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ADVANTAGES OF IRON CORE IN A TOKAMAK*

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Summary

Several of the experimental tokamak fusion devices to date have used iron cores to reduce the power supplied to the poloidal field coils. As the machines grow in size, iron cores are not receiving emphasis in the U.S. Planned tokamak programs in other countries, e.g. JET, include iron cores in their designs. It is felt that this de-emphasis of the iron core has stemmed primarily from the expediency of using the more costly power supplies rather than having to deal with the relatively involved effects that iron cores have on the poloidal fields and the plasma MHD equilibria.

Recent design studies of the Joint European Torus (JET)[1] have indicated substantial savings of the power supplies in the plasma start-up phase by the use of an iron core, without impeding the required equilibrium fields for a D-shaped plasma. Current studies at ORNL on high beta D-shaped plasmas[2] and the poloidal field systems for high beta plasmas in the iron core ISX device[3] have provided substantial improvements in understanding the iron core effects on the plasma. Operations of high beta fusion plasmas in an iron core tokamak reactor are now considered doable.

Recently, TNS[4] and DEMO[5] studies and the ohmic heating study by Los Alamos Scientific Laboratory[6] have shown that air core tokamaks in the 1000 Megawatt (electric) range require poloidal field power supplies with a capital cost between $100 and $200 million (20-30% of the total cost of the fusion system concept being studied). ORNL has conducted some preliminary studies of the use of an iron core and the results have been particularly encouraging. To better understand these results, it is necessary to first list and discuss the generally recognized key concerns about the air core approach. (Table 1)

TABLE 1
The Key Concerns About Air Core Systems

1. High power needs of PFS (P>1 GW)
2. High energy needs of PFS (E>1 GJ)
3. Energy storage components required
4. Needed economic high power switches - not available without costly development
5. Certain OH coil maintenance nearly impossible
6. Probable requirement for superconducting OH coils

Discussion of Key Concerns

1. The requirement to handle the high electrical power in an air core PFS is major cost ($100-200 million) driver. The cost of the major PFS electrical components such as switches and rectifiers is a nearly linear function of the peak power handled. These elements comprise over eighty (80) percent of the total PFS electrical equipment capital cost. The energy storage equipment necessary to buffer the utility grid system from sudden energy demands beyond its capacity would account for about twenty (20) percent.

2.-3 The air core design concepts under consideration for TNS and DEMO machines require energy pulses during the initiation and startup phase of each burn cycle that exceed the capability of any U.S. utility. This 1-1.3 GJ peak energy demand dictates a buffer or isolation from the grid by use of some energy storage device such as a motor-generator-flywheel or a homopolar generator. Either would account for about twenty (20) percent of the PFS total cost. Each would require development to meet the long life pulsing demands. It is estimated that the homopolar generator would require tens of millions of dollars to develop, an order of magnitude larger than that required to assure the same pulse life for the motor-generator-flywheel equipment.

4. At the peak power levels that these machines demand, only solid state switches could be used without significant development - and the numbers of solid state devices that must be ganged to make switches of these ratings dangerously stretches the available component experiences. New, economic switching systems must be developed for these powers.

5.-6 An air core machine requires the distribution of the OH coils around the plasma for optimum flux linking. An iron core device will permit coil locations that substantially ease the assembly and maintenance difficulties because the return legs of iron assure the proper flux paths. Some OH coils in air core designs must be placed under, and to the inside of the plasma, and are practically impossible to maintain. It will be seen that significant advantages appear to accrue from the use of an iron core. (Table 2)

TABLE 2
Potential Advantages of an Iron Core

1. Maintainability - Ease of remote handling
2. Less Cost - By order of magnitude
3. No Energy Storage Machine
4. Little Need for Superconducting PF Coils
5. Less Electrical Development by Order of Magnitude
6. Siting Flexibility in Availability of Commercial Power. (Can hook directly to most U.S. grids)

A quantitative comparison of the iron core vs air core concepts was carried out on a preliminary basis by using a representative tokamak reactor design with the following self-consistent reference parameters. (Table 3)

The following sections will discuss in more detail the impact of using an iron core in a tokamak reactor. In the area of plasma engineering, poloidal field and MHD equilibrium considerations with an unsaturated iron core will be discussed. The question of proper poloidal field coils to maintain D-shaped plasmas of relatively high $\bar{\beta}$ (7%) with a saturated iron core is also discussed in Section 2, where it is considered feasible. Estimates of the required iron core size, volt seconds, magnetic flux and its influence on force loading on the superconducting toroidal field coils are shown in Section 3. Conceptual designs of the mechanical structure of an iron core device are presented in Section 4. Favorable impacts on the OH power supply cost and complexity are indicated in Section 5 followed by a brief conclusion in Section 6.

* Work performed by UCCND for the Department of Energy

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TABLE 3
Tokamak Reference Parameters

Profile Averaged Beta β	.10
Volume Averaged Beta $\bar{\beta}$	.07
Plasma Radius	1.5 m
Plasma Elongation	1.6
Wall Loading	2.25 MW/m^2
Plasma Current	4 MA
Aspect Ratio	5
TF Max Field	8 T
Field on Axis	4.2 T
Ripple on Plasma Edge	2% (peak to mean)
No. of TF coils (S.C.)	18
Major Radius (plasma)	7.5 m
Major Radius T.F. Coil	7.62 m
Iron Core (Dia)	6 m
Coil to Plasma Distance, Δ	2 m
TF Horizontal Bore	7.12 m
TF Vertical Bore	10.51 m
Plasma Volume	533 m^3
First Wall Area	592 m^2
Thermal Power (Burn)	2100 Mw
Thermal Power (Average)	1995 MW
Thermal Efficiency	.35

Plasma Engineering

The magnetic field spatial and temporal variations required by the plasma physics can be supplied with or without the aid of an iron core. It is evident that for a given iron core cross sectional area, the total flux swing available between the saturation values is bounded. Also, the operation during iron core saturation has many of the same characteristics as does operation with an air core. For some experimental devices the pulses will be short enough to permit total operation in the unsaturated region. However, for a longer pulse machine the likelihood is that a transition from unsaturated to saturated conditions will occur during each pulse and the attendant nonlinearities must be considered. These effects point to a reexamination of the poloidal field system and its capability in maintaining the desired plasma shape over long pulses. These and other facets are discussed here.

Effects of Iron Core on Poloidal Fields

The iron core alters the poloidal field by producing an iron image field in response to current loops in the vicinity. The net external field ($\underset{\sim}{B}^{EF}$) that determines the plasma position and shape can be written as,

$$\underset{\sim}{B}^{EF} = \underset{\sim}{B}_C^{VAC} + \underset{\sim}{B}_C^{IM} + \underset{\sim}{B}_p^{IM} = \underset{\sim}{B}_C + \underset{\sim}{B}_p^{IM} = \underset{\sim}{B}^{ID}, \qquad (1)$$

where B_C^{VAC} is the vacuum poloidal field due to coils in the absence of the iron core, and $\underset{\sim}{B}_C^{IM}$ and $\underset{\sim}{B}_p^{IM}$ represent the iron image fields due to the coil and plasma currents, respectively. Thus, the required coil field ($\underset{\sim}{B}_C$) to be produced should be the ideal equilibrium field ($\underset{\sim}{B}^{ID}$) subtracting $\underset{\sim}{B}_p^{IM}$.

The $\underset{\sim}{B}^{ID}$ for a D-shaped plasma has been studied previously.[2] The plasma cross section depends primarily on the curvature of the net external field. A convenient indicator for the curvature of the equilibrium field is the vertical field decay index, defined as

$$n = -\partial(\ell n B_z)/\partial(\ell n R), \qquad (2)$$

where B_z is the vertical component of $\underset{\sim}{B}$ and R is the tokamak major radius. The decay indices n_{ID} from B_z^{ID} and n_C from $B_{C,z}$ are computed and plotted in Fig. 1 in the case of D-shaped plasmas in ISX-B with unsaturated iron core.[3] It is seen that the curvature of the external field is strongly altered by the presence of the iron core.

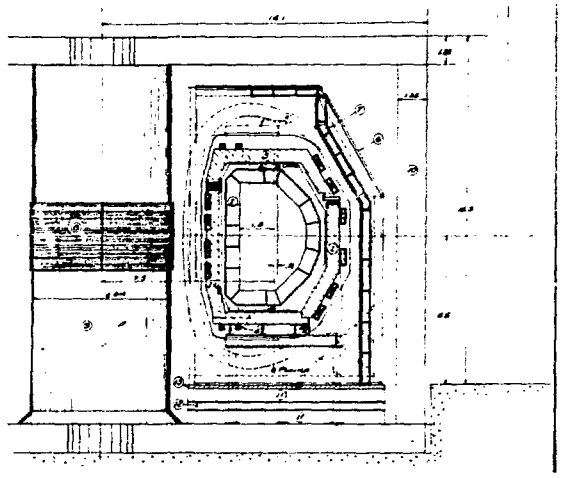

Figure 1 - Elevation Section

Poloidal Field Coils Based on Unsaturated Iron Core

In present day tokamaks, the plasma start-up and steady-steady phases usually occur before the iron core saturates. The image field from an unsaturated iron core has been approximated by two and three-dimensional iron models, producing good agreements with experimental measurements.[7] Using these models, one finds that a shell-like coil system (see Fig. 1) is optimal in controlling the plasma position and D shape for large betas, and in permitting the required access for neutral injections.[8] The coil system has the following characters:

1. It consists of three sets of coils: inside, outside and D-shaping coils (See Fig. 1).

2. Before iron saturation, the net current (ampere-turn in the coils (ΣI_{EF}) is equal and opposite to the plasma current (I_p).

3. The currents in the inside and outside coils (I_I and I_O) are opposite to I_p, which in turn is in the same direction as the D-shaping current (I_D).

4. The ratio I_O/I_I is adjusted to center the plasma.

5. I_D is adjusted to maintain the desired elongation and D-shape of the plasma.

Note that the Ohmic heating (OH) coils are eliminated when the shell-like coils are used, although bias windings (See Fig. 1) are still needed to make full use of the iron magnetization.

The conceptual behaviors of the plasma current and

various coil currents in a burn cycle are plotted in Fig. 2, showing several phases. These phases are

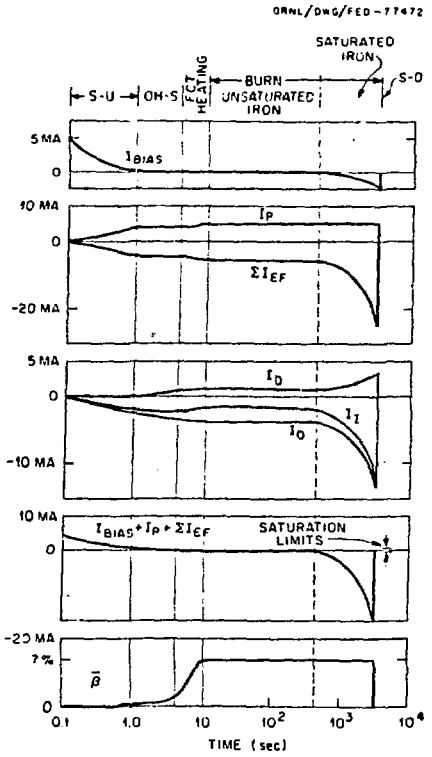

Figure 2 - Plasma and Coil Currents

start-up (S-U), Ohmic heating and shaping (OH-S), rapid heating in the sense of flux conserving tokamak (FCT-Heating),[9-10] steady-state burn (BURN) and the plasma shut-down (S-D). During the OH-S and FCT-Heating phases, I_I, I_O, and I_D are adjusted to center the plasma and maintain the proper shape. The high β MHD equilibria during BURN can be exemplified by a typical equilibrium in a coil configuration similar to that of ISX-B,[11] as shown in Fig. 3.

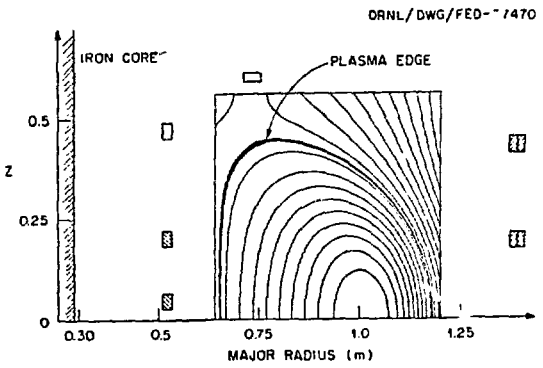

Figure 3 - MHD Equilibria

Operations with Saturated Iron Core

The BURN phase can be extended if operations with saturated iron core are possible. In this case, $|\Sigma I_{EF}|$ begins to become progressively larger than $|I_p|$. The added coil current can be considered as an air-core OH current (I'_{OH}) superimposed on the currents.

One can estimate the size of I'_{OH} for a substantial increase in the overall voltsecond capability, by assuming

$$B_{SAT}\ \pi R_{IR}^2 = B'_{OH}\ \pi R_C^2, \tag{3}$$

$$B'_{OH} = \mu_o I'_{OH} / R^2 + b^2. \tag{4}$$

The LHS of Eq. 3 represents the iron saturation flux, which is set equal to the added OH flux. The added "air-core" field (B'_{OH}) can be estimated by an equivalent solenoid of half height b and radius R_c, the radius of the inside EF coils. With B_{SAT} = 2T, R_{IR} = 3 m, R_C = 4.5 m, and b = 2.5 m, Eqs. 3 and 4 give I'_{OH} = 2.6 MA, for an added volt-second of 57 Webers. This is sufficient to extend the burn phase by roughly 10 min. in the current design.

If I'_{OH} is limited by the resistive power loss acceptable in the EF coils, which is assumed to be 60 MW and roughly one-fifth of the peak power required for plasma start-up, the pulse length can be extended further. The typical single turn resistance in the coils is 3 x 10^{-6} μΩ. Assuming that I'_{OH} is equally distributed between the inside and outside coils, one obtains $I'_{OH} \approx$ 6 MA. This adds over 130 Webers to volt-seconds and over 20 min. to pulse length.

Additional extension of the pulse length is possible if the iron core can be back-biased to beyond saturation before S-U. This requires an increased S-U power supply, but also results in an extended BURN phase by permitting further increases in I'_{OH}. The conceptual behaviors of the coil currents for saturated iron core are also included in Fig. 2. More detailed calculations are required to determine the desirable level of iron core saturation for an economic reactor. Detailed considerations in magnetics engineering for an unsaturated iron core will be presented in the next section.

Discussion

It is seen that, by the use of the shell-like EF coils,[8] the plasma position and D-shape at high β can be maintained in an iron-core tokamak reactor. The conventional OH coils are eliminated, simplifying the construction of the reactor and promoting the innovative mechanical design to be discussed in Section 4. By superimposing a modest OH-like current in the EF coils, operations with saturated iron core may be possible, resulting in a substantial extension of the pulse length. These potentials of an iron core with a shell-like coil system will be tested in the high beta experiments in ISX-B[3] and ORMAK-Upgrade.

In plasma engineering, our results also call for more detailed studies of plasma stability as influenced by the iron core, and of equilibrium evolution of D-shaped plasmas in a long time scale, and of their correlations with iron core saturation, plasma heating, plasma fueling and ash removal.

Magnetics Engineering

In the previous section it was indicated that the plasma engineering to be accomplished in a tokamak device is not materially different whether using an

iron core or air core. Where pulse lengths may require a transition from an unsaturated to a saturated state, new considerations need to be expanded.

This section will discuss the magnetics of air core and iron core poloidal field systems and show the significant differences in maximum stored energy and maximum MVA ratings. This indicates that potentially large reductions in cost and complexity of the electrical system can accrue with the use of an iron core. It will also point out various methods of operating the iron core system for very long burn times that will require some time in saturation. It will also introduce the problem of the interaction of the iron core (return legs) and the toroidal field (TF) coils.

Basic Magnetics of Air Core and Unsaturated Iron Core

In this section, the equations that govern the sizing of the coils will be presented. The equations are based on the simplest models for air core and iron core systems.

The iron core system is an iron yoke that passes through the bore of the device usually occupied by the central solenoid of the ohmic heating system and continues around the outside of the TF coils to complete the magnetic circuit. The excitation windings are localized in the base of the device.

The simplest system of this type to visualize is one with a single return leg (as used with ISX). For the moment, assume that the yoke has a constant circular cross section of radius a, and at the start of the cycle the field in the iron is B_{Fo}. Then the flux contained by the iron system is

$$\phi = \pi a^2 B_{Fo} \tag{3-1}$$

where B_{Fo} is just the upper operating point for the iron. The stored magnetic energy in the system is

$$W_F = \frac{1}{2} \phi^2 R_M \tag{3-2}$$

where

$$R_M = \frac{\ell_\rho}{\mu_o k \pi^2} \tag{3-3}$$

and ℓ_ρ is the average perimeter of the yoke, and k is the relative permeability.

It may be advantageous to have a larger area in the return legs of the yoke than in the bore so that the return flux does not drive the iron at the corners of the yoke too far into saturation.

In addition, the return leg may be split into several legs. One return leg over each TF coil will provide similar loads on each TF coil due to the iron. This will not impair access to the device, nor increase the amount of iron needed. Nor will this affect the simple calculations presented here.

The air core equations presented here are based on the long solenoid characterization and consider the end effects to be secondary. The outboard coils of the poloidal field system are necessarily placed there to do an effective job of guiding the field around the TF coils and thus make these approximations good enough for rough comparisons.

The flux linked by the plasma is just the flux through the bore of the solenoid and through the solenoid windings. The field across the midplane of the coil is assumed to be constant and vary linearly to zero through the windings. For this model, the total flux is

$$\phi = \frac{\pi a_2^2 B}{3} \left(1 + \frac{1}{\alpha} + \frac{1}{\alpha^2}\right) \tag{3-4}$$

where a_2 is the outside radius of the coil windings, α is the ratio of the outside radius of the windings to the inside radius of the windings, and B is the design field. For a long solenoid the design field is

$$B = \mu_o \, j \, a_2 \left(1 - \frac{1}{\alpha}\right) \tag{3-5}$$

where j is the current density in the winding cavity including structure, coolant, and insulation.

The stored energy is

$$W_A = \frac{1}{2} \phi I \tag{3-6}$$

by using equations 3-4 and 3-5

$$W_A = a_2^2 \, \ell \, B^2 \left(\frac{\pi}{6\mu_o}\right) \left(1 + \frac{1}{\alpha} + \frac{1}{\alpha^2}\right) \tag{3-7}$$

where ℓ is the length of the solenoid. This expression assumes an auxiliary coil system that forces the flux through the center of the solenoid to be constant over its length. The auxiliary OH coil system will guide the field around the TF coils and make this approximation fairly good. These additional coils are not included in the energy and power estimates that follow.

Comparison of Iron and Air Core

If the material in the iron core is C 1010 mild carbon steel, the relative permeability of the iron is 80 at a maximum operating field of 2 T and an H of 19.9 kA/m. The total flux swing between the operating points is

$$\phi = 2 \, \pi a^2 B = 113 \text{ Wb} \tag{3-10}$$

where a = 3.0 m.

The approximate volt-second requirements for initiation and start-up can be obtained from the volt-second requirements of a similar TNS device. The scaling is assumed to be linear in major radius since the plasma inductance will scale linearly if the plasma shape is kept constant. The TNS device chosen required 43 Wb for initiation and start-up with a major radius of 5.7 meters (this does not include the volt seconds contributed by the EF coils). The tokamak device in this study has a major radius of 7.5 m and will require about 57 Wb from the OH system for these two phases. This leaves 56 Wb for FCT heating and burn. Assuming 0.1 v plasma loop voltage in the last two phases, there will be enough flux swing available for about 9 minutes of burn with the 113 Wb available before iron saturation.

The maximum stored energy in the iron core system is 36 MJ; and is calculated using Eq. 3-4 and 3-7 where ℓ_p = 64.2 m, a_2 = 3.0 m, K = 80, and ϕ = 56.5 Wb. The ampere-turns is just H at the maximum operating point times the length of the winding or .358 MAT.

The maximum magnetic energy in an air core system that fills the same volume and provides 56.5 WG on half its current swing is 997 MJ. This is calculated by using Eq. 3-4 to get B = 2.457 where a_2 = 3.0 m, ℓ_p = 18 m, and α_2 = 1.25; then Eq. 3-5 to get the

ampere-turns 35.2 MAT, and Eq. 3-6 for the energy.

The peak MVA of each system occurs during the plasma initiation phase. If the plasma loop voltage is 500 V, then the air core system requires 1.76×10^4 MVA and the iron core requires 179 MVA.

	Peak MVA	Peak MJ
Air Core	17,600	997
Iron Core	179	36

Table 4 - Peak Ohmic Heating MVA & MJ

Other Modes of Operation

There are several design options to be considered in this area. One of the most important is the operating mode of the poloidal field system. There are basically two ways to operate this system. First, one could just use the iron core as a very effective OH driving system and design a system similar to the air core EPR designs,[1] but take advantage of the better coupling between the OH system and the plasma to reduce the power supply requirements. Second, there is the method described in Section 2. Then there is a combination of these two systems that consists of a set of superconducting windings located between the TF coils and the iron. These coils would be used to provide additional volt-seconds needed for very long burns. For this case, one would choose an initial bias for the iron core so that the effective permeability is very high and the coupling between the plasma and the coils is very good. This will minimize the power requirements in the start up phase. The volt-seconds needed for burn are obtained by increasing the field with the superconducting magnets and eventually saturating the iron core. The transition to the saturated state will be slow so that the EF system has ample time to provide any additional control of the plasma position that may result from that transition. The hybrid system may add some complexity to the mechanical design, but it may be more than off-set by a significant improvement in the electrical plant output.

Interaction of the Iron Core and the TF Coils

The mechanical loads due to magnetic fields on the TF coils are given by

$$\vec{F} = \vec{J} \times \vec{B}$$

where $\vec{F}$ is the force per unit volume, $\vec{J}$ is the current density in the TF coils. In the air core case, $\vec{B}$ is due to all the transport currents in the system. In the iron core case, $\vec{B}$ also includes the field due the interaction of the transport currents with the iron core. By using one iron return leg over each TF coil, the symmetry of the system will be such that the additional loads will be in the plane of the TF coil. Experience has shown that in plane loads are much easier to handle than out of plane loads. It will be important to analyze these loads and design the TF coils to withstand them.

Mechanical Engineering

The reactor concept used in this preliminary study and discussed in previous sections shows potentially significant advantages in the mechanical design, assembly and maintenance. The highlights of these advantages include:

No "hidden" poloidal windings are required
No bucking cylinders needed
Manufacturing tolerances loosened for TF coil manufacturing
Heat loss paths to TF coil greatly reduced
OH windings outside major radius eliminated

The following detailed discussion of the mechanical design concepts covers these salient features.

The iron core design concept previously discussed consists of a center column 6 cm in diameter. Surrounding this column and making a complete magnetic circuit are eighteen legs, one around each TF coil. Splitting the return this way reduces any TF coil loading problems that may result from using single return legs. Each leg is 1.25 x 1.25 meters, giving a total iron cross section equal to the area in the center column. An elevation of the reactor showing pertinent dimensions is shown in Fig. 1. In this figure, in addition to the iron core, a TF coil frame, blanket, shield, plasma driving and shaping windings and a core bias winding are shown. A plan view is shown in Fig. 4.

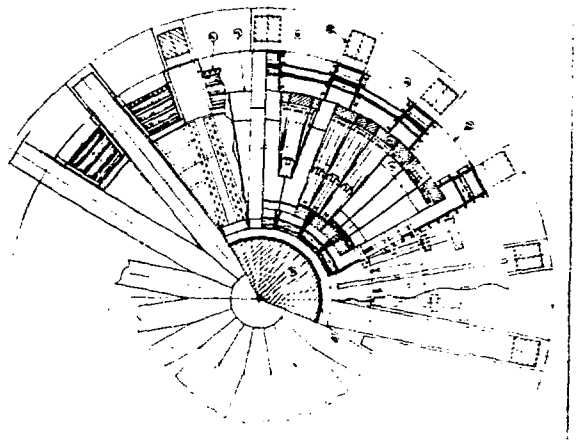

Figure 4 - Plan View

Not shown on this drawing is the support structure for the blanket and shield. The shield is mounted on legs off the reactor foundation and the blanket is supported off the shield. The top section of the shield is made to rotate on bearing surfaces located on the bottom section. By breaking four connections on the two driving windings between two TF coils, a segment of this rotatable shield is removed. This opening provides access for removal of the blanket. As this opening is rotated around the torus, each blanket segment can be removed with no additional breaks in the poloidal field coils. The general functions of these windings are discussed in the previous section.

There are fourteen poloidal field coils, and each consists of a single water cooled conductor of 300 KA capacity. Each turn is made up of coil segments bolted to the outside of the shield structure. Connections between coil segments are made with bolted clamps capable of being made or broken by remote means. Each conductor is composed of nine 2" x 2" copper bars in parallel in a square matrix. Each conductor has a 1/2" hole in the center for water cooling. Permanent coil connectors are affixed to each end of the coil segments which manifold the water cooling and provide terminals for the connecting clamps.

These water cooled copper coils should have a high degree of reliability, and there is little probability that faults will develop. If any repair should be required, access to the segments is possible and failures can be rectified without disassembly of the machine. Once installed it is not necessary to disturb

these coils except for the four connections that have to be broken to provide access for blanket segment removal.

Around the center core is located a bias winding. This winding is also made of 2" x 2" copper conductors with 1/2" water passage. This winding is made of 5 conductors wound in hand for 13 turns. The winding length is about 3.3 meters. The total ampere turns for this bias winding is 2 MAT. If required, it is also possible to place some bias windings on the legs of the iron core. None are shown in the figure.

The blanket and shield are made up of segments both poloidally and toroidally. In the toroidal direction, there are 54 blanket segments and 36 shield segments. The poloidal segmentation is shown in the elevation drawing. The blanket segments are removed vertically thru the open pocket in the rotatable shield.

By employing an iron core, the poloidal coil system is greatly simplified. With this configuration, maintenance of the system, while still difficult, becomes practical and can be accomplished.

An equally important improvement resulting from the use of the iron core is effected in the mounting and restraining of the TF coils. The coils are rigidly premounted in a frame, and this frame with the coil is transferred to the reactor assembly area. All frames are assembled into a torus and rigidly interconnected into a monolithic cylinder.

Two heavy plates, one on each side of the coil, are bolted to the sides of the coil bobbin. The bolts are distributed around the coil so that the highest concentration of bolts is where the maximum stress on the coil is located. This mounting assures that coil stresses are transferred evenly from the coil to the mounting plates. Cover plates are attached to the side plates so that the coil frame forms a rigid structure encasing the coil. The plates extend beyond the coil all around the periphery except where the coils noses nest at the center of the torus.

At the center location, the plates are machined into a wedge shape so that the frames can nest, forming a continuous polygon around the hub of the torus, but they do not bear against a centering column. The nesting of the coil frames is used to locate the coils, and this nesting is not depended upon to react the centering forces of the coils.

When the iron center column is installed, the 18 bottom return yokes are put in place. On top of each return yoke the coil gravity load insulating pads are placed. These pads consist of a three member lamination. Blocks of G 10 insulation are put on the iron legs. On top of this is placed a nitrogen cooled plate and on top of this another G 10 insulation block. A stainless steel disc is next placed on top of all the 18 legs, forming a continuous donut on which to mount the TF coils.

The TF coils, in their frames, are set on this base plate. External flanges on the bottom outside face of the coil side plates are bolted to the base plate. This mounting rigidly connects the bottoms of all TF coils into a continuous ring around the bottom of the torus. Flat ribbed plates are bolted between coil frames up the vertical edge of the frames, across the top and also across the plane between the top and the vertical sides. Thus, the entire TF coil structure is formed into a continuous monolithic structure.

All centering forces and overturning moments are taken in this plate structure which acts as a torque frame. All structure is covered with a reflective insulation, the interstitial spaces between the layers of insulation is at the pressure of the secondary vacuum enclosure thereby reducing heat conduction losses to a minimum. The only heat conduction path is thru the gravity load bearing insulated pad.

The plate structure bolted onto the coils is field installed so that no close tolerances are involved in assembling the toroidal TF system and structural frame. For blanket replacement only the top plates between coils need be removed.

Where penetrations are required thru the plates as for beam injectors, pumps, diagnostics, etc. reenforcing rings are welded around penetrations, the size of these rings being determined by the size of the penetrations. With the larger aspect ratio of 5, the space between TF coils is sufficient to place shadow shields around large penetrations to protect the TF coils.

Electrical Engineering

Recent air core tokamak power reactor studies have provided an increased focus on the problems of supplying the large pulsed energy needs of the poloidal field system.[1-2] The difficulties obtain from the inordinately large amounts of electrical energy that must be rapidly transferred between a source and the poloidal field system. The source may be the utility grid system but, for the levels of power required as indicated by the referenced studies, a buffer or storage system is mandated to protect the utility from excessive transients. The energy levels defined in the air core tokamak investigations as necessary for the required volt-seconds are in the 1 gigajoule range. The associated power peaks are in the 1 gigawatt regime. The comparable iron core tokamak requirements are developed in Section 3 and are also shown in Table 3.

Costing exercises in the referenced air core tokamak studies have shown unit costs of electrical equipment (switches, rotating machinery, etc.) to be near first order relations to the energy or power levels. Machinery costs are primarily determined by the amount of energy to be stored and supplied. The switch, rectifier and inverter costs are more specifically driven by the peak volt-amperes that must be conducted. Representative unit costs are:

Two-way dc switch with two commutating circuits;

$$\$ = 5.33 \times 10^4 \ (\text{MVA})^{.88}$$

DC homopolar generator;

$$\$ = 1.6 \times 10^4 \ (\text{MJ})$$

Motors;

$$\$ = 1.71 \times 10^5 \ (\text{MW})^{.8}$$

The total pulsed electrical system costs for the air core tokamak reactors studied approached 25% of the total reactor system cost.

The use of iron cores can significantly reduce the electrical power and energy transients required for plasma initiation and maintenance (described in Sections 2 and 3). The reductions indicated should mean an electrical system cost savings of at least two-thirds for a machine with superconducting TF coils. Additional cost advantages may be realized if the power levels could be reduced to where available switchgear could be used as opposed to using an extension to SCR technology. An obvious area of potential cost reduction is the lessened requirement for energy storage. The utility would likely be able to supply

the total transients, thereby eliminating the need for any storage buffer.

It thus appears from preliminary studies that 15% to 20% of the total projected capital cost of a tokamak power reactor could be saved as a result of the reductions in the electrical system cost. Additional detailed analyses are called for to verify these potential significant advantages and to delineate what advantages, if any, may arise.

Conclusions

While an iron core tokamak design concept for the 1000 $MW_{(e)}$ reactor size range has been under consideration for only a few months, the study has resulted in certain advantages that appear to offer significant payoffs. These iron core related major advantages are enumerated as follows:

1. The use of iron reduces the need for a complex superconducting poloidal coil system.

2. The use of the shell-like, high beta EF coils[5-8] eliminates the conventional OH coils and may allow long pulse operations with saturated iron-core.

3. The simplified poloidal system (for the iron core device) requires power supplies that are much less expensive and complex. The reduction in cost of these supplies is expected to exceed 70%.

4. Maintenance of a tokamak is made possible by the use of iron because it eliminates the hidden poloidal coils which are difficult if not impossible to replace or repair.

5. Structural problems are simplified since TF coils can be enclosed in "frames". These frames are consolidated into a monolithic structure so that a center bucking column is eliminated.

6. The frame structure, field assembled removes need for close tolerances on large fabricated components. Assembly of the torus is therefore simplified.

7. The problem of electrical energy storage can be greatly reduced.

8. Siting of the system will be much less a function of the local utility's capacity.

Recommendation

These advantages of using an iron core are so significant that a concentrated analyses is required to delineate the design approaches and the concomitant developments needed. The iron core ISX operation is an excellent test bed for many of the operational considerations and should be used as much as possible in the analyses.

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