divertor modules must be removable without disturbing other equipment (except shielding).
3. The joints of vacuum vessels must be accessible for leak detection and repair.
4. Access to coolant and electrical connections, including breeding module service connections, is required for remote coupling/uncoupling hardware.
5. TF coil joints must be readily accessible for semicontact disassembly (after removal of shielding).
6. All vacuum-vessel penetrations (heating, fueling, or diagnostics) require isolation valves so that injectors and diagnostics can be replaced without disturbing the vacuum integrity of the plasma vessel.
7. The ion sources in the neutral beam injectors must be accessible for remote replacement.

3.6.2. *Procedures*

With the exception of the breeding modules, the basic maintenance concept for TORFA-D2 is essentially the same as that for FED-R, a similarly sized test reactor being studied at the FEDC.$^{(6)}$ The disassembly concepts developed for FED-R are illustrated in Fig. 22.

1. Remove pellet injector.
2. Disassemble upper PF coil coolant and electrical connections and support columns from lower coil (12).
3. Remove upper coil with attached supports to laydown area.
4. Install jackstands under lower PF coil.
5. Disconnect and remove vacuum ducts.
6. Unbolt lower PF coil support columns at floor (12).
7. Lower PF coil clear of TF coil.
8. Disassemble and remote intercoil structure.
9. Disconnect TF coil coolant manifold and electrical connections.
10. Disassemble TF coil joints (2).
11. Install lift fitting and attach overhead crane hook.
12. Install upper and lower jackscrew fittings, remove bolts, and separate joints.
13. Translate coil leg radially outward and up.

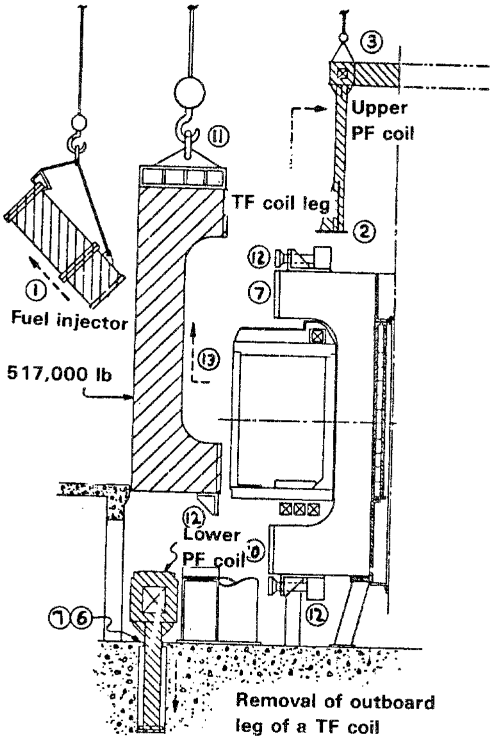


Fig. 22. Basic disassembly scenario for the FED-R, showing 13 required operations.

A preliminary list of basic maintenance equipment for the fusion device magnets includes the overhead crane, hoist cables, lighting fixtures for the TF coil outboard legs and upper PF coil segments, TF coil bolt extractors (1.7 m pull), TF coil joint separators, and jackstands.

3.6.3. Removal of PF and TF Coils

Each internal PF coil has three joints located at 120° intervals. Through bolts at each joint clamp the individual turns together. The PF coils are removed by first removing two TF coil outboard legs, then unbolting the PF coil joints and withdrawing the three segments.

Each TF coil has two joints, each containing about 50 fingers. The joints can be disassembled by semicontact operation (i.e., with long-handled tools) because the dose rate at the joint is 20 mrem/h at 48 h after reactor shutdown. A TF coil outboard leg weighs about 250 tonnes.

After the two joints are disassembled, the coil leg is moved 1.5 m radially outward, then lifted vertically. The total time for this operation is 100 to 150 h, which is dominated by the time needed to disassemble the joints. A reduction in time may be possible if alternate concepts for demountable joints are used.

After one or more outboard TF coil legs are removed, internal components such as PF coils and vacuum vessel sections can be retracted as shown in Fig. 22. Divertor modules can be replaced without prior disassembly of a TF coil.

3.7. Blanket Replacement

3.7.1. Material Replacement Time and Cost

In each 30° segment of the tokamak are about 120 chains of breeding slugs that must be replaced. Each segment also has fuel rods from cassettes that must be changed periodically. Segments that do not have beam ports have 96 breeding rods divided among two cassettes. Those segments with beam ports have an additional 240 short rods in the cassette above the beam port.

We believe it will be most economical to remove the entire cassette assembly and replace it with a complete new assembly. The removed cassettes would return with the service machine to its shielded parking area in the reactor bay. From that point, the cassettes could be transported to the fuel-processing building in a heavily shielded shuttle car traveling in a tunnel parallel to the one containing the slug conveyor belt. The same shuttle car would return with emptied cassettes, which it would deliver to the fuel preparation facility for reloading with new rods.

The blanket configuration permits the fuel-changing machine to remove two or three cassettes simultaneously (depending on the segment being serviced). This removal and reassembly operation would require one 8-h shift.

To changeout the duct fuel chains, the fuel-changing machine must be turned 180° and be remounted on the floor dowels. Replacement of the 120 fuel chains would probably be accomplished in three groups of 40 each. The machine will have to return to its shielded parking station after each group of 40 chains has been replaced to get a new supply of slug chains. This operation will require about two 8-h shifts when turnaround and resupply are included. Therefore, one full day is occupied by the fuel change of one segment. Since blanket sections will be missing during this scenario (the cassettes), neutron production will have to stop during this period. The copper magnets will be shut off during fuel change. This added time for shutdown and restart adds perhaps 4 h to the overall time, making a total of 28 h.

If total blanket fuel replacement is desired in all 12 segments, we predict that the time required will be 14 days. A cycle period of 2 months would result in 77% reactor availability if routine maintenance can be completed during the blanket-change period.

Should zoned breeding be advantageous, the above scenario would have to be changed. The top and bottom cassettes would be changed less frequently because they represent the rear zone of the blanket. Other rear zones are present in the ducts, so individual guide-tube rows would also have to be changed less frequently.

3.7.2. Beryllium Refabrication

Impurities (principally iron and nickel) can be minimized but not totally eliminated in the beryllium blocks. This neutron multiplier is likely, after several years' exposure to thermonuclear neutrons, to show swelling, spalling, and cracking. The coolant may also corrode unplanned exposed surfaces that are not protected by the aluminum anticorrosion layer.

It may be necessary to replace the beryllium several times during the 40-y life of a production reactor. Removal and total disassembly of the ducts will be necessary. The total and bottom cassettes may never have to be refabricated because they are at the rear of the blanket.

Once the other duct wall is cut away, the beryllium blocks can be removed by a robot. Neutron activation of trace impurities will make this necessary. To separate plated aluminum, the beryllium will have to be chemically treated. Each block will then be reduced to powder (chips) by grinding or other mechanical abrasion. It may prove desirable to melt and zone-refine the beryllium to remove impurities resulting from corrosion chemistry. If so, formation of the powder would be accomplished after melting and recasting of billets.

The same pressing, sintering, and machining operations used to make the first set of blanket parts can be employed on reprocessed beryllium, but they must be carried out remotely! The impurities present in the beryllium will still contain dangerous levels of induced radioactivity. Our national resources of beryllium are insufficient to consider disposing of thousands of tonnes of "used" beryllium and reconstructing the blanket with virgin material.

4. CONCLUSIONS

4.1. Qualitative Comparison of the Two Reactors from Mechanical Design Point of View

4.1.1. General Shape

The obvious difference between the tandem mirror and tokamak reactors is the compact form of the TORFA-D2 "donut" when contrasted to the linear form of a tandem mirror. The overall building volume required to house a tokamak is about two-thirds that required for a tandem mirror of the same fusion power. The tandem mirror, however, has the advantage of practicality in its shape besides the obviously simpler manufacturing geometry of a cylinder versus a torus. Two blanket servicing machines, one planting and one harvesting, can easily work simultaneously on a TMR (one above the central cell and one below).

The tokamak can only be approached from one side, the outside of the torus. Poloidal field coils and machine supports preclude access from above or below. The presence of TF coils restricts access to the outside of the torus. The tandem mirror also has magnets covering 30 to 50% of the central cell, so neither design has an advantage.

The blanket servicing machine for the tokamak must be larger and hence heavier than that for the tandem mirror. It plants and harvests, one function above the other, simultaneously. For complete blanket service, this heavier machine must be lifted 12 times from one operating position to the next. It cannot roll on a circular track because of the presence of six neutral beam source boxes (see next section).

4.1.2. Beam Aperture

The central cell of the tandem mirror reactor does not have neutral beam apertures. All beam injection in a tandem mirror is into the barrier cells and quadrupole anchors that provide the end plugs for the reacting plasma column. The fractional coverage of central-cell plasma by the breeding blanket reaches about 95% even when end-loss neutron streaming is taken into account. The tandem mirror also has reacting plasma in nonblanket regions of the end plugs. No calculation of this effect has been completed. We estimate that this end-plug rate could reach 10 to 15% of the total rate and that overall neutron losses could reach 15–20%.

Plasma heating in the TORFA-D2 tokamak is accomplished by direct beam injection into the reacting plasma toroidal column. The amount of energetic beam required calls for six beam ports. Half of the 12 TF coil intervals must provide a window for beam entrance. The blanket coverage in that window is sacrificed. The necessary position of that window is "prime real estate" for the blanket since neutron wall loading tends to be greater in equatorial regions at the outer wall. We estimate that 17% of the 14.6 MeV neutrons are lost due to incomplete blanket coverage because of beam ducts and other penetrations, especially the divertor hardware.

4.1.3. Magnets

The tandem mirror reactor has copper insert coils in the end-barrier cells. The requirement for magnetic fields in excess of 20 T in those regions forces us to use normal conductor. Only those parts of the barrier coils that experience fields of less than 15 T can be of niobium–tin superconductor. Where the field drops below 9 T, niobium–titanium will be used. The power consumed by the copper inserts has been calculated to be about 60 MW. All other magnets in the tandem mirror reactor are superconducting, both in the central cell and the end plugs.

The TORFA-D2 tokamak reactor uses normal, water-cooled copper TF coils. Also, those PF coils that lie within the TF coil loop are normal copper. Two poloidal coils that lie outside the TF coils are planned to be of niobium–titanium superconductor. The power consumed by all the normal copper magnets is 270 MW.

The normal coils are demountable. In weeks, they permit maintenance and repairs to be made that would require a year or more if the TF coils were superconducting. This demountable design greatly lowers the time and cost of scheduled maintenance. It also reduces the consequences of unplanned reactor shutdown.

4.1.4. Blanket Comparisons

The construction and serviceability of the tandem mirror reactor blanket modules give it several advantages over the tokamak.

1. The cylindrical shape of the tandem mirror simplifies fabrication.
2. Having the blanket integrated with the tandem mirror first wall simplifies maintenance because disassembly requires fewer remote operations.
3. One service machine offers access to the top of the blanket, while a second machine offers separate access to the underside of the reactor. These fuel-change machines roll on tracks and access any section of the breeding blanket unhindered by beam lines.
4. The mechanical failure of a module is remedied by removing that unit and replacing it with a standby module. The tokamak repair scenario depends on failure location. If the fault is in the outer duct, repairs can be effected simply by removing that duct. If the inner duct is involved, a complex disassembly procedure must be followed. Separate first-wall segments cause the added complication.
5. The blanket is rigidly attached to a simple support base through the integral shield. Tokamak blanket sections are supported separately on various sections of the machine frame. Tokamak biological shields are also mountred separately and must be removed individually before blanket maintenance.
6. Blanket coverage is more complete in a tandem mirror reactor. The TORFA-D2 tokamak has torus-segment support frames about 10 cm thick. These, along with the torus-segment flanges that must also be "inside" the blanket, cause a nontrivial amount of parasitic neutron capture.

The tokamak has two advantages over the tandem mirror:

1. Cassette blankets are light and can easily be removed and replaced.
2. Outer ducts are simple to replace once shield segments are removed.

4.1.5. First Wall and Vacuum Seal

The first wall of a tandem mirror reactor is not subjected to the severe surface heat load experienced by the tokamak. Neutron energy deposition for the two designs will be comparable.

We plan to install a separate cooling circuit for the first wall in both reactors. To handle the high surface heat load, the circuit in the tokamak will be larger. Coolant supply in the tandem mirror reactor can be from the circuits used to water-cool the shield. The coolant supply to the tokamak first wall will come from manifolds attached to the permanent frame structure. Separate plumbing connection operations must be completed during the blanket-assembly scenario.

The two first-wall designs were influenced strongly by the vacuum seal design and by the need to provide for thermal expansion and swelling. The cylindrical blanket/shield of the tandem mirror reactor allows the vacuum seal to be circular and at the back of the shield. However, it is quite large, having a mean diameter of over 5 m. The modules have about a 2-cm axial separation in the blanket area near the plasma, so thermal and irradiation growth can be readily accommodated.

The tokamak has its vacuum envelope inside the blanket, which leads to a structurally separate torus composed of 12 similar wedge-shaped segments (6 with and 6 without beam ports). The segments are mounted to the machine frame by 12 vertical window-frame structures that rise from the rigid base plate of the reactor. These "window frames" carry pressurized seal diaphragms and their own cooling provisions. Each torus segment has two end flanges that provide the seal contact surface. The segments must be clamped or bolted to the vertical frames to provide seal reaction force. As can be seen in Fig. 16, the inboard half of the flange perimeter is inaccessible to humans or robots. The frames in that region are provided with wedge-shaped sockets that trap the flanges and take the seal force. The outboard half of the flange perimeter will be clamped in one of two ways. Using specially designed bolts and nuts that can be easily removed by remote maintenance tools is one approach. The other is to use quick-acting clamps—perhaps hydraulically or pneumatically operated—that grip the flange and frame. Because space is very limited, the bolt solution looks most attractive. Also, clamps represent a lot of mass for the parasitic capture of neutrons.

The seal in the tokamak is also composed of concentric inflatable metal diaphragms, and its shape is similar to the racetrack or oval. While its major dimension is similar to the tandem mirror reactor seal, it is only about half as wide. The noncircularity of the seal will make it more expensive than the tandem mirror design.

The lower third of the vacuum torus is occupied by a plasma divertor. This cavity will contain replaceable, water-cooled plates on which escaping ions impinge. To cool these divertor plates will require quantities of water comparable to the coolant demands of the first wall. Integration of the divertor into the plasma chamber causes the seal dimensions of the TORFA-D2 to approach those of the tandem mirror reactor.

4.1.6. Repair and Maintenance of Breeding Blanket

We have divided our comments on repair and maintenance into four categories: (1) tandem-mirror-reactor good features, (2) tandem-mirror-reactor difficult problems, (3) TORFA-D2 good features, and (4) TORFA-D2 difficult problems. The order of listing is not an indication of relative importance.

4.1.7. Tandem-Mirror-Reactor Good Features

1. Cylindrical central cell
2. Many short identical modules
3. First wall part of blanket
4. No beam injection in blanket area
5. Module replacement by simple crane and transporter motions
6. Shield, magnet, and cradle are reusable to assemble a "standby" module

4.1.8. Tandem Mirror Reactor Difficult Problems

1. Assembly of guide tubes, neutron multiplier, and flow baffles. Many pieces must not be free to vibrate when in operation. Hydraulic excitation from flow turbulence is a strong energy source.
2. The large-diameter vacuum seal requires a withdrawal scheme to create clearance for module removal. The roll-sock seal or welded bellows, both of which are expensive to fabricate, are the only methods that might have enough flexibility to provide several centimeters of clearance.
3. The swelling and cracking of beryllium may necessitate rebuilding the blanket from reprocessed beryllium. The beryllium will be radioactive from impurity activation, and it will cost more to process it than to fabricate new pieces from virgin material. The limited resources of beryllium may compel the use of reprocessed beryllium.

4.1.9. TORFA-D2 Good Features

1. Cassettes are light and easy to replace. The small outer ducts under the beam ports are also easy to replace.
2. The outer duct of the blanket is comparatively light and can be replaced without disturbing the plasma vacuum.
3. All blanket components can be removed without disturbing either the TF or PF coils.
4. Guide-tube bends are simple. Most tubes lie in a single plane.

4.1.10. TORFA-D2 Difficult Problems

1. To extract the inboard blanket duct, one must remove both the outer ducts and the torus vacuum segment. These complex remote operations call for highly specialized service tools.
2. Because of the swelling and cracking of

beryllium, we may have to rebuild the blanket from reprocessed beryllium. The beryllium will be radioactive from impurity activation, and it will cost more to process it than to fabricate new pieces from virgin material. The limited supply of beryllium may compel the use of reprocessed beryllium.

3. The oval vacuum seal is comparatively difficult to build.
4. The many pieces composing a duct assembly must not be free to vibrate due to hydraulic excitation.

5. SUGGESTIONS FOR TECHNOLOGY PROOF TESTING

5.1. Fuel Slugs

5.1.1. Cladding

Breeding-slug design will have an important cost impact. Several methods can be used to apply cladding to breeding alloys. The methods of construction should be tested, and careful cost comparisons should be made. Many millions of slugs will be processed over a life of a production reactor.

5.1.2. Slug-Chain Tests

Pulling long chains of fuel slugs through the blanket sounds simple; however, there are some potential problems. All of the guide tubes must be curved, and some will require smaller bend radii than will others. Friction, which is the most important factor, will be determined by the number of bends and the radius of each turn. The inside surface finish of the guide tubes and the need for special coatings must be investigated.

The clearance between the pull cable and the bore of the hole down the center of the fuel slug could be crucial to success. The pull cable exerts forces as a compression on the back of the column being pulled. The individual slugs may tend to turn sideways in the tube depending on the ratio of their length to diameter, the presence of low-friction "piston rings" on the slugs, the diametrical clearance between the slug and guide tube, and the pull-cable hole clearance. We suggest that this fuel-chain concept be tested with dummy slugs having the dimensions and cladding of the actual slugs, as well as a variety of tube bend radii.

Another series of tests using the same components, but without employing the pull cable, should be run to push the slugs through the tube. The cable can possibly be eliminated, reducing parasitic neutron losses and providing more space for breeding.

5.1.3. Remotely Operated Chain Connectors

Remotely operable connectors for the ends of the fuel chains should be designed and tested. Since many chains must be pulled simultaneously, these connectors must be simple, inexpensive, compact, and highly reliable.

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APPENDIX A: COST COMPARISON SUMMARY

Components	Tandem mirror	Tokamak
Magnets		
End plug and shields	188	
Central cell	30	
TF coils		113
PF coils		22
Bucking cylinder, OH solenoid, and intercoil structure		13
Neutral beams at \$2/W	200	300

Shields	54 (Central cell)	45
Microwaves	100	15
Electrical systems		
PF electrical		38
TF electrical		12
AC power conversion		36
Direct converter and power conditioning	6	
Copper coil electrical	10	
Vacuum system vessels	38	22
Divertor modules and ducts		18
Pumps		1
Cryopanels and refrigeration	10	
Outgas cyclers and roughing	10	
Torus support		2
Blanket		
Beryllium (neutron multiplier)	84	100
Structure	2	3
Instrumentation and control	40	
Plasma and blanket diagnostics		32
Information and control systems		35
Tritium handling and pellet injection (excludes blanket processing)	45	45
Remote maintenance equipment	50	
In reactor building		33
In hot cell		27
Breeding-slug changeout machines	22	12
Cooling systems		
All coils and accessories	23	19
Cooling towers	15	35
Blanketing first wall	22	25
Facilities		
Reactor building	55	44
Hot cell	12	41
Electrical equipment building	12	8
Mockup and shop building	11	11
Tritium processing building	12	14
Ventilation building	8	12
Radioactive waste building	6	6
Administration building	4	4
Site improvements	12	12
Transfer tunnels	15	—
Cryogenics building	5	3
Electrical equipment	15	15
Electrical bulks (see electrical systems)	65	—
Fuel-fabrication building	5	5
Totals	1186	1178

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