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FED/INTOR REACTOR DESIGN STUDIES*

DISCLAIMER

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TABLE OF CONTENTS

1. INTRODUCTION

During the December INTOR meeting in Vienna, all participating delegates presented home country reactor designs, incorporating reduced size TF coils with multiple torus sectors. This represented a departure from the baseline INTOR design which features larger access-limited TF coils which can accommodate the removal of a full torus sector between adjacent TF coils. The motivation behind this action was cost. System studies presented at this meeting indicated that the dominate Tokamak cost drivers were the TF and PF coil systems, plus the associated power conversion equipment. This implies that if the TF coil is reduced in size, the PF system cost will decrease and, in like manner, the cost of the power conversion system.

Unfortunately, the nature of a Tokamak design does not foster simple solutions as the previous statement might suggest; rather, design changes made in one system are found to have a strong impact on other systems, the machine performance, or maintenance. In this particular case, a reduction in capital cost may merely be offset by an increase in operating cost.

A reactor design study was undertaken which employs three design increments to transition from a U.S. FED Reference design (similar in size to INTOR) to a minimum size TF, multiple torus sector concept in order to properly assess the impact of departing from the baseline design. Although the study centers on the U.S. national design, it is felt that the design process and results are applicable to INTOR.

This study is not expected to be completed until the July INTOR meeting; therefore, this document gives only a status report.

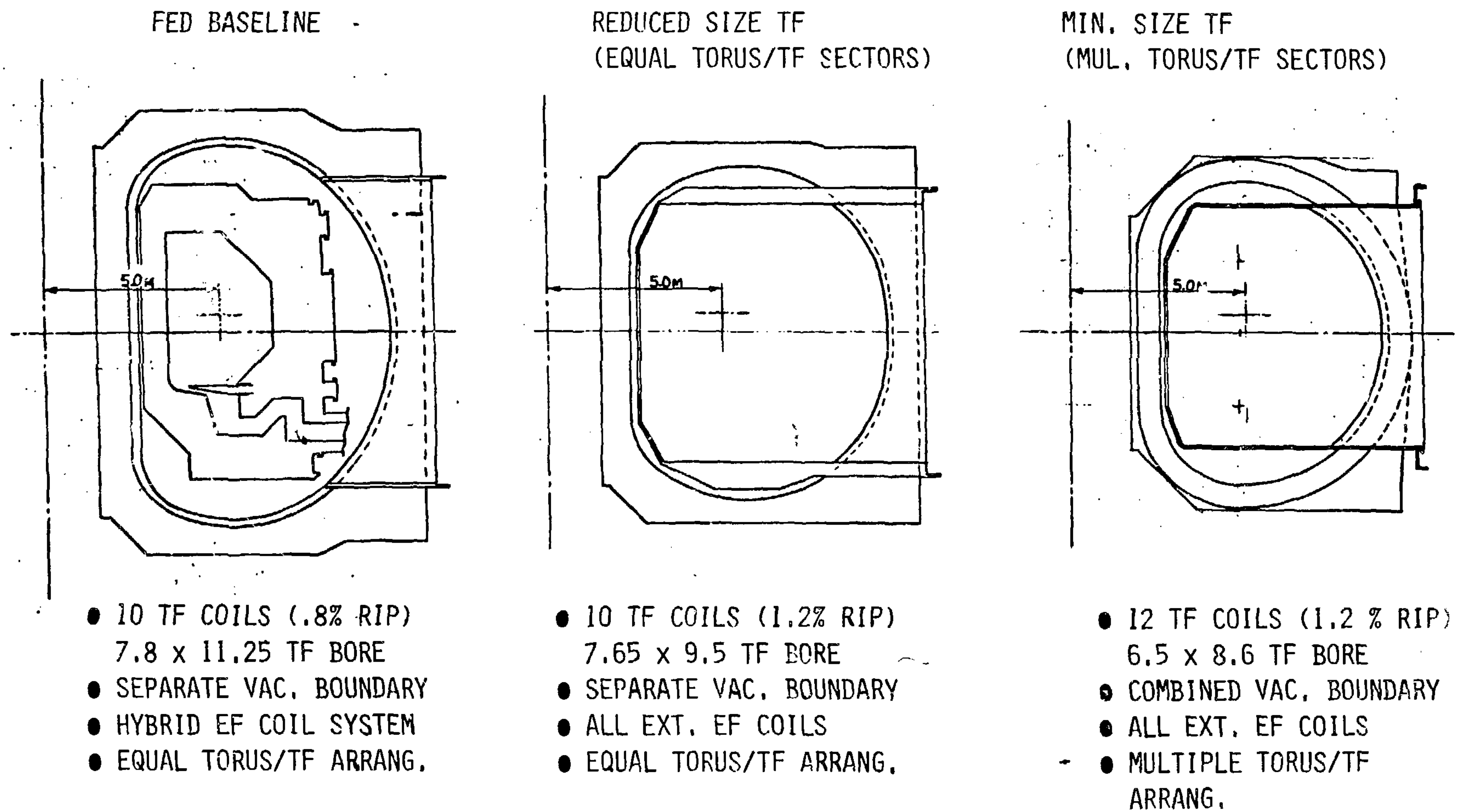
2. REACTOR DESIGN DEFINITION

Figure 1 illustrates three reactor designs which provide a stepwise transition in TF coil size from the access-limited TF coil used in the baseline FED design to a minimum size, ripple-limited, multiple torus sector concept. The reduced size TF coil, shown in the center, provides the specified 1.2% ripple with 10-TF coils, yet still allows equal torus sectors (ten) to pass between adjacent TF coils. A separate vacuum boundary is also incorporated in the reduced size TF design concept. Aside from reducing the size of the TF coil, incorporation of an all-exterior EF coil system is the only other system that was altered from the FED baseline configuration. The minimum size TF coil concept, pictorially shown at the right in Fig. 1, provides a 12-TF coil ripple-limited system, a combined vacuum boundary, multiple torus sectors, and all-exterior EF coils. With the TF coil size defined, the remainder of the study proceeds to look at the design definition of the three major areas which provide the greatest configuration impact on the reactor design: (1) the vacuum boundary, (2) the poloidal field system, and (3) the torus segmentation approach.

3. VACUUM BOUNDARY

The question at hand involving the design of the vacuum boundary is associated with the option of incorporating either a separate vacuum boundary between the superconducting TF coils and torus plasma chamber or a combined vacuum boundary. The design drivers are reactor cost and maintenance. The main issues that must be evaluated in attempting to select a vacuum boundary approach are:

Fig. 1. Reactor design definition



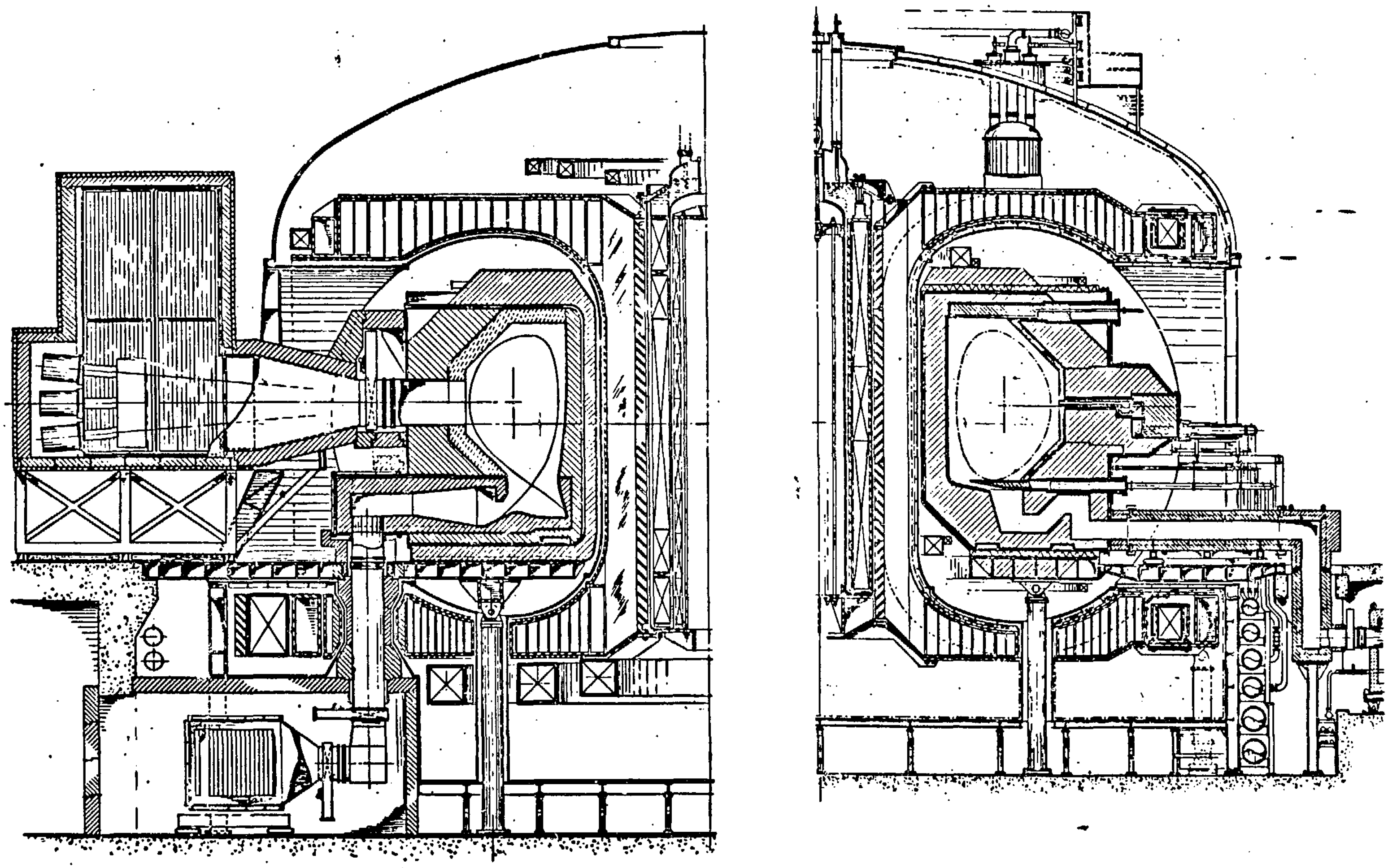
1. Vacuum boundary design/fabrication feasibility
2. Thermal stress characteristics during bakeout
3. Tritium permeation
4. Leak detection approach
5. Dielectric break requirements
6. Control coils installation

Figure 2 illustrates the separate vacuum boundary design concepts established on the INTOR and the U.S. FED baseline designs. The details of the U.S. FED cryostat design are shown in Figs. 3 and 4, identifying the structural arrangement and joint interfaces. The design was carried out in sufficient detail in order that an assembly and maintenance evaluation can be made of the cryostat component and its interaction with other Tokamak systems.

The possibility of incorporating a combined vacuum boundary along the inboard region between the TF coil and torus in the FED baseline design is also under investigation (see Fig. 5). In this approach, the local combination of vacuum boundaries is the only departure from the baseline design. The radial build between the plasma and TF coil can be reduced by approximately 17 cm, which has an estimated $100M savings potential in the overall reactor cost. A structural analysis was performed on this approach and confirmed that an acceptable stress level is maintained during the condition of bakeout. The details of this analysis will be presented in the final report.

The vacuum boundary for the reduced size TF coil concept required some modifications over the baseline cryostat design. Figure 6 shows an elevation view of the reduced size TF coil incorporating a modified cryostat design. For this size device, the EF coils are located all exterior to the TF coil, plus shield material was added to the platform and roof area of the cryostat structure. Figures 7 and 8 illustrate

Fig. 2. INTOR and FED baseline vacuum boundary concepts



INTOR FED

Fig. 3. FED cryostat structural arrangement

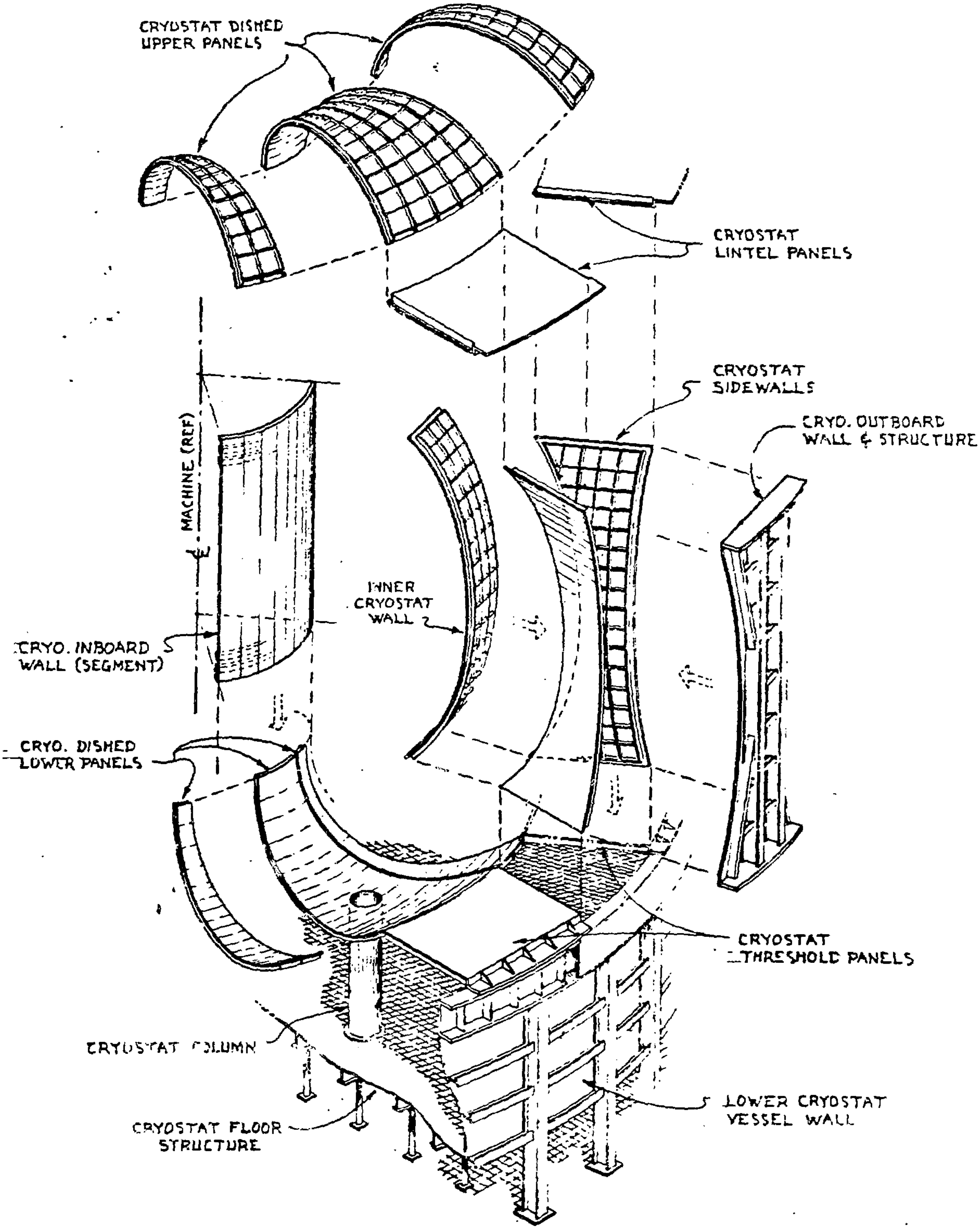


Fig. 4. FED cryostat interface definition

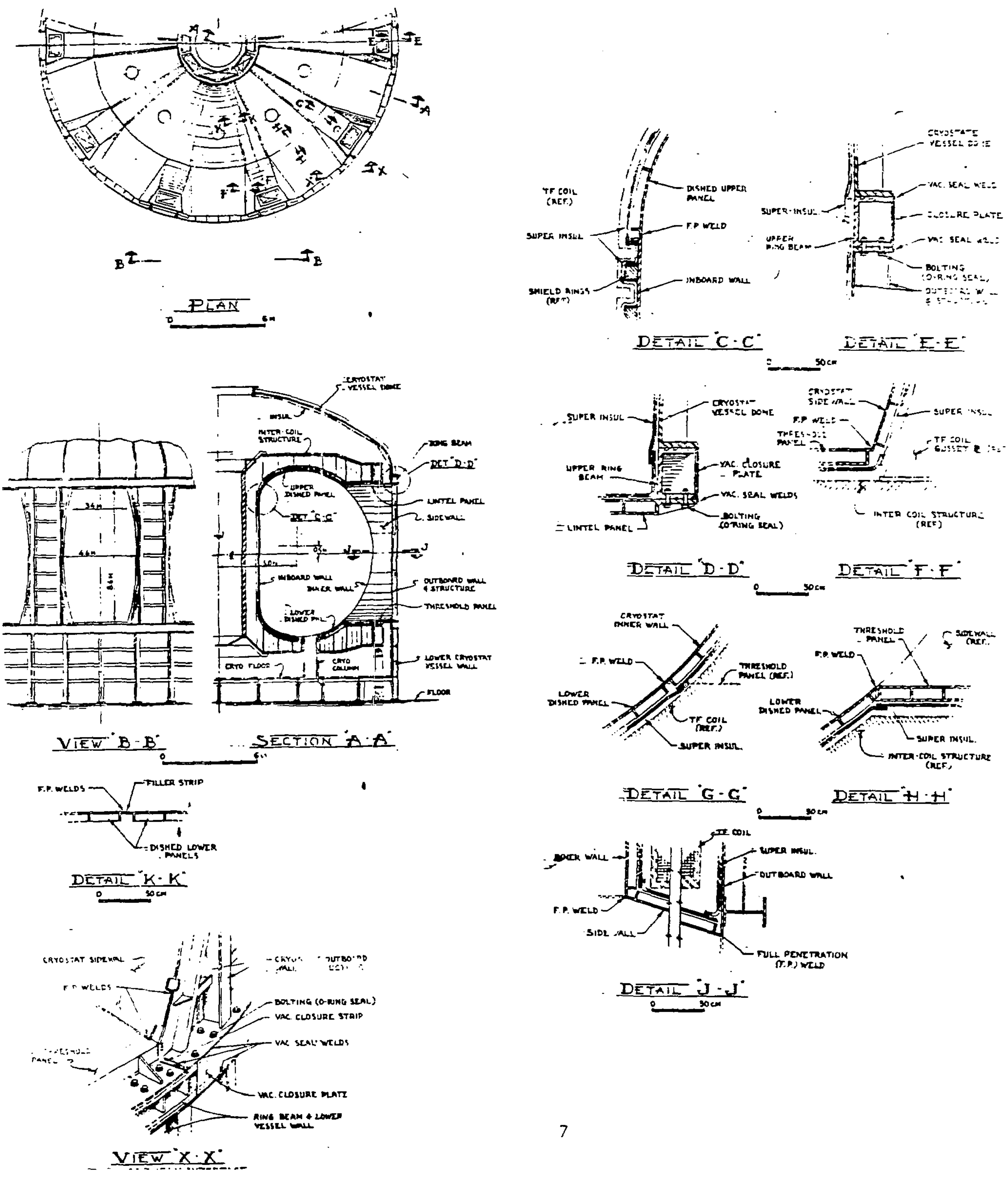


Fig. 5. FED baseline combined vacuum boundary option

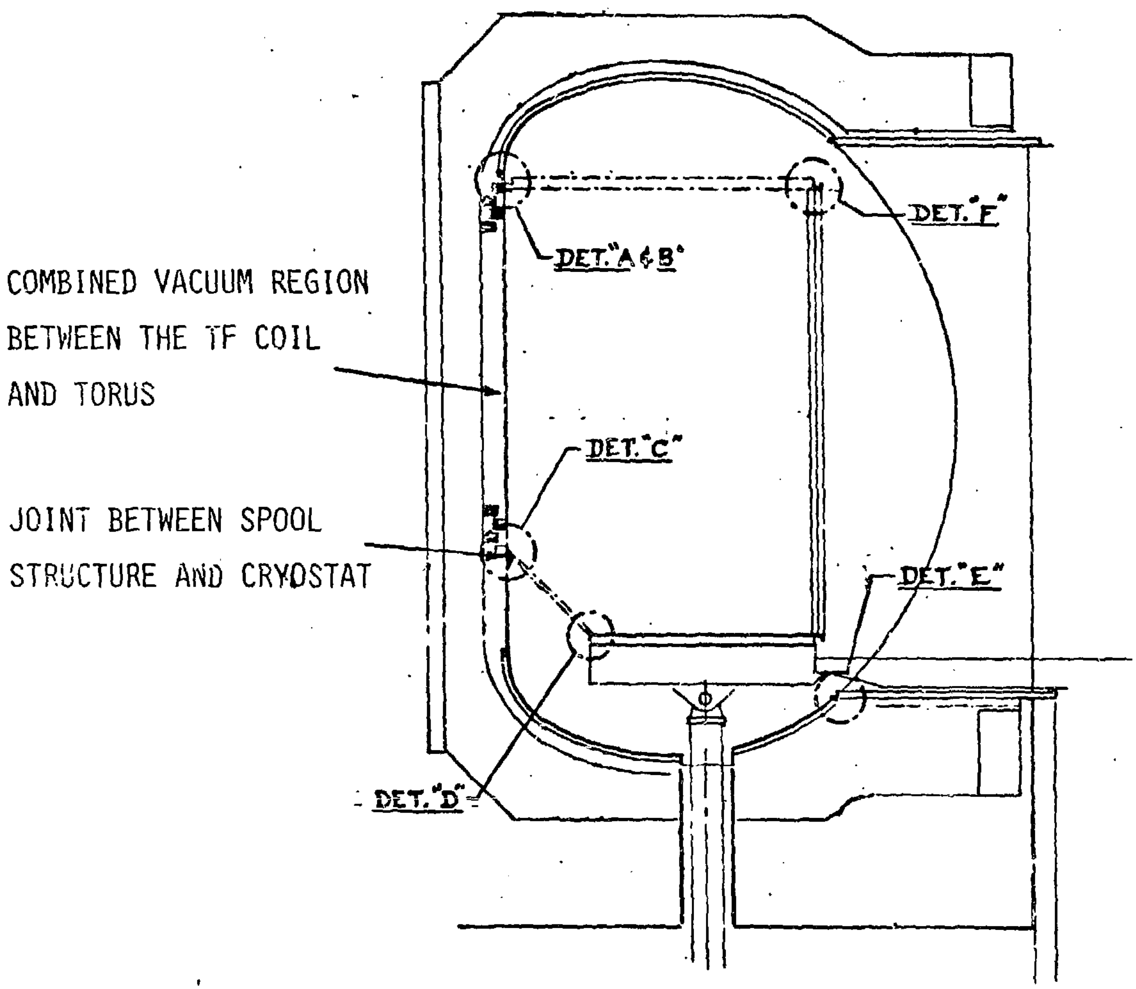


Fig. 6. Elevation view of the reduced size TF coil concept

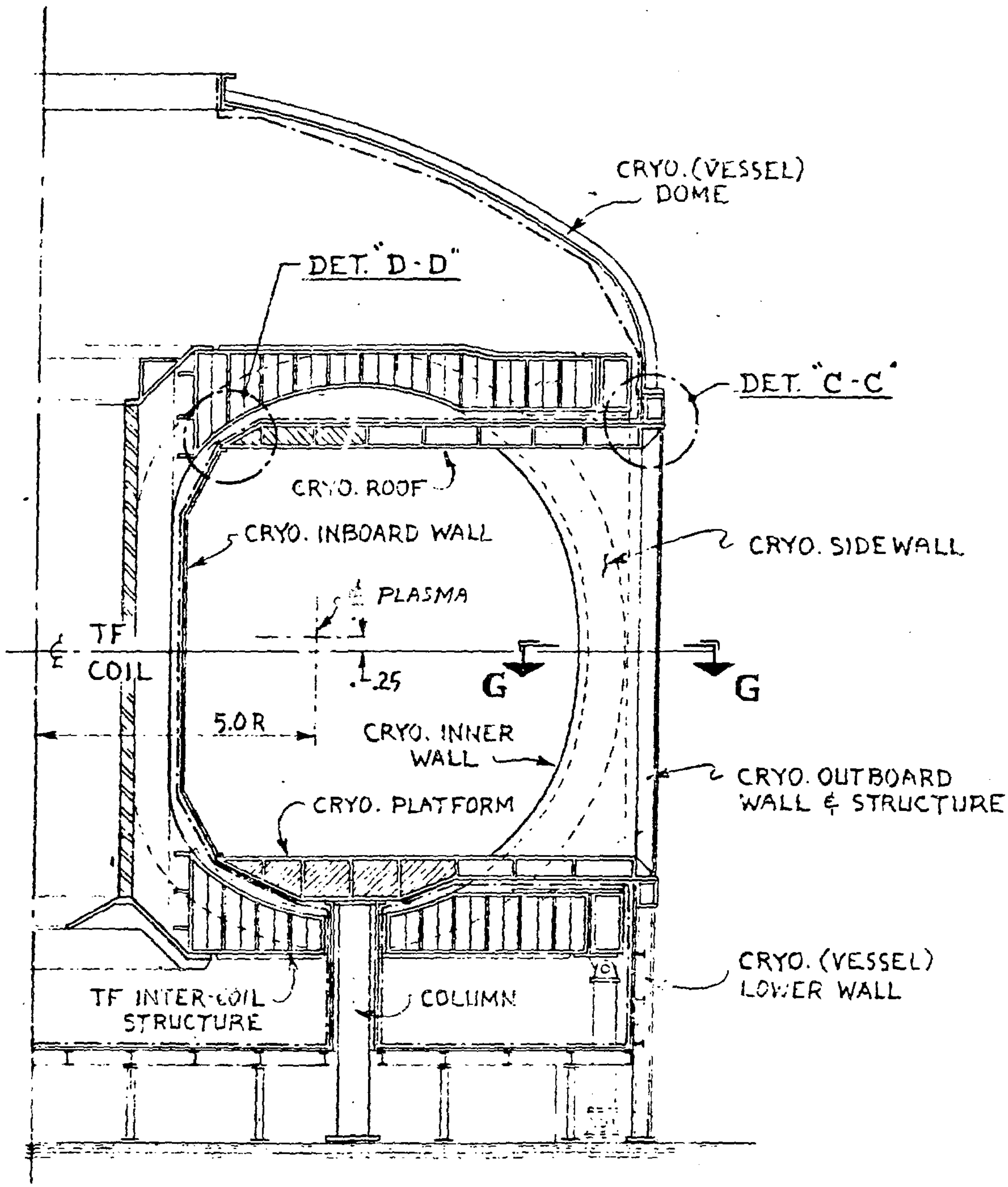


Fig. 7. Cryostat structural arrangement for the reduced size TF coil concept

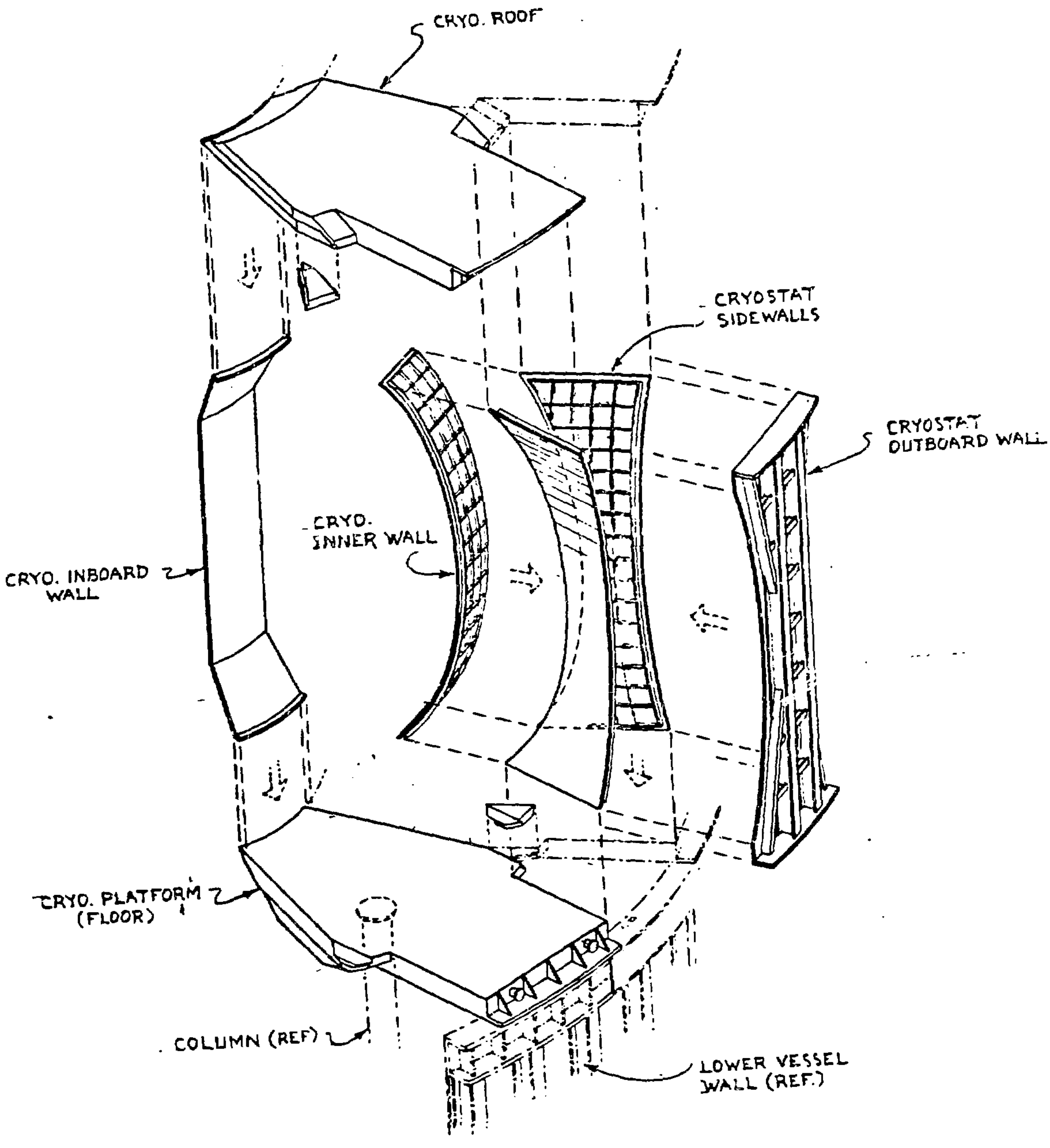
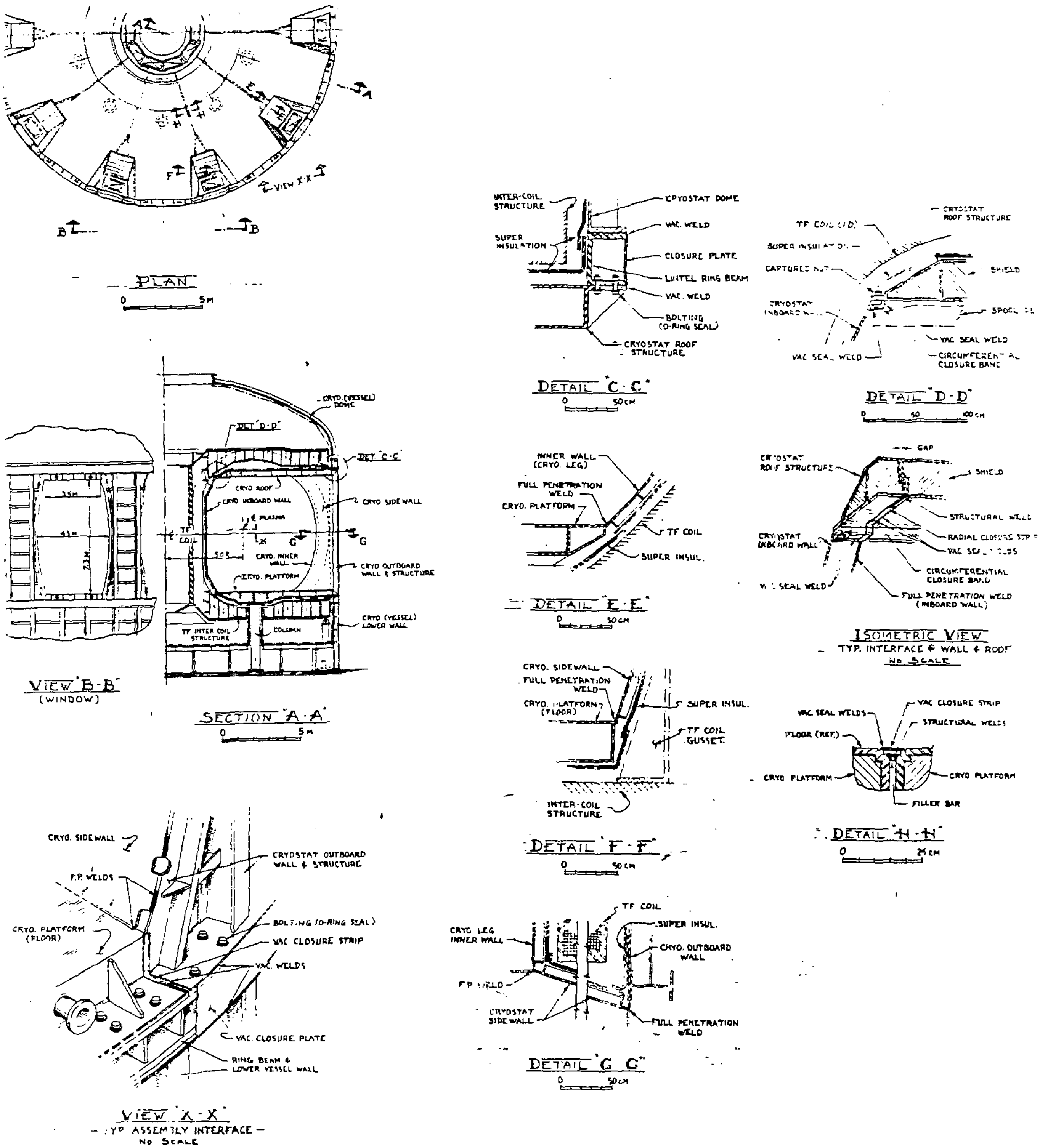


Fig. 8. Cryostat interface definition for the reduced size TF coil design



the cryostat design features for this concept. Combining shield material with the cryostat, plus adopting an all-exterior EF system allows space for a separate torus vacuum boundary to be located inside the confines of the cryostat.

The minimum size TF coil configuration (shown pictorially in Fig. 1) incorporates a complete combined vacuum boundary between the TF coil and torus plasma chamber. The design details of the vacuum boundary are illustrated in Figs. 9 and 10. A finite element model is being developed to determine the stress characteristics of the vacuum boundary structure during the torus bakeout condition. This analysis will also be completed by July.

The design definition of the vacuum boundary has been established for each reactor concept (FED baseline, reduced size TF and minimum size TF concept). Work is continuing to evaluate the maintenance, stress characteristics, tritium permeation, leak detection approaches, dielectric break requirements, and control coils installation.

4. PF SYSTEM EVALUATION

The PF system and the location of PF coils has a major cost and maintenance impact on a Tokamak device. Figure 11 illustrates possible coil locations that have been identified for each of the three reactor designs under investigation. A departure from the FED baseline PF coil arrangement is evident in two areas: (1) an option is being considered for locating the lower outboard EF coil in a position outside the TF coil (similar to the INTOR baseline design), and (2) consideration is being given to locating both outboard EF coils in a separate vacuum cryostat, independent of the TF coil cryostat. Figure 12 shows the design concepts that are under investigation for supporting a repositioned lower outboard EF coil.

Fig. 9. Combined vacuum boundary for the minimum size TF coil design

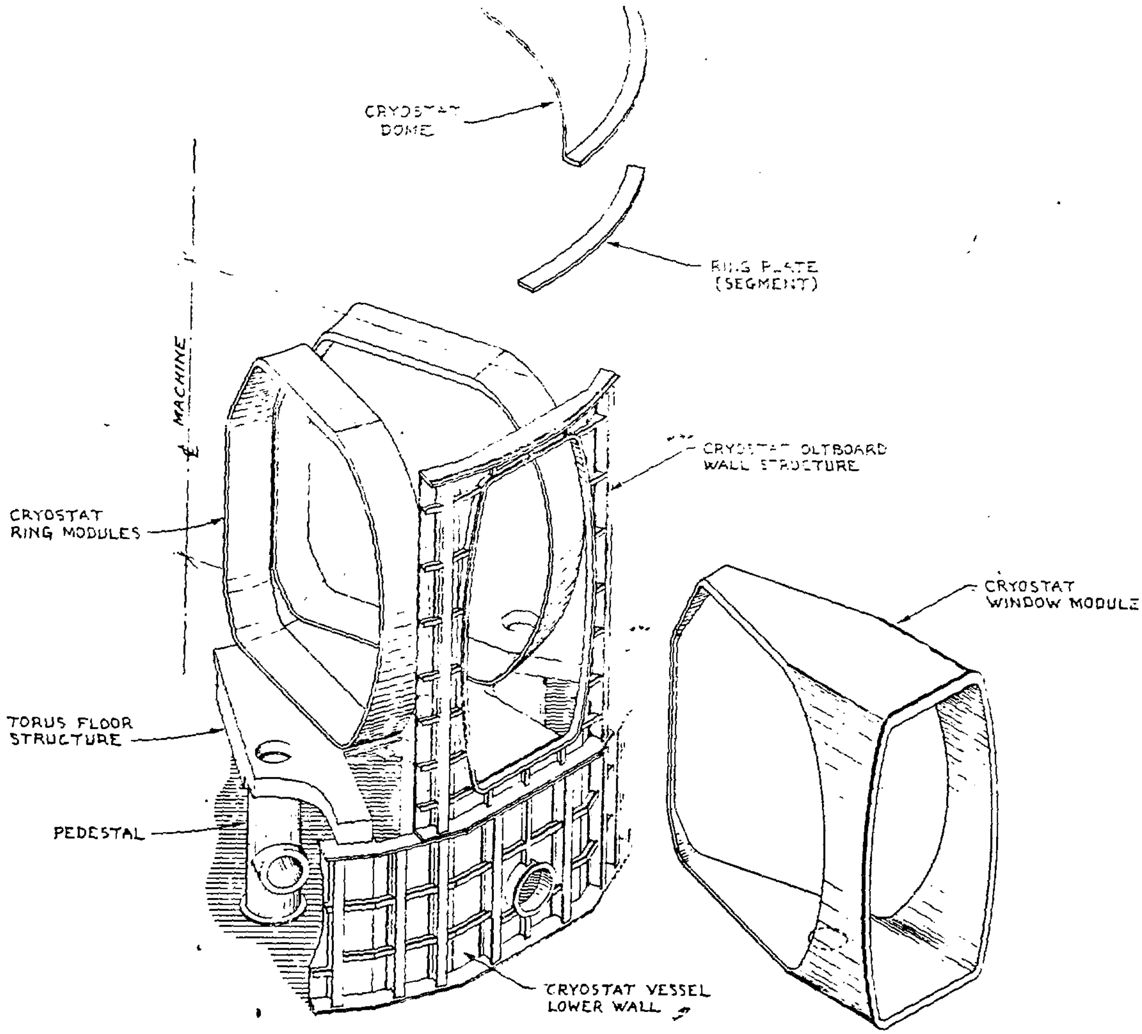


Fig. 10. Combined vacuum boundary interface definition

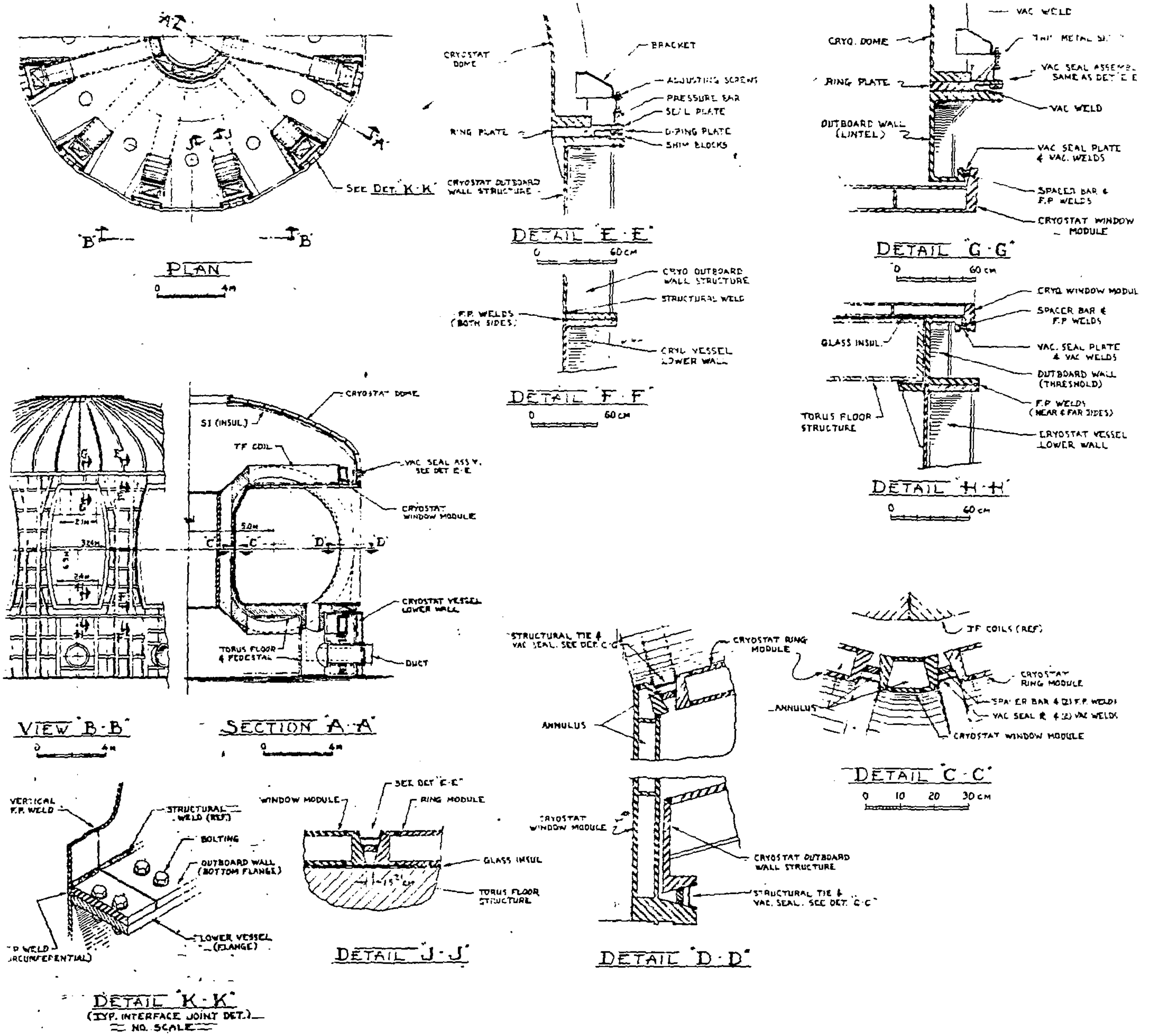


Fig. 11. PF coil locations being considered for each reactor design under investigation

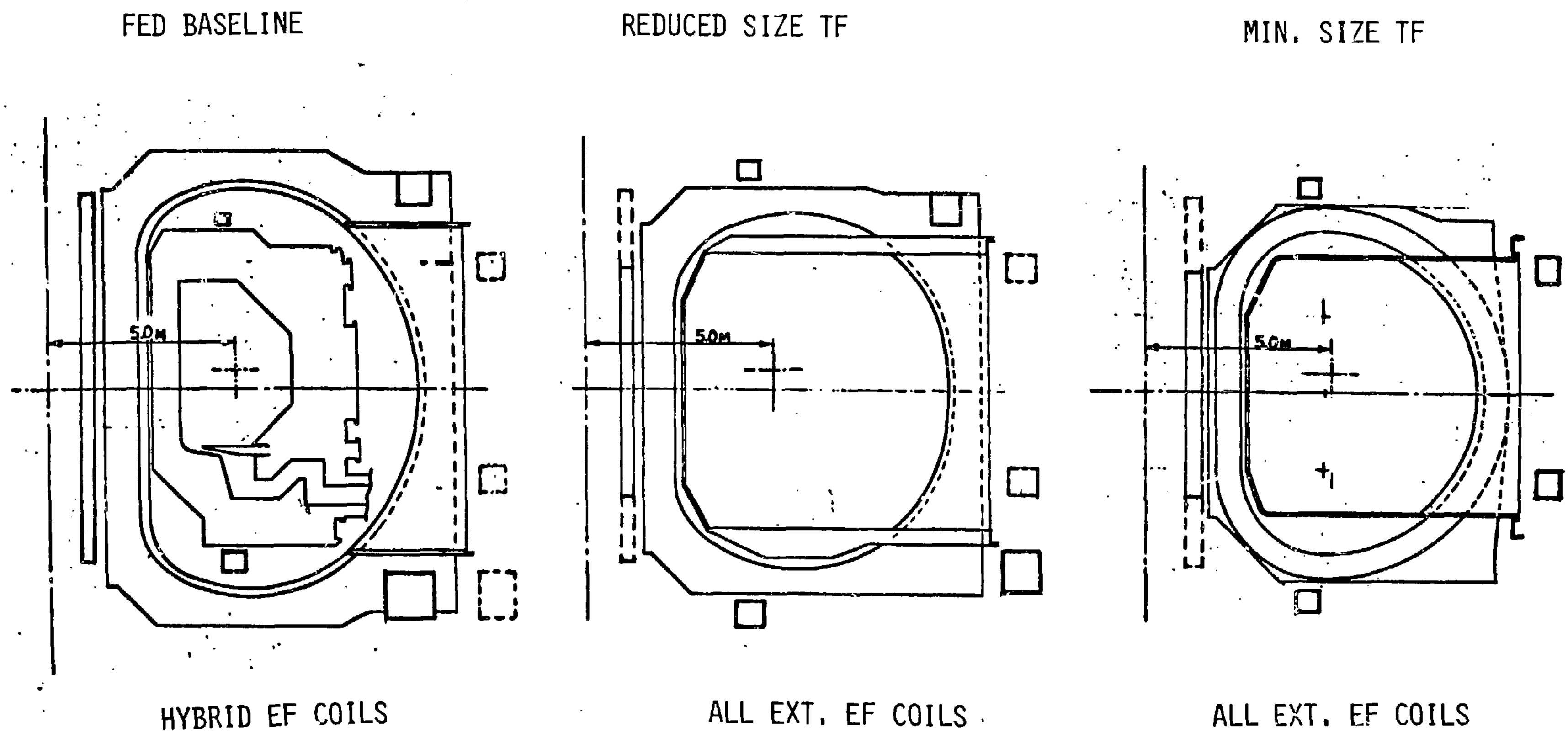


Fig. 12. Design concept for supporting a repositioned lower outboard EF coil

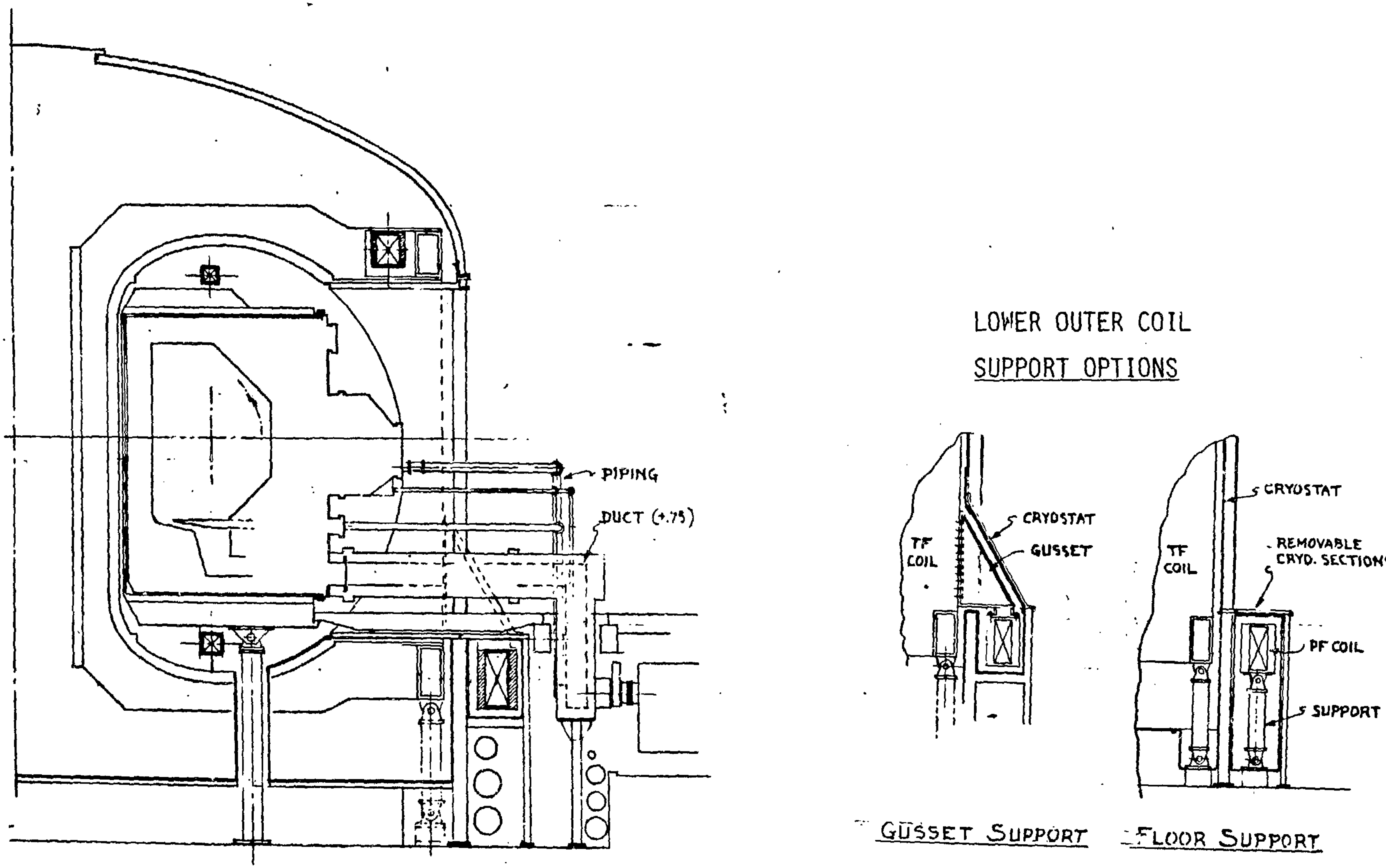


Figure 13 identifies the design concept that will be used to locate the outboard EF coils in a separate vacuum boundary, plus position them closer to the plasma horizontal centerline. The coils are located in a position that allows access to the plasma chamber for all diagnostic components and test modules. When a complete torus sector is removed, the outboard EF coils are repositioned vertically to gain access to the torus sector.

In order to determine the impact of the PF magnetic system, in terms of magnetic fields, forces, and power supply requirements, on the different reactor designs, PF currents were defined for both a pump limiter and poloidal divertor shaped plasma for various PF coil locations. The plasma requirements that were met are:

- 5.0-m major radius
- 6.5-MA plasma current
- 1.6 Elongation
- .2 Triangularity
- Continuous scrape-off for a pump limiter or null coincident with the defined plasma edge for the divertor case

The EF currents defined are for a high beta plasma at the end of burn, with the assumption that the OH solenoid current was at its maximum value.

Figures 14, 15, and 16 show pictorially the range of coil locations considered and the required EF currents to shape the plasma. Refer to Fig. 11 to correlate the EF coil locations with the three reactor designs being considered. The divertor condition on both the reduced size and minimum size TF coil configuration required a reduction in the solenoid current, plus the addition of an upper EF coil in order to establish a divertor plasma shape that had a 1.6 elongation.

Fig. 13. Outboard EF coils are shown located in a separate vacuum boundary, plus supported in a manner that allows vertical access

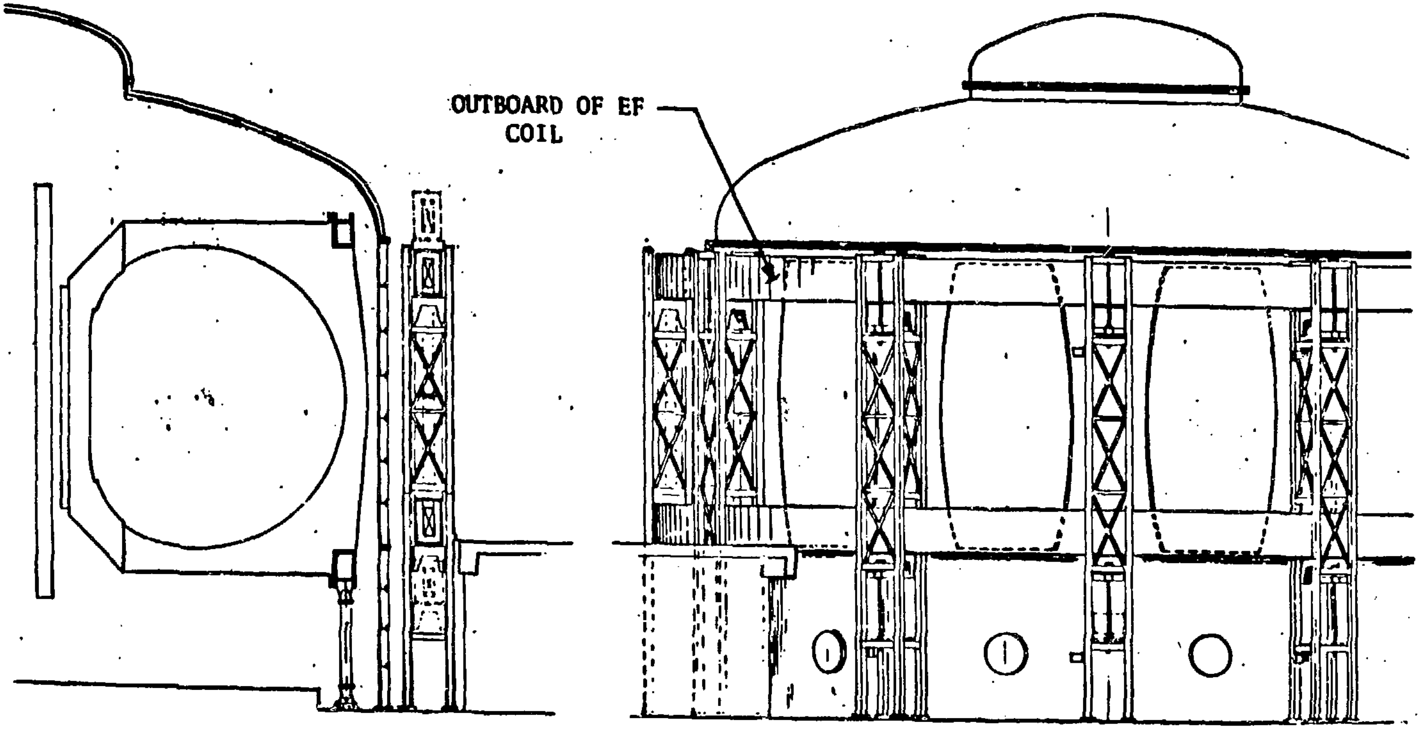


Fig. 14. FED baseline PF coil configuration options

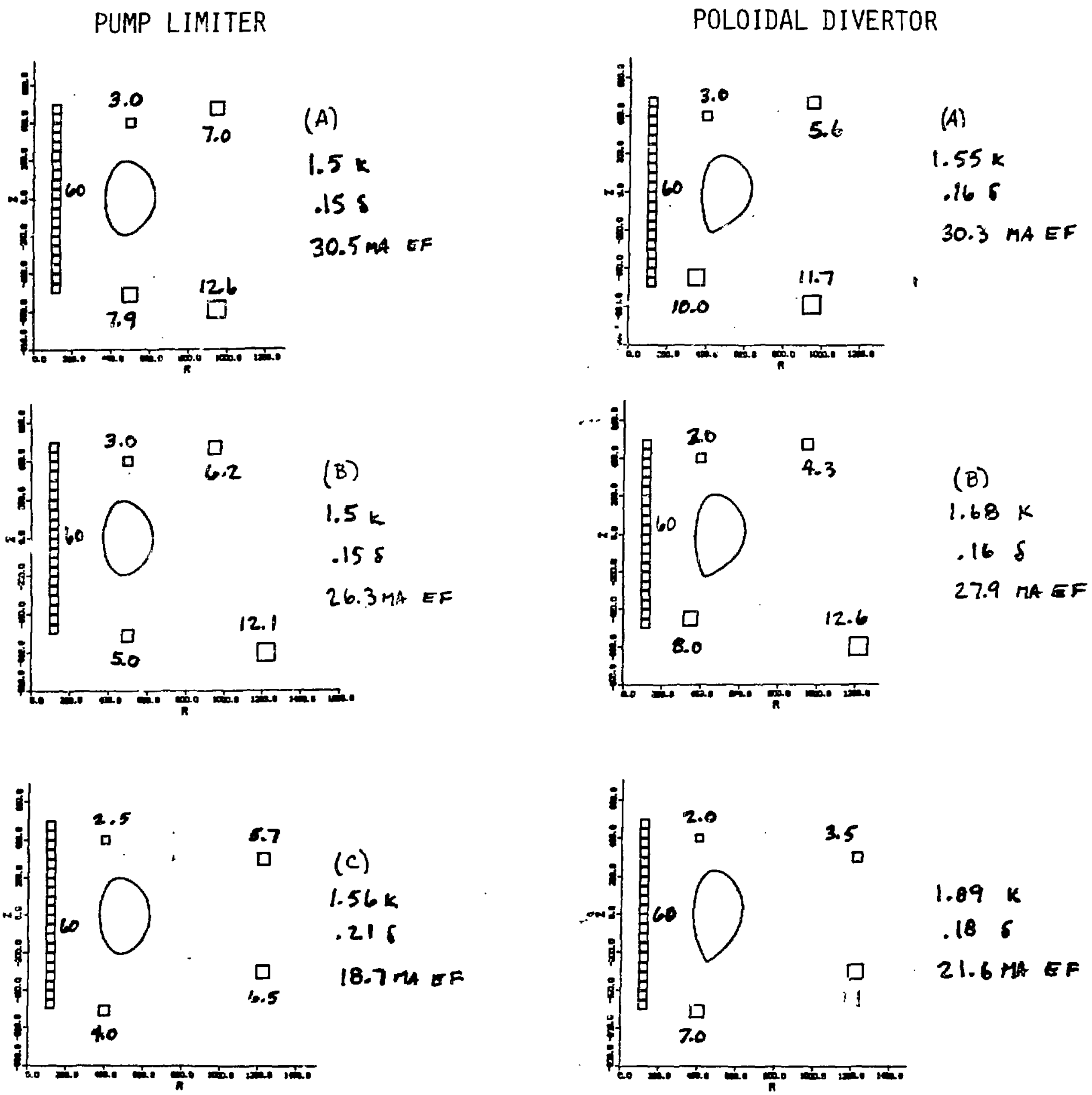
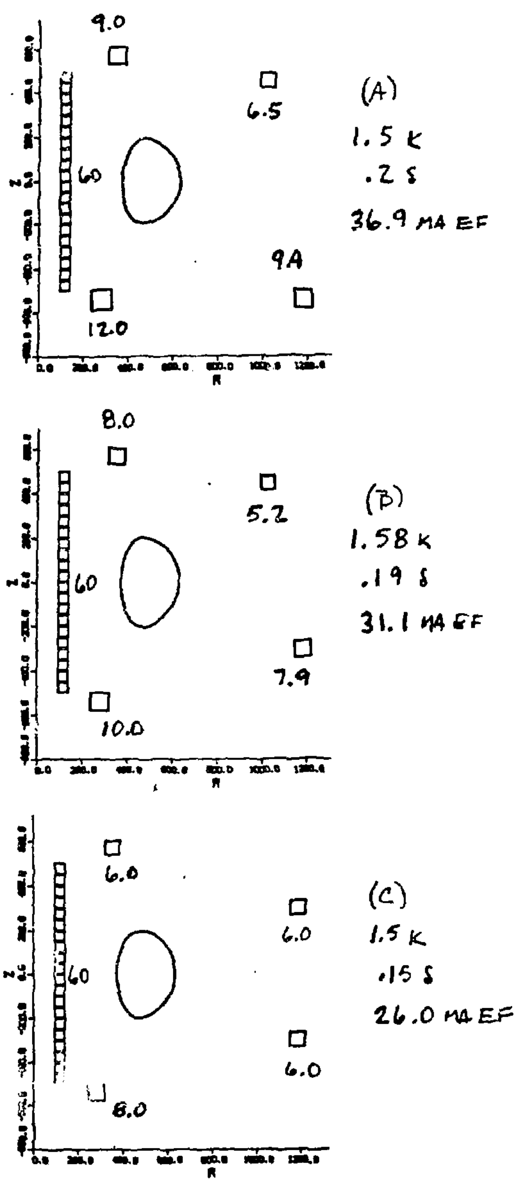


Fig. 15. PF configuration options for the reduced size TF concept

PUMPED LIMITER



POLOIDAL DIVERTOR

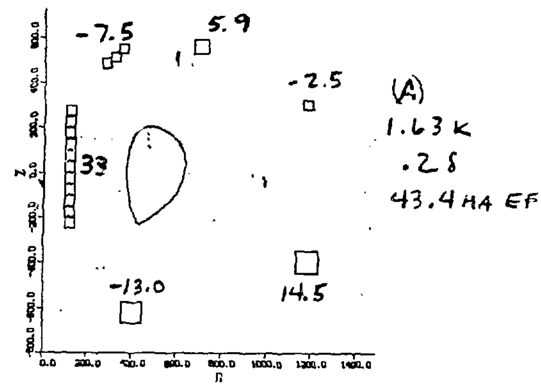
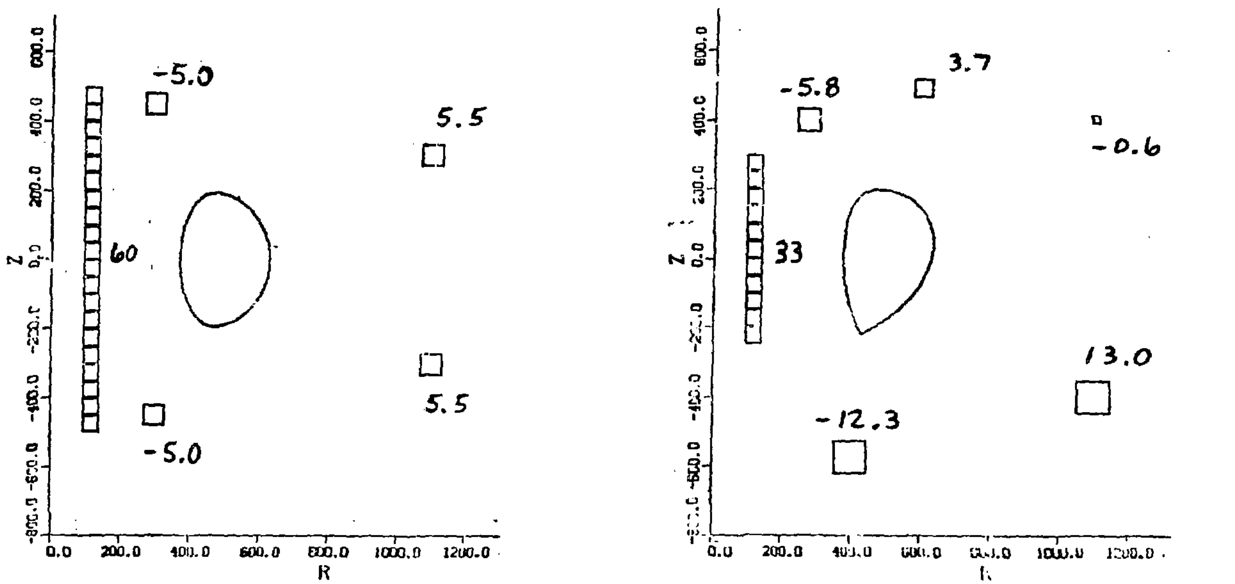


Fig. 16. PF configuration for the minimum size TF coil concept

Pumped Limiter　　　　Poloidal Divertor



Pumped Limiter

1.5 K

.2 δ

21.0 MA EF

60.0 MA OH (AT END OF BURN)

Poloidal Divertor

1.61 K

.2 δ

35.4 MA EF

33.0 MA OH (AT END OF BURN)

After the EF currents were defined for the pumped limiter and poloidal divertor condition for various coil locations, the next step was to identify a method of evaluation. The PF system impact on the TF coils should be evaluated in terms of the out-of-plane forces and fields imposed on the TF coils; the PF system must supply sufficient volt-seconds for plasma start-up and burn; the influence on the overall reactor cost must be assessed; and finally the maintenance of the PF coils and their impact on maintenance of other Tokamak systems must be evaluated. Table 1, when completely filled in, will present a top-level summary comparing the reactor designs and PF coil arrangements being considered. Once this data is available, the PF system will be better understood in terms of its interaction with coil placement, impurity coil approach, maintenance, and reactor cost. The designs can then be redefined to provide configurations having the same ignition margins and burn times, so that they can be evaluated on a comparable basis.

5. TORUS SEGMENTATION ASSESSMENT

The primary thrust of the capital cost reduction effort of the Tokamak device has been associated with the reduction in the size of the TF coils. The main impact of this action is the decrease in the TF window size and the increase in the number of torus sectors. An evaluation must be made to determine the incremental increase in maintenance cost and reduction in reliability that might be associated with the departure from the equal torus segmentation approach adopted in the FED (and INTOR) baseline design to the multiple torus sector approach of the minimum size TF coil design (see Fig. 17). A number of different multiple segmentation approaches will be investigated in greater detail before adopting any one concept

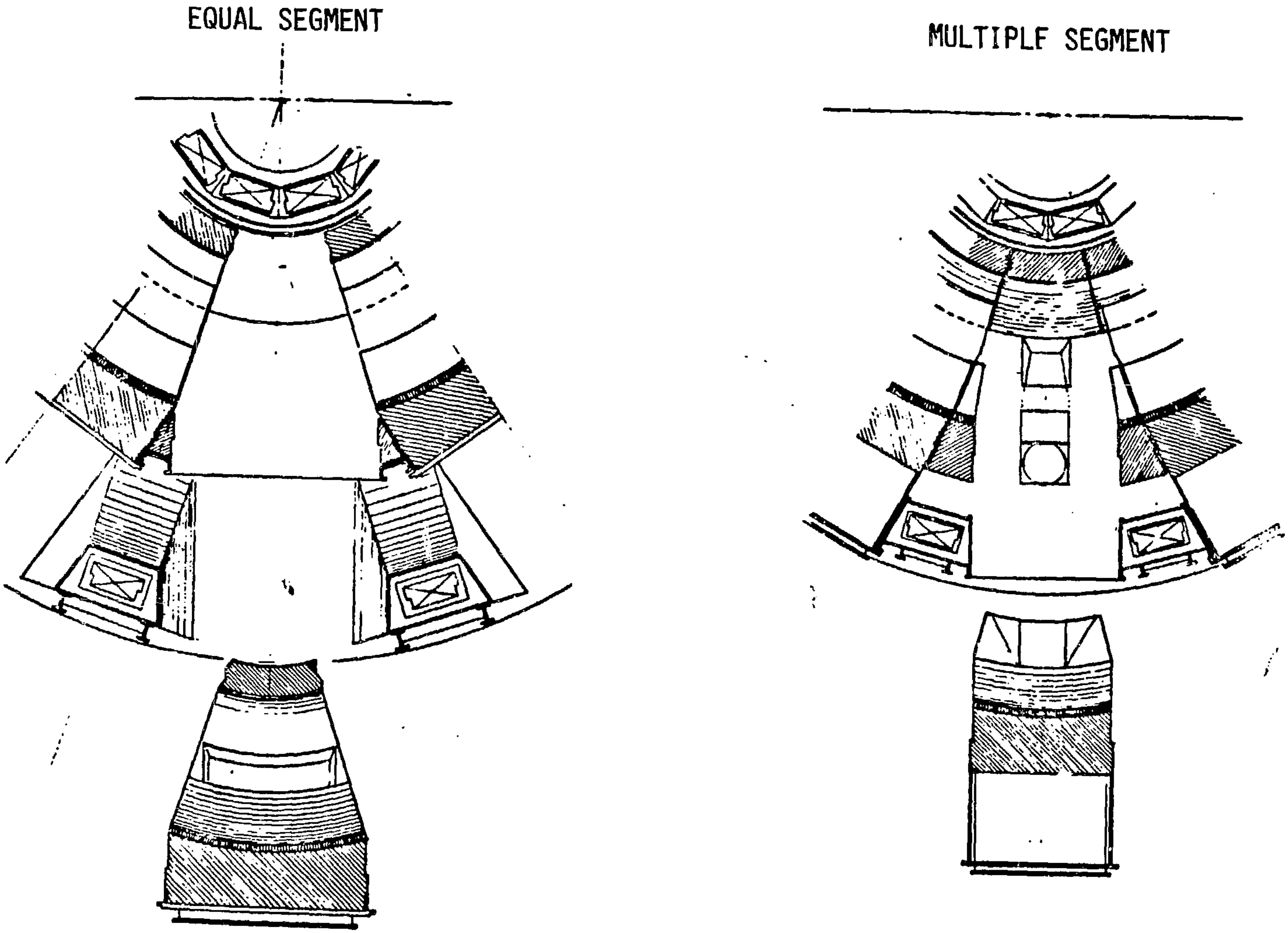
Table 1. Summary of PF configuration study

CONFIG	IMPURITY CONTROL METHOD	TOTAL PF CURNT (MA) OH/EF	TF OT MOMENT (MN-M)	TF PEAK RUNNING LOAD (MN/M)	TF PEAK PULSED FIELD (T)		BURN TIME (SEC)	REACTOR COST (M$)
					B PERP	B TANG		
BASELINE	PL (A)	60/30.5	968	27.6	2.4	2.1		
	(B)	60/26.3	779	18.7	1.6	1.9		
	(C)	60/18.7	551	7.2	1.2	1.6		
	PD (A)	60/30.3	764	15.4	1.3	3.7		
	(B)	60/27.9	667	9.5	1.0	3.0		
REDUCED SIZE TF	PL (A)	60/36.9	613	19.1	1.7	1.1		
	(B)	60/31.1	550	15.0	1.6	0.9		
	(C)	60/26.0	495	12.5	1.2	0.8		
	PD (A)	33/43.4	906	27.8	2.5	1.9		
MIN SIZE TF	PL	60/21.0	297	11.6	1.4	0.8		
	PD	33/35.4	480	22.3	2.5	1.7		

NOTE: 1 - Magnetic field and forces are defined for the case of a plasma disruption at the end of burn

2 - See Figs. 14-16 for identification of PF location option (A, B, C)

Fig. 17. Comparison of shield segmentation approaches



A promising idea has been developed for the multiple torus segment concept that allows the FED baseline pumped limiter blade to be removed in one piece between TF coils. Full-size drawings will be available for the March INTOR meeting.

6. CONCLUSION

Upon completing the design studies identified in this report, an overall assessment of the design options can be made that will form the bases to define the configuration of the next major Tokamak device. The TF coil size will be defined, along with the vacuum boundary, the PF coil arrangement, and the torus configuration. After the configuration is established, an overall performance and cost re-assessment should be made to finally trade off device performance with machine capital and operating costs to establish a reactor design point for a given set of design requirements.