JAERI-Tech
2000-006

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February 2000

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編集兼発行　日本原子力研究所

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(Received January 6, 2000)

This paper describes assessment of buckling for the vacuum vessel (VV), the back plate (BP) and the BP supports of IAM-v2 based on elastic and elasto-plastic analyses.

The VV and the BP of IAM-v2 consist of a double wall shell structure. The BP is installed in the VV by flexible plates, and the blanket modules are mounted on the BP. The function of BP is to maintain the structural integrity of VV by sharing various kinds of loads with VV, and to keep the tritium leak boundary by separating VV coolant loop from blanket coolant loop.

Since the VV and the BP are subjected to various loads such as electro-magnetic load, seismic load and thermal load, it is required to keep the structural integrity for these loads. The assessment on elastic and plastic buckling has been carried out for the electro-magnetic force at toroidal field coil fast discharge which causes the dominant compression in inboard wall of VV and BP.

Analytical result shows that the elastic buckling of VV and BP will not occur because the critical elastic buckling pressure values are much larger than the values that causes yield stress. The elastic buckling of BP supports will not occur, either. In the assessment of plastic buckling, the buckling pressure values are within the limit, considering the geometrical imperfection of ±10 mm. Therefore, it is confirmed that there is no problem for the buckling of VV and BP.

Keywords : Buckling, Back Plate, RC-ITER, TF Fast Discharge

低コストITER(IAM-v2)の真空容器とバックプレートの座屈評価

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（２０００年１月６日受理）

本報告書は、低コスト ITER（IAM-V2）の真空容器、バックプレート、バックプレート支持脚について、弾性、弾塑性解析により座屈の評価を行ったものである。

IAM-V2 の真空容器とバックプレートは二重壁の構造物で構成される。バックプレートは、板バネで真空容器内に設置され、ブランケットが取り付けられる。バックプレートの機能は、種々の負荷を真空容器と分担することで、真空容器の構造健全性を維持すると共に、ブランケット冷却水のループと真空容器冷却水のループとを分離することで、トリチウム漏洩の境界を確保することである。

真空容器とバックプレートには、電磁力、地震荷重、熱荷重等が負荷されるので、これら負荷に対して構造の健全性を保つことが要求される。ここでは、真空容器とバックプレートのインボード側壁に最も高い圧縮力が作用するトロイダルコイルの高速放電時の荷重に対し、弾性、塑性の座屈評価を行った。

弾性の座屈評価では、限界圧力が塑性を生ずる圧力より十分大きいため、弾性範囲内では座屈が起こらないことが確認された。バックプレートの支持脚についてもバックリングが生じない。また、塑性座屈では、形状の幾何学的なずれを±10mm 考慮しても、座屈圧力は基準値以下である。従って、真空容器とバックプレートについてバックリングの問題はない。

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1.Introduction

The VV and the BP of IAM-v2[1] consist of a double wall shell structure. The BP is installed in the VV by flexible plates, and the blanket modules are mounted on the BP. The function of BP is to maintain the structural integrity of VV by sharing various kinds of loads with VV, and to keep the tritium leak boundary by separating VV coolant loop from blanket coolant loop.

In cases of a TFC current discharge and asymmetric disruptions such as VDEs, induced poloidal currents in VV and BP interact with the toroidal magnetic field causing compressive stress in the VV inboard wall, BP and its support structure. This could cause buckling of the structure. The most severe poloidal currents will be induced by an event during toroidal field coil fast discharge (TFC fast discharge). Therefore, the elastic and plastic buckling analyses have been carried out to obtain the critical pressure in each of walls at the TFC fast discharge.

For the BP support, only tensile stress appears during the TFC fast discharge so that buckling problem will not occur. Therefore, it is important to evaluate the buckling of the BP supports during events such as an earthquake that causes compression on the BP support. Based on the dynamic response analyses of IAM-v2 during the SL-2 equivalent load, assessment of buckling for the BP supports has been done.

2.Analysis Model

To precisely evaluate buckling mode, it is required to make model at least 180 degree sector in order to calculate buckling mode. Fig. 2.1 shows the elastic analysis model which includes the VV and the BP. Table2.1 and 2.2 show the analytical condition of VV and BP for TF coil fast discharge. The boundary conditions of the sector consist of coupled degrees of freedom for all corresponding node pairs on the symmetry planes. Coupling the corresponding node pairs in all three directions means that the components have been considered continuous.

Fig. 2.2 shows the elasto-plastic analysis model for a 30 degree sector. The elasto-plastic analysis has been performed for the buckling at m=6 based on the results of elastic analysis. Tables 2.3 and 2.4 show stress strain curves and mechanical properties of the structure materials, respectively.

The elastic and elasto-plastic models include the inboard and the outboard walls of VV and BP, and their supports. The VV and the BP supports are modeled using shell elements and the shell elements of BP supports are connected with VV walls by rigid elements.

The following model simplifications have been implemented:

-the number of poloidal ribs in VV inboard and outboard walls is 2 ribs in a 20 degree sector and that of BP is 5 ribs,

-the poloidal ribs are equally spaced,

-there is no toroidal rib,

-the port openings are not modeled,

-there is no faceting at outboard wall.

3. Load conditions and limit

3.1 Load conditions

The electromagnetic loads during TFC fast discharge with its time of 6.5 sec has been calculated for a 20 degree sector model [2] and the loads are transferred to that of a 180 degree sector model. The analysis conditions for the electromagnetic analysis are in the case of IAM-v2.

In the case of elasto-plastic analysis, the load evaluation with small steps has been applied to allow convergence of the program (ABAQUS).

3.2 Load Limit

The ITER Structural Design Criteria for In-vessel Components defines the load factors for different loading condition levels to be assumed to prevent load-controlled buckling[3].

The load factors (Γ_I) are shown in table 3.1 and defined as

$$\Gamma_I = \frac{\text{(Load that would cause buckling at the design or service temperature)}}{\text{(Load that occurs in design or service conditions)}}$$

4. Results

4.1 Elastic analysis

Table 4.1 shows the calculated results for the 180 degree sector model. The buckling modes are defined in terms of the parameter "m". This parameter indicates the number of waves of the buckled structure at the inboard wall.

The VV indicates the minimum critical pressure of 25.4 MPa at m=7. Figs. 4.1 and 4.2 show the VV buckling mode at m=7. The critical pressure is defined as the sum of maximum pressure on the inboard and the outboard walls. The maximum pressures on the inboard and the outboard wall of VV are 0.79 MPa and 0.98 MPa, respectively. The sum of the pressure on VV wall is 1.77 MPa. The minimum critical pressure of VV is 14.4 times larger than the pressure during TFC fast discharge.

The minimum critical pressure of BP at m=4 is 34 MPa. Figs. 4.3 and 4.4 show the buckling mode at m=4. The maximum pressures on the inboard and the outboard wall of BP are 0.55 MPa and 0.81 MPa, respectively. The sum of the pressure on BP wall is 1.36 MPa. The minimum critical pressure of BP is 25 times larger than the pressure during TFC fast discharge.

The maximum compression of the outboard wall of VV in toroidal direction are analyzed to be 65 MPa [4]. The critical pressure of BP that generates a compression equal to yield (ultimate) stress is 4.7 MPa (12.4 MPa). Therefore, before the structure reaches the critical elastic buckling pressure the structure is well into the plastic regimes. The buckling load for the VV and BP has to be calculated considering the effect of the material plasticity.

4.2 Elasto-plastic analysis

Table 4.2 shows a summary of the maximum radial displacement of the VV inboard wall as a function of the pressure load. The analysis has been carried out for a 30 degree sector model at m=6. Because it is not reasonable to make 180 ° sector model for elastic-plastic analysis at this stage. Fig.4.5 shows the radial displacement of VV and BP inboard walls. The radial displacement of BP is smaller than that of VV.

The critical pressure of increasing the displacement of VV wall is estimated to be 9.0 MPa and the load factor of 5.1 that is within the limit defined in ITER

ISDC. Fig.4.6 shows the deformation of the VV and the BP at the VV pressure of 9.0 MPa.

In order to examine the effect of geometrical imperfection, the analysis has been also performed using the 30 degrees sector model with +/-10 mm geometrical imperfection. The results are shown in Fig.4.7 and 4.8. Fig.4.7 shows the radial displacement of inboard wall of the VV and the BP. Fig. 4.8 is the comparison of the VV displacement with and without geometrical imperfection. The effect on critical pressure of geometrical imperfection is not large for the buckling due to external pressure [5],[6].

5. Buckling of BP support

The BP supports, shown in Fig. 5.1, are subjected to vertical loads in the cases of plasma disruption and earthquake. It was found that the critical load is 25.9 MN for an inboard support and 31.5 MN for a outboard support, respectively.

Seismic analyses have been reported as a progress report for the previous TASK FORCE of concept improvement on RTO/RC-ITER [7]. The maximum vertical load is 2.1 MN in the case of seismic load corresponding to SL-2 for an inboard support. In the case of slow VDE, that for a outboard support is 2.4 MN. The safety margin is estimated to be approximately 12.3 and 13.1, respectively. No instability problem is expected.

6. Conclusions

[1] The elastic critical buckling pressure of VV and BP for IAM-V2 is 25.4 MPa and 34 MPa, respectively. The pressure values are much larger than the values that causes yield stress.

[2] According to inelastic analysis, the radial displacement of BP is smaller than that of VV. The inelastic critical pressure of VV is estimated to be 9.0 MPa and the load factor of 5.1 that is within the limit of 3.0 defined in ITER ISDC.

[3] BP support buckling is not expected to be a problem.

Acknowledgements

The authors would like to express their gratitude to Dr. T. Shoji and department of ITER Project for their valuable discussions and comments. They would acknowledge Drs. T. Tsunematsu, A. Kitsunezaki and .M.Ohta for their support.

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[3] ITER ISDC, IRB 3421.

[4] J. Ohmori, et al., Report for Task Force, INT-9007 Rev.1,11 Jun. 1999.

[5] JSME, Mechanical Engineer's Handbook, A. Foundamentals,1996 4, A4-93.

[6] G. Sannazzaro, Report for Task Force, Inelestic buckling of the RTO-ITER VV inboard wall due to TFC fast current discharge, 4 May,1999.

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Table 2.1 IAM-V2 Geometrical data

	Vacuum Vessel	Back Plate
1, Inboard wall thickness (mm)	380	160
2, Inner and outer shell thickness (mm)	55	Inner wall 50 Outer wall 70
3, Number of poloidal ribs /20° sector	2	5
4, Flexible support / 20° sector	15 plates 30t×2000 l×900 w	Inboard 10 plates Outboard 12 plates 12 t×420 l×400 w

Table 2.2 Analytical condition of TF discharge

Analytical Model	Vacuum Vessel, Back Plate, TF Coil Case, Radial Plate
VV Wall thickness	Inner Wall 60 mm Outer Wall 60 mm
BP Wall thickness	Inner Wall 50 mm Outer Wall 70 mm
TF coil case thickness ( ) are thickness in nose part	Inner Wall 70mm Outer Wall 135mm (336mm) Side Wall 125mm (100mm) Back Wall 140mm Radial Plate 49mm- 7plates
Discharge time constant	6.5 sec
Resistivity	VV Inner Wall (80 $\mu\Omega\cdot$cm) VV Outer Wall (80 $\mu\Omega\cdot$cm) TF Coil Case (55 $\mu\Omega\cdot$cm)

Table 2.3 Stress strain curve for the material

VV, BP (SS316IN-IG)		BP support (Alloy 625)**	
Strain	Stress (MPa)	Strain	Stress (MPa)
7.69E-4	140	1.42E-3	260
2.91E-3	166	2.91E-3	318
6.0E-3	188	6.0E-3	360
0.01	200	0.01	383
0.02	206	0.02	403
0.1	260	0.1	560

** The stress strain curve for alloy 625 is estimated by alloy 625 material data.

Table 2.4 Material Properties at 150℃

	SS316LN-IG	Alloy 625
1, Young modulus (MPa)	182000	183000
2, Poisson's ratio	0.3	0.283
3, Ultimate stress Su (MPa)	443	750
4, Yield stress Sy (MPa)	166	310
5, Allowable stress Sm (MPa)	147	207

Table 3.1 Time-independent load factors (Γ_I) for load-controlled Buckling [2]

Loading conditions	Load factor (ITER ISDC)
Design	3.0
Level A	3.0
Level C	2.5
Level D	1.5
Test	2.25

Table 4.1 Critical pressure (MPa) of VV and BP in elastic buckling

VV		BP	
Mode type: m	Critical pressure [MPa]	Mode type: m	Critical pressure [MPa]
		3	52.3
4	38.2	4	34.0
5	29.3	5	36.3
6	26.1	6	39.6
7	25.4	7	42.6
8	26.3	8	45.8
9	27.9	9	49.4
10	30.2		
11	33.1		
12	36.5		

Table4.2 Maximum radial displacement of the inboard wall

Pressure(MPa) on VV wall	Load Factor	VV Displacement (mm)	BP Displacement (mm)
1.77	1	0.85	0.71
2.48	1.4	1.10	0.92
3.19	1.8	1.36	1.14
3.89	2.2	1.62	1.36
4.60	2.6	1.92	1.58
5.31	3	2.51	1.82
6.02	3.4	3.99	2.15
6.73	3.8	7.33	2.80
7.43	4.2	11.8	4.18
8.14	4.6	17.9	6.76
8.85	5	27.8	10.9
9.03	5.1	40.4	14.8
9.20	5.2	63.4	19.7
9.38	5.3	95.0	26.3

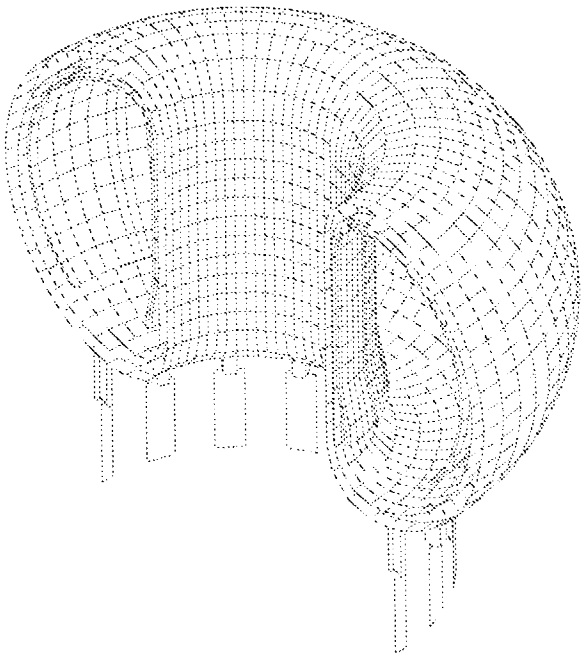


Fig 2.1 Elastic buckling analysis model of 180° sector

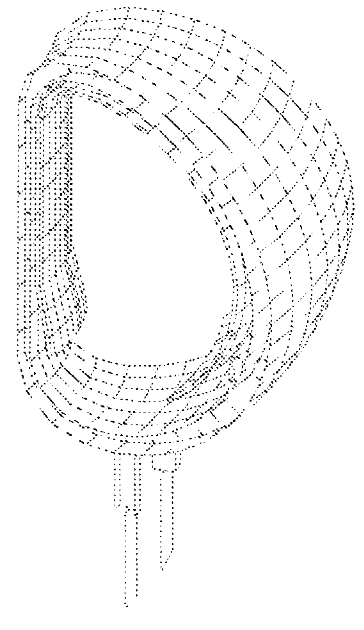
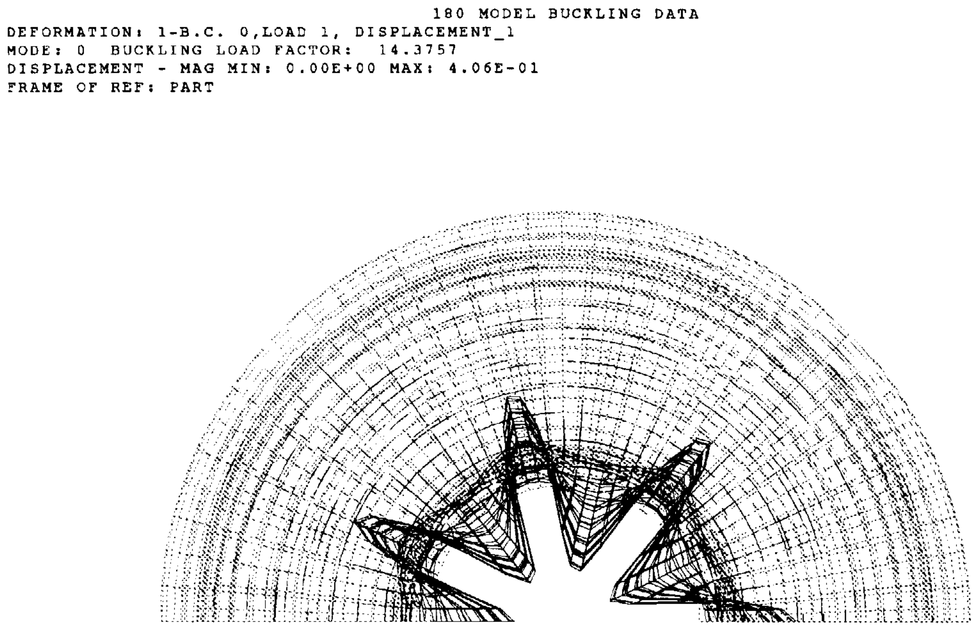
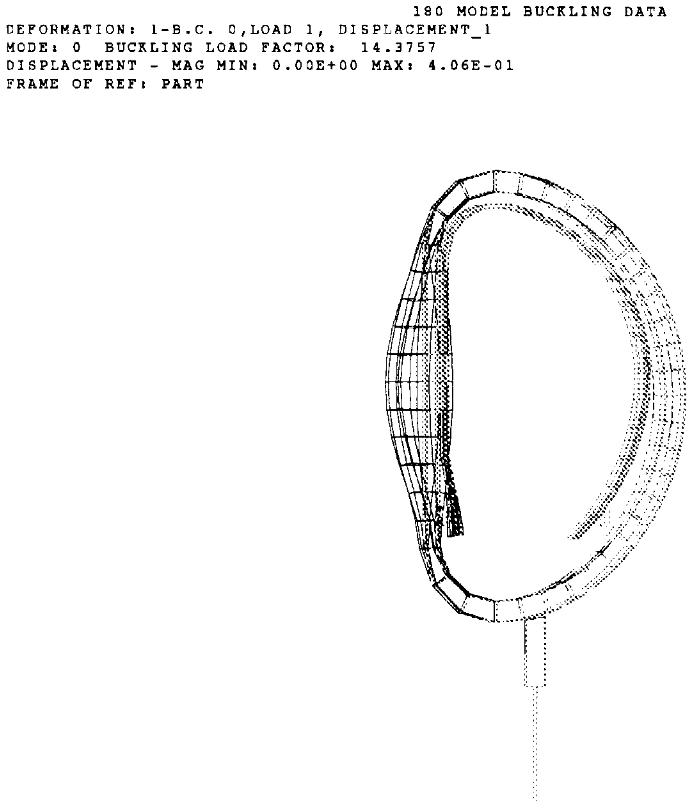


Fig.2.2 Inelastic buckling analysis model for 30° sector



```
                                   180 MODEL BUCKLING DATA
DEFORMATION: 1-B.C. 0,LOAD 1, DISPLACEMENT_1
MODE: 0  BUCKLING LOAD FACTOR:  14.3757
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 4.06E-01
FRAME OF REF: PART
```

Fig.4.1 VV buckling mode of 7



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                                   180 MODEL BUCKLING DATA
DEFORMATION: 1-B.C. 0,LOAD 1, DISPLACEMENT_1
MODE: 0  BUCKLING LOAD FACTOR:  14.3757
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 4.06E-01
FRAME OF REF: PART
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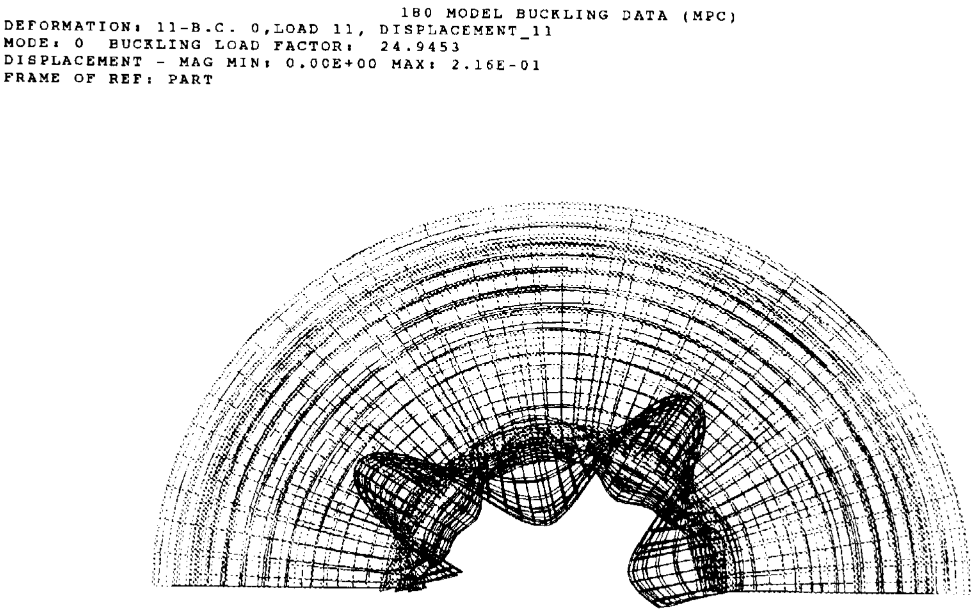
Fig. 4.2 Deformation of VV buckling mode of 7



```
                                    180 MODEL BUCKLING DATA (MPC)
DEFORMATION: 11-B.C. 0,LOAD 11, DISPLACEMENT_11
MODE: 0  BUCKLING LOAD FACTOR:  24.9453
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 2.16E-01
FRAME OF REF: PART
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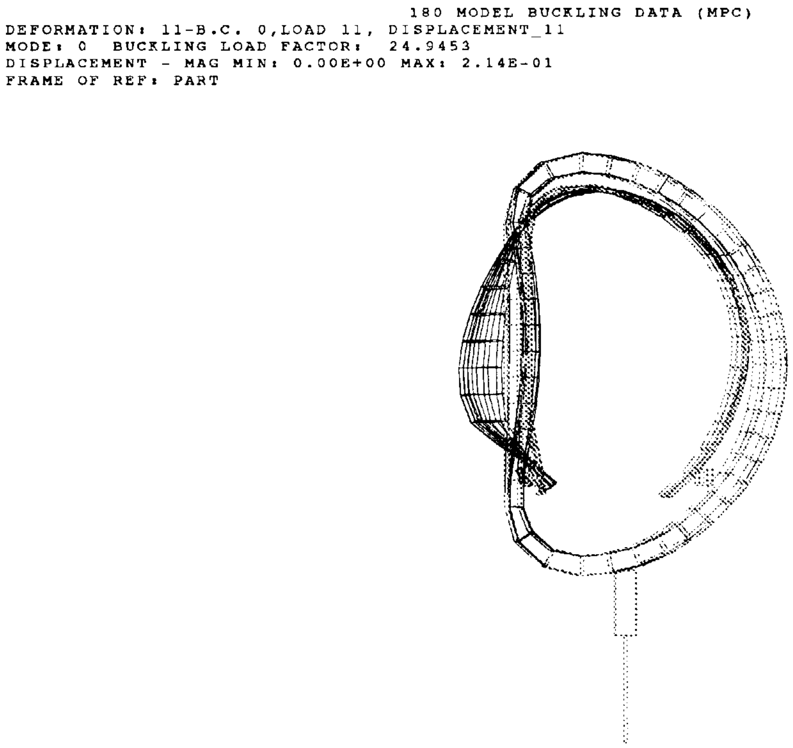
Fig. 4.3 BP buckling mode at m=4



```
                                    180 MODEL BUCKLING DATA (MPC)
DEFORMATION: 11-B.C. 0,LOAD 11, DISPLACEMENT_11
MODE: 0  BUCKLING LOAD FACTOR:  24.9453
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 2.14E-01
FRAME OF REF: PART
```

Fig.4.4 BP buckling mode at m= 4

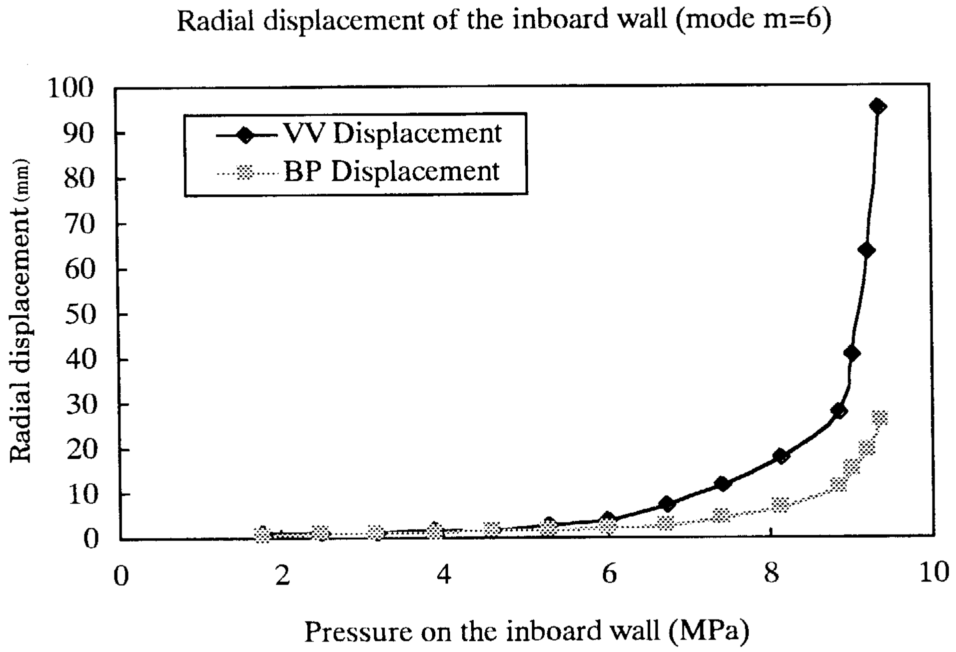


Fig. 4.5 Radial displacement of VV and BP inboard wall

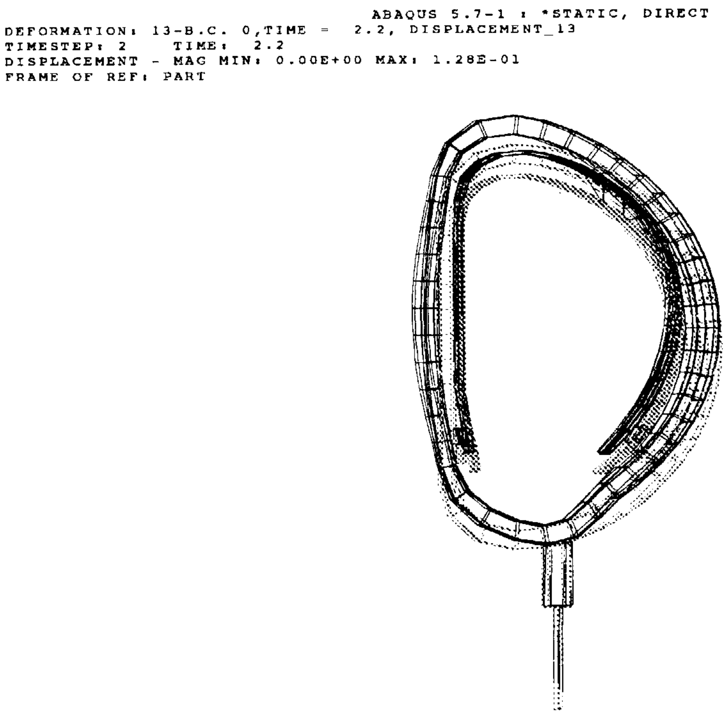


Fig. 4.6 Deformation of VV and BP at the VV pressure of 9.0 MPa

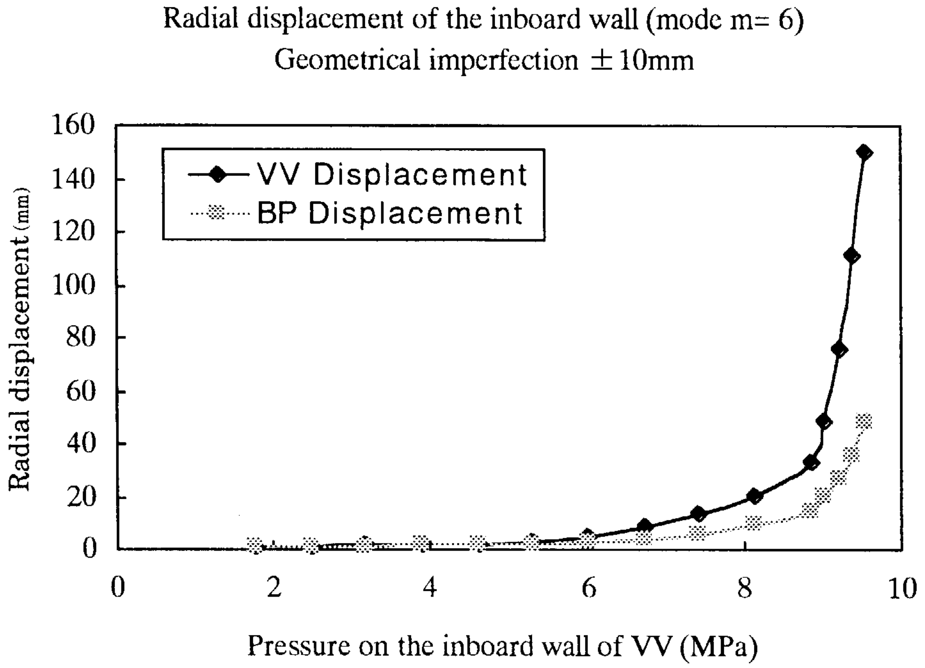


Fig. 4.7 Displacement of VV and BP for geometrical imperfection ±10 mm

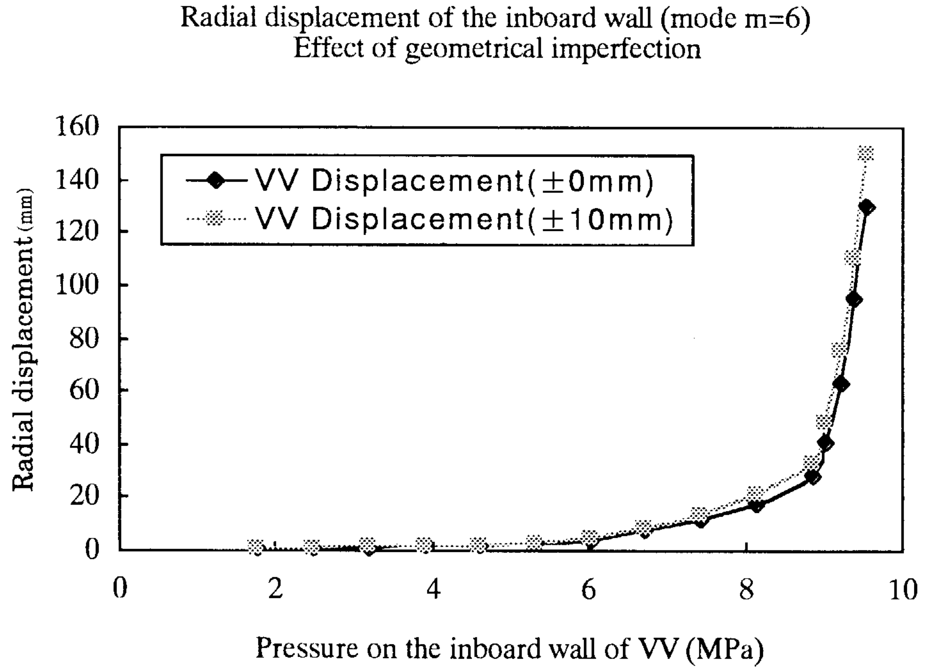


Fig. 4.8 Comparison of VV displacement of no imperfection and that of geometrical imperfection ±10 mm

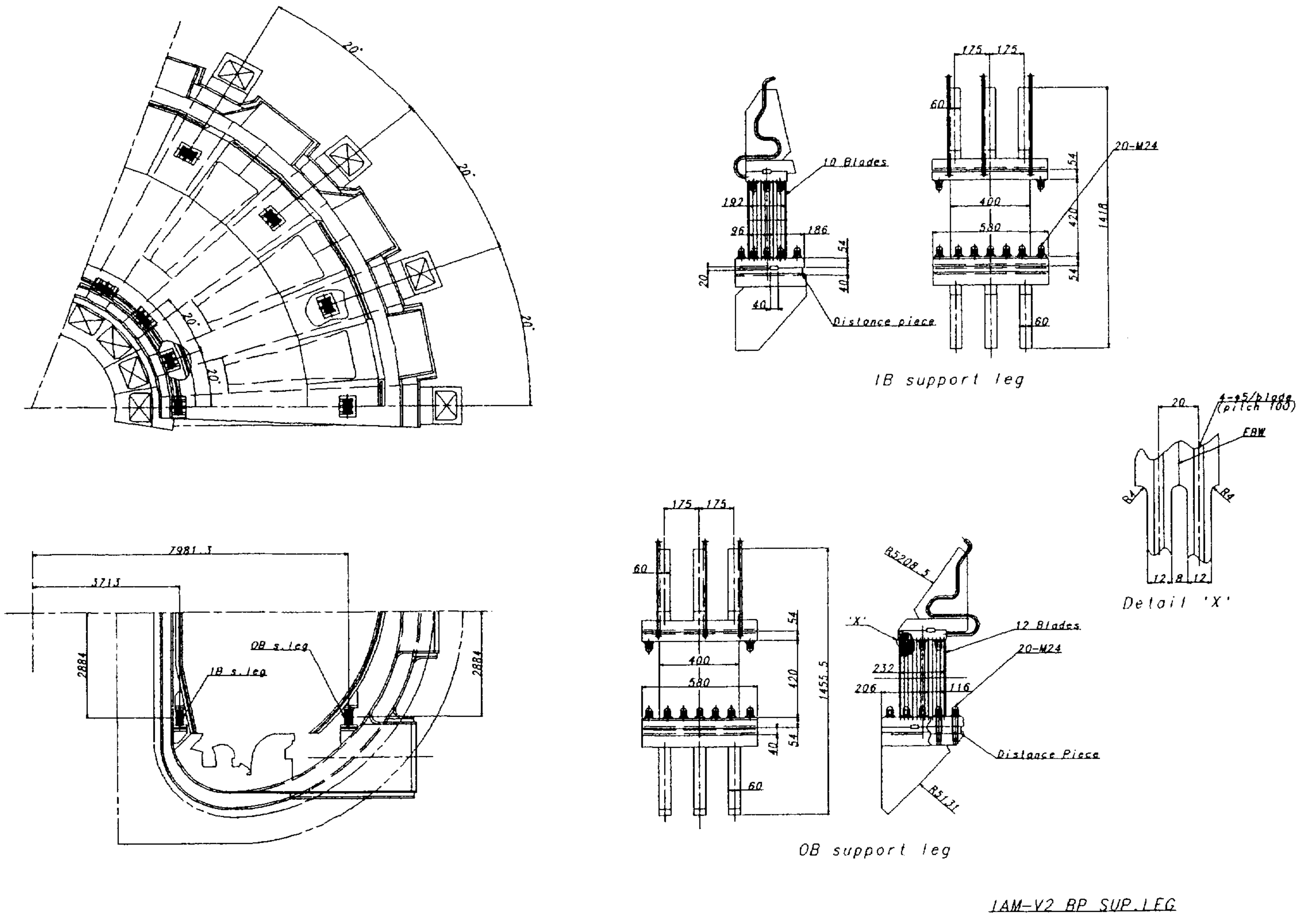


Fig. 5.1 Back Plate Support

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
長さ	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	$m\cdot kg/s^2$
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	$N\cdot m$
工率，放射束	ワット	W	J/s
電気量，電荷	クーロン	C	$A\cdot s$
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	ジーメンス	S	A/V
磁束	ウェーバ	Wb	$V\cdot s$
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	℃	
光束	ルーメン	lm	$cd\cdot sr$
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

$1\ \mathrm{eV} = 1.60218\times10^{-19}\ \mathrm{J}$

$1\ \mathrm{u} = 1.66054\times10^{-27}\ \mathrm{kg}$

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

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

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

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

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

$1\ \mathrm{Ci} = 3.7\times10^{10}\ \mathrm{Bq}$

$1\ \mathrm{R} = 2.58\times10^{-4}\ \mathrm{C/kg}$

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

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

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)

1. 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。
2. 表4には海里，ノット，アール，ヘクタ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。
3. 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。
4. 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(=10^5dyn)	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘度　$1\ \mathrm{Pa\cdot s(N\cdot s/m^2)} = 10\ \mathrm{P}$(ポアズ)(g/(cm·s))

動粘度　$1\ \mathrm{m^2/s} = 10^4\mathrm{St}$(ストークス)($\mathrm{cm^2/s}$)

圧力	MPa(=10 bar)	kgf/cm²	atm	mmHg(Torr)	lbf/in²(psi)
	1	10.1972	9.86923	7.50062×10^{3}	145.038
	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(=10^7erg)	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 cal = 4.18605 J(計量法)
= 4.184 J　(熱化学)
= 4.1855 J　(15 °C)
= 4.1868 J(国際蒸気表)

仕事率　1 PS(仏馬力)
= 75 kgf·m/s
= 735.499 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)

ASSESSMENT OF BUCKLING FOR VACUUM VESSEL AND BACK PLATE OF RC-ITER (IAM-V2)