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Summary

The equilibrium field (EF) coil system for the Argonne Experimental Power Reactor (EPR) and the methods by which it has been designed are described. The number of coils, their placement, and the currents in them are fixed by considerations of the trade off between the stored energy in the coils and the closeness with which the required magnetohydrodynamic (MHD) equilibrium can be matched. The bulk of the equilibrium field is produced by superconducting coils outside the toroidal field (TF) coils. These coils are decoupled from the ohmic heating (OH) system. Normal conducting coils just outside the vacuum chamber are also provided for fine control. The amount of D-shapedness of the plasma cross section is found to be limited. The reference design EF coil system configuration is described, and the internal configuration of the conductor and implications of the EF coil system on the reactor burn cycle and on the driving system costs are discussed.

General Procedure

Reference Equilibrium

In order to determine an EF coil system, a reference MHD equilibrium is first chosen. The equilibria used in these studies are determined by fixed-boundary MHD calculations as described in Refs. 1-2. These calculations depend on the choice of plasma parameters. One of the more important of these parameters is β_t, the ratio of the plasma pressure to the toroidal magnetic field pressure. The reactor power increases with β_t, but so do the requirements on the EF system. The achievable values of β_t for a reactor are not yet known but are expected to be roughly 7% for the Argonne EPR.[2] To be conservative the coils are designed for β_t = 8%.

Among the outputs from the MHD calculations is the flux function, $\psi_{ext}(R,Z) = 2\pi RA_\phi(R,Z)$, for the required EF field. (A_ϕ is the azimuthal component of the external field vector potential.) The flux function for the fixed boundary calculations is only known inside the plasma, and it is the purpose of the EF coil system to match this flux function as accurately as necessary to reproduce the desired plasma shape and other plasma parameters.

The locations of the EF coils are subject to a number of constraints: It has been the Argonne philosophy to place the EF coils outside the TF coils. The principal reason is that maintenance of these coils after the reactor becomes hot would be extremely difficult if they were inside. Placed outside, they are easily raised or dropped if it is necessary to work on them. Use of superconducting EF coils is also facilitated by a position outside of the TF coils. Additional difficulties are that the space inside the TF coils is crowded, access to other components is impaired, and initial fabrication is much more difficult.

A second constraint is that the EF system should be decoupled from the OH system. (Since the two must be operated with different time variations, large voltages would be induced in each other if they were coupled.) Decoupling is done by placing the EF coils on an OH flux line, connecting them in series, and requiring that the total current in them add to zero.

A third constraint is that the EF coils cannot be placed too near the TF coils since they produce an undesirably high field on the TF coils. In the present design the centerlines of the EF coils were kept approximately 1 m away from the TF coils.

There are other positions the EF coils cannot occupy as well. The neutral beam ducts prevent coils from being placed too near the midplane on the outside, and the OH solenoid prevents coils from being placed too near the major axis. Space must be left between two coils near the top (and bottom) outside to allow the vacuum ducts to penetrate.

Trimming Coils

The EF coils are expected to provide the bulk of the required field. It is felt, however, that these coils may be too far from the plasma and may be too restricted in their location to provide adequate fine control for a probably sensitive high β_t plasma or to prevent tendencies of the plasma to move. For this fine control the initiation-trimming (IT) coils are used. These coils, which are also necessary for the early plasma startup, are segmented, normal copper conductors located just outside the vacuum vessel. The necessary currents (≤0.5 MA) in these coils are sufficiently small that they do not affect the reactor power balance. They are sufficiently shielded to prevent undue radiation enhanced resistivity, and they can be annealed. They would be feed-back controlled to maintain the plasma position and to provide any fine tuning not provided by the EF coils. The EF coils are designed, however, as if the IT coils did not provide any of the required equilibrium field.

Mathematical Method

In order to find the required currents for fixed positions of the EF coils, the following quantity is minimized as suggested in Ref. 3:

$$\varepsilon = (1 - r) \sum_{n=1}^{N} (\psi_n - \psi_{ext,n})^2 + r \sum_{i,j=1}^{K} L_{ij} I_i I_j + \lambda \sum_{i=1}^{K} I_i \, , \qquad (1)$$

where $\psi_{ext,n}$ is the desired flux function given at N points, n=1,...,N; ψ_n is the actual field due to K EF coil pairs at (R_k, $\pm Z_k$), k=1,...,K. (An expression for ψ_n is given in Ref. 1.); r is a parameter which determines the relative importance of the first (field error) term and the second (stored energy) term; and λ is a Lagrange multiplier associated with the constraint that the currents add to zero.

The inductance matrix, L_{ij}, is calculated as follows:

$$L_{ii} = \mu_0 R_i \left[\log \frac{8R_i}{a_i} - \frac{7}{4} \right] \qquad (2)$$

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$$L_{ij} = \mu_0\sqrt{R_iR_j}\left[\left(\frac{2}{k} - k\right)K(k) - \frac{2}{k}E(k)\right] \text{ if } i \neq j \qquad (3)$$

where

$$k^2 = \frac{4R_iR_j}{(R_i + R_j)^2 + (Z_i - Z_j)^2},$$

and K(k) and E(k) are the complete elliptic integrals of the first and second kinds, respectively. The self-inductance terms depend on the coil size. (a_i is the minor radius of coil i.) Since the coil size depends on the currents in the coils (The current density is assumed fixed.), it is necessary to iterate the procedure until consistent sizes and currents are obtained.

By varying the quantity, r, a better (or worse) match to the desired field can be obtained at the expense of increased (or decreased) stored energy. Experience has indicated an average relative error of ≤0.4% in the flux function is necessary to provide an adequate match to the plasma boundary and other parameters.

The optimum EF system is found by changing the coil locations and number of coils until the lowest stored energy is obtained for a given error (near 0.4%).

Argonne EPR Reference Design

EF System Configuration

It is generally felt that elongated plasma cross sections with outwardly pointing D-shapes are beneficial to the achievement of high β_t. These configurations tend to have more highly shaped required external fields than the circular cross section cases.[1] An example is shown in Fig. 1. It is especially hard to produce the field near the upper, inside part of the cross section with coils far from the plasma and with no coils to the left (in Fig. 1) of the plasma (because of the TF coils and OH solenoid). (It can also be noted that these fields should also be unstable to vertical excursions since the $\vec{J} \times \vec{B}$ force has an upward component. The vertical positioning would have to be feed-back controlled via the IT coils.)

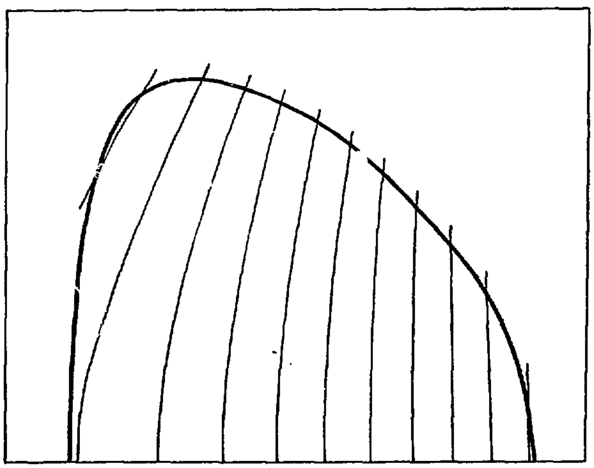

Fig. 1. A typical required external field for an elongated D-shaped plasma. The major axis is on the left. This cross section has κ = 1.65 and d = 0.50.

Figure 2 shows the stored energy versus field error curves for three elongations (κ = height/width = 1.00, 1.30, and 1.65) and two D-shapes. (d = 0 is elliptical, and the plasma becomes more D-shaped as d increases. The actual relations are given in Ref. 2.) The curves for d = 0.50 (the value for the cross section in Fig. 1) are off the graph to the top for all three elongations. It can be seen that the higher elongations require more stored energy and that there is a limit to the sharpness of the D-shape that can be formed with a reasonable EF system located outside the TF coils.

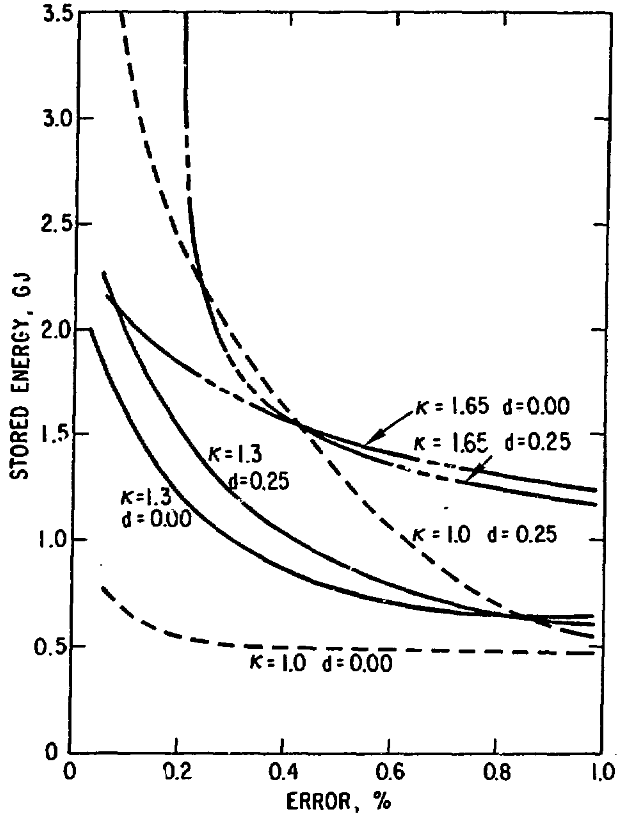

Fig. 2. Stored energy versus field error, illustrating the relative difficulty of obtaining elongated, D-shaped equilibria. The d = 0.50 curves are off the graph. All cases have an aspect ratio of 3.5. Typically, an error of ≈0.4% is sufficient to match the plasma parameters.

The Argonne EPR Reference Design[2] has κ = 1.65 and d = 0.25. The D-shapness, d, was limited by the above considerations. The EF system parameters for β_t = 8% are summarized in Table 1. Figure 3 shows how closely this configuration matches the β_t = 7% reference value if the currents are all reduced by 0.95. The "actual" boundary was calculated using a slightly modified version of the Princeton free-boundary equilibrium code. The inductance and decoupling of the EF and OH system have been verified independently by more accurate field calculations using the distributed current in the actual coil configurations as shown in Fig. 4.

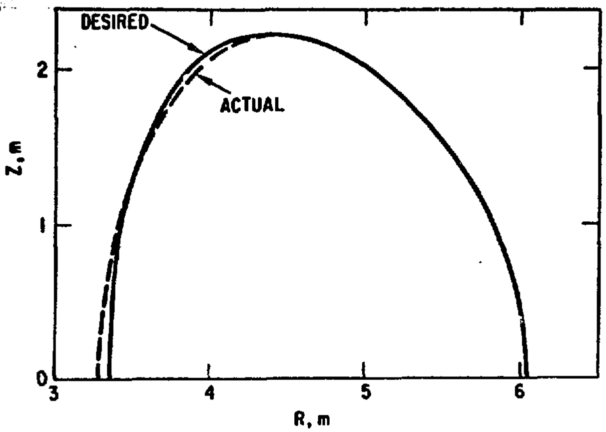

Fig. 3. The plasma boundary due to the actual EF coil system compared to the desired boundary for β_t = 7%. The EF current is 95% of the design value.

TABLE 1. Coil Configurations
(The numbers given are for coil pairs, one above and one below the midplane.)

Coil	R (m)	z (m)	ΔR (m)	Δz (m)	NI (MA-turns)	Conductor Length (MA-m)
1	2.04	5.38	0.48	0.25	-4.24	54
2	2.38	5.62	0.48	0.25	-4.24	63
3	3.00	6.00	0.40	0.50	7.14	135
4	4.80	6.05	0.88	0.50	15.56	469
5	8.05	4.27	0.43	0.50	-7.61	385
6	9.59	2.36	0.38	0.50	-6.61	398
Total:					0	1504

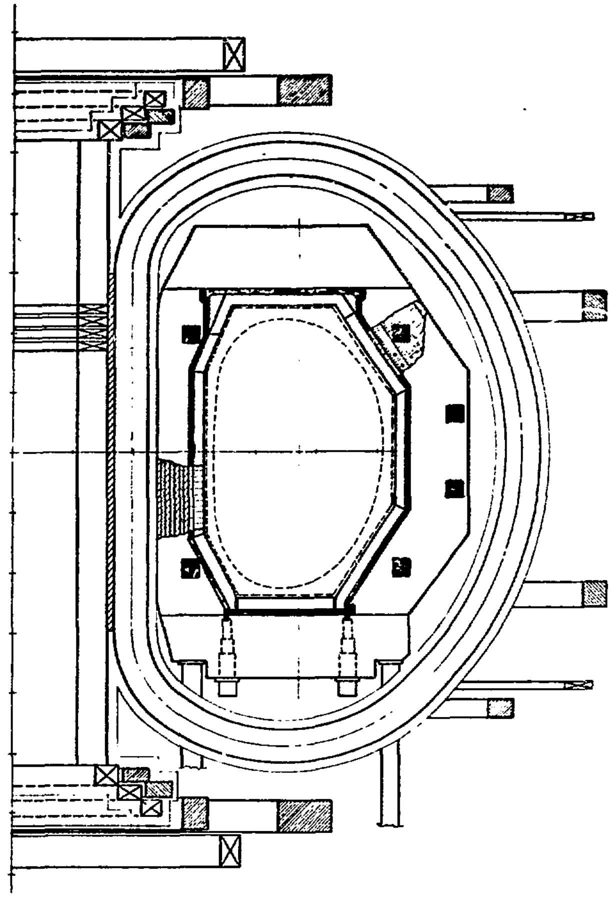

Fig. 4. A cross section of the Argonne EPR showing the EF coils (crosshatched), the IT coils (black), and the OH coils (X).

Superconducting Coils

The EF coils are cryostable with NbTi superconductor and copper stabilizer. They operate at 4.2 K and are cooled by pool-boiling helium. The operating current is 70 kA, and the current density is 1730 A/cm^2.

The 70-kA conductor, shown in Fig. 5, is designed to be cryostable and still have low ac losses. It consists of 70 basic cables wound around a backbone strip of solid G-10 or stainless steel braid. Each basic cable, in turn, consists of six basic strands of copper and NbTi-copper composite wound around a stainless steel cable. The basic strands are individually cryostable. The coils and conductors are described further in Ref. 4.

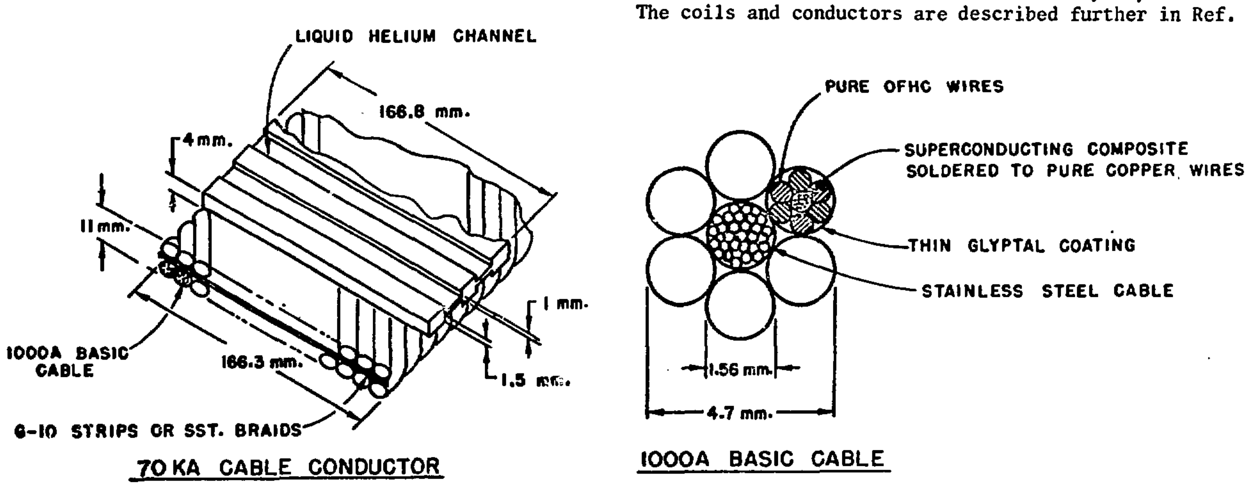

Fig. 5. 70-kA cryostable conductor for the EF coils.

Reactor Implications

The coil design described above is based on the external field distribution needed by the plasma at peak power. During the startup, burn, and shutdown the field must be varied continuously to keep the plasma in MHD equilibrium. At any given time in the burn cycle the required field is a function of the plasma pressure and current. Burn cycle simulations (of the type described in Refs. 2 and 5) determine the currents and voltages in the EF coils as a function of time. For the EPR with the EF coil design described above and using a typical startup scenario, it takes a maximum power, P_{EF}^{max}, of about 1.6 GVA to run the EF system.

The EF coils are driven by a thyristor-type rectifier-inverter power supply operating out of a superconducting energy storage coil. The cost of this supply (≈40 M$ for the above value of P_{EF}^{max}) is one of the major costs of the driving system, and minimizing the EF power supply cost generally dictates the choice of startup time and other parameters of the burn cycle. To first order the value of P_{EF}^{max} scales linearly with the maximum stored energy in the EF system. Thus, the optimization design process described above, which minimizes the stored energy, is critical in reducing the overall reactor costs.

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