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STRUCTURAL ANALYSIS OF SUPPORT STRUCTURE FOR
ITER VACUUM VESSEL

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Structural Analysis of Support Structure for ITER Vacuum Vessel

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ITER vacuum vessel (VV) is a safety component confining radioactive materials such as tritium and activated dust. An independent VV support structure with multiple flexible plates located at the bottom of VV lower port is proposed. This independent concept has two advantages: (1) thermal load due to the temperature difference between VV and the lower temperature components such as TF coil becomes lower and (2) the other components such as TF coil is categorized as a non-safety component because of its independence from VV. Stress analyses have been performed to assess the integrity of the VV support structure using a precisely modeled VV structure. As a result, (1) the maximum displacement of the VV corresponding to the relative displacement between VV and TF coil is found to be 15 mm, much less than the current design value of 100 mm, and (2) the stresses of the whole VV system including VV support are estimated to be less than the allowable ones defined by ASME Section III Subsection NF, respectively. Based on these assessments, the feasibility of the proposed independent VV support has been verified as a VV support.

Keywords: *ITER, Vacuum Vessel, Flexible Plates, Independent Support Structure, Safety Component, Stress Analysis*

ITER 真空容器支持脚の構造解析

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ITER 真空容器はトリチウムや放射化ダスト等の放射性物質を閉じ込める安全機器である。本報告では、真空容器支持脚について、真空容器下部ポートから支持する独立支持構造を提案する。この独立支持方式は2つの利点を持つ。一つは、真空容器とトロイダル磁場コイルとの大きな温度差による熱荷重が軽減される点であり、もう一点は、トロイダル磁場コイルが真空容器と独立であることにより、安全機器として分類される必要がない点である。この支持脚の健全性を評価するため、真空容器の詳細モデルを用いて応力解析を実施した。その結果、真空容器とトロイダル磁場コイルとの相対変位は、設計クリアランスの 100mm に対して 15mm に押さえられた。また、支持脚を含む真空容器の応力は ASME Section III Subsection NF で定められた許容値以下に押さえられた。これらの評価によって、提案する独立支持構造が真空容器支持脚として成立することが確認された。

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1. Introduction

The International Thermonuclear Experimental Reactor (ITER) is a Deuterium and Tritium burning tokamak facility developed under the international collaboration of Japan, European Union, the Russian Federation, the United State of America, the People's Republic of China and Republic of Korea, aiming at scientific and technological demonstration of fusion energy¹⁾. The major structure of the ITER is composed of three types of superconducting coils (poloidal field coil (PF coil), toroidal field coil (TF coil) and central solenoid coil (CS coil)) and a vacuum vessel (VV), as shown in Fig. 1, which are operated at quite different temperatures of 4 K and 150 °C, respectively. Support structures, such as gravity supports for TF coil and VV, must be flexible in the radial direction to accommodate the deformation caused by the temperature difference between initial assembly and operating conditions, while keeping high rigidity in the vertical and toroidal direction in order to withstand the whole dead weight of the tokamak and the seismic force, etc. Based on these viewpoints, multiple plates are adopted as the flexible support structures of the major ITER components such as TF coil and VV, as shown in Fig. 2.

In the current design of the ITER, the support structure of the VV is mounted on the TF coils, as shown in Figs. 1 and 2, in order to minimize the relative displacement between TF coil and VV under the horizontal loads such as seismic load²⁾. The design has two critical issues, i.e., (1) one is that a large load on the support structure is caused by the relative thermal displacement due to large difference of operating temperatures between TF coil and VV, and (2) the other is that the TF coil will be categorized as a safety component, because the supporting structure of the VV, which is a safety component confining radioactive materials such as tritium and activated dust, is directly connected to the TF coil. In particular, the latter issue gives a large impact on the schedule and procurement for ITER construction, so that it is necessary to change the category of the TF coil as a non-safety component.

The present paper therefore proposes a design of the VV support structure, which is independent from the TF coil. Stress analyses are performed in order to verify the feasibility of the new independent VV support structure from the TF coil.

2. Basic Concept of VV Support Structure

The VV support structure of ITER is not a simple support, but it must satisfy several requirements. Therefore, the support structure must be designed with considering these requirements. Necessary features of the support structure are as follows:

- (a) to accept displacement due to the temperature difference between initial assembly (room temperature) and operating condition (150 °C),
- (b) to sustain loads caused by its own gravity, earthquake and electromagnetic force
- (c) to resist radiation induced by the fusion reaction, and
- (d) to reduce the relative displacement between the VV and the superconducting magnet.

First of all, mechanical system of the support structure must be decided. Considering the requirement (a) and (b), the following systems are possible to adopt:

- support with sliding pad and damper
- multiple flexible plates

Regarding the former system, the sliding pad can accept thermal displacement. The damper does not prevent thermal expansion because the movement is very slow. On the other hand, the damper resists seismic and electromagnetic loads which are implied rapidly. However, this system is rather complicated and unreliable so periodical inspection is needed. In addition, the oil needed for the damper will be hardened by radiation so it does not satisfy the requirement (c). Thus, this report selected the latter system: multiple flexible plates. The reference design of the ITER also adopts this concept.

The flexible plate can be bent easily by the out-of-plane loads while it sustains the in-plane ones. The vacuum vessel is axisymmetric so the thermal deformation is in the radial direction. Therefore, the support composed of multiple flexible plates located perpendicular to the radial direction can accept thermal expansion while it resists the gravitation, earthquake and electromagnetic force.

Secondly, it must be decided whether the VV is supported independently or not. From the point of requirement (d), the VV support structure had better to be supported from the magnet because the relative displacement is expected to be reduced if they move together. However, from the viewpoint of safety, it is not favorable because not only the VV but also the magnet must be categorized as safety component if they are mechanically connected. In this case, the required reliability becomes higher and the design of the magnet becomes more complex. Therefore, this report selected the independent support structure.

The third point is the location of the support system. Below the bottom of the main vessel, there are

structures called “Intercoil Structure” connecting the TF coils together and PF coil (PF-5), as shown in Fig.3. If the support structure is located there, it will interfere with the Intercoil Structure. Therefore, the VV must be supported at the outer place. The vacuum vessel has ducts called “port” at the upper, equatorial and lower positions. There are 9 or 18 lower ports (number depends on the version of design) and the supports can be located at the bottom of them.

As a result, this report proposes the independent support system with multiple flexible plates located at the bottom of VV lower port, for the VV support structure. The respective VV supports consist of an assembly of 20 flexible plates, whose dimensions are 2000 mm in length, 1250 mm in width and 32 mm in thickness, and a support leg connected at the bottom of the lower port by welding. The material of the plate is a stainless steel (SUS-316L(N)-IG, a kind of SUS-316 with higher strength) specified by ITER Project³⁾. The flexible plate assembly is connected between the support leg and cryostat ring by the Inconel-718 bolts with a diameter of 90 mm, as shown in Fig.3.

According to the design change of the VV support located at the lower port, the reinforcements of lower port will be necessary for vertical and horizontal loads, mainly at the joint between lower port and VV sector. The reinforcements are designed taking into account the interference between the reinforcements and the other components such as TF coils with different temperature, as shown in Fig. 4.

3. Applied Standard and Load Condition

For the ITER VV support structure, ASME Section III Subsection NF, “Rules Construction Nuclear Power Plant Components-Subsection Supports”⁴⁾ is selected. The loads for the VV support are combination of dead weight, thermal load, electromagnetic (EM) load and seismic load. The EM load is peculiar to the tokamak device. When the plasma current vanishes by some reasons, an induced current flows on the surface of the VV. The current in the magnetic field induces the EM force, which is applied on the VV. There are two patterns of the vanishment of the plasma current, which do not happen in the same time. One is a Centered Disruption (CD): the plasma discharges at the center of the VV. The other is a Vertical Displacement Event (VDE): the plasma moves downward until the bottom of the VV and then its current vanishes. The VDE is considered as a load condition in the following analysis because the VDE is generally more serious for the VV support due to larger total load than that of the CD. In addition, the Troidal Field Coil Fast Discharge (TFCFD) has to be considered for analysis, because the TFCFD may happen in the same time with the VDE.

Table 1 shows the actual load conditions in the structural analysis performed in this paper. Dead weight is estimated to be 90 MN that includes the all weight of VV and port components. Thermal load is produced by the temperature rise of VV in the plasma and baking operations. In the plasma operation, temperatures of the VV support are assumed to be 20°C at the lower flange of the flexible palates and 100°C at the bottom surface of the VV lower port, respectively. During baking operation, temperature of lower port will be changed to 140°C from 100°C for plasma operation. Bending stress of the flexible plates due to thermal displacement of the VV is classified to the primary stress according to the ASME Sec. III Subsection NF.

In the ITER, the VDE is categorized into three types by magnitude of loads: VDE I, II and III. EM loads of VDE I and VDE II are 60 % and 75 % of that of VDE III, respectively⁵⁾. The EM loads of VDE III are 72 MN and 25 MN in the vertical and horizontal direction, respectively⁵⁾. The seismic load of off-normal operation (S1) is defined as the static load of 0.6 G (54 MN) in vertical and horizontal direction because the ITER reference design assumes 0.2 G of dynamic load⁴⁾ and the value is multiplied by the dynamic amplification factor 3. This factor was decided by the result of the dynamic analysis⁶⁾. The seismic load of normal operation (S0) is assumed to be 1/3 of that of S1, 0.2 G (18 MN)⁷⁾.

4. Stress Analysis of VV Support

4.1 Analysis condition

Stress analyses have been performed to assess the integrity of the VV support. Table 1 shows possible load combinations for normal and off-normal operations. Among them, the most severe combinations are selected for analyses for normal operation (case 1) and off-normal operation (case 2), respectively.

4.2 Analysis model

A VV model composed of 180-degree torus with ports and VV supports has been used for the stress analysis of the VV support, as shown in Fig. 5. The detail of the VV support model is also shown in Fig. 6. The VV is composed of a double walled-structure, i.e., the inner and outer VV walls, port walls and rib structure for reinforce between the inner and outer walls are precisely modeled in the analysis model. In the analysis model, the VV wall, port wall and VV support flange are modeled by shell elements. The reinforcements of the VV support are modeled by solid elements in order to calculate the stress distribution in detail. In addition, the connection bolts of the VV support are modeled by beam elements to estimate the stress of the bolts. The vertical and horizontal loads are treated as the body forces of VV and ports. A symmetric boundary condition is applied on the nodes at the edges of the model in the toroidal direction, while the nodes at the lower edges of VV supports are fixed in the all directions.

4.3 Analysis results

(1) Outline of analysis results

Analysis results for the respective load combinations for normal and off-normal operations (case 1 and 2) are shown in Figs. 7~14 and are summarized in Table 2. The detailed results of the severer condition of case 2 are described below.

For case 2, the maximum displacement of the VV corresponding to the relative displacement between VV and TF coils, which is the most important for the assessment of the proposed independent VV support, is found to be 15 mm, much less than the current design clearance of 100 mm at the upper port perpendicular to the horizontal force as shown in Fig. 15. The displacement of the independent VV support is

therefore confirmed to not be an issue because there is enough clearance of 85 mm between the VV and TF coils.

The maximum Tresca stress of 426 MPa appears at the bottom edge of the innermost flexible plate as shown in Fig. 16. Due to the large maximum stress, detailed stress assessment is performed below for the verification of the feasibility of the flexible plates, based on the ASME Sec. III Subsection NF

(2) Stress assessment of the VV support

Using the analysis result of the flexible plate, shown in Figs. 17 and 18, the stress on the cross section at the lower edge of the innermost plate is categorized into a primary membrane stress (P_m), a primary bending stress (P_b) and a peak stress, as shown in Table 2. The stress of the plate is not uniform in the cross section because the bending moment is loaded on the plate. The P_m of the plate is estimated to be 49 MPa as the average stress in the cross section, based on the Subsection NF. The P_b is also estimated to be 151 MPa as the variable component of stress distribution along the width direction of the plate, based on the Subsection NF. The estimated P_m of 49 MPa and the $P_m + P_b$ of 200 MPa are within the allowable ones of 176 MPa and 264 MPa, respectively, and evaluation of peak stresses in the support is not required by the Subsection NF, so that the feasibility of the flexible plate of the VV support has been verified based on this Subsection.

(3) Stress Assessment of bolt

Results of the analysis show that the maximum tensile loads of connection bolts made of Inconel-718 for VV support are 1.235 MN for normal operation and 2.748 MN for off-normal operation, respectively. Table 3 shows the estimated loads and stresses of the bolt, according to the variation of the pre-tensions. All of the bolt stresses are within the allowable ones defined in ASME Sec III NF, for both normal and off-normal operations.

5. Conclusion

ITER VV is a safety component confining radioactive materials such as tritium and activated dust. The VV support structure is the independent support system with multiple flexible plates located at the bottom of VV lower port. This independent concept from TF coil has two advantages comparing to the current design directly connected between VV and TF coil: thermal load due to the temperature difference between VV and TF coil becomes lower and the TF coil is categorized as a non-safety component because of its independence from VV. Stress Analyses have been performed for the VV support structure using a precisely modeled VV structure. The results are summarized as follows:

1. Maximum displacement of the VV corresponding to the relative displacement between VV and TF coil is found to be 15 mm, much less than the current design value of 100 mm at the upper port perpendicular to the horizontal force. The displacement of the independent VV support is therefore confirmed to not be an issue.
2. Stress assessment is performed for the flexible plate where the Tresca stress becomes maximum according to the analysis result, so that the estimated stresses are less than the allowable value defined in ASME Sec. III NF.
3. The stresses of the connection bolt of the independent VV support are also estimated within the allowable ones defined in ASME Sec. III NF.

Based on the above results, the feasibility of the proposed VV support concept has been verified as a VV support. More detailed seismic analysis of the whole system will be performed to obtain the more exact relative displacement between VV and TF coil as a future study.

Acknowledgements

The authors would like to acknowledge Dr. K. Shibamura of the Japan Atomic Energy Research Institute for their continuous suggestions and encouragement.

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Table 1 Possible Load Combination and Analysis Condition

Cat.	Load Combination	Allowable Stress and Buckling Safety Factor	Analysis Condition	Thermal Load [$\Delta T^{\circ}\text{C}$]	Load [MN]	
					Vertical	Horizontal
Normal	Weight	Sm (Membrane)		-	90	-
	Weight+Baking+S0	1.5Sm (Bending)		120	108	18
	Weight+VDE II	3Sm (Thermal)		80	144	18.8
	Weight+VDE II+S0	3 (Buckling Safety Factor)	Case 1	80	162	36.8
	Weight+VDE II+TFCFD	1/2Su (Bolt Load)		80	144	18.8
Off-normal	Weight+Baking+S1	1.2*Sm (Membrane),		120	144	54
(Limit)	Weight+VDE III	1.2*1.5Sm (Bending)		80	162	25
	Weight+VDE II+S1	2.0 (Buckling Safety Factor) 1.25*1/2Su (Bolt Load)	Case 2	80	198	72.8

Table 2 Analysis Result and Stress Assessment for VV support

Analysis Condition					Analysis Result		Stress Assessment					
Cat.	Load Combination	Analysis Case	Thermal Load [ΔT°C]	Load [MN]		Max Displacement between VV and TF Coils [mm]	Max Tresca Stress [MPa]	Primary Stress			Peak Stress	
				Vertical	Horizontal			Pm [MPa]	Pm+Pb [MPa]	Estimated Allowable		
								Estimated Allowable	Estimated Allowable			
Normal	Weight+ VDE II+S0	Case 1	80	162	36.8	7	272	38	Sm=147	114	1.5Sm =221	272
Off-normal (Limit)	Weight+ VDE II+S1	Case 2	80	198	72.8	15	426	49	1.2Sm =176	200	1.8Sm =264	426

* Sm = 147 MPa³⁾

Table 3 Bolt Stress of the VV support

	Normal Operation			Off-Normal Operation		
	Bolt (M90)		Clamped part by bolt**	Bolt (M90)		Clamped part by bolt**
	Load [kN]	Stress [MPa]	Load [MN]	Load [kN]	Stress [MPa]	Load [MN]
Applied maximum tensile load of a bolt	1.235[MN]			2.748[MN]		
1. Pre-Tension of a bolt 1.73MN / 300 MPa	205	356	-0.82	245	425	0.30
2. Pre-Tension of a bolt 2.30MN / 400 MPa	263	456	-1.39	302	525	-0.28
3. Pre-Tension of a bolt 2.88MN / 500 MPa	320	556	-1.97	360	625	-0.85
Allowable stress*	Su/2 = 685 MPa		-	1.25×Su/2 = 856MPa		-

* Bolt material: Inconel 718(100°C) Su=1,370MPa³⁾

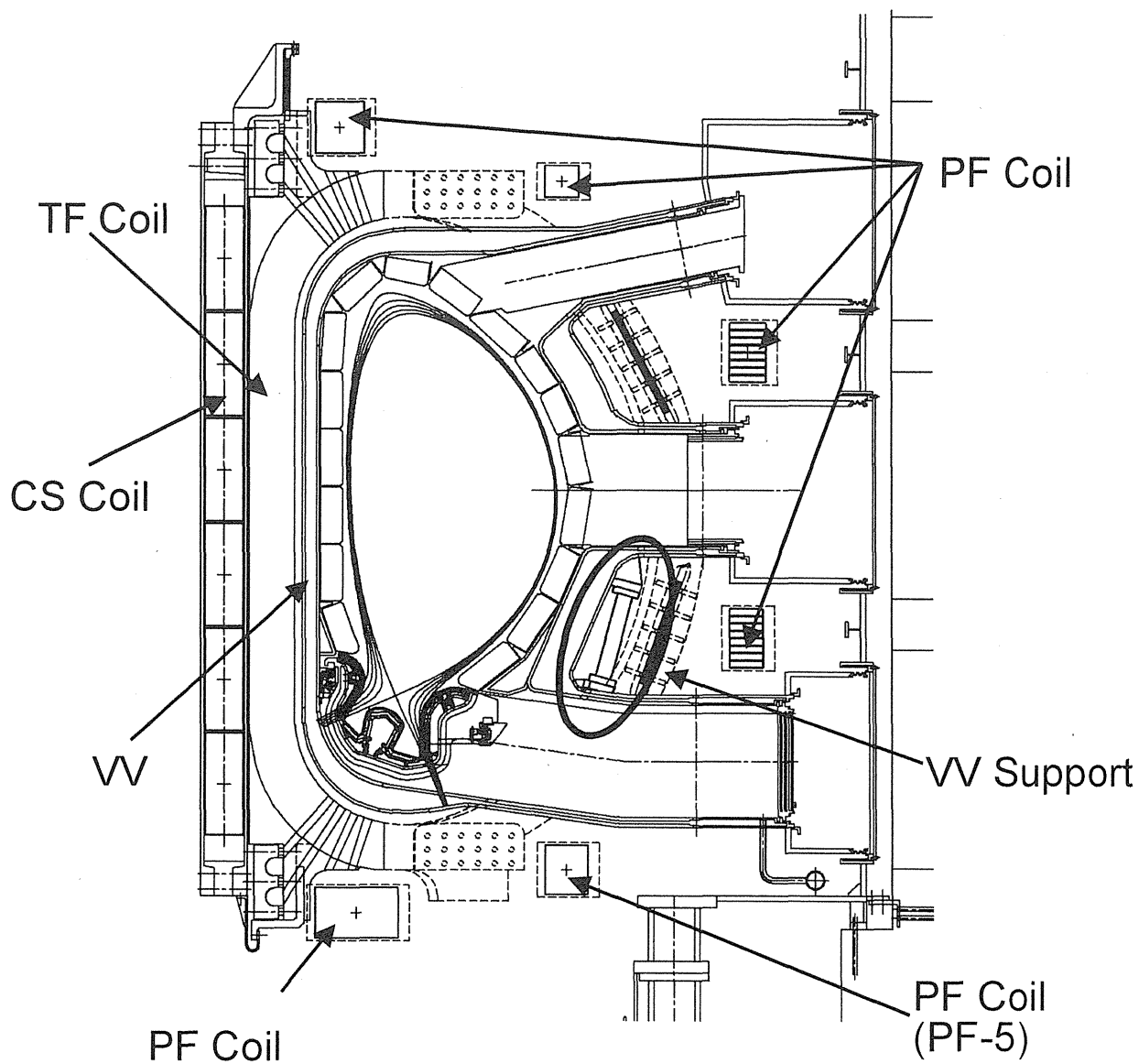


Fig.1 Overall layout of ITER reference design

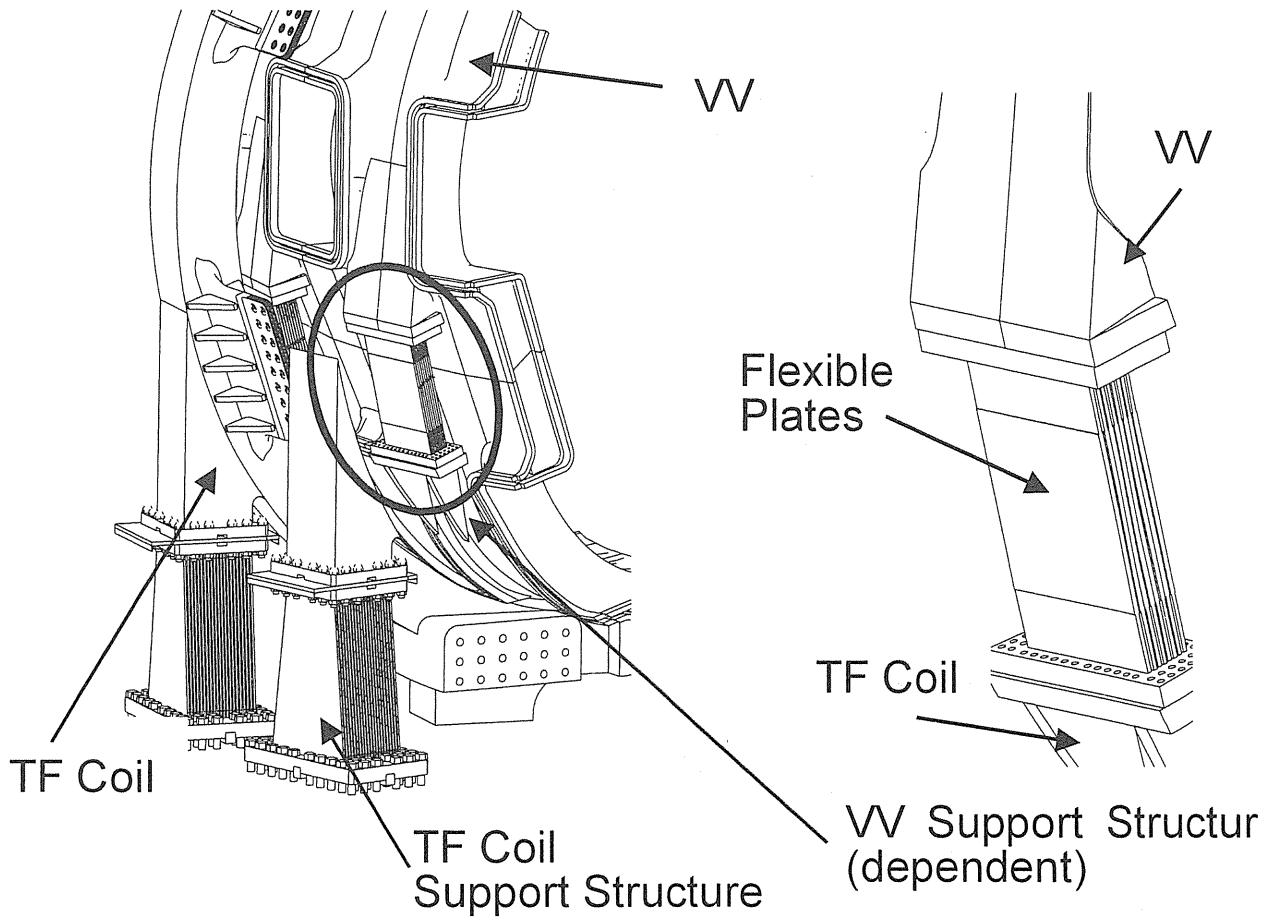


Fig. 2 Support structure of ITER TF coils and VV using flexible plate

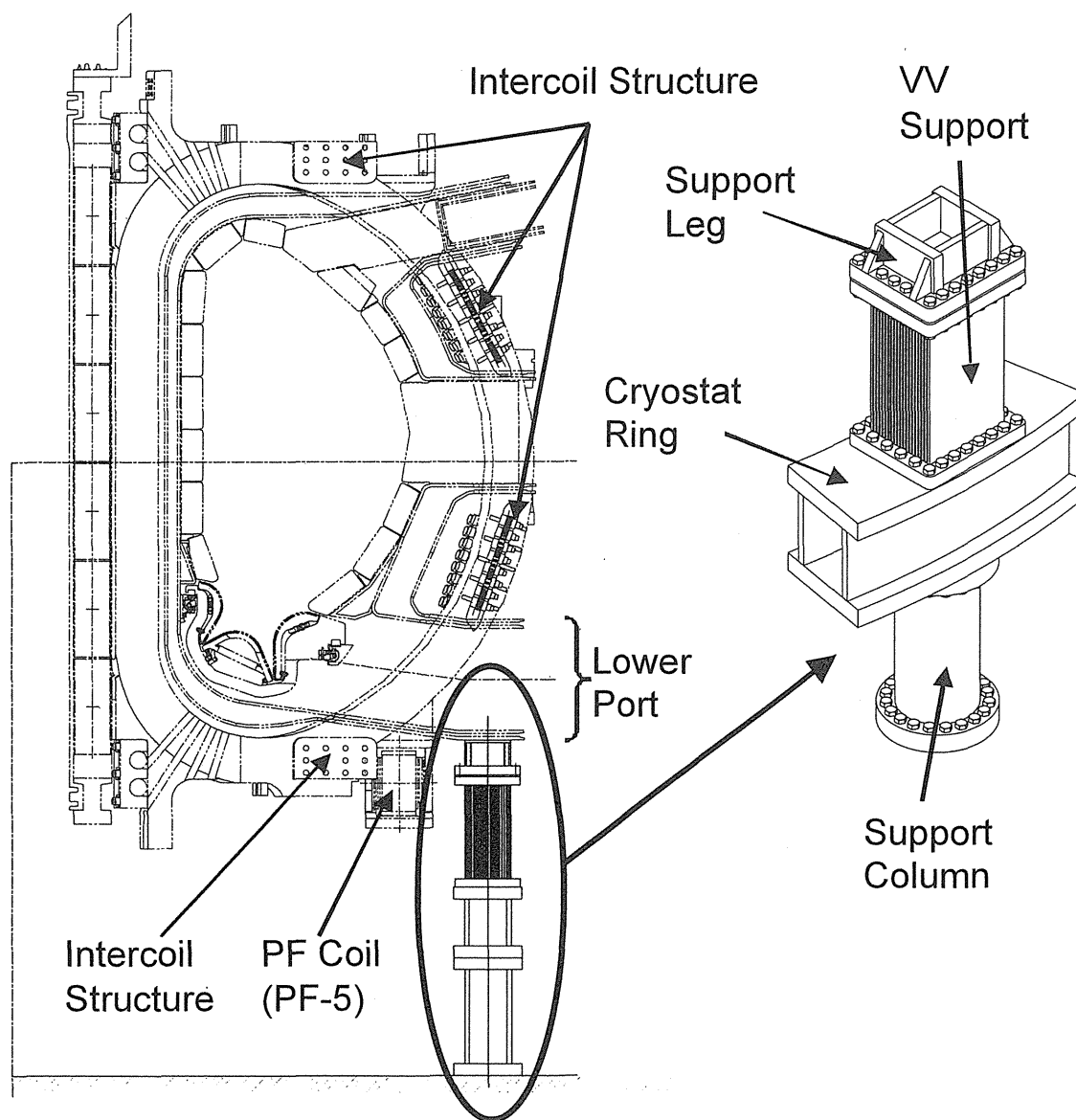


Fig. 3 VV support structure

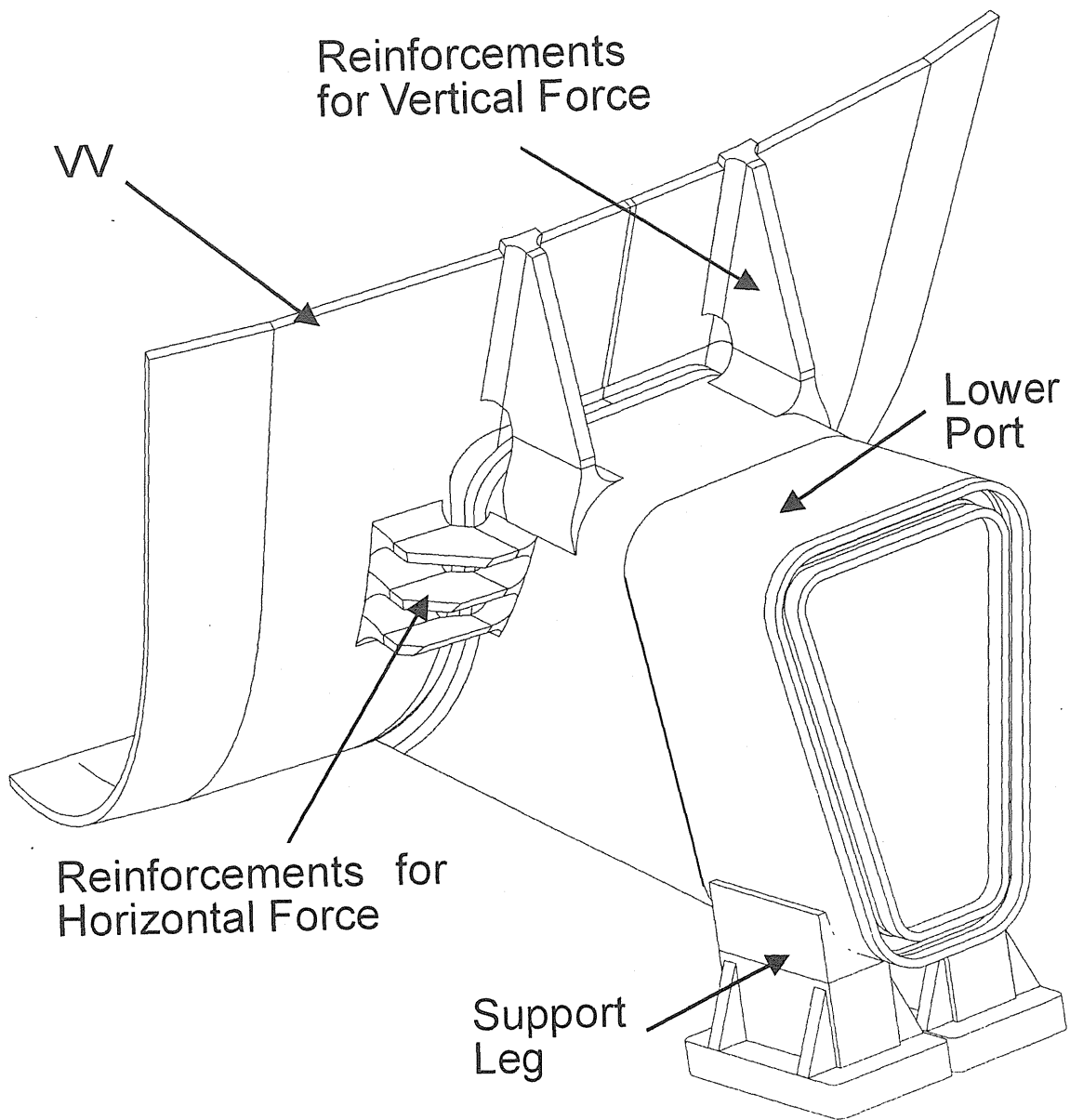


Fig. 4 Reinforcements of lower port

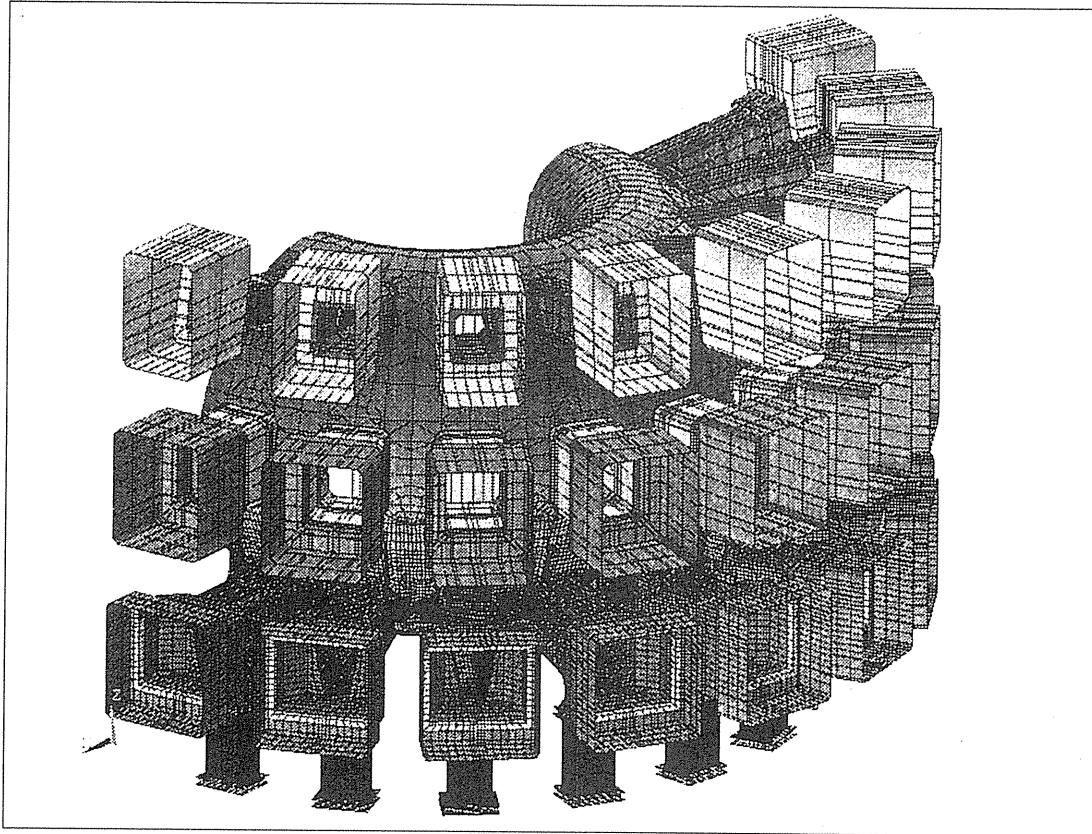


Fig. 5 Analysis model of 180° sector

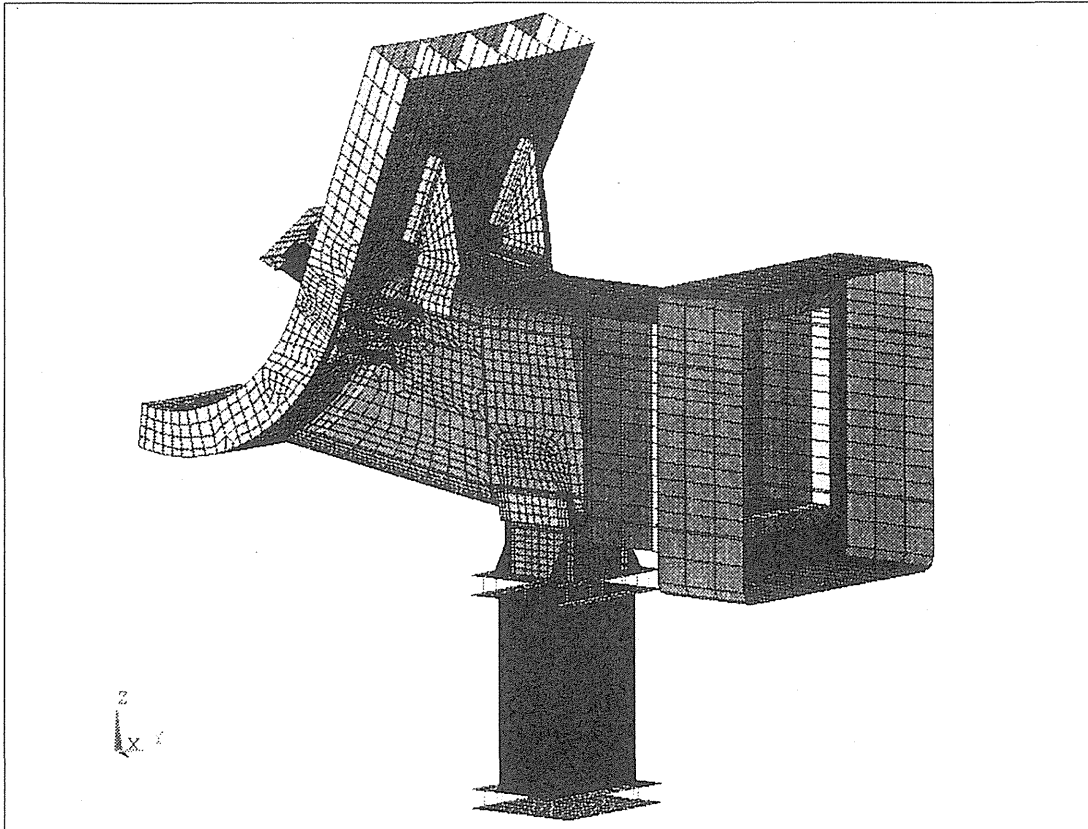


Fig. 6 Detail of VV support model

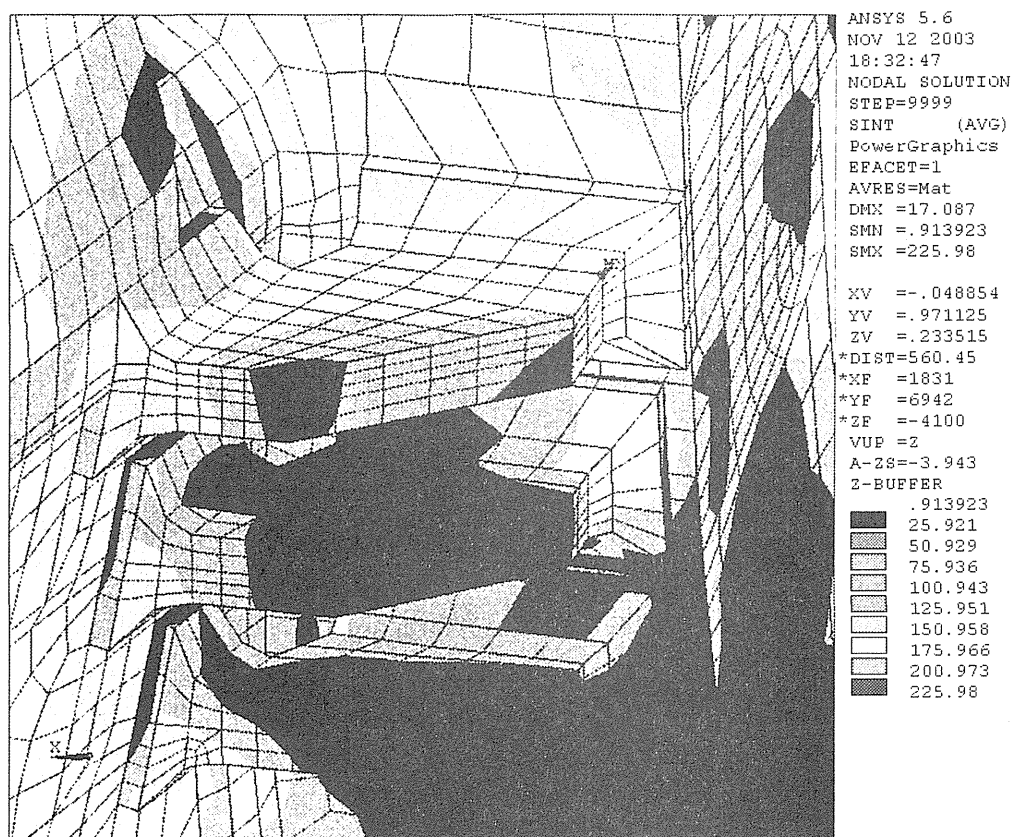


Fig. 7 Tresca stress of reinforcement (case 1)

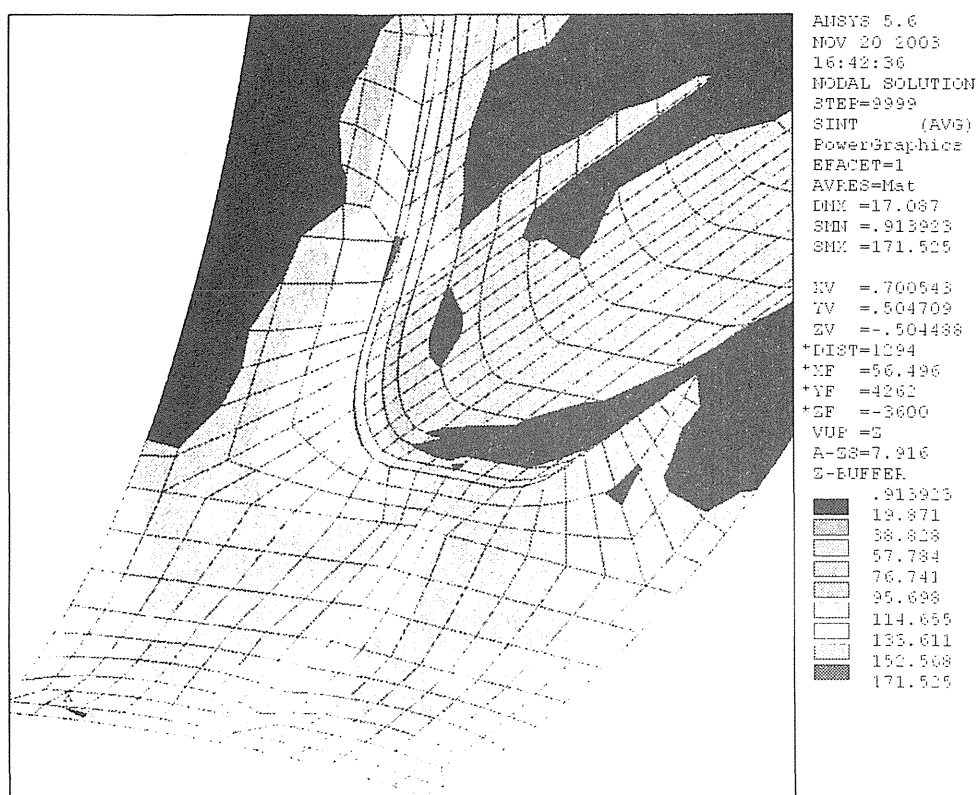


Fig. 8 Tresca stress of lower port (case 1)

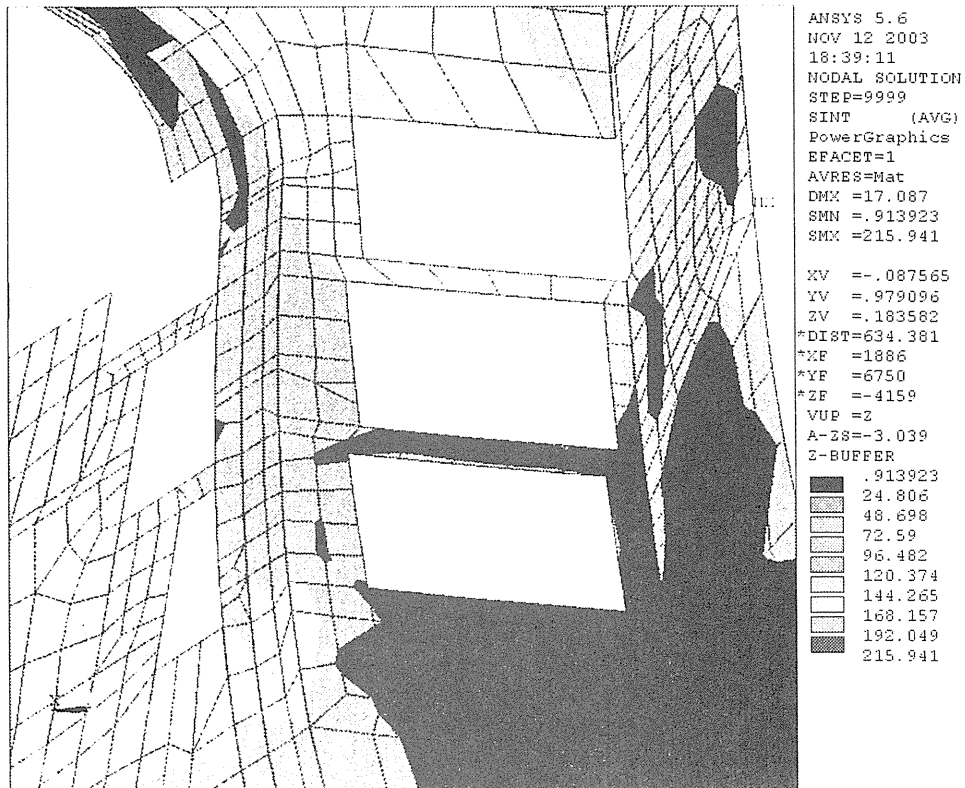
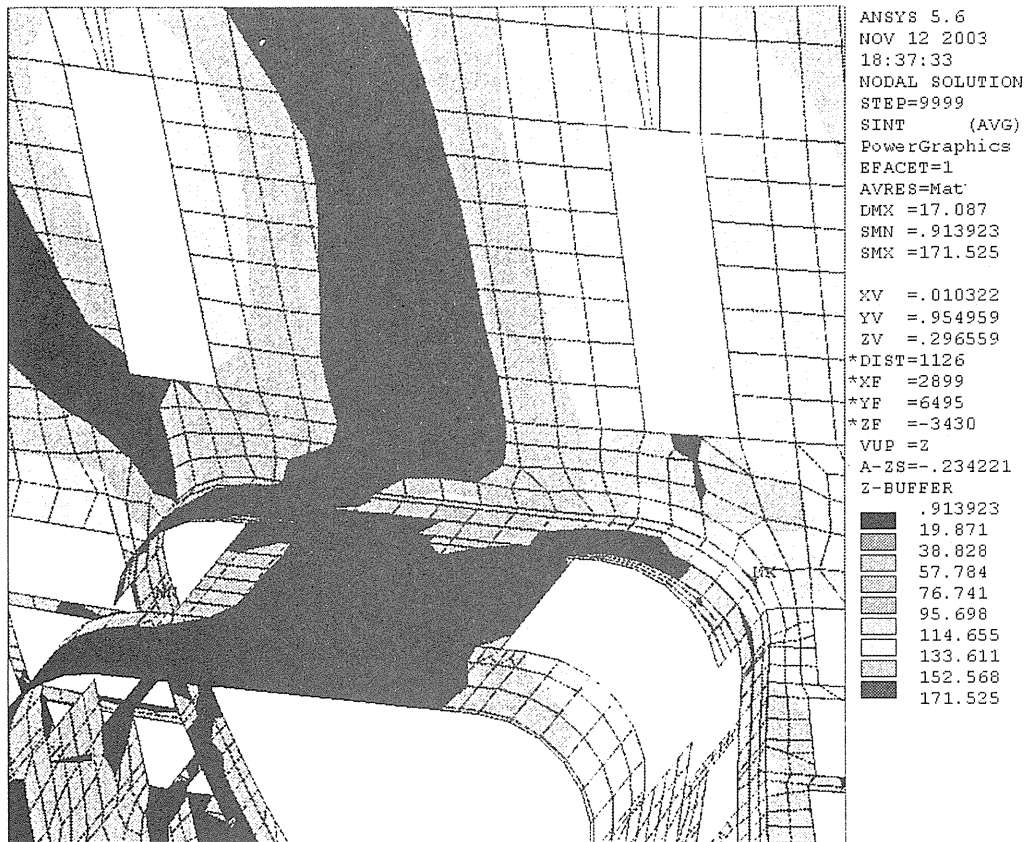


Fig. 9 Tresca stress of lower port and VV shell (case 1)

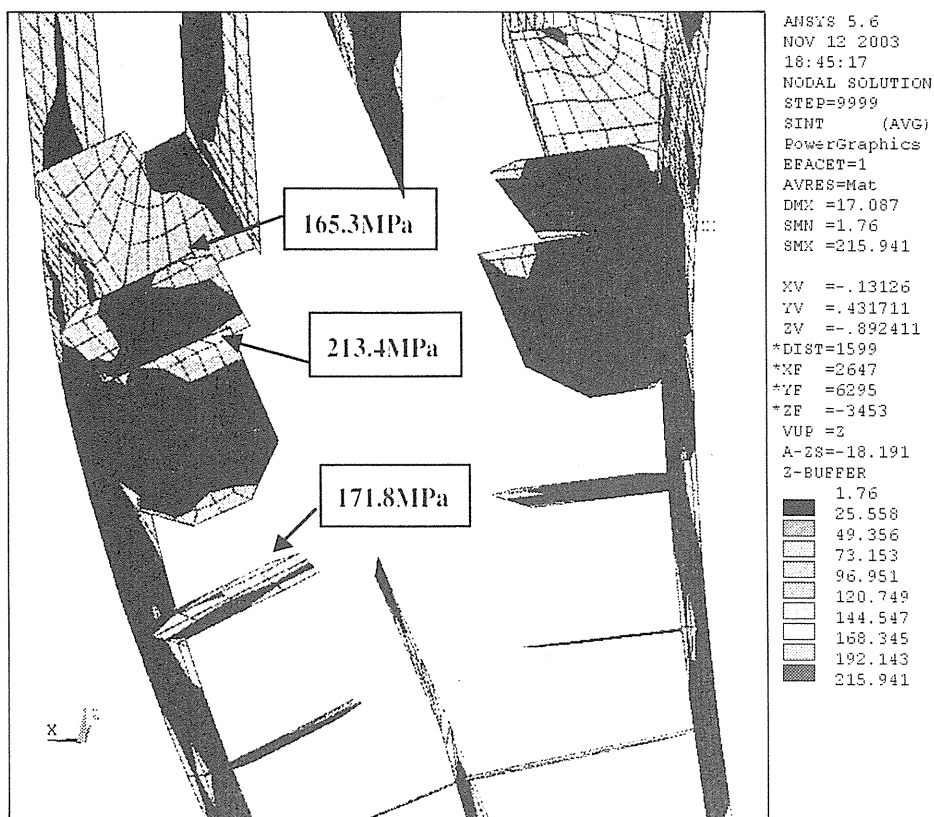
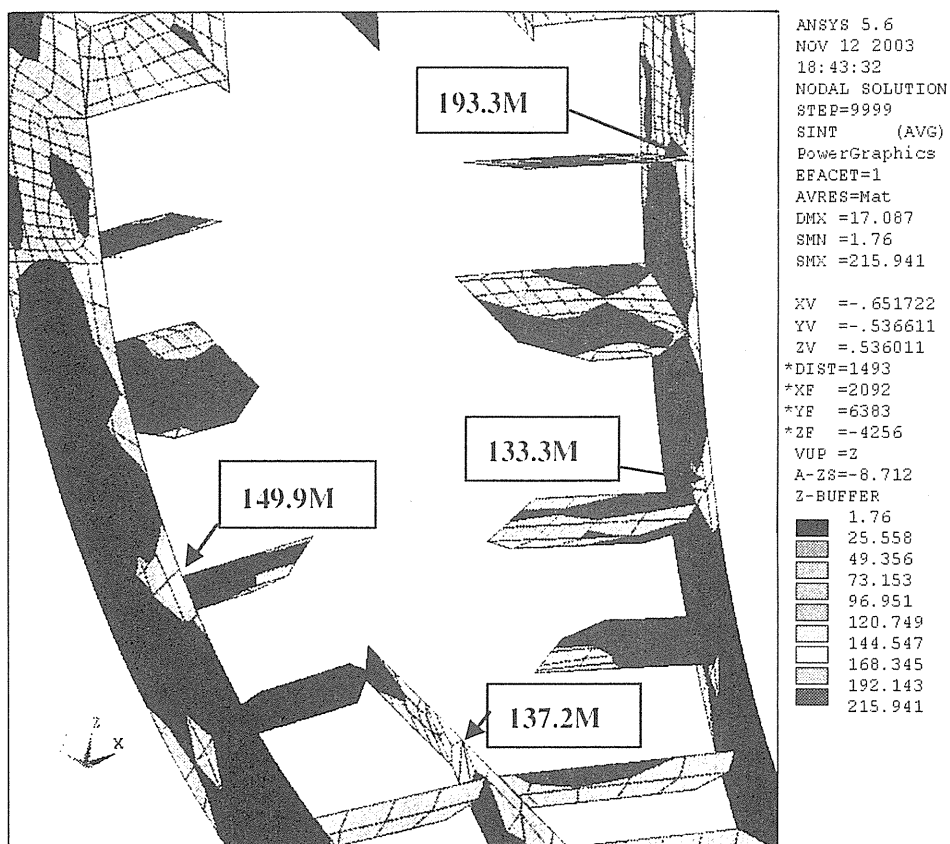


Fig. 10 Tresca stress of ribs (case 1)

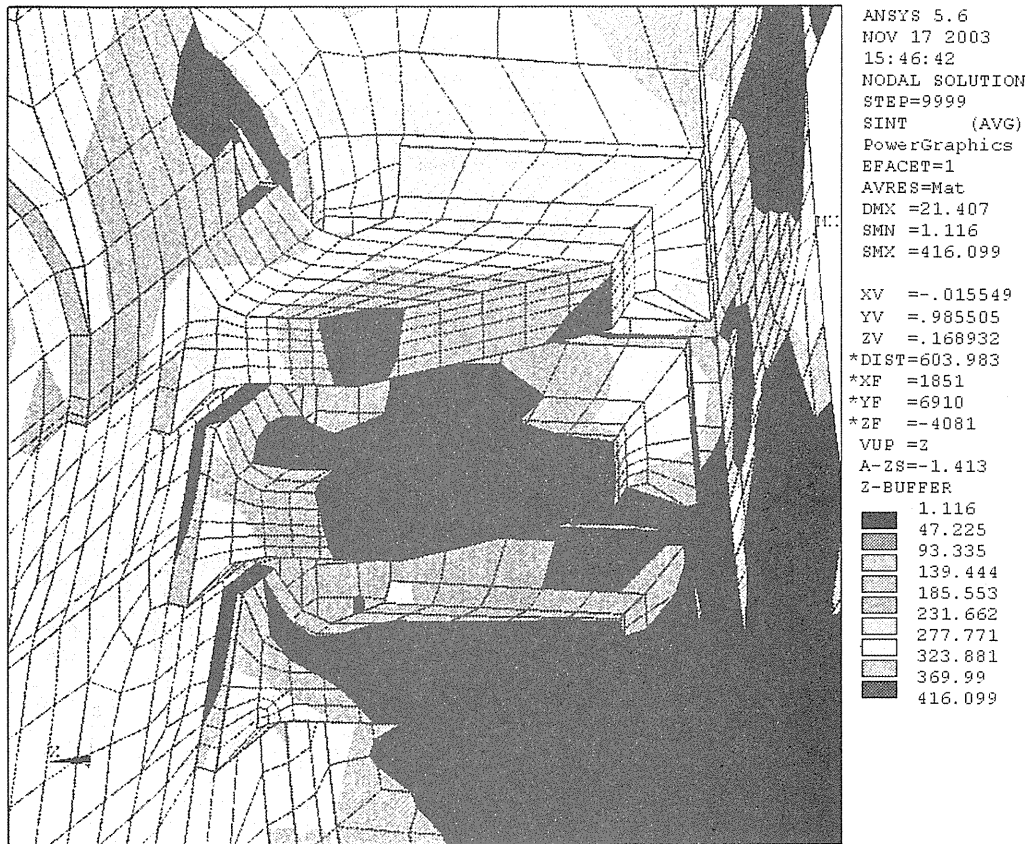


Fig. 11 Tresca stress of reinforcement (case 2)

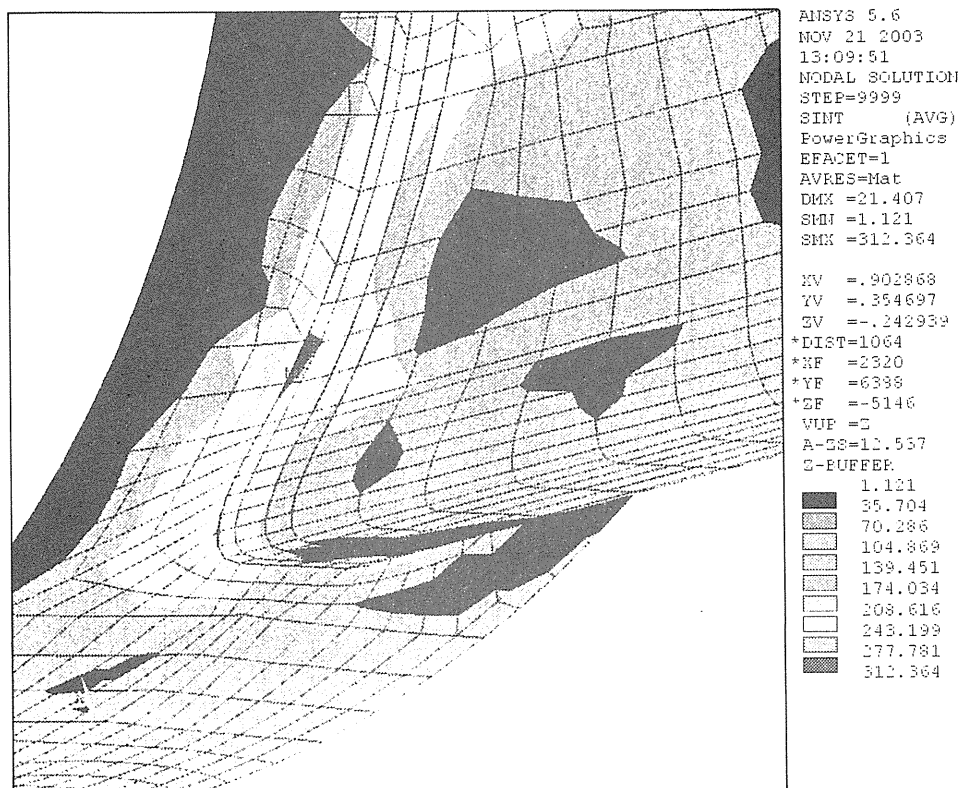


Fig. 12 Tresca stress of lower port (case 2)

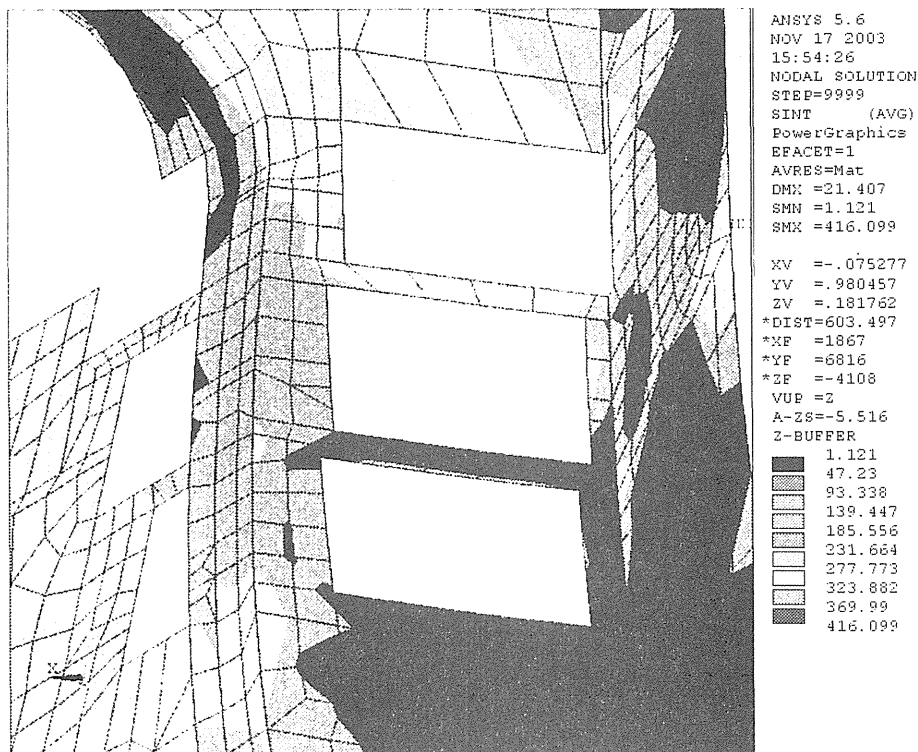
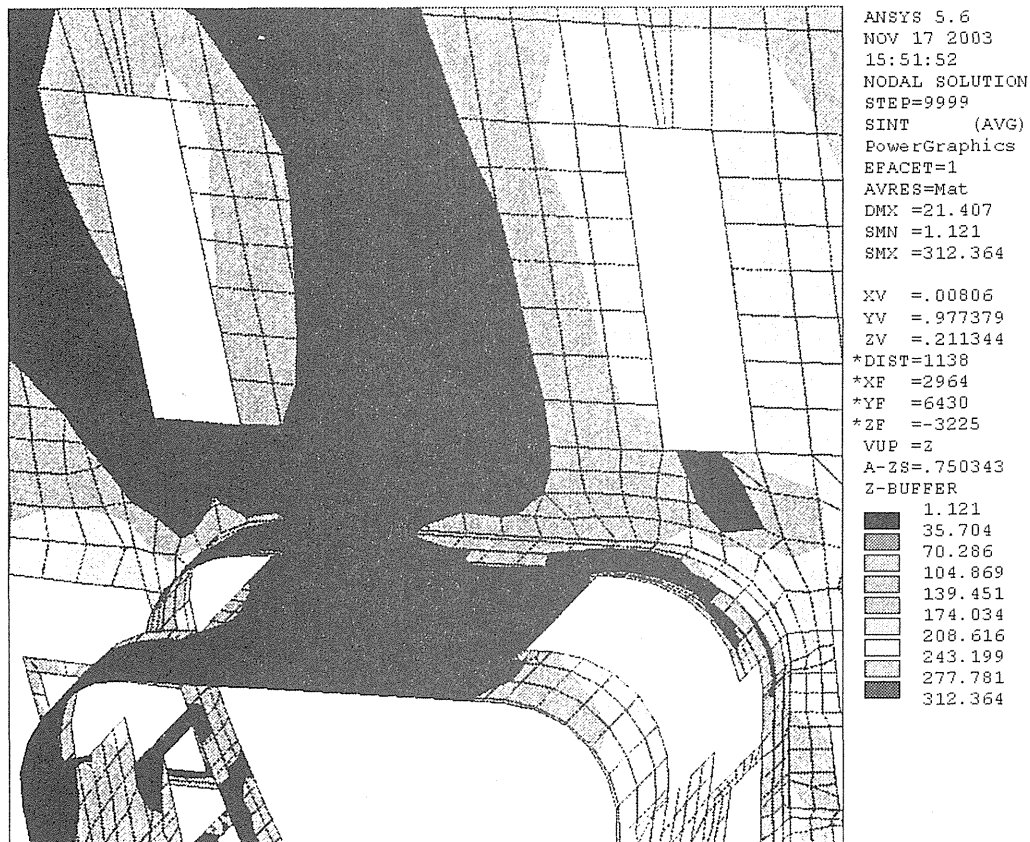


Fig. 13 Tresca stress of lower port and VV shell (case 2)

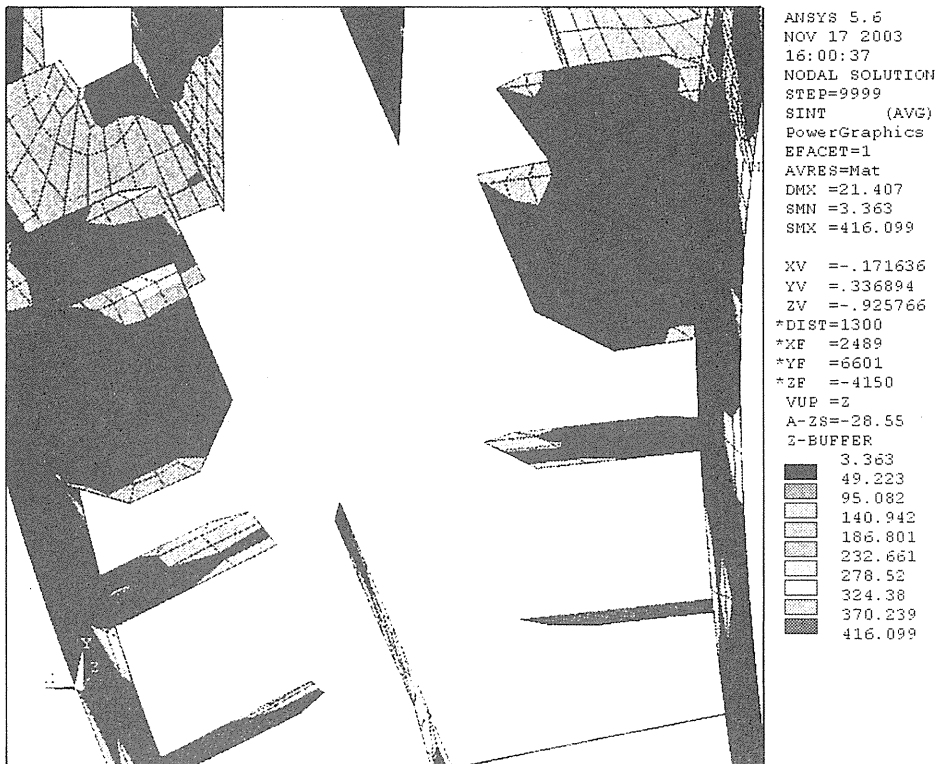
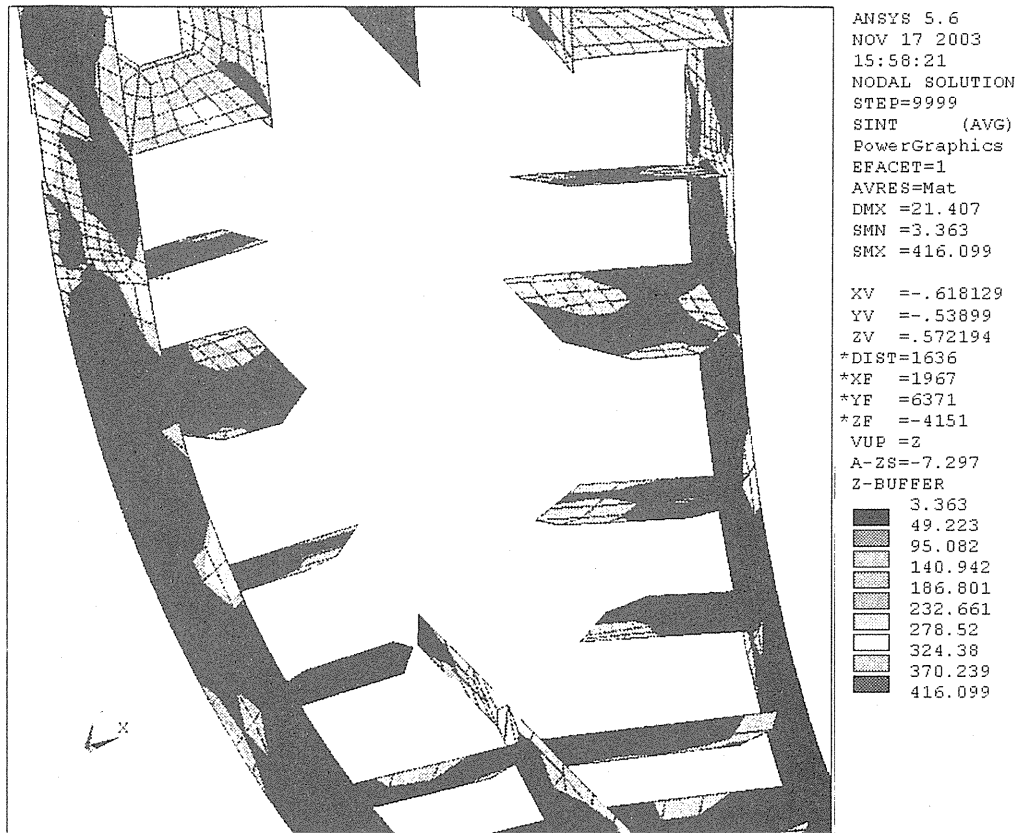


Fig. 14 Tresca stress of ribs (case 2)

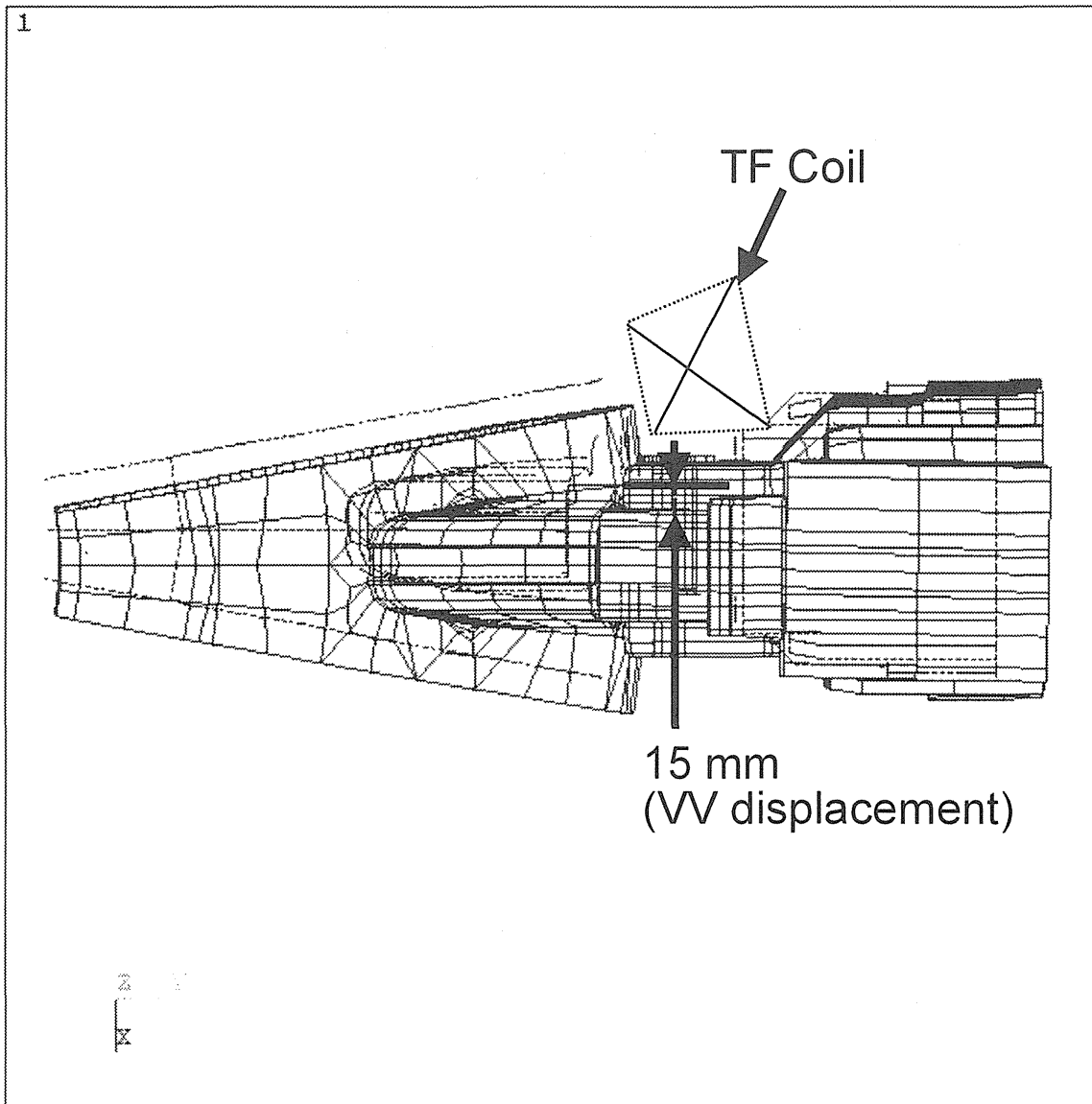


Fig. 15 VV displacement (case 2)

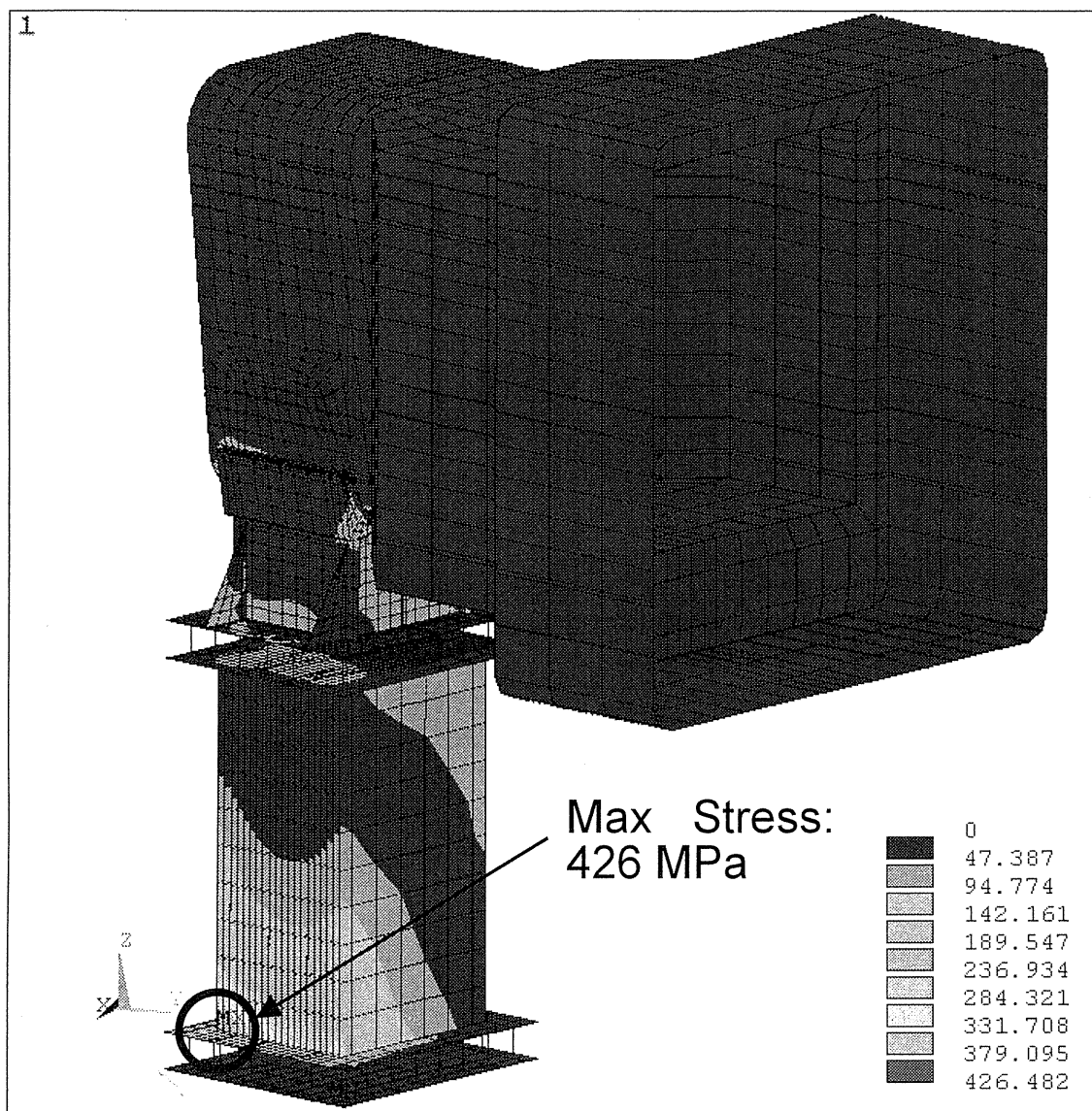


Fig. 16 Tresca stress distribution (case 2)

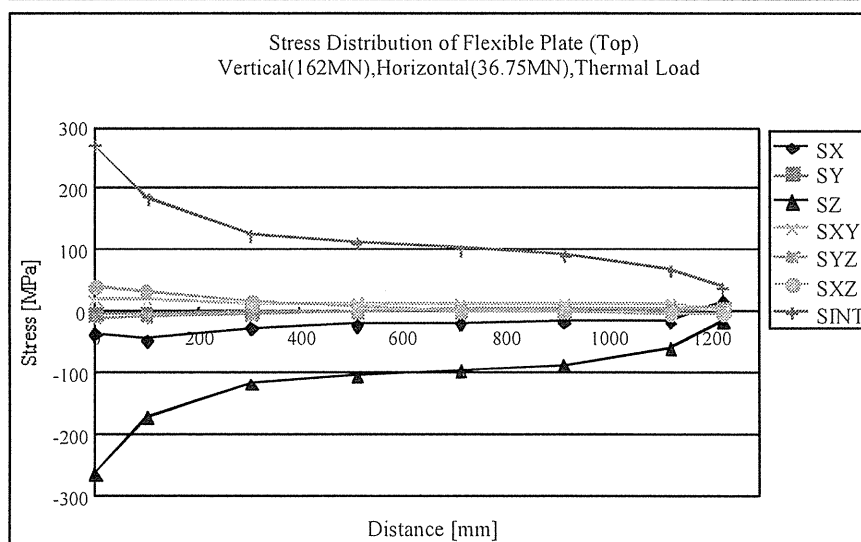
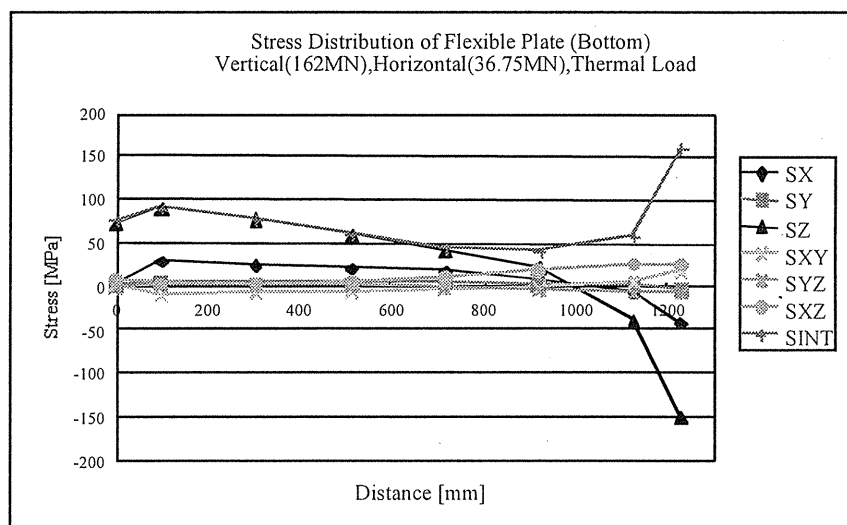
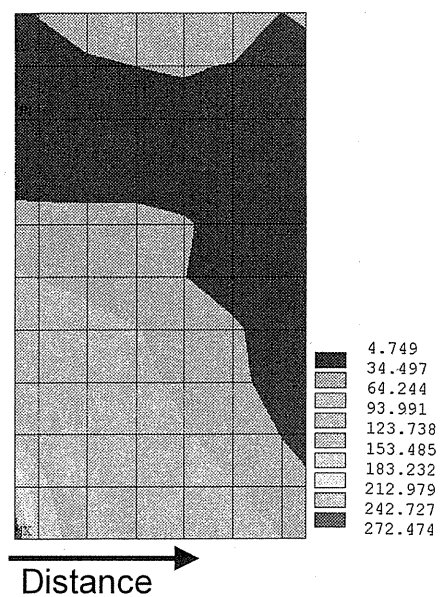


Fig. 17 Stress Distribution of Flexible Plate in Normal Operation

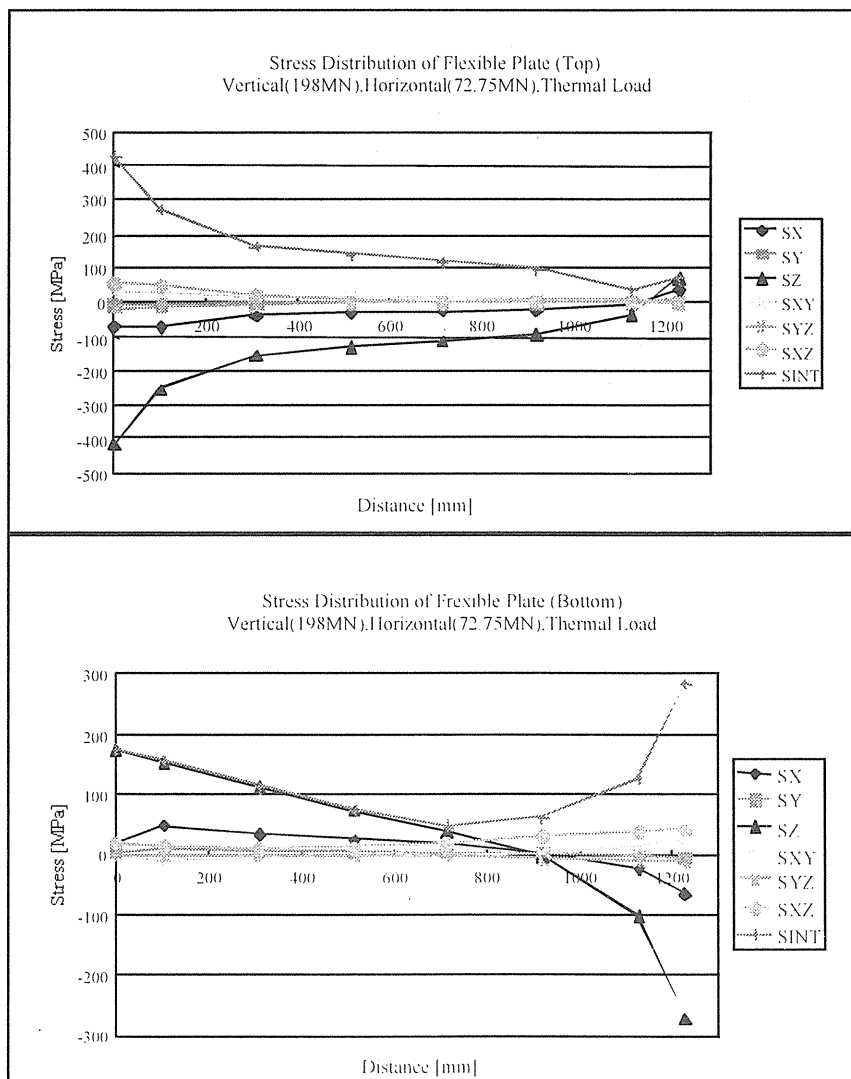
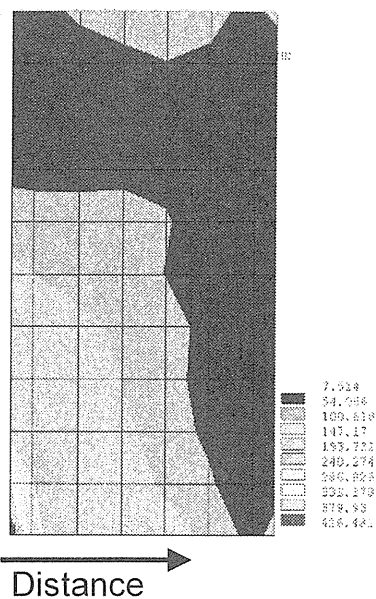


Fig. 18 Stress Distribution of Flexible Plate in Special Operation

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国際単位系 (SI) と換算表

表 1 SI 基本単位および補助単位

量	名 称	記 号
長	メートル	m
質 量	キログラム	kg
時 間	秒	s
電 流	アンペア	A
熱力学温度	ケルビン	K
物 質 量	モ ル	mol
光 度	カンデラ	cd
平 面 角	ラジアン	rad
立 体 角	ステラジアン	sr

表 3 固有の名称をもつ SI 組立単位

量	名 称	記号	他の SI 単位 による表現
周 波 数	ヘルツ	Hz	s ⁻¹
力	ニュートン	N	m·kg/s ²
圧 力, 応 力	パスカル	Pa	N/m ²
エネルギー, 仕事, 熱量	ジュール	J	N·m
工 率, 放 射 束	ワ ッ ト	W	J/s
電 気 量, 電 荷	クーロン	C	A·s
電位, 電圧, 起電力	ボ ル ト	V	W/A
静 電 容 量	ファラド	F	C/V
電 気 抵 抗	オーム	Ω	V/A
コンダクタンス	ジーメンズ	S	A/V
磁 束	ウェーバ	Wb	V·s
磁 束 密 度	テスラ	T	Wb/m ²
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	°C	
光 束	ルーメン	lm	cd·sr
照 度	ルクス	lx	lm/m ²
放 射 能	ベクレル	Bq	s ⁻¹
吸 収 線 量	グ レ イ	Gy	J/kg
線 量 当 量	シーベルト	Sv	J/kg

表 2 SI と併用される単位

名 称	記 号
分, 時, 日	min, h, d
度, 分, 秒	°, ', "
リットル	l, L
トン	t
電子ボルト	eV
原子質量単位	u

$$1 \text{ eV} = 1.60218 \times 10^{-19} \text{ J}$$

$$1 \text{ u} = 1.66054 \times 10^{-27} \text{ kg}$$

表 4 SI と共に暫定的に維持される単位

名 称	記 号
オングストローム	Å
バ ー ン	b
バ ー ル	bar
ガ ル	Gal
キ ュ リ ー	Ci
レ ン ト ゲ ン	R
ラ ド	rad
レ ム	rem

$$1 \text{ Å} = 0.1 \text{ nm} = 10^{-10} \text{ m}$$

$$1 \text{ b} = 100 \text{ fm} = 10^{-28} \text{ m}^2$$

$$1 \text{ bar} = 0.1 \text{ MPa} = 10^5 \text{ Pa}$$

$$1 \text{ Gal} = 1 \text{ cm/s}^2 = 10^{-2} \text{ m/s}^2$$

$$1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq}$$

$$1 \text{ R} = 2.58 \times 10^{-4} \text{ C/kg}$$

$$1 \text{ rad} = 1 \text{ cGy} = 10^{-2} \text{ Gy}$$

$$1 \text{ rem} = 1 \text{ cSv} = 10^{-2} \text{ Sv}$$

表 5 SI 接頭語

倍数	接頭語	記 号
10 ¹⁸	エクサ	E
10 ¹⁵	ペタ	P
10 ¹²	テラ	T
10 ⁹	ギガ	G
10 ⁶	メガ	M
10 ³	キロ	k
10 ²	ヘクト	h
10 ¹	デカ	da
10 ⁻¹	デシ	d
10 ⁻²	センチ	c
10 ⁻³	ミリ	m
10 ⁻⁶	マイクロ	μ
10 ⁻⁹	ナノ	n
10 ⁻¹²	ピコ	p
10 ⁻¹⁵	フェムト	f
10 ⁻¹⁸	アト	a

(注)

- 表 1～5 は「国際単位系」第 5 版, 国際度量衡局 1985 年刊行による。ただし, 1 eV および 1 u の値は CODATA の 1986 年推奨値によった。
- 表 4 には海里, ノット, アール, ヘクトールも含まれているが日常の単位なのでここでは省略した。
- bar は, JIS では流体の圧力を表わす場合に限り表 2 のカテゴリーに分類されている。
- EC 閣僚理事会指令では bar, barn および「血圧の単位」mmHg を表 2 のカテゴリーに入れている。

換 算 表

力	N (=10 ⁵ dyn)	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘 度 1 Pa·s (N·s/m²) = 10 P (ポアズ) (g/(cm·s))

動粘度 1 m²/s = 10⁴ St (ストークス) (cm²/s)

圧	MPa (=10 bar)	kgf/cm ²	atm	mmHg (Torr)	lbf/in ² (psi)
	1	10.1972	9.86923	7.50062 × 10 ³	145.038
力	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322 × 10 ⁻⁴	1.35951 × 10 ⁻³	1.31579 × 10 ⁻³	1	1.93368 × 10 ⁻²
	6.89476 × 10 ⁻³	7.03070 × 10 ⁻²	6.80460 × 10 ⁻²	51.7149	1

エネルギー・仕事・熱量	J (=10 ⁷ erg)	kgf·m	kW·h	cal (計量法)	Btu	ft·lbf	eV
	1	0.101972	2.77778 × 10 ⁻⁷	0.238889	9.47813 × 10 ⁻⁴	0.737562	6.24150 × 10 ¹⁸
	9.80665	1	2.72407 × 10 ⁻⁶	2.34270	9.29487 × 10 ⁻³	7.23301	6.12082 × 10 ¹⁹
	3.6 × 10 ⁶	3.67098 × 10 ⁵	1	8.59999 × 10 ⁵	3412.13	2.65522 × 10 ⁶	2.24694 × 10 ²⁵
	4.18605	0.426858	1.16279 × 10 ⁻⁶	1	3.96759 × 10 ⁻³	3.08747	2.61272 × 10 ¹⁹
	1055.06	107.586	2.93072 × 10 ⁻⁴	252.042	1	778.172	6.58515 × 10 ²¹
	1.35582	0.138255	3.76616 × 10 ⁻⁷	0.323890	1.28506 × 10 ⁻³	1	8.46233 × 10 ¹⁸
	1.60218 × 10 ⁻¹⁹	1.63377 × 10 ⁻²⁰	4.45050 × 10 ⁻²⁶	3.82743 × 10 ⁻²⁰	1.51857 × 10 ⁻²²	1.18171 × 10 ⁻¹⁹	1

$$1 \text{ cal} = 4.18605 \text{ J (計量法)}$$

$$= 4.184 \text{ J (熱化学)}$$

$$= 4.1855 \text{ J (15 °C)}$$

$$= 4.1868 \text{ J (国際蒸気表)}$$

仕事率 1 PS (仏馬力)

$$= 75 \text{ kgf·m/s}$$

$$= 735.499 \text{ W}$$

放射能	Bq	Ci
	1	2.70270 × 10 ⁻¹¹
	3.7 × 10 ¹⁰	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58 × 10 ⁻⁴	1

線量当量	Sv	rem
	1	100
	0.01	1

(86 年 12 月 26 日現在)

