A FIRST ORDER STUDY FOR AN IRON CORE OH SYSTEM FOR TNS*

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Introduction

Conceptual studies of EPR[1,2] and TNS[3] have shown that tokamaks air core poloidal coil systems are expensive and may require the development of large superconducting pulse magnets, development of reliable low-cost high-power switches, and power supply options in addition to large SCR systems. These studies indicate that a considerable fraction of the total capital cost of the device will be in the power supplies and magnets of the poloidal coil system. The high cost of these systems is due to the very large power required to initiate the plasma and the smaller, but still large, power required in the OH system to establish plasma current. There is considerable work being ~~planned and~~ done on alternative ways to initiate the plasma with much lower power requirements; such as small radius startup, starting the plasma with the closely coupled equilibrium coils, ~~and microwave~~ startup. ~~This method was chosen for consistancy with earlier design.~~

Another way to reduce the required power, that may be used with the ~~other~~ options just mentioned, is to use an iron core ~~in the~~ forms ~~of~~ a complete magnetic circuit. Smaller tokamak devices such as ORMAK and ISX use an iron core to improve the coupling between the plasma and the poloidal field magnets.[4] A saturated iron core is proposed for JET. The FCT concepts put forward by ORNL allow devices to be built with aspect ratios on the order 4 to 5, which will allow considerable space in the bore of the device for an iron core to be operated in a less saturated state than in the JET proposal.

The purpose of this paper is to present a comparison of the high cost parameters, for an air core system, between an air core and iron core ohmic heating (OH) system. The comparison will be done for the OH system by replacing the air core OH magnets with an iron core and a set of magnets to operate it. Both systems will be oeprated in the same mode, i.e., the air core and iron core systems will be required to supply the same volt-seconds on the same schedule, and both systems will use the same equilibrium field coil system. The comparison is not between two optimized systems, but between two systems that differ only in the type of OH system they use.

The comparison will be done on the basis of the peak power required in the OH power supply circuits necessary for initiation of the plasma and on the basis of the peak stored magnetic energy.

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 continuously wrapped around the iron core rather than localized, because there is not enough flux swing between the iron saturation limits to satisfy the OH flux swing requirements.

The air core equations presented here are derived for long solenoids and do not take end effects into account. The outboard coils of the OH system should do an effective job of guiding the field around the TF coils and make these approximations good enough for these 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 coils is assumed to be constant and vary linearly to zero through the windings. For this model the total flux is

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

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

$$B = \mu_o \, j \, a_2 \left(1 - \frac{1}{\alpha}\right) \tag{2}$$

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

The stored energy is

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

by using equations (1) and (2)

$$W_A = a_2^2 \, \ell \, B^2 \left(\frac{\pi}{6\mu_o}\right) \left(1 + \frac{1}{\alpha} + \frac{1}{\alpha^2}\right) \tag{4}$$

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.

The simplest system of this type to visualize is one with a single return leg. For the purpose of this report the windings will be assumed to cover the iron yoke. For the moment, assume that the yoke has a constant circular crosssection 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

$$\phi = \pi a^2 B_{FO} \tag{5}$$

where B_{FO} is just the field at the upper operating point for the iron. The stored magnetic energy in the ohmic heating system is

$$W_F = \frac{1}{2} \phi^2 R_m \tag{6}$$

where

$$R_m = \frac{\ell_p}{\mu K \pi a^2} \tag{7}$$

and l_p 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 loads on each TF coil due to the iron. This will not impair access to the device nor increase the amount of iron needed and will not enter the simple calculations presented here.

Comparison

There is not a single TNS but many. One of these designs has been chosen as an example for this exercise. It has a major radius of 5.7 m and requires 53 WG of flux for the entire cycle to be supplied by the ohmic heating system. The equilibrium field coils also supply some flux but for this study the iron and air core systems are operated in the same way so the equilibrium system will be assumed to be the same in the two systems. In practice the iron core system will probably be operated in a different mode. Of the 53 Wb just mentioned 43 Wb are used in the plasma initiation and startup phases, and 10 Wb are used ~~for the FCT~~ [during?] heating and ~~a~~ for a 30-second burn.

One way to characterize an ohmic heating system is by its initial bias conditions. The initial bias is the ratio of the maximum field in the ohmic heating system at the start of the cycle to the maximum swing of the field during the cycle, i.e., if a system is to swing from +6.0 T to -6.0 T with an initial field of 6.0 T its bias is 0.5.

Three air core bias conditions will be considered: 0.5, 0.81, and 1.0. The 0.5 bias case is near the optimum for a copper coil OH magnet system and is not too bad for a superconducting coil system. The ~~bad~~ undesirable feature of 0.5 bias for the superconducting system is that the rate of change of field will be fairly high after the current reverses direction and is increasing and this makes the magnet design more difficult. The 0.81 and 1.0 bias cases take the rapid rates of change of field with the current decreasing. The 0.81 case is biased so that the current is zero in the ohmic heating coils at the end of the plasma initiation and startup phases, then the rate of change of field will be slower for the heating and burn phases after the current reverses. In the 1.0 bias case the current decreases to zero during the entire plasma cycle and will end the burn phase at zero current.

Sizes and other relevant parameters for the iron core and air core cases are listed in Table 1 and a semilog bar chart comparing the stored magnetic energy in each system at the start of the plasma cycle, and the peak MVA of the four cases are shown in Figs. 1 and 2. A brief description of the two types of systems follow.

A mild carbon steel has been chosen for the iron yoke. It has a relative peameability of 80 at an operating field field of 2T and an H of 20 kA/m. The radius of the core is 1.87 m. The copper windings are around the iron in the bore and around the return leg. The water-cooled copper excitation windings are 100 mm thick in the bore and 200 mm thick on the return legs of the yoke. A packing fraction of 0.7 has been assumed. The height of the TF coils is 10 m but the length of each leg is taken as 12.5 m for clearances above and around the TF coils.

The air core solenoids all have an outside radius of 1.97 m and an overall current density of 15 mA/m^2. The inside radius of the magnet is allowed to vary as the initial bias conditions change for each case. The peak hoop stress in the solenoids was checked for each bias case and found to be within acceptable limits.[4]

In the following cost estimates ~~If the costs that follow~~ the price of the magnets has not been included, but the air core magnet costs seem to be higher than the costs for the iron core costs because they store more energy and will require some structure to hold them. ~~The costs of~~ the iron core cost will be considered as a part of the electrical system but it will also serve as structure for its excitation windings.

Many other costs have not been included in these estimates. For example, the cost of an auxiliary energy storage device, cost of electrical bus work and the costs of refrigerators if superconducting magnets are used.

The ohmic heating power circuits are priced on the following schedule: $4 \times 10^4\ (\mathrm{MVA})^{.8}$ dollars for a DC switch with reverse diode. The iron core, the 0.5 bias air core, and the 0.81 bias air core cases are priced with dual rectifiers; the 1.0 bias air core case only requires a unipolar supply and a switch. The charging supply for the 1.0 bias case has been neglected because it has not been determined how fast the system has to be charged.

Estimates for the cost of the iron core vary from \$1.00 per pound to \$2.80 per pound. The \$2.80 per pound is for a more complicated core and includes more than the capital cost of the assembled iron. The iron in this case is used as a key structural member of the device; it probably won't be in a TNS device. This figure is included as an upper bound on the cost. The dual rectifier scales to \$3.8M and the DC switch scales to \$1M. The total cost for this subset of the iron core ohmic heating system is \$15M to \$33M.

The subset of the power system costs for the air core cases is shown in Table 2. One should note that the full (1.0) bias case does not use a dual rectifier supply. The least expensive of the air core power supply subsets ($51M) is more expensive than the upper bound on the iron core cost estimate ($33M). The difference is even more striking if the unit costs increase. Assuming a $(MVA)^{.8}$ scaling and taking the costs from the LASL[2] report on ohmic heating studies for EPR the cost estimate for the 0.5 bias case is $159M while the iron core costs range from $25M to $43M.

Conclusion

A simple comparison has been made between an air core and an iron core ohmic heating system for a particular device, and it was shown that the peak power requirements can be substantially reduced by the use of an iron core. These power levels are handled by industry today. It was also shown that for an ohmic heating system initiated plasma that the cost of the power system (iron core, dual rectifier, and DC switch) is less than the cost for a subset of the power system for an air core system (dual rectifier and DC switch).

There is considerable work being done on other methods of initiating the plasma none of which seem to be incompatible with the use of an iron core system.

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Table 1. A important parameters for the comparison of air core + iron core system.

	Iron Core	Air Core		
		.5	.81	1.0
Coil Radius (m)	1.87	1.84	1.71	1.70
Field (T)	2.5	2.3	3.9	5.0
Ampere Turns (MAT)	.99	18.4	31.2	39.7
kA in OH unit with 4 turns (3 kV voltage)	312	5.78×10^3	9.8×10^3	1.25×10^4
Stored Energy initial (MJ)	11	244	671	1051

This is the radius of the iron core and the inside radius of the copper windings.

This is the operating limit of iron core when plasma is [illegible]. The field at the end of a [illegible] is 2.7 T. This requires 30 MAT. See Fig. 4.

Table 2. Cost breakdown for a subset of the air core power system for three bias conditions

Bias	Max. MVA	Power Supply ($M)	DC Switch ($M)	Total ($M)
.5	5.78×10^3	41	10	51
.81	9.81×10^3	62	15	77
1.0	1.25×10^4	43	20	63

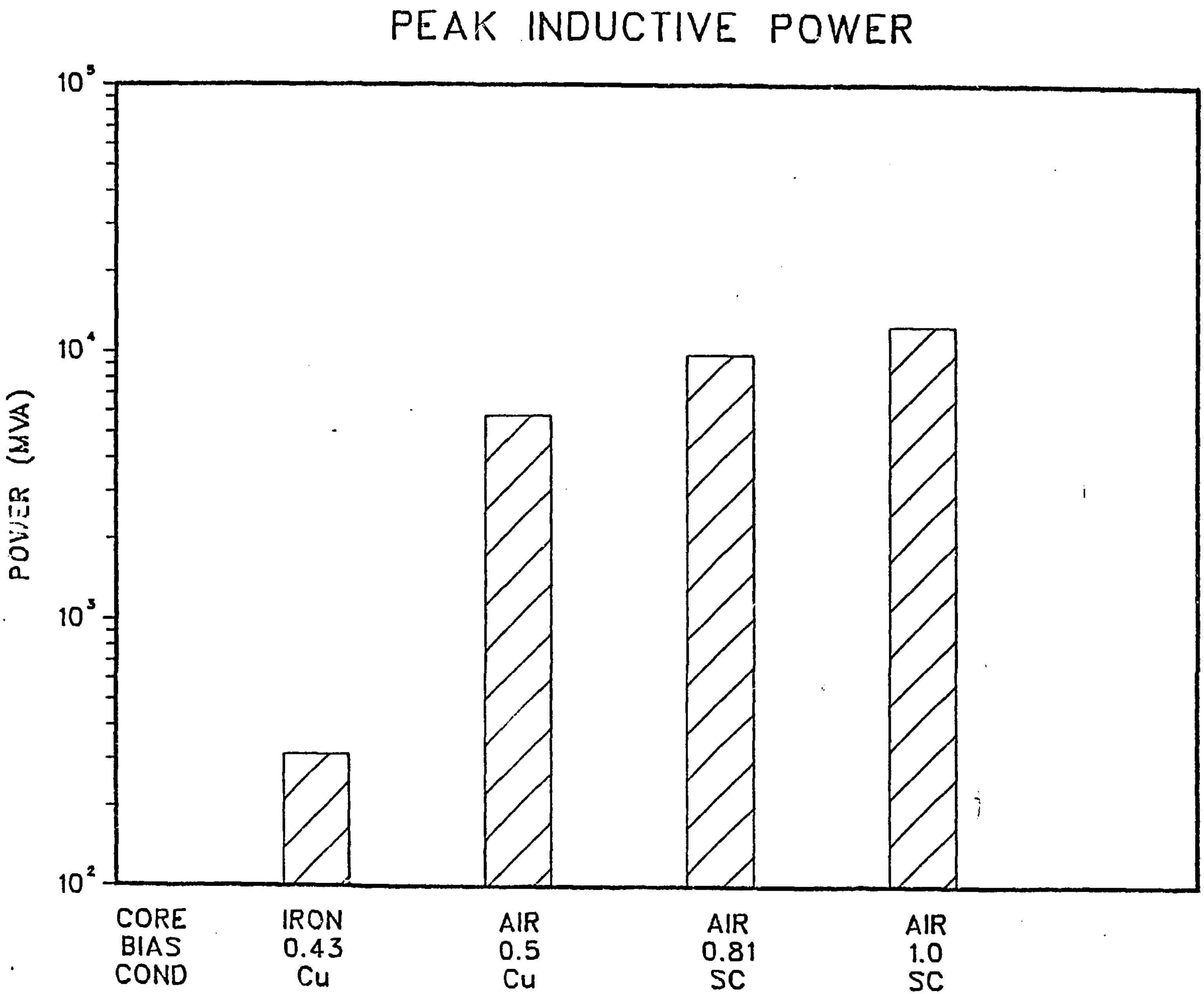

Fig 2. Comparison of peak MVA in ohmic heating system power demand for plasma breakdown for four combinations of core material, bias,

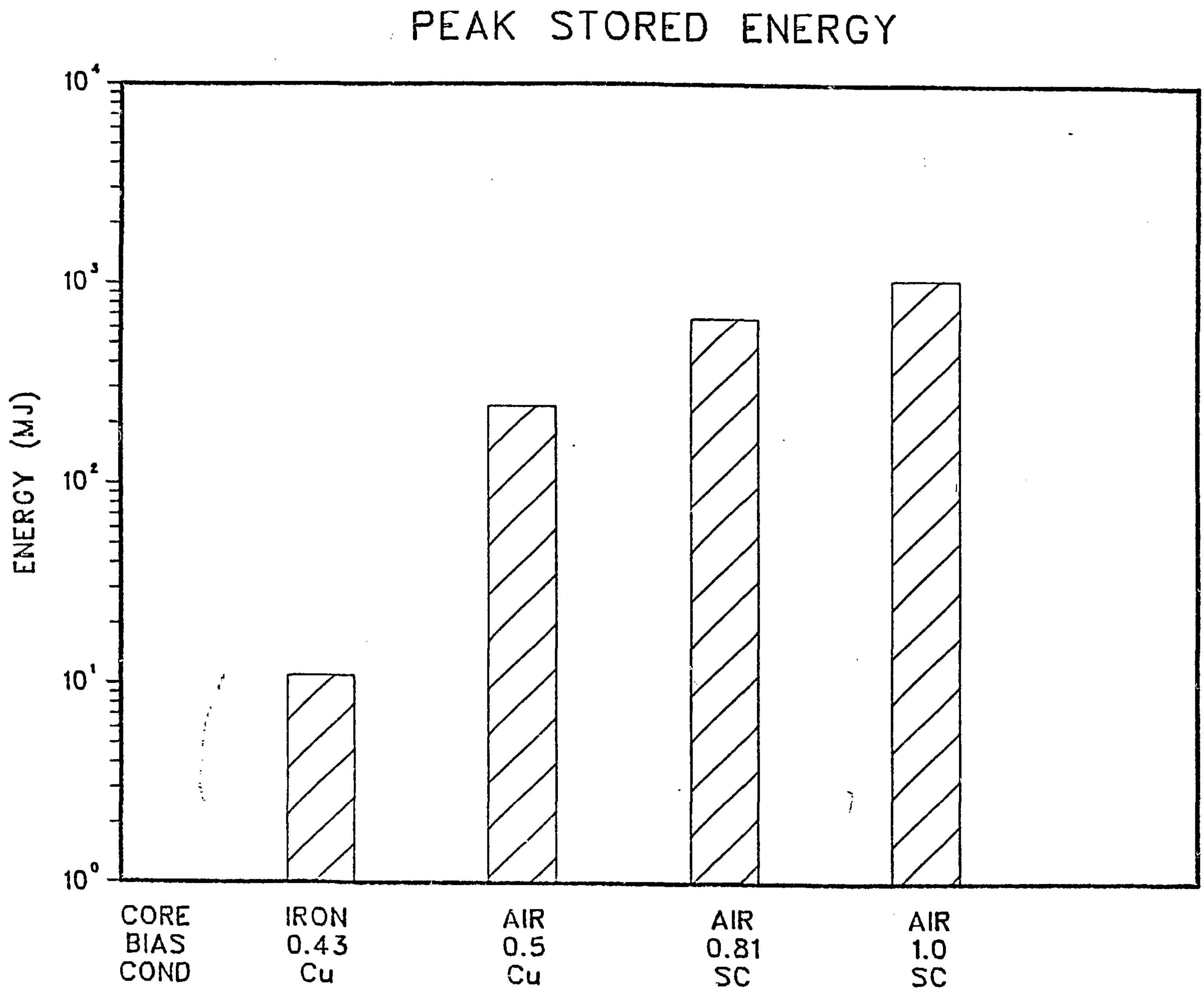

Fig 1. Comparison of magnetic energy stored in the ohmic heating system just before plasma breakdown for four combinations of core material, [illegible]

References

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~~This paper only considers the method of breaking down the neutral plane with high voltage applied [illegible] the [illegible] [illegible] system~~

(4)

This paper only considers the method of breaking down the neutral gas with a high voltage induced by the ohmic heating system.