



# The UWMAK-II Study and Magnet Design

R.W. Boom, R.W. Conn, and W.C. Young

June 1976

UWFDM-166

Presented at 9th Symposium on Fusion Technology, Garmisch-Partenkirchen, Federal Republic of Germany, 14-18 June 1976.

***FUSION TECHNOLOGY INSTITUTE***

***UNIVERSITY OF WISCONSIN***

***MADISON WISCONSIN***

## **The UWMAK-II Study and Magnet Design**

R.W. Boom, R.W. Conn, and W.C. Young

Fusion Technology Institute  
University of Wisconsin  
1500 Engineering Drive  
Madison, WI 53706

<http://fti.neep.wisc.edu>

June 1976

UWFDM-166

Presented at 9th Symposium on Fusion Technology, Garmisch-Partenkirchen, Federal Republic of Germany, 14-18 June 1976.

R.W. Boom, R.W. Conn, and W.C. Young  
University of Wisconsin-Madison

### Abstract

The conceptual design of a Tokamak fusion power reactor, UWMAK-II [1] with a special emphasis on the superconducting magnet designs is described. The reactor is designed to generate 5000 MW(th) during the plasma burn and to deliver 1716 MW<sub>e</sub> continuously. The structural material is 316 stainless steel and the primary coolant is helium. UWMAK-II is a low aspect ratio, low magnetic field design and includes a double null, axisymmetric poloidal field divertor for impurity control. In addition, a carbon curtain, made of two-dimensional woven carbon fiber, is mounted on the first vacuum chamber wall to protect the plasma from high Z impurities and to protect the first wall from erosion by charged particle bombardment. The blanket, which is designed to minimize the inventory of both tritium and lithium, utilizes a solid breeding material (LiAlO<sub>2</sub>) with beryllium as a neutron multiplier. The breeding ratio is between 1.11 and 1.19 depending on the method of homogenization. The total energy per fusion is 21.56 MeV, which is fairly high.

The UWMAK-II toroidal field (TF) magnets are a set of 24 "extended D" superconducting coils of TiNb in Cu with stainless steel structure. The shield can be opened and a blanket module removed between coils without removing the TF coils. The vertical field (VF) coils have been deliberately placed inside the TF coils to minimize the energy stored in the poloidal magnetic field. The design philosophy for the VF coils is crucial when they are placed inside the TF set and this is discussed in detail. Toroidal coil design is discussed as based on a simple analytic solution for a constant tension "D" sector. Magnet protection and safety circuits are described.

### 1.0 UWMAK-II Design

This paper provides a general description of the UWMAK-II conceptual Tokamak reactor system [1] with special emphasis on the problems related to the superconducting magnets. In earlier work, [2-3] we presented a conceptual Tokamak fusion reactor design, UWMAK-I, based on the deuterium-tritium (D-T) cycle with liquid lithium acting as the coolant, moderator, and tritium breeding material. The structural material chosen was 316 stainless steel and the design was conservative in terms of materials choices and operating conditions. It generated several fundamental results, one of which is the need to periodically replace the reactor first walls because of radiation damage. Overall, there are many advantages to a system like UWMAK-I and these are documented in references 2-3. Nevertheless, two of the major areas of concern were the maximum temperature limit of 500°C in the stainless steel due to compatibility problems and the relatively large tritium inventory (8.7 kg) in the liquid lithium coolant. In addition, there were twelve toroidal field coils which produced a large (~20%) magnetic field ripple and the removal and disassembly of the first wall for repair or replacement involved moving very heavy modules (3500 metric tons).

UWMAK-II is a conceptual Tokamak fusion reactor designed to generate 5000 MW(th) during the plasma burn and to deliver 1716 MW<sub>e</sub> continuously. The structural material is 316 stainless steel and the primary coolant is helium. As in earlier work, most design choices were guided by the philosophy that decisions should be based, wherever possible, on present day technological capabilities. The major characteristics of the design are summarized in Table 1 and a general view of the main reactor is shown in Fig. 1. UWMAK-II is a low

aspect ratio, low magnetic field design and includes a double null, axisymmetric poloidal field divertor for impurity control. In addition, a carbon curtain, made of two dimensional woven carbon fiber, is mounted on the first vacuum chamber wall to protect the plasma from high Z impurities and to protect the first wall from erosion by charged particle bombardment.

The blanket is designed to minimize the inventory of both tritium and lithium while achieving a breeding ratio greater than one. This has led to a blanket design based on the use of a solid breeding material ( $\text{LiAlO}_2$ ) with beryllium as a neutron multiplier. The lithium is enriched to 90%  $^6\text{Li}$  and the blanket coolant is helium at a maximum pressure of 750 psia ( $5.2 \times 10^6 \text{ N/m}^2$ ). The breeding ratio is between 1.11 and 1.19 depending on the method of homogenization. One-dimensional discrete ordinates neutron and gamma transport calculations were used. Detailed Monte Carlo calculations which take into account the more complicated geometry, give a breeding ratio of 1.06. The total energy per fusion is 21.56 MeV, which is fairly high.

In addition, the use of solid breeding material may allow the tritium inventory in the blanket to be very low, approximately 130g if 50% dense (and approximately 730g if 90% dense  $\text{LiAlO}_2$ ) is used and if sintering of the ceramic can be prevented. The radiation damage problems are similar to those in the UWMAK-I study [2-4] and the results for UWMAK-II again indicate that periodic replacement of the first 20 cm of the blanket modules approximately every two years will be required.

The toroidal field (TF) magnets are a set of 24 "extended D" superconducting coils of TiNb in Cu with stainless steel structure. There are  $10^7$  ampere turns per coil of 10,000 A conductor dispersed at an average current density of  $814 \text{ A/cm}^2$ . The field at the plasma center is 3.67 tesla and the maximum field on the TiNb superconductor is 8.30 tesla. The extension of the "D" shape beyond the outside edge of the shield allows the shield to be opened as indicated in Fig. 1 and a blanket module removed between coils without removing the TF coils. The vertical field (VF) coils have been deliberately placed inside the TF coils to minimize the energy stored in the poloidal magnetic field. This value is now  $10.4 \times 10^9$  joules compared to  $53.4 \times 10^9$  joules in UWMAK-I, where the VF windings are placed outside the TF coils. The design philosophy for the coils is crucial when they are placed inside the TF set and this is discussed below. A superconducting air-core transformer is used and the transformer (OH) windings are outside the main TF coils.

The basic operating cycle for a Tokamak reactor is important to the design of the coils. For UWMAK-II, the assumption is that a combination of a divertor and a low Z liner will provide sufficient impurity control to allow long plasma burns. Nevertheless, the burn time is infinite (5400 sec) and the outline of the basic cycle is given in Fig. 2. During the initial 10 seconds, the plasma current rises linearly with time to its final value of 14.9 MA. This means that the average plasma current density is  $19 \text{ A/cm}^2$  and the plasma radius increases from some small value ( $\approx 50 \text{ cm}$ ) to 5 m as  $\sqrt{t}$  over this time period. During this initial 10 seconds, the currents in the vertical field (VF) or divertor coils also increase to their final values. The ohmic heating (OH) windings change current in such a way as to provide the requisite time changing flux to drive the plasma current. The placement of the OH and VF coils in an R-Z plane and the currents in these coils are listed in Table 2. Over the next 5420 seconds, the currents in the OH windings continue to change, albeit slowly, in order to maintain the plasma current against the resistive drop due to the

finite plasma conductivity at the operating conditions. Thus, the values of the current in the OH windings at the end of the plasma burn are also listed in Table 2.

Some of the main technical aspects of the UWMAK-II study are described in this paper. Clearly, however, it is not possible to include all the detail associated with producing the design summarized here. For greater detail, the reader is referred to the main report on the UWMAK-II reactor [1] written by the fusion study group at the University of Wisconsin and to a preliminary description of that work [5].

| TABLE 1                           |                           | TABLE 2             |      |                                                            |                                                             |                                                            |       |
|-----------------------------------|---------------------------|---------------------|------|------------------------------------------------------------|-------------------------------------------------------------|------------------------------------------------------------|-------|
| Major Characteristics of UWMAK-II |                           | Divertor Current    |      |                                                            |                                                             |                                                            |       |
|                                   |                           | R(m)                | Z(m) | I(10 <sup>6</sup> amp)                                     |                                                             |                                                            |       |
| Structural Material               | 316 SS                    | D1                  | 8.2  | 6.5                                                        | -3.70                                                       |                                                            |       |
| Coolant                           | He                        | D2                  | 8.8  | 10.0                                                       | +4.89                                                       |                                                            |       |
| Breeding Material                 | LiAlO <sub>2</sub>        | D3                  | 11.5 | 12.3                                                       | -1.46                                                       |                                                            |       |
| Neutron Multiplier                | Be                        | D4                  | 11.5 | 9.5                                                        | +3.40                                                       |                                                            |       |
| Fuel Cycle                        | (D-T), Li                 | D5                  | 14.6 | 8.0                                                        | -1.57                                                       |                                                            |       |
| Number of Toroidal Field Magnets  | 24                        | D6                  | 19.0 | 5.0                                                        | -6.82                                                       |                                                            |       |
| Magnet Superconductor             | TiNb                      |                     |      |                                                            |                                                             |                                                            |       |
| Impurity Control Methods          | Divertor +<br>Low Z Liner |                     |      |                                                            |                                                             |                                                            |       |
| Neutron Wall Loading              | 1.16 MW/m <sup>2</sup>    | Transformer Current |      |                                                            |                                                             |                                                            |       |
| Plasma Dimensions                 |                           | R(m)                | Z(m) | I <sub>0</sub> (10 <sup>6</sup> amp)<br>Initial<br>Current | I <sub>s</sub> (10 <sup>6</sup> amp)<br>(End of<br>Startup) | I <sub>f</sub> (10 <sup>6</sup> amp)<br>(Final<br>Current) |       |
| Major Radius                      | 13 m                      | T1                  | 3.61 | 1.00                                                       | 2.74                                                        | 1.66                                                       | -4.13 |
| Plasma Radius                     | 5 m                       | T2                  | 3.72 | 3.00                                                       | 2.64                                                        | 1.60                                                       | -3.99 |
| Aspect Ratio                      | 2.6                       | T3                  | 3.94 | 4.99                                                       | 2.39                                                        | 1.45                                                       | -3.61 |
| First Wall Radius                 | 5.5m                      | T4                  | 4.25 | 6.96                                                       | 2.26                                                        | 1.37                                                       | -3.41 |
| Burn Time                         | 5400 sec.                 | T5                  | 4.66 | 8.92                                                       | 1.89                                                        | 1.14                                                       | -2.85 |
| Rejuvenation Time                 | 330 sec.                  | T6                  | 5.43 | 13.50                                                      | 2.22                                                        | 1.15                                                       | -3.36 |
| Duty Factor                       | 0.942                     | T7                  | 6.50 | 15.05                                                      | 2.21                                                        | 1.34                                                       | -3.34 |
| Power Cycle                       | He-Na-Steam               | T8                  | 7.25 | 17.00                                                      | 1.66                                                        | 1.00                                                       | -2.51 |
| Estimated Plant Factor            | 0.80                      | T9                  | 8.22 | 19.3                                                       | 1.46                                                        | 0.88                                                       | -2.20 |
| Power Output During Plasma Burn   | 5000 MW(th)               |                     |      |                                                            |                                                             |                                                            |       |
| Average Electrical Power          | 1716 MW <sub>e</sub>      |                     |      |                                                            |                                                             |                                                            |       |

## 2.0 Superconductive Magnet Design

All of the UWMAK series of Tokamak reactor coil designs are cryogenically stable coils cooled in liquid helium to 4.2 K. The major design emphasis at Wisconsin has been on the toroidal field (TF) coils which are of the constant tension "D" design. The poloidal field coils have received less emphasis since they present less of a problem for full size reactors. We have assumed for the relatively long 10 sec. rise times that dc cryogenically stable conductors would be satisfactory poloidal coils. The design problem is simply to assure that temperature rises above T<sub>c</sub> will not occur during the one short pulse per 90 minutes for UWMAK-II. There is admittedly some uncertainty concerning the rise time as needed by the plasma as well as the lower limit on rise time which can be tolerated by a typical poloidal coil. The conductor temperature rise during pulsing will be limited by the use of internal high resistance barriers between TiNb filaments to limit circulating currents.

The vertical field coils which are wound in place inside the toroidal field magnets must be very conservatively designed in order to avoid replacement. Such extra reliability is obtained: (1) by winding 20% extra turns so that parts of a coil may be shorted out for continued use without replacement and (2) by using enough extra TiNb so that the full super-current can be carried at 5.2 K even though 4.2 K pool cooling is used. The extra amount of TiNb requires a large ΔT disturbance of 1 K before current starts to leave the filaments and, on recovery from a local normal transition, provides an extra driving potential to cause

more rapid return of the transport current to the superconductor filaments. In general, the mechanical strain of the poloidal coils is kept well below 0.1% by using enough interleaved steel banding stressed less than 40,000 psi ( $2.76 \times 10^8 \text{ N/m}^2$ ).

The TF coils are of the Wisconsin [6] embedded conductor design in which each turn is epoxied into a groove in a thin disk structure, see Fig. 3. A magnet sector is formed by bolting together 19 such disks with micarta spacers for cooling so that each sector is a solid structure and not a loose "jelly-roll" which would need external structure. To provide redundancy and avoid replacement, 19 disks per sector are used while a conservative design, similar to the above poloidal coil choices, would provide the needed field with 15 disks. There are two degrees of redundancy: the mechanical load is carried by 19 disks although designed for 17 and the field is produced with 19 disks at a reduced current, 26.7% less than the stability limit with 15 disks. Convenient terminations at the top of each sector provide for the possibility for shorting out disks without warming up a sector.

The overall shape of each "D" magnet sector is chosen so that only constant tension forces are present. Moses and Young [7] have derived an analytical expression for the local radius of curvature  $\rho$  for a constant tension toroidal magnet of N discrete sectors

$$\frac{\rho}{R} = \left[ \frac{\rho_2}{R_2} \left( 1 + \frac{1}{N} \right) - \frac{1}{N} \ln \frac{R}{R_2} \right] / \left( 1 + \frac{1}{N} \cos \phi \right), \quad (1)$$

where  $\rho$ ,  $R$ ,  $\rho_2$ ,  $R_2$  and  $\phi$  are sketched in Fig. 4. Expressions for  $H_{R1}$ ,  $H_{\max}$  and  $R_{H\max}$  can be easily obtained [8]. It is a simple task to obtain the shape of a "D" coil with aid of Eq. (1); it has been shown that the shape agrees to within less than 1% with more elaborate finite element stress analyses. Because either procedure involves assumptions it is possible that Eq. (1) is more accurate than more elaborate methods.

There are bending moments in the "D" structure in the neighborhood of the connection between  $H_{R1}$  and  $R_{H\max}$ , Fig. 4, except for one particular  $H_{\max}$  which defines a unique shape where there is a perfect tangent at  $H_{R1}$ . The non-constant tension region requires extra structure.

The problem of magnet safety and protection for UWMAK TF coils has not been emphasized in previous publications. We have discussed a structural scheme to handle the toriodal collapsing forces if a sector coil loses current due to losing vacuum, losing helium, shorting to ground, developing a local hot spot or developing an open circuit. The lateral support around the perimeter of each TF coil is needed to: (1) adjust the coils to their equilibrium position and to provide the stiffness needed for magnetoelastic stability (2) to hold the coils in place during poloidal field pulses and (3) provide lateral support for the coils during catastrophic failure of one or more TF coils. The last situation needs the most support and the proposed means of support is sketched in Fig. 5. The impulsive forces are such that a toroid tries to straighten out into a long straight solenoid. In Fig. 5 sliding joints are shown in the structure vacuum wall perimeter which relieve the wall tension near the failed coil or coils so that the main load is carried by compression around the toroid. If the intersector structure were to carry these loads in tension much more structure would be required. Typical forces are given in references [1,8] for the worst case of two adjacent TF sector failures occurring simultaneously.

For safety and protection each TF coil will be in a separate dewar so that in time of trouble only the bad coil needs to be discharged. Normally all TF coils would be operated

in series with a three-phase Graetz bridge, see Fig. 6, with all switches open. If a fault develops in coil No. 1 then all switches would be closed except for switch No. 1 and the series power supply would be switched from +10 v to -10 KV typically. The normal low voltage overcomes lead losses while the emergency high negative voltage would discharge coil No. 1. Most of the energy in coil No. 1 would be mutually coupled out to adjacent persistent coils 23, 24, 2 and 3. The uncoupled energy, approximately 25% of the energy in coil 1, would be discharged by the Graetz bridge back into the three-phase utility power grid. The characteristics of a Graetz bridge are such that the voltage will rise during the decay. Therefore this discharge is far superior to the L/R discharge characteristic of a dump resistor. The important feature of this method is that only one percent of the total stored energy needs to be removed and that it can be removed in less than a minute. The advantages are that temperature rises during discharge can be limited to  $T_{\max} = 54 \text{ K}$ , ref. [8], provided early detection of a fault is made. In contrast, overheating would result if the total toroidal magnet were discharged at 10 KV or for the 100 minutes required. The disadvantage is that the total surface of each "D" coil former disk must be insulated to withstand 10 KV and care must be taken to avoid voltage breakdown in helium vapor.

A more complete account of the UWMAK magnet designs is given in the three design study reports [1,2,8] and in the other publications mentioned. UWMAK-III is more advanced and involves the use of high purity aluminum matrix conductors and 2219 aluminum alloy TF coil formers. The justification for the use of aluminum is currently undergoing laboratory experimental verification. Another UWMAK design topic not covered here is the use of superconductive energy storage magnets to supply pulsed energy for the poloidal coils [9].

#### Acknowledgement

The research on UWMAK-II has been supported by grants from the United States Energy Research and Development Administration and the Wisconsin Electric Utilities Research Foundation.

#### References

- [1] CONN, R.W. ET AL., "A Conceptual Tokamak Power Reactor Design-UWMAK-II," Nuclear Engineering Department Report, UWFD-112 (University of Wisconsin-Madison, Oct. 1975).
- [2] KULCINSKI, G.L. ET AL., "UWMAK-I, A Wisconsin Toroidal Fusion Reactor Design," Nuclear Engineering Department Report UWFD-68, Vol. I (Nov. 1973) and Vol. II (May 1975) (The University of Wisconsin-Madison).
- [3] KULCINSKI, G.L., CONN, R.W., "Conceptual Design of a 5000 MW D-T Tokamak Fusion Reactor," in Fusion Reactor Design Problems (IAEA, Vienna, 1974; Special Nuclear Fusion Supplement) p. 51.
- [4] CONN, R.W., KULCINSKI, G.L., "Technological Implications for Tokamak Fusion Reactors of the UWMAK-II Conceptual Design," Proc. First National Topical Meeting on the Technology of Controlled Nuclear Fusion (CONF-740402-P1, U.S.A.E.C., 1974) p. 56-71.
- [5] CONN, R.W. ET AL., "Major Design Features of the Conceptual DT Tokamak Power Reactor, UWMAK-II," in Plasma Physics & Controlled Nuclear Fusion Research 1974 (IAEA, Vienna, 1975) Vol. III, p. 497-509.
- [6] YOUNG, W.C., BOOM, R.W., "Constant-Tension Magnet Windings for Tokamak Reactors," Proc. Fourth International Conf. on Magnet Technology, NTIS, Springfield, VA (1972), p. 244.
- [7] MOSES, R.W., YOUNG, W.C., "Analytic Expressions for Magnetic Forces on Sector Toroidal Coils," Proc. Sixth Symposium on Engineering Problems of Fusion Research, 1975.
- [8] BOOM, R.W., MOSES, R.W., YOUNG, W.C., "Magnet Design of Toroidal Field Coils for the UWMAK-Tokamak Systems," to be published, Nuclear Engineering and Design, North Holland Publishing Co., Amsterdam, 1976 and Nuclear Engineering Department Report UWFD-158.
- [9] PETERSON, H.A., MOHAN, N., YOUNG, W.C., BOOM, R.W., "Superconductive Inductor-Converter Units for Pulsed Power Loads," Int. Conf. Energy Storage, Compression, and Switching, Asti-Torino, Italy (1974), Plenum Press (1976), p. 309-319.

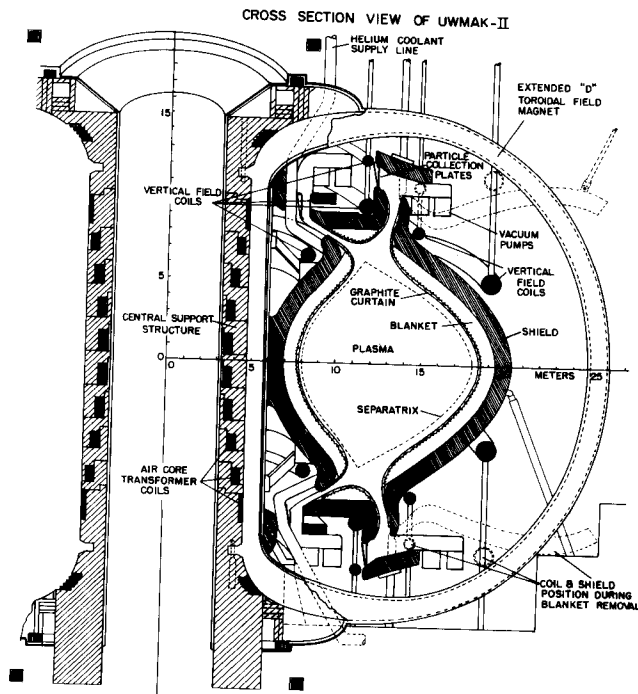


Figure 1  
Side view showing TF, VF and transformer coils.

One operating cycle

| Phase 1                   |                                         | Phase 2               | Phase 3                          |                       |                                 |
|---------------------------|-----------------------------------------|-----------------------|----------------------------------|-----------------------|---------------------------------|
| 10 Sec. Current Rise Time | 20 Sec. Heating to Operating Conditions | 90 Minute Burn Period | 100 Sec. Plasma Current Decrease | 50 Sec. Chamber Purge | 150 Sec. Transformer Coil Reset |

TIME

Figure 2  
UWMAK-II cycle.



DETAIL OF UWMAK-II T.F. MAGNET CROSS SECTION

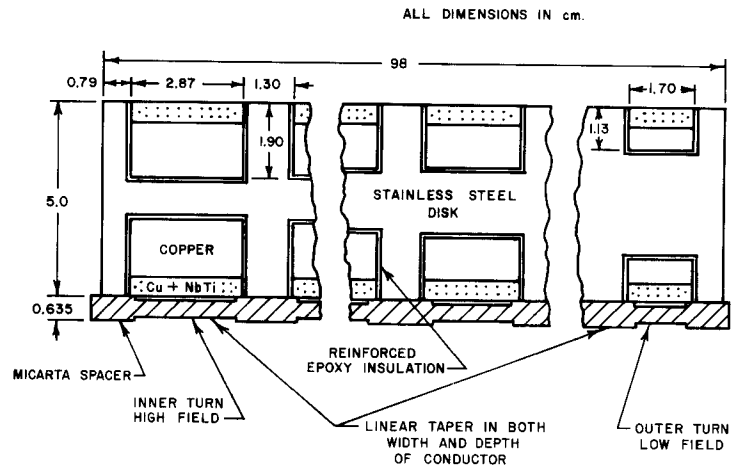


Figure 3

Cross section of the conductor and structural disk.

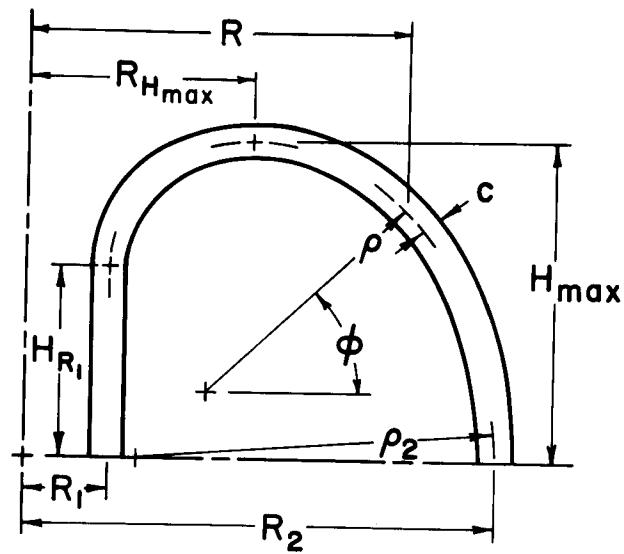


Figure 4

Side view of a constant tension coil.

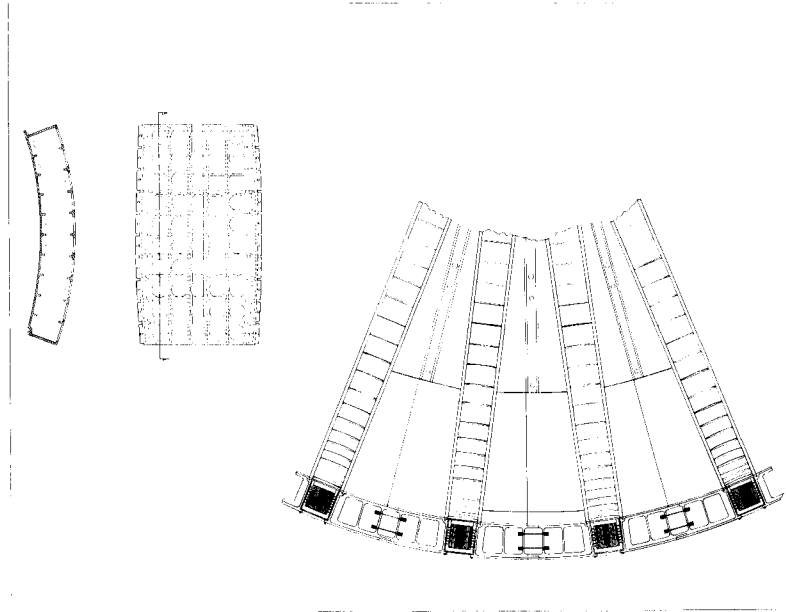


Figure 5  
Secondary vacuum shell and lateral support.

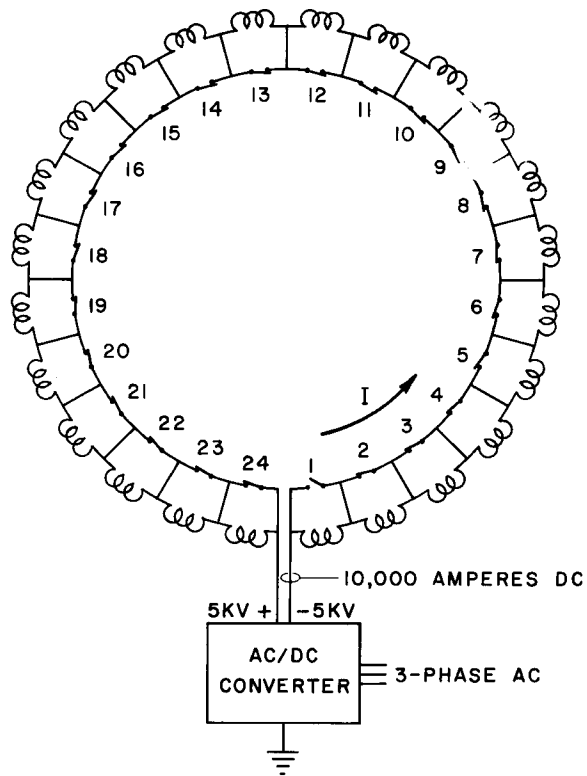


Figure 6  
TF coils shown shorted for rapid discharge of faulted coil.