ALTERNATE OHMIC HEATING COIL ARRANGEMENTS FOR COMPACT TOKAMAK*

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Introduction

In this report, the results for a number of ohmic heating (OH) coil arrangements which will allow the reduction of the major radius of Experimental Power Reactor (EPR) tokamaks will be given. In each case the results are compared, at least indirectly, to the reference case, Fig. 1, which has the OH solenoid inside the central core of the reactor.

The goal for the alternate geometries studied was to stay within the requirements imposed by the EPR conditions on the plasma and to produce as much or more OH V-s as the reference case. The requirements which were imposed are:

1. achieve a toroidal magnetic field at the plasma center ≥3.4 T without exceeding the peak field capability of the superconducting materials while maintaining an inboard blanket and shield thickness of about 0.9 m,

2. produce the OH V-s without developing magnetic fields over the minor cross-sectional area of the plasma,[2] and

3. produce the OH V-s without developing magnetic fields of more than 0.5 T anywhere in the TF coil region.[3] (A lower value would be better.)

Figure 1 shows the reference case and defines some of the terminology used in the other cases. The geometries which are more fully discussed later in the report are shown in Fig. 2. In all the figures, the equ**brium coils are not included because they are bey the scope and intent of this study. The reference case has the solenoid coil located inside the central core and the profile coils located outside the TF coil envelope. Thickness of the TF coil was scaled from the latest EPR-77 design at ANL according to Ampere's law. The magnetic field at the outside radius of the inner leg was kept at a value of 5 T for all studied cases. Because it is a "long" solenoid and placed in the central core of the TF coil, it inherently satisfies requirements 1, 2, and 3 most easily. Case 2, Fig. 2, has a concentric pair of completely-shielded long solenoids surrounding the inner legs of the TF coils and a set of completely-shielded profile coils surrounding the inner legs of the TF coils. Because the outside radius of the inner legs of the TF coils remains constant in our case studies, the major radius of the plasma must be slightly increased for this case. Case 3 has 16 long, narrow solenoids located inside the blanket and shield and completely-shielded profile coils inside the TF coil envelope. Almost the entire circumference is occupied with solenoids in this case. It introduces the concept of making the shield electrically active instead of passive as it is in most other designs.[4,5] The shielding space is partially filled with electrical conductors and used to produce V-s. It is inherently easier to assemble and maintain this coil than it is for case 2. Case 4, an extension of case 3, has 16 long narrow solenoids inside the blanket and shield. However, the solenoids are contoured around the plasma. This configuration is expected to eliminate the need for some of the profile coils inside the TF coil envelope. It should be comparatively simple to install and maintain this type of coil system since the solenoids could and should be designed to be removable through the space between the TF coils. Cases 2', 3', and 4' have the same arrangements of OH coils as cases 2, 3, and 4 respectively, but with the addition of a long solenoid in the central core to increase the V-s capability.

Alternate Geometries

In the following sections the various alternate geometries for the OH coil will be discussed in some detail. These discussions are based only on the geometries of the current distributions shown in the accompanying figures. The exact values for the supply currents or the current densities used are beyond the scope of this paper, but current densities of less than 3000 A/cm^2 are generally used in the various coil sections.

The calculations for these various geometries were done with a code, AIRCOIL, developed at Argonne.[6] This code will calculate the magnetic fields at specified points in a radial plane for a maximum of 60 input coil sections in a cylindrically symmetric magnet structure. It will also iteratively adjust the locations and the numbers of turns for specified coil sections in order to reduce the magnetic fields in a specified region. This optimizing method was used to help us establish the attainability of the requirements given above for the OH coil. For the solenoid ring options, the resultant fields in a radial plane which were generated by the solenoid coils in the ring had to be determined. This involved the superposition of the magnetic fields in the radial plane of interest for each coil in the ring. The results of this calculation were then input into AIRCOIL as a constant bias field and the optimizations of the locations and numbers of turns for the cylindrical, profile coils were done in the customary way.

The reference coil shown in Fig. 1 is the usual design with a central solenoid used to generate the core flux and the profile coils to keep the core flux in the return path from entering the plasma region. The major radius for the plasma in this case is 4.2 m. This coil develops a core field of 5.02 T with an integrated flux of 11.4 Wb between the vertical axis of the machine and the inner edge of the plasma. The maximum flux linkage that could be developed for an OH coil with the outside diameter shown (190 cm) is about 16 to 18 Wb.[7] The reference core field was chosen at about 5 T, knowing it is not a maximum value but that it is probably an easily attained value and will not require any more detailed calculations to establish this fact as would a 50% higher value. This type of coil is familiar to OH coil designers and can easily be made to satisfy the requirements for the stray fields in the plasma and TF coil regions.

The first alternate OH coil geometry, case 2, is shown in Fig. 3. This case consists of two concentric solenoids located just outside of the inner legs of

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the TF coils. The major radius of the plasma was increased to 4.62 m to allow room for these coils while maintaining the full 0.9 m thickness for the inboard blanket and shield. Above and below these solenoids are the profile coils, which consist of cylindrical coils with some carrying reverse currents and which direct the flux from between the solenoids to travel outside the plasma region. The flux density between the solenoids is about 6.4 T. This coil satisfies requirements 2 and 3 summarized above; it produces 18.5 Wb of core flux and gives a large plasma area with less than 10 G and does not produce more than 0.5 T in the TF coil region. It does, however, sacrifice some of requirement 1 because of the necessary increase in the major radius of the plasma. Another disadvantage of this case is the fact that the current density in the solenoid coils is around 5000 A/cm^2, which is too high for a real coil at the present time. Another disadvantage of this case is the fact that all of the OH coils lie inside the TF coil envelope. This will produce serious problems during the fabrication and repair of this machine.

The second alternative, case 3, is shown in Fig. 4. This geometry contains 16 solenoids uniformly spaced at a radius of 210 cm in a ring between the plasma and the TF coils. These solenoids have an outside diameter of 70 cm and are 7.0 m high. They are placed so that there is about 15 cm of shield between the plasma and the solenoid coils and about a 10 cm space between the solenoid ring and the inner leg of the TF coil. It is anticipated that the core of each of the solenoid coils can be filled with a non-magnetic and electrically-resistive shielding material. The major radius of the plasma is 4.2 m but the effective inboard shield and blanket thickness is somewhat reduced at periodic locations around the axis of this machine. The flux density inside each solenoid is 6.3 T giving a net core flux of 24.2 Wb. The region in the plasma which contains stray fields of less than about 10 G is outlined in Fig. 4. This geometry, therefore, satisfies requirements 1 and 2 above. Requirement 3 is satisfied completely but there is a region in the TF coil in which the fields approach 0.5 T. This region is located adjacent to the top edge of the solenoid coils and is outlined in Fig. 4 as containing more than 10 kG, but this was an earlier result.

In order to improve this last condition for this geometry, one could decrease the flux density in the solenoid coils giving a reduced core flux, or one could increase the distance between the TF coils and the solenoid coils. There are several ways of doing the latter, but each of the alternatives has some negative aspects. To increase the distance between the TF coils and the solenoid coils, the solenoid coils can be reduced in diameter; and to compensate for the loss of solenoid area, the core flux densities can be increased, which could be a problem. The major radius of the plasma could also be increased, which is a disadvantage, but it will allow for the improvement of the net shielding for the TF coils. Some combination of these different solutions could be utilized in some optimum design. It is not clear, however, at this point that this problem of high stray fields in the TF coils is necessarily a serious one. The area involved is rather small and is at a vertical position which would allow the introduction of enlarged coolant paths in the radial dimensions of the TF coils.

There are some other possible alternatives which will give an improved design. One is shown in Fig. 4 in a phantom outline. This is the addition of a core solenoid like that used for the reference case in Fig. 1. This will add at least 11.4 Wb of core flux. With this coil and using the solution above, which calls for the reduction of the solenoid fields in case 3, a total core flux of at least 27.5 Wb could be produced.

Another possibility is to add the core solenoid to case 3 giving a net core flux of at least 36.1 Wb. This core solenoid can similarly be added to case 2, resulting in case 2'. This will give a core flux of at least 29.9 Wb. These cases were not calculated in detail to establish the stray fields in the plasma and TF coil regions. It is not expected, however, to add any significant fields in these regions since these coils can produce, by themselves, better results than the geometries to which they are added.

Another alternative geometry is to bend the solenoid coils away from the TF coils in a radial plane and only in the regions near the ends of the solenoids. This argument can be carried still further, by extending the ends of these bent solenoids around the plasma region to some extent. Calculations for this case, case 4 in Fig. 2, have not been performed, but it can be expected that this will not significantly alter the results for the core flux that were found in case 3. We do expect, however, that the high fields in the TF coil region can be reduced still further to acceptable values. An added advantage is also anticipated. This is the reduction and possible elimination of the cylindrical profile coils contained inside the TF coil envelope.

The final case that we have considered, case 4', involves the addition of a core solenoid coil to case 4. This will then give a net core flux of at least 36.1 Wb and will comfortably meet all of the requirements stated above.

Results and Conclusions

The main features of our study are shown in Table I. The V-s listed are calculated assuming a complete reversal of the field in the OH coils. Case 2 meets all the requirements except for 1, and the major radius is not greatly reduced from the current EPR design of 4.7 m. However, if the coils were made of copper, they could be put inside the shielding and used to produce a large amount of fast OH V-s. This would allow a reduction of the major radius to 4.2 m as in the other cases, and greatly reduce the fabrication and repair problems associated with having coils inside the TF coils. In addition, an OH solenoid must be inserted in the central core for production of slow OH V-s. As would be expected, case 3' and 4' produce the most V-s because of the addition of the OH solenoid in the central core. Case 4' is the most attractive from the point of view of fabrication and repair since all of the coils are removable through the spaces between the TF coils. In addition, these coils could be made of copper to produce a large amount of fast OH V-s while the central core solenoid could be used to produce slow OH V-s. Also, the copper coils can be used for active shielding of the TF coils from the induced fields due to the plasma. Time has not, however, permitted us to study this possibility.

References

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TABLE I

Summary of Alternate OH Heating Features

Case Number ([illegible])	Major Radius (m)	Minor Radius (m)	Magnetic Field at Major Radius with 9 T TF Field (T)	OH with Field Reversal (V-s)	Area in Plasma with Fields ≤ 10G (m^2)	Maximum Field in TF coil (T)
1	4.2	1.4	3.5	22.8	7.0**	.05
2	4.62	1.32	3.2	37.0	5.5	.5
3	4.2	1.4	3.5	48.4	4.0	.42
4	4.2	1.4	3.5	48.4*	4*	<.4*
2'	4.62	1.32	3.2	59.8	5.5	.5*
3'	4.2	1.4	3.5	72.2	4*	.6
4'	4.2	1.4	3.5	72.2	4*	<.4*

*Values are estimated

**Approximately the entire plasma area

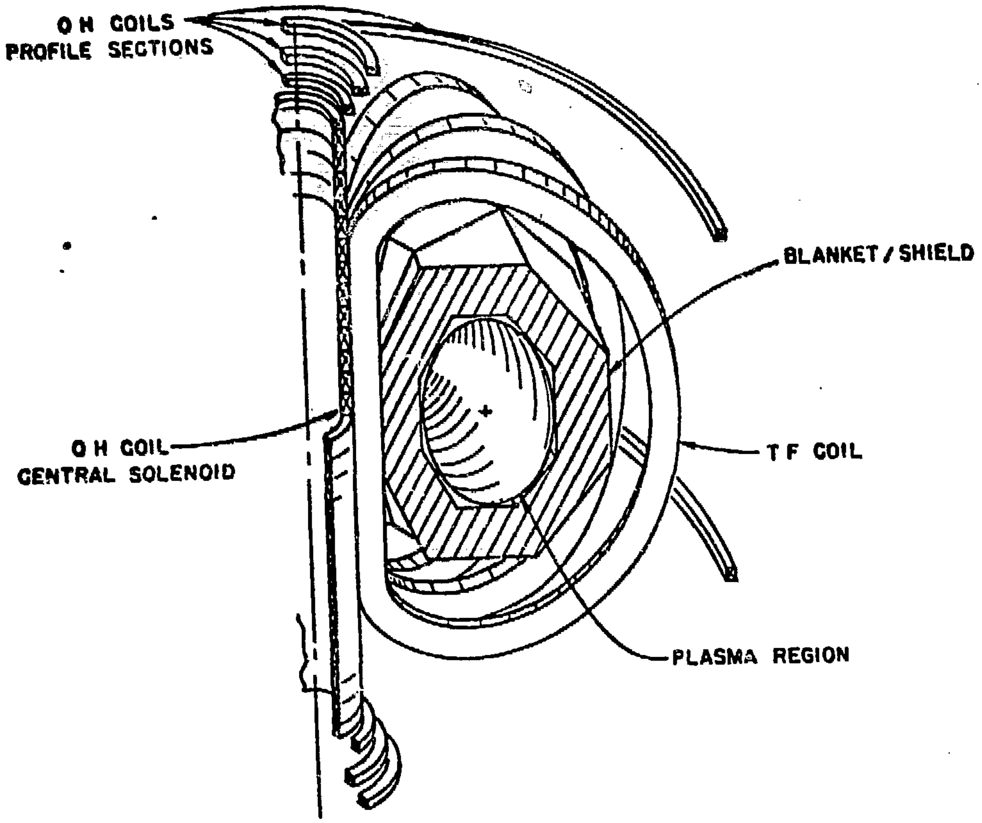
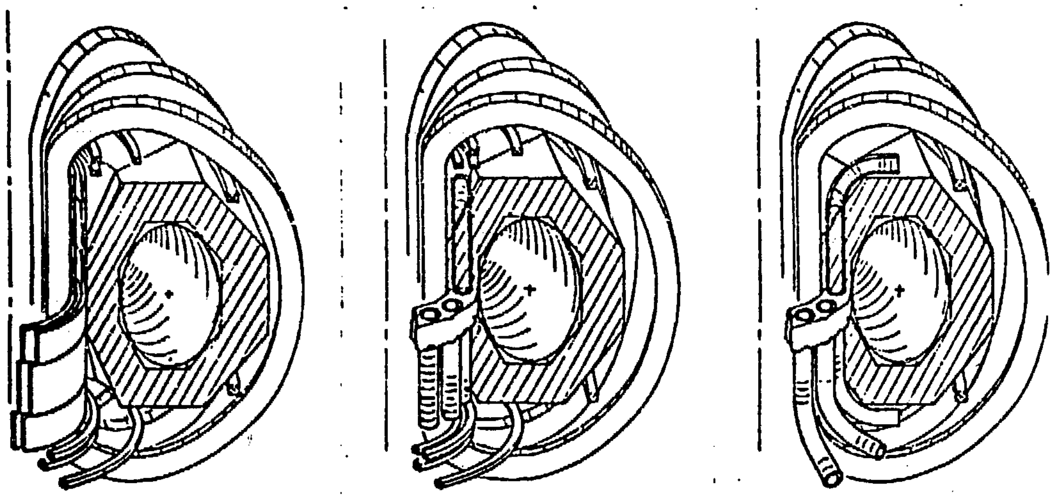


Fig. 1. Reference OH coil geometry case 1, with definitions of machine parts.



Case 2

Case 3

Case 4

Fig. 2. Alternate OH coil geometries

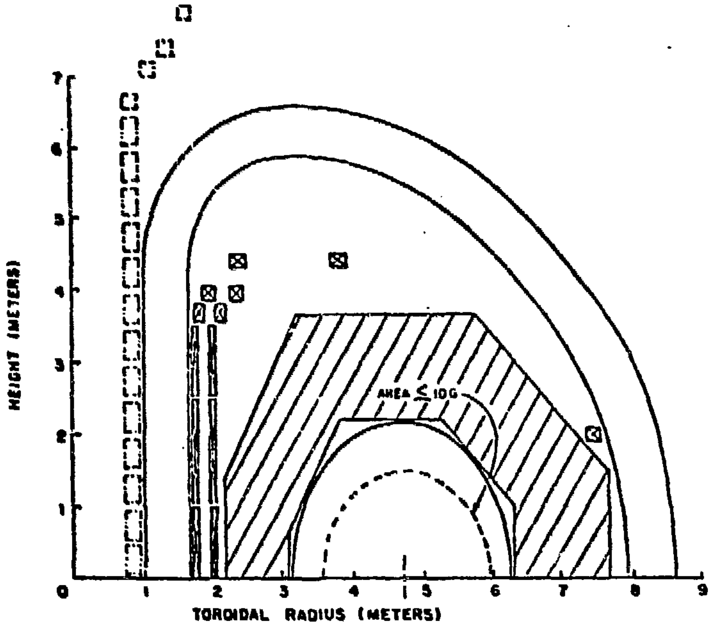


Fig. 3. Details of the geometries and results for case 2 and case 2' (case 2' includes the core solenoid shown in phantom).

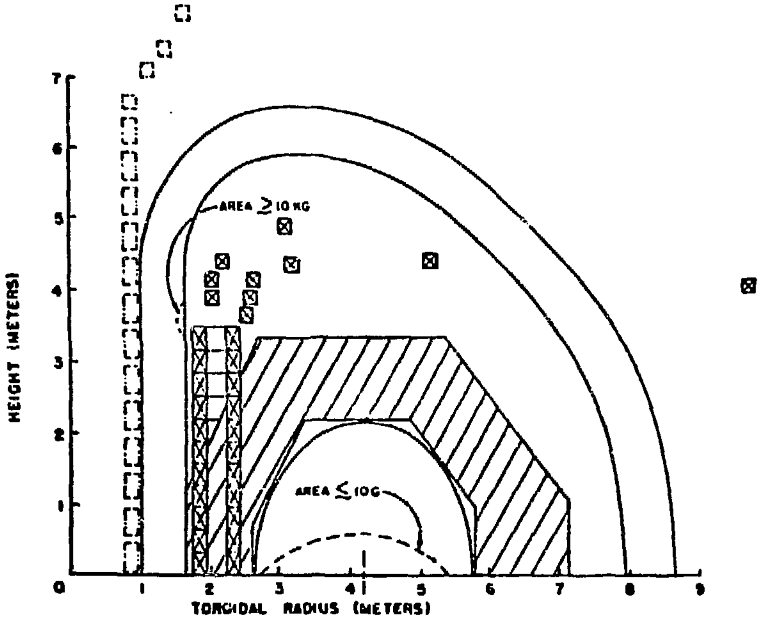


Fig. 4. Details of the geometries and results for case 3 and Case 3' (Case 3' includes the core solenoid drawn in phantom). The area in the TF coil shown to contain ≳ 10 kG fields actually contain fields ≲ 4 kG in the latest results.