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RESISTIVE DEMOUNTABLE TOROIDAL-FIELD COILS
FOR TOKAMAK REACTORS

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## Summary

Readily demountable TF (toroidal-field) coils allow complete access to the internal components of a tokamak reactor for maintenance or replacement. The requirement of readily demountable joints dictates the use of water-cooled resistive coils, which have a host of decisive advantages over superconducting coils. Previous papers have shown that resistive TF coils for tokamak reactors can operate in the steady state with acceptable power dissipation (typically, 175 to 300 MW). This paper summarizes results of parametric studies of size optimization of rectangular TF coils and of a finite-element stress analysis, and examines several candidate methods of implementing demountable joints for rectangular coils constructed of plate segments.

## Introduction

One of the most serious disadvantages cited by critics of the tokamak is its inherent inaccessibility, with the vacuum vessel and internal poloidal-field (PF) coils interlocking the toroidal-field (TF) coils, and the isolated location of the blanket modules inboard of the fusion plasma. This apparent major disadvantage can be eliminated by the implementation of TF coils that are *readily demountable*. The resulting tokamak reactor is then no more inaccessible than a light-water fission reactor, for example, where complete accessibility is obtained upon removal of the cap of the pressure vessel.

The requirement that the TF coils be readily demountable, with minimal reactor downtime and minimal impact on TF coil performance, dictates the use of water-cooled resistive coils fabricated of copper or aluminum (rather than superconducting or cryogenic coils). Other advantages of resistive coils are the following: (i) They are unaffected by pulsed fields; (ii) they require less shielding against neutron irradiation than do superconducting coils; (iii) they have simple refrigeration systems; and (iv) with construction from plate segments, they can be factory-built and the plates transported to the reactor site for assembly.

The TF coils of a tokamak reactor must operate in the steady state. Resistive coils can operate continuously when they are sufficiently massive.[1] At the values of $<\beta>$ = (plasma pressure/ magnetic field pressure) now thought to be achievable in tokamaks (viz., $<\beta>$ = 6 to 10%), the magnetic field required for satisfactory performance of tokamak reactors in at least some important applications can be sufficiently low so that the resistive power dissipation is acceptable,[1-4] i.e., comparable with the sum of the power losses in the other reactor components (PF coils, blanket coolant systems, plasma heating systems, pumps and HVAC).

A previous paper analyzed optimization of the size of resistive TF coils of rectangular bore for certain types of tokamak reactors.[1] Later papers discussed the reactor features that are possible using such coils,[2] and provided more details on the coil optimization and on magnetic stress and thermal aspects.[3] The present paper describes results of a finite-element stress analysis of rectangular TF coils for fusion neutron generators and power reactors, and also examines candidate methods of implementing demountable joints.

## Parametric Study

Figure 1 shows a schematic view of the TORFA device[2] featuring rectangular resistive coils. Reference 3 gives a detailed parametric study relating coil geometry, mass, and resistive power dissipation, $P_{res}$, to the desired neutron wall loading and the peak magnetic field $B_M$ at the coil windings. Figure 2, taken from Ref. 3, shows the variation of $P_{res}$ for the family of rectangular coil geometries of the type illustrated in Fig. 1 that produces a neutron wall loading of 0.5 MW/m$^2$, for reasonable assumptions of fusion plasma performance. For fixed coil shape parameters, there is a minimum

$P_{res}$ in the range 125 to 190 MW, which occurs at very large coil dimensions and mass, but at modest magnetic field strength. The fusion power output $P_{fus}$ for this configuration may be too large to be practical. For coil half-bore $a_c$ = 4 m with $B_M$ = 5 to 6 T, $P_{res}$ is only slightly above while the coil mass is considerably below their values at the minimum $P_{res}$. With the wall loading still at 0.5 MW/m², $P_{fus}$ is in the range of 650 to 800 MW.

For a given coil geometry, both $P_{res}$ and the bending stress are proportional to the square root of the required neutron wall loading.

We define the reactor electrical power gain referred to the coil power loss as $Q_c = 0.28 \times M_{bl} \times (P_{fus}/P_{res})$, where $M_{bl}$ is the blanket energy multiplication and a thermal-to-electric power conversion efficiency of 35% is assumed. Figure 3 shows $P_{res}$ as a function of $Q_c$ and $B_M$ with $M_{bl}$ = 1, for reactors of fixed shape parameters. Note that at a given $B_M$, higher $Q_c$ is obtained by increasing the reactor size ($a_c$). Of course, $Q_c$ can be substantially increased also by employing a multiplying layer of depleted uranium or other materials in the blanket, to give $M_{bl} >> 1$.

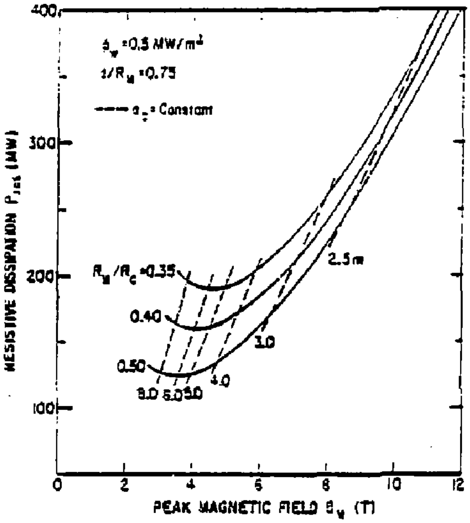


Fig. 2. Variation of TF coil power loss with $B_M$, for constant neutron wall loading of 0.50 MW/m². $R_c$ is the coil major radius, $a_c$ is the coil half-bore, and $R_M$ is the position of max. field $B_M$.

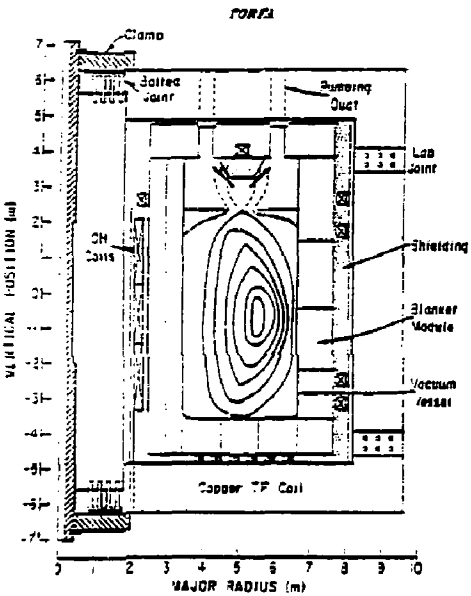


Fig. 1. Elevation view of tokamak reactor with rectangular resistive toroidal-field coils. Coil joints are shown schematically only. Magnetic surfaces in the plasma are indicated.

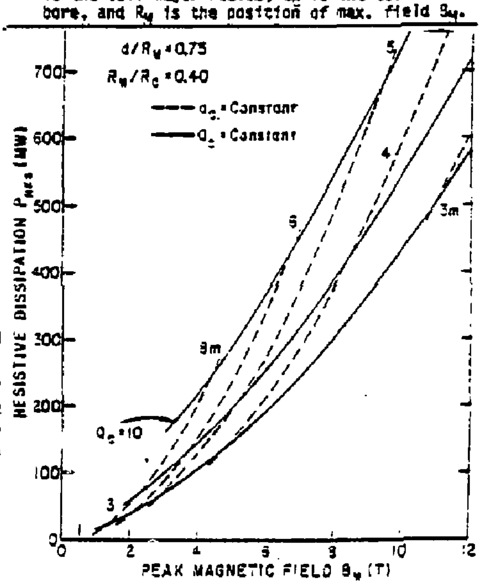


Fig. 3. Variation of $P_{res}$ with field at conductor $B_M$ and fusion electrical power gain $Q_c$.

## Magnetic Stresses

A rectangular TF coil has the most convenient shape for manufacturing and for access to the internal reactor components, but compared with other shapes (such as the Dee), it generally poses the most severe magnetic stress problems, caused mainly by bending moments. The stress distribution in a TORFA-type copper coil, illustrated in Fig. 1, was determined by means of a finite-element analysis (MSC Nastran, using 250 elements). The inboard legs of the coils are assumed to be wedged together. The results of this analysis are summarized in Figs. 4 and 5, which plot the major principal and maximum shear stress contours, respectively, for $B_M = 7.5$ T. Marked on Fig. 4 is the point of inflection in the upper leg of the coil, where the bending stresses are minimum; this is the area most suitable for the inclusion of a joint. A similar region can be identified on the outboard leg to the right. Both the major principal and the maximum shear stresses in these areas are approximately 33 MPa (4800 psi).

The highest stress levels encountered are of the order of 175 MPa (25,000 psi) for the major principal stress in a small region of the inboard leg. Even this stress level is within the capability of copper, so that the limiting field for this rectangular coil is probably $B_M \approx 8$ T.

The peak bending stresses for this coil geometry have been calculated also from the theory of rigid frames[3], and are in reasonable agreement with the results of the finite-element analysis. The highest stresses are found at the inboard and outboard corners. However, only the finite-element method gives the exact locations of the peak and minimum stresses.

Severing the coil conductors in order to make a demountable joint reduces the coil strength in that location by as much as a factor of 3. Hence joints should be placed at the locations of minimum bending stress, which can be identified by analyses such as the one illustrated in Figs. 4 and 5.

## Fabrication Considerations

The present conceptual design approach advocates construction of the TF coils from high-conductivity copper alloy plate segments that are riveted or bolted together. Manufacturers can presently roll high-conductivity copper plate (such as CDA-102) in thicknesses up to 6 cm for sizes up to 4 m in length and 1 m in width, with the final product at least half-hard. Each segment of a rectangular TF coil would be constructed by joining two or three of the maximum-sized plates by soft soldering or lap riveting. With either technique, the strength of the plate would be retained. Detailed description of the plate parameters is given in Refs. 1 & 3.

There is no winding process for the TF coils. The large number of identical plate sections allows essentially mass production with automated machining procedures. The insulating material could be fabricated in the form of plates to be compressed between adjacent conductor plates upon coil assembly, or the insulating material could be bonded to each conductor. The plate construction lends itself to the use of inorganic insulation that can be highly radiation resistant.

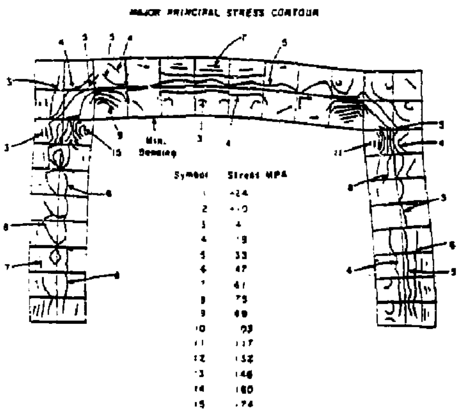


Fig. 4. Major principal stress contours calculated by a finite-element analysis for a rectangular TF coil. Maximum toroidal field at the inboard coil windings (on the left) is $B_M = 7.5$ T. [809014]

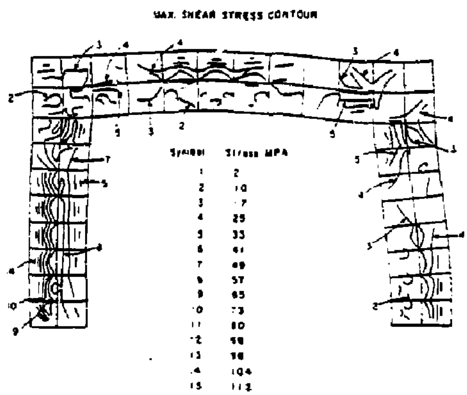


Fig. 5. Maximum shear stress contours calculated by a finite-element analysis for a rectangular TF coil. Maximum toroidal field at the inboard coil windings (on the left) is $B_M = 7.5$ T. [809013]

## TF Coil Joints

Successful engineering of the joints for the TF coils of a tokamak reactor requires that the greatest attention be paid to the design of joints that are *readily demountable*, that are reliable, and that if necessary can be repaired easily by remotely controlled machinery.

A contact pressure of at least 1500 psi is necessary between two plates being joined, in order that the electrical resistance of the joint be negligible. Exertion of this pressure requires either bolting or hydraulic techniques. Table I lists the various types of joints that have been examined. A butt joint probably takes up the least amount of space, but it requires very careful alignment and a fairly elaborate clamping system to exert the required compressive stress. A lap joint, on the other hand, offers the simplest overall joint assembly, but requires the most space and is unsuitable for the inboard joints. The pins used in finger joints must also take up shear stress.

The joint concepts discussed in the following are the outcome of our preliminary conceptualization of jointing schemes that would be amenable to remote handling techniques.

### Position of Inboard Joint

It is not practical to place the inboard joint at the corner as depicted in Fig. 1, because of (i) severe restriction on space and accessibility for the joint, especially if the TF coils are wedged together, and (ii) the very high stress in this region (see Figs. 4 and 5). The position of the joint must be moved outward to the region of minimum stress, as indicated in Fig. 6.

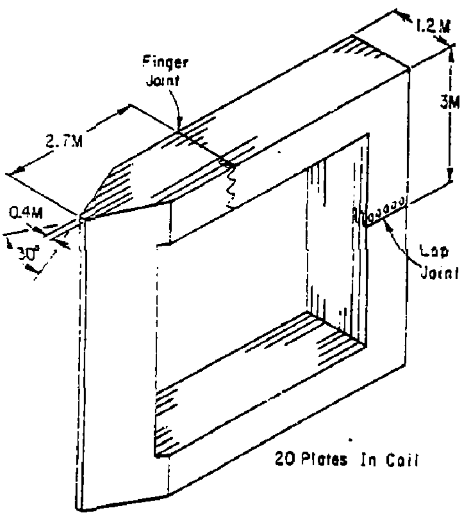


Fig. 5. Illustrative demountable joint positions for a rectangular TF coil constructed of plates. [81-P008]

Table I

Candidate Demountable Joints

| Type of Joint | Method of Applying Clamping Pressure |
|---|---|
| Lap | - Bolts (e.g., ISX outboard joints; PDX) |
| Finger | - Recessed pins and through-bolts (e.g., ISX inboard joints; Doublet III) |
| Vertical Butt | - Bolts and clamping ring attached to center column (e.g., Fig. 1) |
| Horizontal Butt | - (i) Bolting together of overlays attached to butted segments. (ii) Clamping ring on outboard side (analogous to Alcator coils). |
| Plug-In | - Hydraulic clamping ring (Note plug-in joints on TEXT device PF coils) |
| Lap | - Hydraulic cylinders (e.g., FM-1) |

It is essential to be able to remove the inboard blanket modules by a simple vertical translation. On the other hand, replacement of the ohmic-heating solenoid is likely to be an infrequent requirement, so that a more tortuous removal procedure can be contemplated. The inboard joint position shown in Figs. 6 and 9 does allow removal of the blanket modules by simple vertical translation, but requires disassembly of the ohmic-heating solenoid before removal.

### Finger Joints

A viable approach is to incorporate a finger joint in the upper arm and a lap joint in the outboard leg (Fig. 6). The concept of the finger joint is shown in Fig. 7. For a TORFA-sized coil[3] fabricated from plates approximately 5 cm thick and 1.2 m deep, it is expected that as many as 50 fingers will be required. The fingers are seen to be tapered so as to ease assembly and are machined in chromium-copper joint inserts, these being soft soldered and riveted to the parent copper arm. No wedging of the fingers is required or desired, the tensile force in the joint being transferred through the split shear pins, which also serve as the current joint. The optimal joint would probably have 2 or 3 shear pins.

The split shear pins are similar to those used in the Doublet III device,[4] and consist of a split copper sleeve enclosing a set of tapered interleaved washers of chromium copper, the larger diameter ones of which are also split. After inserting the shear pins, the nut is tightened, causing the shear pin to expand and ensuring a tight fit in the hole. This tight fit together with the magnetic tensile load would supply the necessary pressure for the current joint. Water cooling lines go around the joint, which are cooled by conduction.

Lap Joints

The outboard lap joint is shown in conceptual form in Fig. 8. Again the magnetic tensile load is transferred by shear pins that also serve as current joints. Ideally, one would like to make the pins as large as possible to reduce the number needed, and large size is certainly possible in this outboard region. For a TORFA-sized coil, as few as 10 pins would suffice per joint. The form of the lap joint shown in Fig. 8 has been chosen so as to eliminate the bending moment produced by a simple lap-joint/shear-pin arrangement. In this way our joint differs from the lap joint on ISX.[5]

Bolted Butt Joints

The TF coil illustrated in Fig. 1 uses bolted butt joints on the inboard side. The inboard corners are also held in place by hydraulically clamped stainless steel plates keyed into the center column. The stresses on the bolts are of the order of 50,000 psi, and would require the use of Inconel or an equivalent alloy. To minimize fatigue problems, the bolts would be replaced every time the joint is disassembled.

As indicated in a preceding section, it is impractical to locate the inboard joint in the position shown in Fig. 1. A more practical concept for a butt joint is discussed below.

Hydraulic Clamping

A great advantage of purely hydraulic clamping (i.e., without bolts), when used with an external shear restraint in the joint area, is that the joint can literally be dismantled by simply releasing the oil pressure to the hydraulic jacks. By staggering the vertical height of adjacent TF coils, it is feasible to use hydraulic joints alone to attach the horizontal sections of each coil to the inboard leg. Another advantage of hydraulic joints is that the creep of the insulation materials can be easily overcome, thus ensuring a constant contact pressure on the copper joining surfaces over long periods of time. The major disadvantage is the need to provide shear restraint so as to stop any slippage that may occur in the joint. A stainless steel casing might be necessary to take up shear stress.

Flanged Butt-Type Joints

In this concept,[5] the clamping force is applied across the joint using *flanges bolted together*, rather than by reaction from an external superstructure, or by direct bolting as in Fig. 1. Spring contacts compensate for fabrication tolerances so as to maintain uniform contact pressure across the joint.

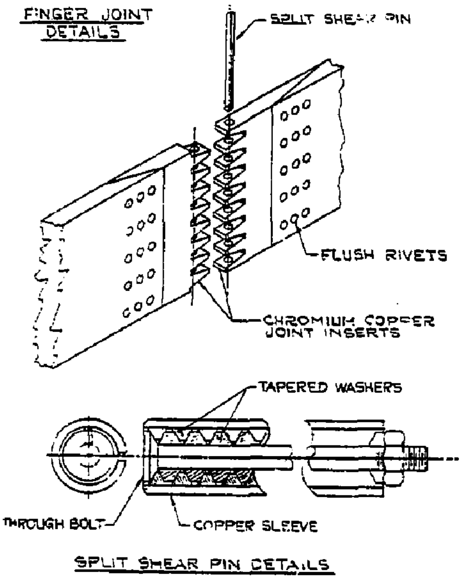


Fig. 7. Details of the finger joint for the configuration of Fig. 6.

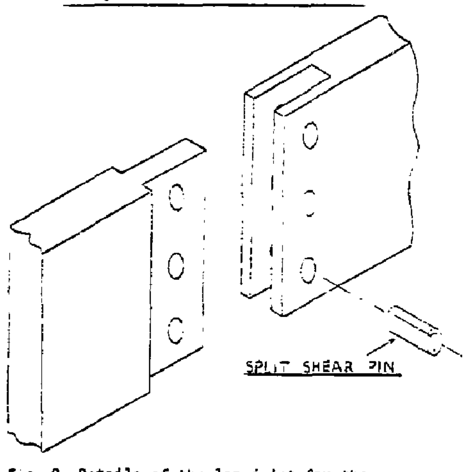


Fig. 8. Details of the lap joint for the configuration of Fig. 6.

As in the preceding, the TF coil set is comprised of 12 nested coils of rectangular shape, each consisting of 20 insulated copper plates with water coolant. Each segment is 1.2 m thick and 1.4 m wide. The joint configuration is shown in Fig. 9. There are four flanged joints for disassembly.

Flanges on Inboard Joint. Because of limited space in the nested region of the TF coils, flanges can be provided at only the top and bottom of the joints on the inboard side. Each flange is an individual unit keyed and retained within a machined slot in the coil stack. The bolt load is transmitted from the flange to the coil stack, and a pin is used to secure the flange in place (see Fig. 9-B). A tapered locating pin and hole are provided on the mating flanges to provide for alignment during assembly of the joint and to prevent movement of the joint.

Flanges on Outboard Joint. As shown in Fig. 9-A, flanges are provided on three sides of the corner joint on the outboard leg. The flange assembly on the upper and lower segments consists of a four-sided case that is assembled over the corner of the coil segment. The bolt load is transferred from the flanges to the coil stack through the back of the flange case, and the case is retained to the coil stack by pins.

The mating flange located on the outboard leg consists of a three-sided flange case that is slipped over the ends of the outboard leg and secured in place by a T-shaped key (see Fig. 9-C). The bolt load is transferred from the flanges to the coil stack through this key. Gussets mounted on the flange cases provide additional flange stiffness.

Spring Contacts. Simultaneous contact and uniform contact pressure will be difficult to attain even with exceedingly tight tolerances. To alleviate this problem, consideration should be given to spring-type contacts that would be located along the edge of the conductor plates and would be secured by brazing into machined grooves. As depicted in Fig. 9-D, five slotted block-type spring contacts are mounted on the edge of each coil plate and secured in place by bolts. The design goals are 1500 psi contact pressure, stress at design load ($B_M$ = 7.5 T) less than 60,000 psi, and deflection at least 0.75 mm at this load.

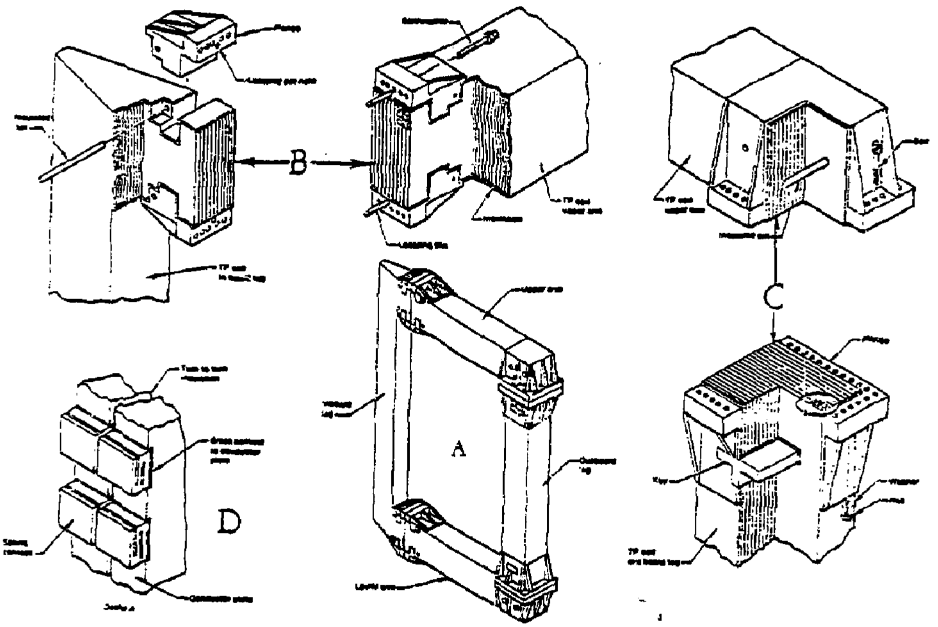


Fig. 9. Flanged butt-type demountable joints for a rectangular TF coil. (A) TF-coil assembly. (B) Inboard leg joint. (C) Outboard leg joint. (D) Detail showing spring contact. [81P0310]

Bolts and Pins. Initial calculations indicate that approximately 32 bolts of 1.5" (3.8 cm) diameter will be required at each joint to provide the necessary preload. Note that reaction loads must be transmitted across some type of insulating material to prevent short-circuiting across the coil plates. Therefore, pins and keys used to attach the flange cases to the coil stack should be sized to minimize compressive loads applied to the insulator.

Permanent Joints

Regardless of the configuration of demountable joints, special conductor sections are required for the transition between the flat plate sections and the wedge-shaped inboard sections on both the upper and lower arms. Numerous permanent joints will be required, which can be lap-riveted and brazed.

For the turn-to-turn crossover connections, consideration should be given to clamped lap-type joints. Tie rods would be used to provide the clamping force, and a nonconducting bushing would provide turn-to-turn electrical insulation. These joints can be permanent, since they would be located on either the outboard leg or the lower arm, and would not be separated upon coil disassembly.

Acknowledgment

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* On leave from MPB Technologies, Inc., Montreal, Quebec, Canada.

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