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Magnet and Dewar for UWMAK-II, A Wisconsin  
Tokamak Fusion Reactor Design**

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### Introduction

Optimization studies seem to indicate that a typical Tokamak power reactor will have a thermal output of 5000 MW, a major radius of 13 m and a minor radius of 5 m. The "D" shaped superconductive toroidal field magnets for such a reactor will probably have a bore of 25 m. Radiation damage to the plasma containment vessel will require its periodic replacement by remote control. This implies that the magnets should be easily removed from the reactor, or alternatively, be large enough to allow section of the containment vessel to be removed from within their enclosure.

Conventional jelly roll superconductive coils work well in simple solenoids but would be difficult to construct and support in large constant-tension "D" shaped magnets. The Wisconsin group has proposed a radically new design for such magnets [1], namely the imbedded conductor concept. Lateral stability of the toroidal field (TF) coils and tritium containment are problems which should be considered in the design of the reactor.

This paper describes the TF magnet and its cryogenic system in UWMAK-II [2] (Fig. 1), a University of Wisconsin conceptual design of a Tokamak power reactor. Solutions to lateral stability of the TF coils and tritium confinement are offered.

## Toroidal Field Magnets

The toroidal field in UWMAK-II is provided by 24 identical modified constant-tension "D" shaped magnets which produce 3.67 T at a radius of 13 m, the plasma center.

The design philosophy adopted is that of maximum reliability, employing present day materials and technology with minimal extrapolation. Fully cryogenically stabilized conductors cooled with liquid helium pool boiling at 4.2 K are used.

These TF coils have a horizontal bore of 19 m and a vertical bore of 28 m. The cross section of a magnet and dewar is 152 cm wide and 135 cm deep as shown in Fig. 3. To provide clearance between the back legs of the TF coils so that blanket modules could be removed, the back legs were extended further than is normally needed. A constant-tension design throughout would have produced a very tall and costly magnet. We, therefore, deviated from the constant-tension design to produce a modified "D" which is not taller than required to accommodate internal system components. Figure 2 shows a cross section of UWMAK-II. The constant-tension part of the TF coil includes the back leg and extends to a major radius of 15 m. From there on, the magnet depth is increased to resist the bending and hoop stresses in the non-constant-tension portion. Additional bracing from the central support structure is also provided for the same reason.

Each TF coil is composed of 19 "D" shaped stainless steel discs 5 cm thick and 98 cm deep. These discs will have grooves forged in both surfaces in which the conductors will be firmly imbedded. The conductor is an OFHC copper backing

strip soldered to a composite strip of OFHC copper matrix containing twisted TiNb filaments. It is insulated with fiberglass epoxy tape, coated with liquid epoxy, and rolled into the grooves. After curing, the insulation facing out of the grooves is machined off exposing the copper surface for cooling.

Figure 4 shows how the discs are assembled. Grooved micarta spacers are placed between discs to allow free movement of the coolant. The whole assembly is then bolted with prestressed aluminum alloy bolts which provide the shear restraint needed to handle the magnets during erection and maintain the assembly tight after cooling in spite of the greater thermal contraction of the micarta.

Electrical connections are made near the top of the TF coils. The conductors spiral towards the inner radius along one surface of a disc, then emerge to the other side and spiral out.

The coil is normally operated with 19 discs at a current which is 26% less than the stability limiting value and carry an electro-mechanical load designed for 17 discs. Therefore, as many as four discs can be removed from the circuit if malfunctions occur without exceeding the allowed current density and stress in the remaining discs. This concept of multiple redundancy is intended to increase reliability and longevity of the coils.

The TF coils are supported entirely on a massive stainless steel cylinder called the central support structure. This central support structure is built up of interlocking cylinders and is designed to contain the ohmic heating coils in a liquid helium bath in addition to restraining the TF coils with shear pins against a large outward radial force. This force results from the fact that the design is not

a constant-tension design throughout and a large horizontal shear force exists at the top and bottom of the inner vertical leg of the coil. The inner vertical leg of each coil exerts a radially inward force on the central support structure and the resultant force from an entire coil is inward.

### Toroidal Coil Dewar and Cryogenic System

Each TF coil is surrounded by its own liquid helium and vacuum dewars as shown in Figs. 3 and 4.

Certain features of UWMAK-II have necessitated a radically new approach in the design of the vacuum dewar for the TF coils. Specifically, the particle collection devices at the top and bottom of the plasma chamber occupy a sizeable portion of the available space, leaving no room for inner blanket and shield supports. This raised the possibility of using a part of the vacuum dewar as a structural member for supporting these components.

In Figs. 2 and 6 it can be seen that the inner legs of the TF coils are surrounded by a common heavy cylindrical dewar subtending the magnets in the toroidal direction. This cylinder is the basis for the support of the inner blanket and shield modules. It is supported on the floor on pedestals protruding between the TF coils as shown in Fig. 2.

Since the TF coils and the central support structure are both at 4.2 K, there is no need to insulate between them at the points of contact. The inner legs of the TF coils share the same vacuum as the central support structure, but this vacuum space does not communicate with the vacuum in the individual dewars branching off

at the top and bottom to cover the curved portion of the coil as shown in Figs. 4 and 6. Thus, if the vacuum deteriorates in one coil, it does not affect the others. Fifteen centimeters of superinsulation will be used wherever the inner dewar is in visual contact with the outer dewar. The total surface area thus covered is  $9120 \text{ m}^2$ .

Figure 5 is a simplified diagram of the cryogenic system for the TF coil. There are three important points to be made here:

1. There should be some liquid helium in reserve above each TF coil to prevent liquid depletion due to rapid boil-off.
2. Provision for rapid lowering of the liquid level by withdrawing it into a special dewar should be made, as a measure against high localized thermal stresses developing as a result of a section of the coil going normal. It is advantageous to drive the whole coil normal while reducing the current.
3. There should be adequate liquid helium in the main storage dewar to provide continuous cooling for some period of time in the event of total liquefier failure.

It is envisaged that a conventional closed loop cooling cycle will be used. The complete system will require ten 3 kW liquefiers with seven in operation and three in reserve. A 300,000 liter dewar will supply 18 hours of emergency cooling. Control of fill and withdrawal will be by remotely operated three way valves. A large rupture disc leading to a common vent manifold will be used for emergency venting.



## Lateral Support Structure and Secondary Vacuum

There are two main reasons why lateral supports are needed between TF coils:

1. Time varying fields from ohmic heating and vertical field coils apply out of plane bending loads on the TF coils.
2. Loss of current in one or more TF coils produces large lateral forces tending to move all the magnets away from the failing magnet.

A significant change was possible in the design of the lateral supports when it was decided to provide a secondary vacuum wall (Fig. 6) within the TF magnet enclosure. In UWMAK-II the lateral support structure is also the secondary vacuum barrier for the plasma confinement region. This reduces the leakage to the primary vacuum of the plasma region, alleviates the danger of a lithium fire and prevents tritium leakage into the reactor building.

A fairly detailed study has been performed to determine the magnitude of the lateral forces due to the failure of one or two adjacent TF coils [3]. Since these forces vary inversely as the distance between magnets and this distance in turn varies almost directly as the distance from the toroidal axis, the wall thickness and reinforcing rib area of the lateral support shell shown in Fig. 6 vary inversely as the radius. This keeps the compressive stress in the shell structure as nearly constant as possible and, in turn, keeps the unit circumferential strain constant too. Under these conditions, each magnet remains essentially plane as it moves laterally.

The transfer of the forces from the coils to the outer dewar wall is by fiberglass epoxy struts (Fig. 3). About 10% of these struts are equipped with special conical springs in permanent contact with the dewar wall. They provide for magnetoelastic stability and lateral support against the forces from the time varying fields. The rest are offset by 0.5 cm and come in contact with the wall only in case of a magnet failure.

The lateral support shells were designed to carry the load in compression only and are equipped with slip joints which separate under tension without breaking the seal. The design has to take into account the decoupling of the motion of the lateral support shell from the secondary vacuum penetrations needed for supporting various system components.

### Heat Losses

The sources and magnitudes of heat losses in the entire TF coil system are itemized in this section.

#### Thermal Radiation

The inside surface of the TF coil outer dewar will face the shield temperature of 400 K [2] while the outside surface will face room temperature. The average radiation loss through the superinsulation was taken as  $7.5 \mu\text{W}/\text{cm}^2$ . For an area of  $11,000 \text{ m}^2$ , the radiation loss is 824 W.

#### Conductive Losses from Struts

The total cross-sectional area of the 15 cm long fiberglass epoxy struts touching the dewar walls is  $26,400 \text{ cm}^2$ . Assuming a conductivity of  $1.7 \text{ W}/\text{cm}$  between 4.2 K and 300 K, the conductive loss is 2.99 kW.

### Lead Losses

A properly designed vapor cooled current lead will have a loss of 5 mW/A or less. The 24 pairs of leads, each conducting 9065 A will have a total loss of 2.17 kW.

### Nuclear Heating

The 3300 m<sup>2</sup> of first wall area receives a neutron loading of 1.25 MW/m<sup>2</sup>. The energy attenuation in the blanket and shield is  $6 \times 10^{-8}$  [2]. About half of the energy leaked is intercepted by the magnets, making the nuclear heating equal to 124 W.

### AC Losses

The time varying fields of the plasma and poloidal field coils induce AC losses in the TF coils. They are comprised of eddy current losses in the copper, super-conductive filament coupling and hysteresis losses. The pulsed field has a component of 0.15 T parallel to the conductor and 0.4 T perpendicular to it in the straight leg. Total AC losses per cycle are estimated to be 0.80 kWh. The average power losses over a 95 minute burn cycle is 502 W.

### Miscellaneous Losses

An additional 1.5 kW is estimated to cover other losses such as conduction through the base of the central support structure, transfer line and storage losses and conductor joint resistive losses.

These losses are summarized in Table 1. The total heat losses are equal to 8.1 kW deposited at 4.2 K. Room temperature power requirement, assuming a performance factor of 400, is equal to 3.24 MW.

### Summary

In summary it must be said that alternate methods for building large superconductive magnets for fusion reactors such as the proposed imbedded conductor concept should be thoroughly investigated.

The lateral support structure for TF coils should be an important part of the overall design of a fusion reactor. It appears that a secondary vacuum barrier can be incorporated into the lateral support system.

Heat losses in a large superconductive magnet can be minimized with proper design.

### Acknowledgment

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2. U. W. Fusion Feasibility Study Group, UWMAK-II A Conceptual Tokamak Reactor Design.
3. W.C. Young and I. N. Sviatoslavsky, Construction Techniques and Stress Analysis of Toroidal Field Magnets for Tokamak Fusion Reactors, presented at the Fifth Int. Conf. on Magnet Tech., Rome, Italy, April 1975.

Table 1  
Summary of Heat Losses

<u>Source</u>	<u>kW</u>
Thermal Radiation	0.824
Conductive Losses from Struts	2.990
Lead Losses	2.170
Nuclear Heating	0.124
AC Losses	0.502
Miscellaneous	<u>1.500</u>
Total	8.1 kW

Table 2

Specifications of UWMAK-II Toroidal Field Magnets

Field ripple along far edge of plasma	2%
Stored energy	62 MWh
Design stress, Stainless Steel at 4.2 K	$4.14 \times 10^8 \text{ N/m}^2$ (60,000 psi)
Design strain in copper	$\leq .002$
Number of magnets	24
Number of discs per magnet	19
Number of conductors turns/disc	58
Conductor current	9065 A with 19 discs 10,131 A with 17 discs 11,482 A with 15 discs
Number of TiNb filaments in conductor	500
Number of aluminum alloy bolts/magnet	2630
Mass of one toroidal magnet	710 MT (metric ton)
Mass of TiNb	164 MT
Mass of copper	8000 MT
Mass of stainless steel in discs	7230 MT
Mass of stainless steel in dewars	1300 MT
Mass of reinforced epoxy in discs	395 MT
Mass of micarta spacers	255 MT
Mass of reinforced epoxy struts	16 MT
Mass of aluminum alloy bolts	95 MT
Cryogenic superinsulation	$850 \times 10^3 \text{ m}^2$
Total heat loss at 4.2 K	8.1 kW
Total heat load at 300 K	3.24 MW

## Figure Captions

- Figure 1 - Artist's conception of UWMAK-II
- Figure 2 - Cross section of UWMAK-II
- Figure 3 - Cross section of T F coil
- Figure 4 - Isometric view of T F coil
- Figure 5 - Schematic of cryogenic system for T F coil
- Figure 6 - T F coil lateral support structure and secondary vacuum

# UWMAK-II Tokamak Fusion Reactor

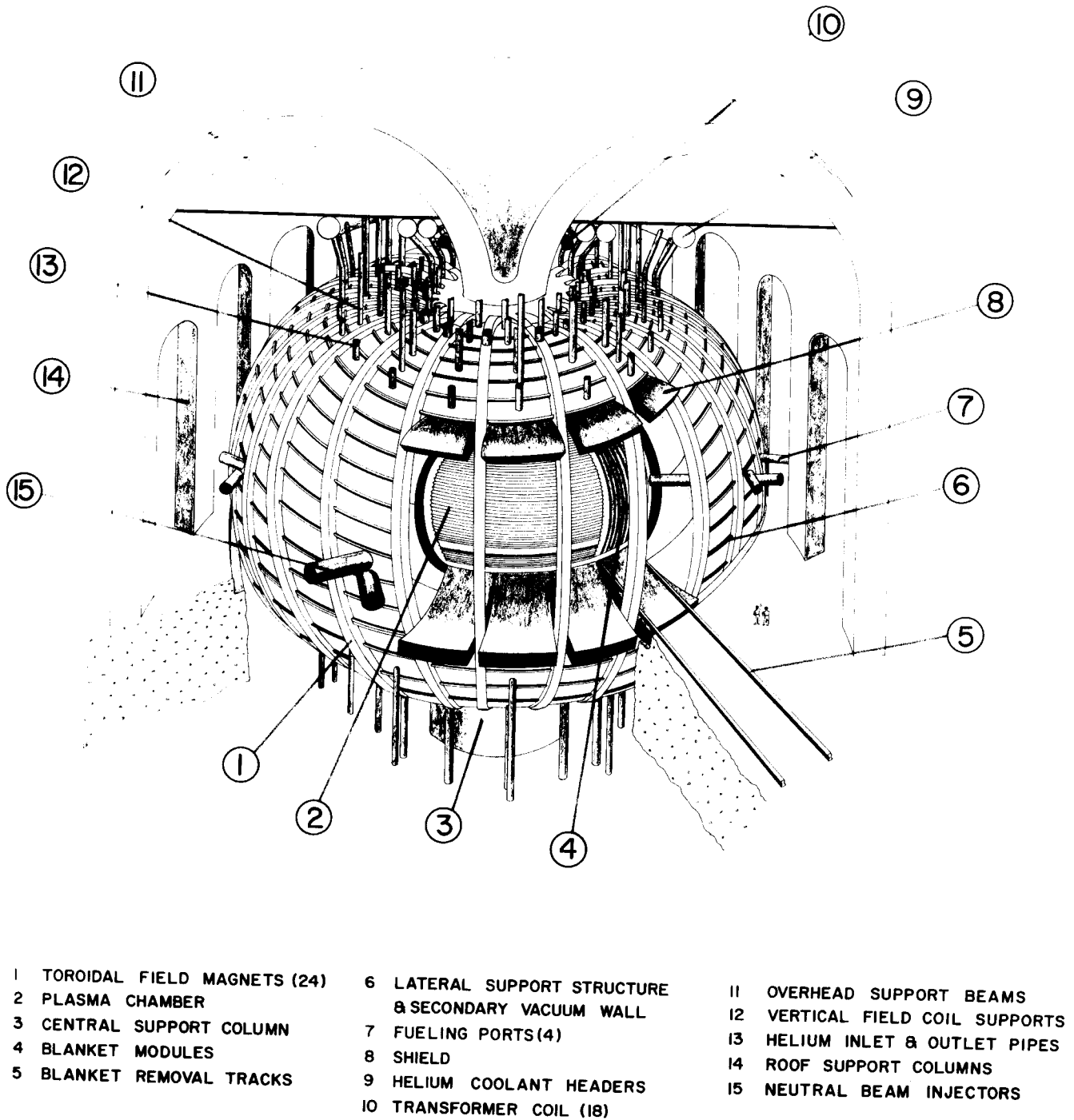


Figure 1



# CROSS SECTION VIEW OF UWMAK-II

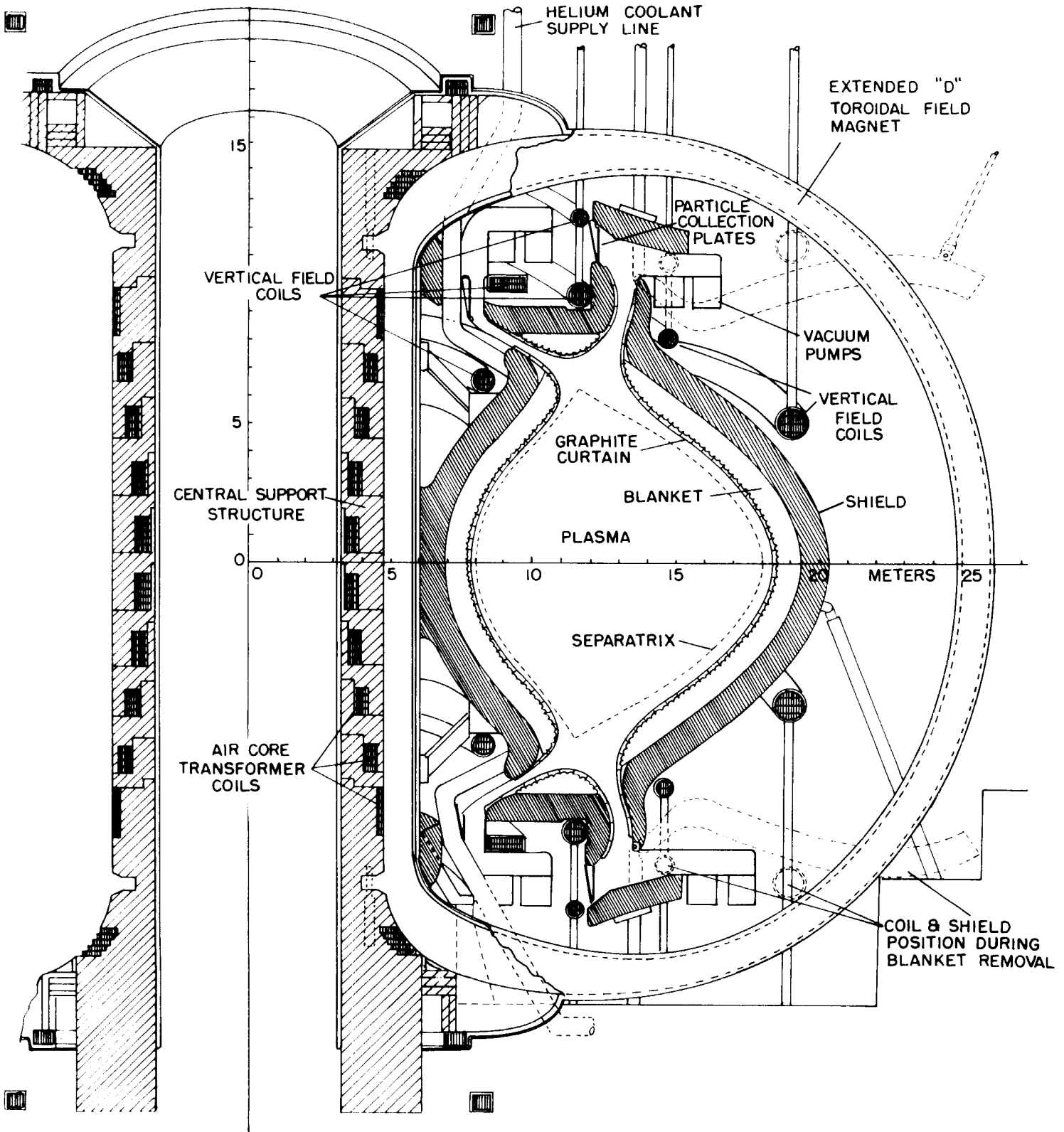
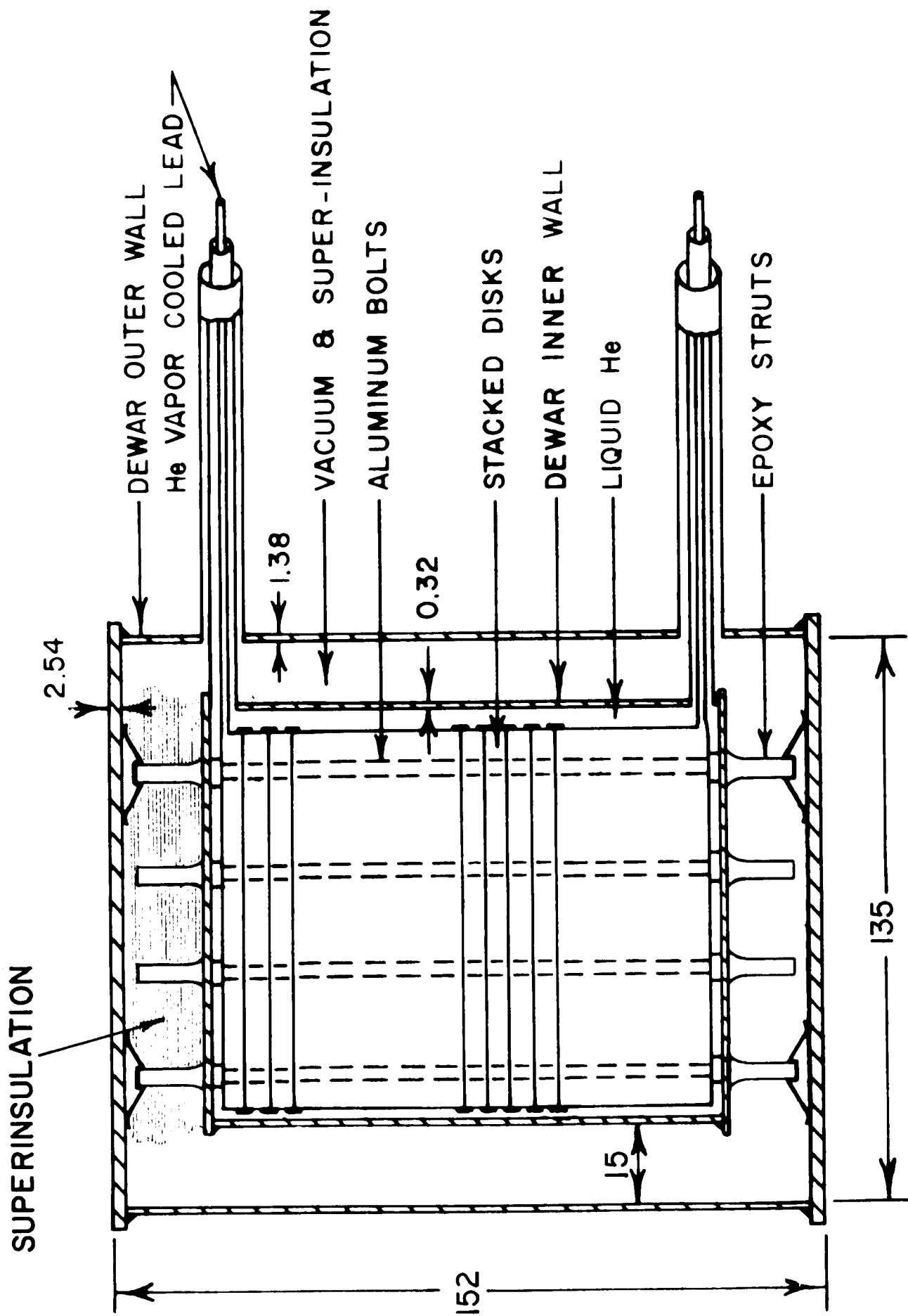


Figure 2

Figure 2



ALL DIMENSIONS IN cm.

Figure 3. Cross section of TF coil

# UWMAK-II TOROIDAL FIELD MAGNET

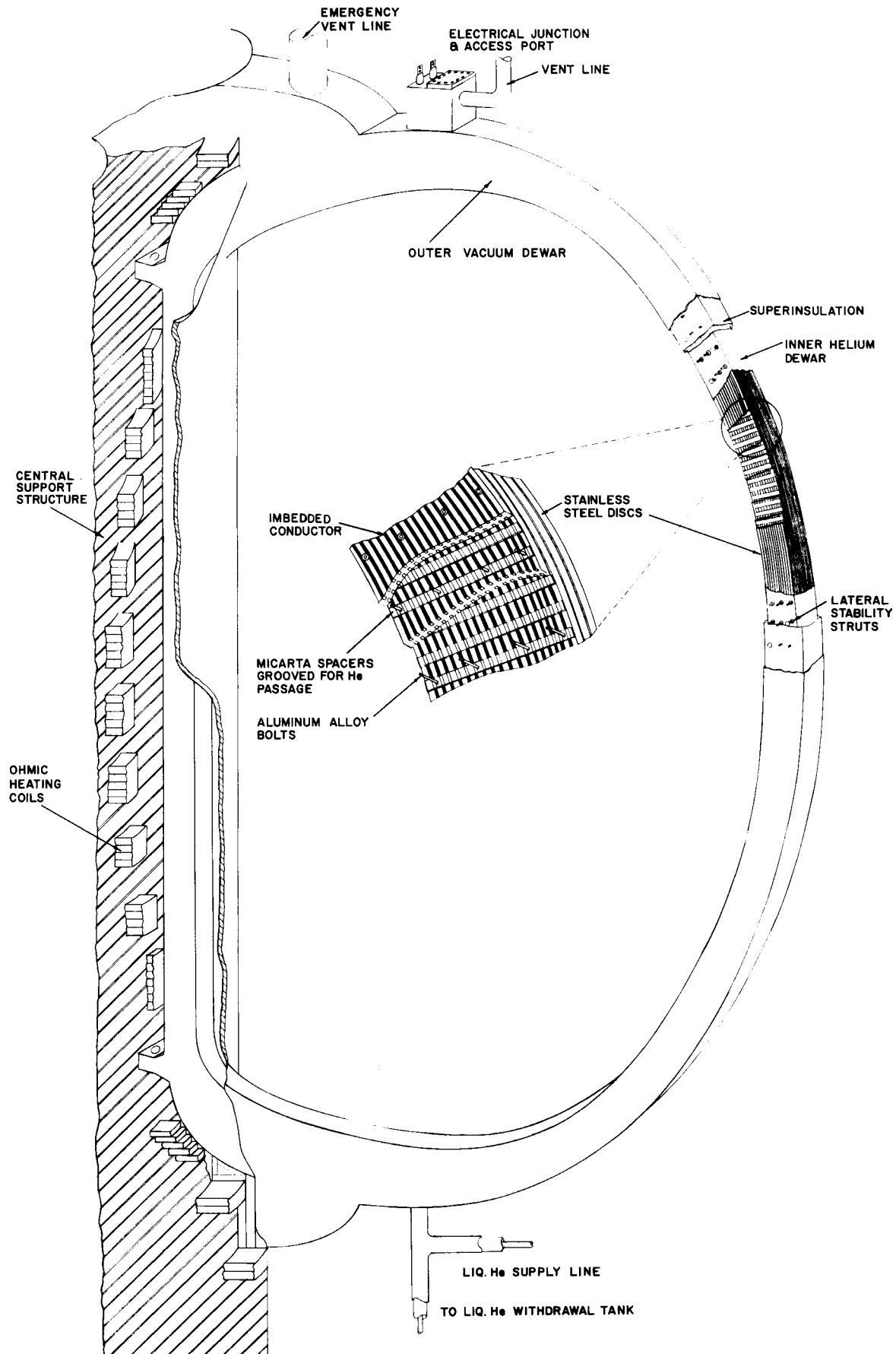


Figure 4. Isometric view of TF coil.

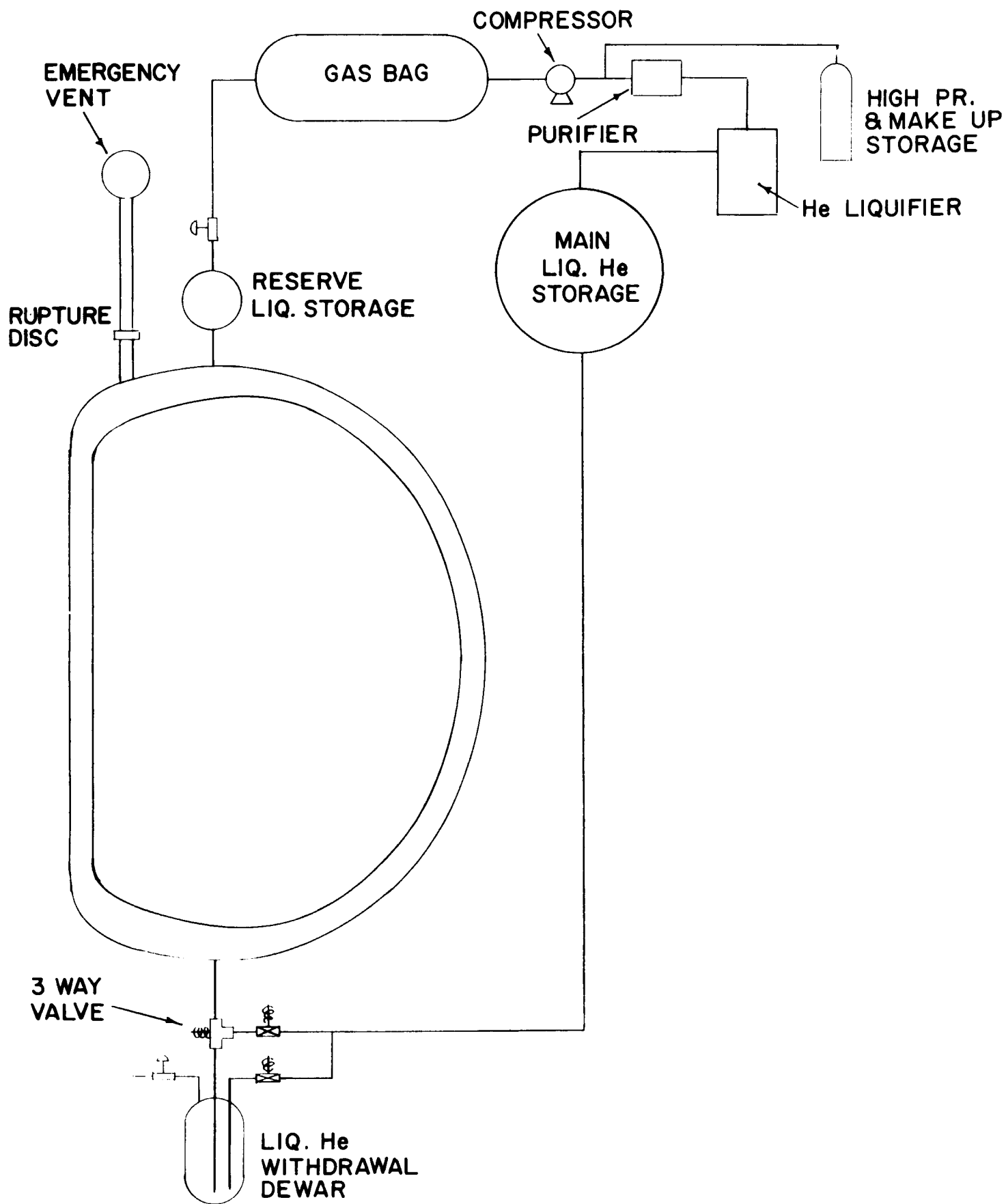


Figure 5. Schematic of cryogenic system for TF coil.

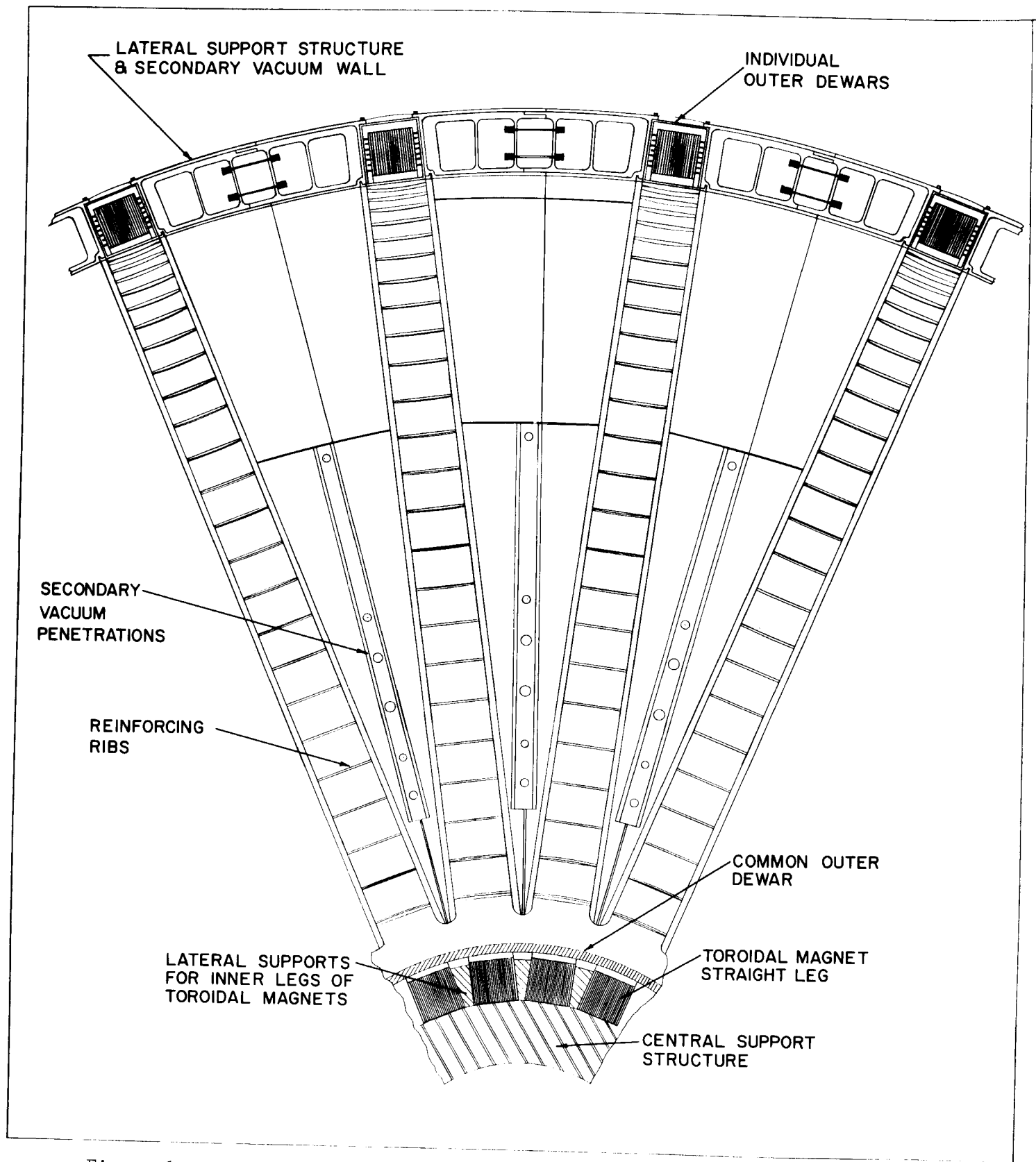


Figure 6. TF coil lateral support structure and secondary vacuum.

TF coil lateral support structure and secondary vacuum.