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CONCEPTUAL DESIGN OF SC MAGNET SYSTEM FOR ITER (VI)

— R&D PROPOSALS —

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- R&D Proposals -

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The International Thermonuclear Experimental Reactor (ITER) is an experimental thermonuclear tokamak reactor in order to test the basic physics performance and technologies. The conceptual design activity (CDA) of ITER required the joint work at a technical site at the Max Plank Institute for Plasma Physics in the Garching, Germany from 1988 to 1990. The technical proposals from Japan were summarized by the Fusion Experimental Reactor (FER) Team and the Superconducting Magnet Laboratory of the Japan Atomic Energy Research Institute (JAERI).

This paper describes the Japanese contributions of the R&D proposals to the magnet system for the ITER. These proposals were discussed in ITER CDA design team and summarized in ITER Technical report No. 20. The development program of Toroidal Field Coil is basically proposed from Japan with the design and analysis reports. The Japanese proposals are almost adopted in the ITER Long-Term R&D program.

Keywords: Superconducting, Fusion, ITER

ITER 用超電導マグネット・システム概念設計（Ⅵ）
－ R＆D計画案 －

日本原子力研究所那珂研究所核融合工学部
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21世紀初頭に完成が予定されている国際熱核融合実験炉（ITER）の概念設計活動の超電導マグネット・システムに対する日本の提案を示す。1988年から90年まで西ドイツのミュンヘン郊外にあるマックスプランク・プラズマ物理学研究所で，このITER概念設計活動は行われた。原研那珂研究所の核融合実験炉特別チームが中心になり，超電導磁石研究室が日本の設計案をまとめたものである。

この報告書は1991年から計画されているITER長期R＆D計画について，日本の提案をまとめたものである。本提案はその後に各国と協議を経てITER案にまとめ挙げられた原案を成すものである。特に，トロイダル・コイルの開発計画は日本においてこれまで検討してきた原型トロイダル・コイル計画の発展として詳細な解析を行って提案したものである。これらの日本の提案はITERの開発計画にほぼ採用された。

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Contents

目　　次

PREFACE

All of technical design reports from Japanese contributors to ITER magnet design are listed below:

JAERI-M 91-120

CONCEPTUAL DESIGN OF SC MAGNET SYSTEM FOR ITER (I)

- OVERVIEW -

(1) Design Basis

(2) Toroidal Field Coils

(3) Central Solenoid Coils

(4) Outer Ring Coils

(5) Mechanical Design Guideline

JAERI-M 91-121

CONCEPTUAL DESIGN OF SC MAGNET SYSTEM FOR ITER (II)

- STRESS ANALYSIS -

(1) Toroidal Field Coils at End of Burn

(2) Toroidal Field Coils at Fault Conditions

(3) Center Solenoid Coils

(4) PF Coil Support Structure and Outer Ring Coil

(5) Winding Rigidity Analysis

JAERI-M 91-122

CONCEPTUAL DESIGN OF SC MAGNET SYSTEM FOR ITER (III)

- AC LOSS -

(1) Analysis and Measurement of AC Losses in Large Superconducting Coil

(2) AC Loss Analysis

(3) AC Loss in Cryogenic Structure

JAERI-M 91-123

CONCEPTUAL DESIGN OF SC MAGNET SYSTEM FOR ITER (IV)

- POWER SUPPLY AND CRYOGENIC SYSTEM -

(1) Power Supply System for Magnet System

(2) Fault Analysis of TF Power Supply System

(3) Cryogenic System

1. INTRODUCTION

The International Thermonuclear Experimental Reactor (ITER) is an experimental thermonuclear tokamak rector in order to test the basic physics performance and technologies. The conceptual design activity (CDA) of ITER required the joint work at a technical site at the Max Plank Institute for Plasma Physics in the Garching, Germany from 1988 to 1990. The technical proposals from Japan were summarized by the Fusion Experimental Reactor (FER) Team and the Superconducting Magnet Laboratory of the Japan Atomic Energy Research Institute (JAERI).

This paper describes the Japanese contributions of the R&D proposals to the magnet system for the ITER. These proposals were discussed in ITER CDA design team and summarized in ITER Technical report No. 20. The development program of Toroidal Field Coil is basically proposed from Japan with the design and analysis reports. The Japanese proposals are almost adopted in the ITER Long-Term R&D program.

2. PROPOSALS OF THE LONG-TERM R&D OF SC MAGNET SYSTEM

2.1 Introduction

2.1.1 General

The superconducting magnet system consists of the Toroidal Field (TF) Coils, the Central Solenoid(CS) Coils, the Diverter Field (DF) Coils and the Outer Ring (OR) Coils. The total heat load of the magnet system is estimated to be around 100 kW at 4-K region. Major features of each coil are listed in Table 2.1. Baird's-eye view of SC magnet system is shown in Fig. 2.1. The magnet system looks like the back bone of the tokamak machine because the tokamak concept is classified to the magnetic fusion.

Table 2.1 Major features of each SC coils

Coil	Bmax	Shape	Outer height or diameter	Aspects
TF	11 T	D-shape	17 m	Large Stored Energy Neutron Damage
CS	13 T	Circle	4 m	High Field
DF	9 T	Circle	9 m	
OR	5 T	Circle	24 m	Large Diameter

2.1.2 Components of magnet system

The magnet system consists of the following components:

(1) TF coils : 16 coils

(2) PF coils : 8 CS coils, 2 DF coils, and 4 OR coils

(3) Coil service : piping and diagnostics

(4) Structural support: TF coils, PF coils and gravity supports

(5) Power supply system:

- 1 TF power supply and protection system
- 16 PF power supplies

(6) Cryogenic system: about 100 kW

2.1.3. Development items for SC magnet system

The following items were required for the SC magnet system during the Engineering Design Activity (EDA).

(1) TF coil

The coil size of ITER and LCT coil is compared as shown in Fig. 2.2. The ITER TF coil will become the biggest superconducting magnet if it is realized.

Replacement of the TF coils is seriously difficult after D/T burning, because the TF coil is a back born of the Tokamak machine and many structural materials are activated. In addition, there is a heavy plasma vacuum chamber and neutron shield inside the TF coil.

The superconducting coil system is requested to have high reliability and performance (maximum field and current density), which directly influence the size of the tokamak machine.

The most serious concern about using only small circular coils in the Scalable Model Test is the difficulties of manufacturing and the uncertainties of load transmission between windings and case. The test coil which has non-circular winding with thick case shall be manufactured and charged under the same mechanical environment as ITER.

Therefore, the development of TF coil is the most important work in the ITER superconducting magnet system.

(2) CS coil

The CS coil is the most difficult for conductor development because high field (13 T) and pulse operation are required. It is not necessary to develop the DF coils because the DF coils has similar characteristics to the CS coils.

(3) OR coil verification test

The developments of a Nb-Ti pulse conductor are in progress in the DPC program in Japan. However, the OR coil is the most difficult to replace among the magnets. The minor modifications to meet the ITER specifications and verification test utilizing the CS Scalable Model Coil will remarkably reduce the size of machine.

(4) Cryogenic component development

The developments of the key cryogenic components are indispensable to establish the ITER cryogenic system whose capacity is around 100 kW. The ITER cryogenic system should be reliable, controllable, effective, and economic. The development of the medium size system such as 8-kW unit is a good milestone to realize the 100 kW cryogenic system.

2.1.4 Basic research for the magnet technology

(1) Characterization of superconducting strand and conductor

The evaluation of trial manufacturing strands and conductors is indispensable to improve the capability of strands and conductors.

(2) Characterization of cryogenic materials

The evaluation of cryogenic materials is indispensable to improve the capability of cryogenic materials. Especially, the irradiation effects on each material are important to improve the neutron tolerance of the SC coils.

2.2 **Specification of developments**

2.2.1 The TF Model Coil

(1) Shape and size

a. Non-circular, race-track coil as shown in Fig.2.3

b. Size: Bore: 3.00 m x 5.00 m, winding: 0.55 m x 1.10 m

- Bore size is 1/3 of ITER
- Aspect ratio (vertical /horizontal) is 1.7 as same as ITER.

c. Thick case : over 200 mm

(2) Three test coil version

a. Bmax : 11 T

b. Iop : 30 kA

c. Jop : 30 A/mm^2

d. Minimum winding radius : 1.50 m

f. Volume of winding : 9.33 m^3

g. Length of conductor : 8250 m /total

h. High field configuration is shown in Fig. 2.4.

i. Mechanical test configuration is shown in Fig. 2.5.

(3) One test coil version

a. The LCT coils can be used for backup coil as shown in Fig. 2.6.

b. Technical detailed is described in reference[1].

(4) Conductor

a. Nb_3Sn monolithic conductor[1]

b. Hollow cooling and low AC loss.

(5) key Development issue

a. Strand : High performance

b. Joint : Compact and low resistivity

c. Insulation Break : Compact and reliability

(6) Testing items in the common facility:

a. Strand : All bronze strand

b. Steel : Thick plate (200 mm) for case

c. Insulation : Withstand to irradiation

<u>Results</u> of R&D of TF Model Coils are as follows:

(1) Conductor : simulate mass production as 8 km length

a. Manufacturing technique

b. Accuracy of conductor

- Conductor: Jc, AC loss, Stability, Stress effect
- Jacket : mechanical properties

(2) Winding : development of non-circular winding technique
accuracy of winding

(3) Joint : production of joint in an actual coil

(4) Case : production over 200 mm case

a. Manufacturing technique

b. Accuracy of case

c. Mechanical property

(5) Finishing :

a. Closing method

b. Void filling between winding and case

c. Accuracy of final machining

2.2.2 CS Model Coil

Specifications of the CS Scalable Model Coils are as follows:

(1) Shape : Circular
(2) Bmax : 13 T
(3) Iop : 40 kA
(4) Jop : 30 A/mm^2
(5) Minimum winding radius : 1.00 m
(6) Size : ID : 2.00 m, OD : 3.20 m, H : 1.16 m
  a. Bore size is 70 % of ITER, 1 mm radius is minimum size for 40 kA conductors.
  b. The CS Scalable Model Coil in the DPC vacuum tank is shown in Fig.2.7.
  c. Comparison of coil size between the ITER CS coil system and the CS Scalable Model Coil is shown in Fig.2.8
(7) Space limit considerations
  a. Outer diameter is restricted by the TF coil.
  b. The cross sectional view of the winding of the CS Scalable Model Coil is shown in Fig. 2.9.
  c. The pancake joint area of the CS Scalable Model Coil is limited as shown in Fig. 10.
(8) Volume of winding : 5.68 m^3
(9) Length of conductor : 4260 m / total
(10) Conductor
  a. Nb_3Sn bundle conductor developed in the DPC-EX[2]
  b. Preformed Armor type conductor and winding technology[3]
(11) Key Development issue
  a. Strand : High performance
  b. Joint : Compact and low resistivity
  c. Insulation Break : compact and reliability
(12) Testing items in the common facility:
  a. Mechanical measurement
  b. Stability test : nuclear and AC loss
  c. Quench test
  d. Cycle test (Over 1,000)

2.2.3 OR coil verification test

The Outer Ring pancake is required to turn the technology of the Demonstration Poloidal Coils (DPC). The specifications of the OR pancake are described as follows:

(1) Demonstration of long cooling path (400 m) and quench protection

(2) Fabrication of long conductor (800 m)

(3) OR pancake : ID 2.0 m same as CS coil size
one or two pancake

(3) Conductor

a. Nb-Ti coaxial bundle conductor

b. Modified DPC conductor[4]

(4) Testing in the common facility:

a. Mechanical measurement

b. Stability test : nuclear and AC loss

c. Quench test

d. Cycle test (Over 1,000)

2.2.4 Cryogenic component development

The conceptual design of the cryogenic system is developed based on the preliminary thermal analysis. The following items are required to develop the key component of cryogenic system[5].

(1) A large scale turbine

a. Mass flow rate : more than 1000 g/s

b. Adiabatic efficiency : more than 70-75 %

c. Wide operation range : 40 - 100 %

(2) A large gas helium compressor

a. Mass flow rate : 2 kg/s - 14 kg/s

b. Oil free centrifugal type

c. Isothermal efficiency : more than 65 %

(3) Cryogenic circulation pump

a. Mass flow rate : 4000 g/s

b. Pump head : 0.25 MPa

c. Adiabatic efficiency : more than 60 %

(4) Cold compressor

a. Mass flow rate : 1500 g/s

b. In/out pressure : 0.05 MPa / 0.13 MPa

c. Adiabatic efficiency : more than 60 %

(5) Wet (or She) turbine

a. Mass flow rate : 2000 g/s

b. Adiabatic efficiency : more than 60 %

2.3. Test Facility Requirements

2.3.1. Common Test Facility

The common test facility are required to examine the model coils.

(1) Cryogenic system

a. Refrigerator : 8 kW at 4 K

b. She pump : 1 kg/s

(2) Power supply system

a. Pulse power supply : 50 kA, 5 kV, 20 s (JT-60 PS)

b. DC power supply : DC 50 kA PS x 2 set

c. DC breakers, dump resistors

d. Bus bar and mode switch

(3) Vacuum tank

(3.1) CS coil

a. Tank : 5 m diam. x 6 m height (DPC)

b. Current lead : 50 kA pair x 2 set

c. Support structure

d. Piping and SC bus

(3.2) TF coil

a. Tank : 9 m diam. x 13 m height

b. Current lead : 50 kA pair x 3 set

c. Support structure

d. Piping ans SC bus

(3) Instrumentation

a. Amplifier of high voltage, strain and temp.

b. Patching

c. Cabling

(4) Data acquisition system

a. Data base computer and software

b. Fast channel : 200 ch x 3 set

c. Slow channel : 1,000

2.3.2 Test Facility for Conductor Developments

During developments of conductors, the existing test facility will be used for evaluations.

(1) Full scale conductor test

a.	Critical current test	: 14 T - 0.4 m diam., 40 kA
b.	Stability test	: 8 T - 1.5 m diam., 40 kA

(2) Verification test during conductor development

a.	Strand	: 13 T - 7 cm diam., 15 kA
c.	Limited conductor test	: 13 T - 10 cm diam., 100 kA
d.	Limited pancake test	: 8 T - 1.5 m diam., 30 kA

(3) Characterization of strand sub-size conductor

a.	Strand	: 15 T - 5 cm diam., 1 kA
b.	Sub-size stability	: 13 T - 24 cm diam., 15 kA
c.	Mechanical test	: 10 ton, 100 ton
d.	Physical property	

2.4 Interpolation of Summary

After agreements of international collaboration through ITER-EDA, there are many benefits for development tasks to use other country test facilities and to exchange hardware information by samples and scientists exchange. We don't need to consider to prepare new facility for investigation of large conductor or coil samples. The international common facility for the scalable model coils has good benefits to develop the components of utility (cryogenic system and power supply system). Also, the common test will be carried out with good collaboration as same as the Large Coil Task.

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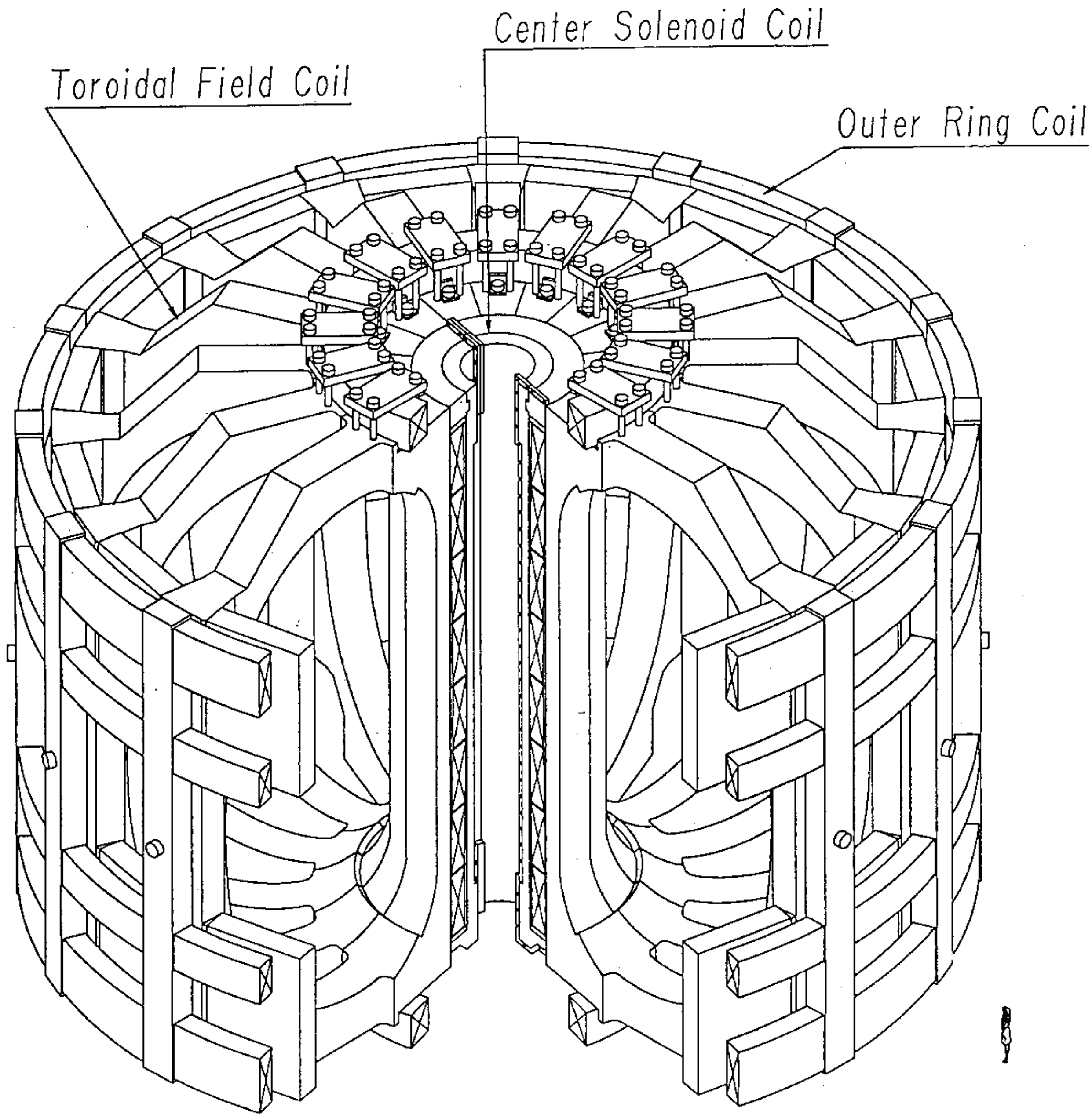

Fig. 2.1 Bird's-eye view of the superconducting magnet system for the ITER

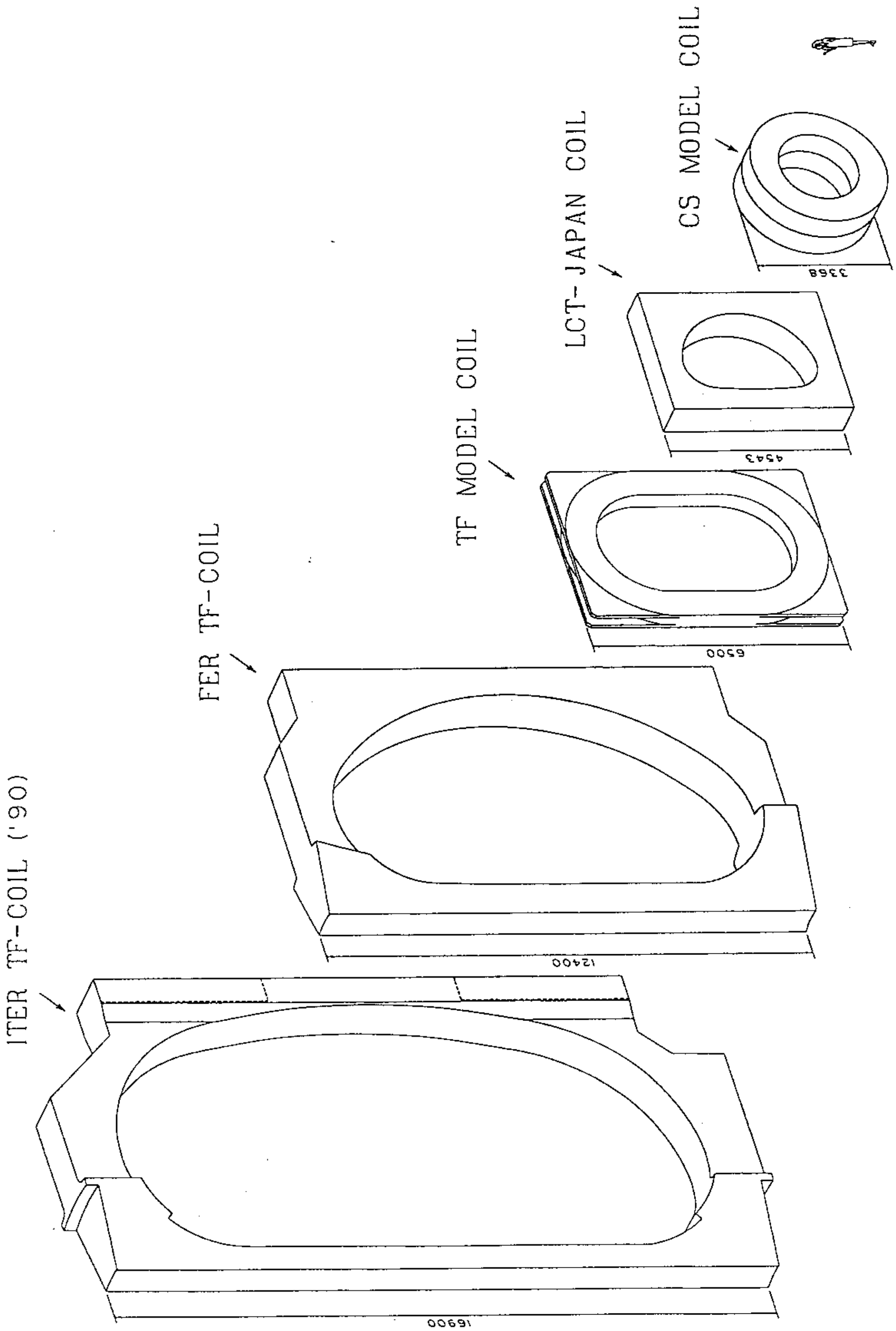

Fig. 2.2 Comparison of coil size among ITER, FER, LCT toroidal field coil and the TF Scalable Model Coil

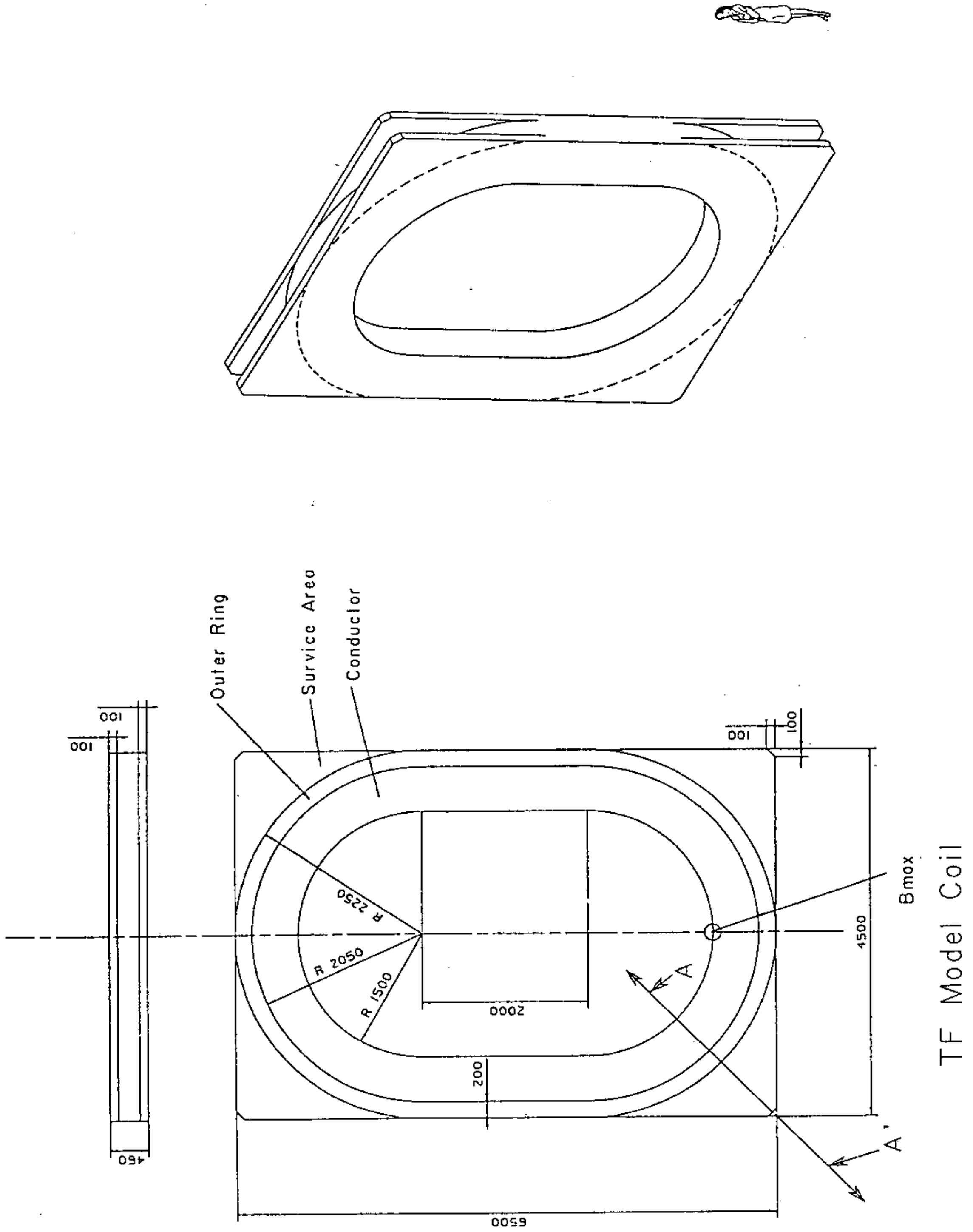

Fig. 2.3 The TF Scalable Model Coil (three test coil version)

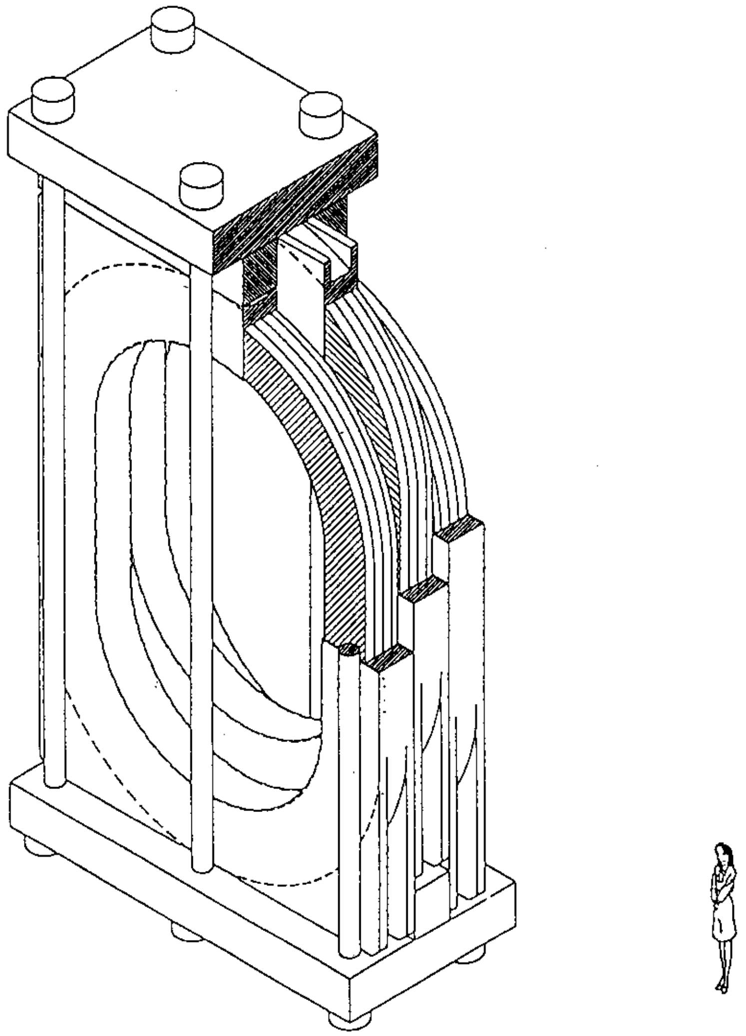

Fig. 2.4 High field configuration for the TF Scalable Model Coil (three test coil version)

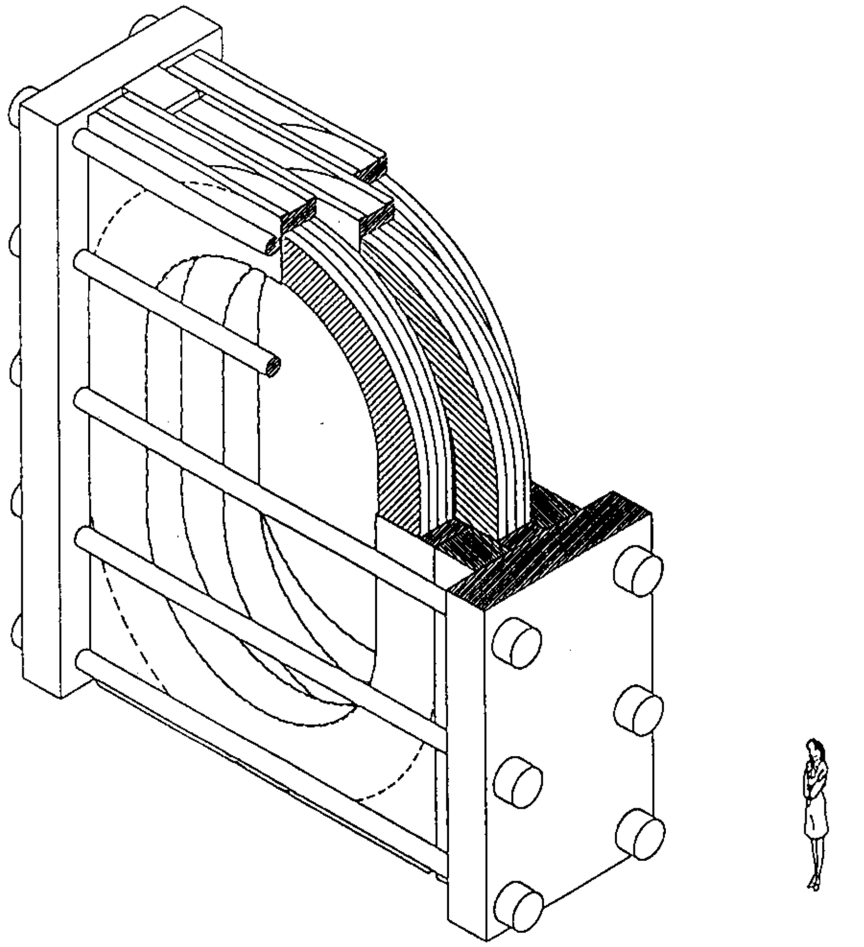

Fig. 2.5 Mechanical test configuration for the TF Scalable Model Coil (three test coil version)

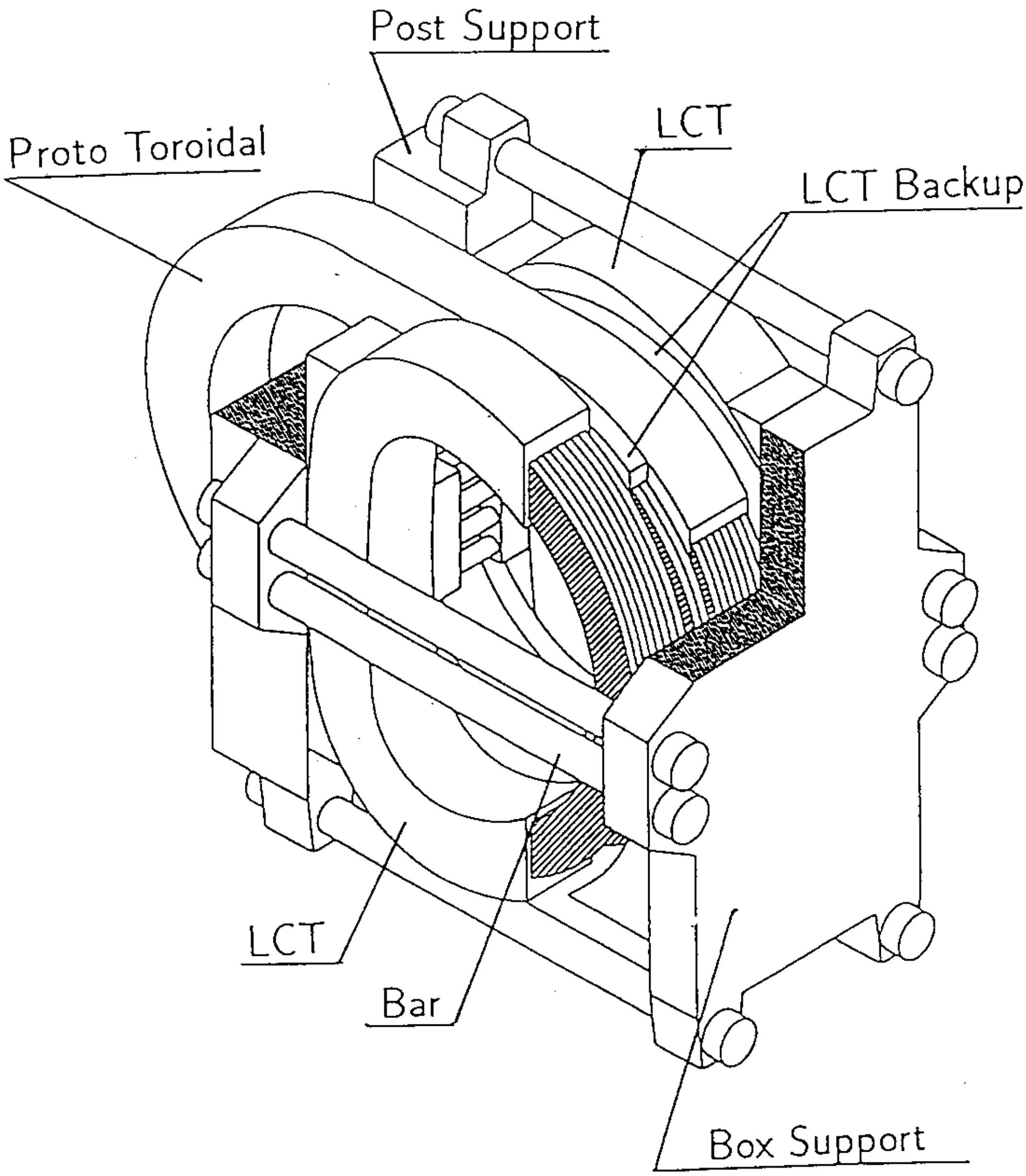

Fig. 2.6 The TF Scalable Model Coil and backup field coils (one test coil version)

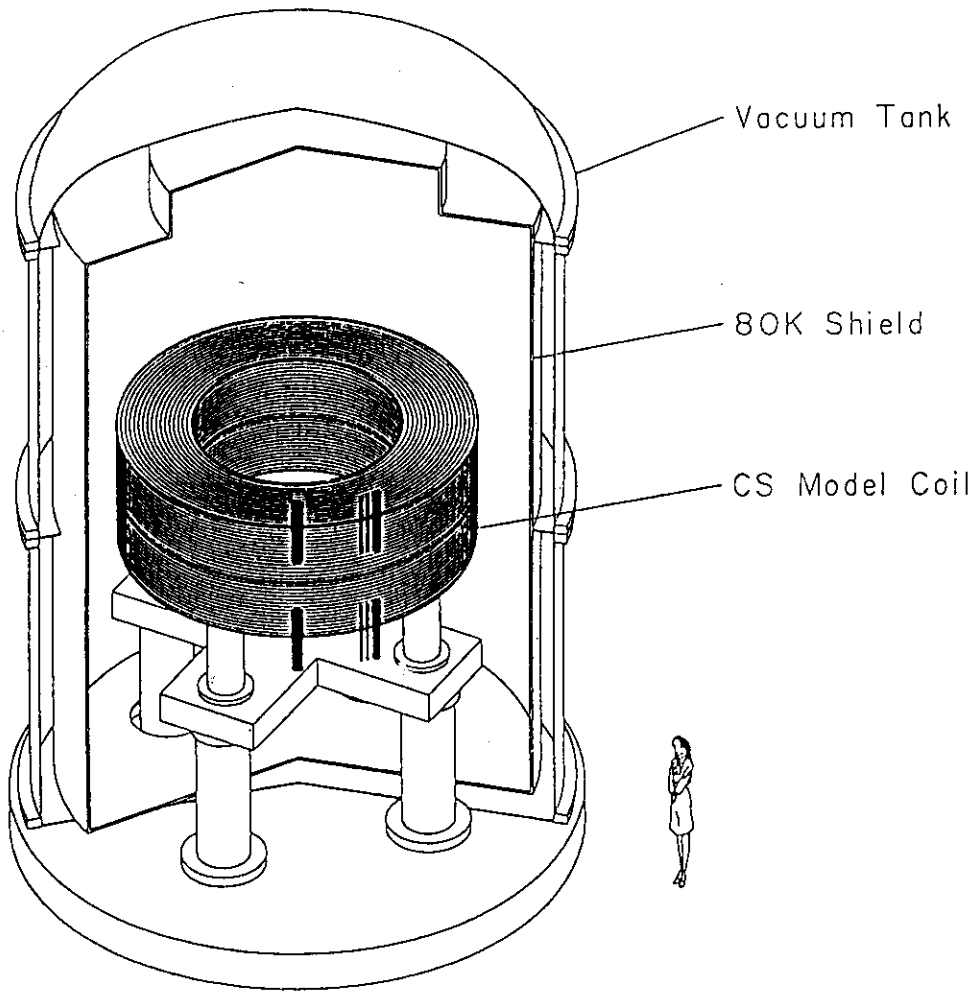

Fig. 2.7 The CS Scalable Model Coil in the DPC vacuum tank

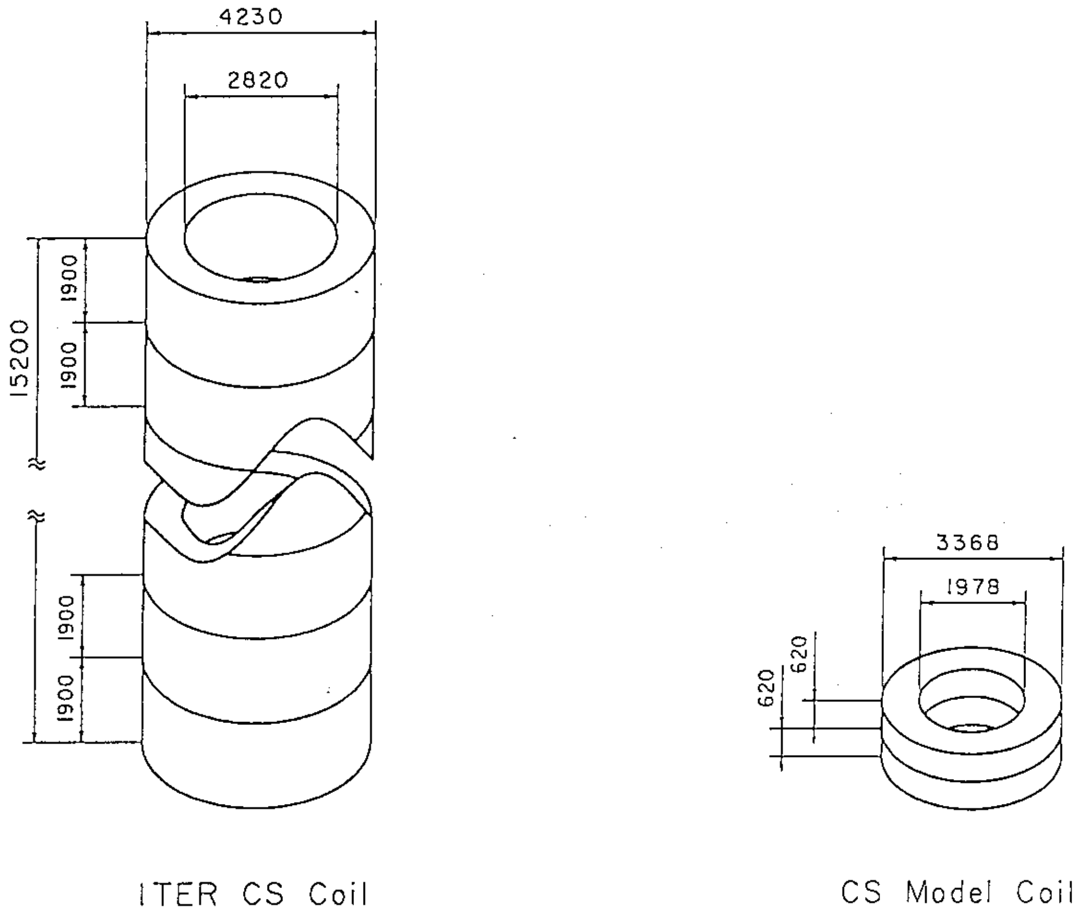

Fig. 2.8 Comparison of coil size between the ITER CS coil system and the CS Scalable Model Coil

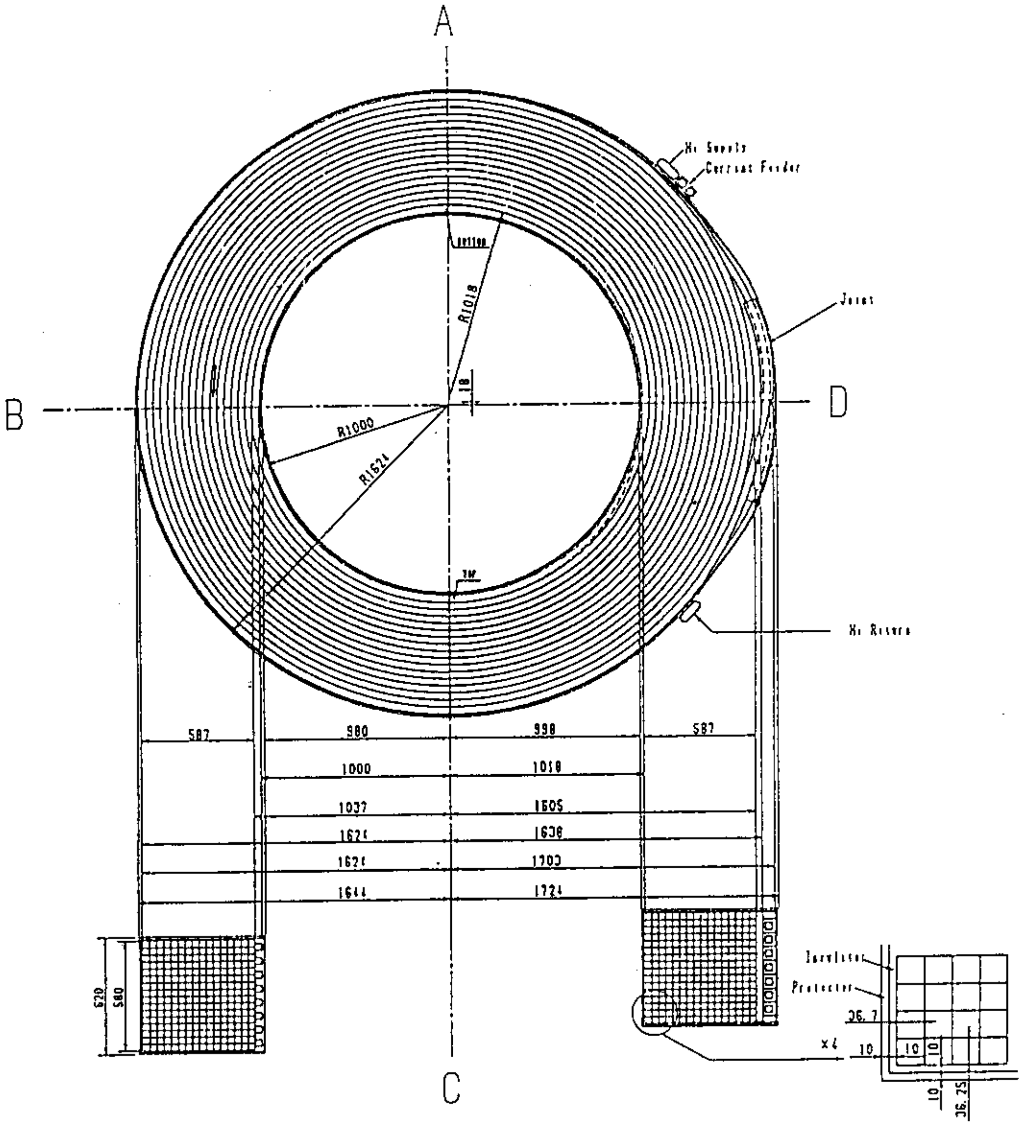

Fig. 2.9 The cross sectional view of the winding of the CS Scalable Model Coil

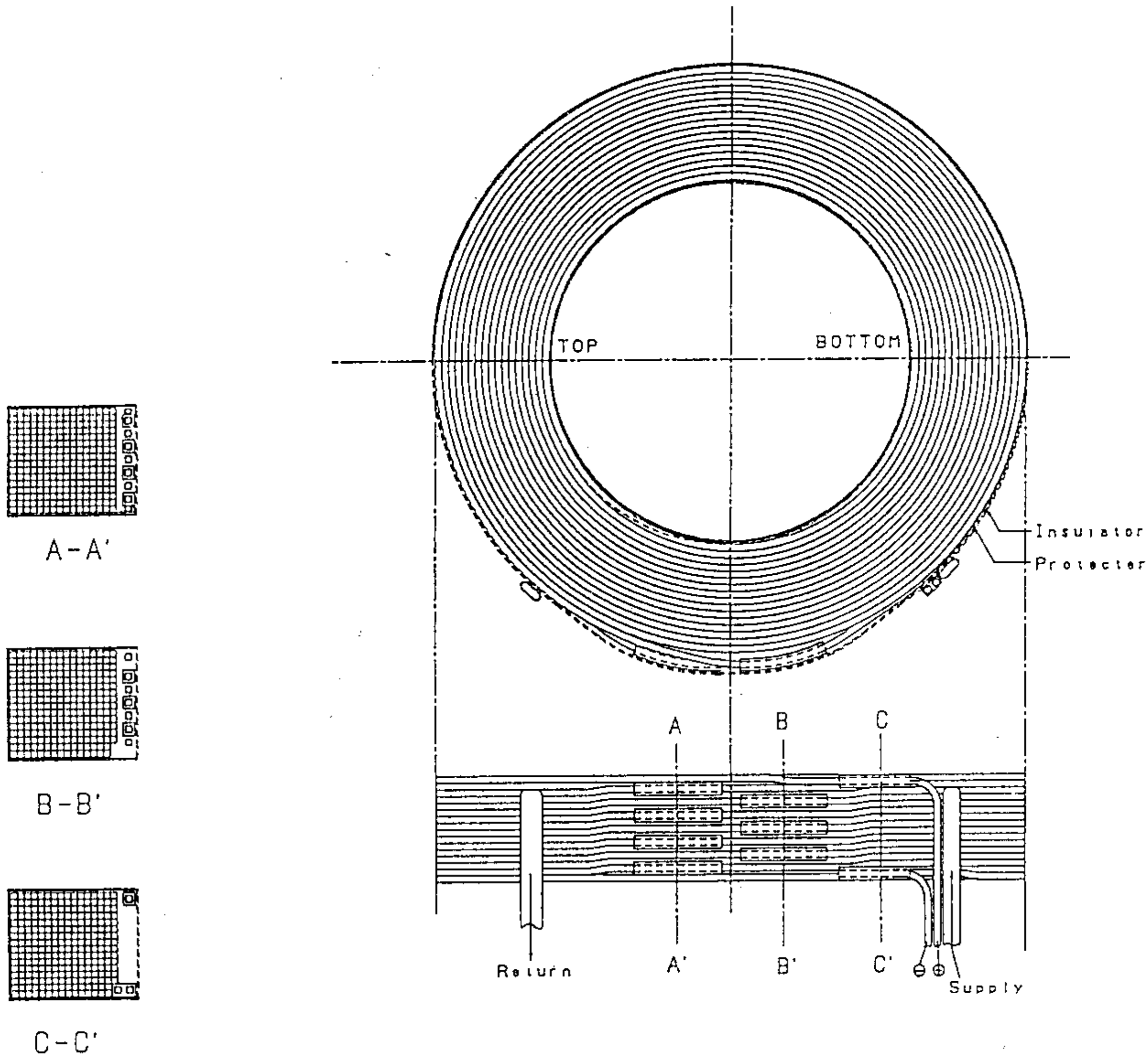

Fig. 2.10 The pancake joint area of the CS Scalable Model Coil

3. DESIGN AND ANALYSIS OF TF SCALABLE MODEL COIL

3.1 Introduction

The TF model coil should be constructed for an emulation of ITER TF coils.

(1) Verification tests of mechanical and electrical properties under high stress similar to the ITER TF coils.

(2) Ic measurement and stability test at 11T, 30kA.

(3) Destructive tests behaviors of coil.

3.2 Concepts of Design

The TF model coil has a race-track shape as shown in Fig. 3.1. The cross sectional area of winding is 550 x 400 mm^2. The model coil has a 20 mm-thick coil case, a 200 mm-thick outer ring and a service area. Major parameters of the coil are listed in Table 3.1.

Three types of tests are planned for the evaluation of the TF model coil. Tests are performed with three test coils, which are manufactured according to the same specification and are connected to each other by the supporting structure. The test coils are examined one by one in the central test position by the following tests.

(1) Mechanical Test

Figure 3.2 shows the coil configuration of the mechanical test. The test coil is set in the mid position shifted 550 mm from the other two coils. Figure 3.3 shows the supporting structure. The supporting structure consists of the Front post, Back post and Bars. The dimensions of this test structure are 6500 mm-high, 6050 mm-wide and 2180 mm-thick.

(2) High Field Test

Figure 3.4 shows the coil configuration of the high field test. The test coil is set on the upper portion of the background coils, 550 mm from the base. Figure 3.5 shows the supporting structure. The supporting structure consists of the Upper beam, Lower beam and Bars. In this case, the dimensions of the test stand are 8530 mm-high, 4500 mm-wide and 2180 mm-thick.

A 3-Dimensional drawing of the model coil, the mechanical test stand and the high field test stand are shown in Figs. 3.6, 3.7 and 3.8.

(3) Fracture Test

To obtain the fault behavior of large superconducting coils, a fracture test is planned. In this test, the outer ring of the test coil is cut in several places by a milling machine and then the coil is charged up.

3.3 Basic Analysis

3.3.1 Cable Length

The TF model coil consists of 5 double pancakes, each of which is wound with a 420 m long cable. The total length of the conductor in the coil is 4.2 km and the total number of turns is 220.

3.3.2 Weight

The weight of a test coil is estimated to be 3.3 tons and the total weight of the system including the supporting structure is around 120 tons.

3.3.3 Inductance

The calculated self-inductance of a coil is 406 mH, the mutual inductance between neighboring coils is 199 mH and the mutual inductance between the background coils is 152 mH. The total stored energy is 1.04 GJ.

3.4 Mechanical Test Position

3.4.1 Magnetic Field

Figure 3.9 shows the distribution of magnetic field along the coil perimeter. Figure 3.10 shows the field contour map in the cross-section of the Front-post-side straight section of the coil. It is very similar to that of the TF coil. The field contour map in the cross-section of the Back-post-side straight section and that at the top of the circular section are shown in Fig. 3.11 and Fig. 3.12' respectively.

3.4.2 Electromagnetic load

As shown in Table 3.2, the radial force of the test coil is 201 MN. It acts on the straight section in the model coil. The axial force on the background coil is 271 MN. From this force, the test coil bears a transverse compressive load.

3.4.3 Stress analysis

(1) Calculation model

The calculation model is shown in Fig. 3.13. This model consists of three test coils (a test coil and two background coils), Front post, Back post and seven Bars. Physical constants used in this calculation are listed in Table 3.3.

(2) Stress analysis

Figure 3.14 shows the displacement diagram of this model. The maximum displacements of the Mechanical Test Stand are summarized in Table 3.4.

The distribution of the longitudinal, the axial, the radial and the Tresca stress on the test coil is shown in Fig. 3.15. From this figure (c) and (d), the maximum value of the Tresca stress and the longitudinal stress becomes 171 MPa and 153 MPa respectively. These stresses are induced by the bending deformation of the coil.

(a) Radial direction stress: The distribution of the radial stress in the cross-section of the Front-post-side straight section is shown in Fig. 3.16. From this figure, radial(z-direction in Fig. 3.12) compressive stress is -91.7 MPa. This value is very large and the same as that on the ITER TF coil. This straight section of the test coil can simulate the radial compressive stress of the TF coil. The coil stiffness in the radial direction can be evaluated from the Front-post-side straight section.

(b) Axial direction stress: Figure 3.17 shows the cross sectional view of the axial stress distribution in the Front-post-side straight section. The maximum value of the axial(y-direction in Fig. 3.12) stress becomes -40.4 MPa, and is a compressive stress. This is a small value in comparison with that of the ITER TF coil. In this calculation model, no axial compressive loads act on the straight section of the test coil. Magnetic forces are applied to the test coil by the back-up coils in the form of axial compressive stresses. Axial compressive stress in the straight section can be increased by optimizing the shape of the spacer which is located between the test coil and the background coils.

(c) Background coil: The distribution of the longitudinal, the axial, the radial and the Tresca stress on the test coil is shown in Fig. 3.18. From this figure, the maximum value of the Tresca stress is 120 MPa, which is not serious. The maximum value of the longitudinal and the axial direction stress becomes -85.1 MPa and 64.7 MPa, respectively. These stresses are induced by the bending deformation of the coil. The maximum value of the radial direction stress becomes -78.9 MPa at the Back-post-side straight section.

Typical stress values of the test coils and the ITER TF coil are summarized in Table 3.5. The distribution of the longitudinal, the axial and the radial stress at the straight part of the ITER TF coil is shown in Fig. 3.19.

3.5 **High Field Test Position**

3.5.1 Magnetic Field

Figure 3.20 shows the magnetic field distribution along the coil perimeter. The maximum field of 11 T along a 3-m-length is experienced. Figure 3.21 shows the field contour map in the cross section at the top of the circular section.

3.5.2 Electromagnetic Load

In this case, the electromagnetic load acts on the circular part of the coil. Stress which are induced by electromagnetic forces in the circular section is similar to that in the circular coil. Stress in the circular coil, as opposed to non-circular coils, are well defined by the TMC and DPC. These electromagnetic forces in the circular section ace nigh but not sections, and stresses in the straight section are not high. This is the safe side of the coil stiffness. The estimated loads are shown in Table 3.2.

3.6 Fracture Test

The fracture test is planned to obtain the fault behavior of large superconducting coils. In this test, the outer ring of the test coil case is cut in several places by a milling machine and then the coil is charged up to investigate where the failure of winding is happened.

3.7 Requirements for the Test Facility

The requirements for the test facility listed in Table 3.6.

3.8 Interpolation of Summary

The TF model coil and its test stand were designed to emulate the environment of the ITER TF coils. Using the designed mechanical test stand, it is proved by the analysis that the required mechanical condition can be achieved in the test coil. With the high field test stand, the required field of 11T can be experienced by the conductor along a 3 m length.

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Table 3.1 Specification of TF model coil

Operating current		30	kA
field		11	T
Size			
height		6.5	m
width		4.5	m
thickness		0.46	m
Cable Length			
Total cable length		3.4	km / coil
Double pancake cable length		680	m / 1DP
x 5 double pancake = 1 coil			
Weight			
Coil weight		33.3	ton/coil
	x3	100	ton
Supporting structure		20	ton
Total weight		120	ton
Inductance			
Self-inductance		406	mH
Mutual inductance			
Test coil & background coil		199	mH
Between background coils		152	mH
Stored Energy			
1 coil		183	MJ
Total		1.043	GJ

Table 3.2 Magnetic forces in each test stand.

Unit: MN

	Mechanical test	High field test
TEST POSITION COIL		
longitudinal	111	-710
axial	-170	-147
radial	-201	161
BACK GROUND POSITION COIL		
longitudinal	107	61
axial	-271	-307
radial	100	155

note; radial:z-direction; axial:y-direction; longitudinal:x-direction in Fig. 4.5

Table 3.3 Physical constants for stress analysis.

Conductor	Er	73.2 GPa
	Eθ	75.6 GPa
	Ez	84.9 GPa
	ν	0.1
	Grθ	31.8 GPa
	Gθz	32.5 GPa
	Gzr	36.6 GPa
Insulator	E	19.6 GPa
	ν	0.1
	G	9.80GPa
Coil case	E	196 GPa
	ν	0.3
	G	75.4 GPa
Outer ring	E	196 GPa
	ν	0.3
	G	75.4 GPa
Post	E	196 GPa
	ν	0.3
	G	75.4 GPa
Bar	E	196 GPa
	ν	0.3
	G	75.4 GPa

Table 3.4 Maximum displacement of the Mechanical Test Stand.

unit: mm

	radial	axial	longitudinal
Max. disp.	-10.3	0.89	4.99

note; radial:z-direction; axial:y-direction; longitudinal:x-direction in Fig. 4.5

Table 3.5 Typical stress value at straight part in winding of TF model coil and TF coil.

unit: MPa

	TF model coil		TF coil
	Test Position	Background Position	EOB
radial	-91.7	-78.8	-75.9
axial	-40.4	64.7	-129
longitudinal	152	-85.1	63.7
Max. Tresca	171	120	745

note; radial:z-direction; axial:y-direction; longitudinal:x-direction in Fig. 4.5

Table 3.6 Test facility requirement for TF model coil.

Vacuum Tank		
Inner diameter		9 m
Height		13 m
Power Supply		DC 50kA-15V x2
Diagnostics System		200 channels x3
		Computer system
Cryogenic System		
Refrigerator/Liquefier		8 kW/ 1200 l/hr
She supply capacity	flow rate	700 g/s
	pressure drop	<2 atm
	temperature	4.0 K to 8.0 K
	pressure	1.2 atm to 10 atm
Current Lead		50 kA x 3pairs

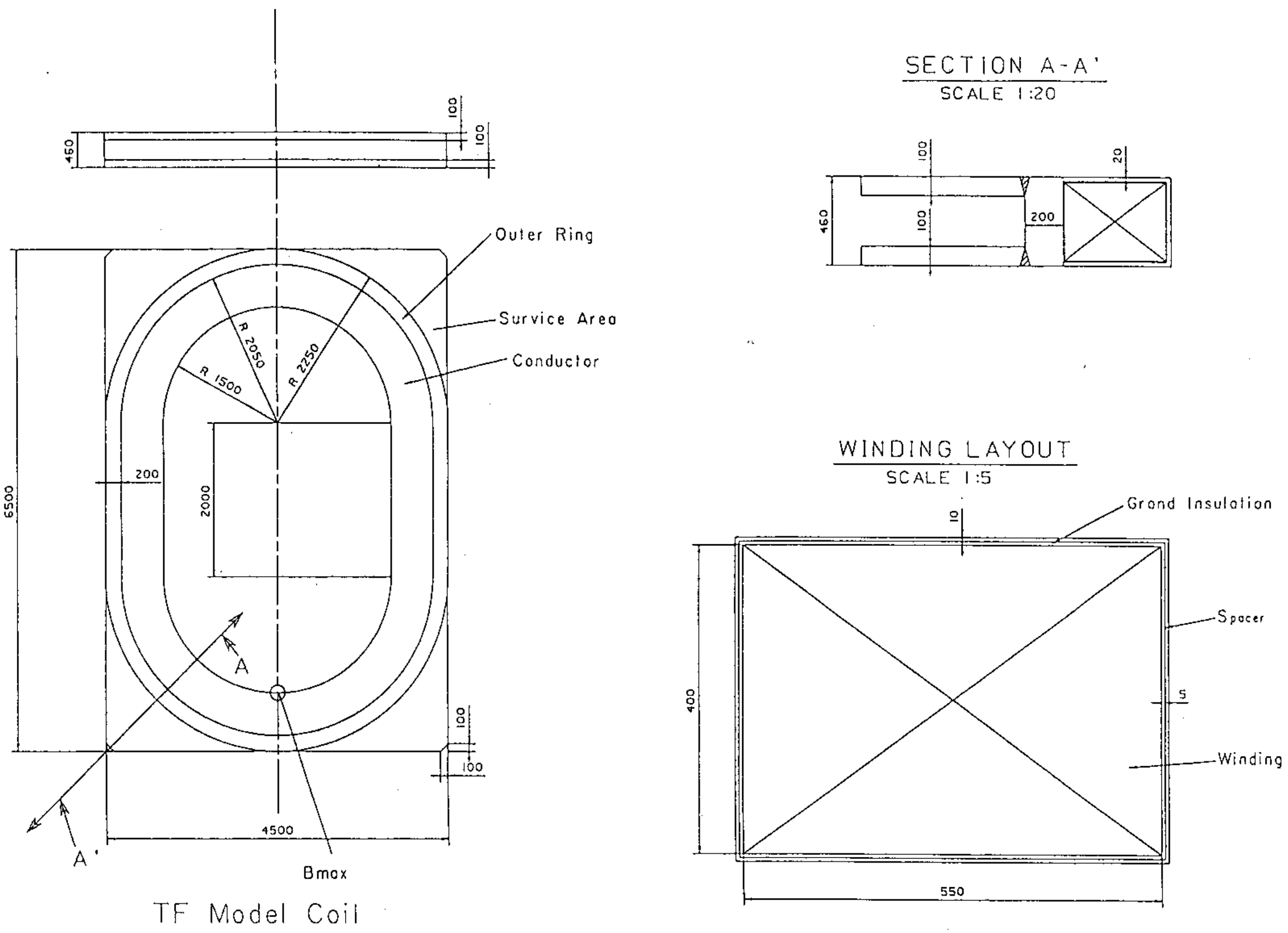

Fig. 3.1 TF model coil.

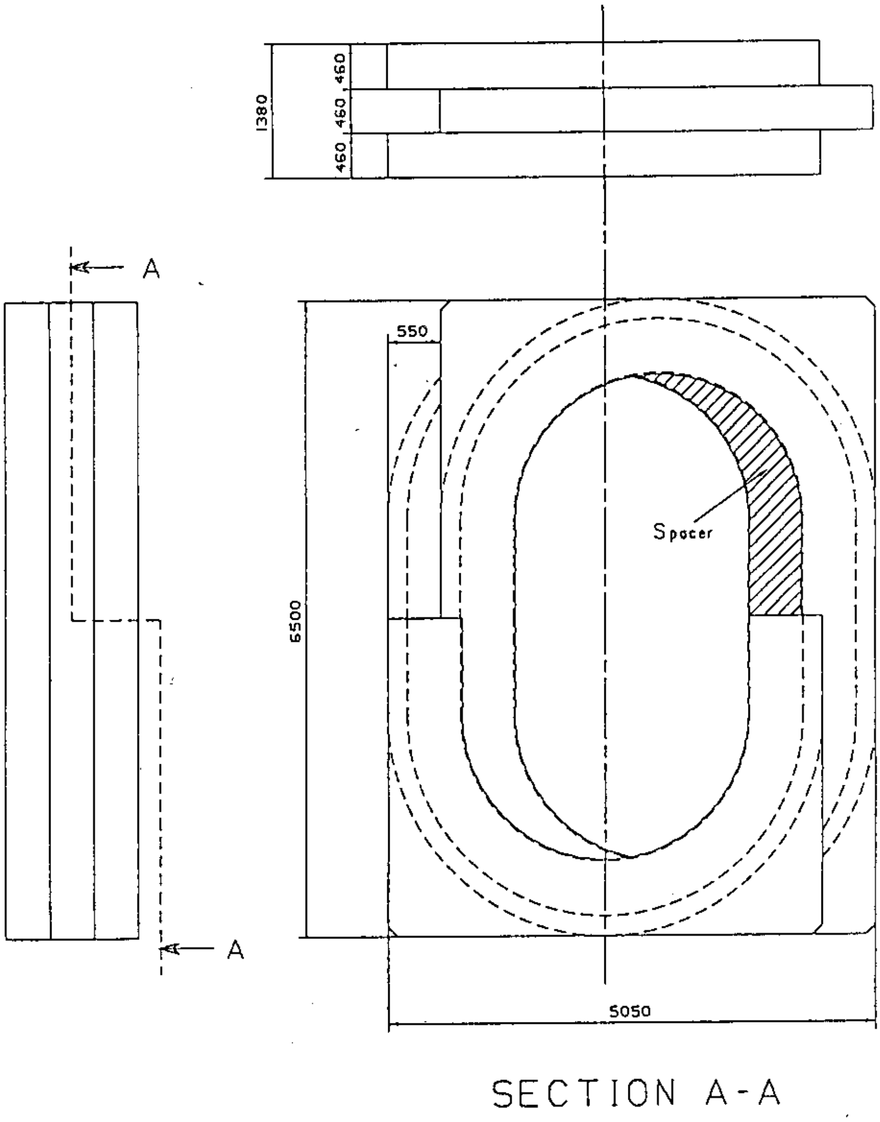

Fig. 3.2 TF model coil configuration at mechanical test.

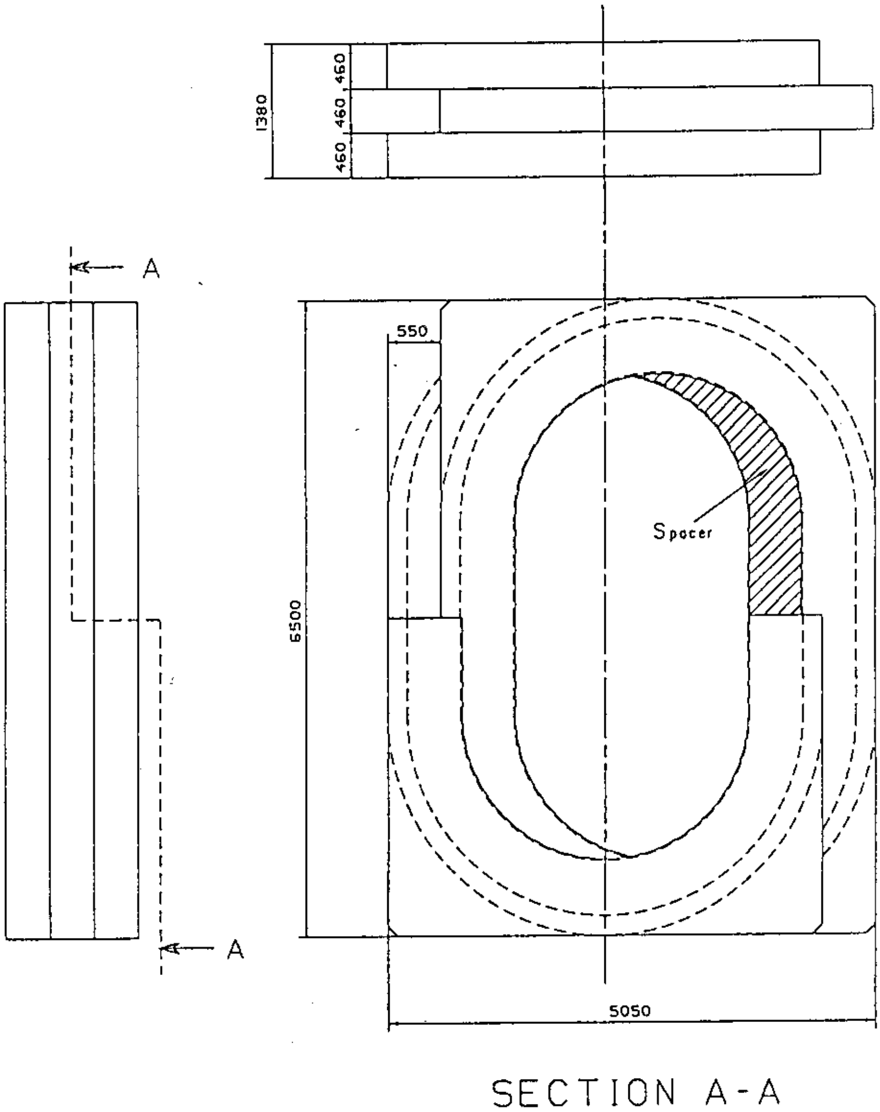

Fig. 3.2 TF model coil configuration at mechanical test.

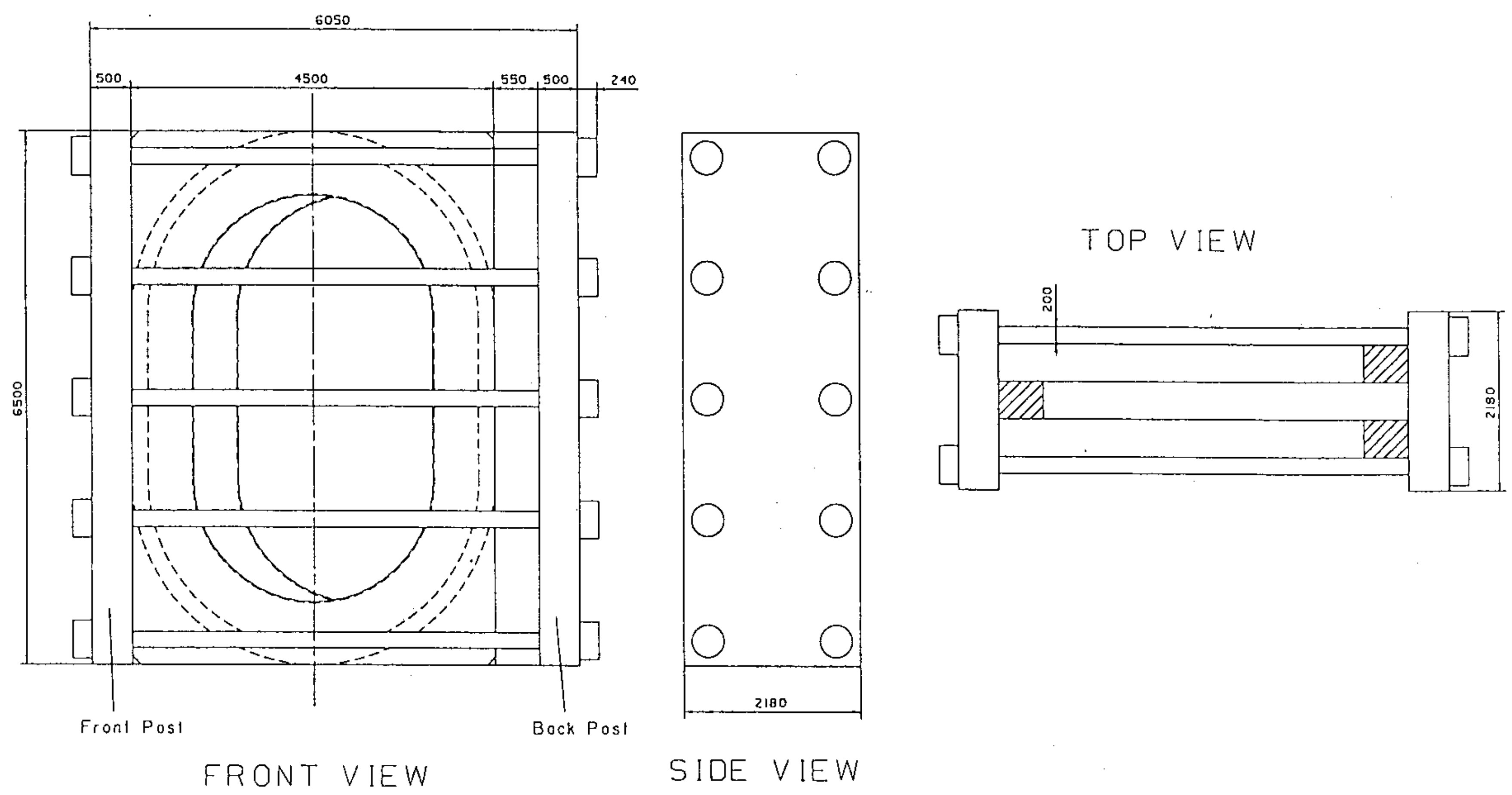

Fig. 3.3 TF model coil supporting structure arrangement at the mechanical test.

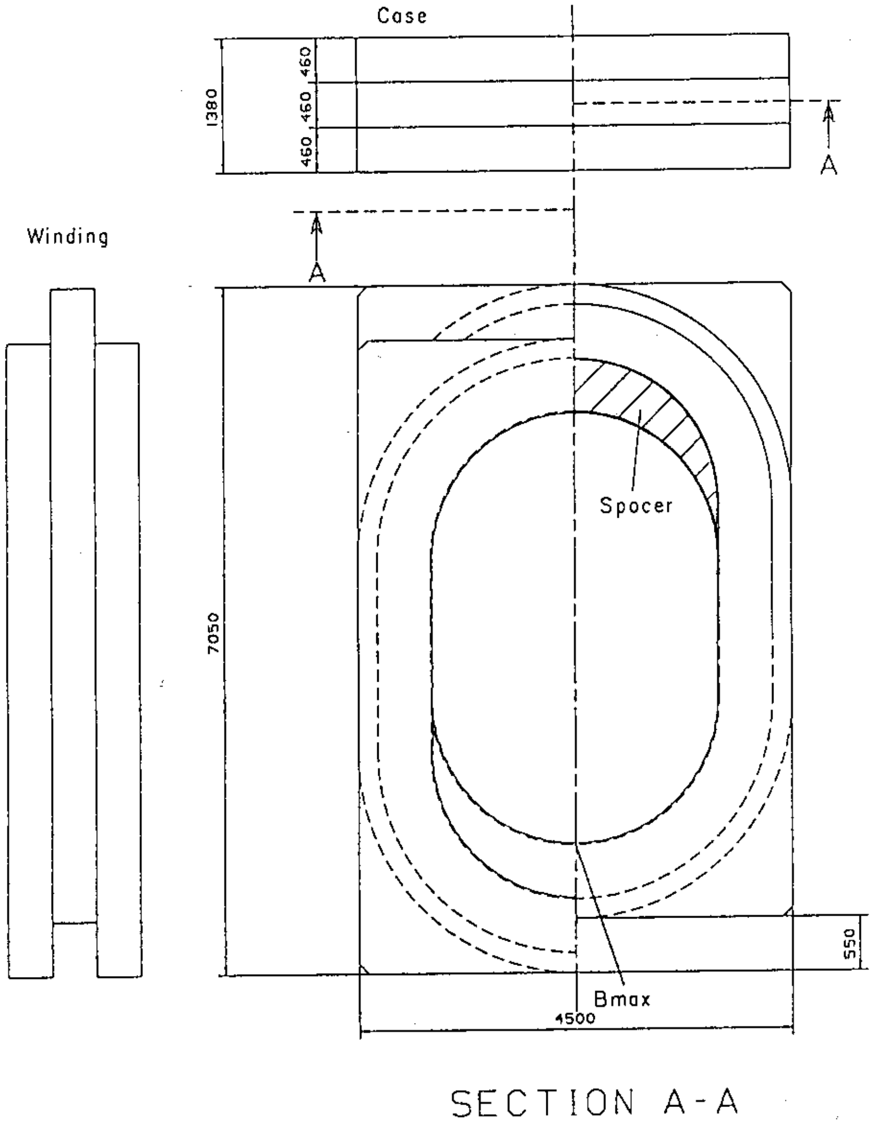

Fig. 3.4 TF model coil configuration at the high field test.

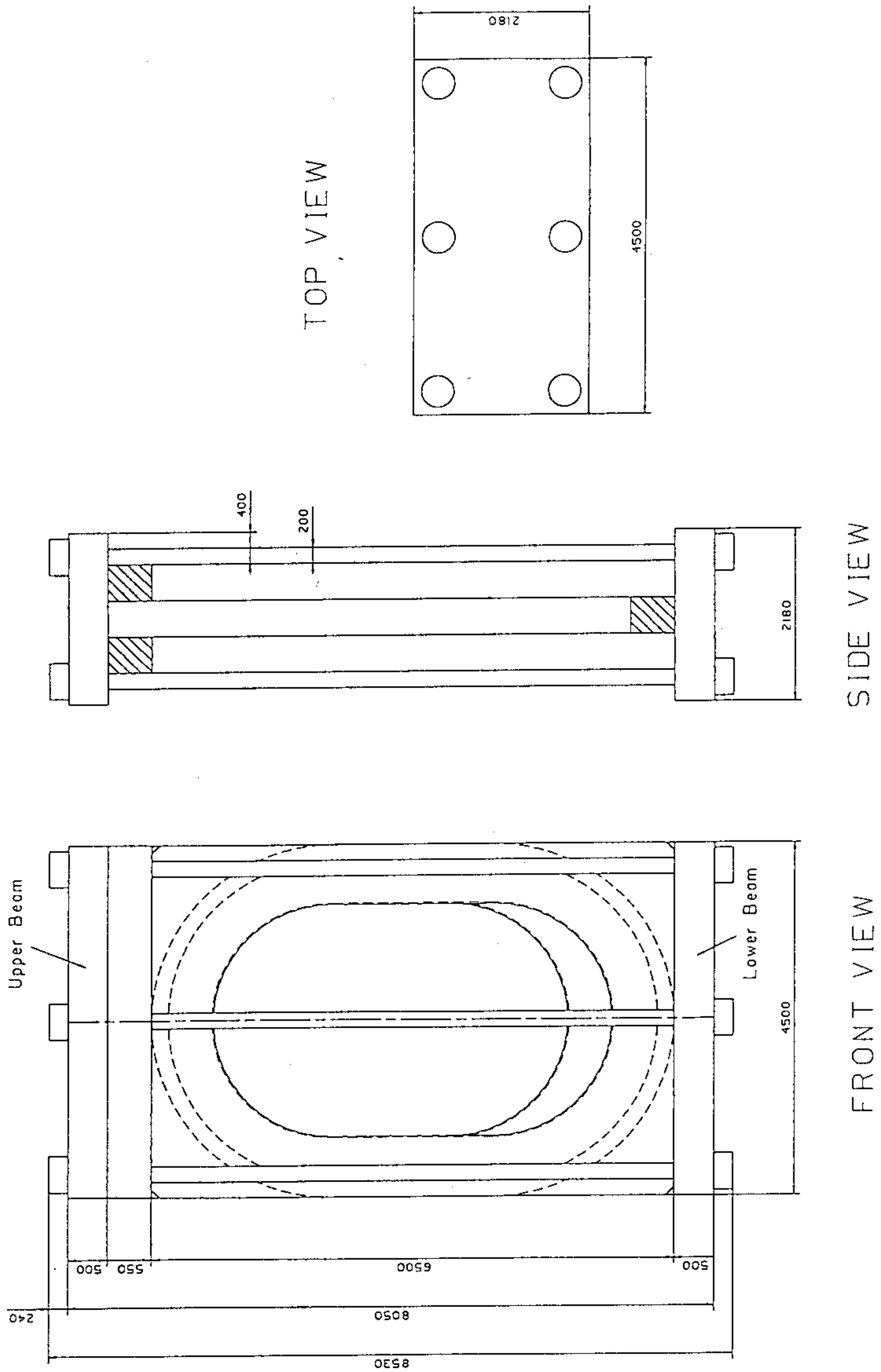

Fig. 3.5 TF model coil supporting structure arrangement at the high field test.

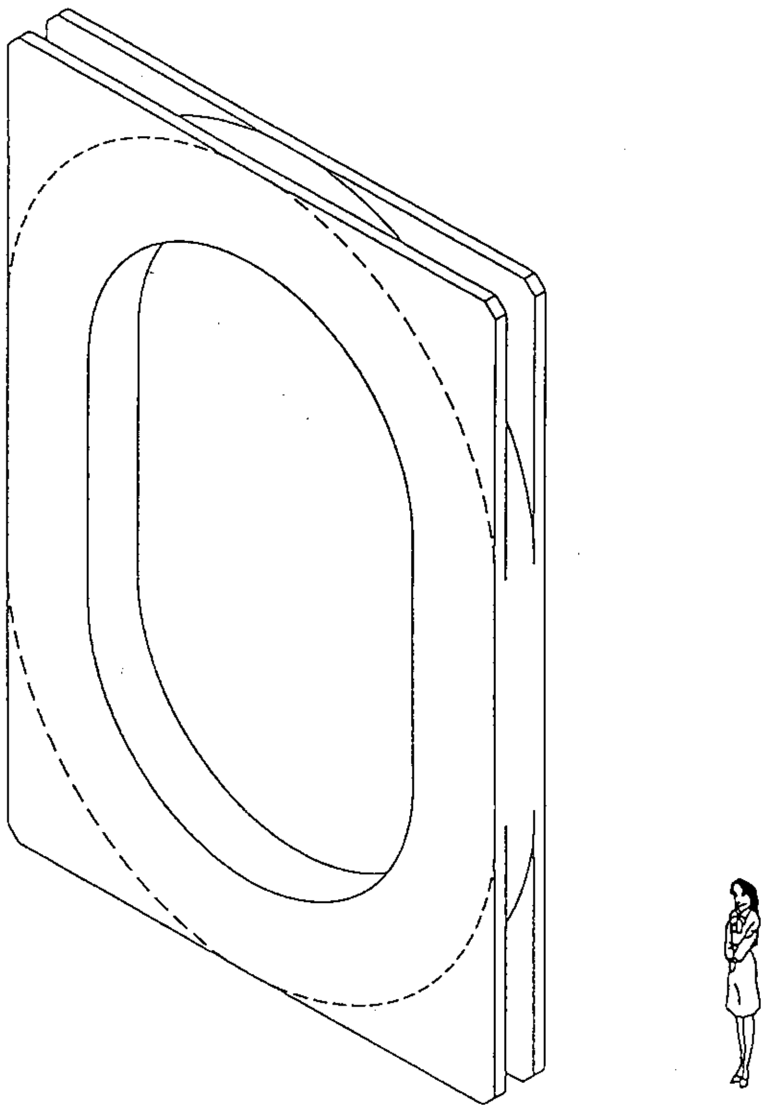

Fig. 3.6 TF model coil.

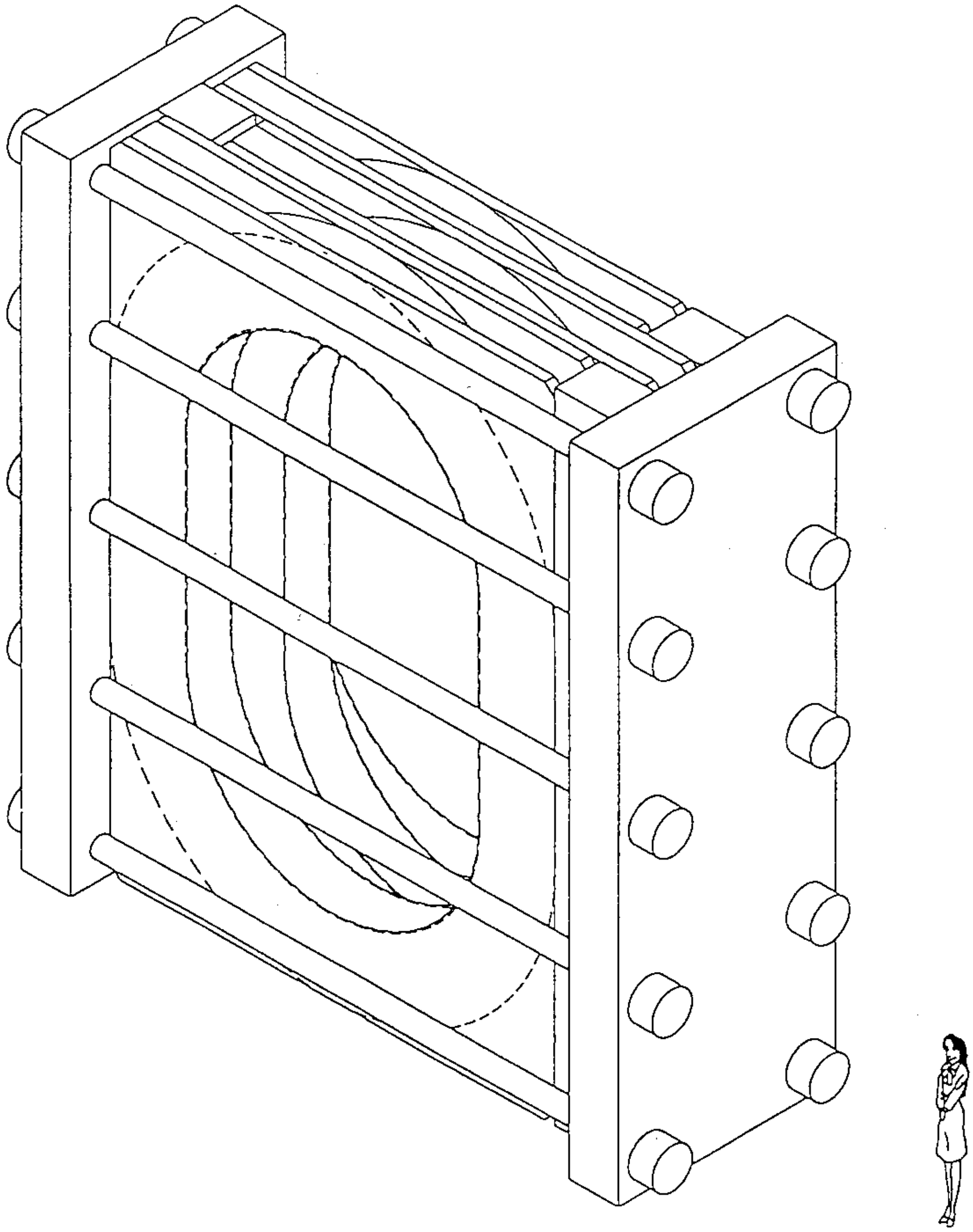

Fig. 3.7 Mechanical test stand.

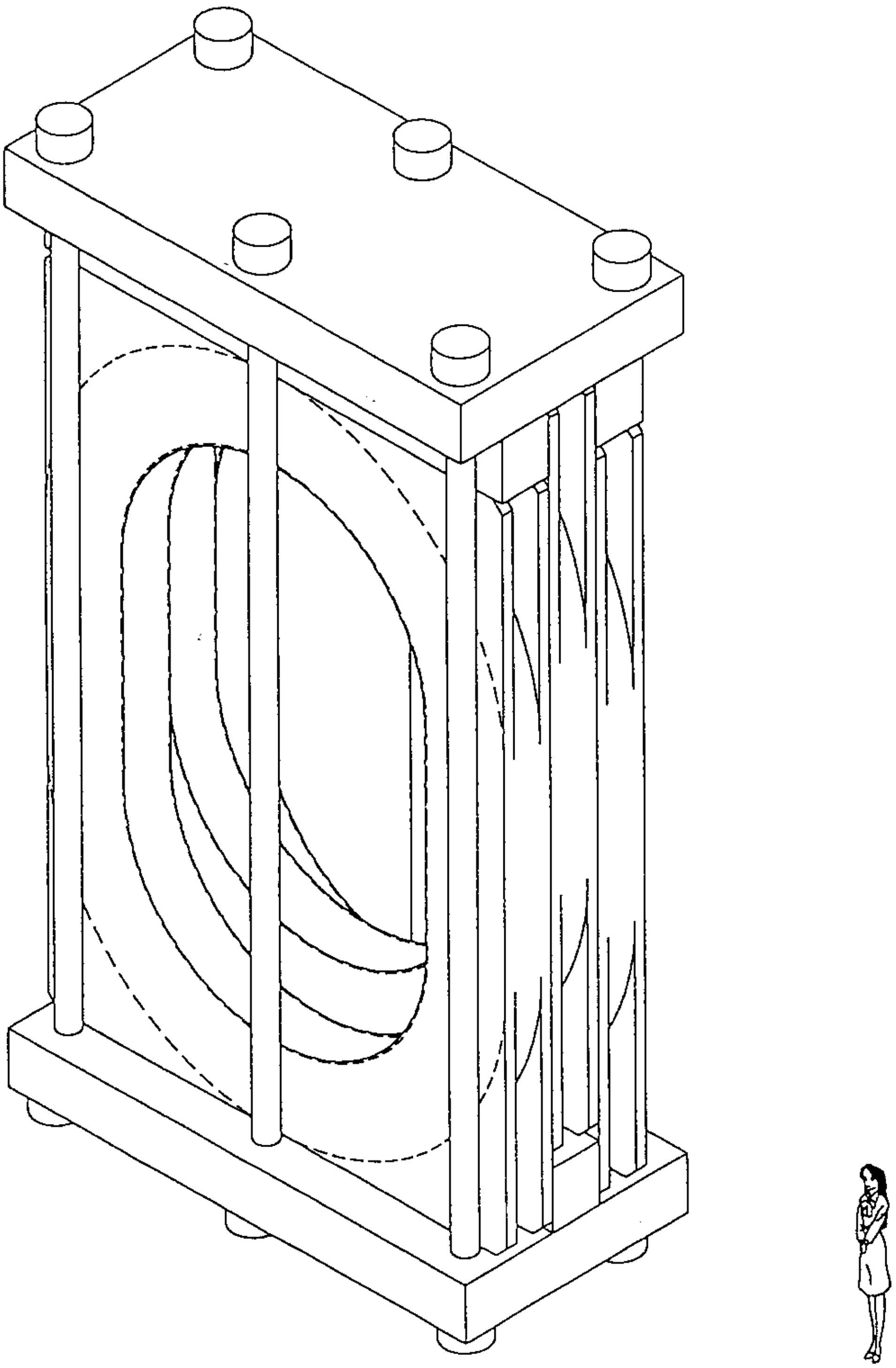

Fig. 3.8 High field test stand.

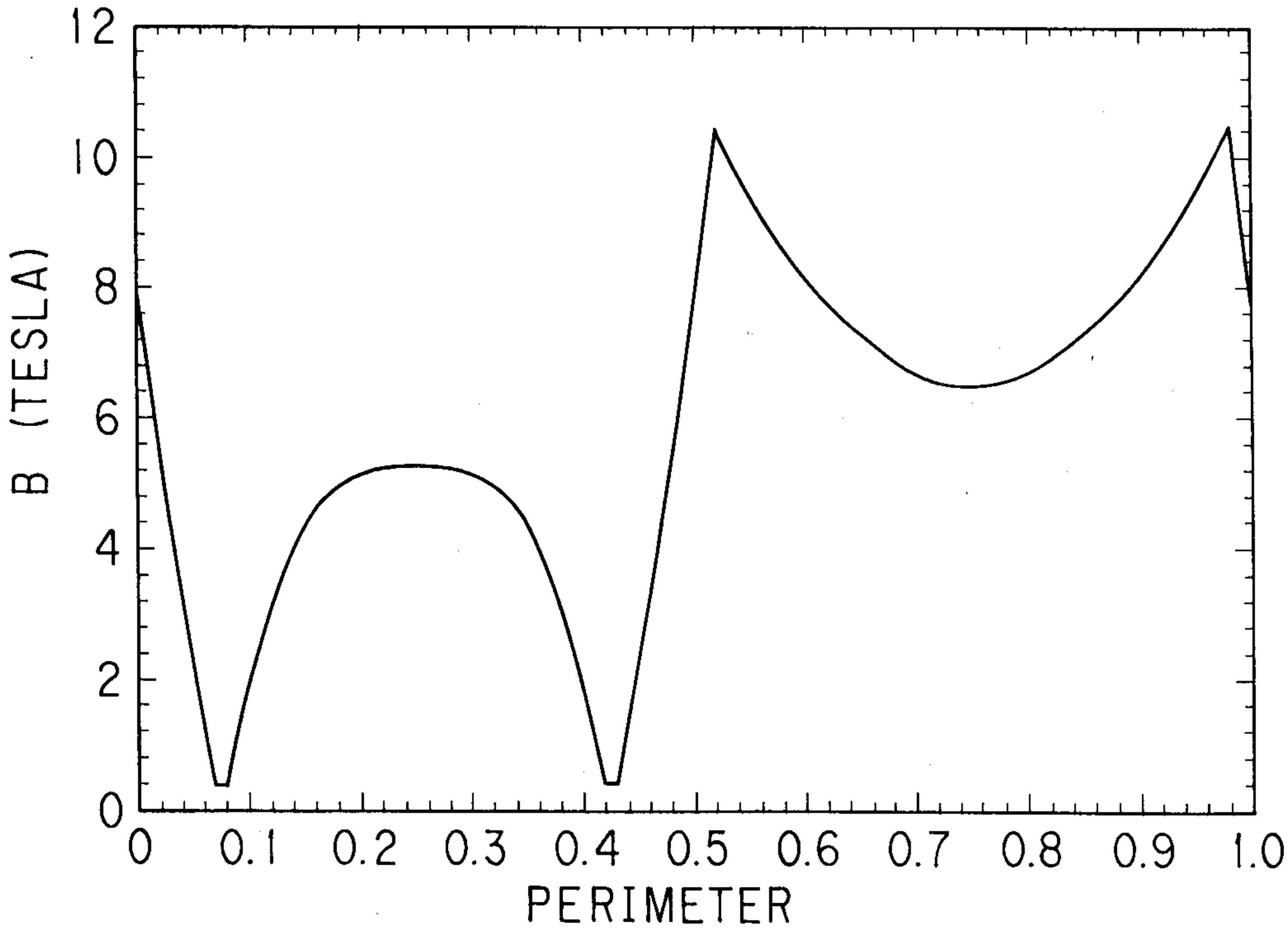

Fig. 3.9 Magnetic field distribution along the test position coil perimeter at Mechanical test stand.

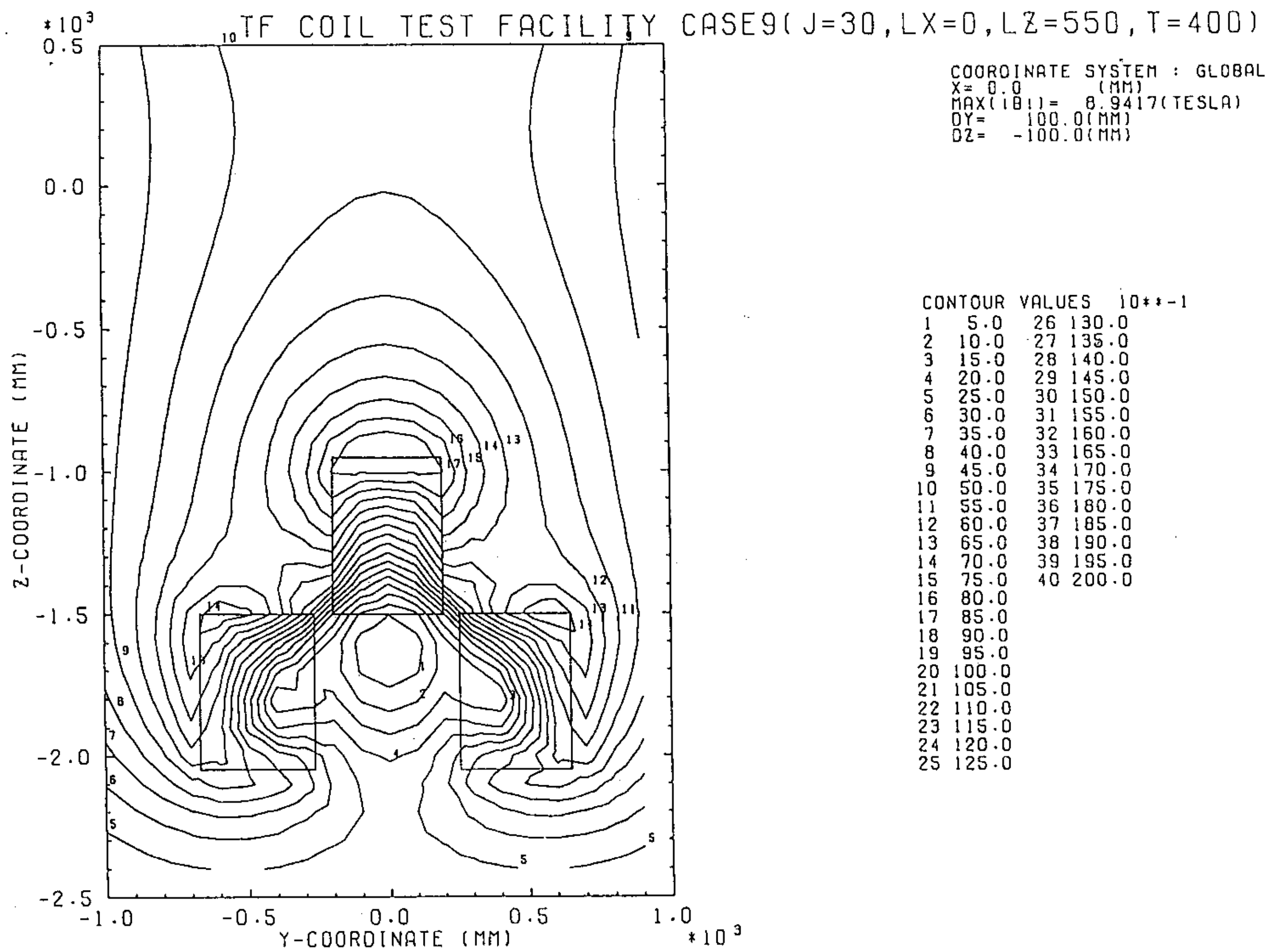

Fig. 3.10 Magnetic field contour map at a cross section in the Front-post-side straight part on Mechanical test stand.

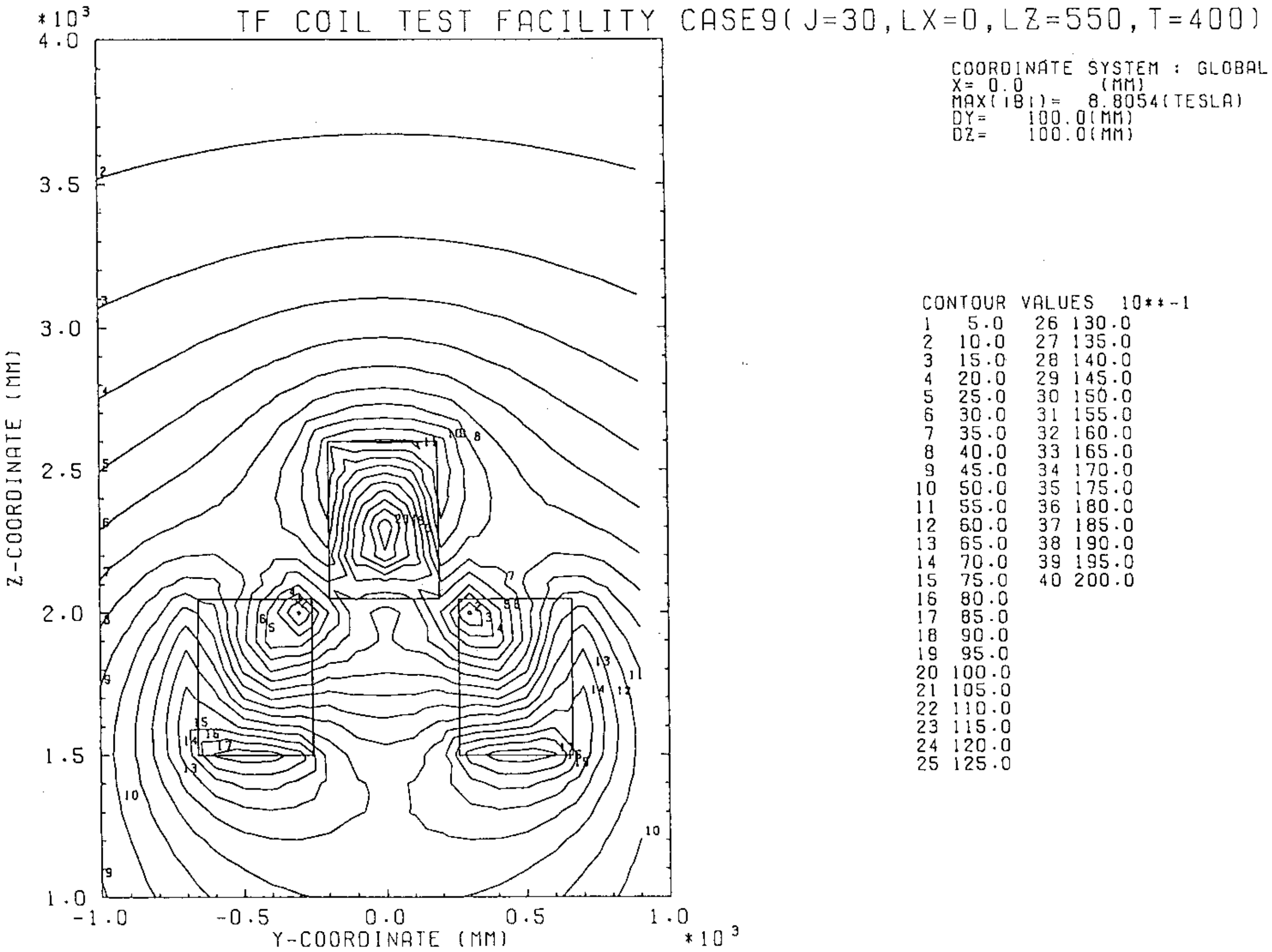

Fig. 3.11 Magnetic field contour map at a cross section in the Back-post-side straight part on Mechanical test stand.

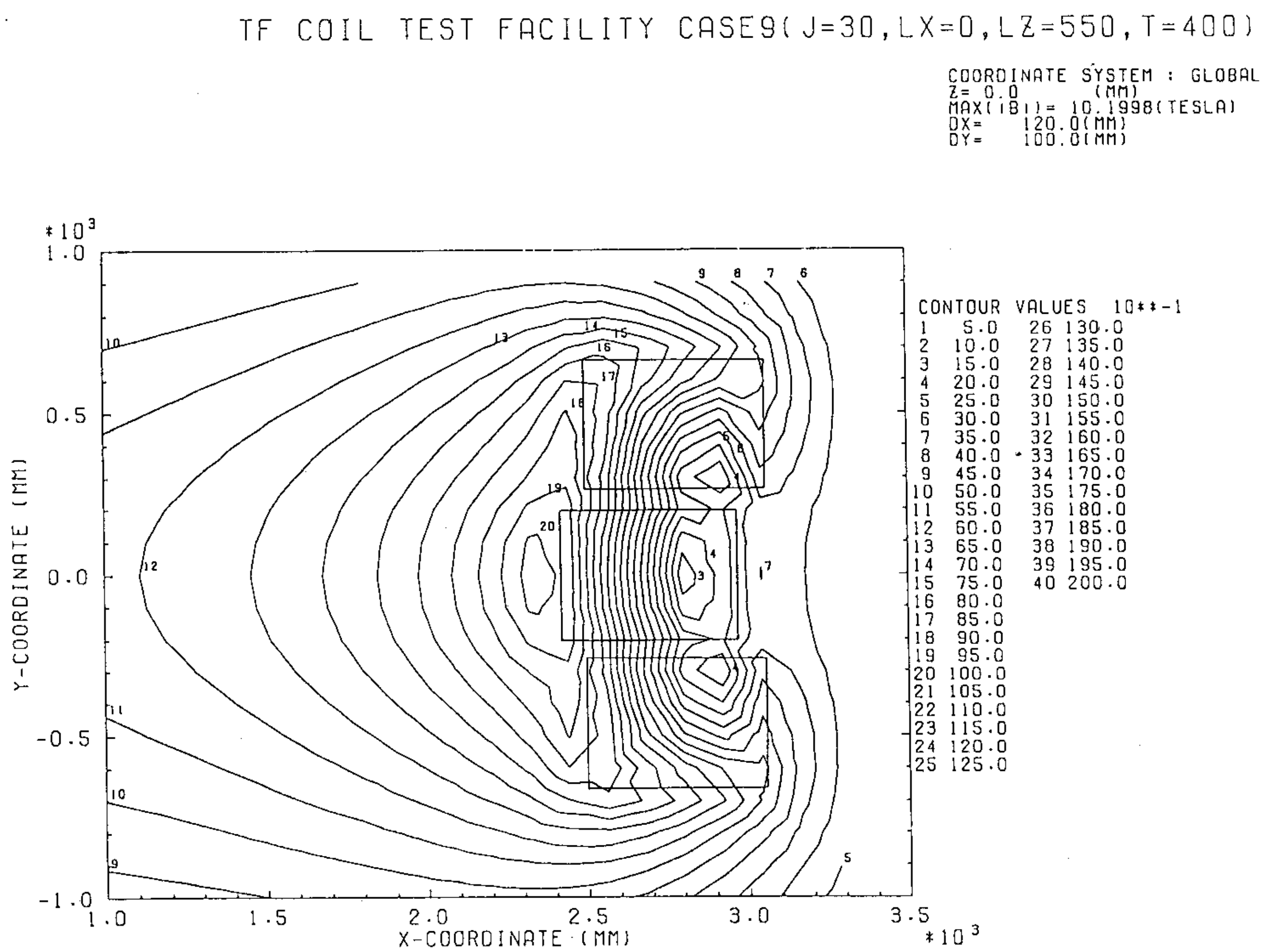

Fig. 3.12 Magnetic field contour map at a cross section in the top of circular part on Mechanical test stand.

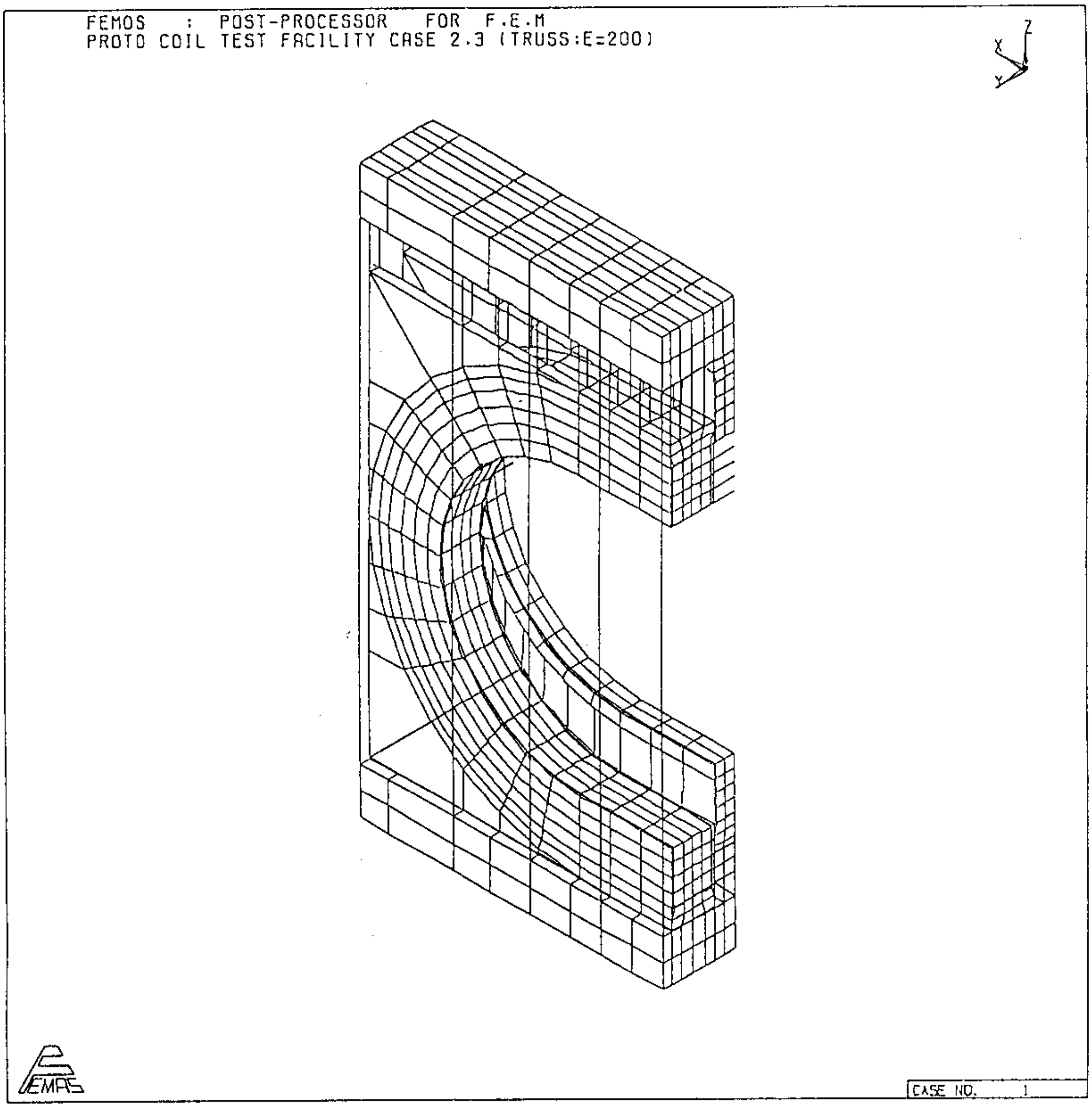

Fig. 3.13 Calculation model of the Mechanical Test Stand.

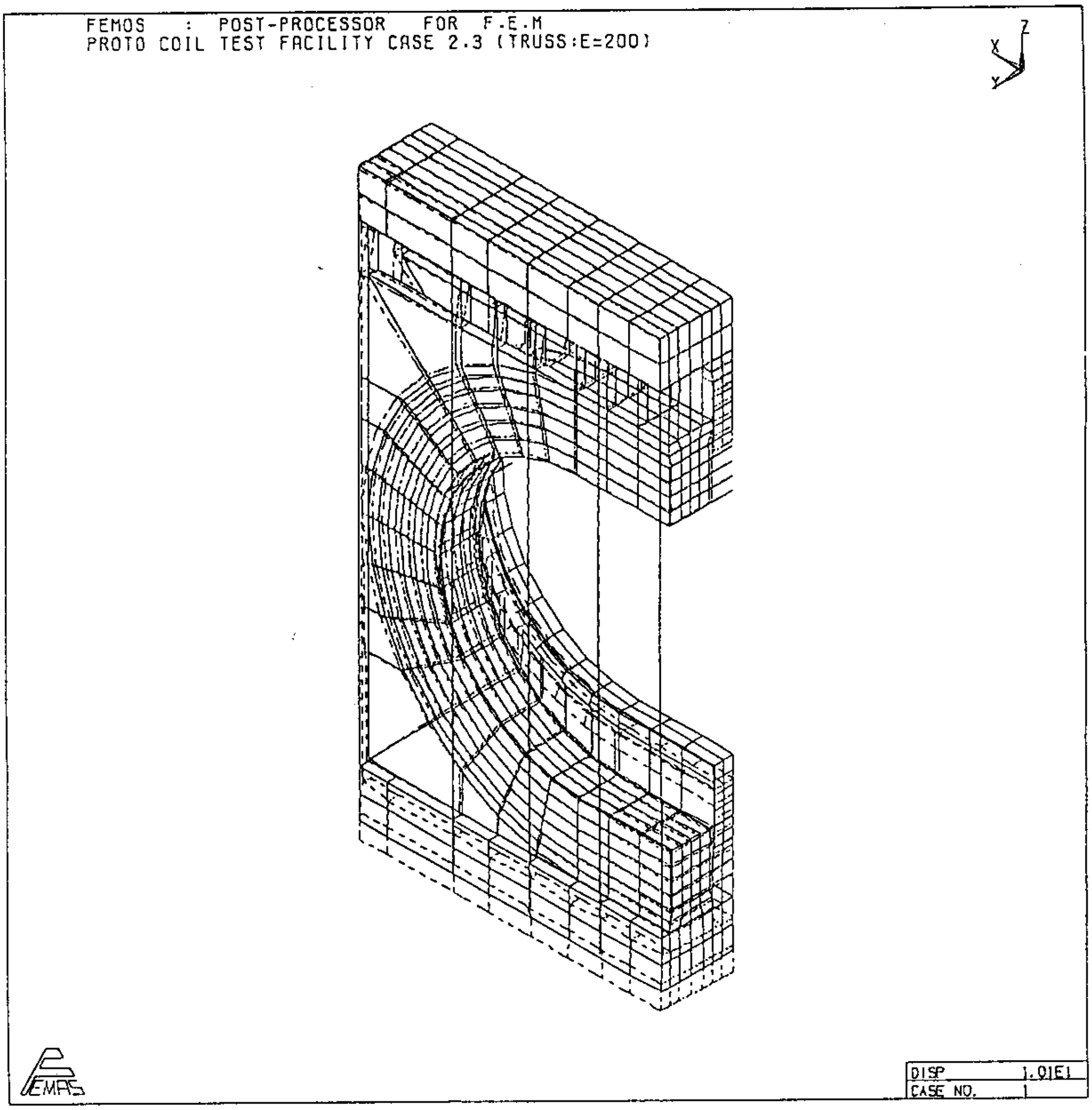

Fig. 3.14 Displacement diagram of the Mechanical Test Stand.

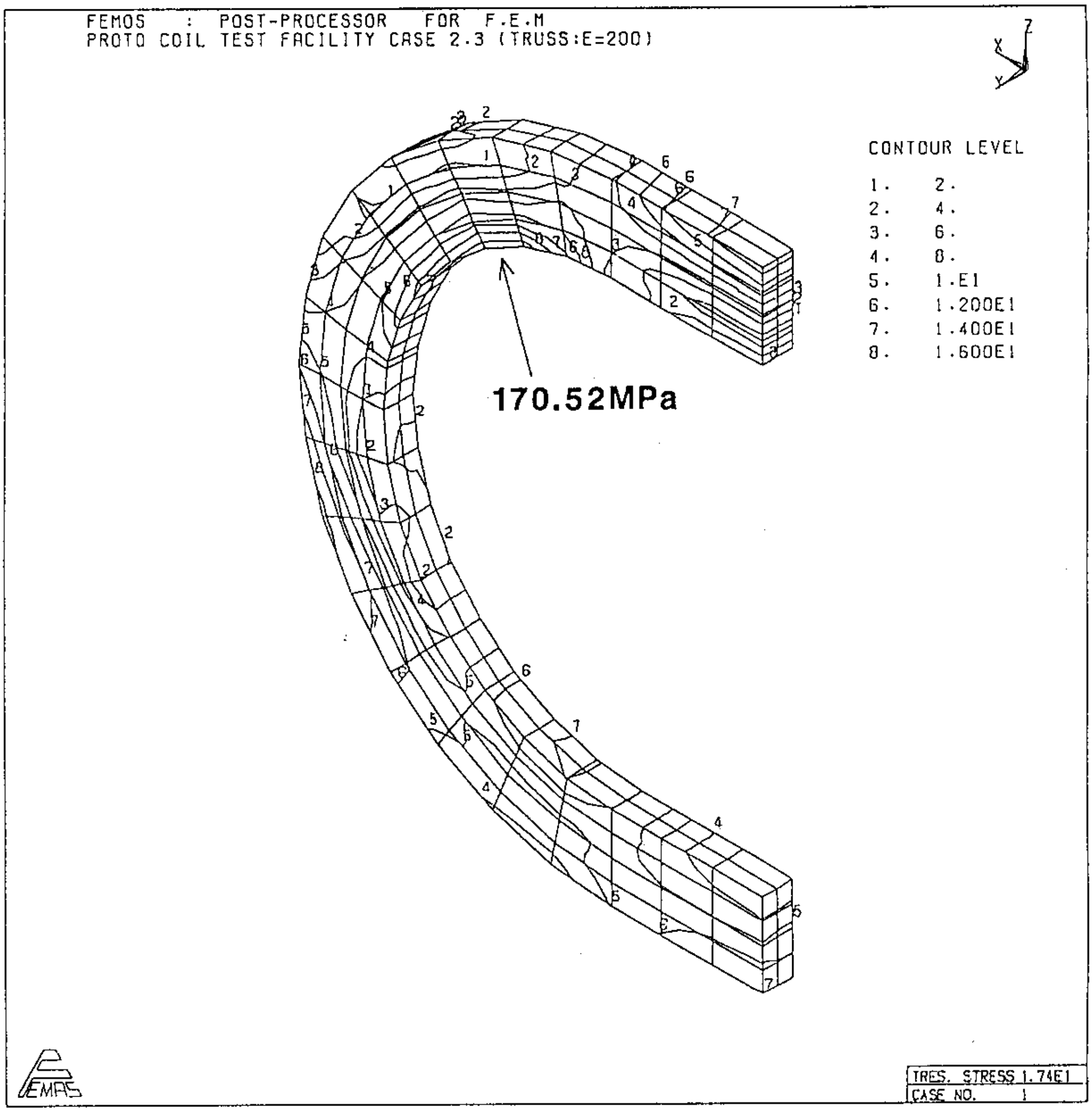

Fig.3.15(a) Tresca stress distribution of the Test Position coil.

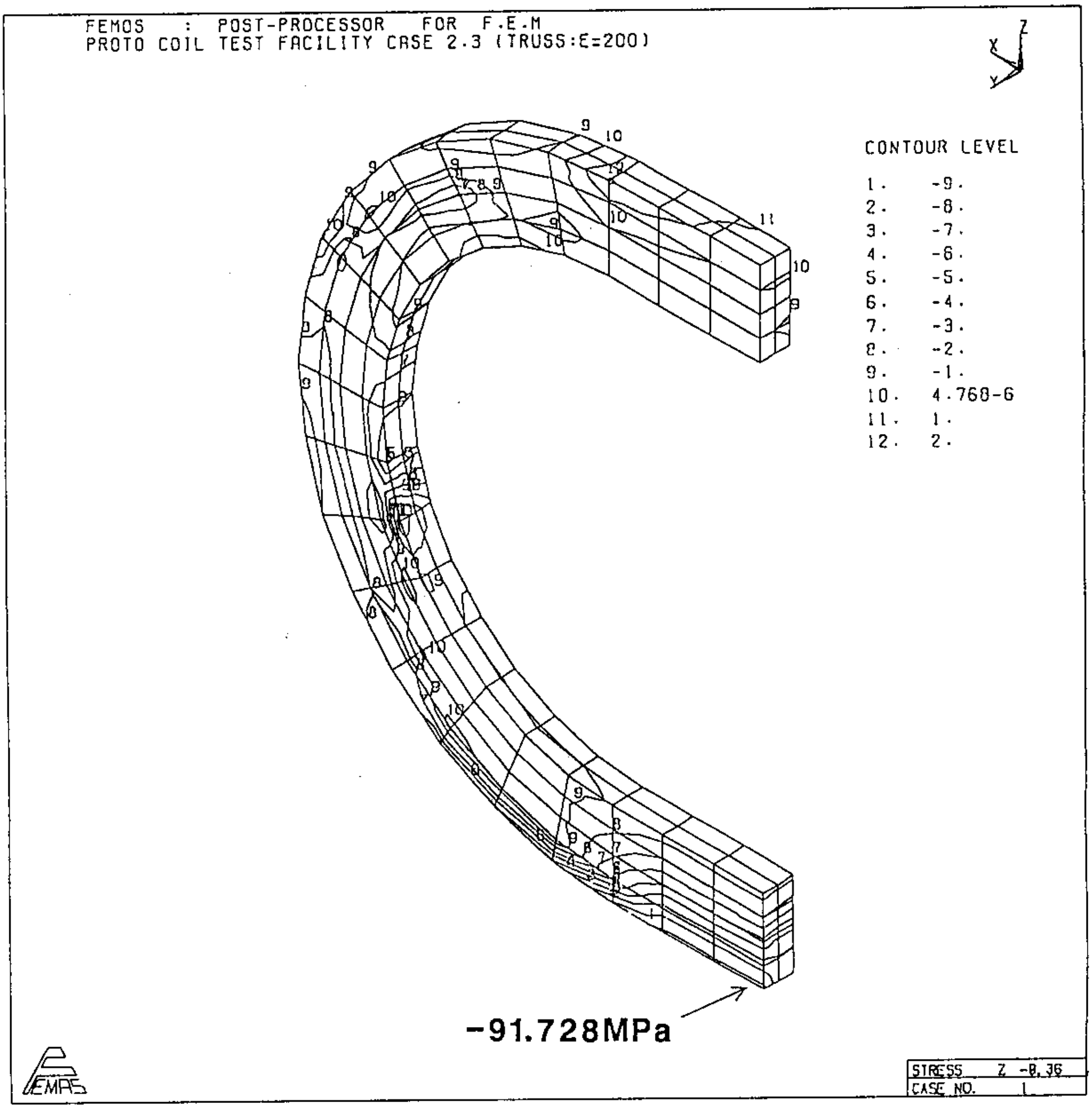

Fig.3.15(b) Radial stress distribution of the Test Position coil.

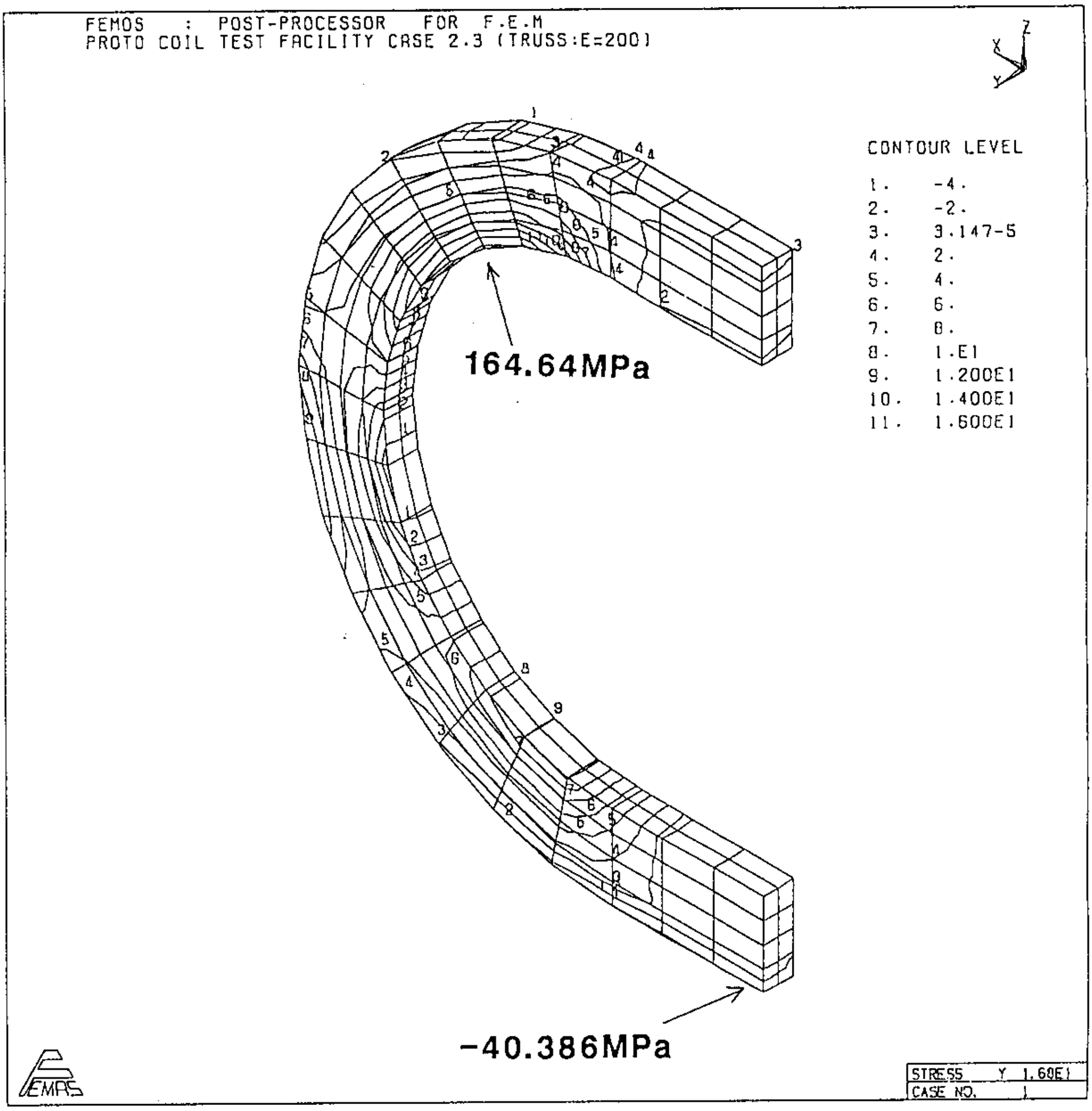

Fig.3.15(c) Axial stress distribution of the Test Position coil.

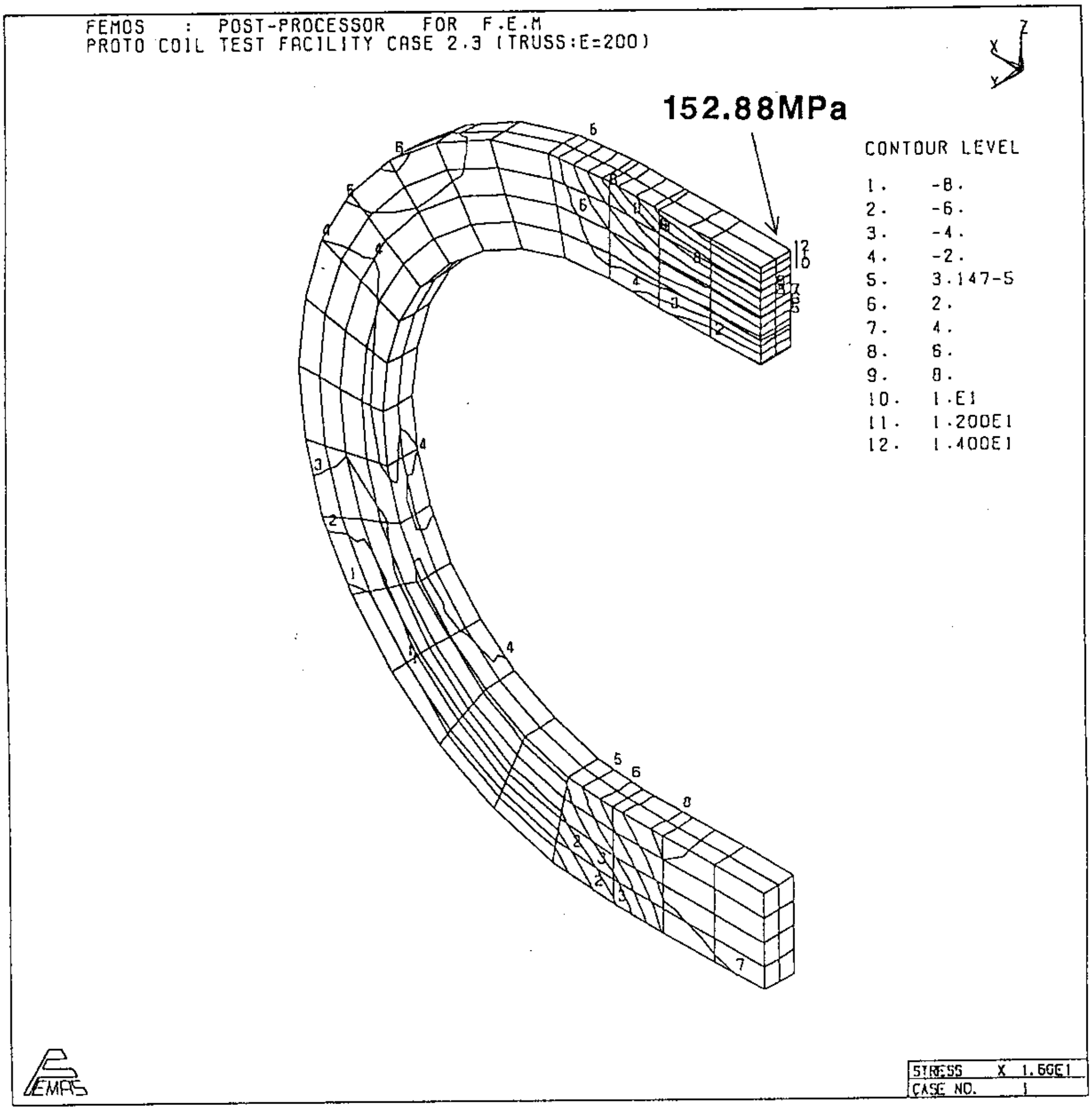

Fig.3.15(d) Longitudinal stress distribution of the Test Position coil.

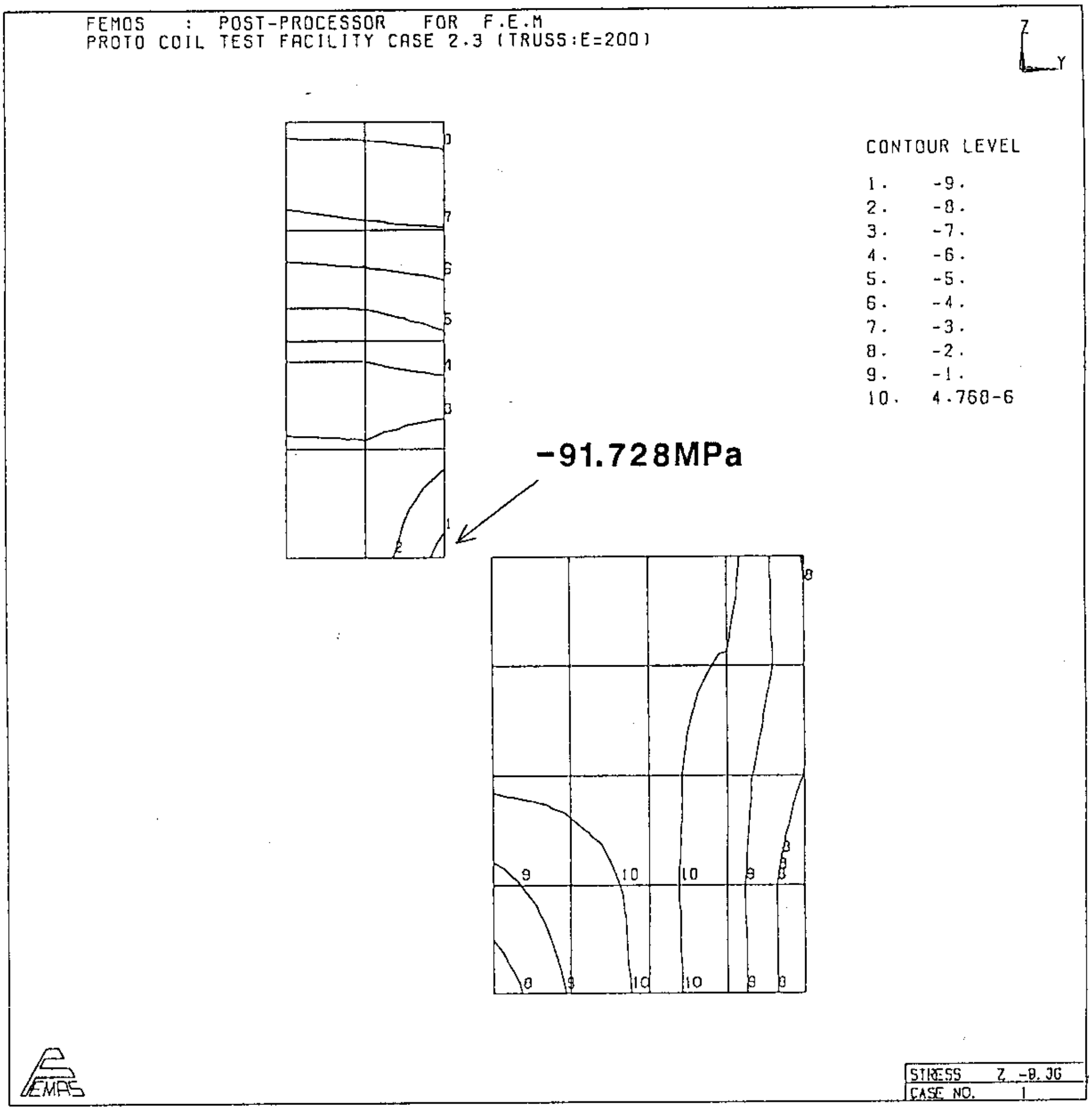

Fig. 3.16 The distribution of the radial stress in the cross-section of the Front-post-side straight part on Test Position coil.

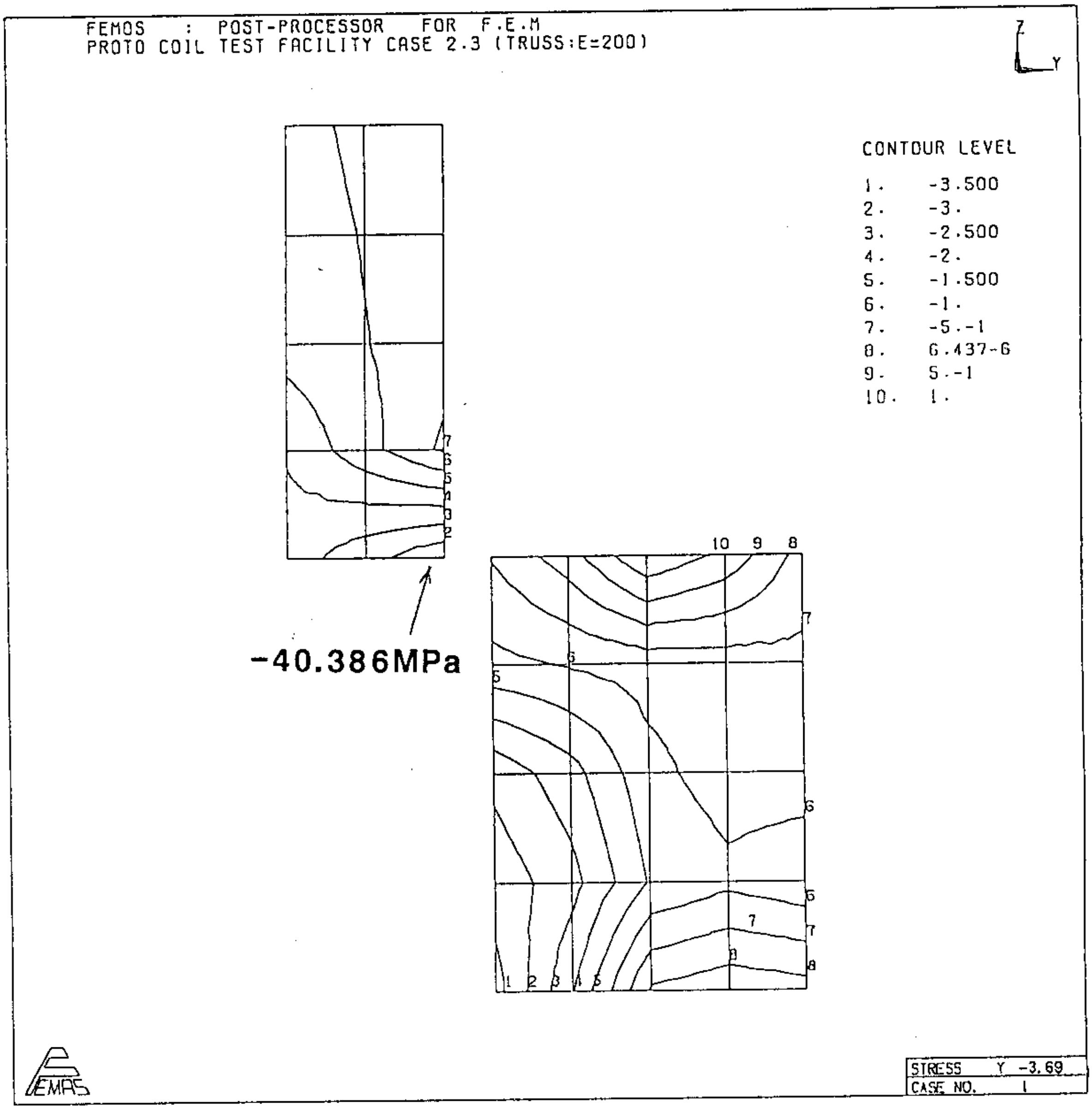

Fig. 3.17 The distribution of the axial stress in the cross-section of the Front-post-side straight part on Test Position coil.

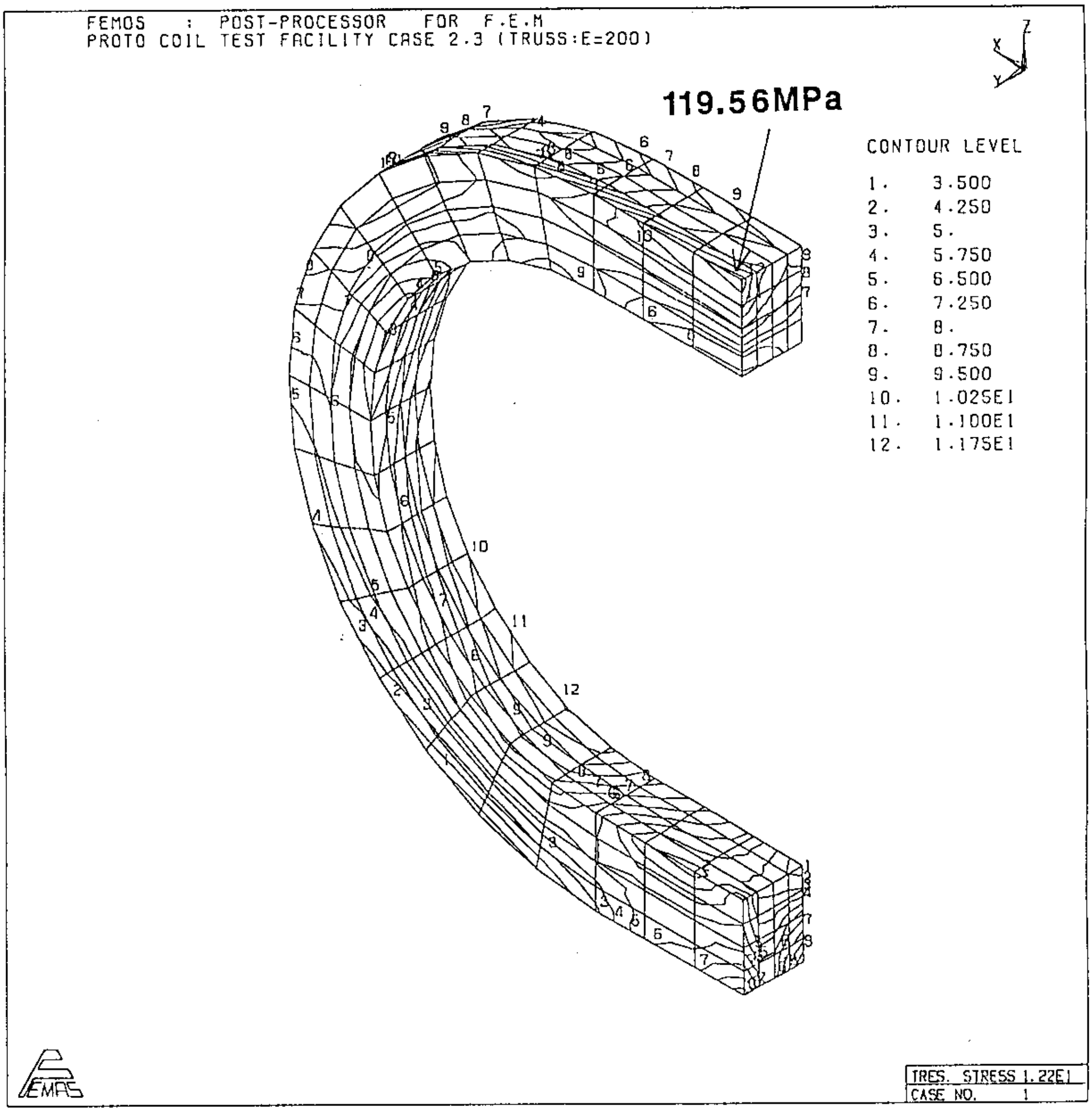

Fig. 3.18(a) Tresca stress distribution of the Background Position coil.

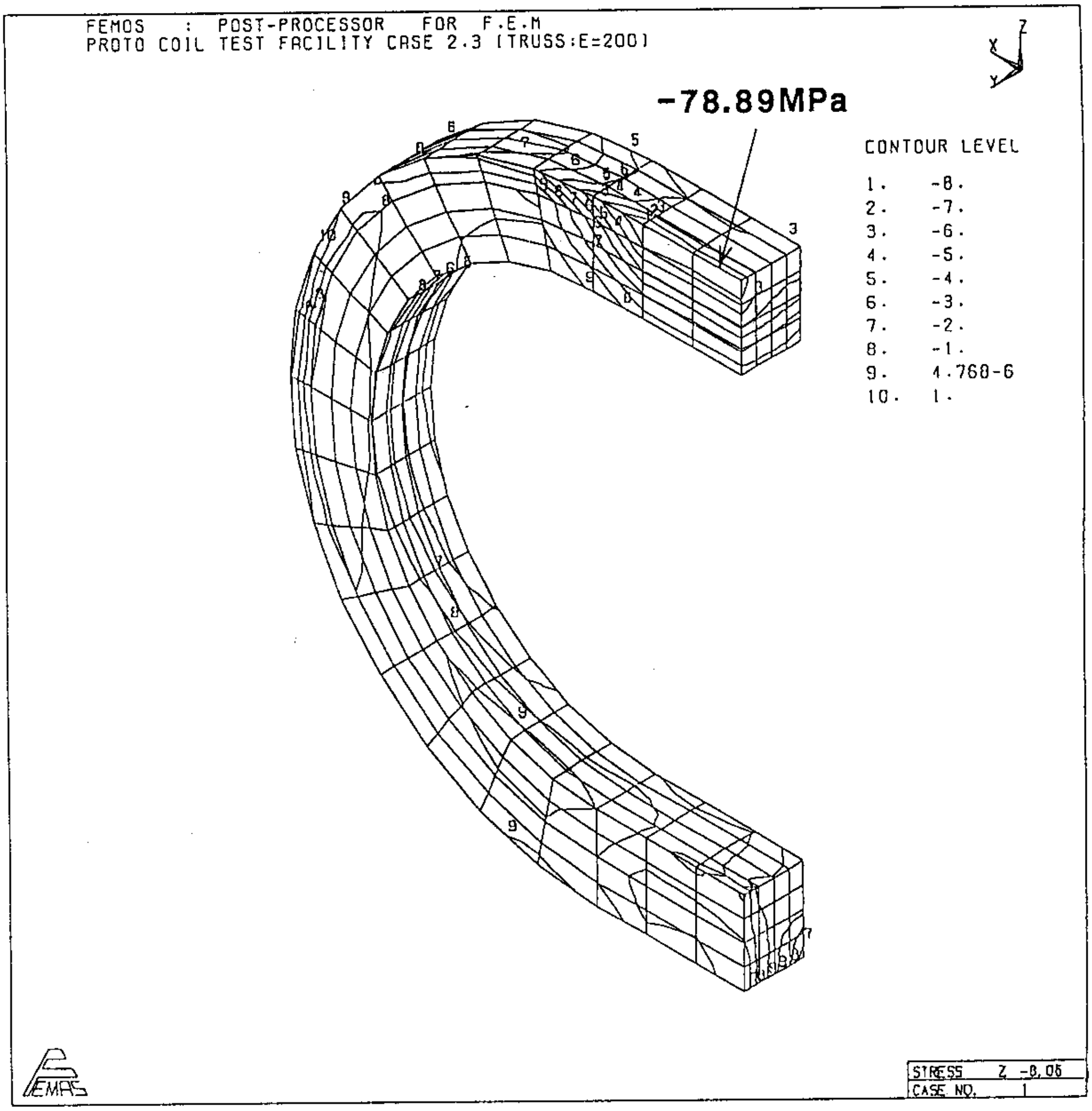

Fig. 3.18(b) Radial stress distribution of the Background Position coil.

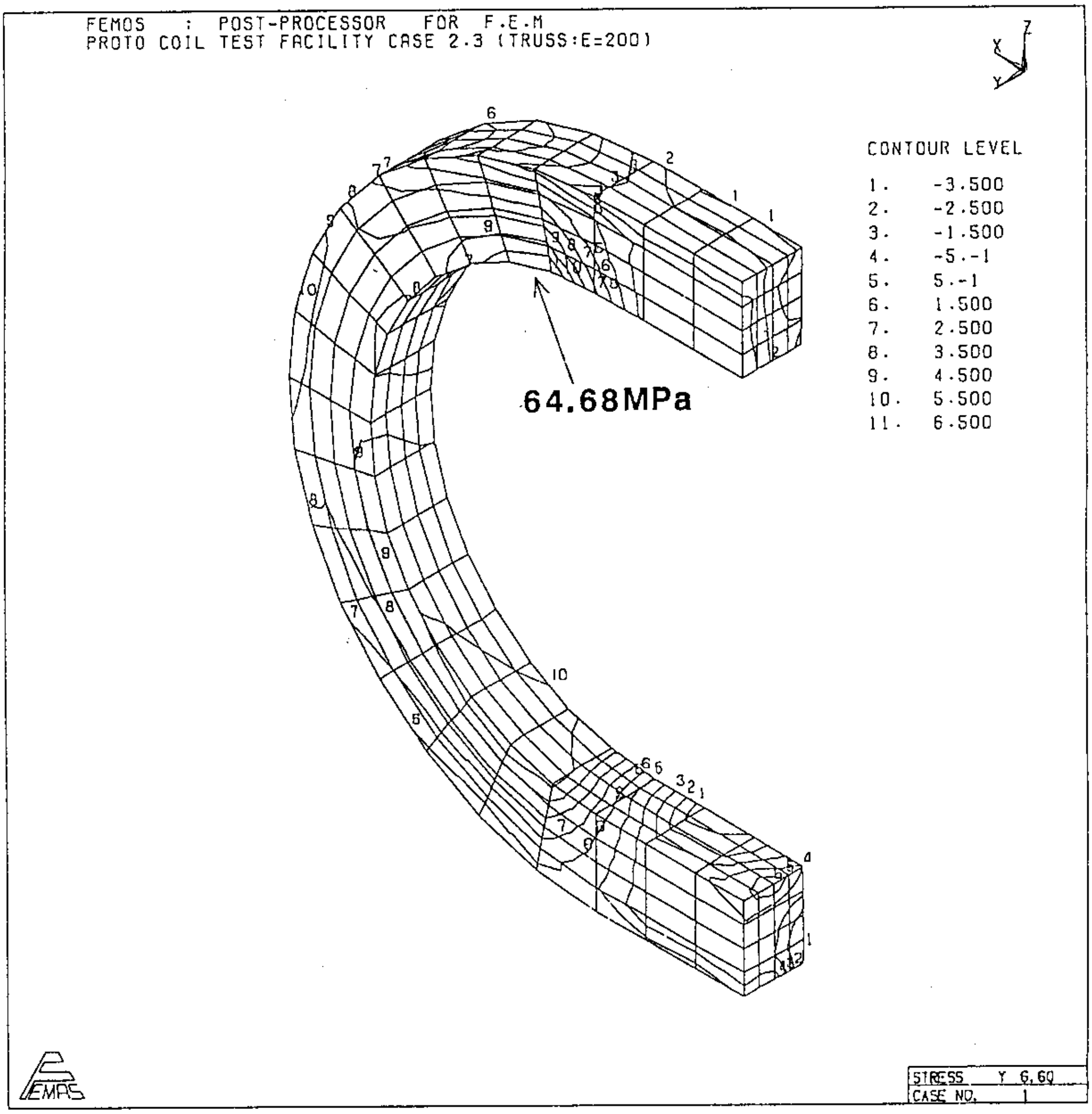

Fig. 3.18(c) Axial stress distribution of the Background Position coil.

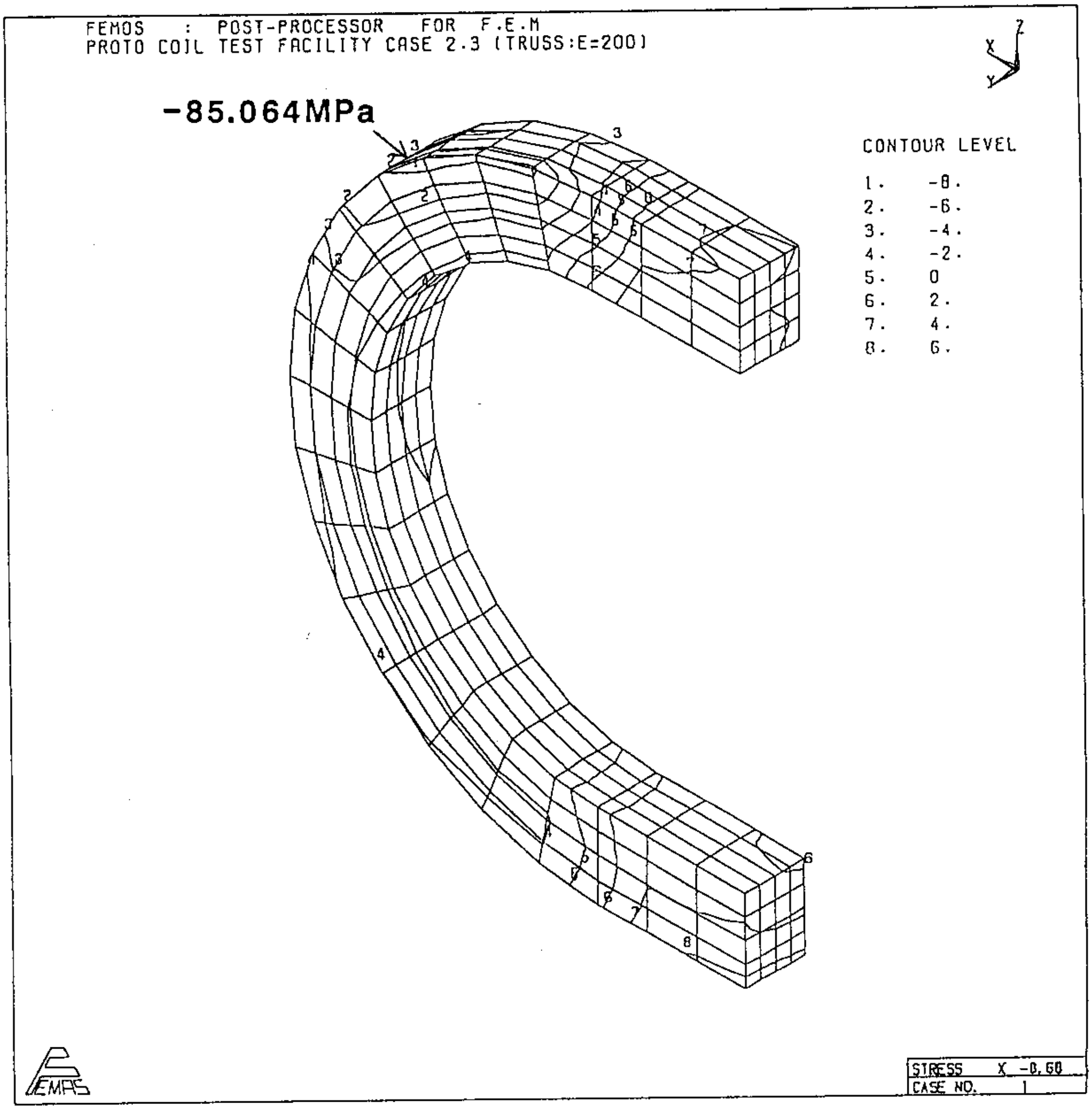

Fig. 3.18(d) Longitudinal stress distribution of the Background Position coil.

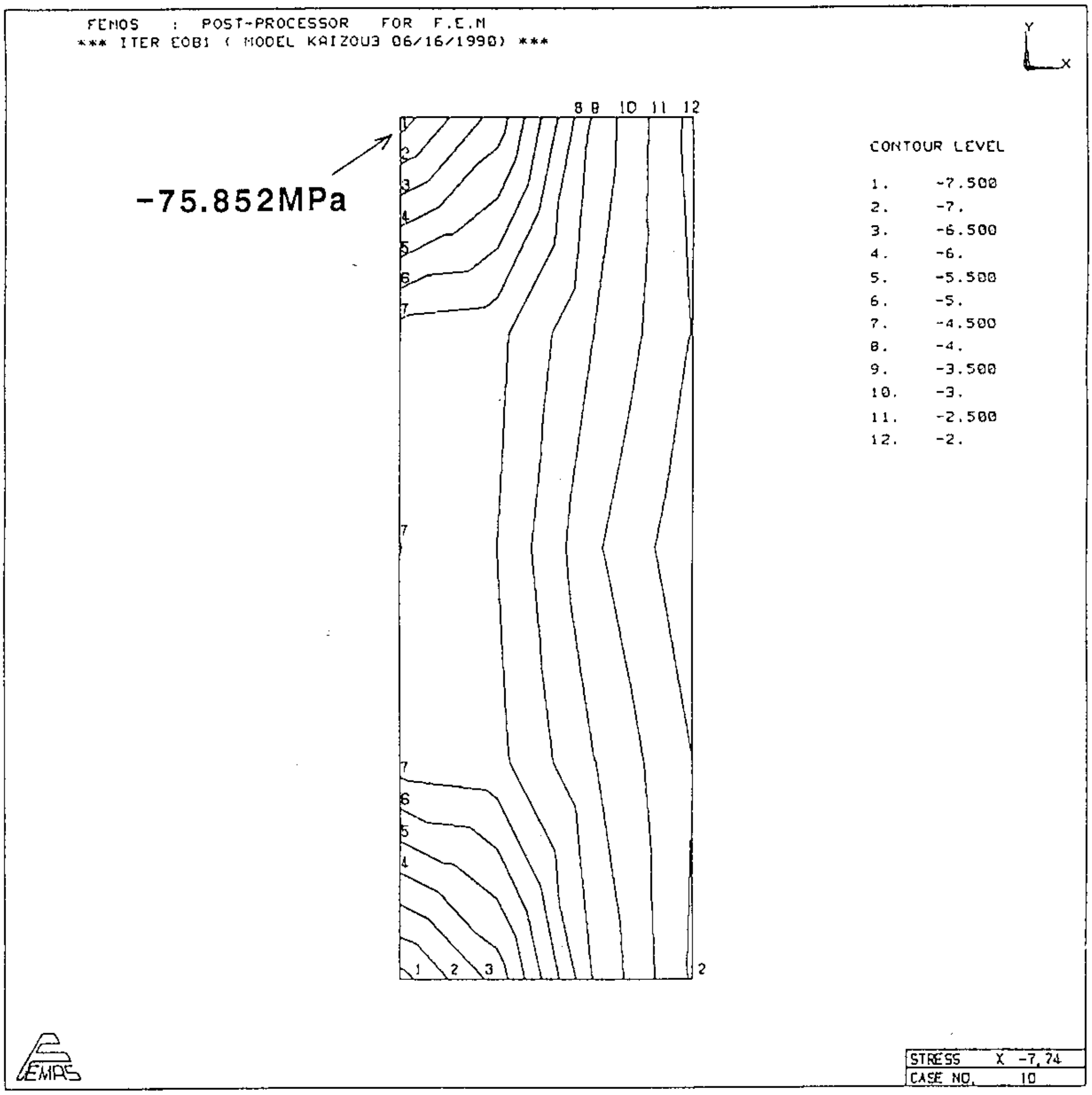

Fig. 3.19(a) Radial stress distribution at the straight part of the ITER TF coil.

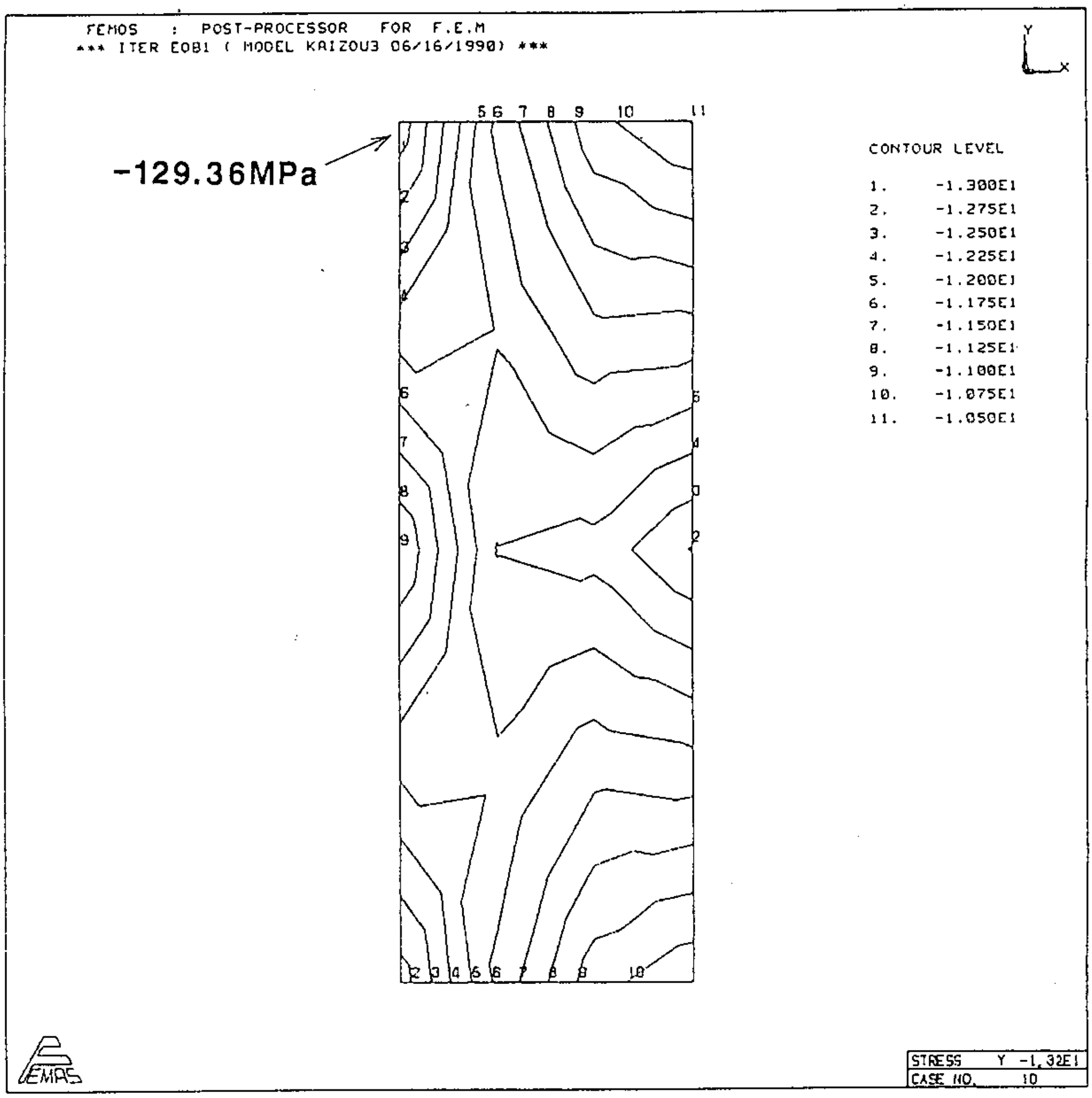

Fig. 3.19(b) Axial stress distribution at the straight part of the ITER TF coil.

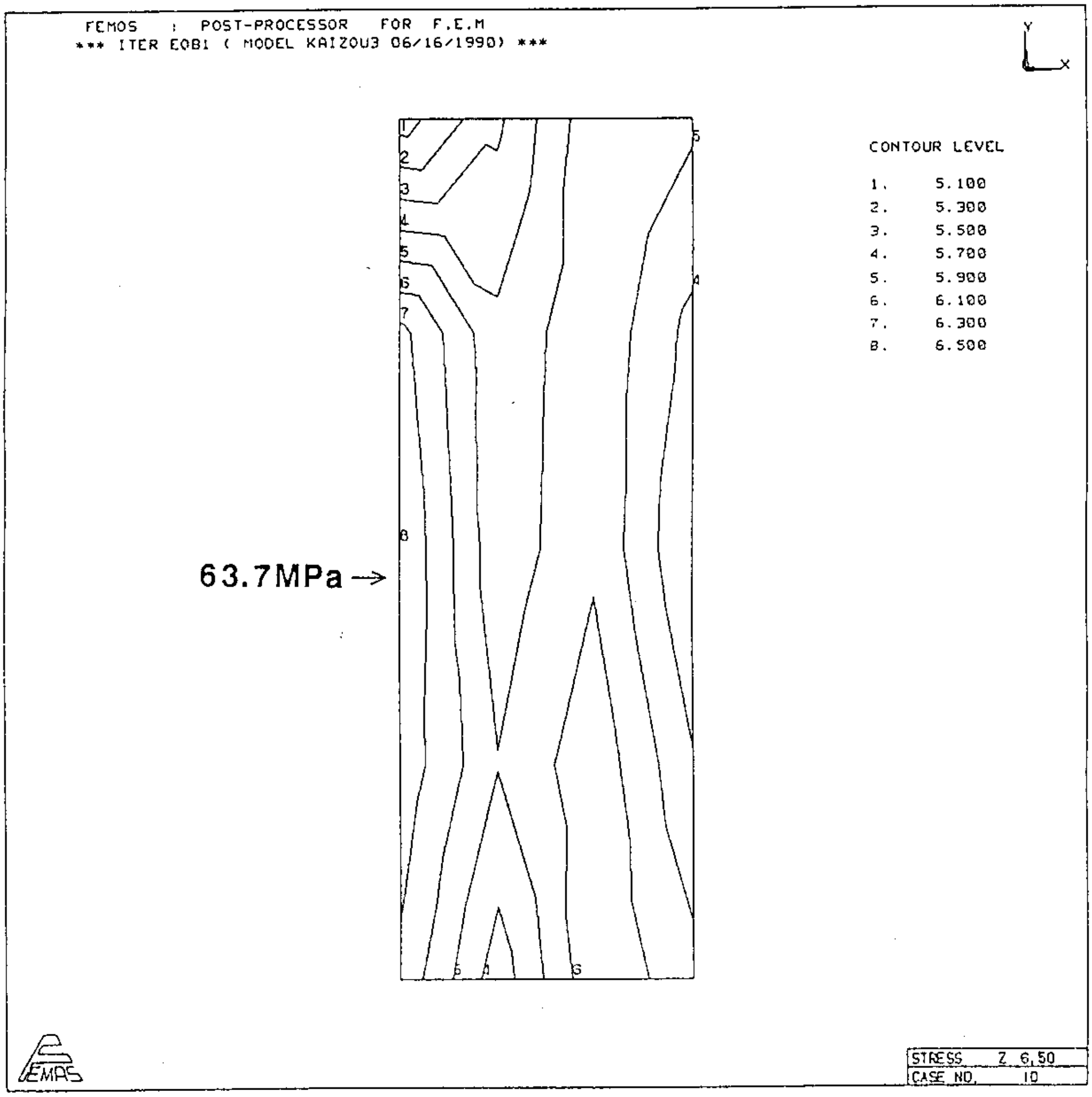

Fig. 3.19(c) Longitudinal stress distribution at the straight part of the ITER TF coil.

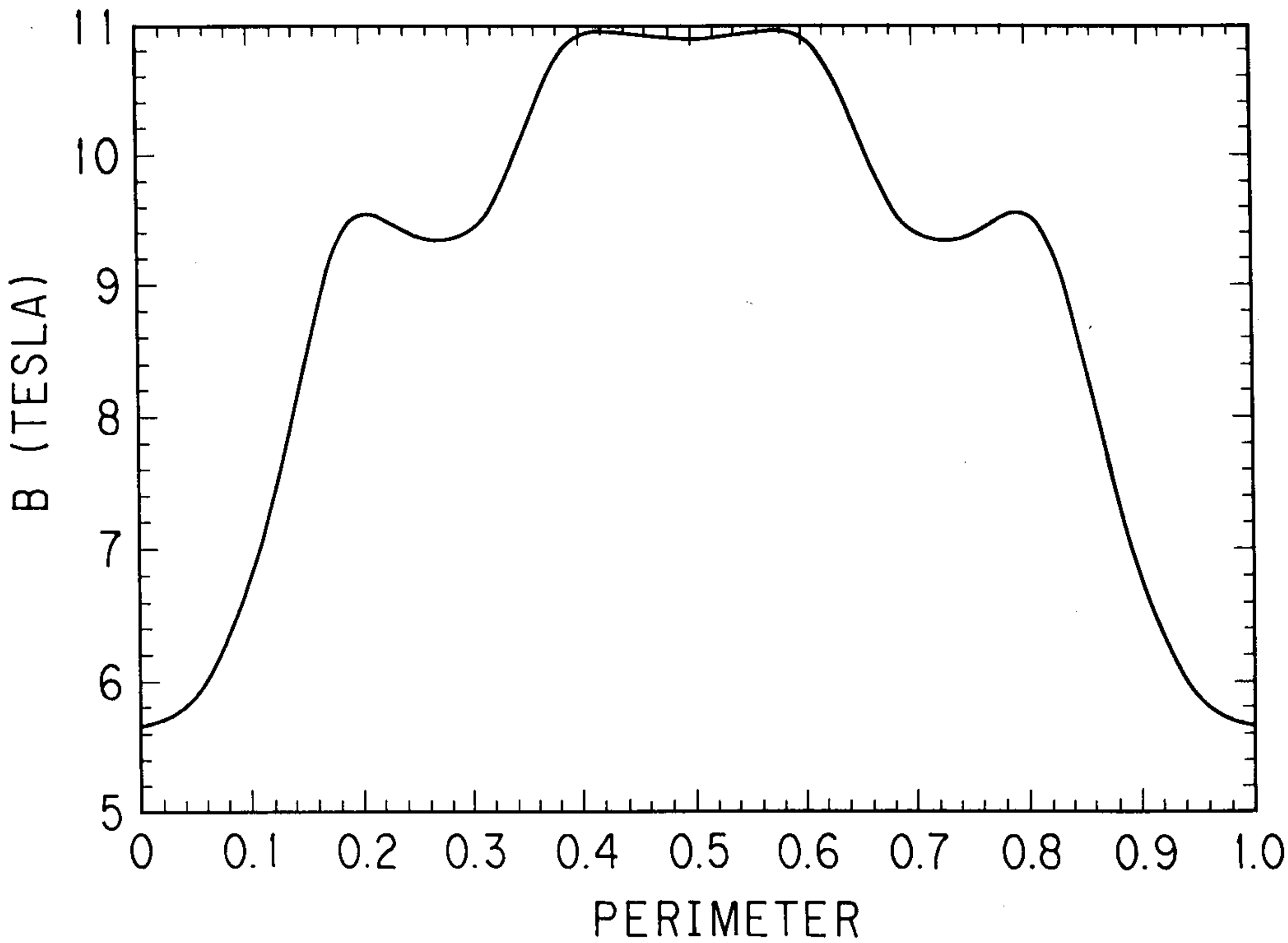

Fig. 3.20 Magnetic field distribution along the background position coil perimeter at High field test stand.

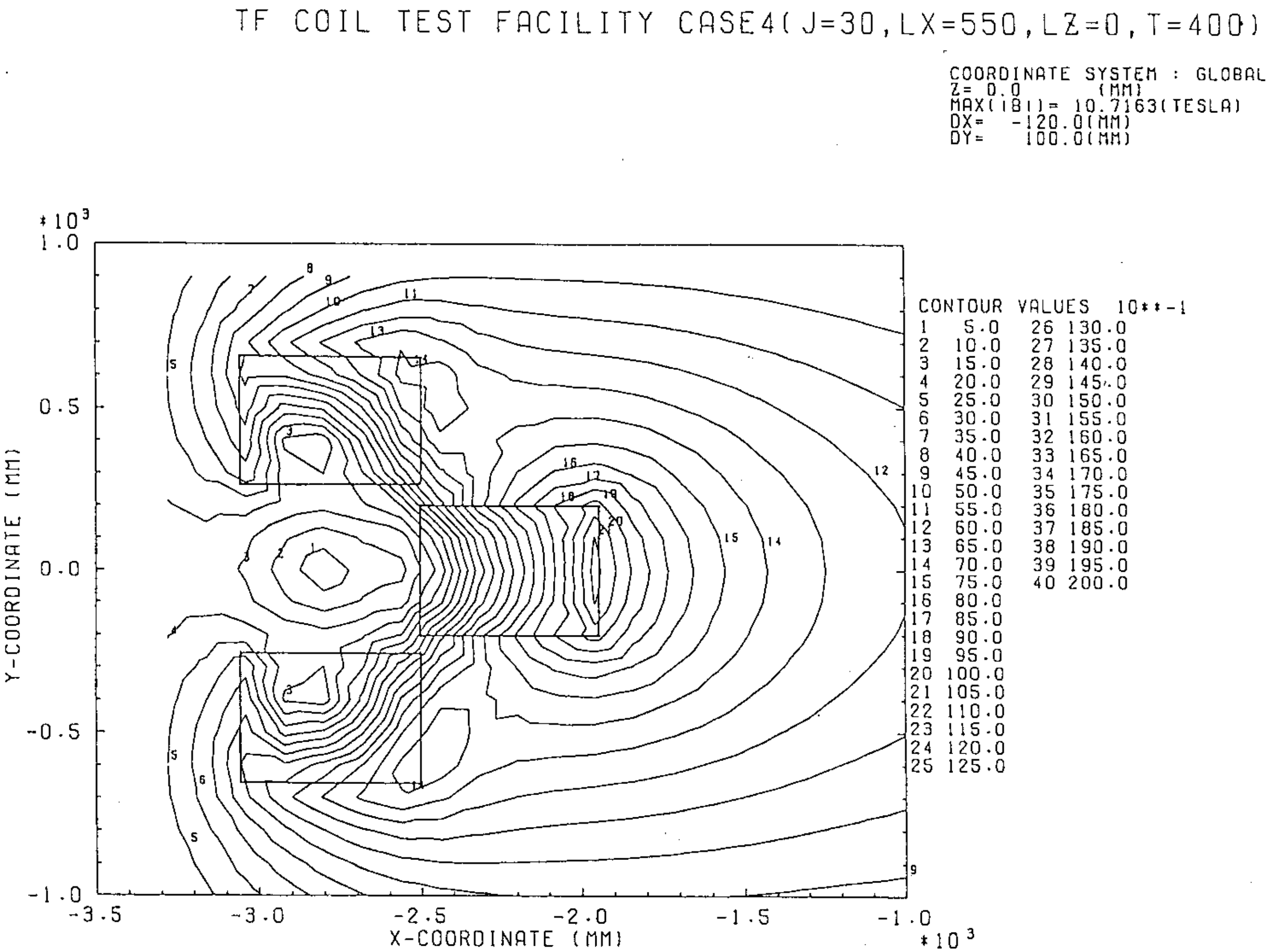

Fig. 3.21 Magnetic field contour map at a cross section in the top of circular part on High field test stand.

4. SUMMARY

The R&D proposals from Japan were discussed in ITER CDA design team and modified. Finally four proposals are summarized in ITER Technical report No. 20. Therefore, there are many differences between the Japanese proposals and ITER Long-team R&D program. However, we understand that the Japanese proposals are essentially adopted in the ITER Long-Term R&D program.

After agreements of international collaboration through ITER-EDA, there are many benefits for development tasks to use other country test facilities and to exchange hardware information by samples and scientists exchange. We don't need to consider to prepare new facility for investigation of large conductor or coil samples. The international common facility for the scalable model coils has good benefits to develop the components of utility (cryogenic system and power supply system). Also, the common test will be carried out with good collaboration as same as the Large Coil Task.

The development program of Toroidal Field Coil is basically proposed from Japan with the design and analysis reports. The TF model coil and its test stand were designed to emulate the environment of the ITER TF coils. Using the designed mechanical test stand, it is proved by the analysis that the required mechanical condition can be achieved in the test coil. With the high field test stand, the required field of 11T can be experienced by the conductor along a 3 m length. We believe that the TF coil is the most important component in the tokamak concepts. The TF coil needs technologies in not only conductor but also supporting of winding and non-circular winding. These problems could not solved during the Large Coil Task. Therefore, development program of the TF coil is essential task in the ITER Long-term R&D.

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