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Maintainability of fusion reactors will be a major criterion in deciding if fusion can become an economic source of energy. This paper examines some of the design considerations which will facilitate maintainability of these reactors. Three critical areas of maintenance are examined, the blanket, toroidal field coils and poloidal field coils. Particular emphasis is given to the problem of accessibility. These design considerations are directly applicable to fusion reactors of toroidal geometry; however, some can be used by other fusion concepts also.

INTRODUCTION

The answer to whether fusion will become a viable source of energy for future generations hinges on many problems that are being worked on today. Progress is being made on many fronts in this country and elsewhere, particularly in plasma physics. However, for fusion reactors to become economical sources of energy, they must demonstrate a high degree of serviceability and maintainability. The large capital investment in a fusion reactor will necessitate that downtime for routine and unexpected maintenance which will have to be done by remote control, must be kept to an absolute minimum in order to increase plant availability and decrease the cost of energy. Therefore, problems of accessibility, blanket segment replacement, servicing of magnets, ease of making and disconnecting coolant and other lines, and many other functions needed to maintain fusion reactors become of paramount importance.

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Rather than addressing the remote maintenance of fusion reactors, we have instead tried to examine some of the design considerations which will facilitate maintainability. The three critical areas examined are blanket replacement, toroidal field coil maintenance and poloidal field coil maintenance. These considerations are based largely on common sense, but draw heavily on the experience gained from three conceptual designs of Tokamak reactors^(1,2,3) and a conceptual design of a Tokamak Engineering Test Reactor.⁽⁴⁾

The ideas presented here have been incorporated into "NUWMAK" (Fig. 1-6), a high β , high wall loading, compact Tokamak reactor conceptual design produced by the University of Wisconsin Fusion Research Team. Although these design considerations are directly applicable to reactors of toroidal geometry, some of the ideas may be applicable to other fusion concepts as well.

DISCUSSION

Conceptual designs of fusion reactors have undergone a tremendous evolution as new ideas continue to emerge and problem areas are identified. Today's designs bear little resemblance to the designs of the early 1970's. Recognition of the importance of maintainability of fusion reactors has been one of the driving forces in the evolution of reactor designs. Sizes and weights of

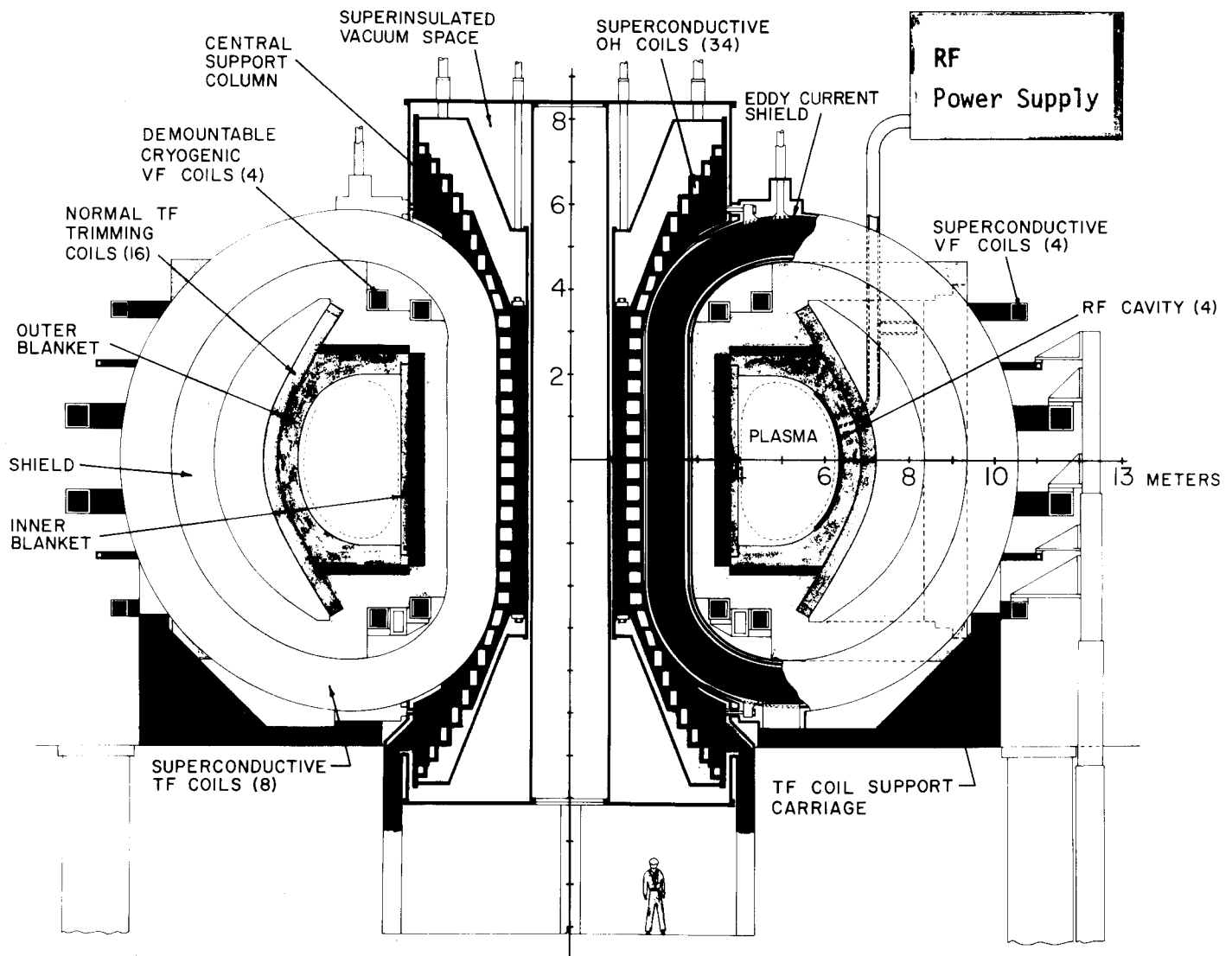


FIGURE 1. Cross-sectional view of NUWMAK.

current fusion reactor components have been drastically reduced, plasma chamber shapes have been simplified, magnet system designs are making accessibility a prime consideration, and problems of fueling, impurity control, vacuum pumping and plasma heating are receiving greater attention.

Early studies have indicated that an optimally sized power plant would be on the order of 5000 MW_{th}⁽⁵⁾. That coupled with a very low neutron wall loading based on incomplete radiation damage data, produced conceptual designs monstrously large and bulky.^(1,2) Later studies, however, have shown that the cost of energy was only marginally dependent on the power output of a reactor between 3000 and 7000 MW_{th}⁽⁶⁾. At the same time new and

more complete radiation damage data predicted a much more optimistic material lifetime at lower temperatures on the order of 300-350 C⁽⁷⁾. The results of remote maintenance studies also showed that it would be virtually impossible to maintain these large reactors economically.⁽⁸⁾ All of these factors combined to reduce the power output and consequently the sizes and weights of the second generation of conceptual reactor designs. As the plasma size was reduced, the sizes and weights of the magnets and other components came down correspondingly.

Similarly, the drive to provide more access to the blanket and inner reactor components has spurred the effort toward reducing the number of

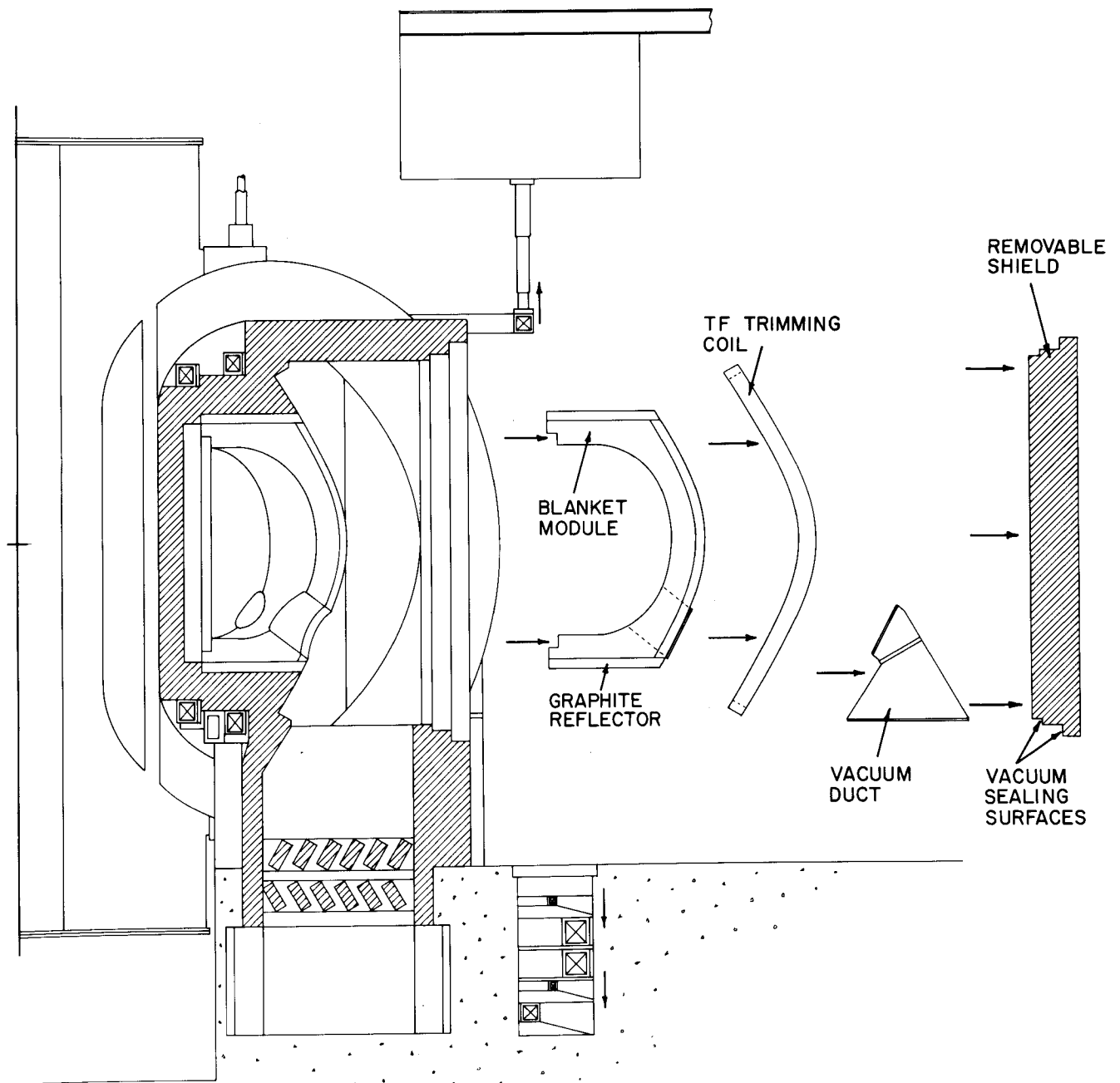


FIGURE 2. View of NUKEMAK showing internal component removal scheme.

toroidal field (TF) coils and the number and placement of the vertical field (VF) coils (Fig. 1 & 3). Some early designs have placed the return leg of the TF coils far enough back to allow unimpeded radial extraction of blanket segments. This concept was used in UWMAK-II⁽²⁾ and more recently, in the Culham Mk-II⁽⁹⁾ design. Although this scheme provides good accessibility for blanket maintenance, the TF coils end up being very large, expensive and difficult to service. The approach adopted at the University of Wisconsin is to

minimize the number of TF coils by using normal water cooled copper saddle shaped trimming coils for correcting the resulting field ripple to acceptable values.⁽¹⁰⁾ These trimming coils are placed immediately behind the blanket and can be readily removed as shown in Fig. 2. The resulting spaces between the TF coils which are equipped with removable shield segments (Fig. 2 & 3) provide maximum accessibility to the inside of the reactor.

Vacuum seals between adjacent blanket segments

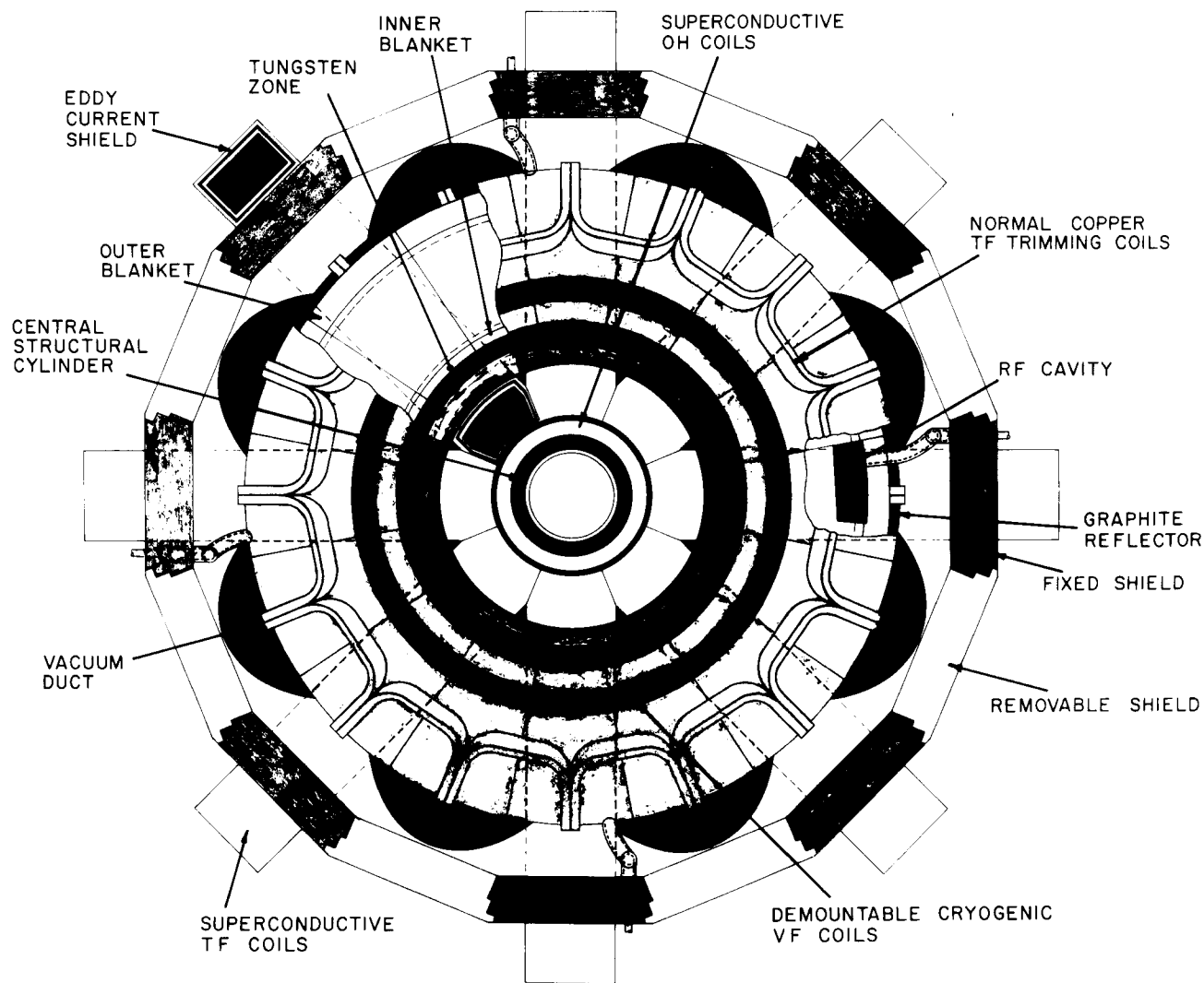


FIGURE 3. Top view of NUWMAK.

have been a source of grief and perplexity to reactor designers. It is now recognized that the most expedient solution to this problem is to place the vacuum barrier at the back of the shield rather than at the first wall.⁽⁹⁾ The blanket segments are placed close enough such that the impedance of the gap between them in the molecular flow regime would allow a pressure difference to be maintained between the plasma chamber and the space surrounding the blanket. Placing the primary vacuum seal at the shield where it is readily accessible (Fig. 2), alleviates the problem considerably. This concept raises the question of whether such a system can be designed clean enough so as not to further complicate the difficult problem of impurity control. Proper material

selection and a well designed vacuum system, however, would help in solving this problem.

The second maintenance area considered in this paper is that of the TF coils. In UWMAK-I⁽¹⁾, blanket replacement necessitated the removal of a complete reactor module comprising a TF coil, blanket and shield, weighing the order of 3500 tonnes. This scheme provided for TF servicing by virtue of the method used for blanket replacement. Some designs⁽²⁾ attempted to provide redundancy by using conservative assumptions and other means. Others have assumed that the reliability of the TF coil system would be so high that the need for removal would not arise, and if it did, the coil would be repaired in place. These may be over optimistic assumptions which could encounter difficulty in

acceptance by the basically conservative utilities. The recent study at BNL called DEALS⁽¹¹⁾ (Demountable Externally Anchored Low Stress Superconducting Magnets), proposes that individual TF coils be taken apart for servicing or for access to other components of the reactor. Some experiments are underway to determine if such joints can be made. In NUWMAK we have reverted back to the UWMAK-I concept but with a mass reduction of an order of magnitude. The number of TF coils were reduced to 8, each weighing approximately 100 tonnes, the number of VF within the toroidal bore were reduced to four and they were made normal cryogenic and demountable. A capability was provided for rotating the VF coils such that the demountable section lined up with the TF coil that needed replacing. In Fig. 4 we show a TF coil being removed from the reactor on a carriage which is a permanent part of the TF coil installation. The carriage can be powered with gas bearings; however, with only 330 tonnes many other possibilities exist. It is no longer necessary to remove the TF coils for blanket change out (as in UWMAK-I); however, should it be necessary to service a TF coil for whatever reason, the capability has been provided to do so in a relatively short time.

Finally, we have considered the problem of maintaining the ohmic heating (OH) and vertical field (VF) coil systems. The OH coils are usually buried within the central column in a very inaccessible area. Servicing them would entail dismantling a substantial fraction of the whole reactor. Since these coils are pulsed and consequently are subjected to cyclic stresses, they should be considered vulnerable and provision should be made for servicing them. In NUWMAK the TF coils are supported on the reactor building floor instead of the central column as has been the case in the UWMAK series. The OH coils are wound on coil forms which are capable of transmitting the TF coil centering forces to a bucking cylinder located at the center of the reactor (Fig. 5 & 6). This eliminates the need for the central support column from being built into the

building floor and makes the top and bottom of the OH coil system accessible for servicing. Figure 6 shows a group of OH coils being removed from the top of the central support column. A smaller group of OH coils are designed to be removed from the bottom, much the same way as shown in Fig. 6. It can also be seen that the central column is supported on posts. This is only necessary during assembly, since the TF coil centering forces would support it during operation. As mentioned in the previous paragraph, the VF coils which are in the NUWMAK toroidal bore are nonsuperconducting, and are designed with a demountable section. This provides the capability of removing them from the reactor. The remaining VF coils are outside the toroidal bore and are superconducting. These coils are readily accessible for servicing.

In the remainder of the paper each area of maintenance is examined separately. The problem is stated and the design considerations are given in concise form.

BLANKET MAINTENANCE

Periodic replacement of blanket segments will have to be made due to radiation damage. Unscheduled replacement will also be necessary because of premature blanket failure.

Problem - Accessibility

Design Considerations

- Provision should be made for rapid withdrawal of the VF coils, which could be mounted on telescoping hydraulic cylinders as shown in Fig. 1 & 5. Some structure will be needed between the hydraulic cylinders, but it could be rapidly decoupled from the coils.
- The number of TF coils should be kept to a minimum to provide large access space between them. Trimming coils which are easily removable can be used to correct field ripple.
- Large removable shield blocks between the TF coils can provide ready access to the blanket region (Fig. 2 & 3).
- A reasonably large space should be provided surrounding the nuclear island to allow maintenance vehicles ready access and room for maneuvering

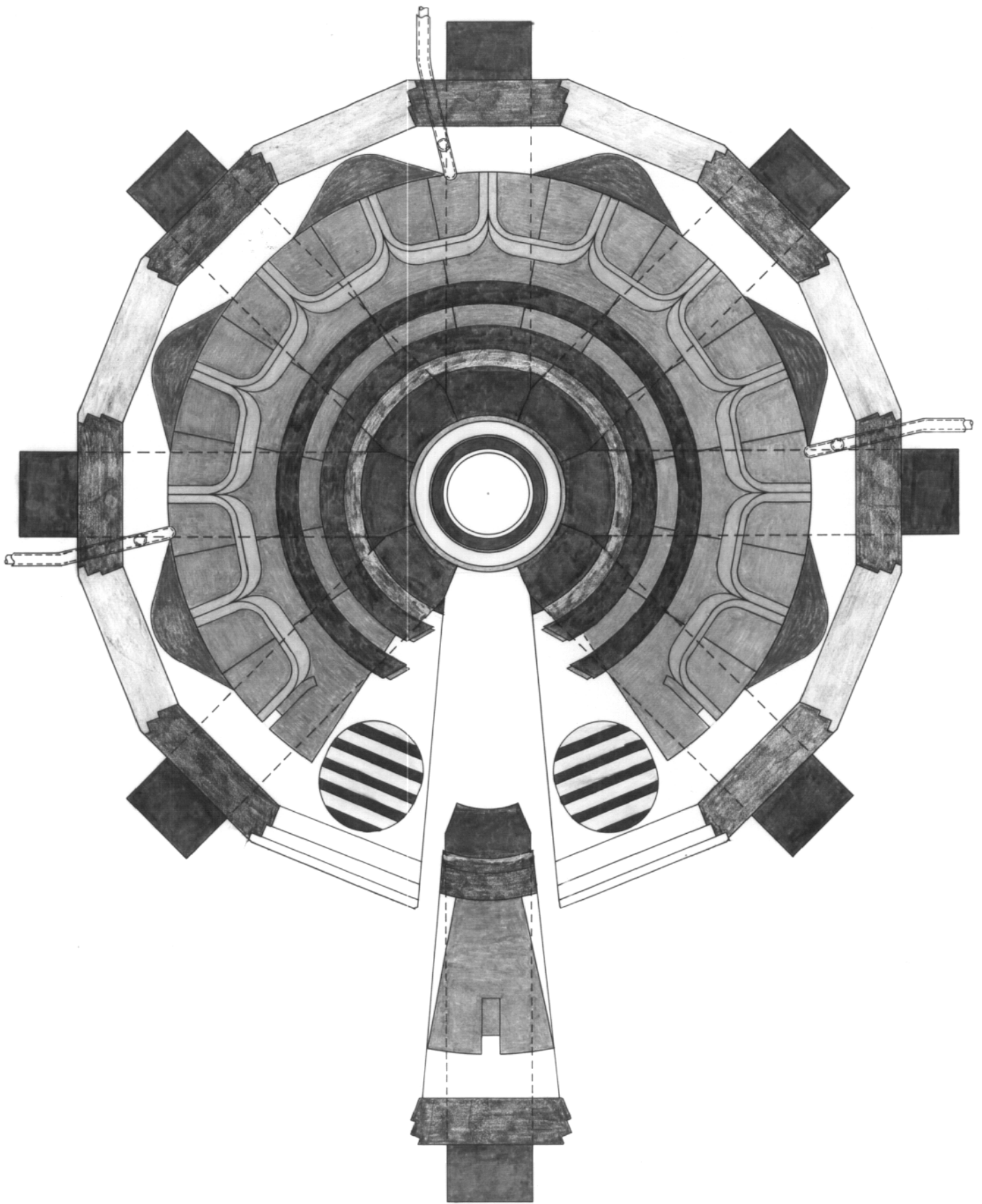


FIGURE 4. Top view of NUWMAK showing a TF coil being removed.

toward designated service areas.

Problem - Removability and Handling
Design Considerations

° Small modularized blanket segments should be used (Fig. 2). The LLL and ORNL cassette concept is a good example of this.

- Provision should be made for draining out the breeding and cooling materials from the blanket to make the segments lighter.
- No seals should be used between blanket segments. The vacuum seal should be made at the back of the shield as in the Culham MK-II and NUWMAK designs (Fig. 1 & 2).
- The number of coolant connections should be minimized.
- The coolant connections should be readily accessible with a large available working space.
- Guides should be provided for facilitating circumferential displacement of blanket segments which lie in line with the TF coils. Similarly guides should be provided for controlled radial extraction of blanket segments from the shield enclosure.

TOROIDAL FIELD (TF) COIL MAINTENANCE

General Design Considerations

- The TF coils should be made as small as possible compatible with the needed space for blanket maintenance.
- The number of TF coils should be minimized to provide large access space between them. As mentioned earlier, easily removable trimming coils can be used for correcting the field ripple.
- TF coils should be supported on the floor. For some earlier designs^(1,2,3) the TF coils were supported on the central column making removal more difficult.

Problem - Avoiding the Gordian Knot

Design Considerations

- The number of VF coils in the bore of the TF coil system should be minimized (Fig. 1).
- These VF coils should be made cryogenic rather than superconducting for easier demountability.
- The internal VF coils should be designed with a demountable section large enough to allow a TF coil to pass through. This section can contain the power lead and coolant connections.
- Provision should be made to rotate the internal VF coils to the location of the failed TF coil as shown in Fig. 4.
- Each TF coil should be provided with its own dewar. Although this sometimes complicates the de-

sign, it is imperative for easy serviceability.

Problem - Removability

Design Consideration

- The mass to be moved must be reduced by removing as many components as possible.
- The seal weld between adjacent shield segments should be made to be easily disconnected by plasma arc or some other form of cutting.
- Each TF coil and associated shield should be mounted on a permanently built in carriage. The carriage can be levitated on gas bearings or transported on rails (Fig. 4).
- Guides should be provided to insure controlled radial displacement of each TF coil.

POLOIDAL FIELD COIL MAINTENANCE

General Design Considerations

- If VF coils must be placed within the bore of the TF coil system, their number should be minimized. External VF coils are both accessible and maintainable.
- Consideration must be given to making the internal VF coils of high purity aluminum operated cryogenically at 25-30 K instead of superconducting. They would be easier to demount and would have less likelihood of failure.
- Joints in these coils should be made for demounting. The slightly higher resistance at the joints will not impair their operation.

Problem - Reacting the TF Coil Centering Force

Design Considerations

- The OH coils should be wound on coil form capable of transmitting the TF coil centering forces to a bucking cylinder located on the inner radius of the OH coils.
- The central column including the bucking cylinder should be made as a self-contained liquid helium dewar which houses the OH coils (Fig. 1, 5 & 6).

Problem - Removing OH Coils

Design Considerations

- The OH coils should be divided into two groups, one serviced from the top, the other from the bottom.

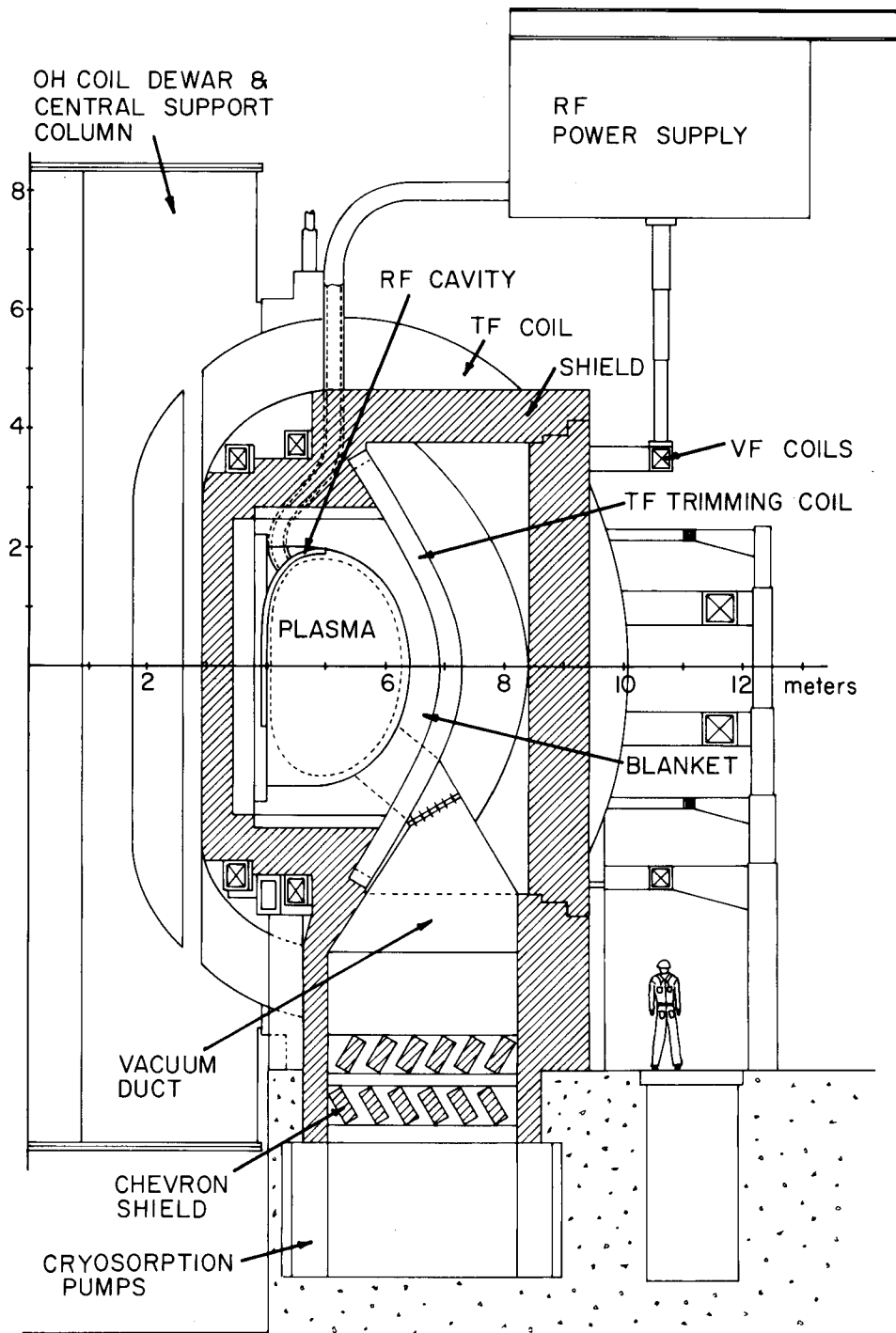


FIGURE 5, Cross-section of NUWMAK between TF coils.

- The separation between the two groups should be used for structure to join the bucking cylinder to the rest of the central column (Fig. 6).
- Some coils can be grouped together on a common coil form in places where individual coils cannot be conveniently removed,
- The central column can be supported on a hydraulic system during assembly. After the TF coils are energized, their centering force will support the column.
- The power leads to each group of coils should be brought to the top or bottom of the dewar for easier connection.
- A service bay should be provided below the central column for maintaining the lower group of coils.

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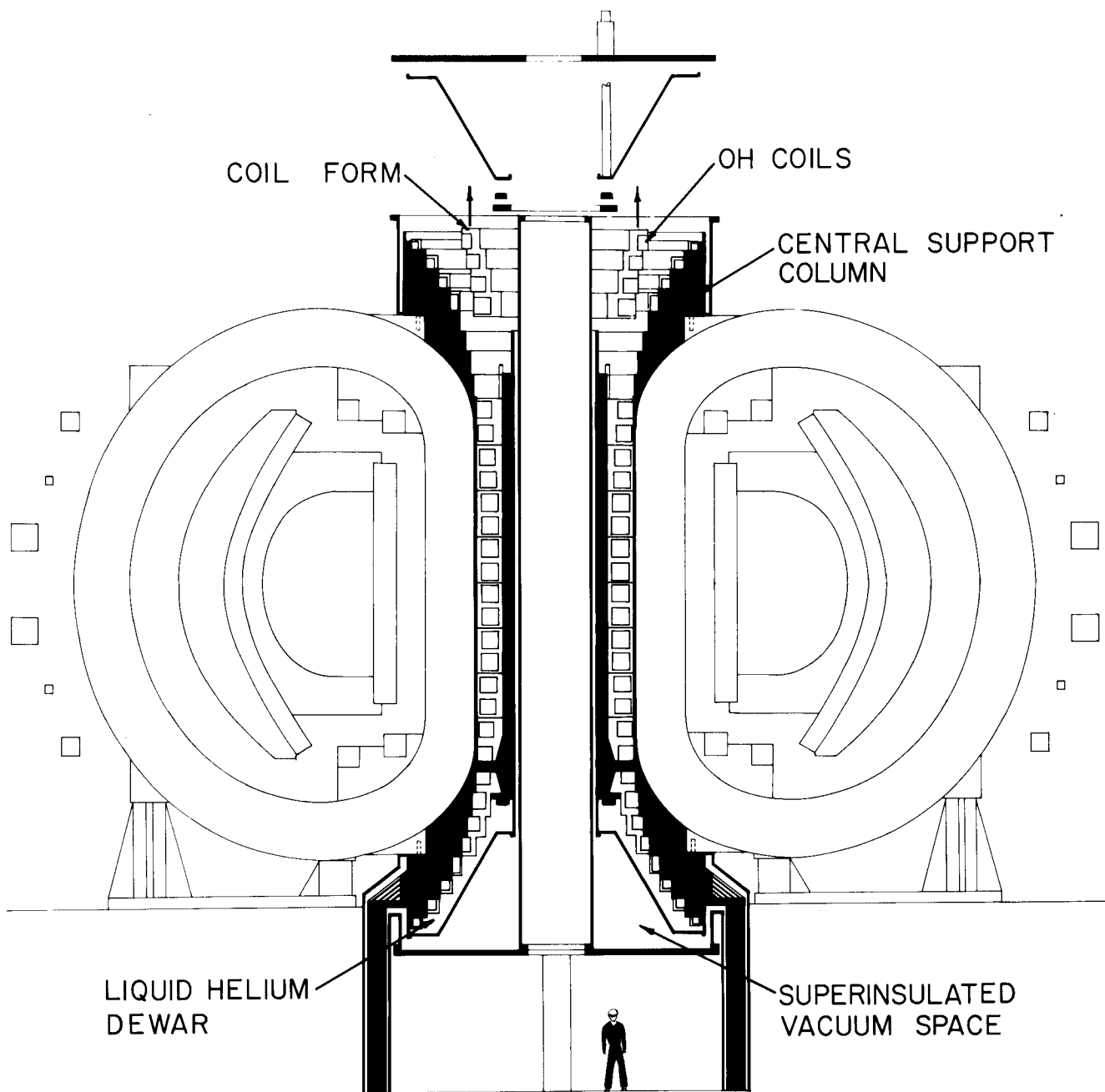


FIGURE 6. Design of a serviceable OH system for NUWMAK.

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