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DESIGN REVIEW OF THE INTOR MECHANICAL CONFIGURATION*

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Summary

The INTOR conceptual design has been carried out by design teams working in the home countries with periodic workshop sessions in Vienna to review the ongoing work and to make decisions on the evolving design. The decisions taken at each workshop session were then incorporated into each national design activity, so that the four national design contributions would progressively converge toward a single design with increasingly greater detail. This paper defines the final INTOR configuration that has evolved during the conceptual design phase, defining the major system design alternatives that were considered and the rationale for selecting the final system configuration.

Introduction

A single tokamak design configuration has evolved during the Phase I conceptual design period representing the combined efforts of all participating countries: USSR, Japan, Europe, and the USA. Figures 1 and 2 show the plan and elevation view of the INTOR design.

The mechanical configuration of the INTOR device must provide sufficient access to the plasma chamber to: permit the experimental objectives to be carried out; allow the device to be remotely maintained; and enable each component to meet its operational requirement within a cost that is reasonable from a capital and operating standpoint. Three major considerations have influenced the evolution of the device configuration: (1) the physics defined operating parameters; (2) the maintenance criteria; and (3) the cost objectives. The major physics considerations which impact the device configuration include the poloidal divertor concept and the EF system. It was found that TF coils sized to meet the torus maintenance requirements will also meet the TF ripple requirements, i.e., the ripple requirement was less stringent.

Because of the potential for seriously delaying maintenance and repair operations through activation of components, the presence of tritium and complex electromagnetic features of the tokamak device, maintenance considerations were established at the outset of the INTOR design study. The maintenance philosophy has led to a modularized design concept, and designing to achieve the required access has had a significant impact on the design of the tokamak systems.

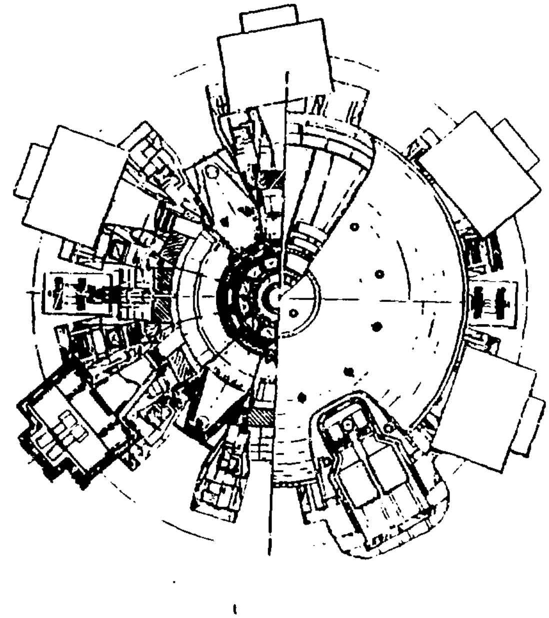

FIG. 1. Plan view

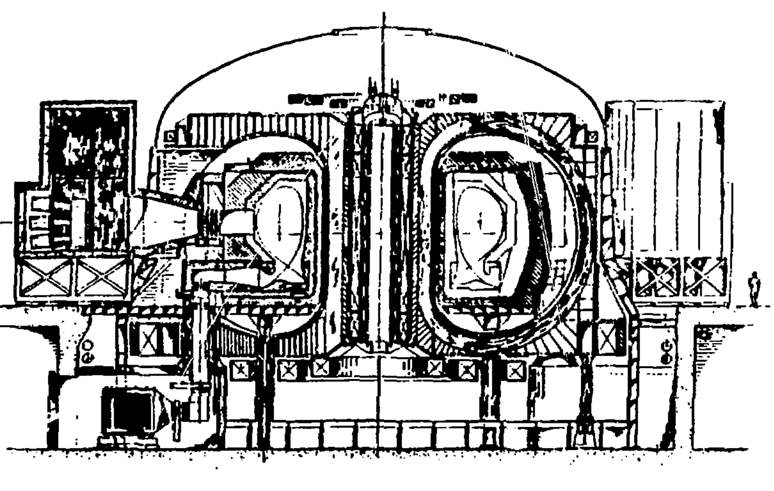

FIG. 2. Elevation view.

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Although cost objectives have not been formally established for INTOR, holding the cost down was an important consideration in the development of the configuration.

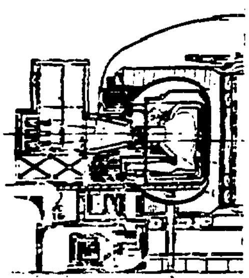
Design Alternatives

Vacuum Topology. High vacuum requirements for the plasma chamber have been a source of design and operations difficulty since the incpetion of the tokamak concept. Design requirements for leak tightness and good practices to minimize outgassing are well understood, however, the tokamak configuration adds another dimension to the already difficult problem of locating the vacuum boundary. In addition, maintenance considerations, especially in a radioactive environment, require a very careful examination of options and overall systems impact. The vacuum requirement for the superconducting (SC) magnetic system is less stringent than the torus requirements; however, because of the configuration complexity, the magnetic system vacuum boundary was considered concurrently with the torus vacuum boundary. Figure 3 shows three options that were considered.

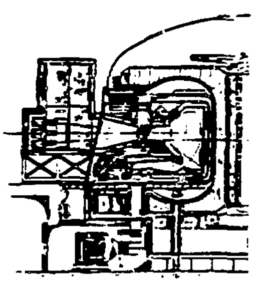
A vacuum seal at the torus was found to be required to isolate the high vacuum region (10^{-7} torr) and reduce the amount of components or feed lines that would be subjected to outgassing and backout conditions. This rules out option (b). The next issue considered was the requirement of a separate [option (a)] or combined magnetic system cryostat where the back, top, and bottom of the torus would provide the magnetic and the torus vacuum boundary [option (c)]. A separate vacuum boundary for the cryostat was selected for INTOR.

The advantages of a separate vacuum boundary for the cryostat and plasma chamber include:

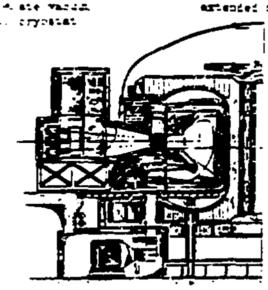
1. Allows testing the SC magnet system before torus is installed.
2. Allows inspection of the vacuum boundary of SC system.
3. Allows repairing the semipermanent portion of the shield without warming up the SC magnets.
4. Added reliability of superconducting magnet system.
5. Improves access for diagnostics.
6. Facilitates baking of torus.



(a) Plasma vacuum boundary at Torus - separate vacuum boundary for cryostat



(b) Plasma vacuum boundary extended outboard of TF coil



(c) Plasma vacuum boundary at Torus - cryostat vacuum boundary combined with Torus

FIG. 3 Vacuum topology options.

The principal disadvantage of the separate vacuum boundary is the addition of 5-10 cm of void space required on the inboard side and the reduced electrical loop resistance that is associated with the separate cryostat.

The final INTOR configuration follows option (a) with a plasma vacuum boundary located at the torus and a separate vacuum cryostat for the superconducting coils. For tritium containment and leak detection, a double containment system was specified at the vacuum interface of the torus sector, at the bellows, and at the removable sector flange seal.

It was possible to design a single vacuum cryostat to contain all of the superconducting coils. The vessel includes individual enclosures for the outer TF coil legs within the common cryostat. With this feature, access to the torus is maintained without penetration of the cryogenic vacuum boundary. Another important feature of this design is that there is a complete separation of the cold and warm components, which eases the structural design requirements for thermal movements of the large structures.

Removable Torus Sector. Two removable torus sector approaches were considered: an approach in which the number of removable torus sectors equals the number of TF coils, and a second approach in which the number of sectors equals a multiple of the number of TF coils.

The torus sector approach with the number of torus sectors equal to the number of TF coils was chosen as the baseline concept. It offered the simplest maintenance operation since the removal of each torus sector from the device is accomplished with a single straight line outward motion between TF coils. A post, inside the bore of each TF coil, remains to form a seal and load bearing surface. From a component standpoint, this approach also allows a single poloidal divertor module to be located in each torus sector, which simplifies its coolant line feed and extraction method.

TF Coil Configuration. The number and size of TF coils in a tokamak device plays an important role in determining the device size, access space between TF coils and the total reactor cost. By using fewer/larger TF coils and by placing a restriction on the vertical position of the outboard PF coils, a TF window can be created to provide access to the torus. Providing a window for torus access was considered essential in establishing a credible tokamak device which can be maintained and was adopted in the INTOR configuration.

Twelve coils were established as the baseline number of coils early in the design activity, in order to minimize the coil size for ripple limit of 75% (peak to average at the plasma edge). However, the final TF coil size of 7.7 × 10.7 m needed to allow adequate tolerance for the torus and divertor module to pass between TF coils resulted in a 0.3% ripple. A 10 TF coil arrangement of the same size coil (7.7 × 10.7) will result in a plasma edge ripple of 0.75% and allow more torus access. Alternatively, 12 or more TF coils with reduced access would result in a reduced coil size. The required access and hence the optimal coil size and number is an important issue requiring a more detailed design study.

It is important to define a structural load path to support the out-of-plane magnetic loads acting on the TF coil in a manner that is compatible with the torus design and maintenance approach. Ideally, the most effective approach in supporting the TF overturning moment is to form a shear tie between the outer TF coil legs by either truss or shear panels. The problem with this approach is the additional torus access restrictions and the requirement of dismantling the intercoil structure for torus removal. Another approach studied involved reducing the TF window for torus access and thereby increasing the width of the TF coil outer leg to more effectively increase its bending stiffness to support the TF coil overturning moment generated by the EF coils. Figure 4 illustrates the TF structural arrangement of this concept. The main drawback in this approach is the complication incurred in the torus design and maintenance approach associated with a 24 torus sector arrangement required for extracting a segment between the reduced size TF window.

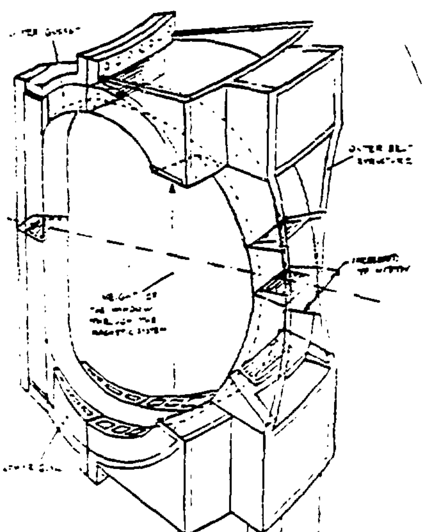


Figure 4

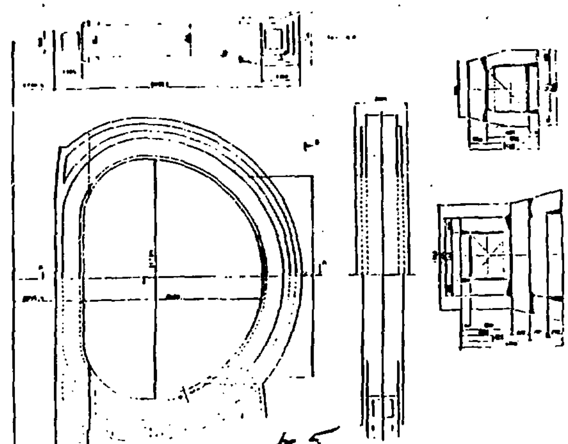


Figure 5 ... that was considered

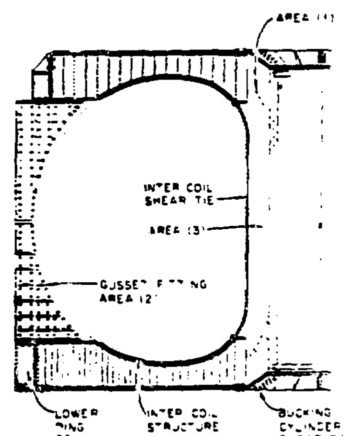


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FIG. Elevation view of TF intercoil structure

To retain a TF window with sufficient access to accommodate 12 torus sectors requires incorporating either a thick wall TF coil design or a built-up structure arrangement. Figure 5 illustrates a thick wall TF case design with additional bending stiffness added by increasing the coil cross section along the outside of the coil. This approach runs into difficulties in terms of eddy current heating in the thick plates associated with the PF coil field changes plus problems in fabrication and void detection.

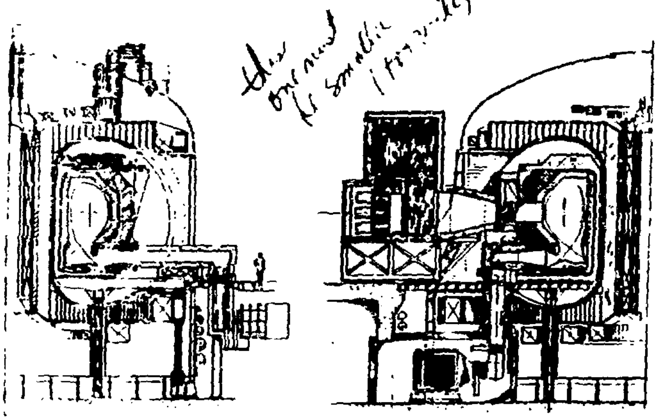
Figure 6 defines the final structural arrangement selected which substantially reduces these problems by incorporating a built-up structure using relatively thin plates with stiffeners.

Divertor Configuration. A double and single-null divertor option was considered early in the conceptual design phase of INTOR. The double-null divertor was found to severely limit access to the torus and to the divertor itself because of the requirement for divertor collectors at the top and bottom of the torus. For this reason, a single-null concept at the bottom was selected in spite of the more difficult design problems associated with the asymmetric PF system and particle loading.

Figure 7 illustrates two poloidal divertor vacuum duct configurations that were considered. Option (a) ran the divertor duct through the TF window and joined the cryopumps outside the SC system cryostat. This configuration had no interference with the TF structure but required a longer duct plus removal of the duct to gain access to the divertor module. Option (b), which was finally selected, ran the divertor duct down through the TF coil intercoil structure to connect with the cryopumps that were located in a shielded vault. This arrangement simplified the maintenance of the divertor module requiring only the removal of an end plate vacuum door to gain access to the divertor module plus shortened the length of the duct. The divertor duct needs only to be detached when removing the complete torus module. The space for the duct through the TF intercoil structure was provided by relocating the lower outside PF coil farther outboard of the TF structure. This modification actually reduced the local magnetic loading at the TF coil with no significant change in the EF coil current.

INTOR Design Configuration

The following sections summarize the main features of the INTOR design.



(b)

FIG. 7. Divertor duct options.

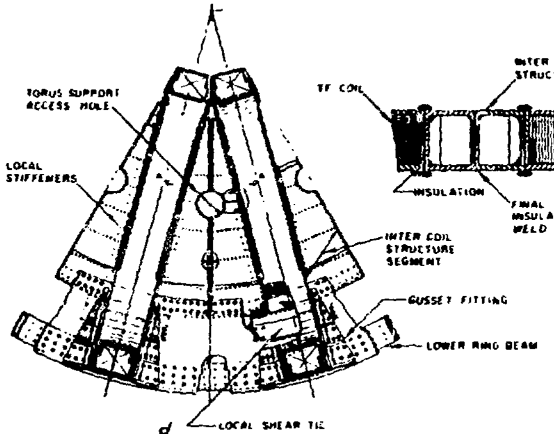


FIG. 8. Plan view of TF intercoil structure.

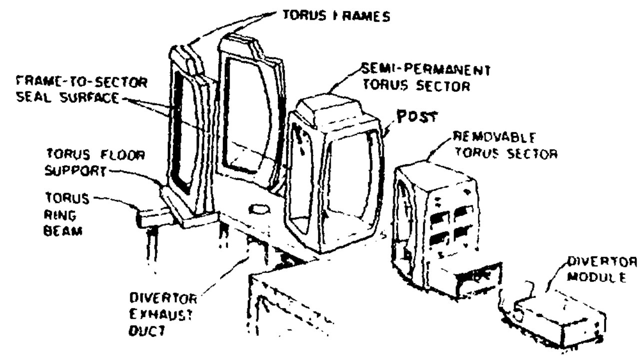


FIG. 9. Torus configuration.

Magnetic System Configuration. In order to simplify the INTOR magnetic configuration, all poloidal field (PF) coils have been placed outside the TF coil bore and along with the TF coils are contained inside the magnetic system vacuum vessel. This simplifies their structural support and provides thermal isolation of the warm and cold structure. A cryoresistive coil system is located inside the superconducting solenoid to provide the initial plasma breakdown voltage and to reduce the field change occuring in the superconducting solenoid.

In lieu of supporting the dead weight of the magnetic components near the machine center, gravity support trusses are located beneath the outer leg of each TF coil. This concept provides access to the PF coils located under the tokamak device. Small diameter PF coils can be replaced by removing at most one TF coil support whereas removal and replacement of the large diameter outer PF coils requires dismantling a portion of the outboard TF vacuum jacket and raising the coil over the outside of the device.

A major effort was expended in the structural design of the TF coil, the intercoil structure, and the analysis to verify the feasibility of the design. The final design uses a stiffened thin plate construction to support the local magnetic pressure loads. Shear ties to the bucking cylinder and contoured gusset plates are added in the TF window area to support the out-of-plane overturning moment. Centering forces are taken up by coil wedging and the bucking cylinder. An outer support ring provides a foundation for the gusset plates and ties them to the intercoil structure. A flanged interface between the TF and intercoil structure simplified the bolted connection and provided space for a glass sheet to electrically isolate the TF and intercoil structure. A structural weld is located at mid-span between TF coils to simplify final installation. Figure 8 illustrates an early drawing of this arrangement that allowed space for an EF coil.

Torus Configuration. Figure 9 illustrates the final torus configuration adopted for INTOR. Shield frames, located in the shadows of the TF coils, house bellows connections for high resistance plus provides the inner surface to form a continuous poloidal frame-to-sector vacuum seal to a semi-permanent torus sector module. The semi-permanent torus sector provides a portion of the shield requirement. This portion of the torus is expected to be highly reliable because of low neutron wall loading attributed to the fact that shielding is provided by the removable torus sector. The removable torus sector is a higher risk component which contains the breeding blanket, inboard shield and divertor in a high neutron flux environment with the potential of plasma disruption. This sector was designed with the principle of single straight-line motion to remove the sector, an integral door seal and rollers to simplify the maintenance operation. The divertor collector plates are the most severely damaged torus components and hence provisions were included for frequent repairs. The divertor was divided into 12 modules, the same number as the torus, to allow for removal of the collector region without detaching the divertor vacuum pumping duct or the removable torus sector itself. The support of the torus is provided by a platform attached to a ring beam and twelve inner support columns located under the torus. The support platform runs through the TF window and is attached to the reactor floor.