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Fusion Power Demonstration III

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Participants

Lawrence Livermore National Laboratory

W. L. Barr, R. H. Bulmer, S. R. Devoto, J. N. Doggett,
J. D. Lee, B. G. Logan, L. J. Perkins, and W. S. Neef

Oak Ridge National Laboratory, Fusion Engineering Design Center

G. T. Bussel, S. A. Freije, G. E. Gorker, J. R. Haines,
W. R. Hamilton, S. S. Kalsi, D. C. Lousteau, W. D. Nelson
P. T. Spampinato, V. C. Srivistava, and G. E. Taylor

Grumman Aerospace Corporation

I. R. Clarkson and T. E. Luzzi

TRW

R. B. Campbell and M. E. Fenstermacher

General Dynamics/Convair Division

K. L. Agarwal, R. W. Baldi, J. E. Burgeson,
J. Farmer, S. D. Peck, and J. C. Yu

Bechtel

S. Ghose

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SCOPE

This is the third in the series of reports covering the Fusion Power Demonstration (FPD) design study. This volume considers the FPD-III configuration that incorporates an octopole end plug. As compared with the quadrupole end-plugged designs of FPD-I and FPD-II, this octopole configuration reduces the number of end cell magnets and shortens the minimum ignition length of the central cell. The end-cell plasma length is also reduced, which in turn reduces the size and cost of the end cell magnets and shielding.

As a continuation in the series of documents covering the FPD, this report does not stand alone as a design description of FPD-III. Design details of FPD-III subsystems that do not differ significantly from those of the FPD-II configuration are not duplicated in this report. The reader is referred to the report, Fusion Power Demonstrations I and II (UCID-19975-1), for system descriptions that are not covered in this document.

Section 1

Introduction

1.0 INTRODUCTION

This report describes the third configuration in the Fusion Power Demonstration (FPD) design study. The device described, FPD-III, is an octopole-plugged tandem-mirror device designed for a minimum-length, ignited central cell. This design differs from FPD-I and FPD-II,¹ which were both designed as minimum-length "engineering-breakeven" devices.

The FPD-III configuration is the first complete design of a reactor incorporating the octopole end plug. The octopole end plug makes use of a coil set in the plug that generates a four-finned plasma cross section instead of the two-finned shape generated by the quadrupole magnets used in earlier FPD configurations. With the octopole end plugs, the hot plug plasma has a high degree of axisymmetry. This is an advantage over quadrupole devices because the transition region between the choke coil and the plug is relatively short. This short transition reduces the central cell losses and, therefore, reduces the minimum central cell length for ignition. We reduced the central cell length from 96 m in FPD-II (a quadrupole design) to 31.5 m in FPD-III. This dramatic reduction in ignition length would in fact allow us to construct an ignited tandem mirror device in the existing Mirror Fusion Test Facility (MFTF-B) vault.

The overall FPD-III configuration (Fig. 1-1) is similar to other recent tandem mirror designs. It has a relatively small diameter vacuum vessel, is configured for easy disassembly, and makes use of relatively thin-long solenoid magnets in the central cell. The end cells contain the choke, mirror, and octopole coils. Although the appearance of this end cell is quite different from the quadrupole, all of the plugging, stabilizing, and particle control properties are maintained.

The technology assumed for the FPD-III design is generally of the same level as employed in the two earlier iterations. The main parameters for FPD-III are the following:

Fusion power	142 MW
Central cell length	31.5 m
Overall machine length	67 m
Recirculating power	67 MW
First-wall neutron flux	0.86 MW/m^2
Direct capital cost (mid-1984 dollars)	1080 M\$

1-2

Fig. 1-1. The FPD-III configuration.

The principal conclusion from the FPD-III design study is that the octopole configuration shows great promise for reducing the size and cost of tandem mirror reactors.

REFERENCE

1. Fusion Power Demonstrations I and II, J. N. Doggett, Ed., Lawrence Livermore National Laboratory, Livermore, CA, UCID-19975-1 (1985).

Section 2

Plasma Engineering

2.0 PLASMA ENGINEERING

INTRODUCTION--THE RATIONALE FOR USING OCTOPOLE PLUGS

The plasma engineering tasks for FPD-III were performed to meet the following three design goals:

- The central cell should be ignited, i.e., the power deposited by the fusion alpha particles in the central-cell plasma volume should balance the total net power loss (leaking charged particles, bremsstrahlung, and synchrotron radiation) from that volume.
- The end-cell magnetic configuration should consist of an octopole coil and an essentially axisymmetric plasma core with magnetohydrodynamic (MHD) stabilization resulting from a combination of the octopole field and a hot electron mantle surrounding the core plasma.
- The central cell length should be the minimum capable of attaining ignition, and thereby achieving a minimum-length compact machine.

The previous phases of FPD, FPD-I and -II (Refs. 1,2), employed quadrupole end-cell magnetic configurations in the form of complex double yin-yang sets with recircularizing transition coils. Quadrupole coils provide a well-tested method to achieve a high-beta MHD stabilization in both a simple mirror^{3,4} and tandem mirror configuration.⁵ The plasma engineering basis for quadrupole-stabilized tandem-mirror-reactor operation was thoroughly investigated in the Mirror Advanced Reactor Study (MARS).⁶ However, during the final stages of the FPD-II study, we found that quadrupole plugs have two major disadvantages for tandem mirrors whether ignition test machines or reactors:

1. The end-cell magnet configuration is complex and expensive because a balance in the geodesic curvature of the nonaxisymmetric fields is required to limit the radial transport of passing ions. This balance is obtained with a double yin-yang assembly.⁶

2. The long characteristic length of the double quadrupole end-cell provides a large plasma volume for the trapping of passing ions from the central cell. Therefore, a long central cell is also required to obtain ignition of the central cell plasma, making it impossible to achieve either ignition test machines that are short and compact or power reactors that are economical and small.

It is important to note that FPD-II was configured with quadrupole plugs,² and we were unable to achieve ignition with a central-cell length of less than about 90 m. In contrast to the double quadrupole, the octopole end-cell configuration produces an essentially axisymmetric end-cell core plasma in an effective solenoidal simple-mirror geometry. In particular, as we will demonstrate below, the short end-cell lengths attainable with the octopole geometry enable us to achieve ignition with much shorter (~30-m) central-cell lengths.

It is interesting to note that the concept of higher order multipole geometries for fusion plasma confinement is not new. In 1961, for example, Gott et al.,⁷ reported the integration of hexapole windings on a simple mirror experiment. Similarly, at Lawrence Livermore National Laboratory (LLNL) in the early 1960's, low-frequency MHD stabilities in the simple mirror machine "ALICE" were effectively suppressed by using additional dodecapole (12-pole) and octopole fields.⁸ Baldwin⁹ investigated higher order multipoles to be used as plugs for tandem mirrors, and Hooper¹⁰ assessed the use of octopoles for the Tandem Mirror Experiment (TMX) at LLNL. In addition, Devoto et al.,¹¹ examined the underlying physics, magnetics, and stability issues for the octopole-stabilized tandem mirror. In addition, Perkins et al.,¹² developed the conceptual design of MINIMARS, which is an economical, compact, tandem-mirror reactor with octopole plugs. Therefore, a theoretical and experimental basis exists for the FPD-III octopole end-cell geometry.

THE PHYSICS BASIS OF FPD-III

The final magnet set selected for FPD-III is shown in Fig. 2-1, and a schematic of the plasma/magnet configuration is shown in Fig. 2-2. In Fig. 2-3, we show the axial distribution of the magnetic field and plasma potential. Note that because of cancellation symmetry, the octopole coil produces a zero net field on axis. Therefore, as Figs. 2-2 and 2-3 show, the near-axis field distribution in the end cell is that of a simple mirror formed by the choke coil and outer mirror coils. The solenoid-like turnaround connections of the octopole bars also contribute to the axisymmetric mirror field.

With the important exception of MHD and radial transport, the physics basis of the core plasma in FPD-III is analogous to that of previous thermal-barrier tandem-mirror machines (for example, see Ref. 6). The radial pressure of the deuterium-tritium (DT) fuel ions in the 31-m long central cell is contained by the 2.5-T solenoidal field, whereas the axial pressure is contained mainly by the high-field (24-T) choke coils at each end. Similarly, nearly all the 3.5-MeV fusion alpha particles are born mirror trapped in the central cell. A small fraction (<10%) of the central cell ions pitch angle scatter into the loss cone, pass into the octopole end cell, and then reflect off the positive plugging potential and return through the central cell. The magnitude of the potential peak (>200 kV relative to the central cell potential--see Fig. 2-3) reduces the central-cell ion end loss sufficiently to allow fusion alpha heating to sustain residual central-cell energy losses that mainly result from end-cell ion trapping. Therefore, the central cell is ignited. The MHD stability of FPD-III is obtained by means of the octopole field and a mirror-confined hot-electron mantle.

In addition to the ion-confining potential peak in the end cell, an intervening "thermal barrier"⁵ is required to moderate electron heat conduction from the peak and, therefore, to reduce end-cell electron-cyclotron resonant heating (ECRH) power. A depression in the end-cell ion density is formed by microstable sloshing ions fueled at each end by a 475-kV negative-ion neutral-beam source. Mirror-trapped hot electrons sustained by ECRH heating at the midplane of the sloshing ion distribution provide the

Fig. 2-1. The FPD-III magnet set (only one of the central-cell sheet solenoids is shown).

Fig. 2-2. Schematic of the FPD magnet and plasma configuration. The split outer-mirror solenoids are represented by a single coil in this figure.

Fig. 2-3. Axial distribution of magnetic field and plasma potential.

negative potential (approximately -186 kV relative to the central cell) required for the thermal barrier (Figs. 2-2 and 2-3).

A list of the principal plasma engineering parameters for FPD-III is given in Table 2-1.

THE OCTOPOLE MAGNETIC CONFIGURATION, MHD STABILITY, AND THE HOT ELECTRON MANTLE

Figure 2-4 shows an isometric view of the FPD-III octopole end-cell magnet set. The main outer octopole coil, located between the high-field choke coil and the outer mirror solenoid, is composed of four discrete window-frame coils and represents the culmination of a detailed study of optimum winding geometries.¹³ The discrete coil version of the octopole coil is preferred over a continuous-wound single-octopole coil because of better winding convenience and ease of maintenance. However, unlike the continuous-wound octopole, the turnaround connections at the outer end of the discrete octopole coil carry solenoidal-like currents that buck the main solenoid fields and contribute to problems in obtaining a sufficient mirror ratio in the mantle. Accordingly, the outer mirror field is formed by a split stepped solenoid that also cancels these deleterious bucking currents. Details of the magnet configuration are given in Table 2-2.

The conventional quadrupole magnetic geometry (e.g., the yin-yang coil pair) is characterized by a minimum- $|B|$ region at the center of the configuration and a field that increases in all directions away from this minimum. However, for higher order multipoles with order N greater than four, the minimum $|B|$ occurs off the central axis with a period $\cos(N\theta/2)$. In addition, the near-axis multipole field components decrease with increasing N , thus the higher the number of multipole bars, the more axisymmetric the near field will be. Because of access requirements, the number of conductor bars that can be placed around the azimuthal circumference is limited, we have selected an octopole ($N = 8$) configuration for FPD-III. In principle, the use of hexapole coils ($N = 6$) is possibly more advantageous because of less complex winding and improved access, although increased radial transport requires greater attention to detail in the design of the magnet set.¹⁴

Table 2-1. Principal plasma parameters for FPD-III.

General

Fusion power (MW)	141.7
Neutron wall loading (MW/m ²)	0.86
Q	11.9
Q _{eng}	≤1
Cold fueling current (A)	81.3

Principal magnetic fields

Central cell (T)	2.50
Choke (T)	24.0
End cell midplane (T)	1.50
End cell outer mirror (T)	8.57
Mantle minimum (T)	1.30

Central cell

Effective length (m)	31.5
Plasma radius (m)	0.45
First wall radius (m)	0.666
Ion temperature (keV)	44.0
Electron temperature (keV)	30.2
Ion density (cm ⁻³)	1.52×10^{14}
n_{ion} (cm ⁻³ s)	6.62×10^{14}
Average beta	0.6
Density profile	Quartic
Alpha density fraction	0.021

Table 2-1. (continued).

<u>End cell</u>	
Length (m)	8.05
Average midplane beta	0.220
Ion confining potential ^a (keV)	205.5
Barrier potential ^a (keV)	186.0
Electron confining potential ^a (keV)	203.3
Trapping current (A)	61.2
Passing density at b (cm ⁻³)	1.57×10^{12}
Peak-to-midplane sloshing-ion density ratio	2.83
ξ_{DT}	1.96
ξ_{α}	4.23
Hot electron energy at b (keV)	411.2
Warm electron energy at a (keV)	201.9
Absorbed ECRH power at a ^b (MW)	0.160
Absorbed ECRH power at b ^b (MW)	5.42
Absorbed neutral beam power ^b (MW)	0.132
Neutral beam trapping fraction (MW)	0.082
<u>Hot electron mantle</u>	
Average beta	0.692
Hot electron mirror ratio	2.0
Hot electron energy (keV)	850
Absorbed ECRH power ^b (MW)	6.22
Dissipated synchrotron power ^b (MW)	4.49
Dissipated scattered power (MW)	1.41
Dissipated drag power (MW)	0.308
Total mantle volume ^b (m ³)	~8

^aMeasured relative to the central cell potential.^bTotal--both ends.

Fig. 2-4. The end-cell octopole magnet set.

Table 2-2. End-cell magnet parameters.

<u>Axial Fields (T)</u>	
Choke coil	24.0
Midplane	1.5
Outer mirror	8.57
Mantle (minimum)	1.3
<u>Choke coil</u>	
Superconductor	Nb ₃ SnTi/Nb ₃ Sn/NbTi
Superconductor pack dimensions $\Delta z \times \Delta r^a$ (m)	1.709 x 0.517
	1.775 x 0.449
	1.975 x 0.196
Superconductor pack current densities ^a (A/m ²)	2.48 x 10 ⁷
	1.80 x 10 ⁷
	1.68 x 10 ⁷
Normal-conducting insert dimensions $\Delta z \times \Delta r$ (m)	0.6 x 0.39
Normal conducting insert current density (A/m ²)	2.48 x 10 ⁷
Normal conducting insert power consumption (MW)	12
Normal conducting insert field contribution (T)	8
Normal conductor material	AMZIRC
<u>Large octopole coil</u>	
Configuration	Discrete four-frame octopole
Winding pack dimensions (m)	0.48 x 0.48
Current density (A/m ²)	2.5 x 10 ⁷
Superconductor	Nb ₃ Sn
Mean radius at midplane (m)	2.29
Axial length of assembly (m)	3.68

Table 2-2. (continued).

Outer mirror coil

Configuration	Split solenoid ^b
Winding pack dimensions ^c (m)	0.25 x 0.47, 0.5 x 0.57
Mean radius (m)	1.61
Current density ^c (A/m ²)	5 x 10 ⁷ 5.5 x 10 ⁷
Superconductor	Nb ₃ Sn/NbTi

^aThree stacked solenoids.

^bTo cancel octopole turnaround bucking currents.

^cTwo split solenoids.

The magnitude of the octopole field relative to the solenoidal mirror field is varied by adjusting both the radial position of the octopole bars and the pack current density, thus placing the minimum $|B|$ outside the core plasma-flux bundle that maps from the central cell. We adjust the position and current of the small inner octopole coil (Fig. 2-4) to cancel any asymmetry of the core plasma at the midplane of the large octopole resulting from the residual octopole fields. This has the effect of substantially reducing the radial deflection of passing ions in the plug.¹¹ Appropriate configuration of this inner-trim octopole coil can ensure that confinement times resulting from ion radial transport in the octopole geometry are much larger than the characteristic times for trapping (and pumping) in the end plug.

The radial profile of the magnetic field at the midplane of the octopole plug is shown schematically in Fig. 2-4. Note that $|B|$ decreases with radius from the axial value to a local minimum and then increases as the coils are approached. We can state the condition for flute interchange stability of our system in terms of an integral along an entire flux tube as

$$\int \frac{1}{R_c r B^2(r)} \frac{\partial p}{\partial \psi} dl < 0 \quad (1)$$

where R_c is the vacuum field radius of curvature and $\partial p / \partial \psi$ is the gradient of the radial pressure profile with respect to magnetic flux ($\psi = \int B \cdot da$). Now our core plasma can be considered to be situated in two axisymmetric mirror regions, i.e., the central cell and end cell (Fig. 2-3), where the $1/rB^2(r)$ weighting always favors the bad curvature drive to the stability integral over the good curvature regions under the mirror coils. Moreover, our core plasma has a quartic pressure profile so that $(\partial p / \partial \psi)_{\text{core}} < 0$ (this behavior at the midplane of the plug is illustrated in Fig. 2-5). Therefore, it is impossible to satisfy Eq. (1) for the core plasma alone. Accordingly, we arrange for the region between the core plasma and the minimum $|B|$ region in the end cell to be filled by a mantle of hot mirror-confined electrons sustained by a separate ECRH system. The added plasma pressure here must be able to form a sufficiently large positive pressure gradient out to the minimum $|B|$ point to ensure that the

Fig. 2-5. Schematic radial profiles in the end plug.

mantle, of limited axial extent, satisfies Eq. (1) evaluated over the entire axial extent of the flux tube.

At radii greater than that of the minimum $|B|$ point, the mantle pressure can be allowed to fall to zero because this is now a good curvature region (Fig. 2-5). With suitable choices for pressure functions in the system, Eq. (1) can be solved for the required minimum mantle beta. We employed the results of Devoto et al.,¹¹ which, for a similar magnet set, showed that the required peak mantle beta ($\hat{\beta}_m$) could be expressed as a linear combination of the central-cell and end-cell betas ($\hat{\beta}_c$, $\hat{\beta}_b$) as

$$\hat{\beta}_m = 1.2 \hat{\beta}_b + 0.56 \hat{\beta}_c . \quad (2)$$

Stability against interchange does not, of course, ensure stability to ballooning modes at high β . However, finite Larmor radius (FLR) phenomena are expected to stabilize all ballooning modes except for $m = 1$. Calculations of this mode in quadrupole-stabilized tandem mirrors have yielded beta limits very close to those predicted by interchange criteria.¹¹ The MHD analysis for octopole geometries at high β is an important on-going research area.¹⁵

Although the end-cell core plasma is essentially axisymmetric, the mirror-confined hot-electron mantle surrounding the core plasma exhibits the characteristic four-pointed convoluted shape of the octopole field far from the axis. Moreover, the mantle occupies magnetic field lines that do not map through the machine; therefore electron scattering losses from this mirror region appear as surface heat loads on the surrounding shielding walls that are located under the large octopole coil. To limit both anisotropy-driven microinstabilities of the hot electrons and mantle ECRH-power requirements, we specify a mirror ratio of two or more for all field lines that pass through the mantle region. In addition, the mantle electrons must respond as an MHD fluid, not as a rigid body, to MHD instabilities in the core plasma and, therefore, must exhibit drift frequencies less than the characteristic MHD growth rate. Further details of the physics requirements for our mantle electrons are given in Ref. 11.

THE IGNITION CRITERION

As we indicated previously, the major raison d'être for the octopole end cell is that it enables ignition for a tandem mirror to be achieved with much shorter central cell lengths. The condition that must be met for ignition of a tandem mirror reactor is that the power deposited by fusion alpha particles in the central cell plasma must be greater or equal to all sources of power loss from this volume. Passing central-cell ions that undergo collisional trapping in the end cell between the potential peak and the choke coil magnetic field peak (see Fig. 2-3) must be removed (or "pumped") at the rate at which they trap, otherwise the end cell would fill with trapped ions and the thermal barrier would be destroyed. To provide this pumping in FPD-III, we configured drift-pump coils above and below the plasma in the end cell and effected a resonance between the coil frequency and the bounce frequency of the trapped ions. The resulting enhanced radial diffusion transports these ions to the unplugged halo plasma surrounding the core plasma, where they are swept to the grounded halo dumps at the ends of the machine.

The ion-trapping rate (and thus drift-pump loss rate) of ions in the end cell scales as the end-cell plasma volume, the square of the end-cell ion density, and the inverse of the central-cell ion temperature to the three-halves power. Drift pumping of trapped ions in the end cell represents the major power-loss mechanism from the central cell plasma (other losses such as axial ion losses and radiation losses are typically less than 10% of the total), thus we can represent the central-cell ignition condition as

$$r_c^2 L_c P f_\alpha \geq c r_{ec}^2 L_{ec} n_{ec}^2 T_c^{-3/2} + S, \quad (3)$$

where r_c , L_c , r_{ec} , and L_{ec} are the radii and lengths of the plasma in the central cell and end cell, respectively; P is the central-cell fusion-power density; f_α is an alpha-confinement factor (see below); n_{ec} is the end-cell ion density; T_c is the central-cell ion temperature; c is a constant; and S represents the small subsidiary central-cell losses (e.g., radiation losses). The implication of Eq. (3) is clear: as the length (and thus volume) of the end-cell magnetic configuration increases, the dimensions

of the central cell plasma must increase so that fusion alpha power can make good the power losses resulting from increased trapping in the end cell.

At this point, one is justified in asking why we cannot simply increase the central cell radius r_c . With this increase we could meet the ignition criteria with a corresponding reduction in the length L_c that would result in a short compact machine. However, in addition to ignition, a second important design criterion exists that must be met. This criterion is conservation of magnetic flux mapping through the machine, i.e.,

$$\pi r_c^2 B_c (1 - \langle \beta_c \rangle)^{1/2} = \pi r_{ec}^2 B_{ec} (1 - \langle \beta_{ec} \rangle)^{1/2}, \quad (4)$$

where B represents the vacuum fields, and the beta corrections are applied to account for the plasma diamagnetism at high beta. Therefore, assuming that end-cell magnetic fields B_{ec} are maintained at their economical maximum, an increase in central cell radius must be matched by a corresponding increase in end-cell radius r_{ec} . Furthermore, accommodation of this increasing end-cell plasma radius by corresponding increases in the end-cell solenoid radii means that the axial distance ($\sqrt{L_{ec}}$) between the solenoids must be increased to preserve the required mirror ratio. Accordingly, increases in both r_{ec} and L_{ec} result in further increases in end-cell trapping volume; this in turn requires a greater central cell length to meet the ignition criteria according to Eq. (3).

Note also that we cannot minimize end cell volumes by simply reducing the end-cell plasma radius r_{ec} to arbitrarily small values. By applying Eq. (4), this would result in small values of the central-cell radius r_c with detrimental effects to alpha-deposition efficiency. In our high-beta, low-field central cell, the gyroradius of the 3.5-MeV fusion alpha particle is typically an appreciable fraction of the plasma radius. Further reductions in plasma radius would result in deleterious alpha absorption by the halo outside the core plasma, with a resulting decrease in the alpha-confinement parameter f_α in Eq. (3). Further details on alpha loss to the halo follow in the next section.

Here then lies the problem with end-cell magnetic configurations such as the FPD-I and -II quadrupoles that have long characteristic lengths. A long

end-cell length requires a long central cell for ignition making it impossible to achieve a short ignition machine. By contrast, the octopole provides a method for obtaining a short end-cell configuration with the minimum end cell length (~ 7 m) determined only by sloshing-ion adiabaticity. This principle is illustrated in Fig. 2-6 where we compare the magnetic configurations for minimum-length ignition machines that are based on the quadrupole (FPD-II) and octopole (FPD-III) end cell geometries, respectively. In Table 2-3, we compare the major physics parameters for these two machines. Note that FPD-II with a characteristic trapping length in the quadrupole end cell of ~ 14 m requires a central-cell ignition length of ~ 90 m, whereas FPD-III with its short octopole end cell and short characteristic trapping length of ~ 5.6 m can ignite in a central-cell length of only 31 m.

HALO AND DIRECT CONVERTER PHYSICS

As noted above, the trapping and pumping of ions in the end cells represents the major power loss from the central cell. Therefore, for our ignition condition to hold, the axial ion loss must be held to a small fraction of the radial drift-pump loss. In FPD-III, this requirement necessitates a large electrostatic plugging potential (ϕ_c) of 205 kV (see Fig. 2-3). Clearly, for the plasma to remain neutral, the total current of ions leaving the machine must equal the electron loss current. Accordingly, most of the ions diffuse radially through drift pumping to the edge of the core plasma where they penetrate the radially decreasing confining potential and then flow axially to the grounded halo scraper at the ends of the machine (see Sec. 3). By contrast, the electron radial loss is small so that virtually all of the electron loss current flows axially to the direct converter, which is biased at $\phi_e = -203$ kV relative to the central cell. Accordingly, directly-converted electrical power is available from the electron channel, whereas only thermally converted power is available from the ion loss channel to the grounded halo scraper.

The central cell plasma is surrounded by a halo plasma. This halo is deliberately enhanced by recycling most of the ions at the end dumps to provide a shield around the core plasma to protect against gas and

Fig. 2-6. Comparison of the magnet sets for FPD-II and FPD-III aligned at the midplane of the central cell. Note that the much shorter end-cell length for FPD-III results in a considerably shorter central-cell ignition length. The discrete central-cell solenoids for FPD-III are represented, in this figure, by a continuous-sheet solenoid.

Table 2-3. A comparison of plasma parameters for FPD-II and FPD-III.

End-cell configuration	FPD-II	FPD-III
	Double quadrupole (yin-yang)	Octopole
Minimum central-cell length for ignition (m)	90	31
Characteristic end-cell length (m)	~20	~8
End-cell particle trapping length (m)	13.6	5.4
Neutron wall loading (MW/m ²)	1.0	0.9
Q	37	12
Absorbed heating powers in end cell (MW)	12.8	11.9

impurities. To act as a shield, the halo density must be about $5 \times 10^{12} \text{ cm}^{-3}$ and the electron temperature above 30 eV. These values ensure that the mean free paths for ionization of any impurity will be much shorter than the thickness of the halo. Impurities coming from the walls, vacuum leaks, or sputtering are ionized in the halo plasma and then flow along the magnetic field lines to the grounded halo dumps situated outside the halo scrapers at the ends of the machine. Thermal conversion of this power is also possible.

Table 2-4 summarizes the power flows to the ends of the machine. Note that, for computational simplicity, FPD-III is configured with only one direct converter region. Recent results for the Tandem Mirror Experiment (TMX-U) at LLNL⁵ indicate that suppression of central-cell radial transport could be achieved by partitioning the direct converter into a number of radial zones.

The halo surrounding the plasma core requires power to maintain the electron temperature against both thermal conduction along the field to the ends and gas-ionization losses. In FPD-III, the halo electrons are heated by a drag on the alpha particles with orbits that pass through the halo. Although the density in the halo is lower than in the core, drag is much stronger in the halo because the electron temperature is low. Any alpha that spends much time in the halo transfers most of its energy to the halo electrons. This process supplies the power needed to maintain the halo, but it also represents a drain on alpha power that would otherwise be available to heat the core plasma and maintain the temperature needed for ignition [i.e., a reduction in the factor $\bar{f}_\alpha$ in Eq. (3)]. In the following section, we discuss the modeling of the alpha energy loss to the halo, thereby providing important information on the central-cell ignition condition discussed above.

ALPHA-PARTICLE ENERGY LOSS TO THE HALO PLASMA

To evaluate the power transferred to the halo, we used two different computer codes.¹⁶ The first code follows alpha particle orbits in an axially symmetrical magnetic field that can vary with radius. In a tandem-mirror central cell, the field is a function of radius because the diamagnetic effect of the plasma at high beta reduces the field more near the axis than farther out. In the long, thin central cell, the field reduction is given by:

Table 2-4. Power flows to the end tank (powers are for both ends).

Core plasma power leakage, P_c (MW)	22.37
Power leakage to halo scraper, P_{hs} (MW)	2.41
Power leakage to halo dump, P_{hd} (MW)	5.72
Directly converted electric power from core plasma, E_{dc} (MW)	14.19
Thermally converted electric power, ^a E_{th} (MW)	5.71
Direct conversion efficiency, E_{dc}/P_c	0.63
Overall electric conversion efficiency, $(E_{th} + E_{dc})/(P_c + P_{hs} + P_{hd})$	0.65

^aIf supplied to a thermal cycle at 35% assumed efficiency.

$$B(r) = B_c [1 - \beta(r)]^{1/2}, \quad (5)$$

where we assume that beta has the same radial dependence as density, and therefore takes a quartic variation

$$\beta(r) = \hat{\beta} (1 - r^4/r_c^4). \quad (6)$$

Here, $\hat{\beta}$ is the peak beta on axis. The code records the time the alpha spends in each of several radial zones in the halo and the time in the core plasma. The total solid angle is divided into many (usually 20) equal increments; an orbit starts with its initial velocity vector pointing into each increment. This process is repeated as the starting point is stepped along in radius. At each starting point the effect is weighted in proportion to the production rate of alphas at that location. Finally, the average time spent by all of the alphas in each radial zone and the drag time τ_d for alphas in each radial zone are used to calculate the energy transferred to each zone. The drag time is given by the following:

$$\tau_d = 2.8 \times 10^{12} \frac{T_e (W_\alpha)^{1/2}}{n_e \ln \Lambda_e G \left(\frac{W_\alpha}{7340 T_e} \right)^{1/2}} \quad (7)$$

with time measured in seconds, energy and temperature in eV, and density in m^{-3} . The function G is given by

$$G(x) = \frac{1}{x} \operatorname{erf}(x) - \frac{2}{\sqrt{\pi}} e^{-x^2}. \quad (8)$$

Using this drag time, we calculate the power transferred in the k th zone as

$$P_{\alpha,k} = P_\alpha G_k \tau_{dk} / \tau_{dc}, \quad (9)$$

where P_α is the total alpha power; G_k is the average fraction of the time spent by all alphas in zone k ; and τ_{dk} and τ_{dc} are the drag times in the k th zone and in the core plasma, respectively.

Two effects are ignored by this code, but this does not appear to be a serious deficiency because these two effects tend to cancel each other. The

first effect is that the code does not allow the orbits to shrink as the alpha loses energy. If the drag were uniform at all points around the orbit, the orbit would tend to shrink toward its guiding center. The orbit would finally reach a size where it no longer passed through the halo, and drag in the halo would end. But, the second effect cancels the first because the drag is greater on one side (the halo side) than the other; therefore, the guiding center should tend to drift toward the side of greater drag. This effect would tend to keep the orbit in contact with the halo.

Our second computer code uses a Monte Carlo technique to calculate the drag at each different radial position, including the halo. It allows the density and temperature profiles to be specified. It follows the orbits as they shrink and as the guiding centers drift while the alphas lose energy. The results from this code confirm the results obtained with the first code, although both give statistical variations. The results from the orbit code vary somewhat, depending on the starting and ending points of the trajectories. The Monte Carlo code is very sensitive to the assumed radial profiles of density and temperature.

Figure 2-7 shows the first part of some typical alpha trajectories in the central cell of FPD. In Fig. 2-7(a), the perpendicular energy is $3/4$ of the full initial 3.52 MeV, and the alphas were born at a radius of 0.25 m. Figure 2-7(b) shows orbits with 1.5 MeV of perpendicular energy that were started at 0.35 m. Notice the variation of the curvature of the orbits, indicating the radial variation of the magnetic field. Figures like this cannot show the large fraction of the alphas that do not pass through the halo. Many alphas, even those created near the halo, do not pass through it because of the initial direction of their velocity vector. The initial direction determines both the component of velocity perpendicular to the field lines and the radial excursion for a given perpendicular velocity. Also, the production of alphas is greatest near the axis and falls off rapidly near the halo. For these reasons it is difficult to estimate the loss to the halo without a rather detailed calculation. Unfortunately the alpha particles that are born with their velocity vectors within the loss cone and are, therefore, lost promptly are not the ones that would have lost their energy to the halo. The two losses are therefore additive.

Fig. 2-7. Alpha orbits in the FPD-III central-cell plasma. The large circle is the boundary of the core plasma at $r_c = 0.45$ m. (a) $W_{\alpha 1} = 2.64$ MeV, $r_{\text{start}} = 0.25$ m; and (b) $W_{\alpha 1} = 1.5$ MeV, $r_{\text{start}} = 0.35$ m.

Figure 2-8 shows a graph of the power lost to the halo plotted against a parameter P that is proportional to the ratio of alpha gyroradius to the plasma radius. This particular gyroradius used in the parameter P was chosen empirically to make the plot a universal curve. Accordingly, a gyroradius corresponding to full energy in the perpendicular direction and a plasma beta equal to half the peak value gave points that all fell near a smooth curve. We therefore define P as

$$P = \left[r_c B_c \left(1 - \frac{1}{2} \hat{\beta}_c \right)^{1/2} \right]^{-1}, \quad (10)$$

where r_c is the plasma radius in meters, B_c is the vacuum central-cell magnetic field in tesla, and $\hat{\beta}_c$ is the peak value (i.e., on axis value) of plasma beta. Although the points shown in Fig. 2-8 were calculated with different peak beta, different vacuum magnetic field, or different plasma radii, all fell close to the smooth curve. Part of the random scatter in the points is due to the random weighting of a particular zone by the starting and ending points of the orbits.

Figures 2-7 and 2-8 show that an ignited central cell should have a plasma radius that is larger than typical alpha orbits in the beta-reduced magnetic field. As discussed above, the increased loss of alpha power resulting from a small plasma radius can be made up by increasing the length of the central cell, by increasing the magnetic field strength, or by decreasing beta so that the ignition criterion is still satisfied.

Fig. 2-8. Fraction of the central-cell fusion alpha power deposited in the halo, expressed in terms of a system parameter P , where P is a function of the central-cell plasma radius r_c , the central-cell B-field B_c , and the central-cell peak beta $\hat{\beta}_c$. The operating points for MARS,⁶ FPD-I,² FPD-II,² and FPD-III are shown.

REFERENCES

1. C. D. Henning et al., Fusion Power Demonstration: Baseline Report, Lawrence Livermore National Laboratory, Livermore, CA, UCID-19975 (1984).
2. Fusion Power Demonstrations I and II, J. N. Doggett, Ed., Lawrence Livermore National Laboratory, Livermore, CA, UCID-19975-1 (1985).
3. T. C. Simonen et al., 2XIIB Plasma Confinement Experiments, in Proc. of the 7th IAEA Conf. Plasma Phys. and Cont. Nucl. Fusion Res., Nucl. Fusion, Supplement, Vol. II, 389 (1979).
4. R. W. Moir et al., Standard Mirror Fusion Reactor Design Study, Lawrence Livermore National Laboratory, Livermore, CA, UCID-17644 (1978).
5. Summary of TMX-U Results: 1984, T. C. Simonen, Ed., Lawrence Livermore National Laboratory, Livermore, CA, UCID-20274, Vol. I and II (1984).
6. B. G. Logan et al., MARS Mirror Advanced Reactor Study, Final Report, Commercial Fusion Electric Plant, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53480, Vols. 1A and 1B (1984).
7. Y. V. Gott, M. S. Ioffe, and V. G. Telkovsky, Some New Results on Confinement in Magnetic Traps, in Proc. of the IAEA Conf. Plasma Phys. and Cont. Nucl. Fusion Res., Nucl. Fusion, Supplement, Vol. III, 1045 (1962).
8. A. H. Futch et al., Stability of a Magnetically Confined 20-keV Steady-State Plasma Research, in Proc. of the IAEA Conf. on Plasma Phys. and Cont. Nucl. Fusion Res., Nucl. Fusion, Supplement, Vol. II, 3 (1965).
9. D. E. Baldwin, Advantages of Higher-Order Multipole Tandem Mirror Plugs, Lawrence Livermore National Laboratory, Livermore, CA, unpublished memorandum (1978).
10. E. B. Hooper, Jr., Octopole Anchor for Tandem Mirrors, Lawrence Livermore National Laboratory, Livermore, CA, UCID-20050 (1984).
11. R. S. Devoto et al., A Small Octopole-Stabilized Tandem Mirror Reactor, Lawrence Livermore National Laboratory, Livermore, CA, UCID-20157 (1984) (to be published in Nucl. Fusion).
12. L. J. Perkins et al., Plasma Engineering for MINIMARS: A Small Commercial Tandem Mirror Reactor With Octopole End Plugs, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-92023 (1985) (to be published in Fusion Technology).

13. MINIMARS: Interim Design Report, J. N. Doggett, Ed., Lawrence Livermore National Laboratory, Livermore, CA, (to be published 1985).
14. R. S. Devoto, Lawrence Livermore National Laboratory, Livermore, CA, private communication (1984).
15. T. B. Kaiser, W. A. Newcomb, and L. D. Pearlstein, Equilibrium and Stability of Higher-Order Multipole Tandem Mirrors at Low Beta, Lawrence Livermore National Laboratory, Livermore, CA (to be published 1985).
16. W. L. Barr et al., "Energy Loss of Alpha Particles to the Halo Plasma in Tandem Mirrors," Bull. Amer. Phys. Soc. 29 No. 8, 1226 (1984).

Section 3
Systems Design

3.0 SYSTEMS DESIGN

GENERAL DESCRIPTION

The third version of the Fusion Power Demonstration (FPD-III) device is designed to produce 140 MW of fusion power. As shown in Fig. 3-1 and 3-2, the device is 67.5-m long with a diameter of 8.2 m and a centerline height of 9 m. The device is assembled from six modular central-cell sections, a fueling/diagnostic sector, and an end cell with a direct converter region on each end.

Each central-cell module (approximately 5.5 m in length and 7 m in diameter) contains the blanket, shield, solenoid coil, and vacuum tank required to make each module a "stand-alone" unit. A typical central-cell unit is shown in Fig. 3-3.

All FPD-III modules, with the exception of the end modules (those closest to the end cells) are interchangeable. The proximity of the high-field (24-T) choke coil to the solenoids in these modules dictates that we provide a special structure to react the high, magnetically-induced axial loads that occur between the windings of the solenoid and the choke coils. We envision a special case for the solenoid as well as permanent structure linking the two coils. The length of the central cells and, thus, the required number of cells were chosen to limit both the magnetohydrodynamic (MHD) effects within the blanket and the weight of the assembly for handling. With the fluids in the shield and the blanket removed, the weight of a module is estimated at 250 Mg (275 tons).

Each module contains a cylindrical, lithium-lead blanket in the area adjacent to the plasma. The recirculating lithium lead enters each module from the interconnecting pipes through a header located in the top of the vacuum vessel at the axial centerline, and exits to the header at the bottom of the vessel. Surrounding the blanket is a shield filled with high-density, stainless-steel balls that protect the outboard superconducting coils from nuclear heating and fluence. The shield is supported by a spaceframe tying the shield to the exterior vacuum wall and the struts that support the module above the ground. A solenoid coil, sized to produce the required 2.5-T field

Fig. 3-1. FPD-III elevation view.

Fig. 3-2. FPD-III plan view.

Fig. 3-3. Central cell module---elevation view.

on axis, surrounds the shield. Because this winding must be reduced in axial length to allow the support structure and piping to reach the shield and blanket, each end is outfitted with extra windings to reduce the field ripple in the gaps between adjacent modules. A single-wall, stainless-steel vessel, reinforced by two circumferential bands, surrounds each module; when the stainless-steel vessel is connected to the other central-cell sectors and the end cells, it forms the vacuum boundary for the device.

Central-cell modules are structurally interconnected by a series of tie bolts used to resist the axial load and by a series of bellows used to form the circumferential vacuum seal. This arrangement allows us to remove the four central modules from the device, independently, for maintenance or repair. The two outer modules are welded to the end-cell vacuum tank and can be removed only after removing the adjacent module. A special sector containing four 60-cm ports, giving fueling and/or diagnostic access to the plasma, is used to connect the two center modules. The design of the connection scheme is shown in Fig. 3-4.

The FPD-III device differs from prior tandem mirror reactor configurations in that the end cell is based on an octopole coil concept. In addition to this coil set (consisting of the choke coils, a transition octopole, the large octopole, and an outer-mirror coil), the end cell contains heating provisions using negative-ion neutral beams and electron-cyclotron resonant heating (ECRH), drift pumping, a halo scraper, and a direct converter. End-cell components are contained in a vacuum vessel 8.2 m in diameter and almost 18 m in length. The vacuum boundary is extended in wing-like appendages for the ECRH and coil-support systems.

The principal feature of the end cell is the octopole magnet. We considered three distinct manufacturing concepts for this magnet before arriving at the arrangement shown in Fig. 3-5. A continuously wound octopole magnet provides the required access for the neutral beam, but is very difficult, and therefore expensive, to manufacture and maintain. An octopole assembled from eight individually-wound window frames, while providing ease of manufacture, results in very limited beam-injection access. Machine configurations based on the continuously-wound and eight-window-frame-octopole end cells are shown in Figs. 3-6 and 3-7.

Fig. 3-4. (a) Module-to-module seal and (b) fueling/diagnostic sector.

Fig. 3-5. Octopole coil, four-window-frame concept.

Fig. 3-6. FPD-III with continuously-wound octopole.

Fig. 3-7. FPD-III with eight-window-frame octopole.

The assembly of four window frames not only accommodates the manufacturing/maintenance and beam-access advantages of the former schemes, but also creates the possibility of improved accessibility to components located within the octopole. As discussed in greater detail later, we propose a structural-support scheme featuring demountable circumferential support, which would allow the upper window frame(s) to be independently removed from the vacuum vessel, exposing other components to top access. Further work in positioning of the outer mirror coil(s), developing schemes for axial load ties between coils, and a check of other than normal operational loads is required to establish the feasibility of this scheme.

Other magnets in the end-coil set include a 24-T choke coil, a smaller "transition" octopole, a correction coil, and an outer mirror coil. All coils, with the exception of a resistive insert coil in the high-field region of the choke, are superconducting. A feature of the four-window-frame-octopole concept is that circumferential currents at opposite ends of the legs flow in opposite directions; a correction coil must be included to compensate for these currents. Because this correction coil must be located in close proximity to the octopole, the octopole must be stepped, creating the geometry shown in Fig. 3-5. The coil weight is supported by struts tied to the vacuum vessel with a trough extension on the underside of the vessel. This extension allows the struts to be of maximum length, minimizing heat flow to the cold coils.

The ECRH is applied at three locations in each end cell. The thermal barrier for point "b" and the electron mantle are at the same axial location (31 cm beyond the midplane of the large octopole magnet). The "b" region is on axis, whereas the mantle is centered 90-cm off axis. The third ECRH system for the potential peak is located at point "a", approximately 1 m beyond point "b" towards the end of the device. The "a" system requires one 200-kW gyrotron, whereas the "b" and mantle systems each use six 1-MW gyrotrons per end.

The thermal-barrier system employs a quasi-optical launching and transport system contained in the wing-like appendage to the vacuum vessel centered on the horizontal midplane. Beam launchers are arrayed axially so that the ECRH beams pass between the windings of the coils. The launchers for the point "a" and mantle systems are placed inside the vacuum vessel. A

waveguide interface penetrates the vessel, carrying the power from the gyrotrons to the launcher. The total prime power required for the three systems is approximately 45 MW.

The 475-keV, negative-ion-based, neutral-beam system is positioned to produce the sloshing-ion distribution in each plug. This was the most difficult system to integrate because of the very restricted space available in the required location (the midplane of the small octopole). In this case the beam must pass through an area already crowded by magnetic windings, structure, neutron shielding, and coil crossovers. The octopole magnets in one end cell are rotated 45 deg about the machine axis relative to those in the other end. Because of the different orientation of the coils in each end cell, one beamline is entered on the azimuthal midplane, whereas the beamline of the other end of the device enters at an angle of 45 deg below midplane.

Drift pumping coils are located at two axial locations in each end cell. A slotted antenna encircles the plasma to pump the ion species trapped in the plasma core in the region of the small octopole. In the outer end of the large octopole, four split-coax sections follow the lobes of the plasma-edge surfaces along the axial extent of the 1-m-long coaxial cavities.

The end cell employs a double-wall vacuum tank with 60 cm of biological shielding and water between the walls. A hatch spans axially from the choke coil to the outer mirror coil and has sufficient circumferential width to allow installation/removal of the end-cell magnets. The vacuum-tank diameter is reduced in the region of the halo scraper/direct converter. The halo scraper/direct converter is installed through a port on the upper side of the vessel.

CENTRAL CELL MAGNETS

The magnet system of FPD-III shown in Fig. 3-8 consists of central cell, choke, and end-plug coils. The central-cell magnet system has six (CC1 to CC3) solenoid modules. Each individual module has a correction coil at each end for reducing the ripple in the plasma region to an acceptable level. The magnetic-field-ripple profile along the plasma axis is shown in Fig. 3-9--this field profile meets the system requirements.

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Fig. 3-8. FPD-III magnet system configuration with window-frame coils for OCT1.

Fig. 3-9. Axial field profile and cross section of coils at $\theta = 0^\circ$ and 22.5° .

System Function Summary

The central-cell magnet system confines the plasma over its entire length. The central-cell length is determined from plasma requirements like particle confinement time (to ensure ignition) and the average beta.

Requirement Summary

The FPD-III central cell is 32-m long; the field required on the plasma axis is 2.5 T. The magnetic-field ripple is limited to less than 1% for achieving the required central cell beta β_{cc} . The length of the central-cell modules must satisfy the physics and engineering constraints. Axial gaps must be provided between adjacent central-cell modules to accommodate coolant feed lines for the nuclear shielding and blanket systems located inside the solenoid modules.

The magnet support structure must be adequate to withstand loads such as magnetic loads, dead weight, 1-g seismic load externally and vertically, and operating pressure differentials.

The FPD-III device is required to operate for ten years at 10% duty factor. During this period, the magnets are designed to withstand 120 cooldown/warmup cycles.

Magnet Configuration and Design

The configuration of the central-cell magnets is shown in Figs. 3-8 and 3-9 and relevant design parameters are given in Table 3-1. Each end-compensated module is 4.5-m long with 1-m axial gap between the modules. The solenoid modules are designed to accomplish the desired winding current density of 6000 A/cm^2 at 3.5 T. The winding design is based on a Nb_3Sn cable-in-conduit conductor and cooled with forced-flow supercritical LHe with inlet and outlet temperatures of 4.2 K and 5.7 K, respectively. The solenoid modules are layer wound. The main solenoid winding is a single layer of forced-cooled conductor. Two additional layers (about 0.3-m axial length) are provided at each end of the main solenoid to provide a ripple correction

Table 3-1. Central-cell magnet-design parameters.

Parameter	Value
Central-cell magnet dimensions	
Mean magnet radius (m)	2.15
Axial length (m)	32
Module design parameters	
Module length (m)	4.5
Radial build (m)	0.09
Axial length of each compensating layer (m)	0.03
Ampere turns/module (MA turns)	10.2
Winding-current density (A/cm^2)	6000
Field on axis (T)	2.5
Peak field at the winding (T)	3.5
Peak nuclear heating rate (mW/cm^3)	1
Operating current (kA)	60.0

function. The conductor conduit thickness is 6.6 mm, which is three times thicker than the thickness of the Westinghouse-LCP conductor. Although fabricating a 6.6-mm wall conduit is impractical, we may be able to build up the desired wall thickness from 3 to 4 concentric layers. Alternatively, the Westinghouse-LCP conductor can be used in "as is" form if a stainless-steel strip for taking hoop loads is cowound with the conductor. The average heat load in the winding is 0.12 mW/cm^3 . This heat load can be removed by LHe flow rate of 5 g/s through a 10-turn cooled-path length. The coils can be safely discharged at 800 V (peak) without exceeding a hot-spot temperature of 280 K.

Conclusion

The central-cell coils can be designed and fabricated using a modified Westinghouse-LCP conductor to achieve the desired winding-current density of 6000 A/cm^2 .

CENTRAL CELL SHIELDING

The shielding for the superconducting solenoids of the central cell is provided by a 55-cm thick, water-cooled steel shield. The design of the shield is based on the FPD-I and FPD-II steel-ball concept.² We selected this concept because of its adequate performance and economy of manufacture. In this design, a compartmented, structural-steel case is filled as densely as possible with steel balls. The remaining volume is filled with water, which is slowly circulated for cooling. The shield attenuates neutron and gamma radiation from the reflector portion of the blanket, and thereby reduces the cryogenic heat load to the solenoid. The shield also reduces to acceptable levels the lifetime radiation damage to the solenoid's thermal and electrical insulation.

There are no penetrations through a central-cell module shield. However, there is a gap between the modules. Conceptually, this gap is plugged by a steel ring encircling the gap inside the vacuum vessel as shown in Fig. 3-4. A more detailed neutron-streaming analysis would be required to verify a detail design.

The shielding required around the fueling module has not been adequately addressed; it would be, however, largely a problem in penetration shielding. The four large penetrations would need to be completely enclosed in a steel shield; once again, a detailed-streaming analysis would be required to verify the design.

FUEL INJECTION SYSTEMS

Two types of fuel injection systems are provided to meet the fueling requirements for FPD-III. Fuel gas-injection systems are included for initial loading and startup. Fuel pellet-injection systems are used to meet the deep-plasma fueling requirements during steady-state operation.

Fuel Gas Injection

The fuel gas-injection requirements are given in Table 3-2. Two independent gas injection systems are provided to meet these requirements for initial loading and startup. Figure 3-10 shows the fuel gas supply, injection-control valves, and instrument and control (I&C). The mnemonics used in this figure are identified in Table 3-3. Either gas injection system can meet all the requirements for low-density-deuterium plasma-physics experiments and for initial loading and startup to high-density deuterium-tritium (DT) plasma operation. The gas-injection systems can supply deuterium gas, but not tritium gas. Therefore, conventional gas-injection systems developed for other fusion machines may be procured without having to upgrade the equipment to meet tritium safety requirements. Both pulsed and analog modes of operation are provided in FPD-III.

Fuel Pellet Injection

Previously for FPD-I and FPD-II,² we determined that a first-stage pneumatic injector, followed by a practical second-stage railgun pellet accelerator, could not provide sufficient entry velocity to fuel the center of the plasma. For FPD-III, our preliminary calculations show that we may be

Table 3-2. Fuel gas-injection design-requirements data.

Number of gas-injection systems	2
Number of central-cell-injection nozzles located near the pellet-injection tubes	2
Maximum deuterium gas flow through a central-cell nozzle (g/h)	120
Number of end cell injection nozzles	
Left and octopole cell	2
Right and octopole cell	2
Maximum deuterium gas flow through an end cell nozzle (g/h)	60
Gas composition (% D2)	>99
Operating control modes	
Mode 1	Pulsed
Mode 2	Modulated

Fig. 3-10. Flow diagram of the fuel gas system.

Table 3-3. Mnemonic definitions used in Fig. 3-10.

D2	Deuterium
T2	Tritium
N	Nitrogen
He	Helium
Pd	Pressure-drop control
RM	Remote manually controlled valve
PCV	Pressure-control valve
M/A	Manual/automatic
FCV	Flow-control valve
PSV	Pulsed-selector valve
LEC	Left end cell
CC	Central cell
REC	Right end cell

able to use a laser pellet driver instead of an electromagnetic railgun to create an ionized fueling plume that has enough pressure to overcome the magnetic-field pressure and reach the center of the plasma. Using the pellet-plasma-plume model for FPD-III developed by Grant Logan of Lawrence Livermore National Laboratory (LLNL) and the most recent FPD-III physics data, we calculated the requirements data given in Table 3-4 for two fueling scenarios. The smaller 1-mm-diam fuel pellet requires a higher pellet repetition rate and has less plasma penetration capability. The larger pellet size is based on the desire to limit the pellet mass to 10% of the plasma mass. More laser energy is required per pellet for the latter case, but the repetition rate is greatly reduced.

We discussed the preliminary requirements given in Table 3-4 with laser suppliers and users, who prefer optical-range lasers because more robust quartz optics can be used at the vacuum boundary instead of the crystalline salt optics needed for infrared CO_2 lasers. Optical-frequency-range lasers can meet the repetition rate requirements, but fall far short of providing the energy needed for even the 1-mm pellet used in reasonably sized laser systems. Infrared lasers can readily meet the energy-per-pellet requirements of FPD-III, but do not meet the pellet rates needed for even the largest pellet permitted. Both the laser suppliers and users at Los Alamos National Laboratory believe that the CO_2 laser has the best potential for meeting our requirements. The system proposed for FPD-III is based on the use of four CO_2 laser beamlines. Four beamlines are used because of the energy density limitations of infrared lenses and windows.

Because of laser cost, only one laser system is proposed for the two pneumatic pellet injectors located in the FPD-III reactor vault (Fig. 3-11). The pneumatic guns are oriented about 5 deg relative to the common laser-beam tube. Both the laser tube and the pellet-injector tubes lie in the horizontal midplane of the reactor. They interface with a common module that inserts into a 24-in. tube that is located in a special fueling- and diagnostic-belt sector about 1-m wide. Three other diagnostic-insert modules are located in this belt sector, one of them is oriented vertically and can be removed from above with an overhead crane.

Table 3-4. Pellet-injector design-requirements data.

Data description	Scenario 1	Scenario 2
Number of pellet injectors	2	2
Fuel pellet diameter ($d = h$)	1.0	1.9
Pellet fueling rate (s^{-1})	32	5
Pellet velocity (m/s)	≥ 1000	≥ 1000
Absorbed laser energy per pellet (kJ)	1.0	6.4
Energy per laser beamline (kJ)	0.25	1.6
Laser pulse width (ns)	28	52
Central-cell plasma radius (cm)	45	45
Pellet plume depth into plasma (cm)	35	65
Approximate stored energy required per pellet (kJ)	50	400
Fuel supply rate		
Deuterium (g/h)	12	12
Tritium (g/h)	18	18
Vacuum load (liters/minute)	1300	1000
Nitrogen supply (g/h)	200	200
Helium supply (g/h)	100	100

Fig. 3-11. Plan view sketch of repeating pneumatic injectors and laser-beam-tube envelopes.

The laser energy is supplied to FPD-III with four infrared laser beamlines, each having four stages (Fig. 3-12). The beamlines are approximately 4-ft wide x 20-ft long x 6-ft high; they will probably be operated on an unstable lasing mode using converging mirrors to eliminate the need for zinc-selenide converging lenses. Each beamline is connected to the copper-mirror coupling assembly through transition sectors containing alignment bellows and infrared windows located on the beamline side of the biological shield. Each beamline is mounted on casters so that each one can be aligned with respect to the copper-mirror coupler.

The copper-mirror coupler and beamlines are located about 30 m from the FPD-III reactor centerline so that large diameter infrared windows can be used to enhance the lifetime of the laser system, and yet require only a relatively small converging tube penetration through the reactor shield: 3-in. diam at the reactor vessel entry to about 3/8-in. diam at the shield-tube exit to the plasma. (The fuel pellet tubing through the shield module is only 1/8 in. and is supported on a rigid structure within the module.)

Figure 3-13 shows that the mirror coupler contains two 90-deg dihedral-angle mirrors located at different elevations to prevent obstructing any of the laser beam directed toward the reactor. This arrangement requires that one of the two horizontal beamlines on each side of the mirror coupler be located at a higher elevation than the other one. The copper mirrors are diamond turned and honed. Laser-beam-induced damage experiments show that copper mirrors have good laser damage resistance and should have good resistance to neutron radiation damage. The main neutron beam passes between the mirror assemblies into the shielded-neutron end catcher, which may also contain plasma diagnostics to take advantage of the small-diameter collimated beam of fast neutrons. Any backscatter of neutrons must pass through shield material at the rear of the mirrors. Under these conditions, the mirrors should have long lives without significant loss of reflectivity. A large diameter vacuum port is located above the mirrors to remove fuel-gas egress from the reactor and any impurities (gases) released by the laser-beam interaction with the mirrors or windows.

The long converging-laser tube requires significant structural support and must be vacuum tight at the joints. Joints outside the reactor vault may

Fig. 3-12. Plan view sketch of laser beamlines and mirror coupler.

Fig. 3-13. Inside view of the mirror coupler for combining four laser beams.

be welded, but joints inside the vault should be bolted at two locations to permit removal of tubing for remote maintenance operations. Although the penetration through the reactor vault wall is only 10-in. and the neutron beam from the reactor penetration is relatively small, some biological-shield wall will probably be necessary around the converging-laser tubing and the mirror-coupling assembly and diagnostics. This wall permits us to control access into the limited induced radiation zone and provides for uninhibited maintenance outside the vault at all times.

MAGNETS

Magnet Configuration

The end-cell magnet configuration shown in Fig. 3-14 was selected to satisfy the physics requirements for plasma plugging and MHD stability. This configuration consists of a choke-coil set (CCC1), a small "transition" octopole (OCT2), a large octopole (OCT1), a bucking coil (M1), and a outer-mirror coil (M2). Dimensional data for coil location, coil geometry, current, and field at conductor are given in Table 3-5. The on-axis field, shown in Fig. 3-15, is highlighted by a 24-T requirement in the choke region at $z = 17.8$ m, falls to a minimum of 1.5 T at $z = 22.2$ m, and repeaks to 8.5 T at $z = 25.2$ m to provide plasma confinement.

Magnet Design

All FPD-III coils, with the exception of the innermost winding of the choke-coil set, are superconducting. Because of the 24-T requirement, a copper winding must be used in the high-field region of the choke-coil set. The two octopole coils as well as the bucking- and outer-mirror coils employ Nb_3Sn cable-in-conduit conductor. This conductor, shown in Fig. 3-16, is a modified version of the Westinghouse-LCP conductor with its performance optimized to achieve higher winding-current density under large nuclear-heating loads. The Tokamak Fusion Core Experiment (TFEX) study shows that this conductor can achieve a current density of approximately 3500 A/cm^2 at 10-T

Fig. 3-14. FPD-III end-cell magnet configuration.

Table 3-5. The FPD-III coil parameters.

Coils	z_m (m)	R_m (m)	Bundle		J (A/cm ²)	MAT	B_m (T)	E (MJ)	I_0 (kA)
			Δz (m)	ΔR (m)					
Mirror coil, M2	25.13	1.325	0.50	0.57	5500	15.67	15	300	10.0
Bucking coil, M1	24.72	1.885	0.25	0.47	5000	5.87	9	150	22.0
Large octopole, OCT1	21.89	2.29	0.48	0.48	2500	5.76	11.5	650	20.0
Small octopole, OCT2	22.5	0.88	0.22	0.22	4000	1.94	7.5	2	25.0
Choke coil, CCC	17.08	1.80	1.71	0.52	2476	22.02	8	1130	
		1.32	1.78	0.45	1803	14.44	12	370	
		1.00	1.97	0.20	1675	6.60	16	24	
		0.36	0.60	0.39	2480	5.80	24	3	
Central cell coils, CCL-CC3:									
Module	Various	2.157	4.50	0.033	6000	8.91	3.5	500	60.0
Correction	"	2.206	0.325	0.066	6000	1.29	3.5		60.0

Fig. 3-15. Axial field profile and cross section of coils at $\theta = 0^\circ$ and 22.5° .

Fig. 3-16. Nb_3Sn cable-in-conduit conductor.

field, when subjected to a nuclear heating load of 1 to 50 mW/cm^3 if the following modifications are made:

1. Employ Incoloy conduit material.
2. React the conductor at 700°C after winding.
3. Develop insulation capable of withstanding the required reaction temperature.
4. After winding, impregnate the stack with epoxy.
5. Provide a larger helium cross-sectional area.
6. Provide supercritical liquid helium at an inlet temperature of 3 K if nuclear heating loads exceed 1 mW/cm^3 .

A set of four concentric windings provide the choke field. These windings use pool-boiling conductors of NbTi, Nb₃Sn, Nb₃SnTi (Ti doped), and the before mentioned copper insert.

We chose the above conductors to best match requirements with known, or reasonable extrapolations of, current technology. However the bucking coil and mirror coil, as presently conceived, require current densities at fields beyond these criteria. Future work must be aimed at reconfiguring the coil set or developing new conductor types that can operate with current densities at the fields given in Table 3-5.

The large octopole (OCT1) consists of four saddle-shaped window-frame windings. The end of the coil facing the bucking solenoid (ABUCK) terminates in a three-step taper. End turn cancellation is provided by the bucking coil, which is radially concentric with this end of the octopole. Each segment of the large octopole is pancake wound with three conductors in parallel to limit the lengths of the cooling paths that remove the nuclear-heat loads. Electrical and cooling leads are located at the axial midplane of the coil, where the coil achieves its maximum radial dimension.

Coil Structural Arrangement

The end-cell coils react with one another and with the central-cell solenoids; these reactions result in significant loads that must be considered

in both the design of the individual coils and the structural system linking the coils. For the solenoid coils, these loads are two dimensional: axisymmetric radial loads, which must be reacted in the individual coil-case structure; and axial loads (in the direction of the machine axis), which must be considered in the design of the coil interconnection scheme. For the octopole coils, the loads are three dimensional: in-plane loads trying to displace the legs radially; out-of-plane loads trying to twist the legs circumferentially about the machine axis; and axial loads trying to displace the coils relative to each other. The radial and circumferential loads on any leg of an octopole are offset by symmetrical relationships to those loads on another leg, and, consequently, can be reacted using standalone-octopole case structure. Note, though, that the axial load must be reacted to an external point.

The magnitude and direction of the net axial load on each end-cell coil are shown in Fig. 3-17. Because of the relative coil positions and the loads, the coils are axially tied into two modules; the first module comprises the two octopoles, the bucking coil, and the mirror coil; the second comprises the choke and central-cell solenoids. The general arrangement of the end-cell coil set is shown in Fig. 3-18.

Figure 3-19 shows a concept for the structural linking of the four endmost coils in the end cell. The two solenoids are structurally tied together resulting in a net load of 6×10^7 N (13.5-million pounds) that pulls the coils away from the octopole. Tying this set of coils to the octopole has many advantages including use of a minimum amount of material, no heat flow through the tie, minimized deflection when loaded, and use of the coil load to offset the axial load pulling the octopole toward the central cells. The disadvantage of this concept is that the tie must be removed to disassemble the octopole and remove the top section(s) of the octopole. Note that this disadvantage is somewhat offset by fact that the solenoids radially "lock" the tapered ends of the octopole, which necessitates some untying and moving of the solenoids in any event. As indicated in Fig. 3-19, the small octopole is axially connected to the large octopole. The bolts are installed from the outer end so that they are accessible when the top section(s) of the large octopole and necessary shielding are removed. The small octopole can be lifted through the gap that results when one window frame is removed.

Fig. 3-17. Magnetic net axial loads on end cell coils.

Fig. 3-18. End cell coil arrangement.

ATTACHMENT: LARGE TO
SMALL OCTOPOLES

ATTACHMENT:
LARGE OCTOPOLE TO
BUCKING/MIRROR COILS

Fig. 3-19. End-cell-coil attachment scheme.

Because the large octopole is actually an assembly of four individual window-frame coil windings, we devised a structural arrangement that could be applied to each segment individually. Along the eight axial legs of the coil, radial forces range from 4×10^6 N/m at the coil centerline to 2.5×10^6 N/m near the ends. These forces are reacted by a series of seven stainless-steel bands 7.5 to 10 cm thick and ranging in height up to 38 cm above the coil case. A 5-cm-thick skin bridges the upper and lower surfaces of the axial legs of the octopole. The skin is not only used to transfer the radial loads into the bands, but also to react the circumferential loads trying to push the two legs apart. The skin, when considered in connection with the 5-cm-thick case around each winding, forms a beam-like structure for transfer of the axial loads from the linked solenoids.

The bands on individual window-frame segments are joined at assembly to complete the required circumferential tie. The bands are positioned so that they do not interfere with the heating requirements. These bands access the plasma through holes provided in the upper and lower skins. Note that a great portion of the loads on the axial legs of the large octopole arises from the leg curvature; i.e., the legs are not parallel to the machine axis, but rather form an arc ranging from 1.5 to 2.3 m away from the axis. The typical window-frame-segment structural arrangement is shown in Fig. 3-20.

The small continuously-wound superconducting-octopole magnet, approximately 200 cm in diam by 120 cm in length, is located under the entrance to the large octopole. Its position, relative to the circumferential legs of the large octopole and the choke coils, results in significant radial loads on the magnet's crossover windings as well as circumferential loadings on its axial legs. The radial loads on the axial legs, although reversing direction along the winding length, are smaller. Stainless-steel bands are again employed to react the radial loads. Bands (each 27 cm wide, which is the full width of the coil winding and case) are required at both ends of the coil. At the end toward the large octopole, a band thickness of 9 cm is required. Because of radial space constraints, the required 11-cm-thick band on the edge near the choke coils is divided into rings on both the upper and lower winding surface, which are tied together in the gaps between circumferential coil legs. Our analysis shows that the 2.5-cm-thick coil case

Fig. 3-20. Window-frame-segment structural arrangement.

surrounding the winding is sufficient to react the loads on the coil's axial legs without additional structure. The required case structure is shown as Fig. 3-21. The module, consisting of the two octopoles and the two solenoids, is attracted toward the choke coil by a net axial load of 4×10^7 N. This load could be reacted either through tie rods to the vacuum tank or through the support structure to either the tank or the choke-coil.

The choke-coil set, consisting of a radial stack of four windings, is attracted toward the central-cell solenoids with a force of 1.2×10^8 N (27-million pounds). However the solenoid is attracted toward the end-cell magnet set with a force of 1.6×10^8 N (36-million pounds), which means that if the two were tied together a net load of only 4×10^7 N would need to be reacted by external structure. The method for making this coil-to-coil tie and the method of reacting the resultant load will have to be addressed in future work. Possible schemes for the latter problem include:

1. Use the central-cell intermodule connection scheme to tie choke coils from opposite ends of the device together (the resulting tension load would offset the axial-compression vacuum load of 5.5×10^6 N, which would result in a more desirable tension load across the joints).
2. Use the structure supporting the coils to transfer the load to the vacuum tank.
3. Use an auxiliary structure tied to the octopole coil module and the choke coil. (The choke and octopole coils have an opposite and equal net load.)

HEATING SYSTEMS

The heating systems for an octopole tandem-mirror configuration differ somewhat from those required in the MARS configuration,¹ as studied in FPD-I and FPD-II.² The conversion from the double pair of quadrupole magnets on the end cell to the octopole magnet pair, exchanges the high-beta anchor region created by an ion-cyclotron resonant heating (ICRH) system for a hot-electron mantle maintained by an electron-cyclotron resonant heating

Fig. 3-21. Frame for small octopole.

(ECRH) system. The mainstay components of the tandem mirror plug (i.e., the ECRH-heated thermal barrier and potential peak, the drift pump systems, and the high-energy neutral-beam-produced sloshing-ion distribution) all remain intact.

The power requirements of the two ECRH systems and the negative beam system that are common to both the MARS and FPD configurations decreased in FPD-III with the octopole. However, most of the ECRH power reduction is offset by the addition of the mantle ECRH power requirement. Table 3-6 summarizes the FPD-III injection-system requirements. The primary differences between the mantle system and ECRH systems designed to date are the following: the factor of three frequency excursion during startup; the relatively low-heating frequency of about 10 GHz; and the annular nature of the region heated by the system. The two frequency features result from the 1.3-T field minimum in the mantle and the very high peak-mantle beta of 90%. A schematic of the mantle is shown in Fig. 3-22.

The drift pump requirements in Table 3-7 are those defined for an early version of MINIMARS. Two regions under the small octopole must be pumped: (1) the core plasma, which is nearly circular; and (2) the edge region, which is made up of the portion of the halo that is not intercepted by the choke coil. We assume that the edge region is similar in shape to the electron mantle shown in Fig. 3-22. The above two regions require significantly different launcher concepts, both with respect to each other and compared with the drift-pumping systems for MARS,¹ FPD-I,² and FPD-II.²

ECRH Systems

For the three ECRH systems, a total of 17.9 MW must be delivered to the plasma. The basic system configuration for each end plug consists of one 25-MW transformer/converter and thirteen parallel-protection and voltage-regulation networks for the gyrotrons. Each gyrotron is followed by a waveguide interface section and a beam launcher. Figure 3-23 depicts the plan view of the end-cell heating-system configuration.

The thermal-barrier system has two quasi-optical transport vessels per end plug; these transport vessels extend from the reactor vacuum vessel. Each

Table 3-6. The FPD-III heating systems requirements.

	Sloshing NINB	Mantle ECRH	Potential- peak ECRH	Thermal- barrier ECRH
Heating locations	a'	90-cm off axis	a	b
z_{axis} (m)	± 19.9	± 22.2	± 23.2	± 22.2
Absorbed power (MW)	0.13	6.22	0.16	5.42
Trapping fraction	0.082	0.75	0.85	0.70
Delivered power (MW)	1.61	8.30	0.19	7.75
Vacuum frequency (GHz)	--	36.4	58.8	42.0
Peak beta	--	0.90	0.216	0.33
Heating frequency (GHz)				
(harmonic)	--	11.5	52.0	34.4
Delivered current (	3.4	--	--	--
Beam energy (keV)	475	--	--	--

Fig. 3-22. Octopole hot electron mantle and plasma core.

Table 3-7. Drift-pumping requirements for FPD-III.

		Frequency (kHz)	Field (G)	Current (kA)	Power (kW)
A. Edge	1	155	165	5.2	--
	2	200	165	5.2	--
	3	245	165	5.2	--
	4	290	165	5.2	--
B. Core	0	330	80	2.8	--
	5	450	8	0.28	--
	6	7000	--	--	160

Fig. 3-23. ECRH/NIF tandem-cell configuration plan view.

ECRH vessel has three beam launchers that consist of an offset conical horn and parabolic reflector. The reflector surface is modulated to apply a phase correction that converts the TE₀₁ waveguide mode into a Gaussian intensity pattern. These FPD-III reflectors are similar to those used on Tandem Mirror Experiment-Upgrade (TMX-U)³ and those planned for Mirror Fusion Test Facility (MFTF-B).⁴ The waveguide interface between the gyrotron and the beam launcher is primarily for mode control; a block diagram of the waveguide interface is shown in Fig. 3-24. The 1-MW gyrotrons operate at a reduced 840-kW level. We assume that the entire system, gyrotron to reactor vessel, is in a vacuum with gate valves located at the gyrotron, the waveguide/launcher interface, and the ECRH/reactor vessel interface.

The mantle and potential-peak systems' beam launchers are located inside the reactor vacuum vessel. The waveguide interface penetrates the vessel wall to the launcher. The mantle gyrotrons operate at a power level of 908 kW, whereas the low-power requirement for the potential permits the use of existing 200-kW gyrotron technology.

The total power to the gyrotrons is 46.6 MW at 80 keV; the power supply is 94.6% efficient so that the line-power requirement is about 49.3 MW. Auxiliary requirements include cooling water (about 9500 g/m), liquid nitrogen (about 26 l/h), and liquid helium (13 l/h).

Sloshing-Ion Neutral-Beam System

The negative-ion-based neutral-beam system, which creates the sloshing-ion distribution, delivers 1.7 A of deuterium at an energy of 475 keV into each plug. The FPD-III beamline configuration is similar to those beamlines described in the FPD-I study.² Each end cell has one beamline with one source per beamline. Because the octopole magnets at one end of FPD-III are rotated 45 deg relative to the other end, one beamline is on the device midplane, while the other beamline is injected at 45 deg below the midplane. The cross section views of the two end cells are shown in Figs. 3-25 and 3-26.

3-47

	MANTLE AND POTENTIAL PEAK	THERMAL BARRIER*
TRANSMISSION EFFICIENCY	78.5% ⁺	80.5% 81.5%
BEAM LAUNCHER EFFICIENCY	97%	95%

+ INCLUDES WAVEGUIDE BENDS, WAVEGUIDE AND EXTRA ARC DETECTOR

* ONE HALF OF THE LINES INCLUDE WAVEGUIDE BENDS AND HALF DO NOT

Fig. 3-24. ECRH waveguide interface and transmission systems.

Fig. 3-25. Sloshing-ion neutral-beam cross-section view--east end.

Fig. 1-26. Sloshing ion neutral beam cross section view--west end.

A Lawrence Berkeley Laboratory (LBL)-type, self-extraction negative-ion source produces 4.06 A. Because the system must be steady state, we assume that the source plasma is generated by rf, and that the cesium is forced through the porous converter plate from the back of the plate to keep the cesium coverage uniform and constant with time. The source gas efficiency is 12%. The ribbon beam is 65 cm x 2 cm in cross section and has a one half degree divergence. Fifteen percent of the current is lost in the 80-keV slotted pre-accelerator, and another 11% is lost in the 475-keV transverse field-focusing transport and accelerator system.

For FPD-III, we replaced the gas-jet neutralizer in FPD-II with a standard gas-duct neutralizer because we did not find an attractive solution for pumping the huge gas load of the jet neutralizer. The neutralizer efficiency is 61% and the target thickness for 475 keV is $6.5 \times 10^{15} \text{ cm}^{-2}$. The gas load from the source and the neutralizer is 5.5-T l/s. The beamline pressure must be less than 2×10^{-5} Torr. For a maximum pumping speed of $8 \times 10^4 \text{ l/s}$ and a 20% recycle factor, the cryopanel area must be $4/1 \text{ m}^2$.

After passing through the neutralizer, the remaining ions are removed from the beam as the ions pass through a bending magnet. The power of the ions is deposited on two ion dumps. The D^+ and D^- dumps collect 360 kW and 200 kW, respectively. We assume that a 1 m^2 cryopanel is adequate for the gas load in the dump region. Eight percent of the neutral-beam current is lost as the beam passes through the magnet, apertures, and drift duct. Since only 8.2% of the beam is trapped in the plasma, 1.45 A or 690 kW is deposited on the neutral-beam dump.

Auxiliary requirements for the entire system include 750 g/m of cooling water, 55 l/h of LN_2 , and 19 l/h of LHe_2 . The beamline current efficiency is 41.9%, whereas the power efficiency is 43.7%. The line-power requirement is thus about 3.7 MW.

Drift Pump Systems

The drift pump systems perturb the geodesic curvature in the end cell to enhance the radial drift of various ion species that become trapped in the end plug. We assume that the plasma in the small octopole is similar in shape to

the hot-electron mantle shown in Fig. 3-22. Figure 3-27 depicts this density profile. The system is segregated into components that pump the core and edge regions. The flat density profile in the core region requires a narrow bandwidth, $\Delta W/W = 0.01$, and three frequencies for pumping the three species of concern. On the other hand, the edge region requires a large bandwidth, $\Delta W/W = 0.5$, which we accomplish by using four frequencies.

We chose a scaled version of the TARA slot antenna at MIT to pump the core region of FPD-III. Two slots form a pair of coupled coils, which are driven in phase. We estimate the flux through each slot based on a uniform field across the slot. Figure 3-28 depicts the antenna and matching network. Each core transmitter channel is matched to the drift-pump coil (DPC) with a resonant circuit. The vacuum Q of the coil is approximately 400, or the plasma load for these frequencies is nearly zero. The transmitter efficiency is about 65%, and the matching network efficiency for the DPC is 25%. The total prime-power requirement for the core system is 2.12 MW.

The edge-drift-pump system consists of four split-coax sections in each end cell. Each coax is driven by one of the four drive frequencies and follows the peak of the plasma lobe. The coax is 10 cm in diam, 0.5 m in length, and has a azimuthal split of 60 deg. The prime power requirement for each tone is approximately 1.25 MW; the total power for the system is 10 MW.

END CELL SHIELDING

The end cell shielding consists of the magnet shields, penetration shields, and biological shield. The biological shield consists of the double-walled vacuum vessel and the water that is held between the walls. The purposes of the end-cell shielding follow:

1. To reduce the nuclear heating of the superconducting magnets.
2. To prevent excessive radiation damage to the magnets and other components.
3. To provide for personnel access to the reactor hall 24 hours after shutdown.

Fig. 3-27. Density profile of the plasma in the small octopole.

Fig. 3-28. Drift pump antenna and matching network.

To minimize cost and maintain performance, we used steel and water shielding wherever possible. We employed tungsten shielding only in areas where space was too restricted for other materials. All of the shielding inside the magnet envelope is water cooled. This shielding is supported away from the magnet cold mass. It is supported by warm structure between the small octopole and the choke coil and the mirror coil shield. The shielding connects to supports that penetrate the structural shell of the large octopole. This shield must be segmented for remote assembly and disassembly. These features make the detail design very complex; and we have not addressed the assembly techniques in this study.

Penetration Shielding

Penetrations are a special problem in the end cell because many are required for the various heating systems and space is limited. All beamlines and other penetrations must be fully enclosed with adequate shielding to prevent streaming neutrons from activating components outside the vacuum vessel. We have not performed a detail design or analysis on penetration shielding, however, we can make some general statements. Where penetrations expose superconducting magnets to "hot spots", a tube-like steel shield will surround the beam. In especially restricted space, the tube will require some tungsten. Outside the envelope of the magnets, we will have more flexibility in the design and choice of materials for the penetration shield.

Large Octopole Shield

To reduce the nuclear heat load on the large octopole to an acceptable level, we must provide shielding equivalent to a 35-cm thickness of 80% tungsten, 10% steel, and 10% water by volume. To achieve these shielding requirements, 60 cm of water-cooled steel plate is used in areas where enough space is available. In places where the plasma mantle restricts the shield thickness, we apply 35-cm tungsten inserts; this arrangement is shown in Fig. 3-29. Detail design of this shield will require a very close integration of both the magnet cold structure and the plasma mantle surface. The detail

Fig. 2-29. End-cell nuclear-shield arrangement.

design should also address the impact of the shield on vacuum-pumping performance.

Small Octopole Shield

The small octopole in FPD-III is designed to operate with a higher nuclear-heat load than the other superconducting coils. A 24-cm-thick cylindrical tungsten shell through the throat of the coil provides the shielding for this small octopole. The shield consists of 80% tungsten, 10% steel case, and 10% volume for water coolant. The space between the legs of the small octopole is filled with water-cooled steel plate to increase the effective shielding to the ends of the large octopole.

The shield between the small octopole and the choke coil, plus the shield through the throat of the end-mirror coil provide structural support for the other shield sections. These shield sections are supported on warm platforms. To fill the steel structure, steel balls are used as a shield in these regions because space is not restricted.

Choke-Coil Shield

The shielding through the throat of the superconducting-choke-coil assembly is provided by water-cooled steel plate. The copper-insert coil also provides shielding for the superconducting coil. The steel-plate shield extends down along the sides of the copper-insert coil and protects it to some degree from direct radiation coming from the central cell and the end cell. The minimum effective shield thickness for the superconducting coils is 55 cm. The gap between the choke coil and the central cell is filled with a steel-balls-type shield, which also provides structural support for the shield and copper insert coil.

HALO SCRAPER/DIRECT CONVERTER DESIGN

When we redesigned the FPD-III end cell to include octopole magnets, the direct-converter configuration benefited because the octopoles altered the

plasma cross-sectional shape making it possible to design all the direct converter elements as flat plates. In this section, we report on our supporting studies concerning plasma shaping materials, sputtering, radiolytic corrosion, coolant corrosive wear, electrical insulation, and tritium permeation.

Design Assumptions and Requirements

The assumptions made for FPD-II² are used for FPD-III. Table 3-8 gives the thermal and electrical power absorbed by the direct converter. One of our major objectives was to produce a low-cost direct converter requiring no special remote handling equipment.

Plasma Shaping

The plasma cross-sectional shape resulting from the effects of an octopole end-cell shape (Fig. 3-30) is constant in the region of the direct converter. After passing through the end mirror coils, the plasma cross-sectional area increases, and the rate at which this area increases determines where the direct converter can be placed to satisfy the thermal and sputtering capability of the favored construction material. The FPD-III end-cell design causes the plasma area to increase at a very slow rate, which, if no other steps were taken, would result in the direct converter being placed at a considerable distance from the end mirror coil. One method of increasing the plasma-area rate of change is to add bucking coils after the end mirror coil (Fig. 3-31). We made the choice of a suitable bucking coil configuration by trial and error; we did not attempt to optimize the magnet design. Figure 3-32 shows the geometry of the bucking coil in relation to the elements of the direct converter.

Design Description

The electron collectors were designed as two elements: an outer collector and an inner collector. The inner collector is a flat plate normal

Table 3-8. Design requirements.

	Power to be absorbed (MW) (both ends)	
	Thermal	Electrical
Inner collector	6.54	14.2
Outer collector	1.64	0.0
Halo scraper	2.41	0.0
Halo dump	5.72	0.0
Total	16.31	14.2

Fig. 3-30. Plasma cross section at $z = 30$ m.

a = PLASMA CROSS SECTIONAL AREA REQUIRED FOR A GIVEN MATERIAL.
 $2(Z_1 - Z_2)$ = REDUCTION OF MACHINE LENGTH BY USING BUCKING COILS.
 THE FLARE OF THE PLASMA CAN BE CHANGED BY INTRODUCING ONE OR MORE BUCKING COILS. IN THE FPD-3 DESIGN WE SHOW TWO BUCKING COILS.

Fig. 3-31. The effect of adding bucking coils on plasma shape.

Fig. 3-32. Direct converter geometry.

to the plasma on the axial centerline of the machine. The outer edge conforms to the magnetic field surface containing the inner collector flux that satisfies the correct fusion power and average pressure in the central cell. The outer collector is made of four flat segments tilted so that the particle impingement at the center of each plate is normal. The edges of the outer collector are masked by the inner collector over the inner edges and by the halo scraper over the outer edges.

The halo-scraper plates are flat plates configured as the surfaces of a pyramid. There are eight segments, where the four larger segments form the surface of the pyramid and the four smaller segments are formed as "chamfers" to the edge of the pyramid. The angle of the scraper plates is determined by the ratio of the heat flux allowed by the chosen construction material to the heat flux normal to the plasma. The surfaces described as chamfers were added to keep the enclosing diametral size to a minimum. The inner edge of the halo scraper is at ground potential. The halo-dump surface is also flat and follows the geometry of and is connected to the halo scraper. The dump surface is normal to the plasma at the center of each plate. The halo-dump surface is vented (5% of its area) to allow the scrape-off plasma to flow into a plenum (behind the vented plate) and be pumped by the reactor vacuum system. Figures 3-33, 3-34, and 3-35 show the design of this direct converter and its support structure.

To simplify installation, removal, and to ease any remote manipulation that might be required, the direct converter is attached to a cover plug of the end-cell vacuum vessel and can be vertically crane hoisted. If repair of any part of the direct converter is required during the lifetime of the reactor, the complete assembly is removed to a hot cell for repairs.

Figure 3-36 is an end view of the plasma footprint on the direct converter elements. To the right of the centerline is a half view of the inner and outer collector. To the left of the centerline is a half view of the halo scraper and halo dump. In FPD, the direct converter elements were designed using the true plasma shape as it varied with the azimuthal angle. The shape is determined from a solution of the EFFI magnetic-field code with plasma corrections on the Lawrence Livermore National Laboratory Cray computer. After the plasma shape is confirmed, the EFFI output is then used

Fig. 3-33. Direct converter design.

Fig. 3-34. Direct converter design (enlarged portion of Fig. 3-33).

Fig. 3-35. Direct converter.

Fig. 3-36. Direct-converter element shape shows plasma footprint on each element.

to define the plasma geometry in the Grumman CADAM system. The CADAM system is then used to perform design studies to select the most satisfactory converter-element shapes and planes. This process represents a significant improvement over the approach previously used on the MARS design,¹ where an approximate axisymmetric plasma shape was used.

Materials

The results from our materials selection study for the direct-converter components are shown in Table 3-9. The FPD device is an experimental reactor and is designed for 5 full power years (FPY) of operation. For FPD, the direct-converter thermal power is discarded; therefore, the coolant temperatures and, consequently, the pressures are lower than in a power reactor where the direct converter thermal power is used. It is possible then, to use less exotic and, therefore, cheaper materials for the direct-converter elements. Table 3-9 shows the six materials that were considered in the design, only the yield stresses at operating temperature are given in the table. Zirconium copper (ZrCu), the molybdenum alloy (TZM), and the vanadium-15 chrome-5 titanium alloy (V15Cr5Ti) satisfy both yield-stress and boiler-code-stress requirements. Inconel (INCO718) satisfies yield, but not boiler code conditions. The 316 stainless steel satisfies neither yield-stress nor boiler-code-stress conditions; HT-9 ferritic steel marginally satisfies the yield-stress conditions. Because of its lower cost, we decided to use the ZrCu material.

Thermal Conditions

Tables 3-10 and 3-11 show the inner and outer collector performance and reference design. The total cooling-water pumping power to the collectors and the halo scraper and dump is 27 kW. All elements have a common system pressure of 0.65 MPa. On the inner collector all channels are in parallel. The design driver for the coolant water pressure drop is the coolant channel path with the highest heat load. The coolant water pressure drop is determined by the Fanning relationship.⁵ Pressure reducing valves are

Table 3-9. Material study.

Material	Maximum front surface temperature (°C)	Combined thermal and pressure stress (MPa)	Yield stress (MPa)
TZM	133	46	896
316SS	406	619	117
HT-9	291	356	386
ZrCu	101	31	220
V15Cr5Ti	237	130	580
INCO718	342	480	910

Reference conditions

Coolant velocity (m/s)	5.7
Coolant in/out temperature (°C)	30/80
Front wall thickness (cm)	0.3
Channel width/depth (cm)	0.6/0.4
Average heating rate (MW/m ²)	0.82
Heating rate peaking factor	2.07

Conclusion--ZrCu chosen based on cost

Table 3-10. Inner and outer collector performance.

	Inner collector	Outer collector
Thermal power (each end) (MW)	3.27	0.82
Area (m ²)	2.76	
Flux		
Average (MW/m ²)	1.19	
Design (MW/m ²)	1.74	1.45
Temperature		
Coolant in/out (°C)	30/80	30/80
Maximum service (°C)	150	187
Stress		
Maximum combined (MPa)	102	85.1
Yield (MPa)	205 (at 150°C)	196 (at 187°C)
Coolant		
Flow rate (m ³ /s)	0.0156	0.0039
Velocity (m/s)	4.3	2.9
Pressure (MPa)	0.65	0.65
Pumping power (kW)	2.9	0.4

Table 3-11. Inner and outer collector design.

	Inner collector	Outer collector
Configuration	Zirconium copper with fully cooled back wall	
Coolant	Water	Water
Coolant channel		
Width (cm)	0.7	0.7
Depth (cm)	0.3	0.3
Channel wall thickness (cm)	0.3	0.3 to 0.9
Front wall thickness (cm)	1.0	1.0
Channel arrangement	In parallel with header	Radial
Channels per sector	57	144
Channels per channel path		9
		9 channels in series
Sector length (cm)	175	
Sector width (cm)	57	
Number of sectors	3	4
Channel paths per sector		16
In/out header pipe size (cm)	10	5.0
Sector header pipe size (cm)	6.4	5.0

required at all channel outlets. The coolant outlet temperature for all channel paths has a common value of 80°C. The coolant scheme is turbulent nonboiling flow for all elements. The coolant flow rate is determined by the coolant inlet and outlet temperature and the thermal power load to the collector. The coolant flow rate and pressure drop determine the coolant pumping power. The inner collector is divided into three sectors of equal width for ease of installation and remote maintenance. The coolant channels in each sector are connected to a sector header which in turn is connected to the main header.

We conducted a system study (Fig. 3-37) to show the effect of varying the inner-collector front-wall thickness on maximum surface temperatures, combined thermal and pressure stress, yield stress, and boiler code (category S1) stress.⁶ Because of the relatively low coolant pressure, the combined stress is dominated by the thermal stress. For very thin front walls (not shown on the figure), the pressure stress will dominate, which will result in a minimum combined stress at some small front-wall thickness. A front-wall thickness of 1 cm was chosen as the reference design value to allow material for sputtering⁷ over the reactor lifetime. At this thickness, the combined stress is far below the yield and boiler code values.

Figure 3-38 shows the variation of the combined stress and maximum surface temperature across the middle of the inner-collector coolant channels. This location is at the point of maximum surface temperature and combined stress for each channel. This curve suggests a method for reducing manufacturing costs of future reactors. Rather than construct an element with uniform coolant-channel size and spacing as was done in this design, more widely spaced channels or perhaps brazed or welded coolant tubes out near the edges of the element could be used.

The four sectors in the outer collector are arranged so that the outside shape is a square. The coolant channels are milled radially with constant width and depth; therefore, the walls between the channels vary in thickness.

The halo-scraper and halo-dump performance and design are shown in Tables 3-12 and 3-13. The scraper and dump are cooled as a unit. The coolant flows from the subheader into the scraper channels and then into the dump channels. The scraper and dump are divided into four sectors. Each sector

CHANNEL WIDTH/DEPTH = 0.7/0.3 cm
 COOLANT VELOCITY = 5.7 m/s
 MATERIAL = ZIRCONIUM COPPER
 POWER DENSITY = 1.74 MW/m²

Fig. 3-37. Inner-collector system study.

SINGLE ENDED POWER=3.27 MW
 FRONT PLATE THICKNESS=1.0 cm
 MATERIAL=ZIRCONIUM COPPER
 CHANNEL WIDTH/DEPTH=0.7/0.3 cm

Fig. 3-38. Variation of stress and temperature on the inner collector.

Table 3-12. Halo scraper and halo dump performance.

Power (each end) (MW)	4.06	
Coolant	Water	
Temperature (inlet/outlet) (°C)	30/80	
Flow rate (m ³ /s)	0.0194	
Pressure (MPa)	0.65	
Pumping power (kW)	14.0	
Coolant velocity (m/s)	6.8	
	<u>Halo scraper</u>	<u>Halo dump</u>
Flux (design) (MW/m ²)	1.01	1.15
Surface temperature (plasma side) (°C)	159.0	145.0
Stress--maximum combined (MPa)	119.0	80.0
Material yield strength (MPa)	203.0	205.0

Table 3-13. Halo scraper and halo dump design.

Number of sectors	4
Configuration	Flat plate sections with a side and chamfer part
Material	Zirconium copper
Coolant channel	
Width (cm)	0.7
Depth (cm)	0.3
Header pipe size (cm)	10.0
Subheader pipe size (cm)	6.4
Channels per sector	
Side part	124
Chamfer part	12
Channel configuration	Coolant flows in series through the scraper and dump
Channels per channel path	4
<u>Halo scraper</u>	
Channel wall thickness	
Side part (cm)	0.3 to 1.25
Chamfer part (cm)	0.45 to 1.22
Front wall thickness (cm)	2.0
<u>Halo dump</u>	
Channel wall thickness	
Side part (cm)	0.7 to 2.1
Chamfer part (cm)	1.2 to 1.9
Front wall thickness (cm)	1.2
<u>Vent arrangement</u>	
Vent area	5% of vented plate
Vent configuration	Centered in every other channel wall
Azimuthal spacing (cm)	2.7 to 5.6
Radial spacing (cm)	3.0 to 6.3
Vent pipe o.d., i.d. (cm)	1.35, 1.0

consists of a side part and a chamfer part. The coolant channels are milled radially in the scraper and dump elements and are of uniform width and depth. The channel wall thickness varies for a minimum value at the inner edge to a maximum value at the outermost edge. The minimum and maximum values are given for the side and chamfer parts of the scraper and dump in Table 3-13.

The halo dump is vented such that the scrape-off plasma can flow into a plenum chamber behind the vented plate and then be pumped away by the reactor vacuum system. The vented area is 5% of the total vented plate area. Vents are located and centered in every other channel wall as shown in Fig. 3-39. The vent diameter is 1.0 cm. The vent azimuthal and radial spacing varies over the faces of the vented plate so as to maintain the 5% vented area. Minimum azimuthal distances are at the inner edge of the vented plate and the maximum at the outer edge. Radial spacing distances are maximum at the inner and minimum at the outer edges. Minimum and maximum dimensions are given in Table 3-13.

Figure 3-40 shows the maximum yield and combined stresses, in addition to the temperature and heating at any azimuthal angle of the halo scraper. The temperature and combined stress, for example, vary from a maximum value at the center of the side part of the scraper (0-deg azimuthal angle) to a minimum at a corner. The discontinuity in the curves at an angle of 41.4 deg occurs at the junction of the side and chamfer parts of the scraper. The calculation of these values for FPD represents a significant improvement over our previous analysis of MARS¹ (i.e., these values would be constant with azimuthal angle using the MARS analysis).

Sputtering

We analyzed the sputtering loss of the halo scraper because the scraper is the element that receives most of the ion flux; consequently, most of the sputtering loss in the direct converter will take place there. Very little net sputtering will take place on the vented plate because the sputtered scraper material will probably redeposit on the plate. A calculation of the scraper sputtering loss using the DSPUT equations⁷ shows that a maximum of 0.7 cm of material will be lost in 5 FPY of reactor operation. This

Fig. 3-39. Halo-dump vented-plate configuration.

Fig. 3-40. The variation of yield stress, temperature, and heating with azimuthal angle in the halo scraper.

calculation was made for a particle density of 1.3×10^{16} particles/cm².s at 30-keV energy. Comparison of DSPUT with a TRIM code analysis for deuterium on copper at energies between 200 eV and 1 keV (Ref. 8) shows that DSPUT agrees with the TRIM code within a factor of two in that energy range. The 0.7-cm loss is probably correct within a factor of two. The halo-scrapers front-plate thickness is 2.0 cm and could be increased at least 50% without introducing unmanageable thermal stresses. Thus, the scraper should be able to withstand a 5-FPY sputtering loss. The frontwall thickness for the outer elements should be able to withstand any small sputtering loss there.

Coolant-Water Erosive-Wear Mechanism

There are three possible mechanisms that could cause mechanical erosion of coolant piping and equipment by the flowing coolant: liquid-droplet impingement, single-phase flow, and cavitation.⁹ Liquid-droplet impingement is not a viable erosion mechanism in the direct-converter coolant system because the coolant is never in the condensing vapor form.

Single-phase erosion occurs in three forms: surface shear stress, normal stress, and nonsteady liquid flow (water hammer). Calculations show that the imposed shear and normal stresses⁹ are many orders of magnitude lower than the ZrCu shear- and tensile-creep rupture stress at evaporated temperature. The shear-creep rupture stress is taken as one half the tensile value. These calculations were made for velocities at least an order of magnitude higher than typical direct-converter coolant velocities. Water hammer could cause a problem. However, hammer damage is structural rather than erosive, and the coolant flow system can be configured and operated to avoid it.

Cavitation on copper and its alloys can be very destructive. Studies at the Vibratory Cavitation Facility at the University of Michigan show that the maximum mean depth of penetration rate, which is the material-volume loss rate per exposed area for BS1433 copper, can be six times that of nickel 270 and 15 to 20 times that of stainless steel.¹⁰

A measure of cavitation initiation is the parameter S defined on Fig. 3-41. If the parameter S for a particular flow system is greater than a parameter S_c , determined for a particular flow component like a valve or an elbow, then no cavitation will take place at that particular flow component. Recommended values of S_c for various piping components in common use in the electric power industry are given in Ref. 11. Examinations of the direct-converter halo scraper and the inner- and outer-collector coolant channels and piping configuration show that an equivalent component with the maximum S_c is the short-radius elbow ($S_c = 30$). In the halo dump, flow around the vented pipes is equivalent to flow through a conventional globe valve ($S_c = 21.0$). Table 3-14 shows the required system-pressure increase needed to prevent cavitation for the flow element velocities given. The pressure increase in the halo dump system is the design driver. For FPD, if the system pressure is increased 4 atm above the design driver to prevent liquid vaporization anywhere in the coolant system, then cavitation will not take place.

Radiolytic Corrosion

The action of ionizing radiation can significantly alter the composition of water employed as a direct-converter-element coolant. A relatively small quantity of oxygen or peroxide resulting from radiolysis can have unfavorable effects on corrosion processes for copper elements.

During energy absorption, both ionizing and reducing radicals are formed in the coolant water.¹² The radicals are not uniformly distributed throughout the water, but are formed in regions of local concentrations or "spurs" resulting from the energy absorption process. Each individual spur is quite small [10 to 15 angstrom units ($\text{\AA}$) in radius] and contain about six radicals. The oxidizing radical is primarily OH and the reducing radical is the hydrogen atom. The distance between these spurs is determined by the linear energy transfer of the radiation (LET, eV per $\text{\AA}$). If the reducing and oxidizing radicals are spatially separated and exist at high concentrations, then the corrosive reactions can take place. If the radicals are more homogeneously distributed, they will recombine and the corrosive reactions will be curtailed.

$$S = \frac{P_s - P_v}{D \cdot V^2 / 2}$$

P_s = SYSTEM PRESSURE

P_v = VAPOR PRESSURE

D/V_s = COOLANT DENSITY/VELOCITY

NO CAVITATION FOR $S > S_c$, WHERE S_c DEPENDS ON FLOW SYSTEM

Fig. 3-41. Cavitation number measure of cavitation initiation.

Table 3-14. System pressure increase to prevent cavitation.

Direct converter element	Velocity (m/s)	Suggested S_c	System pressure increase (atm)
Halo dump	6.0	21.0	3.7
Halo scraper	10.0	3.0	1.5
Inner collector	7.2	3.0	0.77
Outer collector	3.3	3.0	0.16

Conclusion--cavitation can be avoided with suitable
increase in system pressure

During the irradiation, intermediate reactions form molecular species such as H_2O_2 , HO_2 , and other H-O molecules.¹² It is the presence of these products, particularly H_2O_2 together with the OH, that accelerates the corrosion (i.e., radiolytic corrosion) of the copper.¹³ Reaction kinetic calculation^{12,14} shows that the initial addition of hydrogen will strongly suppress the formation of the H_2O_2 and O_2 species and will, therefore, strongly suppress the radiolysis. This kinetic theory is in good accord with previously observed special cases of importance in reactor technology. Two experiments are reported¹² that support the kinetic theory analysis. In one of the experiments,¹⁵ the authors show that at a hydrogen concentration of 14 cm^3 (STP) per kilogram of 0.15 mole fraction of boric-acid water solution, no dissociation is observed at the highest energy absorption rates. The boron-fission reaction should enhance the radiolysis over that of the pure water in the direct converter. In the other experiment,¹⁶ 5 cm^3 of hydrogen per kilogram of 0.10 mole fraction of boric-acid water solution suppressed the radiolysis. Whyte¹⁷ suggests that the introduction of 30 cm^3 (STP) of dissolved H_2 per kilogram of coolant water will completely suppress the radiolytic corrosion of copper. A calculation using Henry's law shows that 2-atm pressure is required to dissolve that quantity H_2 at the maximum coolant temperature of the FPD direct converter. The coolant system pressure is 6.5 atm in FPD. A calculation shows that the fire hazard of the hydrogen released from solution upon system depressurization is negligible. The FPD device contains 3.2 m^3 of direct-converter coolant.

Coolant-Line Electrical Insulation

In FPD the inner and outer collectors are held at 179 and 89 kV, respectively, with reference to the grounded vacuum vessel. In addition to an electrical load, these elements accommodate a large thermal load and are cooled by water flowing through pipes that are grounded at the coolant pumping equipment outside the reactor. Shorting of these elements to ground is through three possible current paths: the coolant-piping metal, the coolant within the piping, and the outside-coolant header surface within the reactor vacuum

vessel. Electrical insulation is accomplished by inserting an insulating plug in the coolant line within the vacuum vessel and by maintaining a low coolant-water resistivity.

Deionizing and demineralizing coolant water systems have been built at a number of research facilities.¹³ Flow rates vary from 30 to 46,000 gallons per minute and the coolant resistivity is maintained to at least $1.0 \text{ M}\Omega\cdot\text{cm}$. The FPD deionizing facility falls within this flow-rate range. Figure 3-42 is a study of the power loss through the coolant for the FPD inner collector. Results are reported in percent loss of the power collected. The collector potential is 179 kV and the collected current is 207 A. The study is for four insert radii varying in length from 5 to 30 cm. The coolant resistivity is $1 \text{ M}\Omega\cdot\text{cm}$. The coolant conductor model is a cylinder of finite constant length between zero-resistant end masses. A correction is made for the resistance at the junction.¹⁹ The effect of this correction decreases as the cylinder length to diameter ratio increases. Figure 3-42 shows that for a 30-cm-long, 10-cm-diameter insert; 0.5% of the collected power is drained to ground at each insert.

Charge streaking across insulator surfaces is a major cause of high voltage vacuum failure in steady-state systems like a tandem mirror. The streaking can be greatly reduced by maintaining the potential drop across an insulator at 200 kV and the average electric field parallel to the insulator surface at 10 kV/cm or less.²⁰ To impede charge buildup, the insulating insert should be placed away from the neutron flux streaming into the direct converter through the choke coil opening. A 30-cm-long insert, required to limit power loss through the coolant, is more than enough to prevent electrical breakdown at the vacuum surface of the insulator. Table 3-15 lists the specifications of the coolant pipe insulating insert. The material, SP-1 polyimide²¹ can withstand the required coolant temperature and pressure environment. The material resistivity is greater than $10^{15} \text{ }\Omega\cdot\text{cm}$ and can be baked for outgassing.

Fig. 3-42. Inner-collector power loss through coolant.

Table 3-15. Electrical insulation system design for the coolant pipe insert.

Potential	
Inner collector (kV)	179
Outer collector (kV)	89
Material	Glass reinforced polyimide
Length (cm)	30
Diameter	
Inner collector (cm)	10
Outer collector (cm)	5
Wall thickness (cm)	1.5
Coolant pressure (MPa)	0.65
Coolant temperature (°C)	80
Connectors	Flanged both ends
Coolant water	Deionized to 1 MΩ•cm resistivity

Tritium Permeation and Inventory in the Direct-Converter Elements

The energetic impingement of tritium ions on the direct-converter surfaces result in a steady-state tritium loss to the wall coolant as well as tritium inventory in the wall. To estimate the extent of these problems, a simple model of tritium diffusion and holdup, which takes into account the recombinative properties of the surface and the depth of the plasma implant, was applied to the direct converter surfaces. The model is based on the recommended approach of Baskes et al.,^{22,23} which has been successfully employed by them in investigations of re-emission of implanted deuterium from stainless-steel walls, thermal absorption, and nuclear reactor profiling of deuterium near surface concentrations.

Table 3-16 shows the single-ended tritium permeation (P in curies/day) and inventory in the direct converter component walls (I in curies) for all the converter elements. The tritium currents, particle energies, and front- and back-face temperatures are also given. Values are given for two wall materials, TZM and copper. The total permeation in curies per day for the copper and TZM is given at the bottom of the table. Current regulations allow water to be transported for processing and disposal at another site if the tritium concentration does not exceed 0.1 curies/liter.²⁴ For the permeation rates and the allowed concentration in the coolant water given above, it is practical to bleed off for disposal and make up with fresh coolant, 377 liters/day in the case of the copper components, and 135 liters/day in the case of the TZM. Therefore it is not necessary to build an expansive tritiated-water processing plant to process the direct-converter coolant water at the FPD experimental reactor site.

OCTOPOLE NUCLEONICS

This section summarizes our work to date in assessing the shielding aspects of the octopole end cell. We do not address the nucleonics of the central cell and choke coils here because they are virtually the same as those discussed in the FPD-I and II documentation.² The radiation limits and the 1-D method of analysis used here to assess the FPD-III octopole coils are

Table 3-16. Tritium permeation and inventory.

Component	Material		Copper				TZM			
	Current (A)	Energy (keV)	T_I/T_0^a (°C)	P^b (C_I /day)	I^c (C_I)	Y^d (yr)	T_I/T_0 (°C)	P (C_I /day)	I (C_I)	Y (yr)
Dump	3.5	0.03	125/55	0.013	6.5	1.2	188/55	0.0037	2.5	0.66
Scraper	107.5	30	101/55	20	1.2×10^4	2.0	147/55	5.5	4.8×10^3	1.5
	0.06	225	101/55	0.063	38	2.0	147/55	0.018	16	1.5
Outer collector	1.35	312	90/55	2.6	1.8×10^3	2.64	109/55	0.6	500	1.58
Inner collector	5.8	403	90/55	15	9.7×10^3	2.64	145/55	7.5	8.8×10^3	3.5
Total (one end)				37.7	2.35×10^4			13.6	1.4×10^4	

a_{T_I} = Hot side temperature; T_0 = cold-side temperature

b_P = Permeation

c_I = Inventory

d_Y = Years to attain steady-state inventory

similar to those used to assess the C-coils for FPD-II. Based on our initial work, this FPD-III octopole end-cell configuration appears to provide sufficient space for shielding. This configuration should allow the small as well as the large octopole to be superconducting. We emphasize that this is a tentative conclusion. When time allows more rigorous and complete analysis to be done, we may find that more shielding space is required in some locations. For example, we have not yet examined the affects of beamline and other required shield penetrations. The following sections summarize the radiation limits imposed, the method of analysis employed, and the application and results of this method when applied to the octopole configuration.

Radiation Limits

In LLNL-FPD-84-016 (Ref. 2, Appendix), we originally set the maximum allowed radiation exposures in superconducting coils at the following limits:

- 10^{11} rads in the insulation;
- 10^{18} n/cm² ($E_n > 0.1$ MeV) in NbTi, for a 20% drop in critical current, 70% of which is annealable at room temperature;
- 4×10^{18} n/cm² ($E_n > 0.1$ MeV) in Nb₃Sn.

In LLNL-FPD-84-48 (Ref. 2, Appendix), we later revised the fast ($E > 0.1$ MeV) neutron fluence limits to allow for more design flexibility:

- 10^{20} to 10^{21} n/cm² range for NbTi with an accompanying 25% lower critical current, using 10^{20} n/cm² in this work;
- 1 to 4×10^{19} n/cm² range for Nb₃Sn should be achievable, using 2×10^{19} n/cm² in this work.

Method of Analysis

Because of the time and expense involved in doing detailed 3-D analysis of the end cell, we developed a 1-D method that we used to iterate the

configuration in a timely manner. This 1-D method consists of the following steps:

1. Calculate heating and damage rates in superconducting coils vs shield thickness using 1-D slab geometry.
2. Calculate 14-MeV neutron-energy currents (wall loading) in 1-D cylindrical and spherical geometries using coil and plasma geometries and plasma source strength.
3. Combine steps 1 and 2 to obtain a 1-D estimate of peak heating and damage rates.
4. Integrate the plasma neutron-line source (located under the octopole coils) as a function of z .
5. Combine 1 and 4 to estimate total heating in the octopoles (our major assumption is that axial neutron transport is not significant).

In the first step, we calculate the heating and damage rates vs shield thickness in 1-D slab geometry using the ONEDANT code and a 30-neutron plus 12-gamma XSLIB data library based on ENDF/B-V. This code and its data library were developed at Los Alamos National Laboratory and were used by the University of Wisconsin for the MARS project.¹

Figure 3-43 shows the configuration used to calculate radiation levels in the coil vs shield thickness. The shield consists of a thick zone of W (79 vol%) + H₂O (10 vol%) + boric acid (1 vol%) + FE 1422 (10 vol%) followed by a thin zone (~4 cm) where TiH replaces the W. This shield results from a preliminary optimization study (see LLNL-FPD-84-45, Ref. 2, Appendix). Figures 3-44 and 3-45 give the heating levels, neutron flux ($E > 0.1$ MeV), and dose rates in the coil vs shield thickness at a wall loading of 1.0 MW/m². The total heating includes both coil and case.

The octopole design differs from the C-coil design in that the space allowed between the shield and superconducting coil is 5 cm instead of 15 cm, and the effective steel thickness in the case is 2 cm instead of 6 cm. To account for this difference, we increased the local heating and damage rates by a factor of 2 over the rates calculated with the 1-D slab model. Total heating in the coil and case is unchanged from the C-coil design.

Fig. 3-43. The one-dimensional slab model.

Fig. 3-44. Neutron flux and heating vs shield thickness.

Fig. 3-45. Insulator dose rates and Cu-dpa vs shield thickness.

In the second step of the 1-D method, we examine end-cell coil geometries, plasma and neutron sources, and neutron source magnitudes to determine 1-D wall loading at the coil where strength and geometry appear to combine with limited shield space to give significant heating and/or damage rates. The final octopole end-cell coil set for FPD-III (see Fig. 3-46) illustrates this process. Figure 3-47 shows the 22.5° cut through the winding packs and the hot, halo, and mantel plasma boundaries as they thread through the end-cell coils. The fusion neutron-line-source strength in the octopole end cell is shown in Fig. 3-48. Examining Figs. 3-47 and 3-48 together, the geometry and source strength appear to combine to give three points where relatively high coil-radiation levels could occur. Starting at the small octopole (at $z \approx 19.4$ m) and working outward, the first point is located in the small octopole coil at $z \approx 19.8$ m. At this point a local maximum in the line-source strength (2.0×10^{16} n/s·m) and the 0.77-m bore of the small octopole combine to give a 1-D wall loading on the coil of ~ 0.0094 MW/m². The space between the coil and the halo plasma is ~ 40 cm. Subtracting 6 cm (2 cm for the case, 1 cm for the insulation, 2 cm for the gap, and 1 cm for the first wall) leaves 34 cm for shielding. With 34 cm of shielding and a wall loading of 0.0094 MW/m², Figs. 3-44 and 3-45 show that peak local heating and other radiation levels in the coil at this point are as follows:

- Peak heating ($\dot{P}$) = 0.51 mW/cm³,
- Peak flux (ϕ ($E > 0.1$ MeV)) = 2.4×10^{17} n/cm²/y,
- Peak rad dose to insulators = 5.6×10^8 rads/y,
- Peak dpa in Cu = 0.00023 /y.

The second point, where a local maxima in coil radiation levels may occur, is at the outer end of the inner bore of the small octopole ($z \approx 20.5$ m). At this corner, we assume that the coil radiation level results from the line source at $z = 20.5$ m and from an integral of the line source between $z = 21$ m and $z = 24$ m. The latter accounts for the fact that the mantel intrudes into the space for shielding, and therefore limiting the minimum space on the end for shielding to ~ 24 cm. This minimum occurs in the 22.5° plane (see Fig. 3-47).

Fig. 3-46. End-cell-coil configuration.

Fig. 3-47. End cell plasma, shield, and coil configuration.

Fig. 3-48. Neutron (DT) line source in end cell.

The line source at $z = 20.5$ m is 1×10^{16} n/s·m and results in a wall loading on the coil of 0.0047 MW/m^2 at $z = 20.5$ m. The integral of the line source between $z = 21$ m and 24 m (where $\dot{S}$ has dropped to 0) is 0.023 MW (see Fig. 3-49). Approximating this 0.023-MW line source by a 0.023-MW point source on the axis at $z = 22$ m results in a wall loading at the corner of the coil of 0.00062 MW/m^2 . The radial and axial space for shielding the inner corner of the coil at $z = 20.5$ m are both 24 cm; thus, the combined heating and damage rates at this point are

- Heating = 1.4 MW/cm^3 ,
- ϕn ($E > 0.1 \text{ MeV}$) = $1.0 \times 10^{17} \text{ n/cm}^2/\text{y}$,
- Dose to insulator = $1.6 \times 10^9 \text{ rads/y}$,
- The dpa in Cu = $0.00070/\text{y}$.

The third point or region, where a local maximum in the coil radiation levels should occur, is in the large octopole adjacent to the upper right-hand corner of the mantel (see Fig. 3-47), where space for shielding drops to ~ 35 cm. This point is in view of the hot-plasma line source between $z = 18$ to 23 m. The integral of the line source between $z = 18$ and 23 m is 5.1×10^{16} n/s, which gives 0.12 MW of 14-MeV neutrons. Concentrating this source on the axis at $z = 22$ m results in a wall loading on the coil of 0.0018 MW/m^2 . This wall loading, coupled with 35 cm of shielding, results in peak heating and damage rates that are about 20 times less than the peak found in the small octopole.

In addition to local peak heating and damage rates in the coil, total neutron-induced heating in the octopole coil set and their cryogenic cases is also important because of the cost of cryo-refrigeration. To estimate this total heating, the end-cell line source under each octopole is integrated in z . These sources are then attenuated by the available shield thicknesses. The integral of the line source located under the small octopole is 32 kW and under the large octopole (excluding the region shared by the small octopole) is 30 kW . Attenuating these sources with shield thicknesses set by the thinnest point found gives the following results:

Fig. 3-49. Integral of the end-cell neutron line source.

Region	Source (kW)	Shield thickness (cm)	Heating coil and case (kW)
Small octopole	22	24	0.95
Large octopole	<u>30</u>	35	<u>0.15</u>
Totals	62		1.10

This method overpredicts heating in the octopole because most of both coils have thicker shielding than the minimum used here and because the coils are not the solid-cylindrical annuli assumed here.

Summary

We have developed an octopole end-cell configuration that allows the small as well as the large octopole to be superconducting. This preliminary assessment is based on a quick and simple 1-D method of shielding analysis. We found that peak heating and damage rates occurred in the small octopole on the outboard end of the inner bore where shield space is at a minimum. We predict that peak heating will be 1.4 mW/cm^3 and that the insulator damage limit at this point will be reached first; thus limiting coil life to 60 years. Total heating in all four of the octopole coils and their cases is predicted to be 2.2 kW; 86% occurring in the small octopoles. Again, we emphasize that this is a preliminary assessment subject to considerable uncertainty, which will require significantly more work to reduce. That's the bad news. The good news is that the heating and damage rates predicted with the 1-D method are at least five times below the upper limits of acceptability. Thus, we can reasonably predict that this end-cell configuration will be acceptable.

ELECTRICAL SYSTEMS

The electrical systems include the electric plant equipment of the ac power system, the power conversion for the confinement magnets, the power

conversion for the microwave and neutral-beam injection (NBI) systems, and the instrumentation and control (I&C) systems.

AC Power System

The ac power system for FPD-III includes the main substation, power distribution equipment, and the feeder cables needed to supply the recycle power loads identified in Table 3-17. This system also includes the 13.8-kV busing, circuit breakers, and dc to ac inverters required for the direct converters and steam-turbine generator if that option is selected. Referring to Table 3-17, the total recycle power needed for steady-state operation of FPD-III is about 133 MW. The table does not include the ICRH power that will be needed for plasma ignition during startup. Nearly half of the recycle power is needed to sustain the octopole end cells.

The FPD-III design has a relatively short central cell with thermal fusion power of 142 MW. Table 3-18 contains power generation data that would be appropriate if we decided to generate electric power rather than dump all the power to cooling towers. Because the machine is small, the engineering Q is only 0.60. From Table 3-18, note that if all the heat were dumped to the cooling towers (no electric power generated), the reject heat load would be 317 MW, which is about 33% more than the 237 MW needed with the power generation equipment.

Figure 3-50 is a block diagram of the proposed ac power system for FPD-III. Mnemonics used in this figure are identified in Table 3-19. A single 115-kV substation provides both the machine and facility power. The prime power for the neutral-beam injectors and ECRH gyrotrons is provided directly from the 13.8-kV line. Two 4160-V substations supply the prime power for the resistive coils, drift-pump coils, and cryogen-system motors. The 4160-V substations also supply the 480-V load centers for the low-voltage power-distribution system. Two 2500-kV·A diesel generators provide 4160-V backup power to the essential electrical loads if a 115-kV power failure occurs. About 50 kV·A of uninterruptible ac power is provided for instrumentation and control.

Table 3-17. Recycle power estimates for FPD-III.

Recycle power load	FPD-III (MW)
NBI power	5
ICRH power	0
ECRH power	60
Drift-pump power	15
Resistive-coil power	23
Superconducting-coil circuit power	2
Cryogenic system power	12
Cooling system and vacuum system power	8
Fueling and fuel processing systems	8
Facility power	<u>5</u>
Total recycle power (excluding tritium cleanup power of 5 MW)	133

Table 3-18. Power generation data for FPD-III.

Power generation data	FPD-III (MW)
Thermal fusion power	142
Total thermal power	184
Thermal power to cooling towers (PREJ)	237
Electrical power output of direct converters	14
Electrical power output of turbine generator	66
Total electrical power generation	80
Total recycle power	133
Net electrical power to utility line (PNET)	-53
$QE = \frac{\text{Total generated power}}{\text{Total recycle power}}$	0.60
$EFFP = \frac{100 (PNET)}{PNET + PREJ} (\%)$	--

Fig. 3-50. Elementary block diagram of FPD-III ac power system.

Table 3-19. Mnemonic definitions.

Mnemonic	Definition
NBI	Neutral-beam injector
LBI	Laser-beam injector
ECRH	Electron-cyclotron resonant heating
DFTP	Drift pump
RC	Resistance conductor
SC	Superconductor
CRYO	Cryogenic
NPS	Number of power supplies
PSVOLT	Power-supply voltage
PSKA	Power-supply current (kA)
BUSLM	Bus length (m)
NBKRS	Number of dc circuit breakers
NDR	Number of dump resistors
EDRMJ	Maximum energy dissipated in a dump resistor (MJ)
PDRMW	Maximum power to a dump resistor (MW)

Electrical Power Conversion Systems

The electrical-power conversion systems include all the power supplies for the confinement magnets and power injection systems for the end cell plasma. In addition, these systems include the protection systems for the magnets, local instrumentation and control, and all power cables and buses.

Power Conversion Systems for the Confinement Magnets. Two coil groups are located close to the plasma in relatively high magnetic fields, namely the inner choke coils and small octopole coils at both ends of the machine. The inner choke coils, of necessity, must be resistive rather than superconducting because of the very high 24-T field and because there is insufficient space to shield a superconducting coil insert from nuclear radiation in this region. The inner octopoles can be located so that adequate nuclear shielding is provided; in addition, the magnetic field is probably low enough to allow the use of superconductors in winding the coil. The power-conversion systems and the ac power demand are based on superconducting magnets (except for the choke coil inserts) to minimize the power-conversion cost and the ac power needed for operation.

Table 3-20 contains the key magnet power-conversion data for FPD-III. Mnemonics used in this table are defined in Table 3-19. The second column of this table refers to the characteristic arrangement of the power-conversion system components for the magnet group. The four types of systems are identified with letters A through D; and generic characteristics of the systems are defined in Figs. 3-51 through 3-54.

The type A system of Fig. 3-51 shows the six main solenoids of the central cell connected in series to a common power supply. A pair of energy-dump resistors are connected across each coil pair and additional dump resistors are connected across each of the four large 60-kA current interrupters. A simple pneumatically-operated switch is used to implement a slow energy dump in lieu of more costly dc circuit breakers. This is possible because of the very low voltage across the low-resistance dump resistor, R_S .

Table 3-20. Magnet-power-conversion data for FPD-III.

Magnet group	Circuit type	NPS	PSVOLT	PSKA	BUSLM	NBKRS	NDR	EDRMJ	PDRMW
Central cell-6	A	1	16	60	100	4	12	400	30
Choke insert-2	D	1	240	100	100	0	0	0	0
Choke BKGRD-2 (CB-1)	B	1	6	9	100	2	4	14	5
Choke BKGRD-2 (CB-2)	B	1	16	10	100	2	4	195	5
Choke BKGRD-2 (CB-3)	C	2	16	12	100	4	8	300	6
Octopole in-2	B	1	6	25	100	2	4	1.1	12
Octopole out-2	B	1	8	20	100	2	4	130	10
Bucking coil-2	B	1	6	22	100	2	4	45	11
Mirror coil-2	B	1	12	10	100	2	4	150	5

Fig. 3-51. Power conversion system for the central-cell solenoid magnets.

Fig. 3-52. Power conversion system for low energy coil pairs (Type B ckt).

Fig. 3-53. Power conversion system for high energy background choke coils.

Fig. 3-54. Power conversion system for resistive insert choke coils (Type D ckt).

Figures 3-52 and 3-53 show the type-B and -C power-conversion systems that apply to the two-coil and single-coil groupings of Table 3-19. The latter applies to high energy coils such as the outside choke-background coil, which has a center tap and separate dump resistors across each half to provide adequate protection if a coil quench occurs.

Figure 3-54 shows the power-supply construction that we would probably use for the resistive-insert choke coils that require high current at much higher voltages than needed for the superconducting coils. A 4160-V substation would provide power to the rectifier transformers through a group of four thyristors per phase. The thyristors control the ac input voltage to all five rectifier transformers. The ten rectifier-module outputs are connected in parallel to a water-cooled bus. A natural air-cooled bus has a large cross-sectional area that would require large penetrations through the vault and inconveniently large leads to the water-cooled insert choke coils. The water-cooled bus can be made of copper pipe to supply water as well as power to the inner choke coils.

Referring again to Table 3-19, the group arrangements are somewhat arbitrary. Two power supplies may be provided for some groups in lieu of one larger power supply to reduce the length of busing and to provide separate control of current in corresponding coils at both ends of the central cell. The bus length is a total bus length for a group of magnets (i.e., if two power supplies are included and the total bus length is 100 m, the bus distance between the power supply and the coil pairs by means of circuit breakers is only 25 m. Busing from the main buses outside the vault to the dump resistors is smaller and is included in the cost of the dump resistors. The cost of estimate, therefore, assumes the power supplies are adjacent to the reactor vault and located close to their respective coils.

Power Conversion for ECRH, NBI, and LBI Systems. Total power to plasma delivery requirements for the ECRH, negative-ion NBI, and the fueling laser-beam injectors (LBI) are given in Table 3-21. The voltage level and efficiency used to determine the ratings of the power supplies are also given in Table 3-21 under data columns 2 and 3. Two power supplies were selected to

Table 3-21. Major ECRH, NBI, and LBI power delivery requirements.

System description ^a	DC power (MW)	Voltage (kV)	Efficiency (%)
Mantle ECRH	8.30	80	35
Potential-peak ECRH	0.20	80	35
Thermal-barrier ECRH	7.75	80	35
Accelerator NBI	1.61	475	32
Fueling laser-beam injector (LBI)	0.04	100	2

^aIn addition, there are also the smaller filament and arc power supplies not identified here.

provide each kind of power, one for each end of the machine. The ECRH power is generated with 26 gyrotrons, 13 for each end of the machine. Each gyrotron is provided with a voltage regulator that also provides the necessary isolation so that common power supplies can be used. The power supply and regulator rating data are given in Table 3-22. Although we may be able to use the gyrotron power supplies to charge the laser beamline Marx generators, for FPD-III we assumed that separate power supplies are necessary.

Figure 3-55 is a one-line diagram showing the major power supplies for plasma conditioning and fueling. The 13.8-kV circuit breakers are a part of the ac power system shown in Fig. 3-50. The regulators include voltage surge arrestors, reactors, filters, diodes, transistors, and vacuum tubes needed to provide voltage regulation and fast protection against faults that may occur.

Instrumentation and Control

We need more time to completely address the FPD-III instrumentation and control issues (I&C). In this section, we briefly describe the following four basic groups of I&C:

1. Plant process,
2. Safety,
3. Plasma diagnostics,
4. Control-building supervisory control and data processing.

Each of these categories has both hardware and software. The major types of equipment in each group are identified in Table 3-23. All higher level control and display consoles associated with the plant process and safety I&C are given under the last category. Table 3-24 identifies ten categories of plant process I&C. If the fusion power of FPD-III is not used to generate electric power, the direct-converter system and turbine-generator systems will not be included in the facility, but more I&C may be needed in the heat-transport system for additional cooling loops and cooling towers.

Table 3-22. Major dc power supplies and regulators.

Description	Quantity	Rating		
		Power (MW)	Voltage (kV)	Current (A)
ECRH power supplies	2	25	85	300
ECRH power regulators	26	2.0	80	25
NBI power supplies	2	2.5	500	5
LBI power supplies	2	1.0	100	10

Fig. 3-55. One-line diagram of major plasma conditioning and fueling power supplies.

Table 3-23. Categories and types of I&C.

Process I&C

- Sensors
- Signal conditioning
- Local processors
- Data multiplexers
- Programmable logic controllers
- Local controls and displays

Safety system I&C

- Sensors
- Signal conditioning
- Hard-wired controls
- Local microprocessors
- Programmable logic controllers
- Local controls and displays

Plasma diagnostics I&C

- Sensors
- Signal conditioning
- Local computers and data storage
- Data multiplexers
- Optical data links
- Local controls and displays
- Remote console controls and displays

Supervisory control and data processing

- Data acquisition from CAMAC equipment
- Optical data links
- Large-scale computers with large, rapid-access storage
- Large mass storage for data archiving
- Complete line of I/O peripherals
- Data links to other large-scale data processing facilities

Table 3-24. Major categories of plant-process I&C.

- Thermal power and heat transport systems (seven major systems).
 - Confinement magnets and their cryogen system.
 - End-cell power-injection systems for plasma conditioning (ECRH, NBI, and drift-pump power).
 - Fueling and fuel processing systems.
 - Reactor and auxiliary component vacuum systems.
 - Direct-converter and halo-scrapers systems.
 - Steam-power-generating systems.
 - Generator and power distribution system.
 - Building facilities such as HVAC, lighting, fire alarm and control, radiation monitoring, and security systems.
 - Remote handling consoles and displays for removal, repair, and maintenance of reactor components and equipment in the reactor vault.
-

Seven groups of heat-transport systems on FPD-III require coolant flow controls to satisfy temperature constraints. These seven groups consist of the following:

1. Liquid lithium-lead cooling systems for the central-cell breeding blankets.
2. Water-cooling systems for auxiliary shielding components and halo-scrapers dumps.
3. Water-cooling systems for the resistive-conducting choke-coil insert coils, busing, and power supplies.
4. Water-cooling systems for ECRH, drift pump, and NBI equipment for end-cell plasma conditioning.
5. Water-cooling systems for the direct-converter collectors.
6. Water-cooling systems for the secondary loops that carry the heat to the cooling towers.
7. Feedwater system if the electrical power generation option is selected.

Water-cooling systems generally require water treatment systems that also need I&C. Some of the cooling systems that interface with the plasma or breeding blanket through a single wall require radiation monitoring instruments to detect tritium leakage. Pump control of coolant flow usually requires speed control of an adjustable speed drive. Valve control of flow usually requires pressure control of a valve position controller.

All but two of the major process control categories of Table 3-24 have safety related I&C that must be able to terminate plant operations to prevent equipment/reactor damage and to isolate tritium leakage contamination. Loss of coolant flow can overheat reactor components and electrical equipment. Instrumentation must be provided to detect loss of coolant flow to many components and shutdown the heat source, which can be the reactor or an electrical-power supply. This generally requires shutting down the reactor and turning off power supplies. A loss of plasma detector is needed to quickly turn off all neutral-beam injectors and terminate reactor operations. Superconducting-magnet quench detectors and detectors of events that could

lead to a quench must be provided. These detectors must be able to initiate a rapid discharge of the superconducting magnets into energy-dump resistors. Radiation monitoring of cooling systems, reactor vault and fuel processing equipment, and associated buildings is needed for detecting tritium leakage and terminating reactor operations. Instrumentation and control systems are needed for turning on large blower motors and operating valves for cleanup.

Some plasma diagnostic instrumentation is needed to control the reactor plasma density, temperature, potential, and reaction rate (neutron flux). Table 3-25 lists the plasma diagnostics being considered for FPD-III, in addition to the type of measurement, mnemonic abbreviations, and type of reactor penetration required.

One of the most serious FPD L&C problems is the very limited space available between magnet coils for the diagnostic instrumentation needed to control the reactor. For FPD-III, we addressed this problem by adding a small sector in the middle of the central cell dedicated to providing penetrations needed for the control and diagnostic instrumentation, and for the fuel injectors. Figure 3-56 is a section view of the proposed sector showing two 24-in. horizontal-receiving tubes and two 24-in. vertical-receiving tubes. One of the horizontal tubes is dedicated to the fueling module. The other horizontal tube is dedicated principally to microwave diagnostics, but may have a horizontal line-of-sight penetration to view a vertical laser beam or ion beam. The upper vertical 24-in. tube is devoted to passive and active optical diagnostics. These diagnostic modules are described in Ref. 25.

The bottom 24-in. tube contains a module having several line-of-sight penetrations for directly viewing the plasma from the underside and for terminating a diagnostic laser beam or ion beam in an energy dump. The underside receiver diagnostics and energy dumps are mounted in a shielded container supported on horizontal rails for removal and replacement, if necessary. The horizontal diagnostic-insert modules can also be removed with a portable, horizontal rail assembly. The vertical assembly is readily removed with the overhead crane.

The end-cell diagnostics also need further investigation. Ion spectrometers used to measure the potential barrier height can be located on the end covers of the reactor. They require holes through the direct

Table 3-25. Selected plasma diagnostics.

Quantity measured	Type of measurement	Mnemonic	Type of penetration
Vacuum pressure	Ion gauge	BGP	Offset
Neutron flux	Neutron counters: fission chambers, scintillation detectors	NCT	Shielded
Heat flow (power)	Calorimeter	CAL	LOS ^a
Integrated heat flow	Bolometer	BOL	LOS
Ion current	Charged particle flux	CPF	LOS
$\phi_{\max}$, particle parallel energy	$E_{\parallel}B$ ion spectrometer	ISP	LOS
ϕ_c , particle perpendicular energy	Neutral flux spectrometer	NFS	LOS
$\int n_e T_e d\ell$	Electron-cyclotron emission	ECE	Offset waveguide
ϕ, B^{TILDE}	Electromagnetic fluctuation	EMF	Offset coaxial line
$\int n_e T_e d\ell$ (low density)	Microwave interferometer	MIN	Offset waveguide
$\int n_e T_e d\ell$ (high density)	FIR laser interferometer	FLI	Offset mirrors
Ion temperature (D_2 phase)	Doppler shift spectrometer	DSS	Offset mirrors
Impurities, n_e, T_e	Ultraviolet spectrometer	UVS	Offset mirrors
Color, impurities	Plasma image (television optics for startup only)	PIM	Offset mirrors
Neutron fluence	Neutron activation system	NAS	Offset pneumatic tubing
Ion temperature (T_2 phase)	Neutron energy spectrometer	NSP	LOS

Table 3-25. (Continued.)

Quantity measured	Type of measurement	Mnemonic	Type of penetration
n_e, T_e	X-ray energy spectrometer	XRS	LOS
$dn/d\theta$	Sloshing-ion sensors	SIS	LOS
$\int n_i T_i dV,$ $n_e T_e dV,$ B, I_p (startup)	Plasma current sensors, magnetic loops	PCS	Offset leads

^aLOS = line of sight.

Fig. 3-56. Section view sketch of the instrumentation and fueling sector located in the middle of the central cell.

converter collectors. This diagnostic instrumentation is described in detail for MFTF- α +T in Ref. 25. Space between the octopole-magnet-coil windows is largely devoted to ECRH, NBI, and drift-pump power injectors. However, there appears to be limited space remaining for neutron, optical, and microwave types of plasma diagnostics. Location of these diagnostics in the octopole region will be addressed during the MINIMARS study to be accomplished in FY85.

The supervisory control and data acquisition system for FPD-III includes the following:

- All large scale data processors and their peripherals,
- Plant process consoles containing controls and displays,
- Data links to the lower-level local computers and CAMAC equipment.

The data acquisition system includes all sensors and signal conditioning not dedicated to control systems, analog to digital conversion, and data control and transmission to the large scale data processors. The CAMAC modules generally provide the front-end functions. A large part of the supervisory control and data acquisition cost is the applications software generally needed for a new generation of computers. If the software developed for MFTF-B could be adopted to a large extent, the software cost could be considerably reduced.

Compared with MFTF-B and Tokamak Fusion Test Reactor (TFTR), the diagnostic instrumentation cost for FPD-III can be reduced by using mostly essential diagnostics that have been previously developed. More process I&C will be required than for existing installations because of the direct converters, neutron shielding, blankets, halo-dump modules, and the tritium-processing and fueling system. The safety system must be augmented to include the fueling and tritium processing facilities. If no power generation options are selected and substantial use of past development of diagnostic sensors and software are fully utilized, we should be able to provide the I&C for about the same cost as the I&C for MFTF-B.

TRITIUM SYSTEMS

The FPD-III tritium systems include equipment for tritium storage, recovery of tritium from the breeding blanket, and cleanup/recovery of tritium released to the atmosphere of the reactor, hot cell, radwaste, or tritium-processing buildings. The major input parameters and assumptions that we used for sizing and evaluating the tritium-system design are listed in Table 3-26.

We assume a fueling rate by pellets of 30 g/h (18 g/h of tritium and 12 g/h of deuterium). Since we expect the FPD-III device to have the capability for long-duration burns, storage of sufficient tritium to fuel the device without continuous processing is impractical. For example, a 1.8-kg inventory of tritium is needed to fuel FPD-III for a 100-h burn if no fuel recycling is used. Therefore, the tritium system is designed to process the fuel on a steady-state basis. Uranium-storage beds, used to store the tritium and deuterium cycled through the reactor, are sized to a capability of 60 g, which corresponds to 2 h of operation. The tritium burnup rate corresponding to the 150-MW fusion power for FPD-III is about 1 g/h.

The breeding-blanket design for FPD-III provides a tritium-breeding ratio slightly greater than 1 to compensate for the burned tritium. The liquid-LiPb breeding material, also used as the blanket coolant, is processed continuously to remove the bred tritium with an equilibrium concentration of 0.001 ppm.

The atmospheric-recovery system is designed to cleanup tritium released into buildings that could potentially contain tritium. These buildings include the reactor building, tritium-processing building, radwaste building, and hot-cell building. Atmospheric recovery units of the type used in Tritium Systems Test Assembly (TSTA) are located in the tritium-processing building. The compressors, catalytic oxidizers, driers, and storage tanks are sized to handle a release of 10 g (96 kCi) of tritium in any of these buildings. The maximum cleanup time allowed before reaching a tritium concentration of $50 \mu\text{Ci}/\text{m}^3$ is five days. The atmospheric recovery system design approach selected for FPD-III uses a single set of equipment for processing all buildings. Ducts and tritium monitoring instrumentation must be provided in

Table 3-26. The FPD-III tritium systems parameters and assumptions.

Fusion power (MW)	150
Fueling rate (gm/s)	
Tritium	18
Deuterium	12
Tritium breeding ratio	1.1
Tritium concentration in LiPb blanket (ppm)	0.001
Sizes of tritium-containing buildings (m ³)	
Reactor building	49,000
Tritium-processing building	10,000
Radwaste building	1,100
Hot cell	13,000

all potentially contaminated areas. The system size is determined by the largest building, which is the reactor building with a volume of $49,000 \text{ m}^3$. Therefore, the required atmospheric processing rate is $4.0 \text{ m}^3/\text{s}$. With this processing rate, the smaller tritium processing building ($10,000 \text{ m}^3$) can be cleaned up to a tritium concentration of $50 \text{ } \mu\text{Ci}/\text{m}^3$ in less than two days.

This atmospheric-recovery system for FPD-III differs from the FPD-I and FPD-II approaches, which included separate equipment for handling each building. The FPD-III reference design saves about \$3.7 million dollars compared with the FPD-I and -II systems.

Estimated tritium inventories in various components for FPD-III are listed in Table 3-27; the total tritium inventory is 0.22 kg (2.1 MCi).

Table 3-27. Tritium inventories
in FPD-III (grams).

Reactor building	
Reactor structure	30
Halo cryopumps	6
Pellet fueler	6
Blanket	<u>1</u>
Total reactor building	74
 Tritium processing	
Storage	36
Pellet preparation	13
Fuel cleanup	44
Cryogenic distillation	<u>54</u>
Total processing	147
 Total	 221

REFERENCES

1. B. G. Logan, C. D. Henning et al., MARS Mirror Advanced Reactor Study, Final Report, Commercial Fusion Electric Plant, Vols. 1A and 1B, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53480 (1984).
2. Fusion Power Demonstrations I and II, J. N. Doggett, Ed., Lawrence Livermore National Laboratory, Livermore, CA, UCID-19975-1 (1985).
3. F. E. Coffield et al., "Polarizing Holographic Reflector for Electron-Cyclotron Resonant Heating (ECRH) on the Tandem Mirror Experiment-Upgrade (TMX-U)," in Proc. of the IEEE, 10th Symposium on Fusion Engineering, December 5-9, 1983.
4. J. J. Yugo et al., "Quasi-Optical Microwave Beam System for ECRH in MFTF-B," presented at the APS 25th Annual Meeting of the Division of Plasma Physicists, Los Angeles, CA, paper 6U10 (November, 1983).
5. W. H. McAdams, Heat Transmission (McGraw-Hill Book Co., Hightstown, NJ, 1954).
6. M. Abdou et al., "Impurity Control and First Wall Engineering, Chapter VII," in U.S. FED-INTOR Phase II Critical Issues, W. Stacey, Ed., PFD INTOR/ICRW82-17 (1982).
7. D. L. Smith, J. N. Brooks, D. E. Post, and D. Heifetz, "A Physical Sputtering Code for Fusion Applications," in Proc. of 9th Symposium of Engineering Problems of Fusion, IEEE Pub. No. 81CH1715-2 NPS (1981).
8. J. Brooks, Argonne National Laboratory, Argonne, IL, private communication (1984).
9. F. G. Hammitt, "Cavitation and Liquid Impact Erosion", in Wear Control Handbook, American Society of Mechanical Engineers (1980).
10. F. G. Hammitt, Y. C. Huang et al., "Volume Loss Due to Cavitation or Liquid Impingement," in Characteristics and Determination of Erosion Resistance, American Society of Testing Materials Special Technical Publication 474 (1970).
11. B. J. Milleville, "The Case for Higher Velocities in Feedwater Piping," in Proc. of the 30th Annual Meeting of the American Power Conference, Chicago, IL (1968).

12. P. Cohen, "Water Coolant Technology of Power Reactors," in Monograph Series on Nuclear Science and Technology, American Nuclear Society (1980).
13. J. Schultz, Design Practice and Operational Experience of Highly Irradiated, High Performance Normal Magnets, Massachusetts Institute of Technology, Plasma Fusion Center, Cambridge, MA, PFC/RR-82-25, DOE/ET-51013-54-UC20B (1982).
14. G. Jenks, Effects of Reactor Operation on HFIR Coolant, Oak Ridge National Laboratory, Oak Ridge, TN, ORNL-3848 (1955).
15. E. J. Hart et al., "The Decomposition of Light and Heavy Water Boric Acid Solution by Nuclear Reactor Radiations," in Proc. of the Intern. Conf. Peaceful Uses At. Energy, Geneva, 1955, 7, 593 United Nations, NY (1956).
16. W. D. Mackintosh et al., Radiolytic Gas Production in Liquid Control Elements for Nuclear Reactors Using Boron as an Absorber, Atomic Energy of Canada Ltd., Ottawa, Ontario, Canada, AECL-2670 (1967).
17. D. Whyte, Forest Park Research Center, Westinghouse Corp., Pittsburg, PA, private communication (1984).
18. M. Harmsen, "System Description SD-5G4 Demineralized Water Systems," Tokamak Fusion Test Reactor, Rev. 2, Princeton Plasma Physics Laboratory, Princeton, NJ (1982).
19. W. R. Smythe, Static and Dynamic Electricity (McGraw-Hill Book Co., Hightstown, NJ, 1950).
20. J. H. Fink, G. W. Hamilton, and J. L. Erickson, "A 24-MW Neutral Beam Injector of 400 keV H^0 ," in Pro. of the 8th Symposium on Engineering Problems of Fusion Research, "Inst. of Electronic and Electrical Engineers, Berkeley, CA (1979).
21. E. I. DuPont de Nemours, Vespel Parts, Product, and Design Manual, Wilmington, DE (1980).
22. M. Baskes, W. Bauer, and K. Wilson, Tritium Permeation in Fusion Reactor First Walls, Sandia Laboratory, Livermore, CA, SAND-82-8698 (1982).
23. M. Baskes, "A Calculation of the Surface Recombination Rate Constant for Hydrogen Isotopes on Metals," J. of Nucl. Mater. 92, 318-324 (1980).

24. D. Dorn, Lawrence Livermore National Laboratory, Livermore, CA, private communication (1984).
25. MFTF- α +T Progress Report, Fusion Engineering Design Center, Oak Ridge National Laboratory, Oak Ridge, TN, ORNL/FEDC-83/9, to be published.

Section 4

Maintenance and Component Replacement

4.0. MAINTENANCE AND COMPONENT REPLACEMENT

REQUIREMENTS

The configuration for FPD-III is an iteration of the FPD-II design,¹ and except for the end cell, the maintenance, and component-disassembly requirements, are essentially the same. The FPD-III end cells contain a magnet system made up of a choke-coil assembly, a major and minor octopole assembly, and a mirror/shaping coil assembly. Except for the choke coils, each of these magnet-system assemblies are interlocked to some degree. Hence, vertical removal through the end-cell hatch is more complex for FPD-III.

The biological shield around the vacuum vessel is designed to limit the surface activation to 0.5 mrem/h, 24 h after device shutdown. Therefore, personnel access in the vault is permitted for the following:

- Inspection;
- Disassembly of electrical, coolant, and structural connections;
- Setup of maintenance equipment if the device shield is not disassembled.

This approach is identical to that of FPD-I and -II.¹ The dose rate of 0.5 mrem/h was established to meet the as low as reasonably achievable (ALARA) guideline that limits personnel exposure to less than or equal to 1 rem/y.

END CELLS

We based the design of the end cells on removal of the primary components as modular units. The direct-converter/halo-scraper assembly is removable as a module and is integral with the shielded access hatch shown in Fig. 4-1. The removal of this assembly is accomplished as a vertical lift using the primary overhead crane (300 ton) supplemented by remote operations using one or both crane-mounted manipulator systems.

The choke-coil assembly is removed through the main end-cell hatchway after disassembly of the appropriate shield modules and service connections.

Fig. 4-1. Removal of structural attachments between octopole frames and mirror/shaping coil assembly.

This module consists of three superconducting coils and one resistive coil with integral shielding. This is the heaviest component in the end cell with an estimated weight of 126 tonnes. Because of the high-operating magnetic field of the resistive coil and its proximity to the plasma, the choke coil assembly is not considered to be a lifetime component. Hence, some finite number of replacements are expected. The frequency of replacement and the duration of downtime can be used to determine the impact on availability, which becomes the basis for using either a complete spare module or replacing of the copper insert in a serial hot-cell operation.

For FPD-III the primary problem is replacement of the minor octopole assembly. This is the smallest end-cell component (7.5 ton) (see Table 4-1), but, because it is nested within the major octopole, its removal requires disassembling either one or two of the major octopole window frame coils, depending on which end cell is affected. Figure 4-1 shows the arrangement of the coil system in the end cell. The octopole coils have a 45-deg axial rotation to each other between the east- and west-end cells. Because of this rotation, removal of the minor octopole is more complex in one end cell (compare Figs. 4-2 and 4-3).

Removal of the mirror octopole requires seven primary operations. All of these operations must be accomplished remotely; a brief description of each is discussed below:

1. Remove the end-cell hatch to provide access for all subsequent overhead operations. The hatch is stored in the vault "laydown" area and also serves as the holding fixture for the frame coils that are subsequently removed from the end cell. Disassembly of the structural attachments and the vacuum seal of the hatch may be accomplished with personnel before pumping out the shield water contained in the hatch.
2. Disconnect electrical and coolant lines to the major octopole frame(s) that will be removed, and also disconnect those lines to the minor octopole.
3. Remove the upper link attachments on the structural ribs of the frame coils (Figs. 4-2 and 4-3).

Table 4-1. Approximate weights for end-cell components.

Component	Weight ^a (tonnes)
Choke-coil assembly	126.0
Major octopole (per frame)	42.5
Minor octopole assembly	7.5
Mirror coil	15.0
Shaping coil	35.0
	} 50.0
Annular shield module	115.0
End-cell main hatch	85.0

^aIncluding estimates for structure.

Fig. 4-2. End cell which requires removal of one octopole frame for access to the mini-octopole.

Fig. 4-3. End cell, which requires removal of two octopole frames for access to the mini-octopole.

4. Remove the small centerline hatch for access to the structural attachments between the octopole assembly and the mirror/shaping coil assembly (Fig. 4-1). Only those attachments into the frame that is being removed need to be disassembled. We estimate that 48 5-cm bolts are needed to react the 60 MN (13.5×10^6 lbs) tensile load at this interface; therefore, each frame interface has 12 bolts. The crane-mounted manipulator is shown removing the upper bolts using an impact wrench in Fig. 4-1. Advanced manipulator systems (presently under development) are suitable for this operation. Note that the telescoping boom requires one articulated joint because of the location of the centerline hatch.
5. Remove a portion of the inner shield annulus (Fig. 4-4) to gain access to the structural attachments between the minor octopole assembly and the frames(s). To reach this shield using the overhead manipulator, a trapezoidal access opening (100 x 90 x 75 cm) is needed through the inner and outer structural shells of the top frame(s) between the third and fourth ribs.
6. Translate the octopole frame that is removed 0.5 m towards the central cell to clear the mirror/shaping coil assembly before vertically lifting the frame from the end cell. In the present configuration, this operation is not possible because the annular shield constrains lateral movement of the frame. Therefore, either the mirror/shaping coil assembly must be moved back 0.5 m or the annular shield must be modularized so that it becomes part of the frame assembly. Additional development of the end-cell configuration is needed to determine the most feasible approach.
7. Lift out the minor octopole assembly after removing the remaining structural attachments to the frames.

DESIGN MODIFICATIONS

We identified four design modifications that were needed in the end cell to improve disassembly and component removal operations:

Fig. 4-4. Access requirements for minor octopole detachment.

1. Add a small centerline hatch (1 x 2 m) behind the main hatch to gain access to the structure of the mirror/shaping coil assembly.
2. Add an access opening through the inner and outer shells of the upper frame(s) and between two ribs to gain access to the annular shield and the structure between the minor and major octopoles.
3. Design the annular shield to have two removable pieces for access to structural attachments and consider eliminating the upper structural attachments between the minor and major octopoles.
4. Evaluate modularizing the annular shield vs moving the mirror/shaping coil assembly to remove the octopole frames.
5. Provide an articulated joint in the telescoping boom of the crane-mounted manipulator to reach the mirror/shaping coil structure.

REFERENCE

1. Fusion Power Demonstrations I and II, J. N. Doggett, Ed., Lawrence Livermore National Laboratory, Livermore, CA, UCID-19971-1 (1985).

Section 5

Plant Facilities

5.0. PLANT FACILITIES

The facilities for FPD-III include a number of generic buildings that would be necessary for any large, self-contained industrial plant, as well as those buildings and services unique to mirror fusion. Accordingly, we have concentrated our bulk design and arrangement effort on the unique aspects of fusion facilities. These core fusion facilities are illustrated in Figs. 5-1, -2, and -3. The core fusion facilities and the facilities not shown in the figures (e.g., the warehouse, maintenance shops, central control room, switchyard, ventilation stack, administrative building, etc.), would fill a site plan that would encompass roughly 50 acres. Although these nonfusion facilities have been included in the cost estimate, they have not been specifically located or detailed at this time.

The core fusion facilities shown in Figs. 5-1, -2, and -3 consist of a central fusion island on a common foundation mat of approximately 4275 m². This mat is surrounded by a number of contiguous buildings on independent foundations. The structures on the common mat include the reactor vault, steam-generator cell, LiPb-processing cell, hot cell, decontamination cell, and component transfer chambers. These facilities are grouped together because of their shared design requirements. These common criteria are seismic design, tornado missile protection, flood protection, radioactive-shielding requirements, tritium confinement, and remote-handling requirements for large components during maintenance operations. This common mat grouping may also permit some wall thickness reductions because of the interior-structure shielding provided by exterior structures.

The mirror device for FPD-III is located in the 23-m-wide x 76-m-long x 27-m-tall reactor vault. This mirror device is located slightly off center to the north side of the vault about 9 m above the mat. We chose this arrangement to accommodate both of the neutral beams on the south side of the vault, thus minimizing vault width. The vault is serviced by a 300-tonne overhead crane, as well as by several smaller manipulator cranes. The main crane is used for large component transfers in the component removal right-of-way along the north side of the vault. Both the overhead crane and its load can access the decontamination cell through a crane door [similar to the Joint European Torus (JET) crane door concept] and a rolling shield door in the east end of the vault.

Fig. 5-1. FPD-III plan view, grade EL-0.0.

5-3

Fig. 5-2. FPD-III plan view, grade EL-13.0.

5-4

Fig. 5-3. FPD-III section view.

The decontamination cell is a 14-m-wide x 23-m-long x 14-m-high chamber either lined with stainless steel, or coated with easily washable epoxy paint. The reactor-vault overhead crane is stored in this cell during machine operation to prevent unnecessary activation of the crane. In addition, all components either entering or leaving the reactor vault must pass through the decontamination cell. Here, for example, activated components leaving the reactor vault are cleaned to remove loose contamination before transfer to the hot or warm cell. This transfer is accomplished by lowering the component through the appropriate steel-covered hatchway onto a rail-mounted transfer carriage in either the hot-cell or warm-cell transfer chambers.

A component with a high enough activation level is sent to the hot cell for maintenance operations. Once lowered onto the transfer carriage, the carriage moves to a position under the hot-cell access hatch, where it can be remotely grappled and raised into the hot cell by the hot cell's 300-tonne overhead crane. The hot cell is roughly 17 x 39 x 14 m high to accommodate several central-cell sectors. Beneath the hot cell is an area for various hot-cell services and activated-component storage.

Components having activation levels that permit hands-on maintenance are transferred to the warm cell from the decontamination cell in a manner similar to the hot-cell transfer. The warm cell is a structural-steel, metal-sided building on a separate foundation approximately 20 m x 40 m x 16 m high. It is served by its own 300-tonne overhead crane, which it shares with the adjacent fabrication, assembly, and mockup building of similar dimensions and design. Thus, remote maintenance operations can be practiced and new components can enter the complex through the fabrication, assembly, and maintenance (FAM) building.

In addition to the hot cell, the south side of the common-foundation mat includes the steam-generator cell and the LiPb-process cell. This area is roughly 17 x 53 x 27 m high and provides space for the 184 MW of steam generation equipment, circulating pumps, tritium extraction equipment, and LiPb storage. This area is serviced by its own overhead crane.

The steam-generator cell is located near the central-cell region to minimize LiPb-piping runs and on the south side of the reactor vault, which prevents interference of the large bore and heavily supported LiPb pipe with

the component removal right-of-way. Also, because the steam-generator cell is located on the common mat, we do not need to account for the seismically induced, differential building motions when providing supports for the heavy LiPb pipe.

The turbine building is a structural steel, non-nuclear grade, metal-sided building. It is located immediately adjacent to the steam-generator cell to minimize main steam and feedwater pipe runs. It is roughly 43 x 45 x 40 m tall, with three internal levels. It houses the 70-MW turbine-generator and all of its auxiliary systems and equipment.

The three structures along the west end of the fusion island are the cryogenic building (25 x 18 x 6.1 m tall), the tritium building (25 x 30 x 12 m tall), and the health physics building (20 x 20 x 3 m tall). The cryogenics building is of standard industrial construction. It is serviced by its own 10-tonne overhead crane and houses the compressors and other components of the cryogenic liquefaction systems. The cryogenics building is fed by a nearby tank farm where hydrogen and nitrogen gas is stored. The health physics building is of similar construction and includes change rooms, personnel radiation control and monitoring, and is the central personnel access point to the various potentially contaminated areas.

Although the tritium building is a reinforced concrete, nuclear-grade structure, it was not located on the common mat. Tritium, which is a beta emitter, does not require significant shielding walls (the reinforced concrete exterior walls are primarily for missile protection). Tritium process piping is essentially small bore and relatively easy to route and seismically support. In addition, the tritium processing equipment and atmospheric tritium recovery units housed in the building produce relatively small structural loads that permit a thinner foundation mat than the common mat.

The power supply building is located on the north side of the fusion island. It is a tee-shaped building to maximize the busbar and cable access both to the reactor vault and to the transformers located along its exposed northern perimeter. This building occupies an 800 m² footprint, is 7.6-m high, and is fabricated as a standard industrial building.

Beneath the power-supply building is the diagnostics building and the laser-fueling vault. These buildings are of standard industrial construction.

They are located slightly below grade to permit "line-of-sight" communication with the device. For example, a focusing tube runs horizontally from the laser vault, through the diagnostics building, and directly to the centerline of the central-cell region of the device. This focused laser beam is used in conjunction with pellet fuelers (located adjacent to the reactor vault in the diagnostics building) to add fuel to the reactor.

Finally, located adjacent to the hot cell and FAM building is the non-nuclear, standard-industrial-construction, auxiliary building (15 x 25 x 6.1 m high). It houses the non-nuclear-grade component-cooling system; the auxiliary boiler; the heating, ventilating, and air conditioning (HVAC) service for nearby facilities; and various miscellaneous systems.

In summary, the arrangement of the facilities described here appears feasible from a preconceptual perspective. However, considerable detail remains to be developed, which is well beyond the scope of this present effort. System process flow diagrams, piping drawings, equipment sizes and outline dimensions, heat transport and power generation cycle, as well as maintenance and operating scenarios must be developed before reasonable conceptual facility arrangements can be designed.

Section 6

Cost Projection

6.0 COST PROJECTION

The total construction cost that we project for the FPD-III facility is summarized in Table 6-1. This cost projection is in millions of mid-1984 dollars and is based on the following assumptions:

- The facility will be constructed on an undeveloped national laboratory site.
- The device will be constructed by a prime contractor who is responsible to the national laboratory for engineering, procurement, and construction.

Our approach to assembling the FPD-III cost projection consists of parallel project design and cost database activities. Early in the project we developed a detailed code of accounts (work breakdown structure), compatible with the FPD-III project, which was below the mandatory level of the standard Fusion Engineering Design Center (FEDC) Code of Accounts to add conformity to the development of the cost projection. We assigned cognizant engineers the responsibility of providing the technical input to project costs for the various components and/or subsystems in the code of accounts. At the point when quantities of material and equipment could be estimated, the cognizant engineers submitted standardized component-design data sheets along with supporting material for their assigned elements in the code of accounts. These design data sheets included the design basis, the design description, and a listing of the pertinent design parameters. This assemblage of component/subsystem design data sheets in conjunction with the cost database file form the basis for FPD-III cost projection.

The cost database file, which is the product of the ongoing FEDC cost database activity, is a catalog of cost coefficients, algorithms, and component costs arranged in a standard format on separate cost data sheets corresponding to specific components and subsystems. These cost data sheets contain engineering, equipment, and labor cost data for different configurations and types of specific component/subsystems. We developed the cost database file from actual cost experience and refined it to be compatible with the FEDC

Table 6-1. The FPD-III projected-cost summary.

Account number	Account title	Cost (84 M\$) ^a
20	Land and land rights	0
21	Structures and site facilities	124.0
22	Reactor plant equipment	859.46
221	Reactor systems	141.4
222	Magnet systems	178.8
223	Power injection systems	123.34
224	Vacuum systems	9.3
225	Power conditioning systems	71.30
226	Heat transport systems	84.0
227	Fuel handling systems	84.5
228	Instrumentation and control	72.6
229	Maintenance equipment	94.1
23	Turbine plant equipment	46.7
24	Electric plant equipment	15.4
25	Miscellaneous plant equipment	25.5
26	Heat rejection system	9.4
	Total direct cost	1080.47
91	Construction services and equipment	54.02
92	Home office engineering and services	108.05
93	Field office engineering and services	101.05
94	Owner's cost	54.02
	Total indirect cost	324.14
	Contingency	421.38
	Total constructed cost	1826.00

^a Millions of dollars.

cost-projection methodology. Table 6-2 shows a detailed cost breakdown of the FPD-III cost elements. We developed and defined these projected costs according to the standard FEDC Code of Accounts and cost element definitions. The total constructed cost of the facility is composed of direct costs, indirect costs, and contingency costs. Direct costs are the equipment, engineering, and labor costs that are specifically identified with a permanent plant component or facility. Equipment costs include the purchase price of commercially available materials and equipment delivered to the site, and the "build-to-print" costs incurred by the project and its subcontractors. The "build-to-print" cost is defined so that it represents the purchase price of the component if it were commercially available and includes materials, fabrication, labor, tooling, packaging and shipping, acceptance testing, as well as recurring manufacturing-support engineering.

We defined the engineering element of direct cost to include the first-of-a-kind, nonrecurring engineering costs. Engineering consists of design management, design engineering, analysis, specification and drawing development, process verification testing, and tool design. Labor costs refer to the cost of craft labor used for assembly and on-site acceptance testing of the permanent plant equipment and subsystems. We calculated direct costs using design parameters and descriptions from the design data sheets submitted by the cognizant engineers and cost data obtained from the cost database file on a similar component/subsystem. Three techniques were used to estimate the equipment cost for a specific component and/or subsystem. These were unit costing, cost algorithms, and "component takeoff" costing. When a solid historical database was available for costing a specific component/subsystem, we used the unit costing method; whereby, the cost is based on cost per unit (weight, area, volume, etc.) of similar equipment. When a good database did not exist, we employed the cost algorithm method of costing. Cost algorithms are empirical costing equations, developed from experience on similar hardware, where the cost is scaled as a function of component design parameters. When the subsystem is composed of standard items, where costs are accurately known, a "component takeoff" method is used whereby the subsystem cost is based on the unit cost and quantity of the components that comprise the system. We calculated engineering cost and labor cost for the component/subsystem using a percentage of equipment cost extracted from the cost database file.

Table 6-2. The FPD-III facility cost projection (numbers in brackets indicate subtotals).

Account number	Account title	Projected cost (84 M\$) ^a
20	<u>Land and land rights</u>	0
21	<u>Structures and site facilities</u>	[124.0]
211	Site improvements/facilities	17.5
212	Reactor building	28.3
213	turbine building	15.4
214	<u>Reactor maintenance buildings</u>	[20.5]
214.1	Hot cell	17.3
214.2	Warm cell	2.4
214.3	Mockup building	0.9
215	Tritium building	10.1
216	<u>Electrical equipment buildings</u>	[17.1]
216.1	Field-coil power-supply building	1.5
216.2	RF power-supply building	0
216.3	Steam-generator building	15.6
217	<u>Other buildings and structures</u>	[15.1]
217.1	Administration building	1.5
217.2	Radwaste building	0.3
217.3	FAM building	4.9
217.4	Diagnostic building	1.1
217.5	Cryogenics building	0.5
217.6	Plant-auxiliary building	0.4
217.7	Switchyard	0.2
217.8	Vent stack	0.1
217.9	Control-room building	3.3
217.10	Security building	0.4
217.11	Warehouse	1.8
217.12	Miscellaneous buildings and structures	0.6

Table 6-2. (Continued.)

Account number	Account title	Projected cost (84 M\$) ^a
22	<u>Reactor plant equipment</u>	[859.46]
221	<u>Reactor systems</u>	[141.4]
221.1	First-wall assembly	1.1
221.2	Blanket assembly	17.6
221.3	Shielding	48.9
221.4	<u>Reactor structures</u>	[54.6]
221.4.1	Reactor support structures	11.2
221.4.2	Vacuum-vessel assembly	39.7
221.4.3	Magnet support	3.6
221.5	<u>Energy and particle removal/control system</u>	[19.2]
221.5.1	Drift pumping	18.0
221.5.2	Halo scraper	0.6
221.5.3	Direct energy converter	0.6
222	<u>Magnet systems</u>	[178.8]
222.1	<u>Magnet assemblies</u>	[169.3]
222.1.1	Central-cell solenoids	20.5
222.1.2	Choke coils	55.4
222.1.3	Small octopole coils	4.1
222.1.4	Large octopole coils	53.0
222.1.5	Plug coils	0
222.1.6	Bucking coils	8.5
222.1.7	Mirror coils	27.7
222.1.8	Axicell magnets	0
222.2	<u>Magnet cryostats</u>	[9.6]
222.2.1	Central-cell thermal shields	6.0
222.2.2	End-cell thermal shields	3.6
223	<u>Power-injection systems</u>	[123.34]

Table 6-2. (Continued.)

Account number	Account title	Projected cost (84 M\$) ^a
223.1	<u>ECRH system</u>	[118.45]
223.1.1	Potential-peak ECRH	2.53
223.1.2	Thermal-barrier/mantle ECRH	115.92
223.2	ICRH system	0
223.3	Lower Hybrid Resonant Heating (LHRH) system	0
223.4	Neutral-beam-injection system (SINB)	..89
224	<u>Vacuum systems</u>	[9.3]
224.1	Internal-vacuum system	1.2
224.2	External-vacuum system	8.1
224.3	Secondary-vacuum systems	0
225	<u>Power-conditioning systems</u>	[71.30]
225.1	<u>Magnet-system power conditioning</u>	[12.0]
225.1.1	Central-cell solenoid power conditioning	4.2
225.1.2	Choke-coil-insert power conditioning	3.8
225.1.3	Small-octopole power conditioning	0.8
225.1.4	Large-octopole power conditioning	0.7
225.1.5	Choke-background-coil power conditioning	2.1
225.1.6	Bucking-coil power conditioning	0.7
225.1.7	Mirror-coil power conditioning	0.5
225.1.8	Axicell-magnet power conditioning	0

Table 6-2. (Continued.)

Account number	Account title	Projected cost (84 M\$) ^a
225.2	<u>Power-injection-system</u>	
	<u>power conditioning</u>	[33.23]
225.2.1	ECRH power conditioning	30.75
225.2.2	ICRH power conditioning	0
225.2.3	LHRH power conditioning	0
225.2.4	NBI power conditioning	2.1
225.3	<u>Energy and particle removal/ control power conditioning</u>	[25.2]
225.3.1	Direct-conversion inverter	2.7
225.3.2	Drift-pump power conditioning	22.5
225.4	Energy storage	0
226	<u>Heat-transport systems</u>	[84.0]
226.1	Blanket heat-transport system	42.2
226.2	Shield heat-transport system	3.7
226.3	Cryogenic-cooling system	33.5
226.4	Water-cooling system	3.9
226.5	Gas-cooling system	0.7
227	<u>Fuel-handling systems</u>	[84.5]
227.1	Fuel-injection system	12.7
227.2	Fuel-processing and purification system	16.7
227.3	Storage and receiving systems	5.0
227.4	Atmospheric-recovery systems	8.6
227.5	Water-recovery systems	0
227.6	Blanket-recovery systems	41.5
228	<u>Instrumentation and control system</u>	[72.6]
228.1	Data-acquisition system	14.5
228.2	Man-machine interface	2.6

Table 6-2. (Continued.)

Account number	Account title	Projected cost (84 M\$) ^a
228.3	Diagnostics	34.5
228.4	Central data processing	9.6
228.5	Software	11.4
229	<u>Maintenance equipment</u>	[94.1]
229.1	Manipulator systems	17.4
229.2	Transport systems	30.5
229.3	Inspection/viewing/ testing systems	16.3
229.4	Remote cutting/welding/ machine tools	4.7
229.5	Mockup equipment	14.4
229.6	Miscellaneous tools	4.3
229.7	Decontamination equipment	2.3
229.8	Radwaste treatment/disposal	4.2
23	<u>Turbine-plant equipment</u>	[46.7]
231	Turbine generators	18.5
232	Main steam system	4.5
233	Condensing system	3.1
234	Feedwater heating	6.8
235	Other turbine-plant equipment	6.0
236	Turbine plant instrument and control	7.8
24	<u>Electric-plant equipment</u>	[15.4]
241	Switchgear	0.9
242	Station service equipment	6.8
243	Switchboards	2.4
244	Protective equipment	1.5
245	Electrical structure/wiring containers	1.3
246	Power and control wiring	2.5

Table 6-2. (Continued.)

Account number	Account title	Projected cost (84 M\$) ^a
25	<u>Miscellaneous plant equipment</u>	[25.5]
251	Transportation and lifting equipment	2.6
252	Air and water service systems	2.7
253	Communications equipment	1.7
254	Furnishings and fixtures	0.6
255	Bulk materials	17.9
26	<u>Heat-rejection system</u>	[9.4]
261	Structures	3.4
262	Mechanical equipment	6.0
	Total direct cost	[1080.47]
91	Construction services and equipment	54.02
92	<u>Home office engineering and services</u>	108.05
921	Project management	43.22
922	Project systems engineering	43.22
923	Project quality assurance	21.61
93	<u>Field office engineering and services</u>	[108.0]
931	Construction management	64.8
932	Inspection	21.6
933	Preoperational testing	21.6
94	<u>Owner's cost (LLNL)</u>	[54.0]
941	Project administration	32.4
942	Inventories and spares	21.6
	Total indirect cost	[324.1]
	Direct + indirect cost	[1414.6]
	Contingency	421.4
	FPD-III total constructed cost	[1826.0]

^aMillions of dollars.

Indirect costs are those costs that are not identified with specific permanent plant facilities, equipment, or systems; but are incurred by the project as a whole. Indirect costs include those costs that cannot be identified with a direct account and those that do not warrant the detailed accounting required for distribution to direct accounts. This type of cost is judged to be best controlled as an indirect account.

Four indirect cost elements were calculated, by subelement, using percentages of the total direct cost. Construction services and equipment include temporary construction facilities, construction equipment, taxes, and insurance. We chose an allowance of 5% of the total direct cost for this element of indirect cost. Home office engineering and services consists of the overall systems engineering, management, and services provided by the prime contractor mainly during the design phase. Major elements are project management (project administration, cost/schedule, technical coordination, data management, etc.); project systems engineering (systems integration, configuration control, safety, systems analysis, etc.); and project quality assurance (procedures development, review, audit, surveillance, reporting). We chose allowances of 4%, 4%, and 2% of the total direct cost for project management, project systems engineering, and project quality assurance, respectively. Field office engineering and services consists of the prime-contractor-associated activities at the job site during construction, and also includes construction management (site supervision, construction scheduling, procurement and contract administration, construction engineering, etc.), inspection (site), and pre-operational testing. We chose allowances of 6%, 2%, and 2% of the total direct cost for construction management, inspection, and pre-operational testing, respectively. Owner's cost consists of the overall project engineering and services cost incurred by the laboratory (LLNL) in addition to initial inventories. Major elements of owner's cost are project administration, inventories, and spares. We chose an allowance of 3% of the total direct cost for project administration and an allowance of 2% of the total direct cost for inventories and spares. These elements are summed to form the total indirect cost of the facility.

Contingency is a cost allowance included in the cost projection to reflect the fact that uncertainties exist in the project definition, unit

pricing, and execution. The magnitude of the contingency allowance depends on the project phase. We chose an allowance of 30% of the subtotal of the total direct cost and total indirect cost to reflect the uncertainties associated with a preconceptual-level cost projection. We did not address the cost of operations and basic research and development in this cost projection.

Section 7

Issues

7.0. ISSUES

ISSUE I

Areas requiring more detail design study to establish feasibility include the following:

Small octopole region. The region around the small octopole is very crowded. Work to date shows that major components of structure and shielding can fit into the space, and that neutral-beam paths are possible through the region. However, details of these components such as piping for the actively cooled shield, coil-electrical leads, and the coil-refrigerant lines will compete with the drift-pumping coil and its associated leads for this space. Methods for assembly/disassembly of these components must be considered as part of the coil installation/removal scheme. Work to date has not addressed these problems.

Axial tie of the choke coil to the last central cell. The mutual force of attraction between the choke coil and the solenoid in the outermost central cell is 1.2×10^8 N (~27 million pounds). Methods to support this load internal to the coils by transferring it from the windings to the coil structure as well as a conceptual design of a method to tie the two coils together should be addressed.

Position of the bucking and mirror coils relative to the large octopole. The general assembly scheme of the end cell, and thus the maintenance concept, is greatly influenced by the relative position of these coils. The present configuration greatly inhibits the possible segmentation of the octopole into discrete modules that could be handled individually. If possible, this segmentation would result in crane access to components installed internal to the octopole, principally the small octopole and shielding, and, therefore, reduce the size of the crane required for the facility because more components could be handled individually rather than as a large assembly.

Drift pump issues. Although there are drift-pumping experimental efforts on both Constance at the Massachusetts Institute of Technology and the Tandem Mirror Experiment-Upgrade (TMX-U) at LLNL, the magnetic configuration and, hence, the type of launcher structure are entirely different from the requirements for an octopole configuration. An improved model to calculate the required field perturbation, B, and a knowledge of the plasma-edge geometry and plasma parameters are necessary before launcher concepts can be developed.

Configuration/maintenance. (End-cell annular shield): The end-cell annular shield substantially complicates the assembly/disassembly of interfaces between the major and minor octopoles. Based on the end cell details developed for FPD-III, there appears to be insufficient access to the minor-octopole support structure. To help solve this issue, the annular shield requires segmentation into modules. These modules must be removable as small pieces near the upper octopole region, and must also have integral attachment as large pieces to the upper octopole frame(s). Detailed configuration development of the end cells is needed to define the modularity of the shield and any size changes to components that are necessary to provide sufficient clearances.

Blanket design. In this study, the thermal hydraulic, MHD, and lifetime and mechanical design problems of a liquid lithium-lead blanket have not been addressed. The space allocated to the blanket is based on preliminary neutronics analyses. Detail design is required with both analysis and component performance testing to establish feasibility. No completely adequate tritium-breeding blanket for a fusion reactor has yet been designed.

ISSUE II

Areas exceeding present technology limits include the following:

Magnetic field strength on superconducting windings. Two coils in the end-coil set, referred to as the bucking and mirror coils, are located in regions of high magnetic fields and simultaneously require current densities of approximately 5000 A/cm^3 . This combination exceeds today's technology.

Pellet fueling system. Considerable uncertainty exists in the physics model used to determine the pellet-laser beam-fueling requirements. Single-shot experiments are needed to determine penetration of the fueling plume into a fusion grade plasma. For the fueling requirements given in this report, there are no laser systems available today that meet both the repetition-rate and beam-energy requirements.