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EVALUATION OF INTOR REACTOR SIZE

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Appropriate reactor size of the International Tokamak Reactor (INTOR) was discussed in the course of determination of design parameters in the Third Session of IAEA INTOR Workshop. The reactor size will be a major topic for discussion in the Fourth Session. This report presents a reference material for the discussion.

Firstly, the design limitations relevant to evaluation of the major radius such as the design limitations in magnets, shielding and repair/ maintenance scheme are identified. Secondly, the design of INTOR-J is examined critically and some improvements are proposed to minimize the major radius. The change in the major radius with the change in plasma conditions is also studied.

Keywords ; INTOR, Tokamak Reactor, Reactor Design, Design Criteria, Magnet, Shield, Reactor Size, Maintenance Scheme

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INTORの炉寸法についての評価

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第3回INTORワークショップで，設計パラメータ選定上炉の寸法の妥当性が大きな問題となり，第4回ワークショップにおいて詳しく論議されることになった。本報告は，そのために用意した資料である。

まず，マグネット，しゃへい，炉体分解修理設計のための諸条件を整理し，これに基づきINTOR-Jの設計の妥当性を設計の一部改良を含めて検討した。つぎに，プラズマ設計条件を変えた場合の炉寸法の変化について検討した。

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1. INTRODUCTION

1.1 General

The capital cost of a tokamak fusion reactor is greatly influenced by the size of the reactor. The reactor size is mainly determined by the scale of the toroidal field (TF) magnets (i.e. bore,stored energy). The scale of TF magnets in turn are determined by the following items:

(1) Plasma cross section (a, κ) ,

(2) B_t on axis,

(3) Plasma major radius,

(4) Divertor concept (poloidal, bundle or non divertor) ,

(5) Maintenance scheme.

In this report, the values of (1) and (2) required to achieve the design objectives such as self ignition are assumed to be given. The freedom of choice exists for selecting the concepts for (4) and (5). As for (3),it is obvious that the reactor size will become smaller with the reduction of major radius. However, it is not desirable to make the radius too small as to sacrifice the reactor reliability. Here the minimization of the major radius is surveyed. Although only the major radius has been seriously discussed in the IAEA INTOR Workshop , it should be noted that it is only one of the above five items deciding the reactor size. The other four items also deserve more serious discussions.

In the next chapter, the design limitations relevant to the evaluation of the major radius are described. In Chapter 3 , the designs of TF and poloidal field (PF) magnets, shielding, maintenance scheme, etc. in the design study of the INTOR-J[(1)] were investigated in detail. Based on the result of the investigation, the reactor size of INTOR-J was evaluated. In Appendix, the major radius compatible with the new set of Plasma Parameters[(2)] was determined. Some comments are given on the dependence of the reactor size on the choice of divertor concept.

1.2 Determination of the plasma major radius

In order to determine the plasma major radius which was seriously discussed in the INTOR Workshops, the following items should be critically examined.

1) In a reactor with high load factor like INTOR, time integrated radiation damage in the TF magnets becomes more of a problem than instantaneous

nuclear heating. Therefore the radiation damage to TF magnet must be suppressed below the allowable value.

① The critical effect in TF magnet caused by the irradiation will be the resistivity increase of the copper stabilizer.

② The resistivity increase may be cured by a room temperature annealing. However, frequent annealing is not desirable because (a) residual defects after annealing shorten the time interval between the annealings, (b) long time required for the warm-up and cool-down lowers the availability.

③ The situation not requiring the annealing during the reactor life can be attained only with unpracticably thick shield. A compromise between the annealing frequency and shield thickness must be made.

④ Shield must be fabricable and reliable. The followings must be considered in the shield design;

(a) Electromagnetic (EM) interaction should be reduced or the shield should endure the EM forces.

(b) High precision fabrication is required.

(c) Should be transportable.

(d) Should be earthquake resistant.

(e) Radiation streaming should be minimum.

(f) Complex shape is inevitable.

⑤ The use of good neutron attenuating materials (e.g. W) will reduce the required thickness at the cost of increased expense. These two should be compromised.

2) Suppress the mechanical stress in TF magnets within the allowable value.

The attainability of the maximum field is of no problem when Nb_3Sn superconductor is used and when 5∿5.5T is required on axis. The limiting factor is the large stress (static and dynamic) generated in the conductor and support structure. At present, there exists no established design criteria for the stress limit at liquid helium temperature. Reasonable design limit should be temporarily determined based on the experience of conventional mechanical structures, the evaluation of relevant materials and the extrapolation of presently available design criteria. The magnet cross section should be designed to hold the maximum stress below such tentative design limit.

3) The maximum magnetic field generated in the PF magnets should be less than 8T. Since the use of NbTi is assumed, many difficulties arise if greater than 8T is generated. This limitation influence the required bore of PF magnets which is determined by the volt·seconds compatible with the plasma current, the coupling coefficient between the PF magnet and the plasma, plasma startup schedule, etc.
4) The stress in PF magnet should be kept below the permissible level. The limit for the cyclic stress should be set and it should be satisfied by the design. This determines the PF magnet size.
5) Superconducting magnet system must be fabricable as well as be highly reliable including the support structure. Its structure should be such as to allow maintenance. This necessitates sufficient considerations in the design of joints between TF and PF magnets, the spacer between the PF magnets (which may serve also as the support for TF magnets), etc.
6) The gaps between the components are necessary.

① The gap between the first wall and blanket is required.
② A gap is required between the blanket and shield.
③* A gap is also required between the shield and TF magnet casing (helium can).
④ Another gap is required between the magnet casing and the conductor.

* There is a proposal to place some movable shield in this gap. Since the shield and TF magnet are independently supported their characteristic oscillation frequency and hence their movements in case of earthquake are different. This problem must be solved for the justification of the proposal.

7) The following components and parts serve as the radiation shield of the TF magnet conductor.

① The first wall (liner, cooling panel, cooling water)
② Blanket (structure and cooling water)
③ Shielding
④ Vacuum chamber (if any) and liquid He can
⑤ Conductor support structure

2. DESIGN LIMITATIONS

The limitations to be considered in the SC magnet design are as follows.

2.1 Radiation dose on the copper stabilizer

The displacement damage limit of the copper stabilizer due to neutron radiation was decided to be 10^{-4} DPA at the 3rd session of the INTOR Workshop. It corresponds to about 2×10^{17} n/cm^2 of neutron fluence (>0.1 MeV), though it changes a little with neutron spectra.

2.2 Allowable strain and stress in TF magnet

1) Strain limit of Nb_3Sn conductor

It is reasonable to set the strain limit of Nb_3Sn conductor to be 0.2 % considering its charactaristics as an intermetallic compound. In future, it may be possible to increase the limit to 0.5 % by the improvements and the accumulation of the experimental data for the Nb_3Sn conductor.

2) Design criteria for copper stabilizer and support structure

At present a proper design criteria does not exist for the cryogenic components such as SC magnet. Therefore we cannot but apply tentatively the criteria based on the ASME B & P.V. Code, Sec. III which is applied to designs of fission reactor components, extrapolating to low temperature range.

① Allowable stress in ASME Sec. III

The maximum shear stress theory is employed in the ASME Sec. III. For the sake of stress evaluation "stress intensity",which is taken to be twice the maximum shear stress, is compared with the allowable stress limits under various design conditions. Moreover, taking into account the differences of the type of stress and their effect on the material failure, the stresses are classified into primary, secondary and peak stress and the allowable stress limit for each of the three stresses is determined.

The basic value of the allowable stress limit is called ' basic stress intensity limit ' and is represented by Sm. Using yield stress σ_y and ultimatetensile strength σ_u of the material, Sm is decided from the following relation in case of the ductile fracture by short load.

$$Sm = \mathrm{Min}\{ \frac{2}{3}\sigma_y, \frac{1}{3}\sigma_u \}$$

Based on this Sm, the allowable stresses for general primary membrane stress (Pm), local primary membrane stress plus primary bending stress (Pl+Pb) and primary stress plus secondary stress (Pl+Pb+Q) are prescribed to be Sm,

1.5Sm and 3Sm, respectively.
The following formula is employed for the evaluation of fatigue strength in ASME Code Sec. III (1963).

$$\sigma_a = \frac{E}{4\sqrt{N}} \ln \frac{100}{100-\phi} + \sigma_w \qquad \text{(proposed by Dr. Langer)}$$

where, σ_a : allowable value of stress amplitude
E : Young's modulus
N : number of cycles
ϕ : reduction of area
σ_w : fatigue strength

In addition to applying the above formula we assume the safety factor for the stress amplitude to be 2 and fatigue lifetime corresponding to the number of cycles to be 20.

(In ASME Sec. III are classified two limitations of the stress for the load controlled type and the strain controlled type. It is reasonable to apply the former limitation for the design of TF magnet.)

② Allowable stress of each material for TF magnet

The stress due to magnetic force belongs to primary stress and the thermal stress caused by the cool-down and warm-up belongs to secondary stress. The following materials are selected for the design of INTOR-J TF magnet.

Support structure (including He can) : 316SS
Copper Stabilizer : OHFC-$\frac{1}{2}$H
Spacer (insulator) : Glass Epoxy

The value of Sm for each material is shown in Table 2.1.

Table 2.1 Low temperature strength of each material (Kg/mm^2)

	σ_u #1	σ_y #1	Sm
316SS	161	68	45.3
OFHC-$\frac{1}{2}$H	45	34	22.7 #2
Glass-Epoxy	75	---	25

#1 Anon., 'Hand Book on Materials for Superconducting Machinery' MCIC-HB-04 (1977)

#2 The value of Sm for copper is determined to be $\frac{2}{3}\sigma_y$ because the copper stabilizer is contained in stainless steel can and is supported by the can after some deformation. Moreover, ultimate elongation ε_u is large (15 %) and the ductility is maintained after yielding.

2.3 Allowable strain and stress in PF magnet

1) Strain limitation of NbTi conductor

There is no practical strain limitation for NbTi conductor. The strain limitation of coil will be decided by the strength limitation of copper stabilizer.

2) Design criteria for copper stabilizer and support structure

The design criteria for PF magnet are the same as those for TF magnet.

3. ADEQUACY OF THE INTOR-J MAJOR RADIUS

3.1 Reactor concept

We conducted the INTOR-J design(1) including most of the main components and repair and maintenance scheme. General reactor concept is introduced first. Overview of INTOR-J is shown in Fig. 3.1. Vertical and horizontal cross-sections of the reactor are shown in Figs. 3.2 and 3.3, respectively.

In order to demonstrate the adequacy of the major radius of INTOR-J, the items described in Chapter 1 are investigated. In the design study, two kinds of designs called the Concept A and Concept B are conducted. In these designs, the sizes of the plasma, first wall, blanket and shield are same while the designs of SC magnets and repair & maintenance scheme are different. However, both designs attempt at minimizing the major radius. The designs of SC magnets (TF and PF magnets) are a little modified to incorporate several modifications.

The cross sections of the first wall and blanket are shown in Fig. 3.4 and that of shield in Fig. 3.5. The radial position and sizes of PF and TF magnets for the Concept A are shown in Fig. 3.6. Figure 3.7 shows the support method of magnets for the Concept A. Figure 3.8 shows the cross section of TF magnet and its gap between the shield. Figure 3.7 also shows the structure of the PF magnets for the Concept A. Similar figures of magnets for the Concept B are shown in Figs. 3.9 ∿ 3.11.

3.2 Dimensions of INTOR-J

The radial dimensions along the mid-plane of the Concept A and B are shown in Table 3.1.

3.3 Evaluation of shielding structure

At first, a stainless steel structure cooled by water was employed as the shielding. Based on the considerations described in 1.2.1).④, water cooled SS 25cm thick was employed in the inner side of the shield where nuclear heating is large. Heavy concrete with W aggregate was used in the outer side. As shown in Fig. 3.5, the shielding is a pressure vessel subjected to one atm pressure difference and its thickness varies between inboard and outboard side. In addition, it must support the blanket. Therefore it must excel in fabricability and hence heavy concrete was introduced to the shielding. The characteristics of the shield are as follows.

(a) Electromagnetic (EM) force

i) Bellows are installed in 12 locations to electrically separate the structure so as to reduce the EM force caused by the saddle shape current.

ii) Concrete is a better electric insulator than SS so that attainment of the required resistivity is relatively easy.

(b) Accurate fabrication

Surfaces of the shielding blocks may be adjusted before pouring the concrete.

(c) Transportation

Concrete may be poured on site and hence heavy weight transportation may be reduced.

(d) Earthquake consideration

As each shield block may be considered as structurally integral, no characteristic vibration of its content will be generated. (On the contrary, if small SS blocks are stacked together, each small blocks vibrate independently thus fracture of nearly pipings may ensue.

(e) Radiation streaming

① There is little possibility for cavity generation in the double layered shield of water cooled SS shield and heavy concrete. This is especially true because concrete may be poured in to fill any cavity.

② In a case of shield using SS balls in a container vessel or stacking SS blocks, packing density change or gaps may be produced by vibrations (e.g. earthquake).

(f) Complexity of the structure

The structure required for the fixture of the content material and cooling becomes comparatively simpler with the adopted shielding scheme than for instance a shield with only SS blocks.

(g) Other features

Many experiences exist for the heavy concrete shield which excels in the fabricability and reliability.

The separation of blanket and shielding is based on the following reasons.

① The reliability of the reactor is improved by separating the high heat generation portion from the bulk shield.

② It will be easier to replace the blanket (even if only those on the outboard side).

3.4 Shielding effect

The result of a parametric survey on the material composition for the inboard shield is summarized in Table 3.2. The critical quantity in the SC magnet is the displacement damage in copper which necessitates an annealing when it amounts to 10^{-4}DPA. The case named W-HC in Table 3.2 was selected for the INTOR-J design. In this case the first annealing will become necessary after 3.2 years of operation. Figure 3.12 shows the distribution of the DPA rates of copper in the Case W-HC. From the figure it may be said that the DPA rate becomes 1/2 when the shield thickness is increased about 5cm.

The following conclusions have been drawn from the results of Table 3.2 and Fig. 3.12.

(a) In order to improve the radiation shielding capability of the shield, tungsten (W) was mixed into the heavy concrete constituting 50% of the volume fraction. The time interval between the annealing processes of the TF magnets is about 3.2 years at 25% availability and 80% duty cycle.

(b) Without tungsten, additional thickness of 5cm (equivalent to SS) is required to obtain nearly the same shielding capability (cf. Table 3.2).

(c) In order to make the TF magnet annealing free during the reactor lifetime of 10 years at 25% availability, the shield thickness must be increased another 8 cm to reduce the DPA rate in copper by the factor of 3.

(d) Accuracy of the shielding calculation

The accuracy of the shielding calculation for the displacement damage rate of copper behind a bulk shield of thickness 90cm without any streaming effect is estimated to be about +100%, -50%. These values correspond to equivalent SS thickness of about +5cm, -2.5cm respectively. The reason for the higher chance of the underestimation of DPA by the present calculation is the neglect of the anisotropy of nonelastic neutrons.[3] When the forward peaking of fast neutrons are fully taken into account, the calculated value of DPA is expected to become larger.

3.5 Evaluation of TF magnet

Two types of TF magnet design have been carried out. Concept A is disc type and cooled by pool boiling. All the central force on TF magnets will be transmitted via discs in between PF magnets to the six columns with pentagonal cross section at the center. These columns support each other mutually. At the stage when Ref.(1) was written, the central force was partially supported by the wedges. Such a support scheme was judged to be difficult from the viewpoint of engineering. The design was changed.

Concept B is pancake type cooled by pool boiling. All the central force is supported by the wedge of the magnet casing. This design was also changed from that in Ref.(1) to improve the space utilization.

Following items must be checked to evaluate the adequacy of TF magnet design.

① Effective use of space
② Fabricability
③ Maintainability
④ Induced stress

(1) Effective use of space

Both Concepts A and B aim at minimizing the required space as much as possible.

① Three types of conductors are arranged in a graded order according to the magnet field strength.
② The outer surface of the shielding is used as the vacuum boundary of the magnet.
③ The arrangement of the conductor was devised so as to minimize the magnet radial thickness while retaining the engineering integrity.

(2) Fabricability

Both magnet concepts are designed taking into account their fabricability. In the investigations so far conducted, no special difficulty in fabricability is found.

(3) Maintainability

Both concepts are designed to be maintenable.

① A minimum space required for the maintenance has been allocated.
② The vacuum boundary of magnets has been specially considered.

(4) Stress induced in TF magnet

Stress on the conductor support structure for the disc type (Concept A) differs from that for the pancake type (Concept B).

In the case of disc type, the electromagnetic force induced in the conductor is transmitted to the stainless steel disc and supported by the disc. Hence the stress induced in the disc will be of problem. On the other hand in the case of pancake type, the EM force is supported by the conductor which consists of Nb_3Sn conductor, copper stabilizer and stainless steel support member. Therefore the stress on copper stabilizer becomes more severe than in the case of disc type.

a. Concept A (Disc type)

① In this design, the maximum stress on disc is calculated to be 27kg/mm^2 by a simplified two dimensional calculation. This value is expected to rise about 30% to 35 ∿ 40kg/mm^2 if detailed calculation is conducted. Taking allowable stress to be equal to Sm, the stress in the disc is judged to be near the limit. There will be some margin if 1.5 Sm may be allowed. Detailed investigation is required to determine the allowable stress.

② The maximum cyclic load due to the mutual interaction with the poloidal magnetic field is estimated to be about 3kg/mm^2. At present, due to the lack of data on fatigue strength at cryogenic temperature no evaluation can be made. However, reinforcement of TF magnet might become necessary from the fatigue strength requirement.

③ The stress on the support disc placed between the PF magnets is about 30kg/mm^2 which is also near the limit.

b. Concept B (Pancake type)

Two dimensional calculations were made. The calculated stress in various parts are given in Table 3.3

① The stress on copper stabilizer 21kg/mm^2 is near the limit.

② The maximum stress on 316SS casing is 28kg/mm^2. This value can be considered in the same way as in Concept A.

③ Cyclic load due to poloidal magnetic field should also be considered.

(5) Overall evaluation

① Both designs of Concept A and Concept B are near the limit with respect to induced stress and utilization of space.

② If structure material with higher strength becomes available in future, the required space will be reduced. At present, 316SS is a good choice as the material for support structures. Not much can be expected of increasing the strength of copper stabilizer.

3.6 Evaluation of PF magnet

The specifications for PF magnets are shown in Table 3.4. Similar evaluation as TF coil will be required for PF coil. Two types of designs Concept A and Concept B are also conducted for PF coil. Concept A employs forced flow cooling. Liquid helium flows through the conductor casing in this concept. Pool boiling is employed in Concept B. In this case, the flow path is shortened to bear larger transient heat load.

Both concepts are designed fully considering the effective space utilization, fabricability, maintenability and also the TF magnet support. As regards the conductor designs, both concepts are based on the latest engineering knowledge. The conductor designs are described in Ref.(1) in detail.

1) Concept A

① Stress

Electromagnetic force generated in the conductor is supported by the conductor casing. The stress induced here becomes a problem. The maximum stress in this design appears as hoop stress in No. 1 and No. 2 coils in Fig. 3.6. These coils are most restricted in space. The maximum stress was calculated to be 22 kg/mm^2 by one dimensional, rough estimation. Considering the cyclic load, this stress is severe for stainless steel.

② Magnetic field

The maximum field (strength) generated is 7.2 T in the No.1 coil. This value can be achieved with NbTi.

③ Bore

The radius of PF coil center is 1.45 m at the midplane. This is 5 cm smaller than the originally specified value in Table 3.4.

The radius is reduced to utilize the space more efficiently. The conductor casing were made thinner in the outer part of the coil where the magnetic field is relatively low. This increases the number of conductor and hence the current density in the outer part. Thus the effective radius of the PF coil center can be made equal to 1.5m. Also the thinning of the conductor casing in the outer part results in more uniform stress distribution.

2) Concept B

① Stress

According to a two-dimensional calculation, the maximum stress of 37 kg/mm^2 appeared in the support structure (SS can) of the No.1 coil in Fig. 3.9. This maximum stress with cyclic mode is very severe for the support structure.

② Magnetic field

The maximum field generated is 7.9 T in the No. 1 coil. This value is within the range for NbTi.

③ Bore

Same as in Concept A.

3) Evaluation

The maximum stress is very severe in both Concepts A and B. The design of PF coil must be made more reliable by the following revisions.

a) The grading of the conductor corresponding to the magnetic field distribution in PF coil should be done. This will result in levelling of the stress.

b) The stress can be lowered by changing the current in PF coils. For instance the current in No.1 coil (OH coil) swings from +3 MAT to -6 MAT at present. This may be changed to swing from +4 MAT to -5 MAT. In order to accomodate such a change, the current in the divertor coil must also be increased. This increase will enhance the $\dot{B}$ on TF coils. The stress may be lowered by such an optimization.

If the above revisions are applied to the design of PF coils, the design will become more reasonable while retaining the present dimensions.

Table 3.1 Radial dimensions of INTOR-J

(in cm)

	Concept A	Concept B
1. Distance between the 1st wall and blanket	$5^{*1}(1.5^{*2})$	$5^{*1}(1.5^{*2})$
2. Blanket thickness	30	30
3. Gap between blanket and shielding*4	5	5
4. Shield thickness	50	50
5. Gap between shield and TF magnet Liq. He can*5	$14\ (1.0^{*3})$	$10.5\ (1.0^{*3})$
6. Liq. He can thickness	2	5
7. Gap between He can and conductor support structure	0.5	2.25
8. Support structure thickness	4	0.7
9. Distance from the first wall to Nb_3Sn conductor	110.5	108.5
10. Total bulk shield thickness	88.5	88.2

*1 A saving of 2.4cm thickness may be acquired if the cooling panel is made to be in contact with the blanket.

*2 Shielding effect equivalent to 1.5cm SS can be expected.

*3 SS thickness equivalent in shielding effect to vapor shield, super insulation and casing.

*4 The gap is required for the support of the blanket structure, fabrication and repair and maintenance. The possibility of reducing its thickness is small.

*5 The gap is a necessary space for the super insulation, vapor shield and their casing. Therefore the gap has little chance of being reduced farther.

Table 3.2 Maximum nuclear characteristics value in the inner SC magnet for 4 types of inboard shield

Case name	W	W-HC	SS-HC	HC
Material composition	W 40% SS 30% Water 30% (Borated)	W 21.0% HC 21.0% SS 30.5% Water 27.5%	HC 21.0% SS 51.5% Water 27.5%	HC 42.0% SS 30.5% Water 27.5%
DPA in copper, DPA/year	4.62×10^{-6}	3.10×10^{-5}	4.58×10^{-5}	4.87×10^{-5}
Total neutron fluence, $n/(cm^2 \cdot 10years)$	1.81×10^{17}	1.16×10^{18}	1.62×10^{18}	1.39×10^{18}
Nuclear heating rate, $Watt/cm^3$	2.14×10^{-5}	1.07×10^{-4}	1.95×10^{-4}	2.29×10^{-4}
Epoxy dose, rad/10years	2.58×10^{8}	8.32×10^{8}	1.28×10^{9}	1.38×10^{9}

Availability, duty cycle and the reactor lifetime are assumed to be 25%, 80% and 10 years, respectively.

Table 3.3 Maximum stress intensity in TF coil components

<table>
<tr><th colspan="3">Components</th><th colspan="2">Maximum stress intensity σ_{max} (kg/mm^2)</th></tr>
<tr><td colspan="3">Inner ring</td><td colspan="2">24.3</td></tr>
<tr><td rowspan="6">Conductor</td><td rowspan="2">1st layer</td><td>Copper</td><td rowspan="2">19.5</td><td>21.3</td></tr>
<tr><td>Insulator</td><td>4.6</td></tr>
<tr><td rowspan="2">2nd layer</td><td>Copper</td><td rowspan="2">17.2</td><td>18.8</td></tr>
<tr><td>Insulator</td><td>4.1</td></tr>
<tr><td rowspan="2">3rd layer</td><td>Copper</td><td rowspan="2">19.6</td><td>21.5</td></tr>
<tr><td>Insulator</td><td>4.7</td></tr>
<tr><td colspan="3">Outer ring</td><td colspan="2">28.3</td></tr>
<tr><td colspan="3">Side board</td><td colspan="2">23.3</td></tr>
<tr><td colspan="3">Spacer</td><td colspan="2">-6.2</td></tr>
</table>

Table 3.4 INTOR Poloidal Field Coil Locations and Maximum Ratings[4]

Coil No.	Block No.	R (M)	Z (M)	N #	Transformer Component (MAT)	Shaping Component (MAT) with divertor	Total (MAT) with divertor	Shaping Component (MAT) without divertor	Total (MAT) without divertor
1	1	1.5	0.5	1	-3.68	-2.34	-6.02	-1.95	-5.63
2	1	1.5	1.5	1	-3.68	-2.34	-6.02	-1.95	-5.63
3	2	1.5	2.5	1	-3.60	*****	-3.60	*****	-3.60
4	2	1.525	3.5	1	-3.60	*****	-3.60	*****	-3.60
5	2	1.675	4.5	1	-3.60	*****	-3.60	*****	-3.60
6	3	2.25	5.4	2	-1.72	10.0	8.28	8.0	6.28
7	3	3.1	6.05	1	-0.86	5.0	4.14	4.0	3.14
8	3	4.5	6.35	1	-0.86	5.0	4.14	4.0	3.14
9	4	6.25	6.1	1	-0.15	+0.0 -1.0	-0.15 -1.15	*****	0.15
10	5	8.5	4.85	1	-0.10	-5.17	-5.27	-3.29	-3.39
11	6	9.9	3.0	1	-0.15	-1.98	-2.13	-2.87	-3.02

Plasma current I_p at the flat-top is 4.7 MA.

: N is a ratio of the coil turns in the same block.

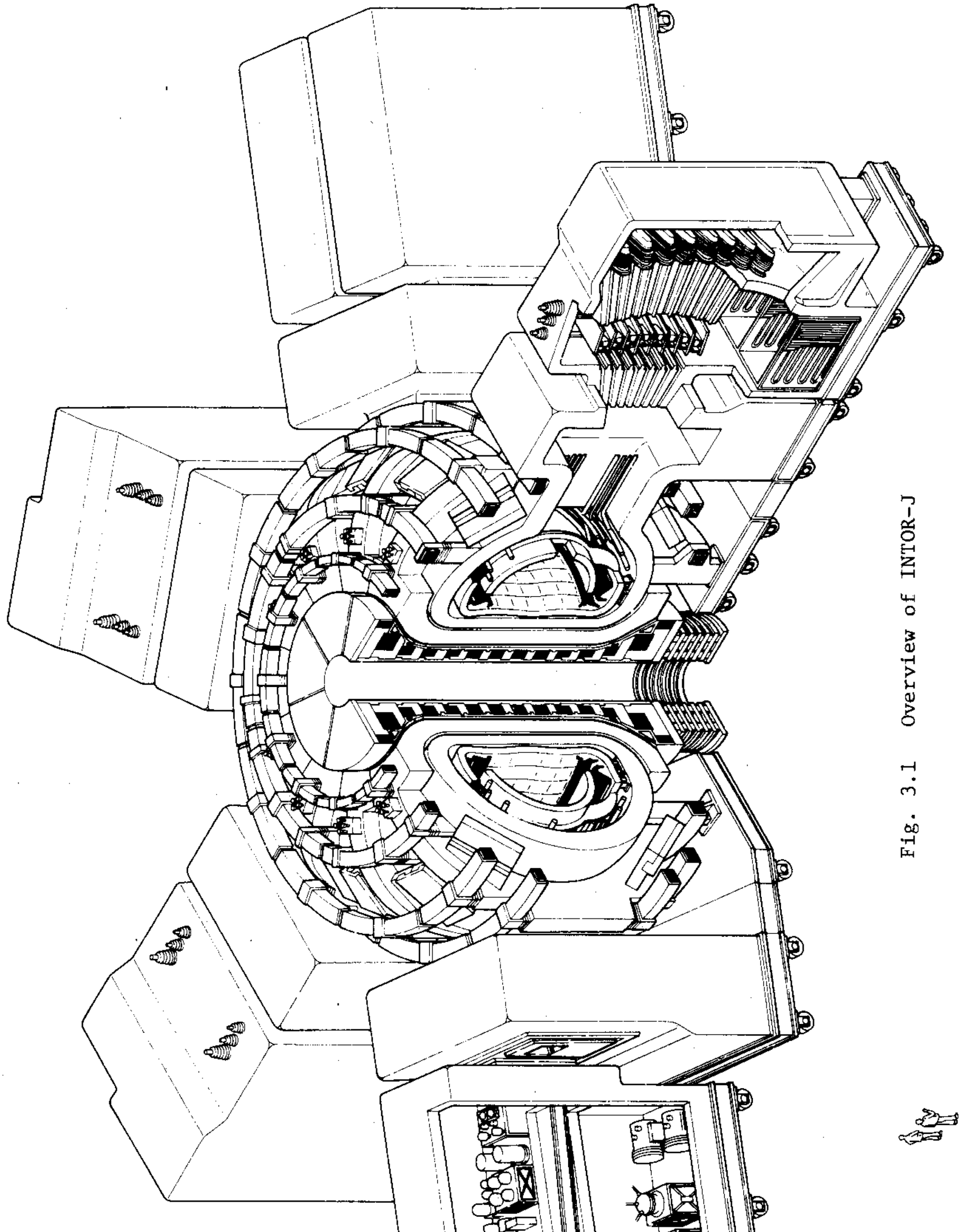


Fig. 3.1 Overview of INTOR-J

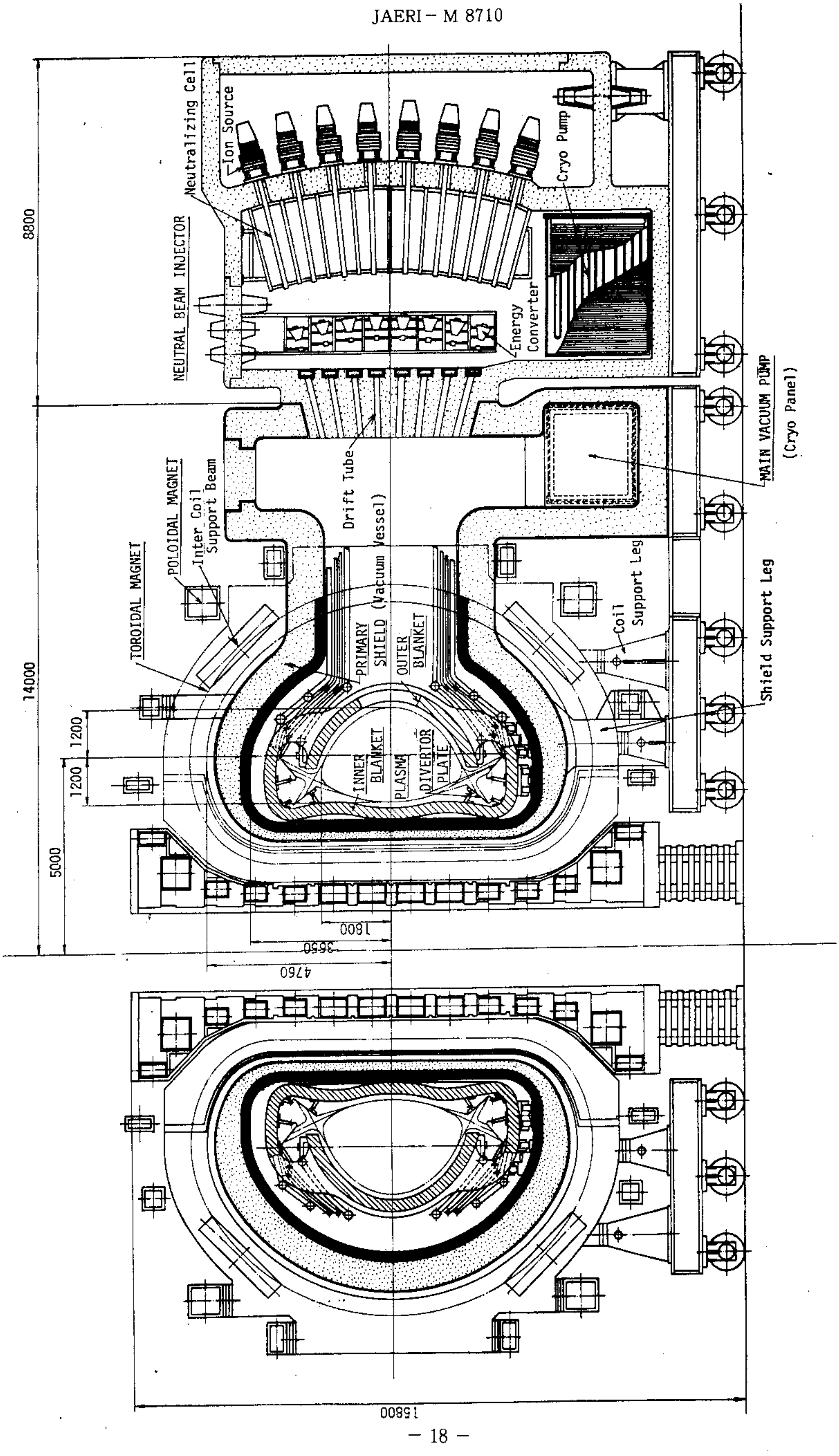


Fig. 3.2 General Reactor Concept of INTOR-J

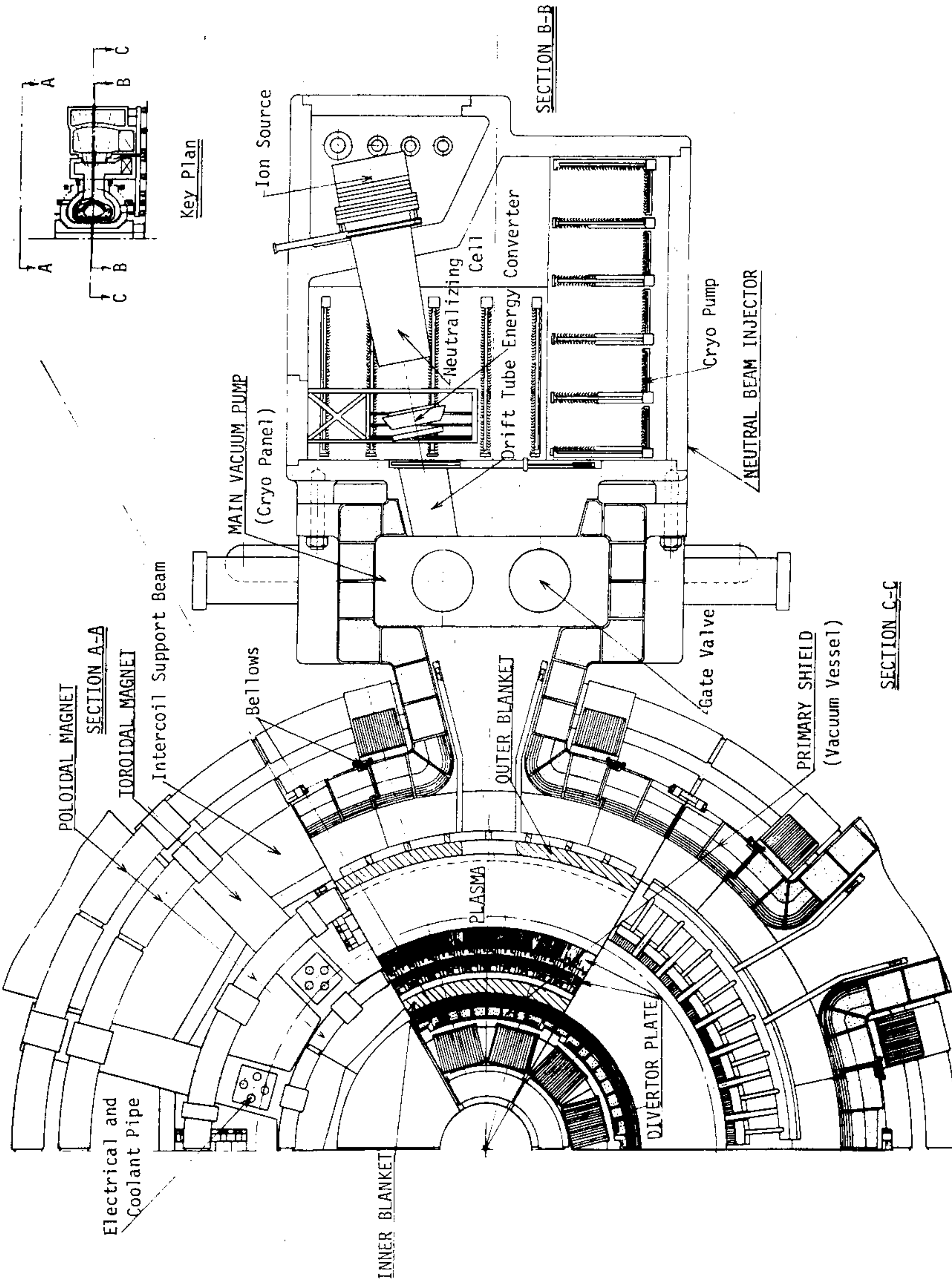


Fig. 3.3 Horizontal View of INTOR-J

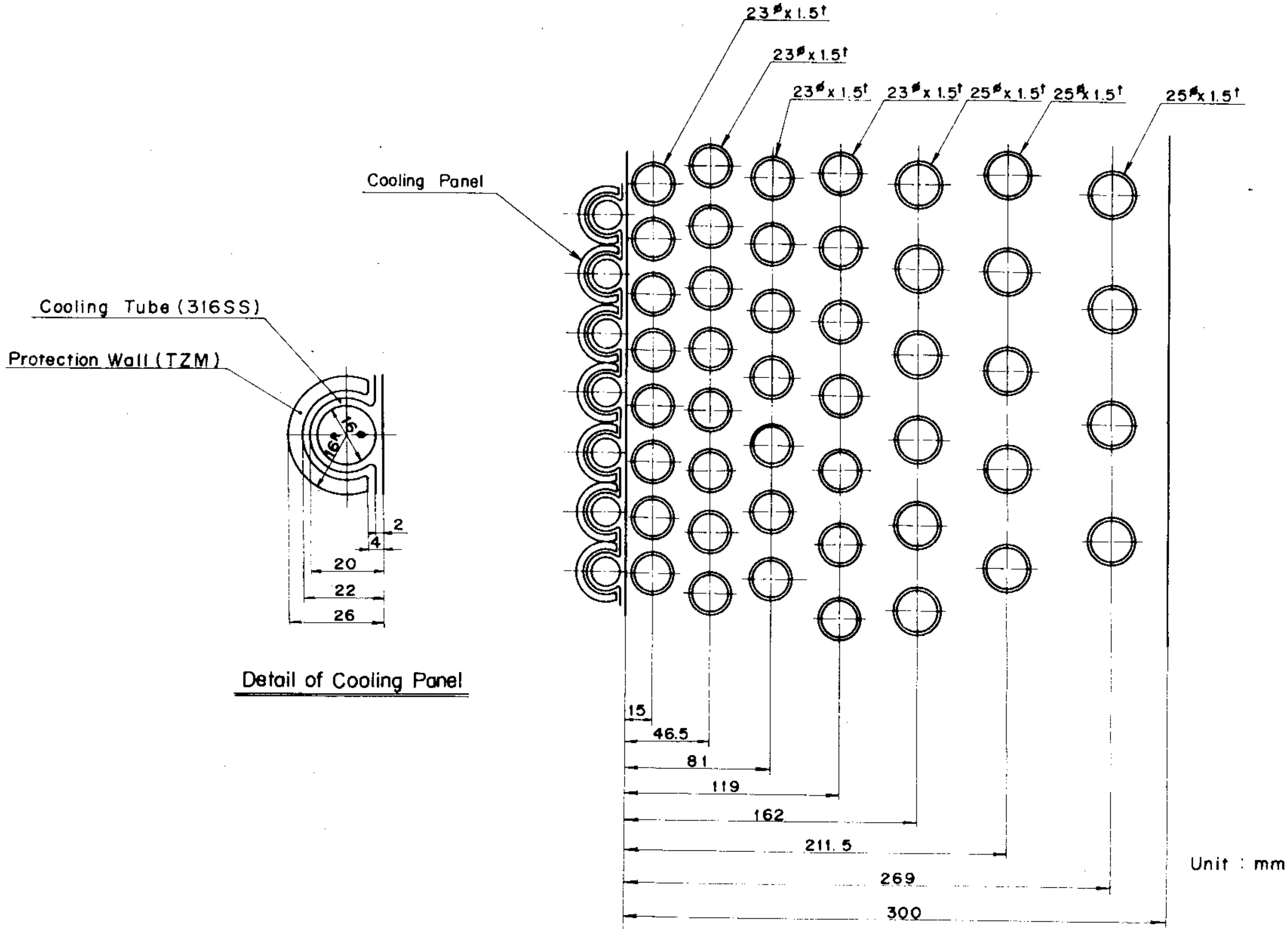


Fig. 3.4 Cross Section of First Wall and Blanket

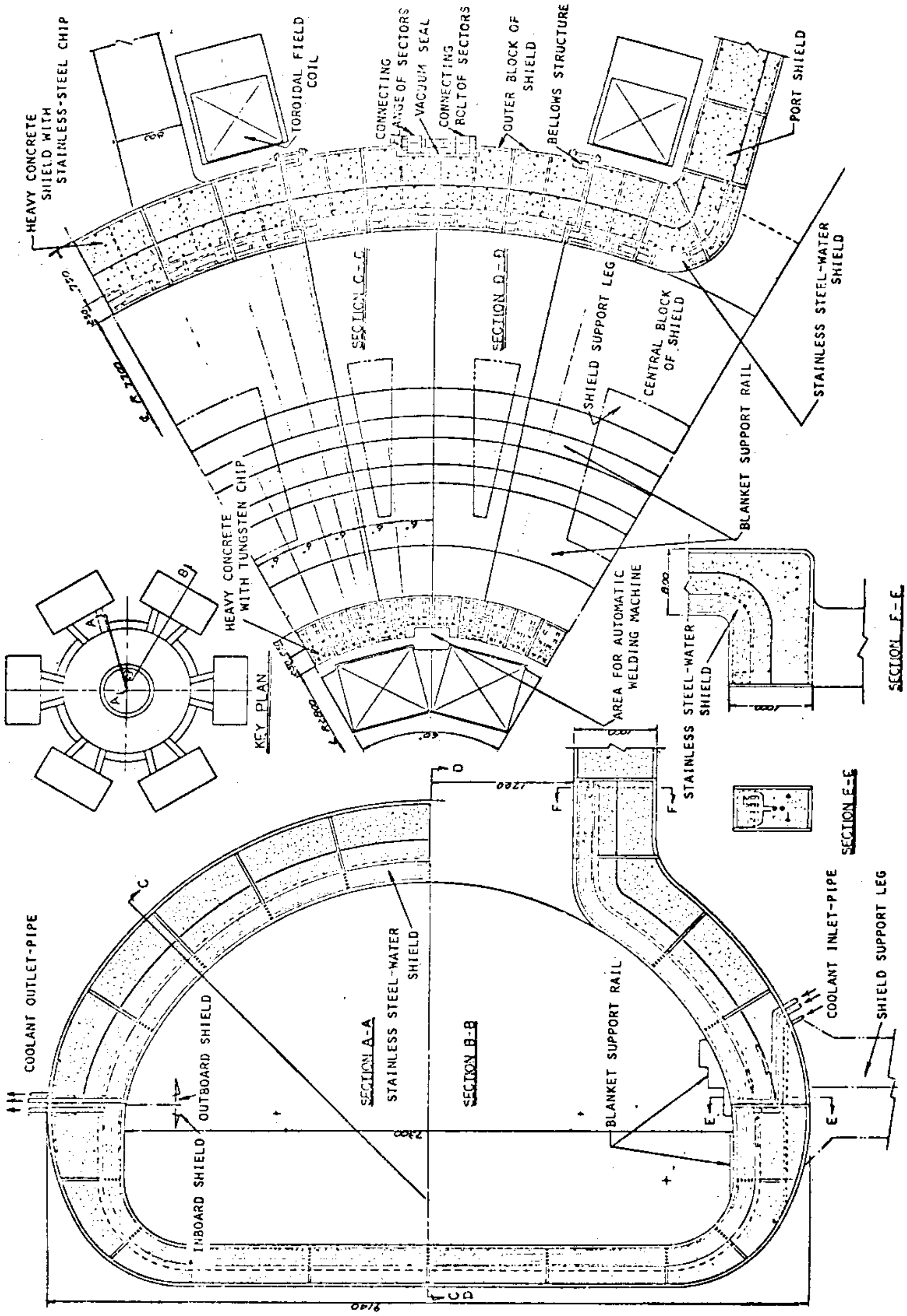


Fig. 3.5 Primary shield structure

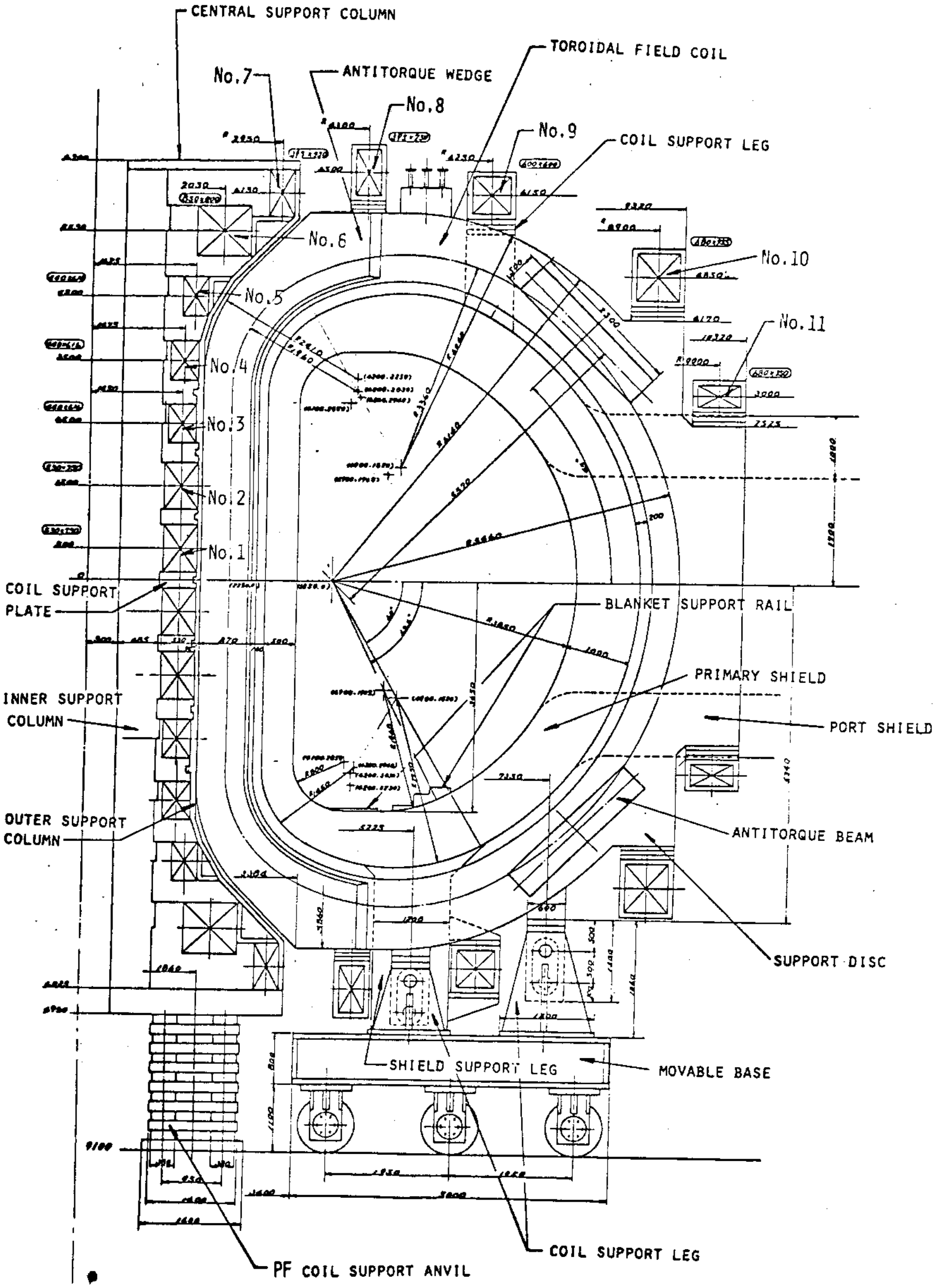


Fig. 3.6 Radial Position and Size of PF and TF Magnets(Concept A)

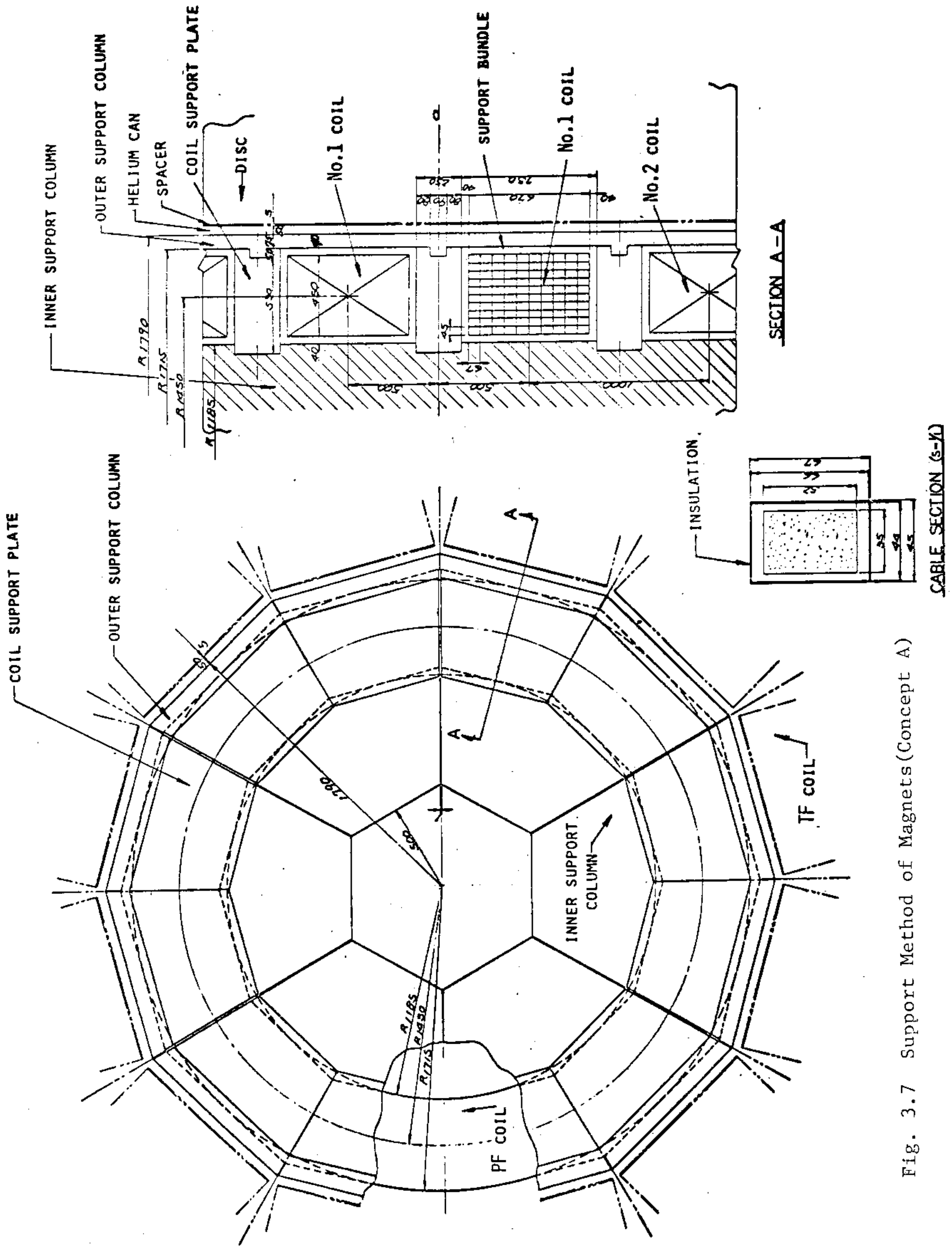


Fig. 3.7 Support Method of Magnets (Concept A)

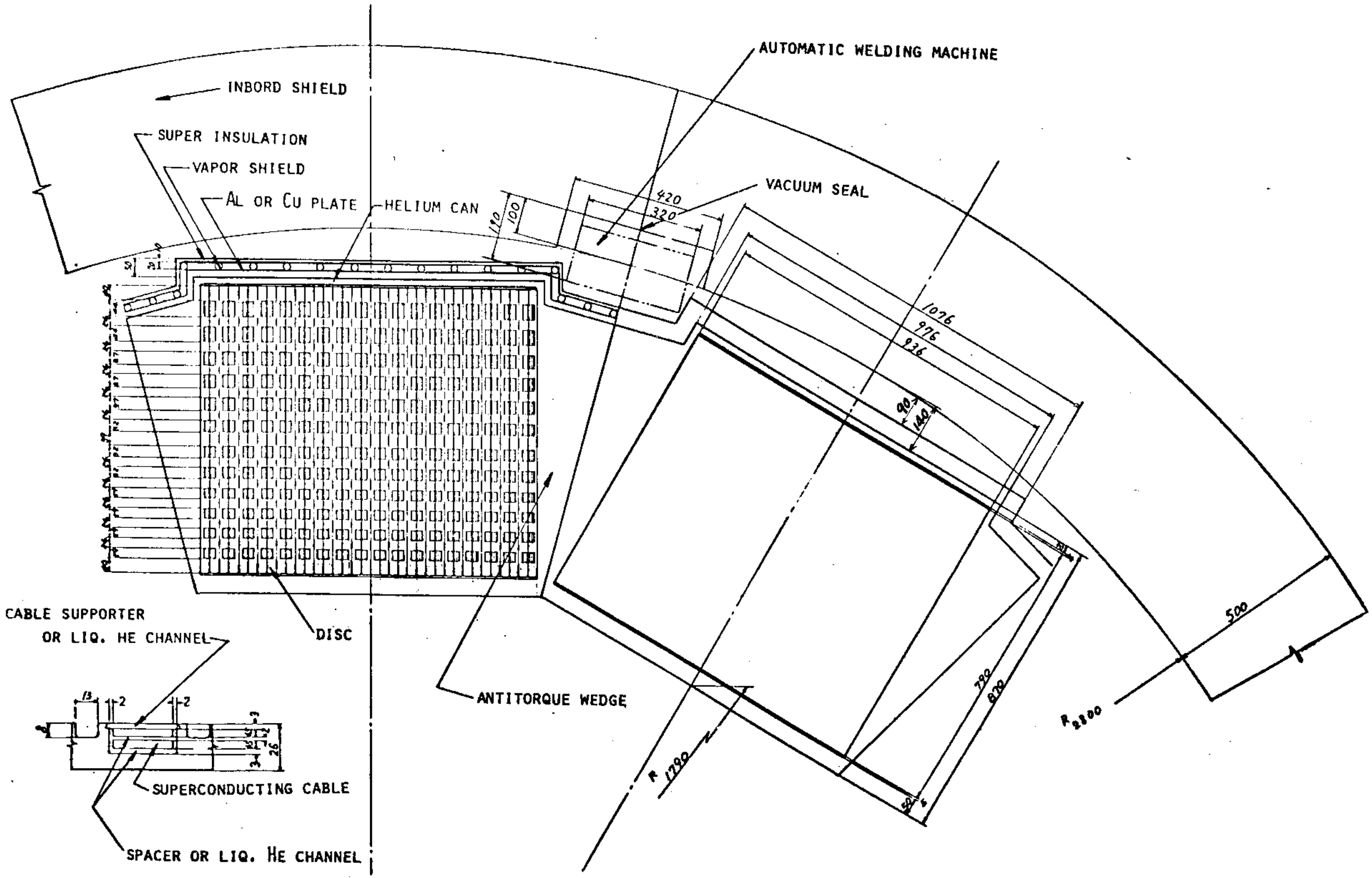


Fig. 3.8 Cross Section of TF Magnet and its Gap between the Shield(Concept A)

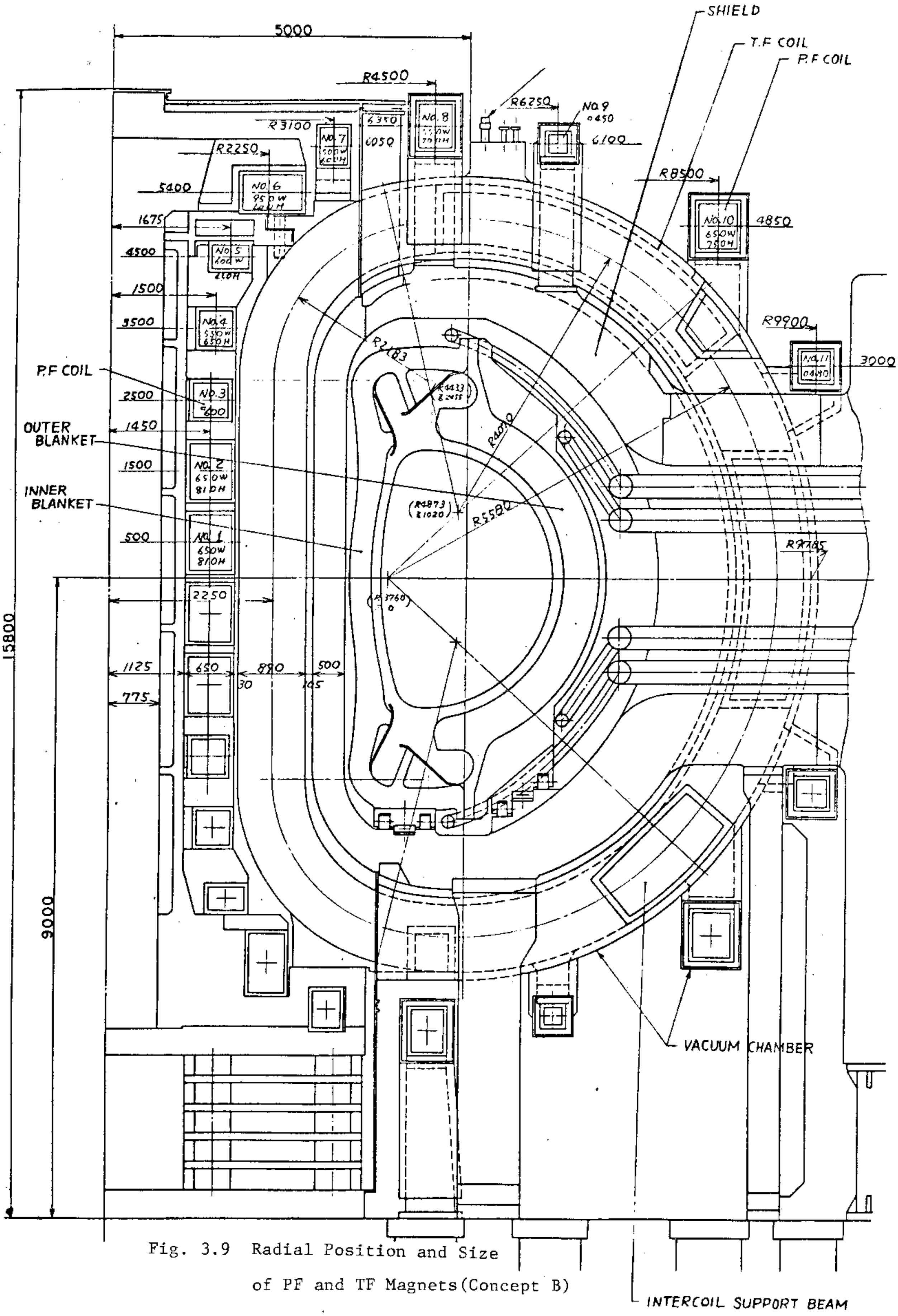
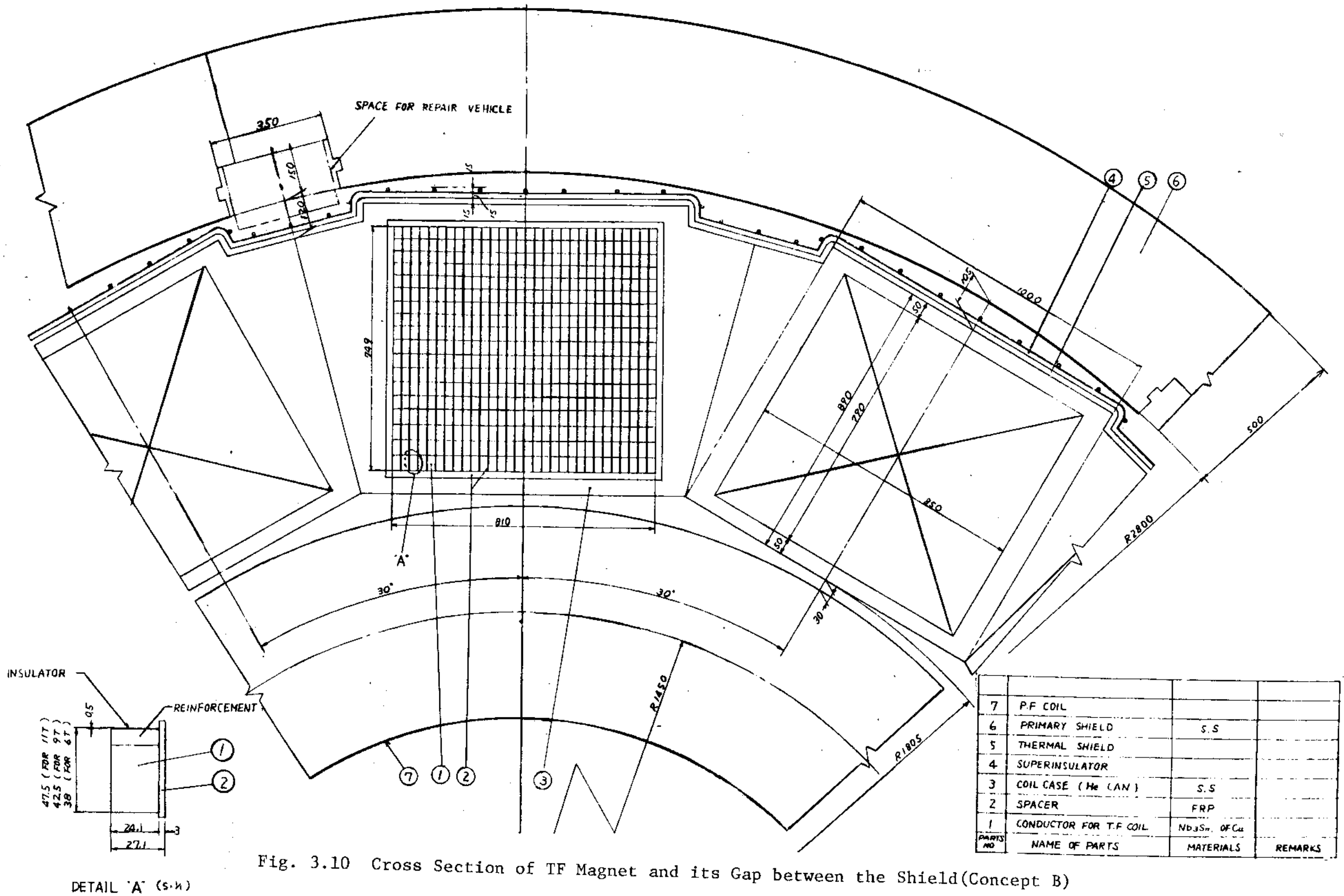


Fig. 3.9 Radial Position and Size of PF and TF Magnets(Concept B)



PARTS NO	NAME OF PARTS	MATERIALS	REMARKS
7	P.F COIL		
6	PRIMARY SHIELD	S.S	
5	THERMAL SHIELD		
4	SUPERINSULATOR		
3	COIL CASE (He CAN)	S.S	
2	SPACER	FRP	
1	CONDUCTOR FOR T.F COIL	Nb_3Sn, OFCu	

Fig. 3.10 Cross Section of TF Magnet and its Gap between the Shield(Concept B)

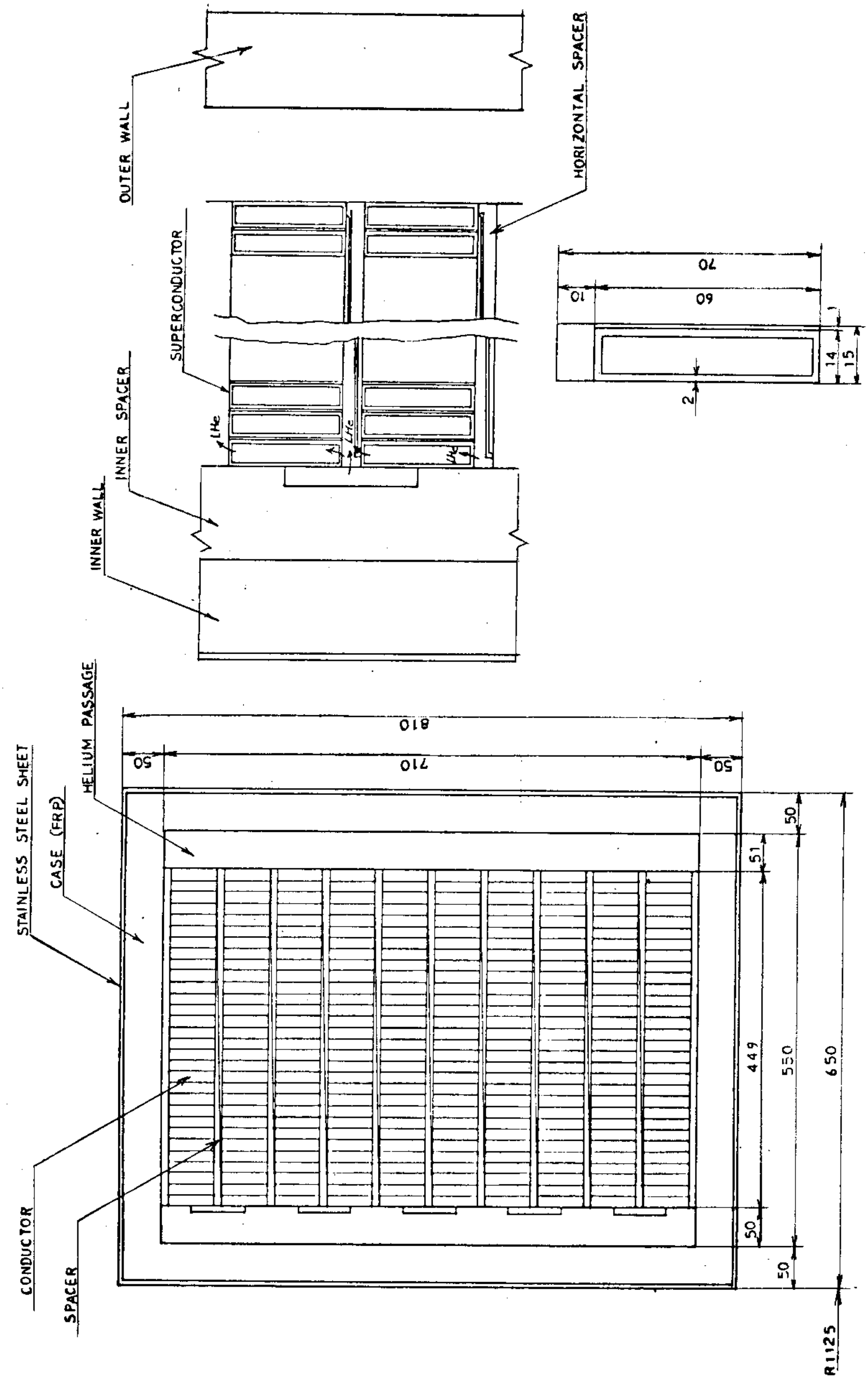


Fig. 3.11 Cross Section of PF Magnet (Concept B)

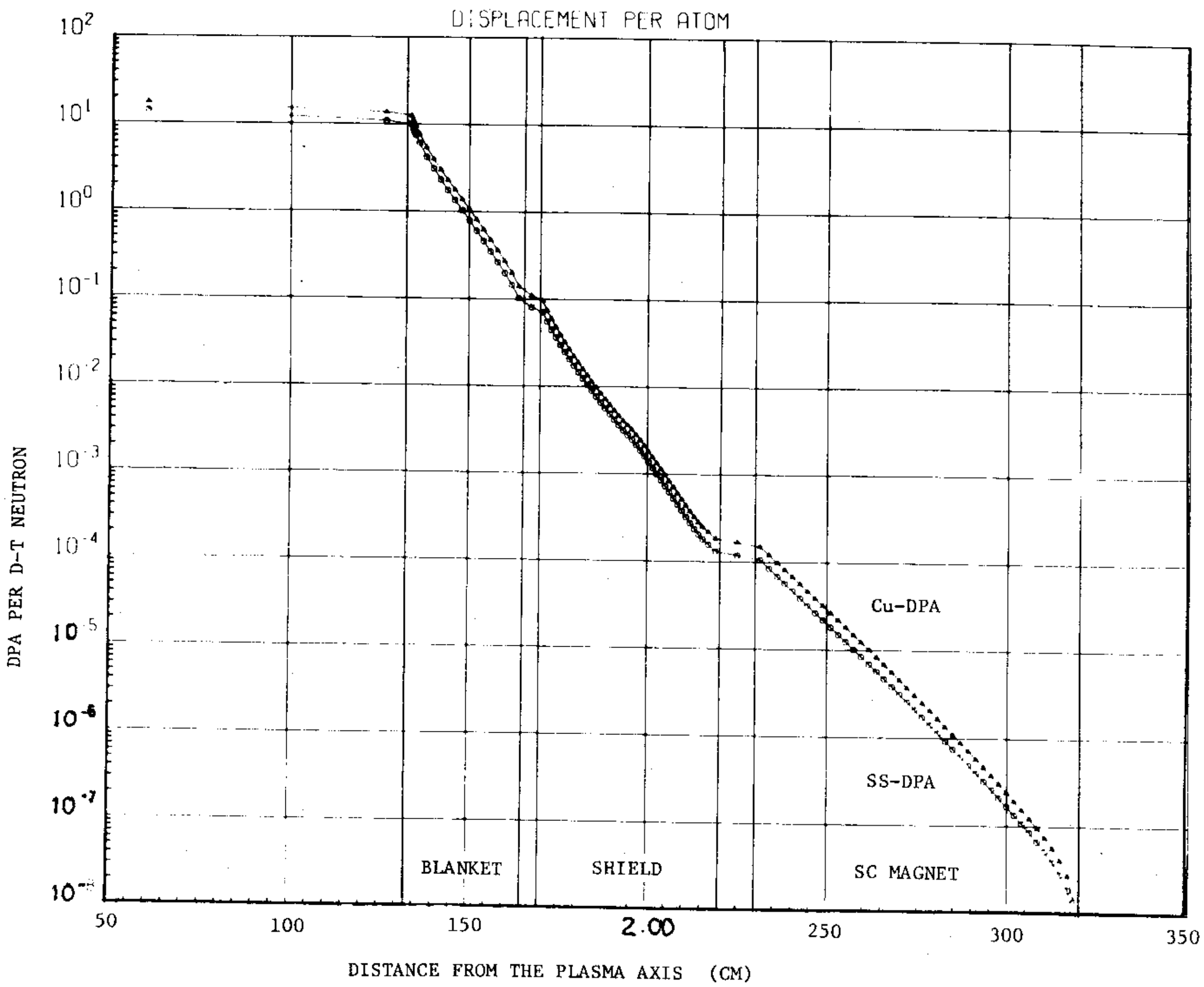


Fig. 3.12 DPA Rates of Stainless Steel and Copper in the Case W-HC Inboard Shield

4. SUMMARY

Although the design is not fully in detail, as reasonable judgements, the following concluding remarks are summarized for the INTOR-J.

4.1 Shielding

① Present design is satisfactory, if the annealing of TF magnets once in 3.2 years is allowed.

② The thickness must be increased 8 cm to extend the time interval between the annealing to 10 years. Therefore careful consideration is required in deciding the annealing frequency.

4.2 TF magnet

Present design is near the engineering limit.

4.3 PF magnet

Present design is near the engineering limit.

4.4 Space between components

Considering the processes for fabrication and repair and maintenance, present values are near the engineering limit.

4.5 Overall assessment

Present design as a whole is near the limit with respect to dimensions. It is desirable to increase the major radius by 10cm and give some margins to each components.

ACKNOWLEDGMENT

Authors would like to acknowledge deeply the people from the industries who participated in this study; Special thanks are extended to the people in Mitsubishi Industries Group and Toshiba Corporation for their enthusiastic contributions on the studies of magnet and shielding.

REFERENCES

(1) Sako, K. et al., "Engineering Aspects of the JAERI Proposal for INTOR (II)", JAERI-M 8518 (1979)

(2) F. Engelmann, V.I. Pistunovich, Tazima, T., "Suggested INTOR Parameters"

(3) Seki, Y. and Maekawa, H., J. Nucl. Sci. Technol., 14 (3), 210 (1979)

(4) Sako, K. et al., "Engineering Aspects of the JAERI Proposal for INTOR (I)", JAERI-M 8503 (1979)

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Appendix : Some Considerations on the New Reactor Size Parameters Suggested by the Physics Group

For reference we have made an examination of the reactor size on the basis of the new suggested INTOR parameters sent by the physics Group after Session 3. The case A (Table A.1) of the two sets has been considered for both non-divertor reactor and poloidal divertor reactor. The evaluations for individual components are described below.

1) PF magnet

The flux swing of the Set A is 115 V.S which increases from 90 V.S of INTOR-J. This demands a change of the design. Although the detailed discussion should be made on the basis of equilibrium analysis and optimization of the coil configuration, the evaluation results on the size of INTOR-J lead to the following results.

a) The radius of the geometrical center of No.1 PF coil is 1.6 m.
b) The ampere-turn is nearly equal to that of INTOR-J,according to a preliminary analysis for coil configurations.
c) The thickness of the support structure has to be increased corresponding to the increase of the coil radius.

In this design also should be carried out such measures for reducing the stress which were described previously for INTOR-J.

2) TF magnet

The TF magnet has been examined on the basis of Concept A of INTOR-J. (The Concept B is considered to lead to the similar conclusion also.)

The width of TF coil increases by an increase of the radius where TF coils locates and as a result there arise rooms which are capable of housing more conductors. The B_t value at R = 5.5 m for the same current density is 5.05 T. In this case the maximum field of TF coil increases by 3.7 % . In order to obtain B_t = 5.2 T at R = 5.5 m, the current density of TF coil has to increase by 3 %. As the result the stress in TF coil increases aggregately by about 10 %. The stress increases furthermore because the vertical cross section of TF coil increases. These considerations demand the increase of the conductor thickness more than 10 %.

3) Shielding

Since the neutron wall loading increases to 1.3MW/m^2 from 1MW/m^2 of INTOR-J, an annealing process is necessary every 2.5 years for the 50 cm thickness of the inner bulk shield and every 10 years for the 60 cm thickness. The choice of annealing frequency is an important issue in the future.

4) Space between Individual Components

The necessary space between individual components is at least as much as that of INTOR-J.

Conclusion

The vertical cross section of the reactor with poloidal divertors and its horizontal cross section are shown in Figs. A.1 and A.2, respectively. Figure A.3 shows the cross section of TF coils.

We conclude that the major radius of 5.5 m given by the Set A is adequate. In the figures there arises a margin of 10cm for the shielding thickness, though the margin changes depending on the annealing frequency. However, since this margin can be used to relax the severity in space for TF and PF magnets, machine construction, repair and maintenance, a large reduction from R=5.5 m should not be made at the present stage of design, though optimization of an allocation of the space margin is recommended.

Alternative Recommendation

The size of a reactor with poloidal divertors(Fig. A.1) becomes inevitably larger than that of a non-divertor reactor having the same plasma size shown in Figs. A.4 and A.5. As shown in Fig. A.6, the plasma with poloidal divertors which can be housed in the non-divertor reactor on the base of Set A is given by the parameters, R=5.3 m, a=1.2 m and B_t=5.4 T. If the design approaches of different reactor concepts are made for the same reactor size, the Set A should be considered as guiding parameters for a non-divertor concept and the above parameters seem to be reasonable for a concept with poloidal divertors.

Finally radial dimensions of INTOR-J and the reactor on the basis of new INTOR parameters are shown in Fig. A.7.

Table A.1 Set A of the New INTOR Parameters Suggested by the Physics Group (2)

Wall radius, a_w (m)	1.5
Major radius, R (m)	5.5
Magnetic field, B (T)	5.2
Plasma radius, a (m)	1.4
Aspect ratio, R/a	3.9
Elongation, b/a	1.6
Plasma current, I_p (MA)	6.6
Flux swing (Vs)	115
Neutron wall loading (MW/m^2)	1.3

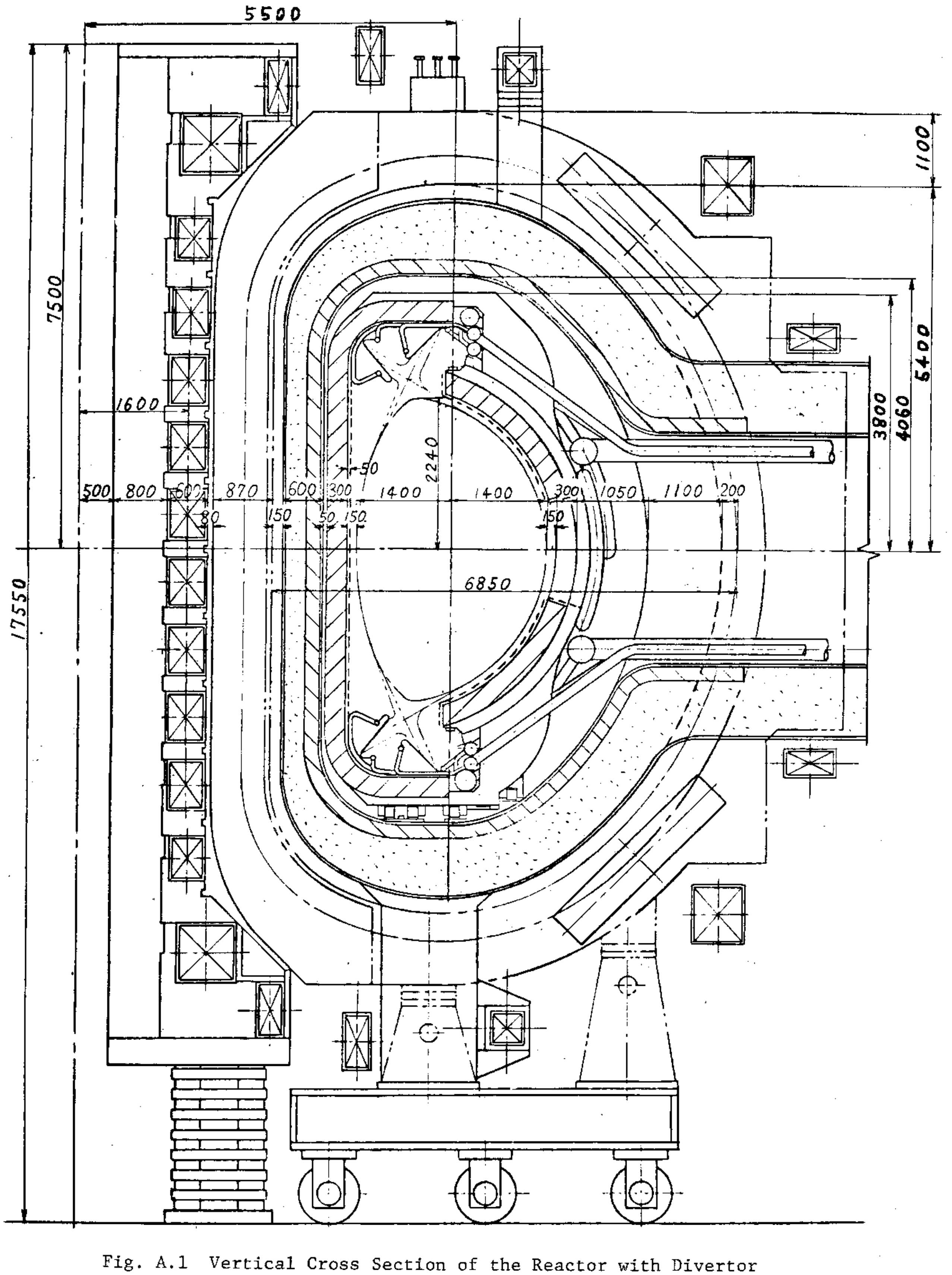


Fig. A.1 Vertical Cross Section of the Reactor with Divertor

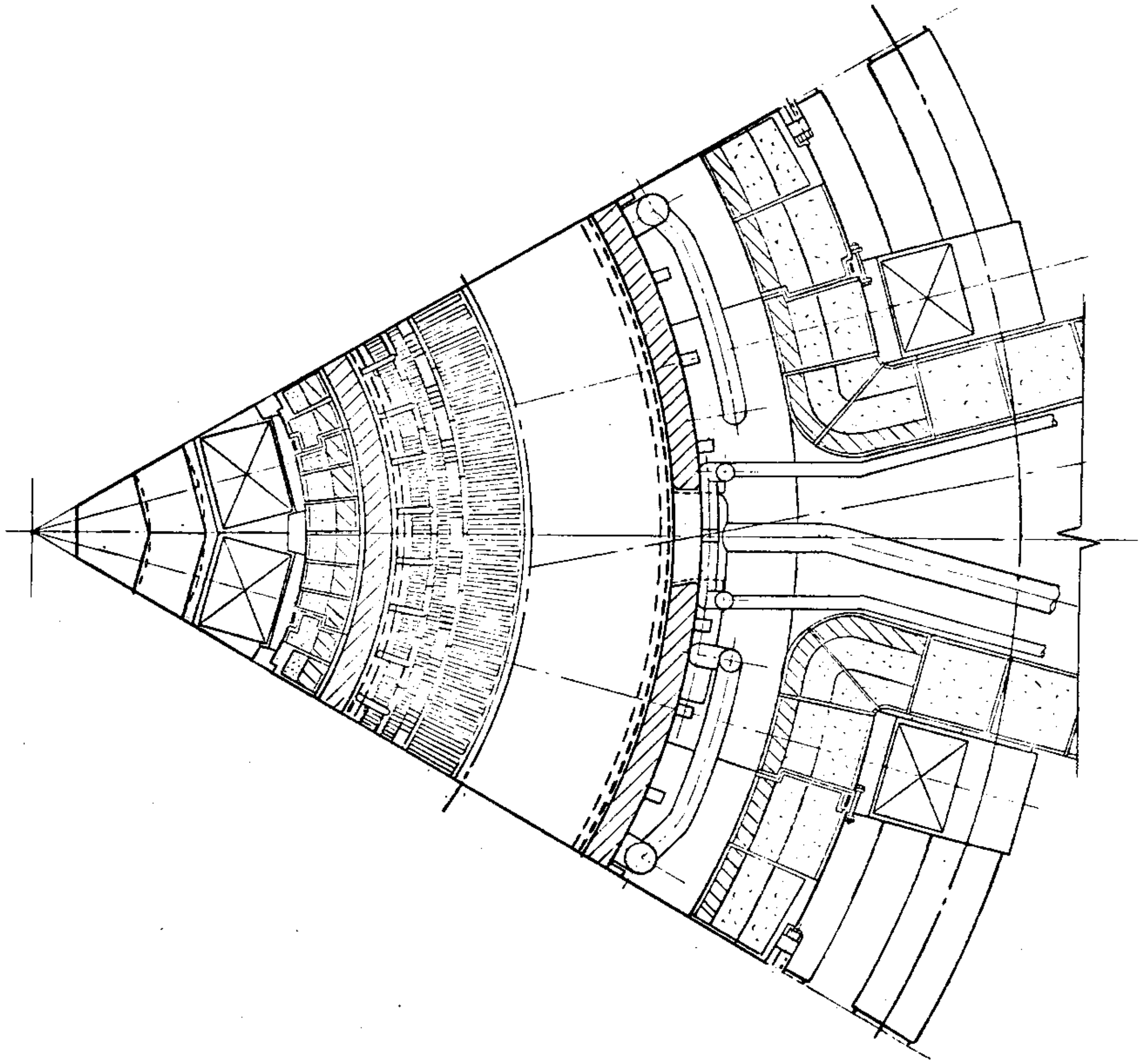


Fig. A.2 Horizontal Cross Section of the Reactor with Divertor

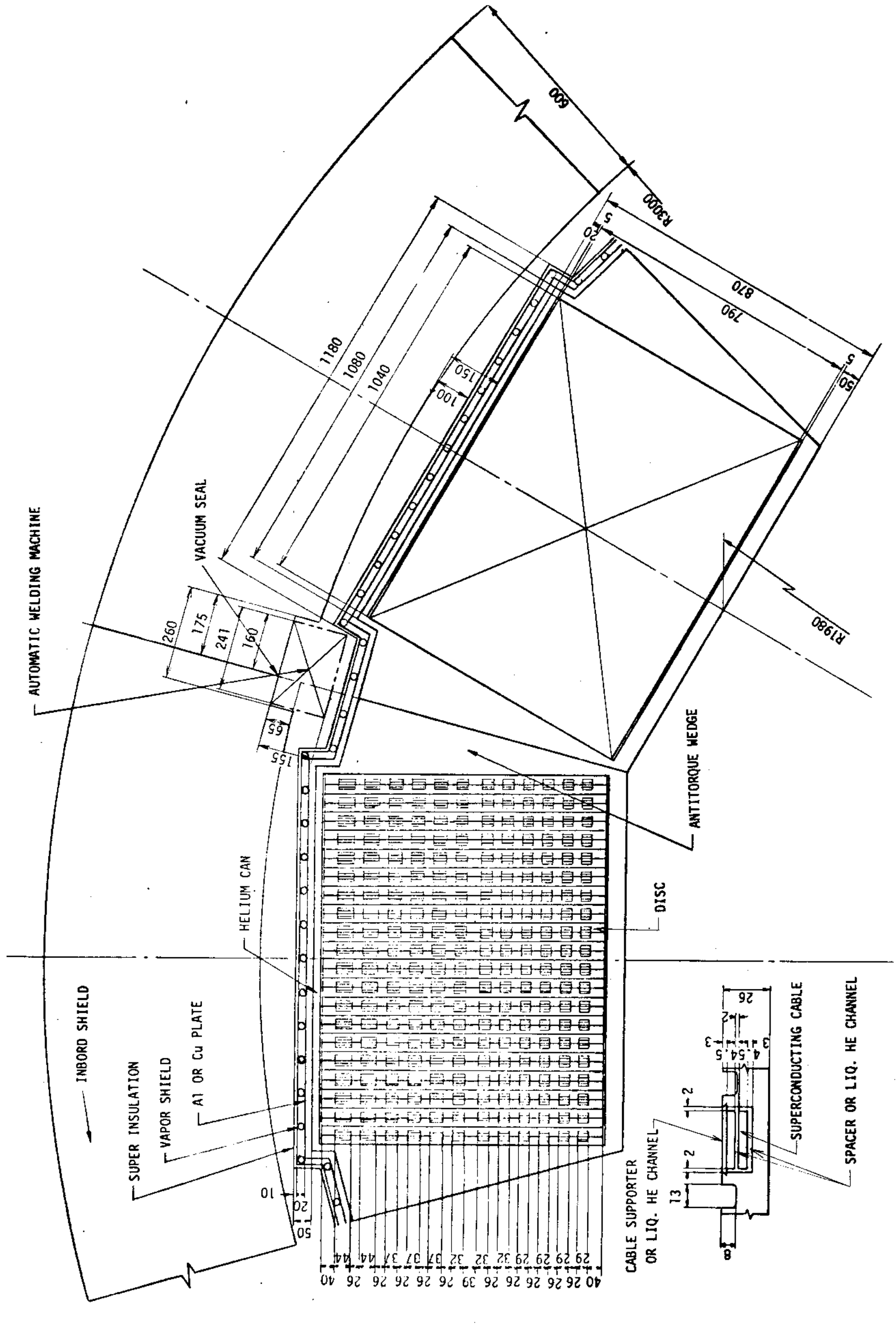


Fig. A.3 Cross Section of TF Coil

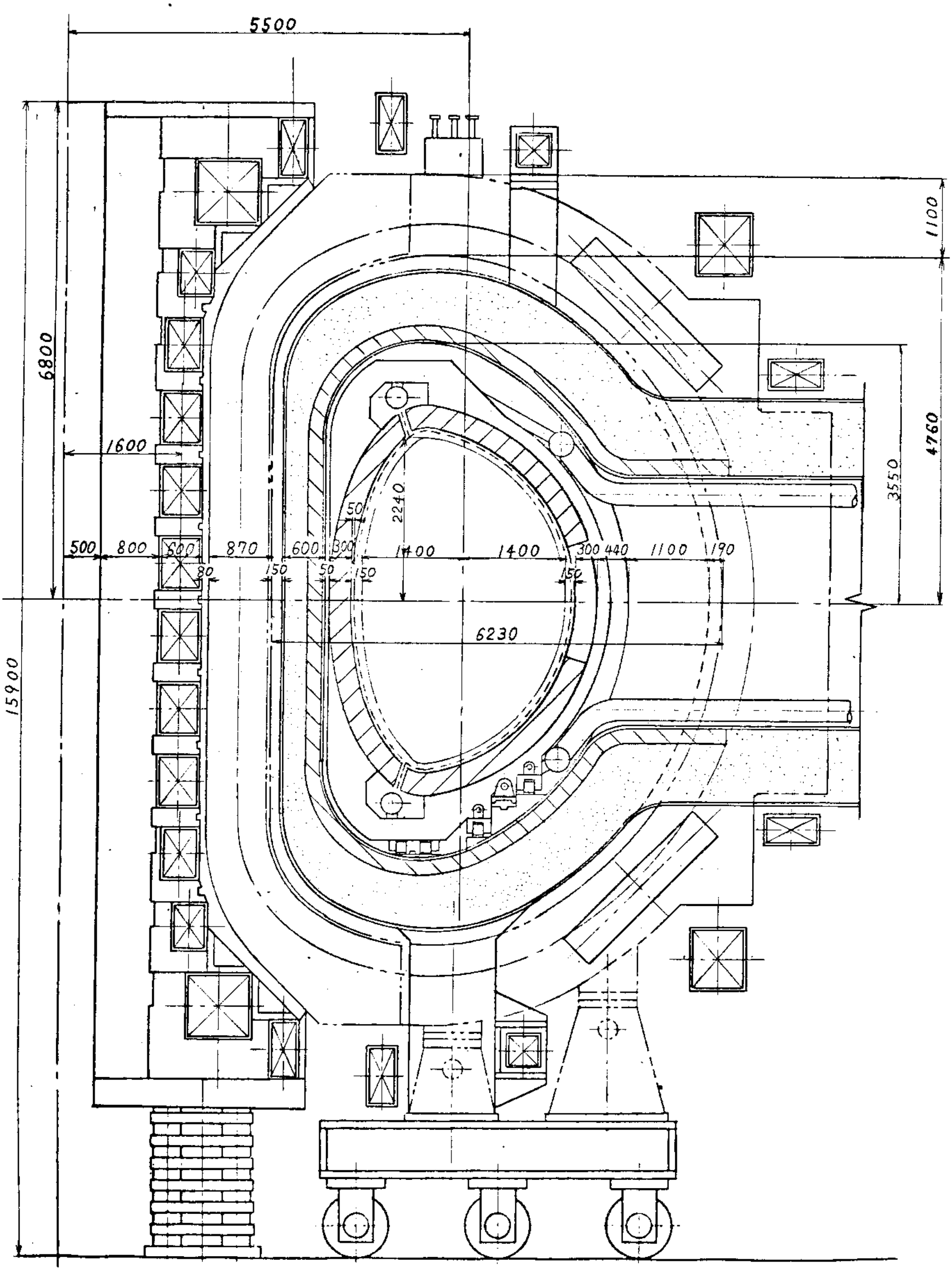


Fig. A.4 Vertical Cross Section of the Non-Divertor Reactor

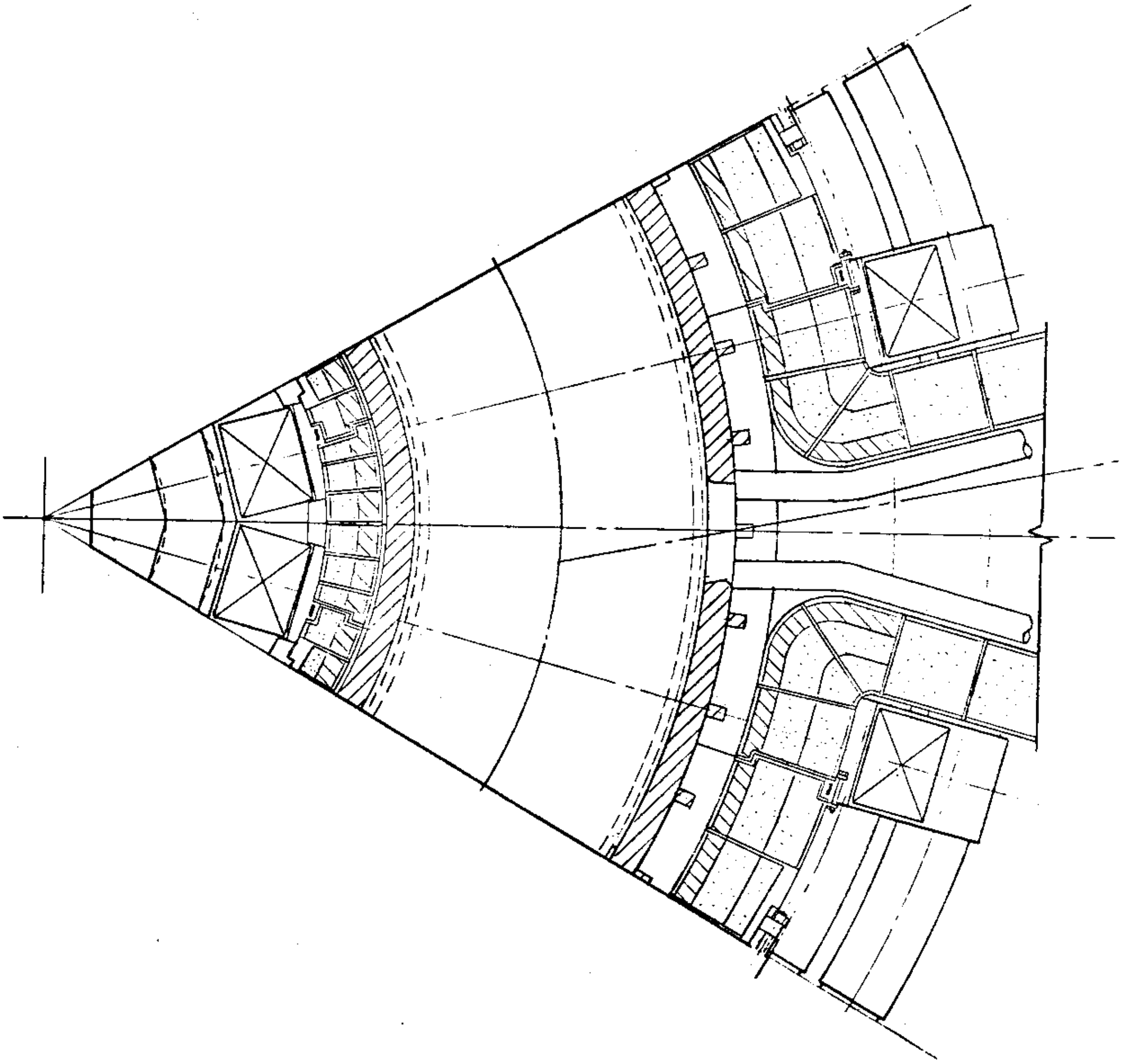


Fig. A.5 Horizontal Cross Section of the Non-Divertor Reactor

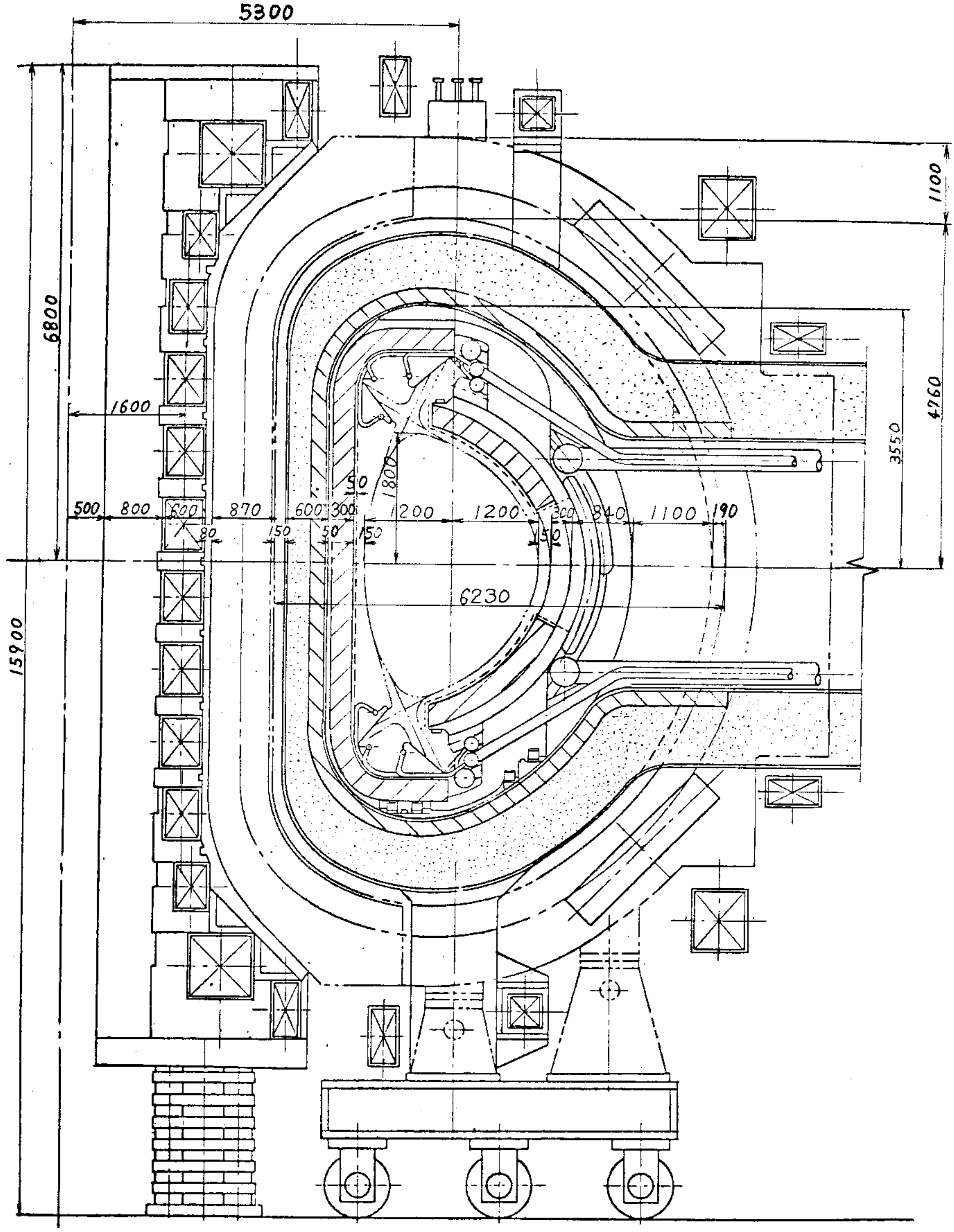
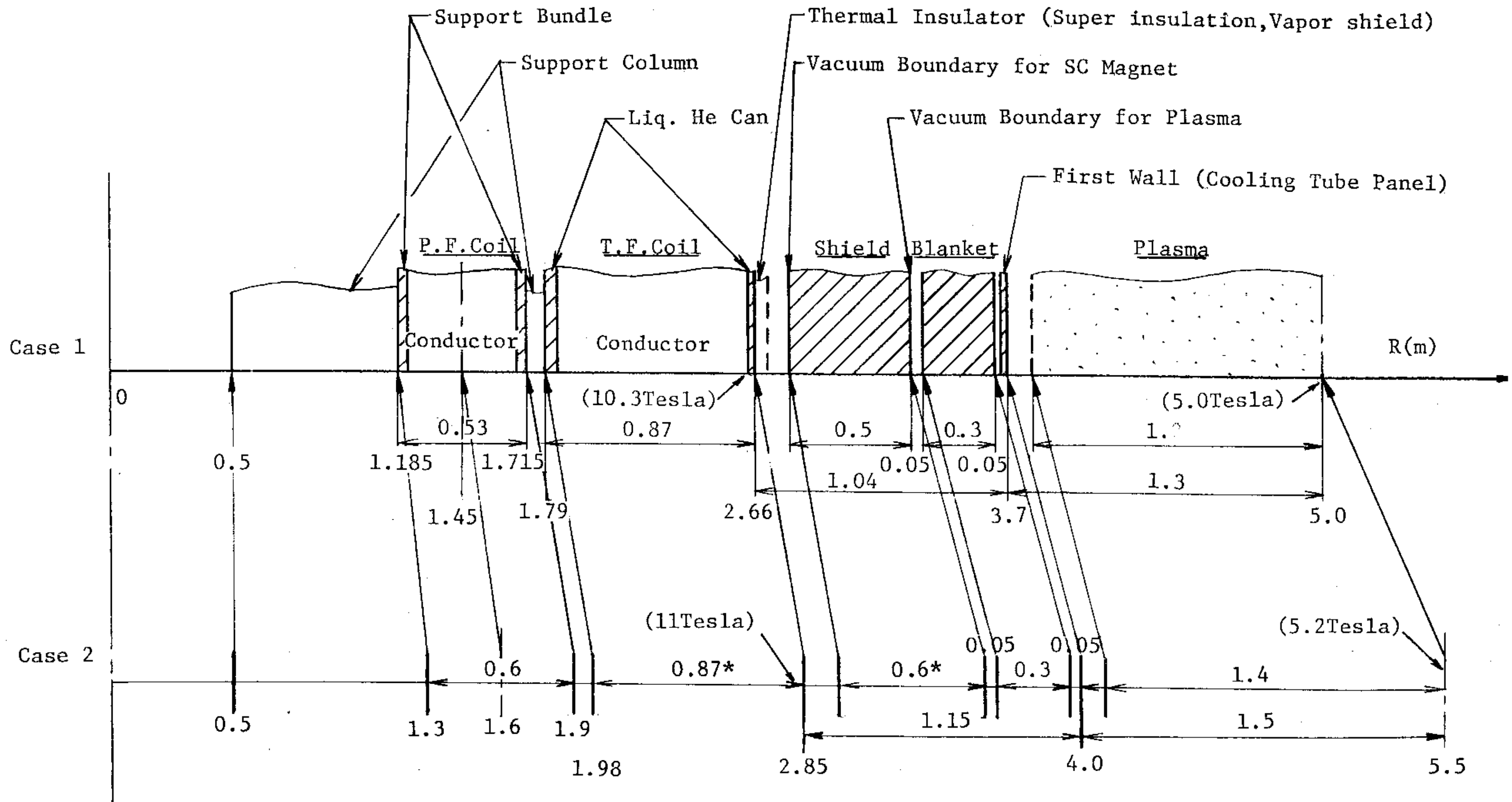


Fig. A.6 Vertical Cross Section of the Reactor with Divertor (Alternative)



* Optimization of the dimensions between TF coil and shielding should be performed.

Fig. A.7 Radial Dimensions of INTOR-J(Case 1) and the New Parameters(Case 2)