Safety Analysis Nitrogen Vessel

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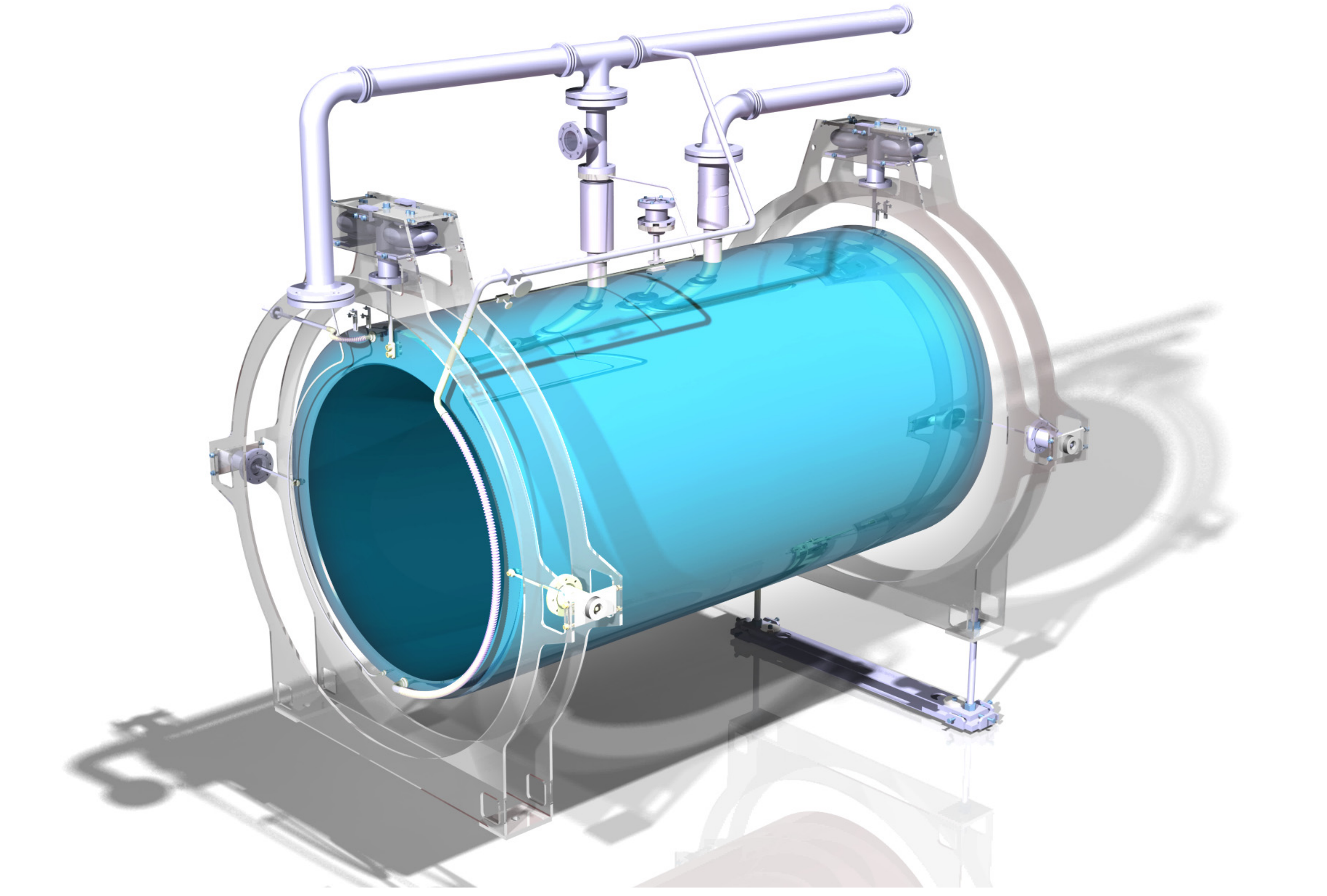
Project: **Gravitational Waves Virgo Cryogenic Link**			
Department: **Mechanical Technology**		Top folder: **West End Tower Cryostat**	



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Distribution list:

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1 GENERAL DESCRIPTION

The current Virgo vacuum level needs to be improved by about a factor of hundred in order to be compliant with the required Advanced Virgo sensitivity. Such an improvement requires baking out the interferometer arms. To separate these arms from the towers that hold the mirrors and allow the bake-out, four cryogenic vacuum links will be installed.
Cryogenic vacuum links are the classical solution to stop the migration of water from unbaked towers to interferometer (ITF) arms.

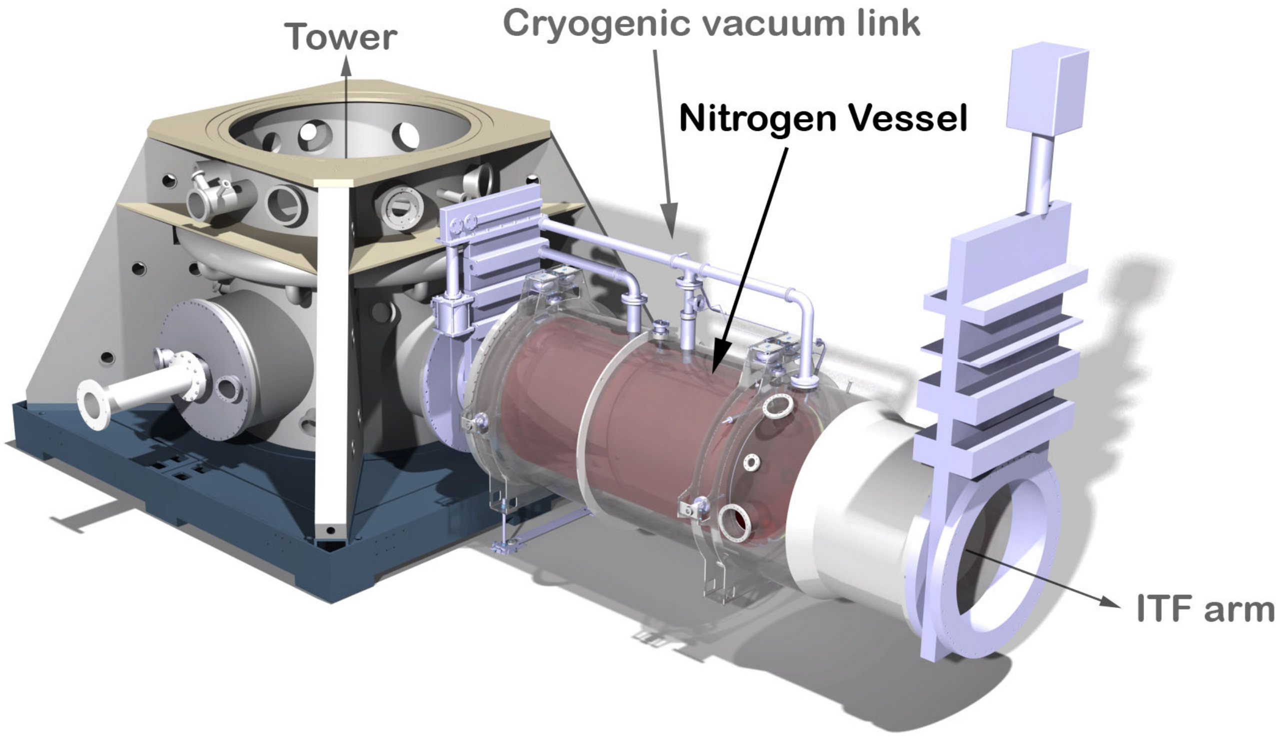


Figure 1, the nitrogen vessel is constructed inside the cryogenic vacuum link.

Inside the vacuum vessel a cold part (nitrogen vessel) of the cryolink will be constructed from aluminum AW 1050A. The inner surface of this link is cooled with liquid nitrogen. This cold part is isolated from the vessel by using two air springs and designed in such a way that thermal expansion does not induce stresses in the outside vacuum vessel.

The system will be building up and tested at an extern company. The final performance tests will be done at Nikhef before installing at Virgo. For this the vacuum vessel will be closed with two end caps, and one extra the support will be added. See in the next Figure 2 the nitrogen vessel in red.

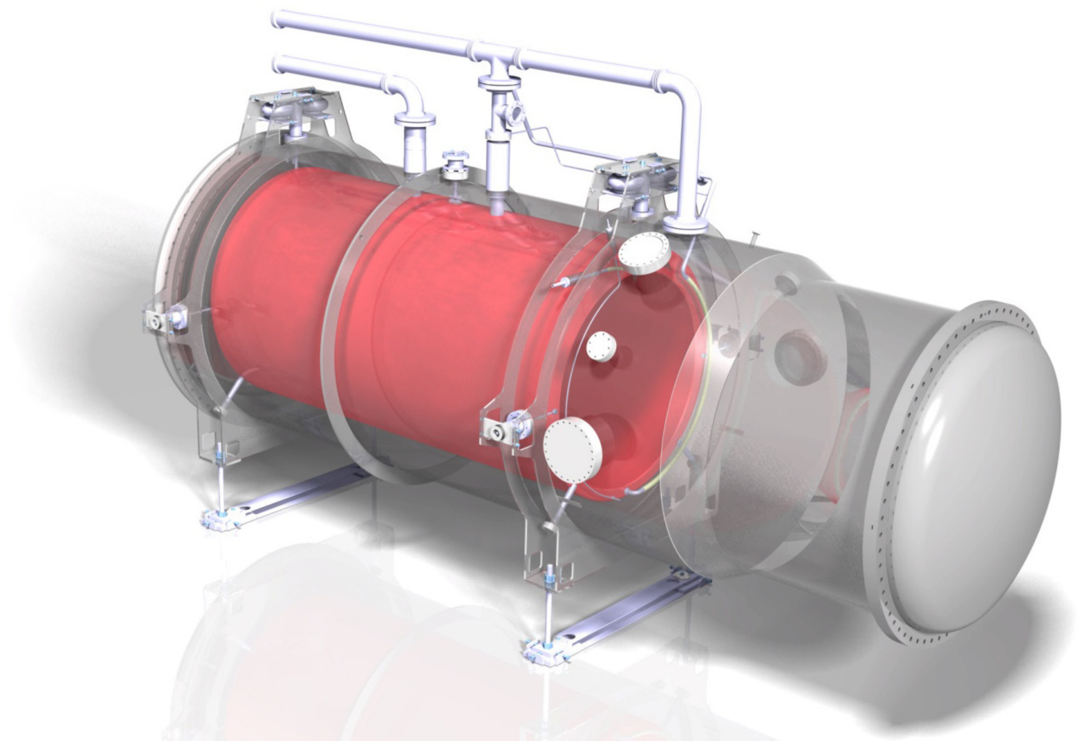


Figure 2, the nitrogen vessel (red) mounted in the cryostat.

2 SAFETY

To prevent failure of the system, the nitrogen system is equipped with a relief valve which will be open at 500 mbar pressure difference. The relief valve is venting through a stainless steel safety line for personal safety. See the following Figure 3:

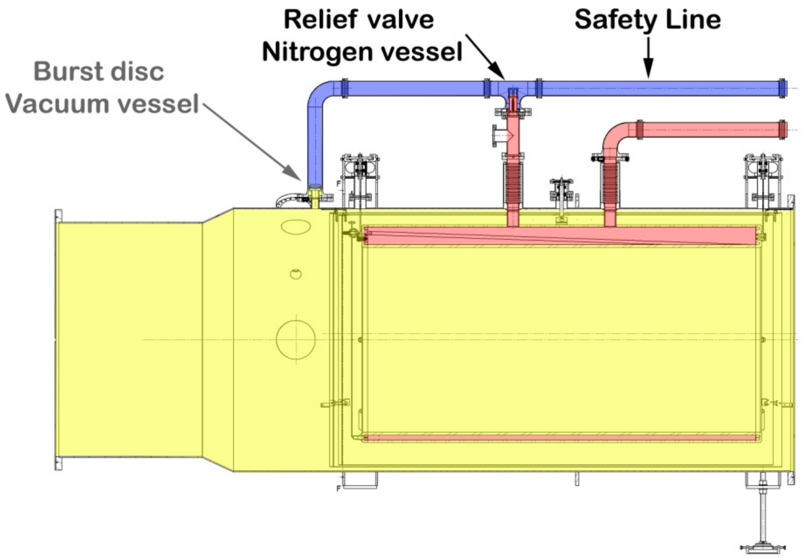


Figure 3, a relief valve is preventing the nitrogen vessel. Yellow = vacuum | red = nitrogen | blue = safety line.

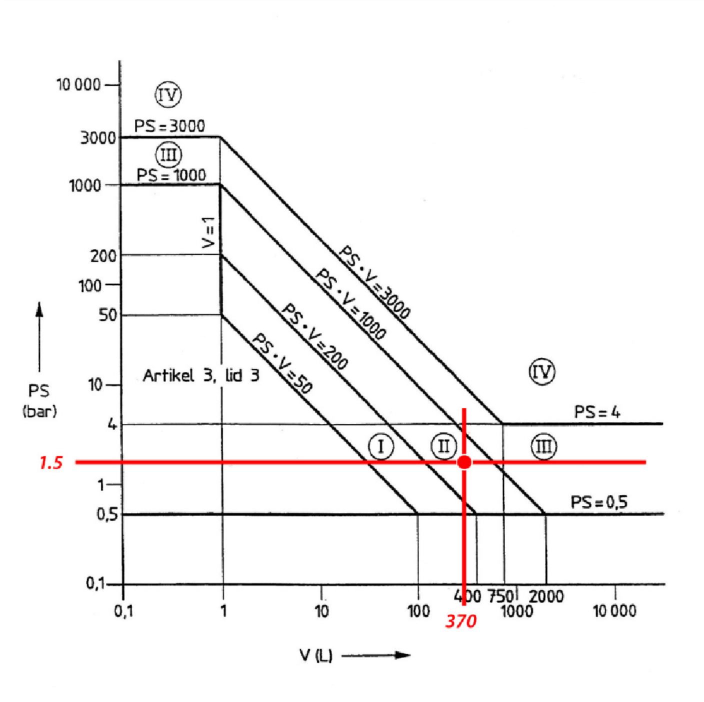
3 DEFINING PED CATEGORY

The **P**ressure **E**quipment **D**irective (97/23/EC) was adopted by the European Parliament and the European Council in May 1997. The PED is a European Single Market Directive that covers pressure equipment and assemblies with a maximum allowable pressure PS greater than 0.5 bar.

Pressure equipment:	Pressure vessel
Media:	Nitrogen (LN^2)
Group:	Non dangerous media
Phase:	Gas
Vessel volume:	370 Liter
Design Pressure PS:	1.5 bar

PS . V = 555 [bar.l]

Tabel 1. Defining the PED category for non dangerous gasses. The red lines indicate the vessel properties.



Following Tabel 1, the vessel must be classified in ***category II***

The following modules are available for category II: A1, E1 and D1

4 CALCULATIONS (FINITE ELEMENT ANALYSIS)

Following the chosen *construction class B* and *welding coefficient z=0.7,* the stress limits according to CODAP **for Aluminium and Aluminium alloys** are:

- Global zones: $f = f_3 = R_m / 3$
- Weld regions: $f_w = z \, . \, R_m / 3$
- Peak regions: $f_p = 1.5 \, . \, f_3$
- Peak/Weld regions: $f_{pw} = 1.5 \, . \, f_w$

R_m= minimum guaranteed value ultimate tensile strength at room temperature

Finite element analyses are done with the finite element analysis module of Ideas ™. Results of the stress analysis are presented in terms of von Mises equivalent stress. In addition the calculated deformations from the stress analysis and the stability (buckling) are presented. The quality of the FEA is verified using the strain energy error norm. A value below 7% is recommended by the IDEAS™ software.

4.1 Operational conditions

Quarter of the pressure vessel is modeled, as the vessel is symmetric about XY and YZ, see Figure 4.

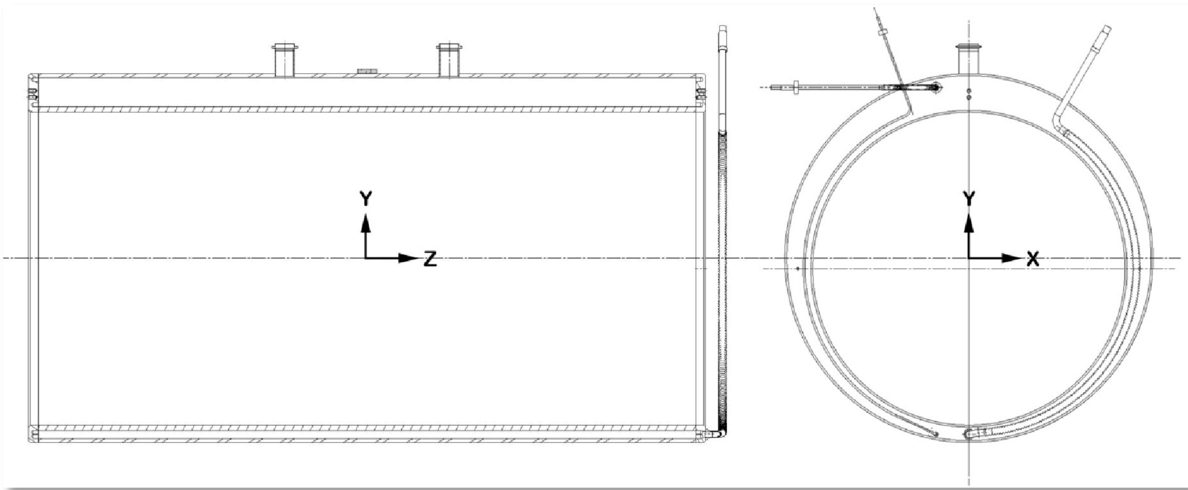


Figure 4. the vessel is symmetric about XY and YZ.

The design pressure of this nitrogen vessel is 1.5 bar. Normal operational condition is without differential pressure. The PS of 1.5 bar is a product of 0.5 bar internal pressure which is determined by the relief valve which opens at 0.5 bar pressure difference, in case of a blocking nitrogen filling line and a vacuum on the outside of the vessel. The operational temperature of the vessel is -196°C (liquid nitrogen at atmospheric pressure). For leak test reasons the vessel will be evacuated (vacuum) at 20°C.

The inner cold part, filled with liquid nitrogen, is hanging with air filled bellows on two ribs of the vacuum vessel; see Figure 5 and Figure 6. The total weight of this aluminum vessel (550 kg) with liquid nitrogen (±300 Liter = 2500 N) on the four flanges is 8000 N.

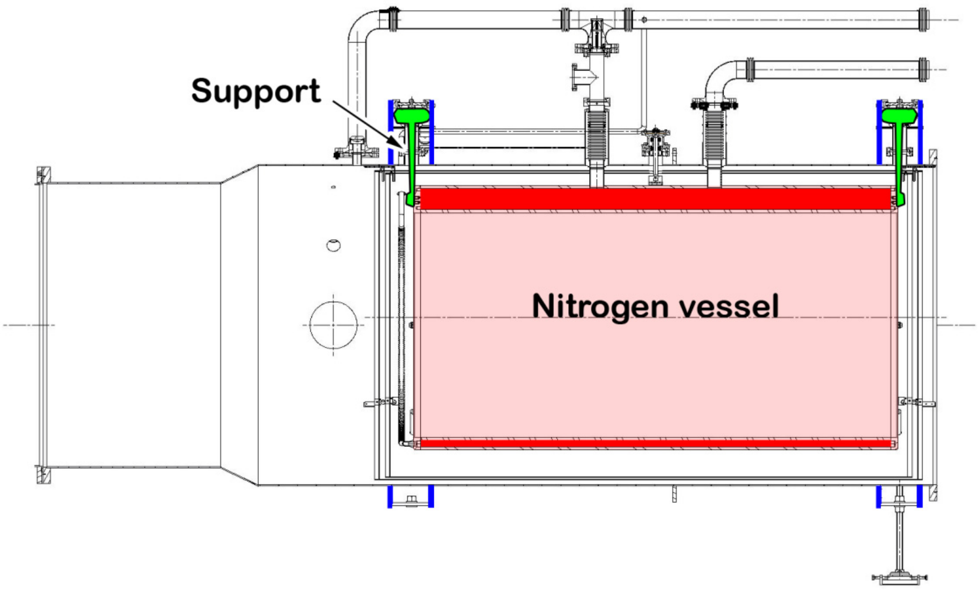


Figure 5. Two suspensions of the cold part (nitrogen vessel) inside the vacuum vessel. Blue are the flanges and green are the suspensions of the inner cold part.

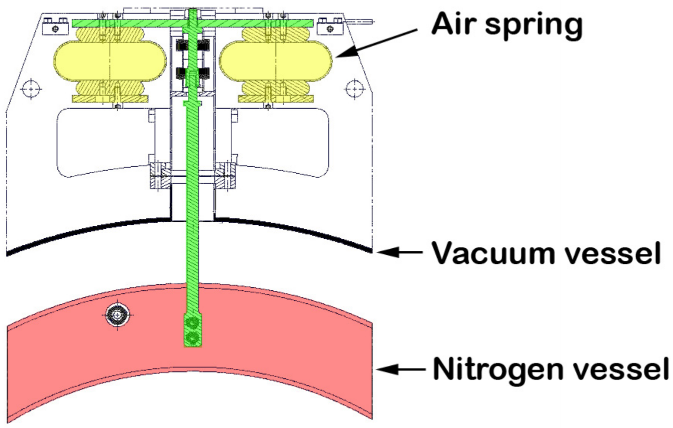


Figure 6. Detail of the suspension.

Tabel 2, summary of the operational conditions

Operational conditions	
Design Pressure	1.5 bar at -196°C) 1 bar at 150°C -1 bar (vacuum) at 20°C
Design Temperature	-196°C .. 150°C
Additional loads	2500 N (300L liquid nitrogen)

4.2 The FEA model

The FEA model is built up from 3D solid parabolic tetrahedron and 2D Thin Shell parabolic quadrilateral elements. All loads are applied without any safety factors.
The vessel is verified for three conditions:

1. Pressure 1 bar | temperature 150°C
2. Pressure 1.5 bar | temperature -196°C
3. Pressure -1 bar | temperature 20°C

The FEA model is built up from 3D solid parabolic tetrahedron and 2D Thin Shell parabolic quadrilateral elements. See for all FEA model constrains the following Figure 7.

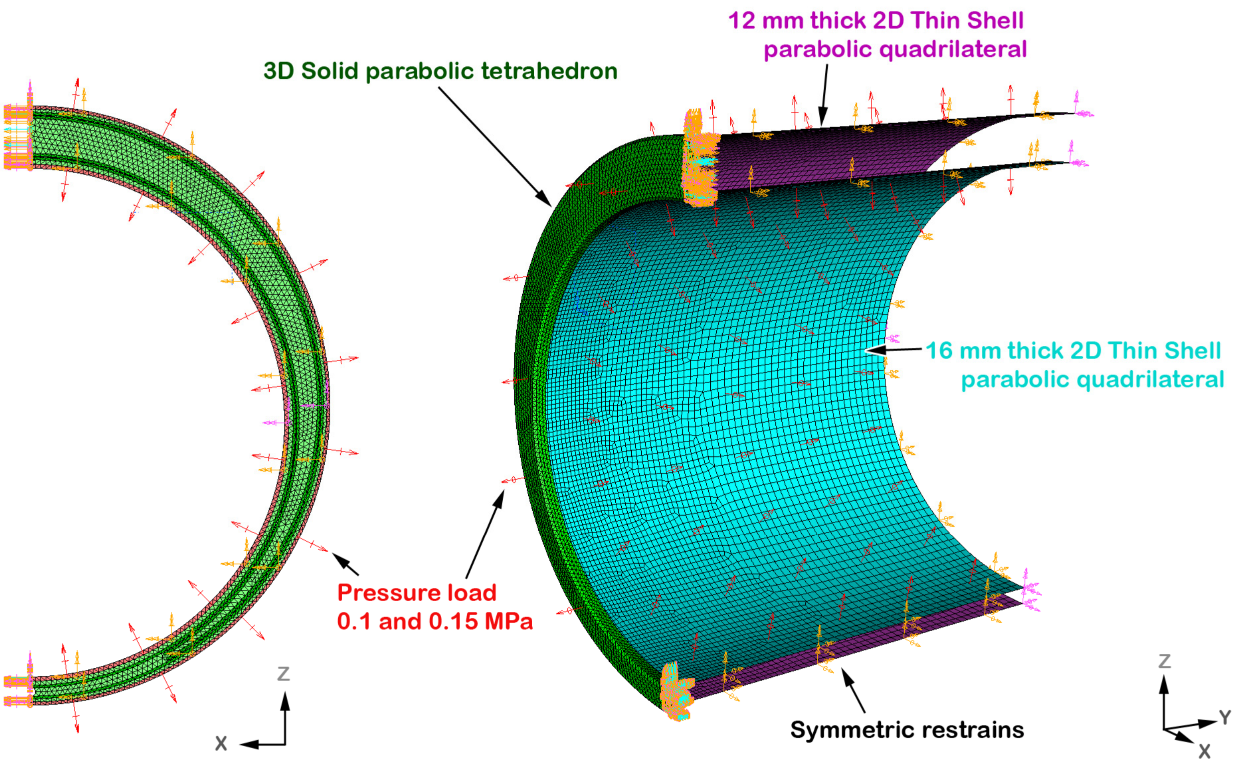


Figure 7, FEA model of the nitrogen vessel.

4.3 Material

The vessel will be made from Aluminium AW 1050A. The material has been selected based on the temperature requirements and the welding ability of the material. A summary of the mechanical properties is given in Tabel 3.

Tabel 3, properties AW 1050A**.**

			***20-25* °C**	***-196* °C**	***150* °C**
Tensile strength	**R_m [MPa]**	**min.**	**80**	**90**	**70**
Yield strength	$R_{p\ 0.2\%}$ [MPa]	min.	70		
Young’s modulus	E [GPa]	min.	69		
Density	ρ [g/cm^3]		7.85		
Poisons ratio			0.33		

The stress limits according to CODAP are:

1. Pressure 1 bar | temperature 150°C

Global zones: $f = f_3 = \frac{R_m}{3} = \frac{70}{3} = 23{,}3\ MPa$

Weld regions: $f_w = \frac{z \cdot R_m}{3} = \frac{0.7 \cdot 70}{3} = 16.3\ MPa$

Peak regions: $f_p = 1.5 \cdot f_3 = 1.5 \cdot 23.3 = 35\ MPa$

Peak/Weld regions: $f_{pw} = 1.5 \cdot f_w = 1.5 \cdot 16.3 = 24.5\ MPa$

2. Pressure 1.5 bar | temperature -196°C

Global zones: $f = f_3 = \frac{R_m}{3} = \frac{90}{3} = 30\ MPa$

Weld regions: $f_w = \frac{z \cdot R_m}{3} = \frac{0.7 \cdot 90}{3} = 21\ MPa$

Peak regions: $f_p = 1.5 \cdot f_3 = 1.5 \cdot 30 = 45\ MPa$

Peak/Weld regions: $f_{pw} = 1.5 \cdot f_w = 1.5 \cdot 21 = 31.5\ MPa$

3. Pressure -1 bar | temperature 20°C

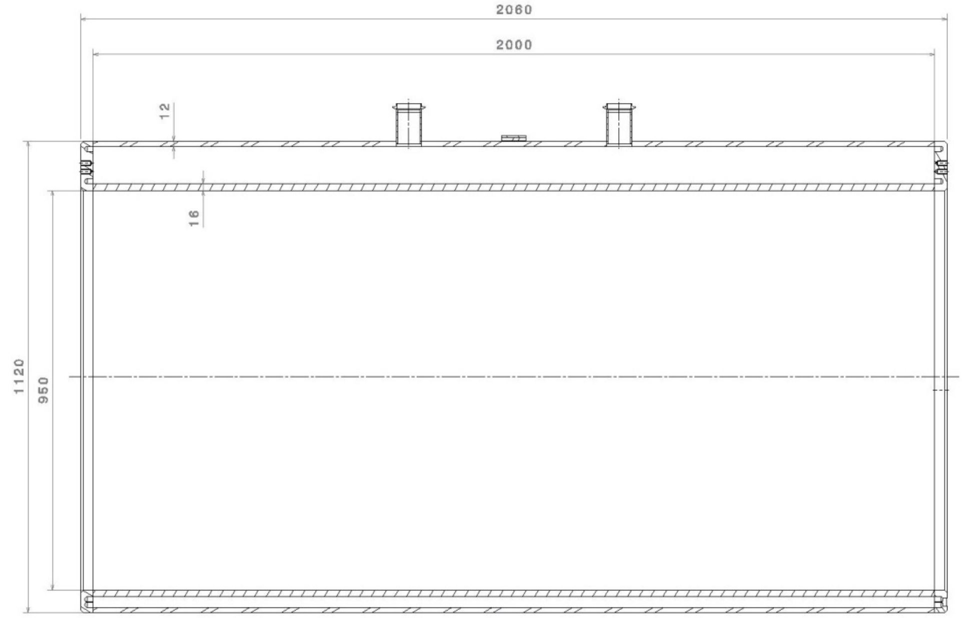
Global zones: $f = f_3 = \frac{R_m}{3} = \frac{80}{3} = 26.7\ MPa$

Weld regions: $f_w = \frac{z \cdot R_m}{3} = \frac{0.7 \cdot 80}{3} = 18.7\ MPa$

Peak regions: $f_p = 1.5 \cdot f_3 = 1.5 \cdot 26.7 = 40\ MPa$

Peak/Weld regions: $f_{pw} = 1.5 \cdot f_w = 1.5 \cdot 18.7 = 28\ MPa$

4.4 Calculation tube



Design Pressure: $\boldsymbol{PS} = 1.5\ bar\ =\ 0.15\ MPa$

Inside diameter: $\boldsymbol{D_{in}} = 1096\ mm$ (outside cylinder)

Outside diameter: $\boldsymbol{D_{out}} = 1120\ mm$

Wall thickness: $\boldsymbol{t} = 12\ mm$

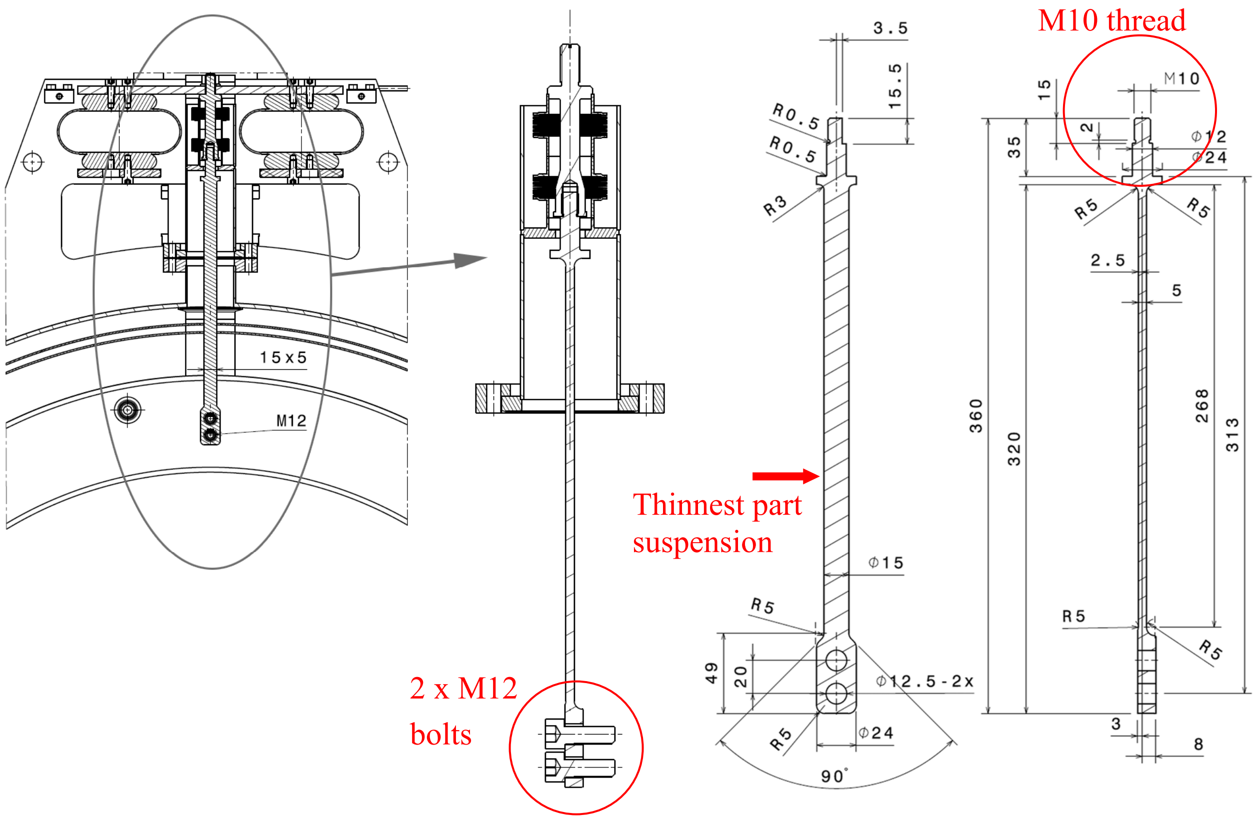
The vessel can be considered as thin-walled vessel because the D_{in}/t ratio (1096/12=91) is higher than 10.

Radial (Hoop) stress: $\boldsymbol{\sigma_r} = \frac{F}{A} = \frac{PS \cdot D_{in}}{2 \cdot t} = \frac{0.15 \cdot 1096}{2 \cdot 12} = 6.9\ MPa$

Axial stress: $\boldsymbol{\sigma_a} = \frac{F}{A} = \frac{PS \cdot {D_{in}}^2}{{D_{out}}^2 - {D_{in}}^2} = \frac{0.15 \cdot 1096^2}{1120^2 - 1096^2} = 3.4\ MPa$

4.5 Calculation Suspension

Two suspensions are used to support the nitrogen vessel inside the vacuum vessel. See the following figure for details of this stainless steel suspension



Suspension:

Material	AISI 304L
Yield strength AISI 304L	**193 MPa** (20 °C)
Weight of the vessel	5250 N
Volume liquid N_2	300 liter (volume vessel = 370 liter)
Density liquid N_2	0.808 g·cm^{-3}
Weight 300 liter N_2	2400 N

Force on each suspension = (weight vessel + 300 liter liquid N_2)/2 = (5250 + 2400)/2 = 3825 N
Cross section thinnest part suspension = 15 x 5 =75 mm^2
Thread cross section M10 connection = 51.5 mm^2

Tension stress suspension: $$\sigma_t = \frac{F}{A} = \frac{3825}{75} = \mathbf{51\ MPa}$$

Tension in M10 thread connection: $$\sigma_t = \frac{F}{A} = \frac{3825}{51.5} = \mathbf{74\ MPa}$$

Bolt M12:

Material	AISI 304
Shear strength (see table 4)	**117 MPa** (17.5 ksi)
Core diameter M12	9.8 mm
Thread cross section M12	75.4 mm^2

The suspension is connected with four (4) bolts to the vessel. Calculation is done in case two bolts (one at each side) are taken all weight of the vessel:
Force on one M12 bolt = (weight vessel + 300 liter liquid nitrogen) / 2 = 3825 N

Shear stress in M12 bolt: $\boldsymbol{\tau} = \frac{F}{A} = \frac{3825}{75.4} = \mathbf{50.7\ MPa}$

The design of the suspension is such a way that extra tension/bending stress in the bolt due to temperature change of the nitrogen vessel (-196 ^{o}**C** .. 150 ^{o}**C)** is negligible.

Tabel 4, allowable shear stress for stainless steel bolts (from the Specialty Steel Industry of North America SSINA)

Type	Finish	Condition and Specification	Diameter d (in.)	Minimum Tensile Requirements		Allowable Shear Stress (ksi)	
				0.2% Yield Strength (ksi)	Tensile Strength (ksi)	No Threads in Shear Plane	Threads in Shear Plane
302** 304 316	Hot Finished	Condition A (Annealed) in ASTM A276-71 Class 1 (solution treated) in ASTM A193-71	all	30.0	75.0	15.0	10.5
302 304 316	Cold Finished	Condition A (Annealed) in ASTM A276-71	≤ ½	45.0	90.0	18.0	12.6
302** 304 316	Cold Finished	Condition B (cold-worked) in ASTM A276-71 Class 2 (solution treated and strain hardened) in ASTM A193-71*	≤ ¾	100.0	125.0	25.0	17.5

* For Class 2: B8M in ASTM A193, the allowable shear stress is 22.0 ksi when threading is excluded from the shear plane, or 15.0 ksi when threads are in the shear plane.
** ASTM A276-71 only.

4.6 FEA results

4.6.1 1 bar internal pressure analysis

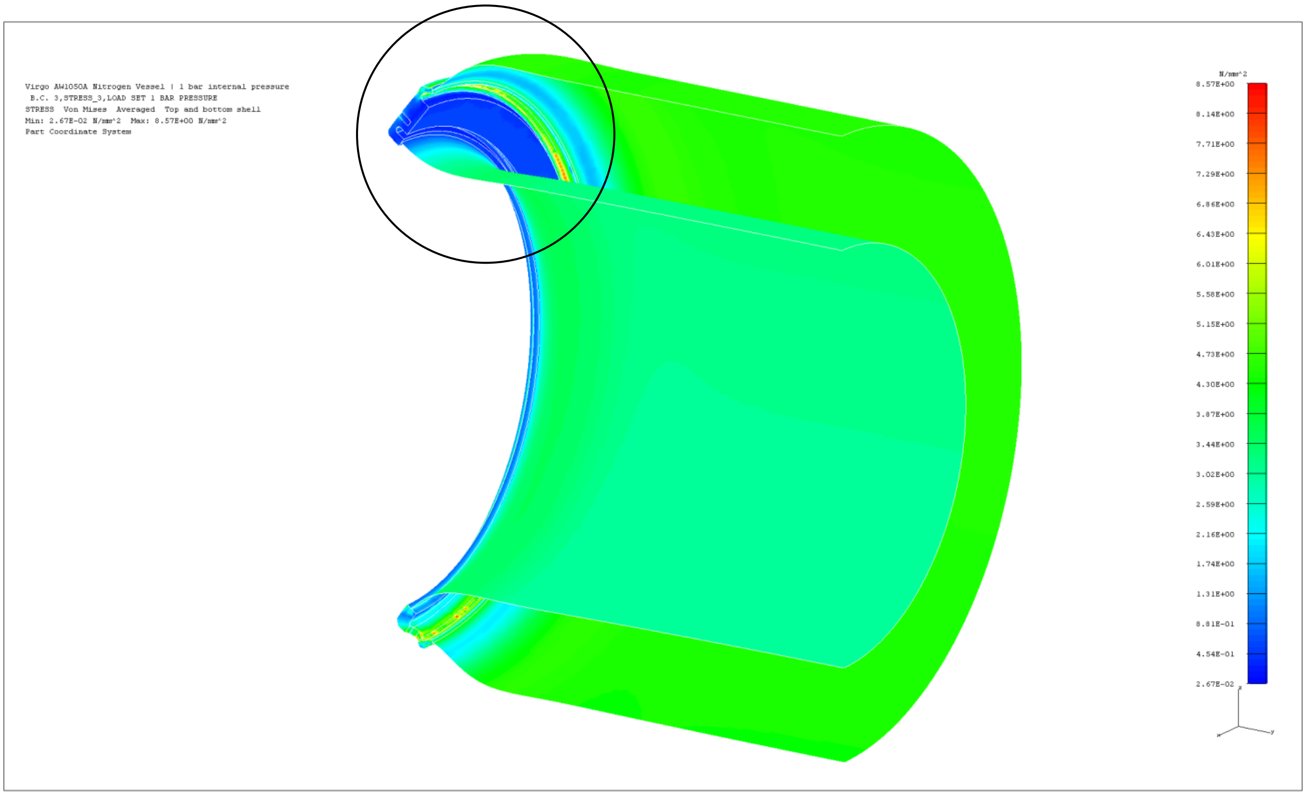


Figure 8, stress result | max stress = 8.6 MPa.

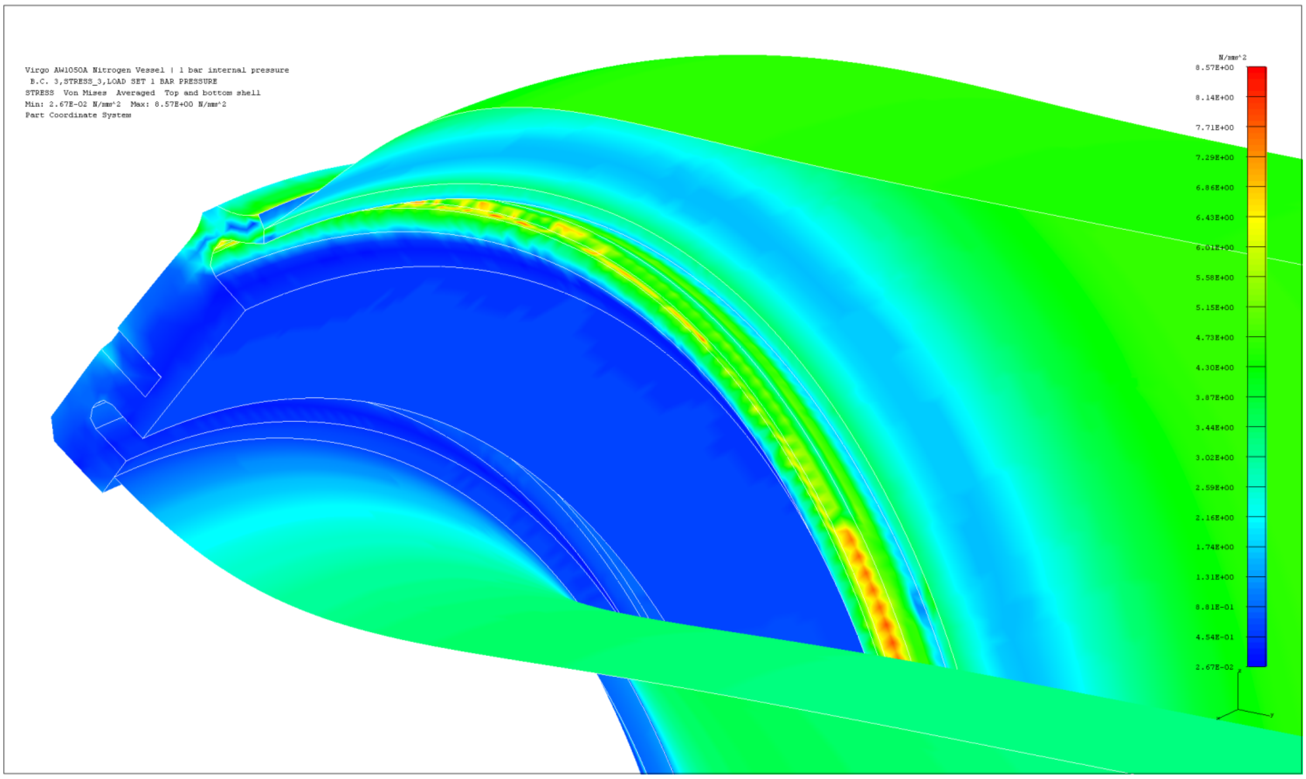


Figure 9, stress result detail | max stress = 8.6 MPa.

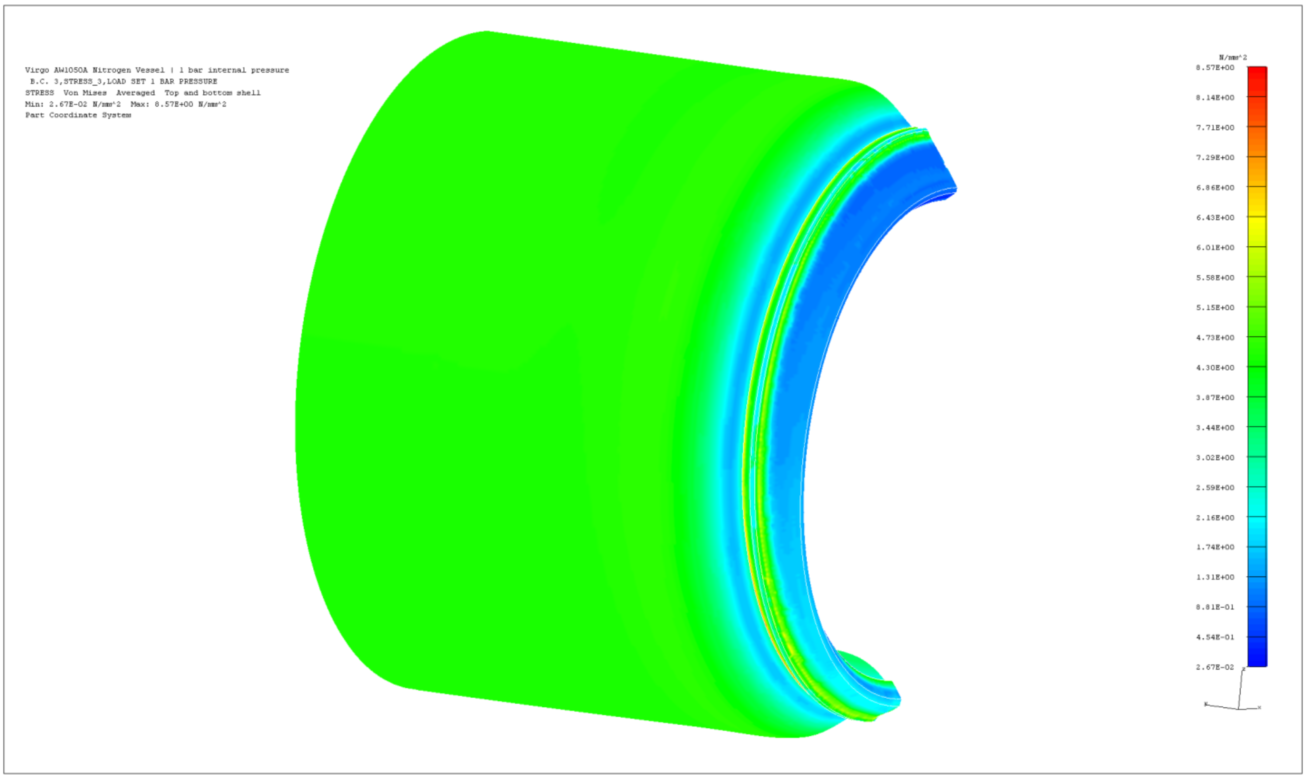


Figure 10, stress result | max = 8.6 MPa.

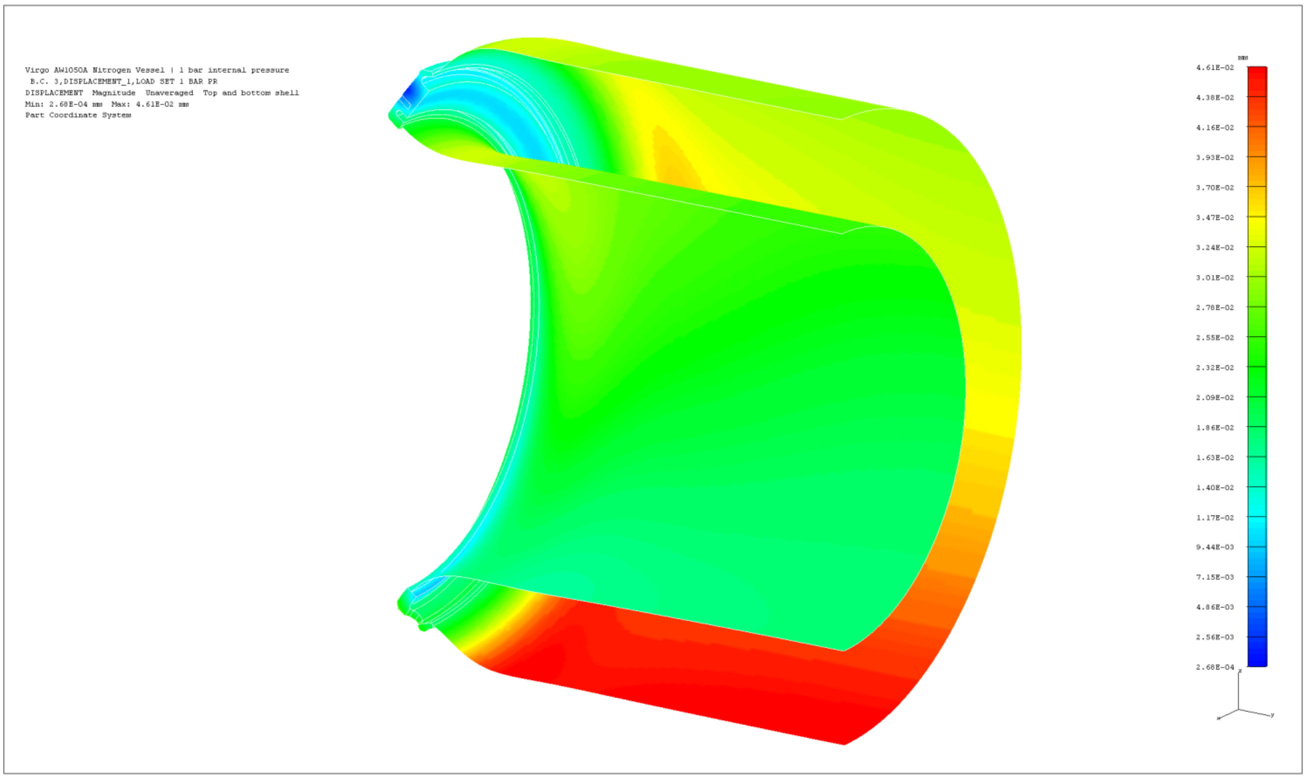


Figure 11, displacement result | max = 0.05 mm.

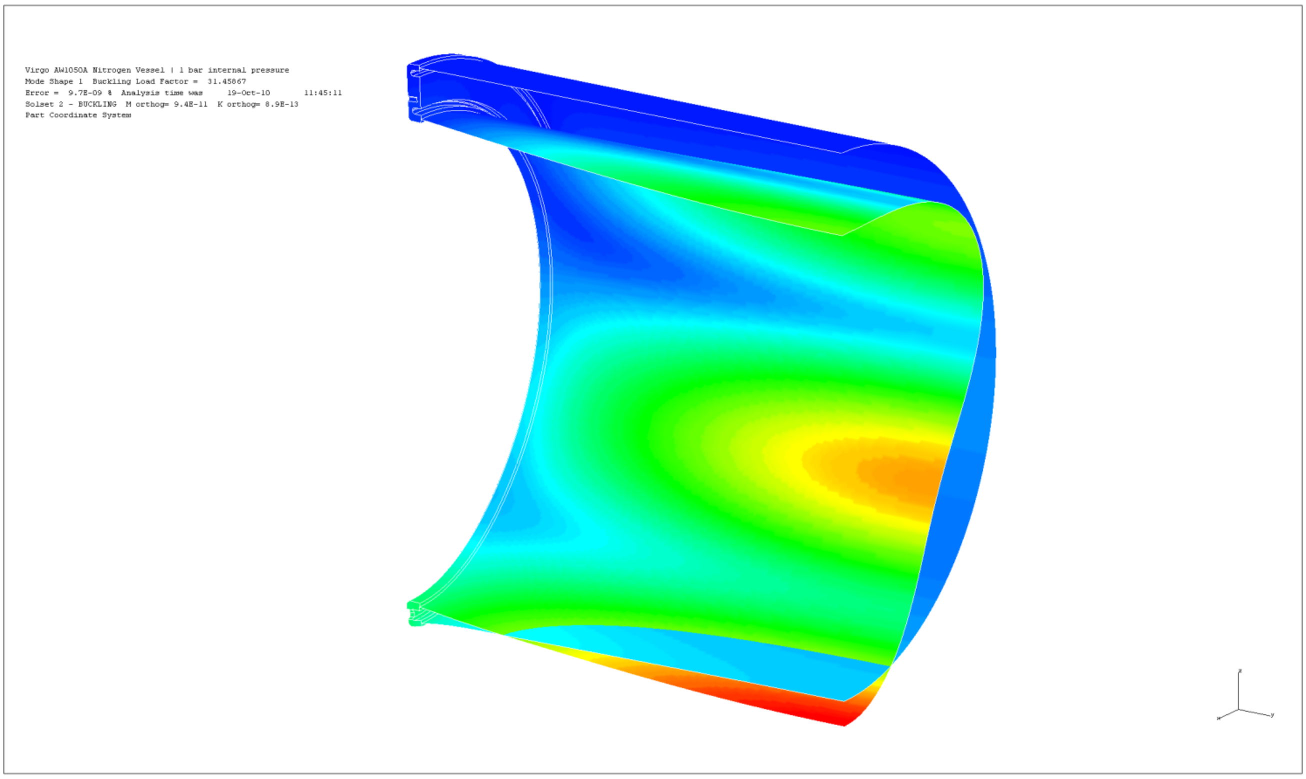


Figure 12, first normal mode result | buckling load factor = 31.5.

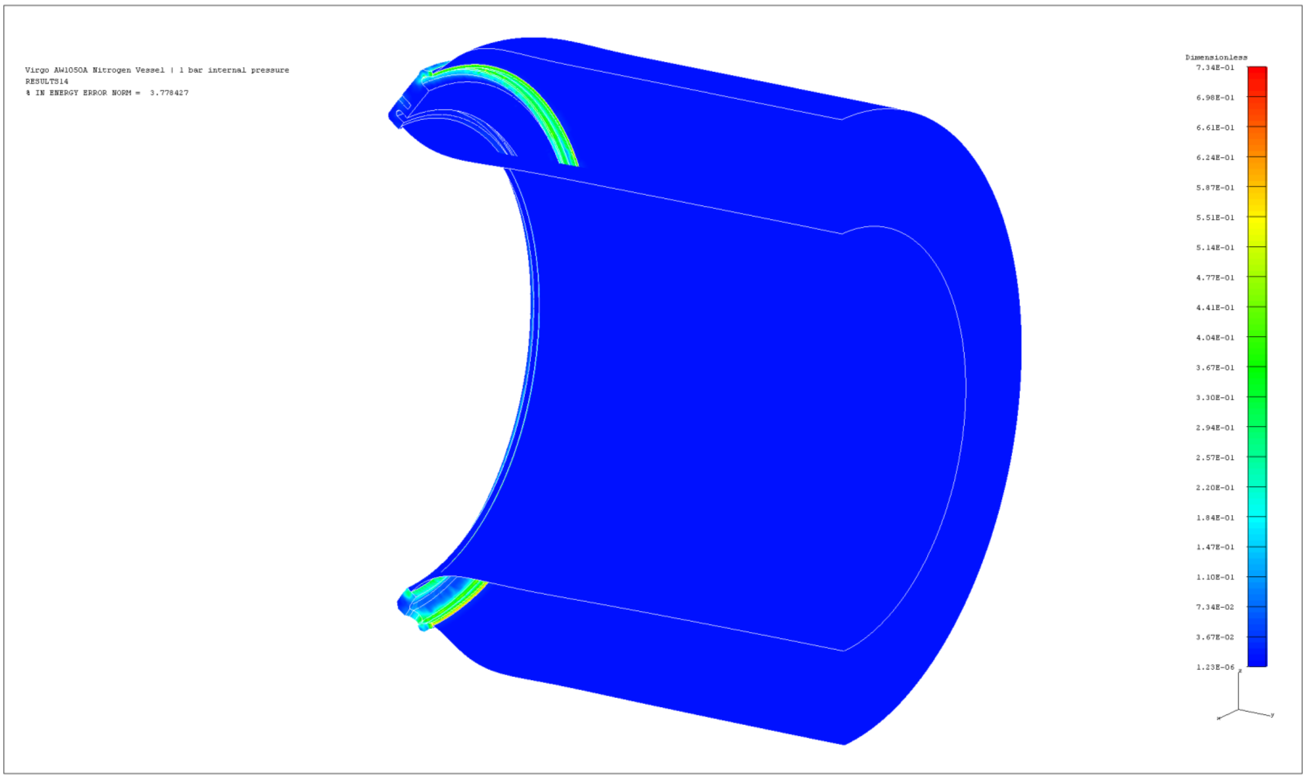


Figure 13, Strain energy error norm = 3.8%.

4.6.2 1.5 bar internal pressure analysis

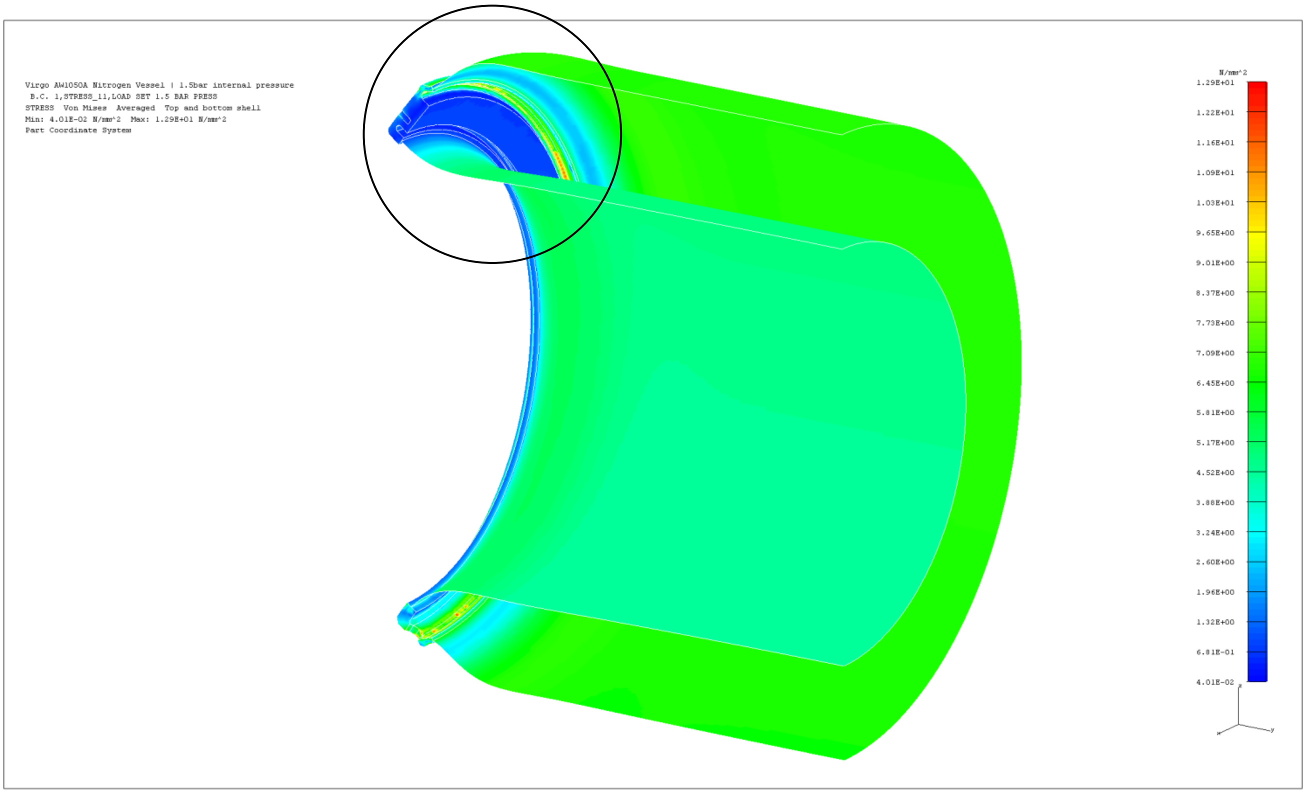


Figure 14, stress result | max = 12.9 MPa.

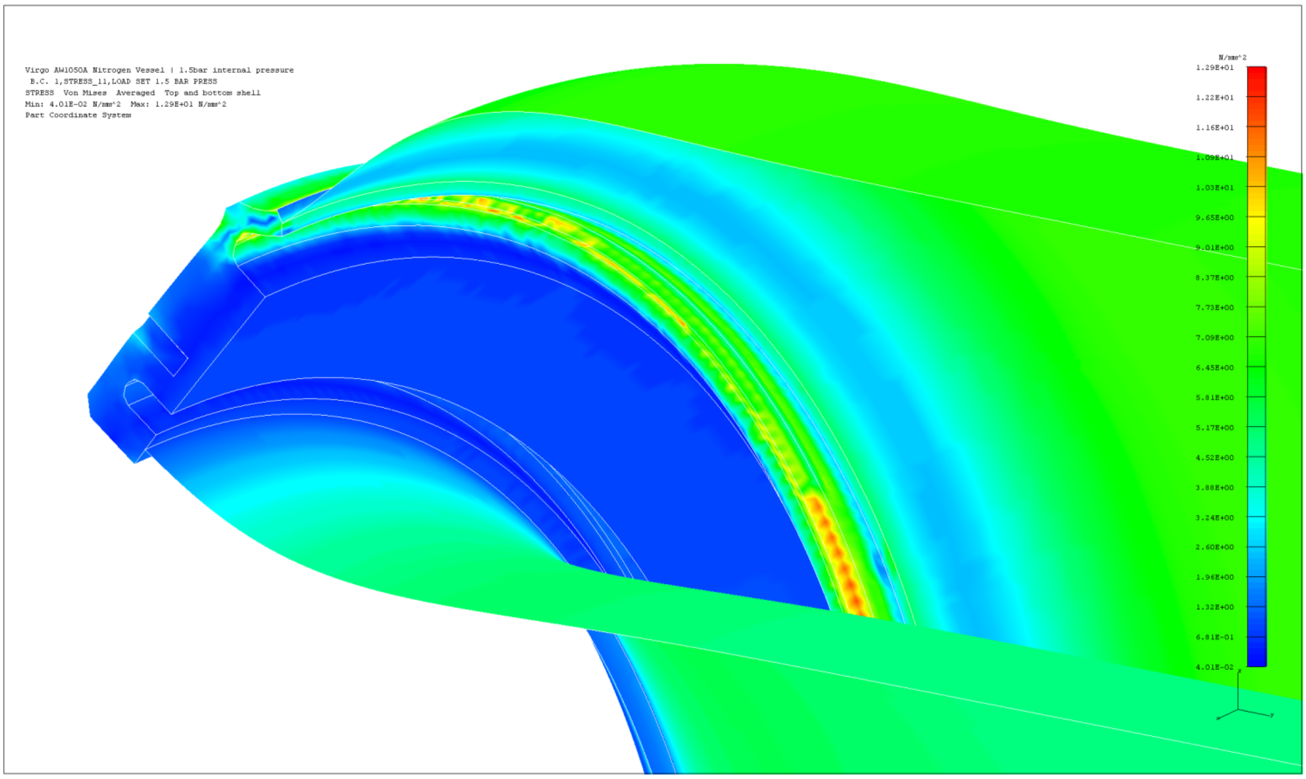


Figure 15, stress result detail | max = 12.9 MPa.

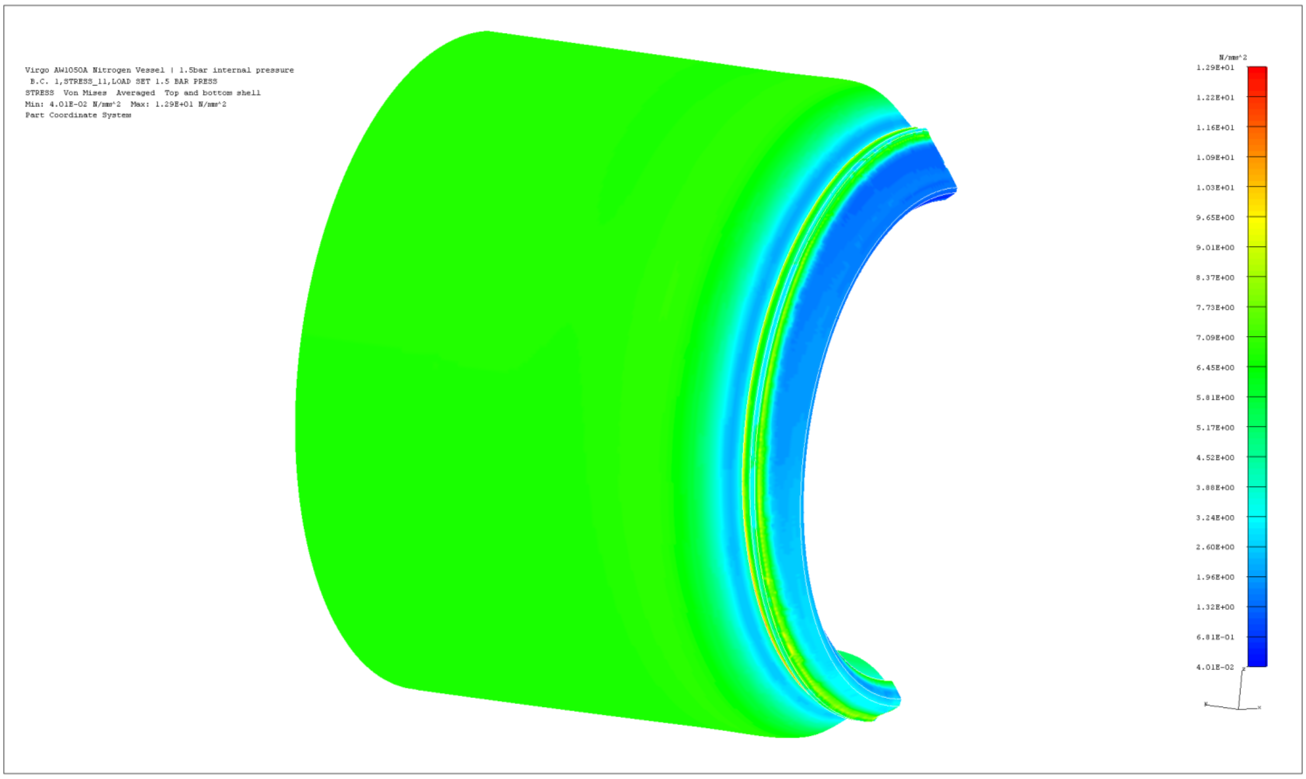


Figure 16, stress result | max = 12.9 MPa.

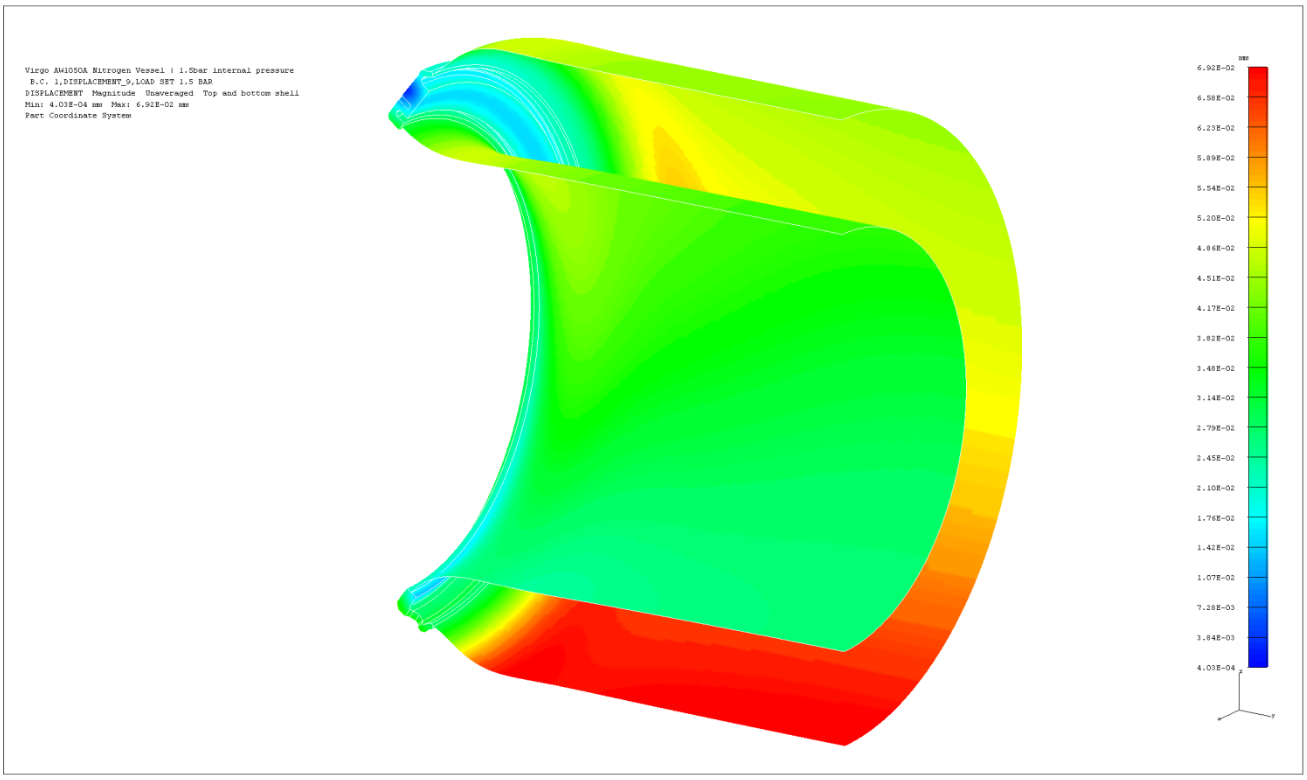


Figure 17, displacement result | max = 0.07 mm.

4.6.3 -1 bar (vacuum) internal pressure analysis

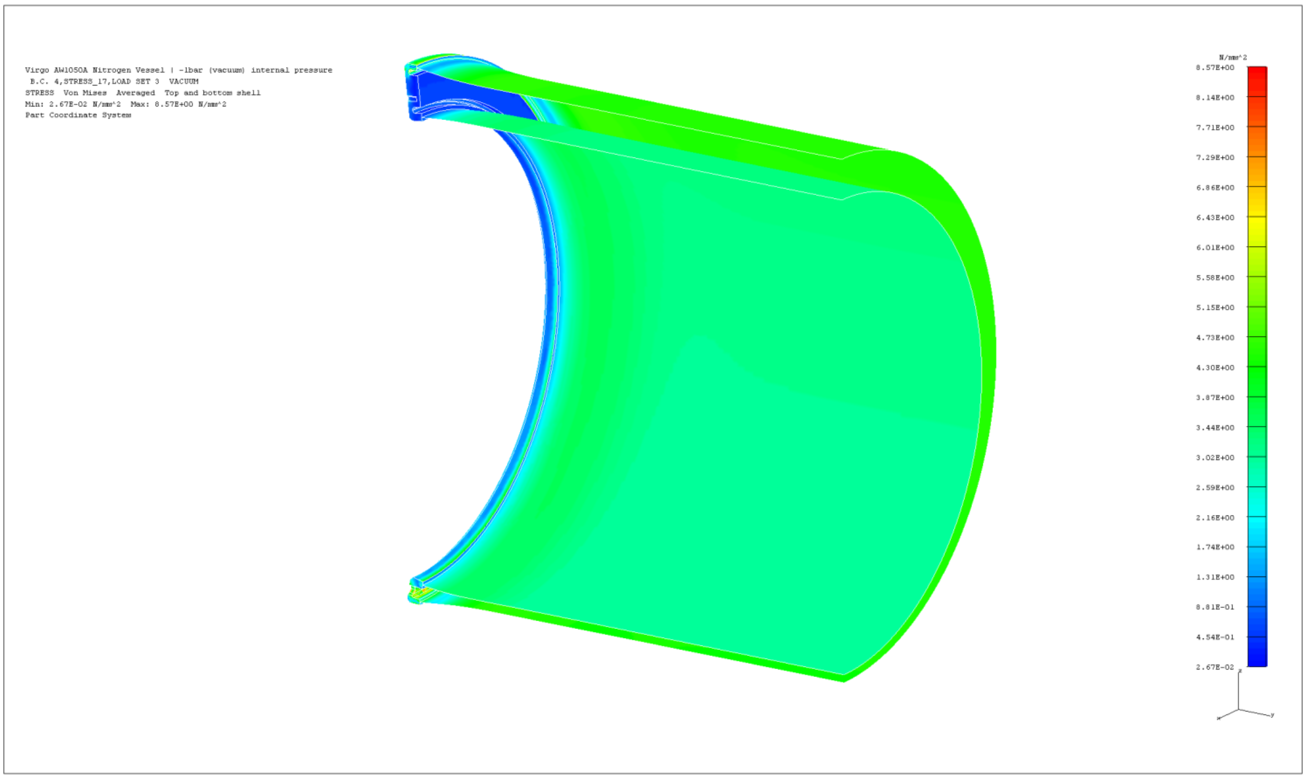


Figure 18, stress result | max = 8.6 MPa.

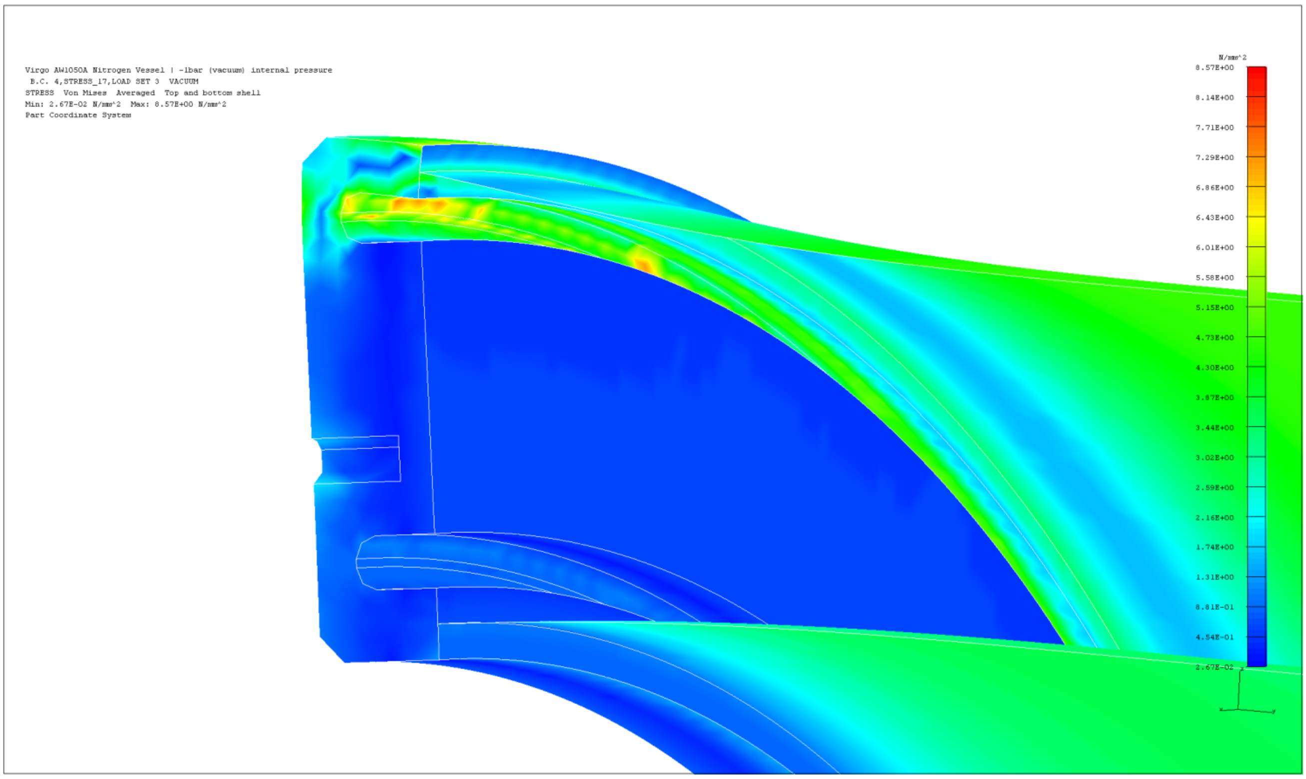


Figure 19, stress result detail | max = 8.6 MPa.

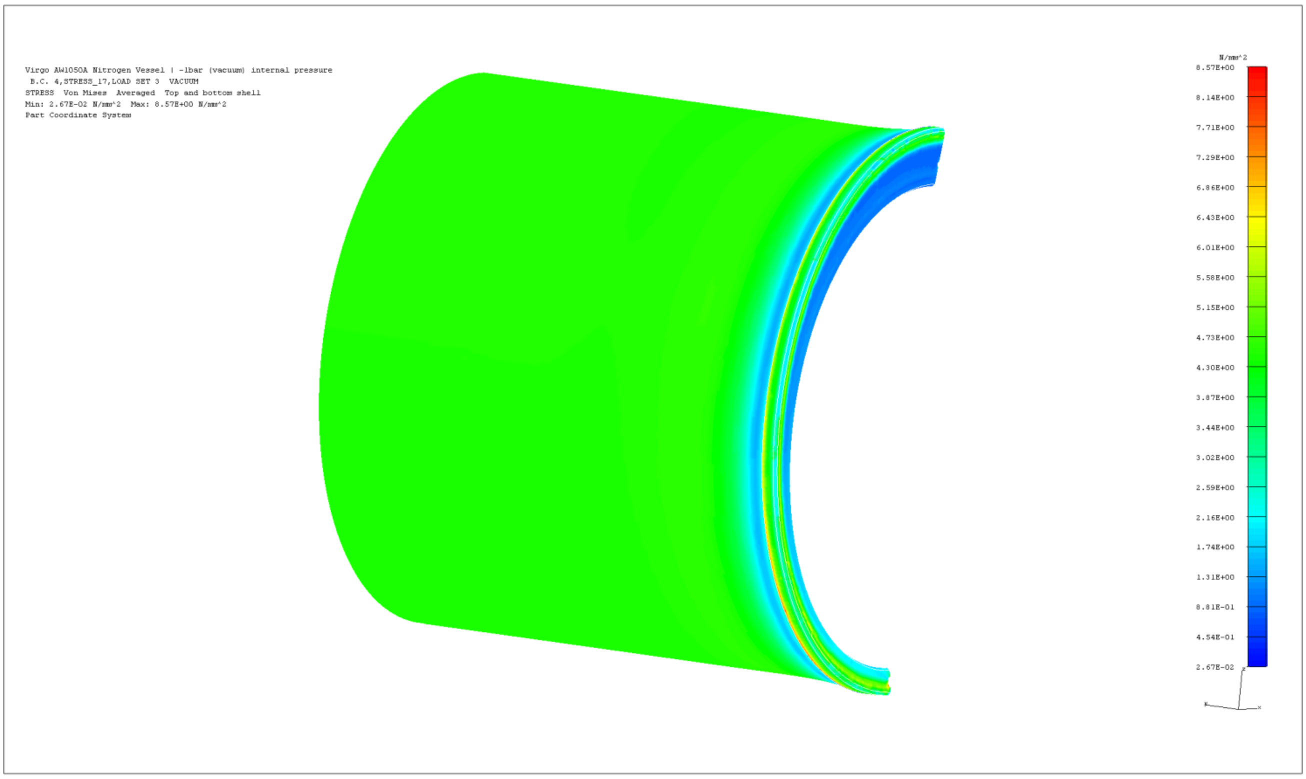


Figure 20, stress result | max = 8.6 MPa.

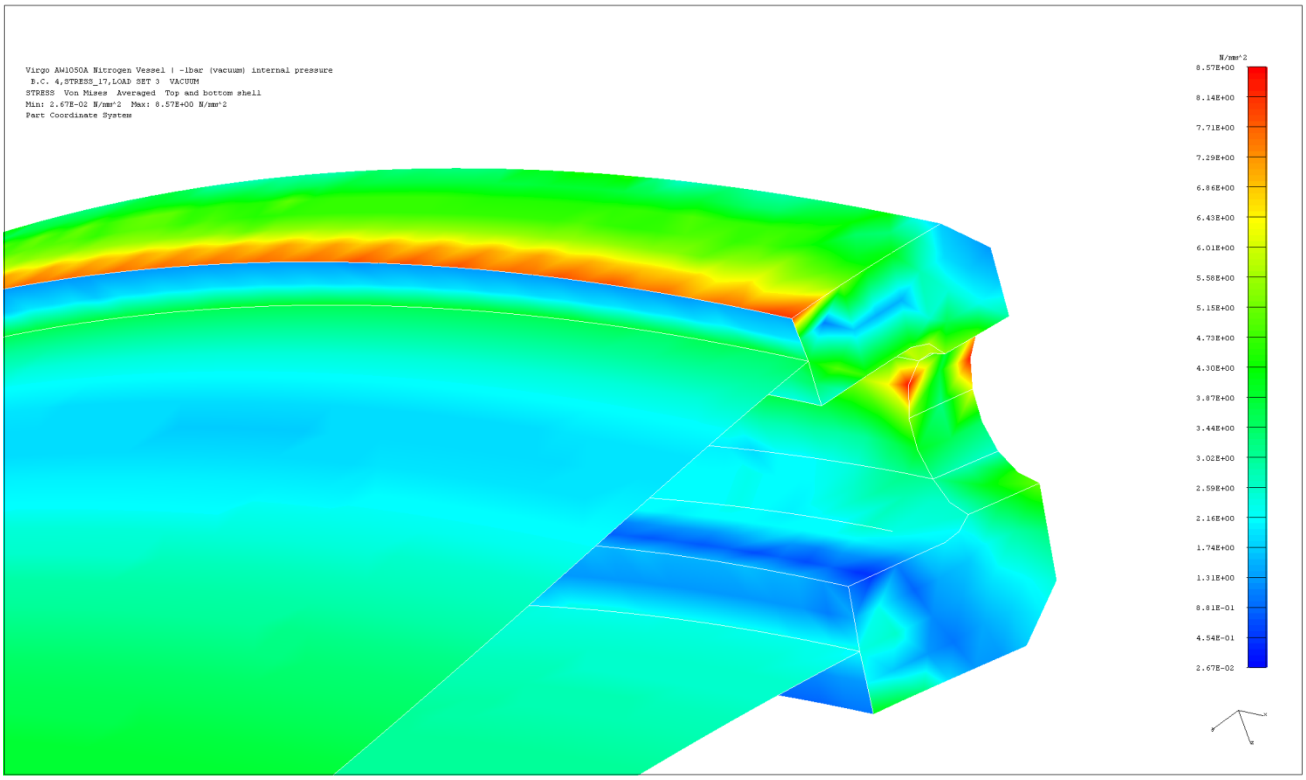


Figure 21, stress result detail | max = 8.6 MPa.

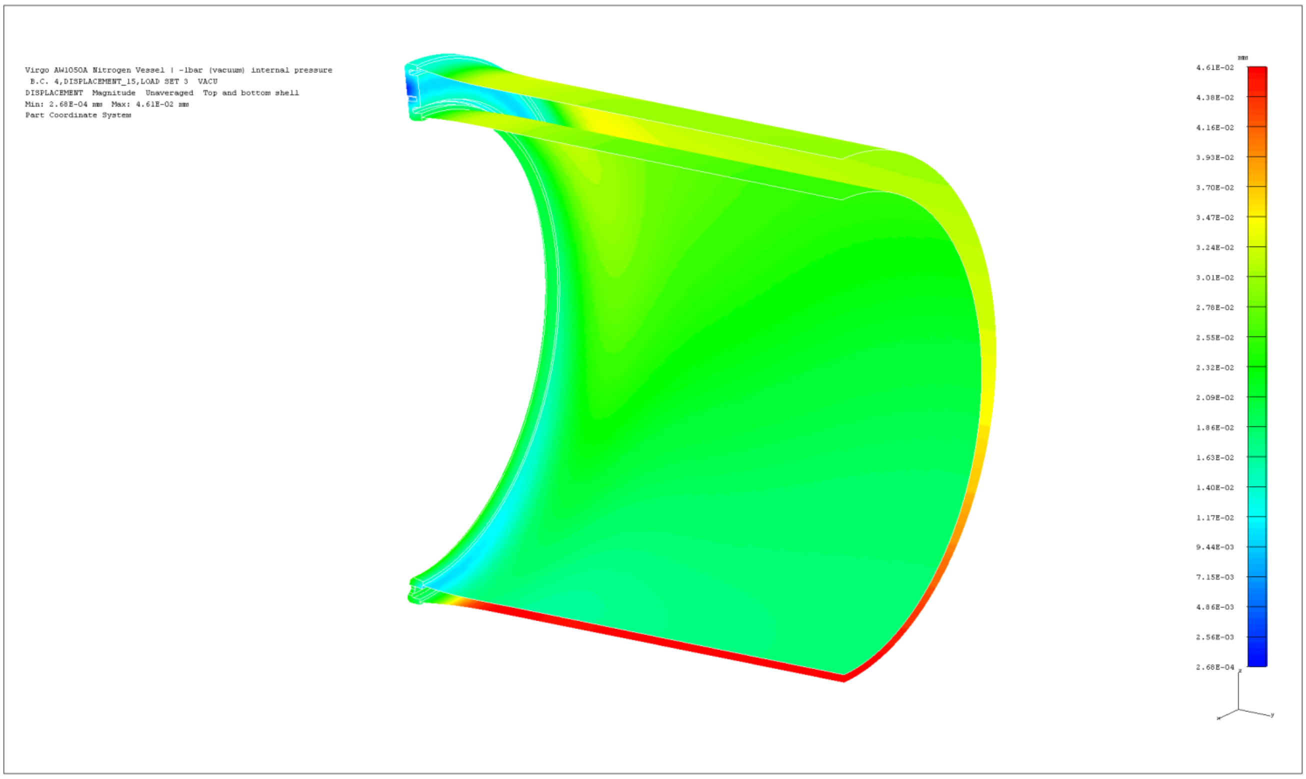


Figure 22, displacement result | max = 0.04 mm.

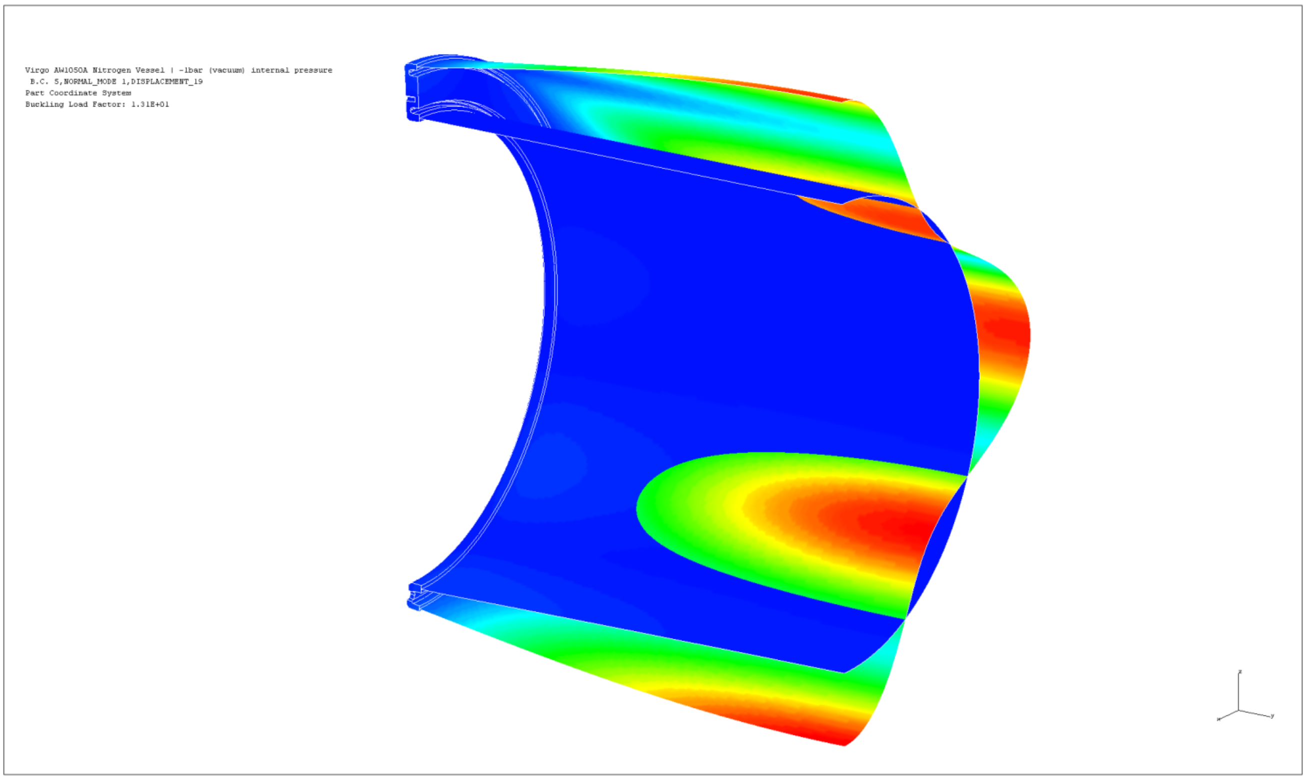


Figure 23, first normal mode result | buckling load factor = 13.

5 RESULTS OF THE ANALYSIS

The results are compared with the requirements defined by the CODAP. The limitations of the analysis are presented, and the compliance with the code is verified.

Assuming the 1 bar analysis, the calculation shows that the expected max stress of 8.6 MPa is well below the acceptable values of 35 MPa for Peak regions. Detail in Figure 9 shows that this max stress of 8.6 MPa is situated in the corner of the end flanges. Stresses in all weld regions are well below the CODAP limit of 16.3 MPa. The maximum displacement of 0.05 is negligible. Buckling analysis shows a buckling factor of 31.5, where a factor of 3 is required, which can be considered as very safe. The tolerances for the fabrication of the vessel will ensure that the shape of the vessel will be in accordance with the model.

Assuming the 1.5 bar analysis, the calculation shows that the expected max stress of 12.9 MPa is well below the acceptable values of 45 MPa for Peak regions. Stresses in all weld regions are well below the CODAP limit of 21 MPa. Tube calculation shows that the general stresses (6.9 MPa) in the vessel are far below the acceptable value for global zones (30 MPa).The maximum displacement of 0.07mm is negligible.

Assuming the -1 bar (vacuum) analysis, the calculation shows that the expected max stress of 8.7 MPa is well below the acceptable values of 40 MPa for Peak regions. Also stresses in all weld regions are well below the CODAP limit of 18.7 MPa. Buckling analysis shows a buckling factor of 13, which can be considered as very safe. The maximum displacement of 0.04mm is negligible.

Hand calculations of the suspension shows that the maximum expected stress of 74 MPa (in the M10 thread connection) is well below the yield strength of 193 MPa. Also the shear stress of 50.7 MPa in the AISI 304 M12 bold connection is well below the shear strength of 117 MPa.

The global value for the strain energy error norm in the vessel of 3.8 % is well below the 7% which is recommended by the IDEAS™ software.

6 SUMMARY

Presented is the safety analysis of the vacuum vessel which will be used at the Virgo institute in Italy. The system must comply with the Pressure Equipment Directive (PED) 97/23/CE. The French construction code for pressure apparatus (CODAP) is used to verify the stresses.

The vessel will be made of aluminium AW1050A .The vessel has three design conditions.
An internal pressure of -1 bar (vacuum at the outside of the vessel) at 150 ^{o}C (bake out of the system without nitrogen), an internal pressure of 1.5 bar (nitrogen; in case of a failure of the inner cold part) at -196°C and a leak test condition at a pressure of -1bar (vacuum) at 20°C.

1. Pressure 1 bar | temperature 150°C
2. Pressure 1.5 bar | temperature -196°C
3. Pressure -1 bar | temperature 20°C

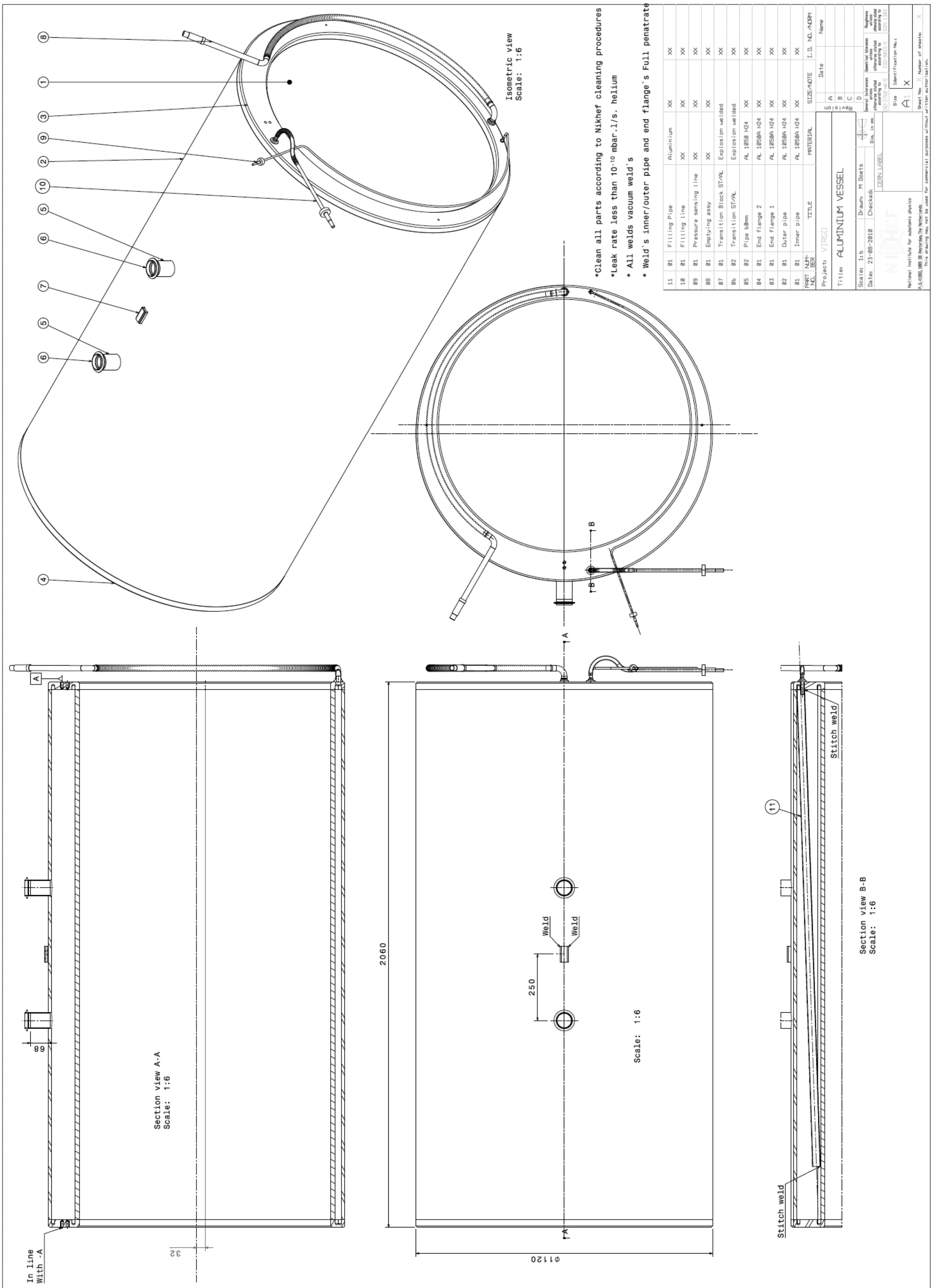
To prevent failure of the system, the system has to equip with a burst disc which opens at max 1.5 bar pressure difference.

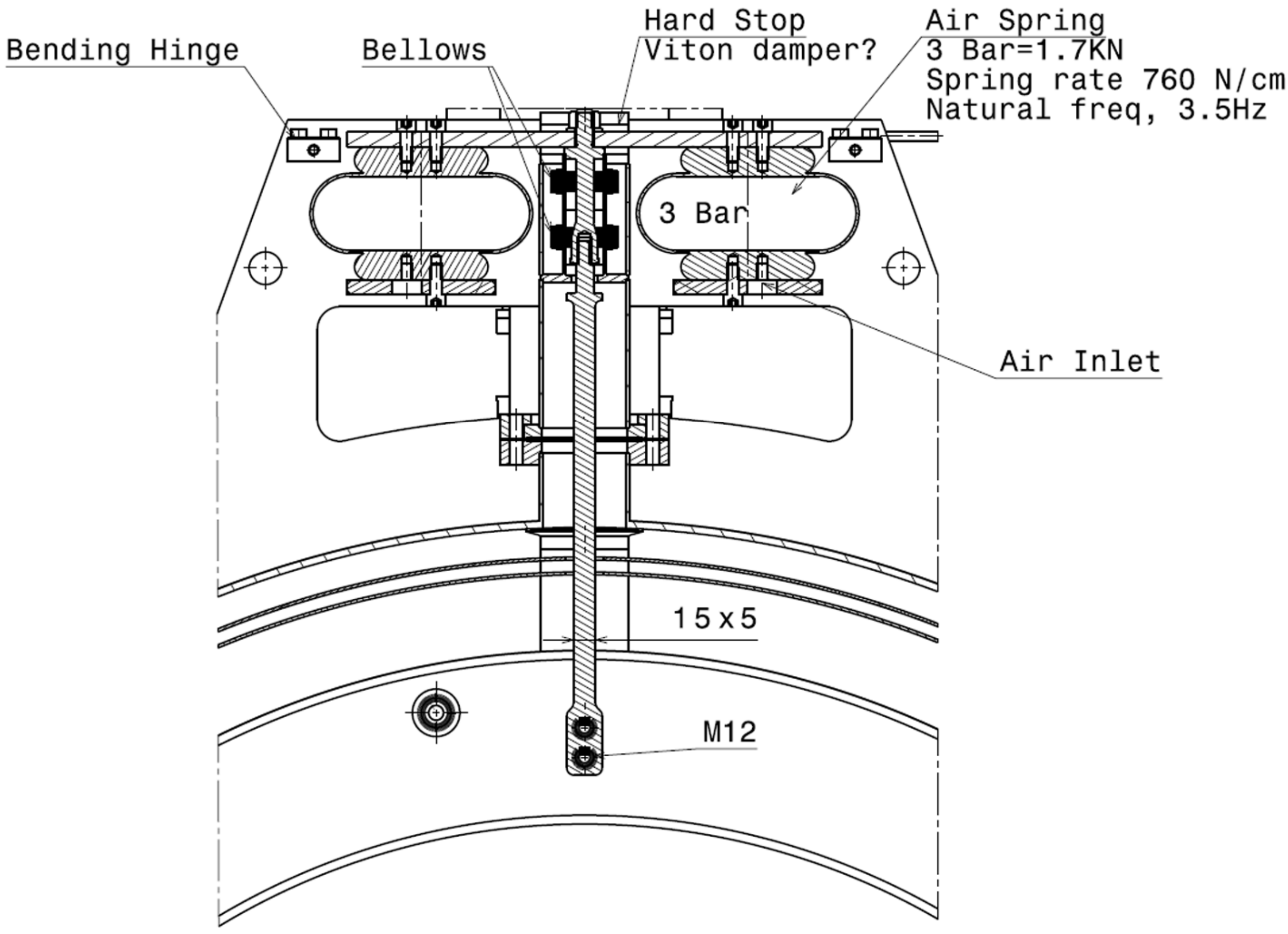
With a volume of 370 liter and a design pressure PS of 1.5 bar, the vacuum vessel is classified in PED category II.

Analysis shows that the vessel is in compliance with the requirements put forth by the CODAP. Also the stability requirements (buckling) lay within the requirements of the CODAP.

7 APPENDICES

7.1 Main technical drawings





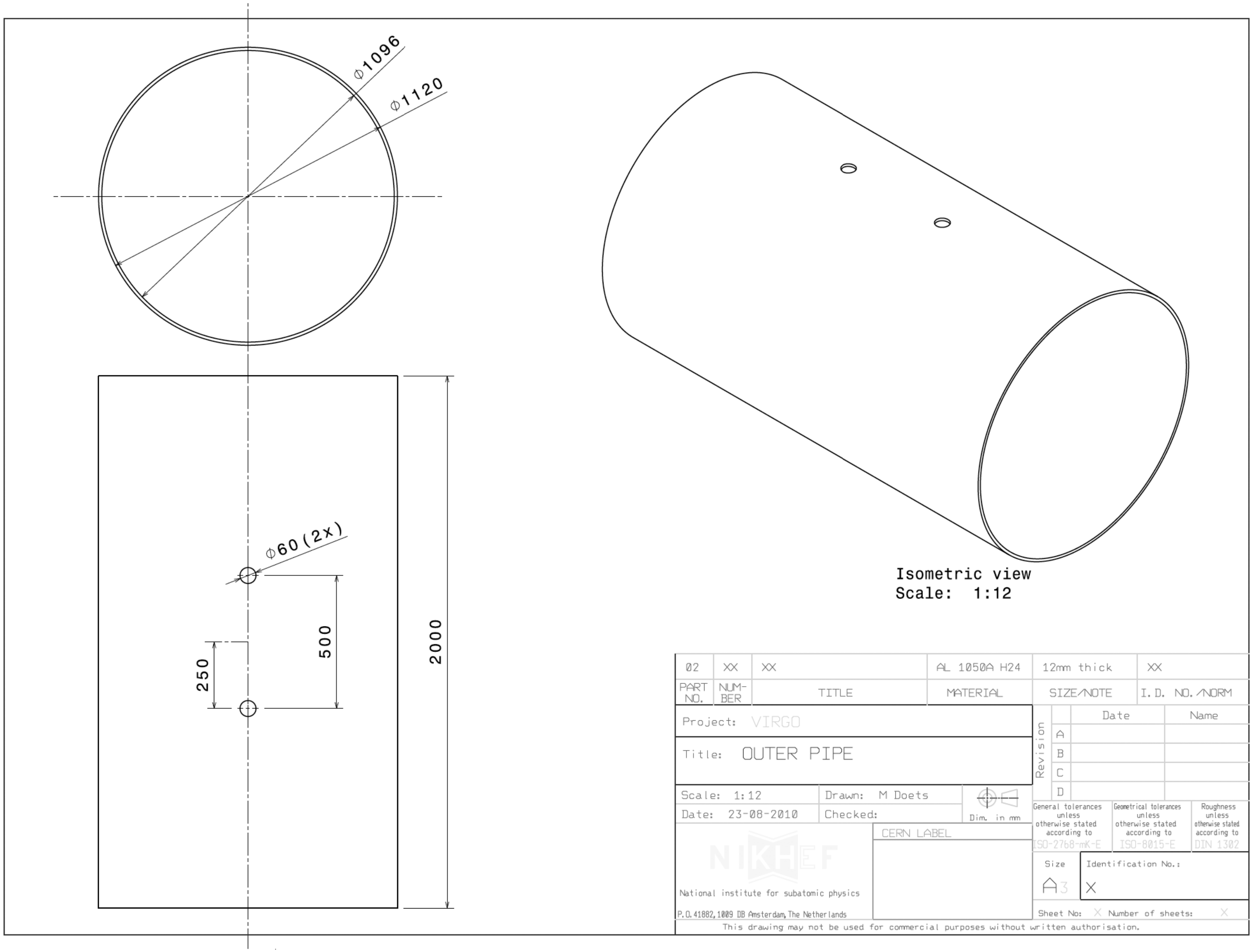
Load +/- 382kg per side

Aluminium vessel 525 kg

+/- LN2 300L=240 kg

75mm^2 x210N/mm^2 (yield)=15750 N

Heat leak 0.5 W



ϕ1096
ϕ1120
ϕ60(2x)
500
250
2000
Isometric view
Scale: 1:12
02
XX
XX
AL 1050A H24
12mm thick
XX
PART NO.
NUM-BER
TITLE
MATERIAL
SIZE/NOTE
I. D. NO./NORM
Project: VIRGO
Title: OUTER PIPE
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Drawn: M Doets
Date: 23-08-2010
Checked:
Dim. in mm
CERN LABEL
Revision
Date
Name
A
B
C
D
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Geometrical tolerances unless otherwise stated according to ISO-8015-E
Roughness unless otherwise stated according to DIN 1302
Size
A3
Identification No.:
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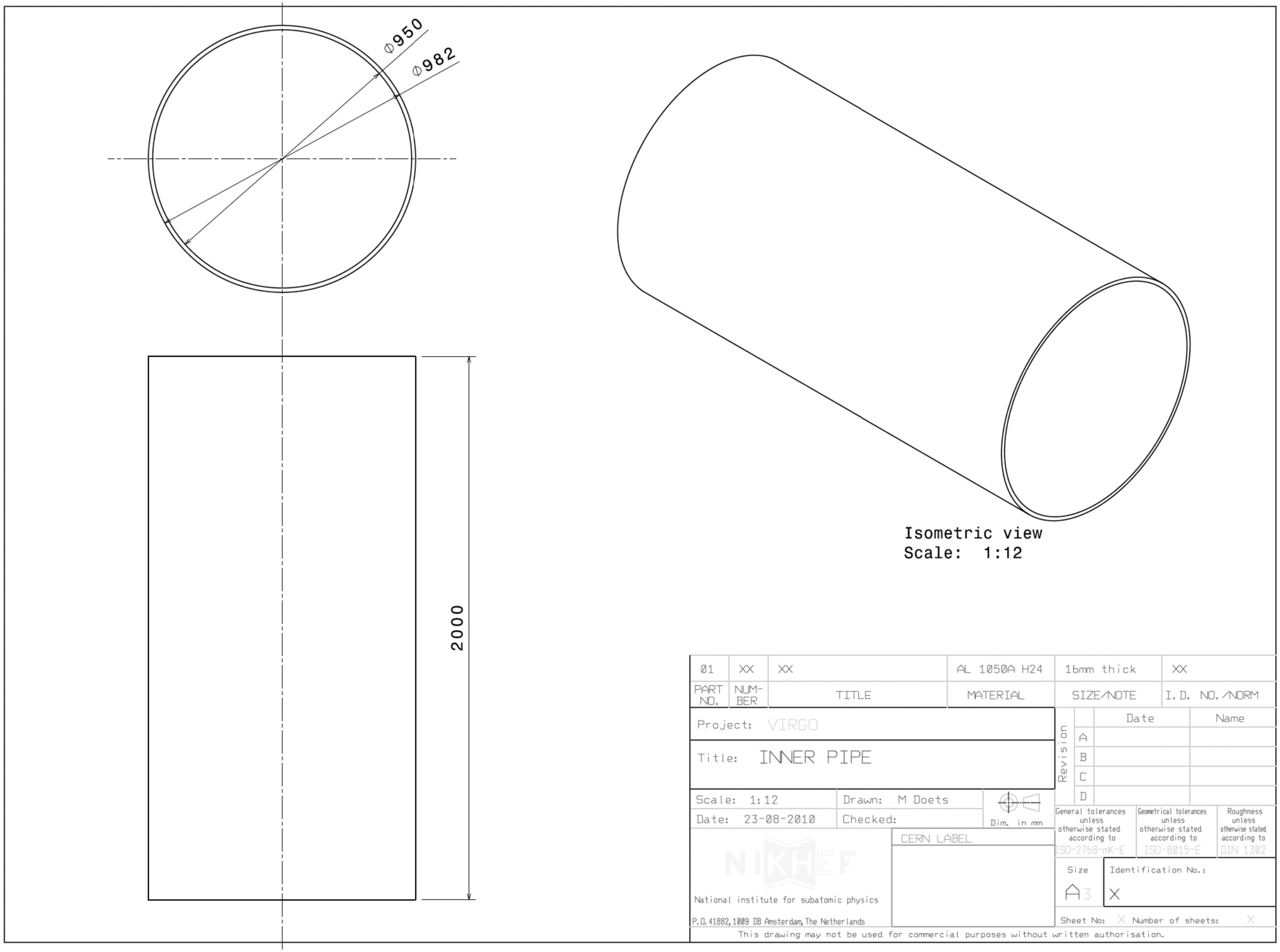
NIKHEF
National institute for subatomic physics
P.O. 41882, 1009 DB Amsterdam, The Netherlands
Sheet No: X Number of sheets: X
This drawing may not be used for commercial purposes without written authorisation.



ϕ950
ϕ982
2000
Isometric view
Scale: 1:12
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AL 1050A H24
16mm thick
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PART NO.
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TITLE
MATERIAL
SIZE/NOTE
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Revision
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P.O. 41882, 1009 DB Amsterdam, The Netherlands
Size A3
Identification No.:
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Sheet No: X Number of sheets: X
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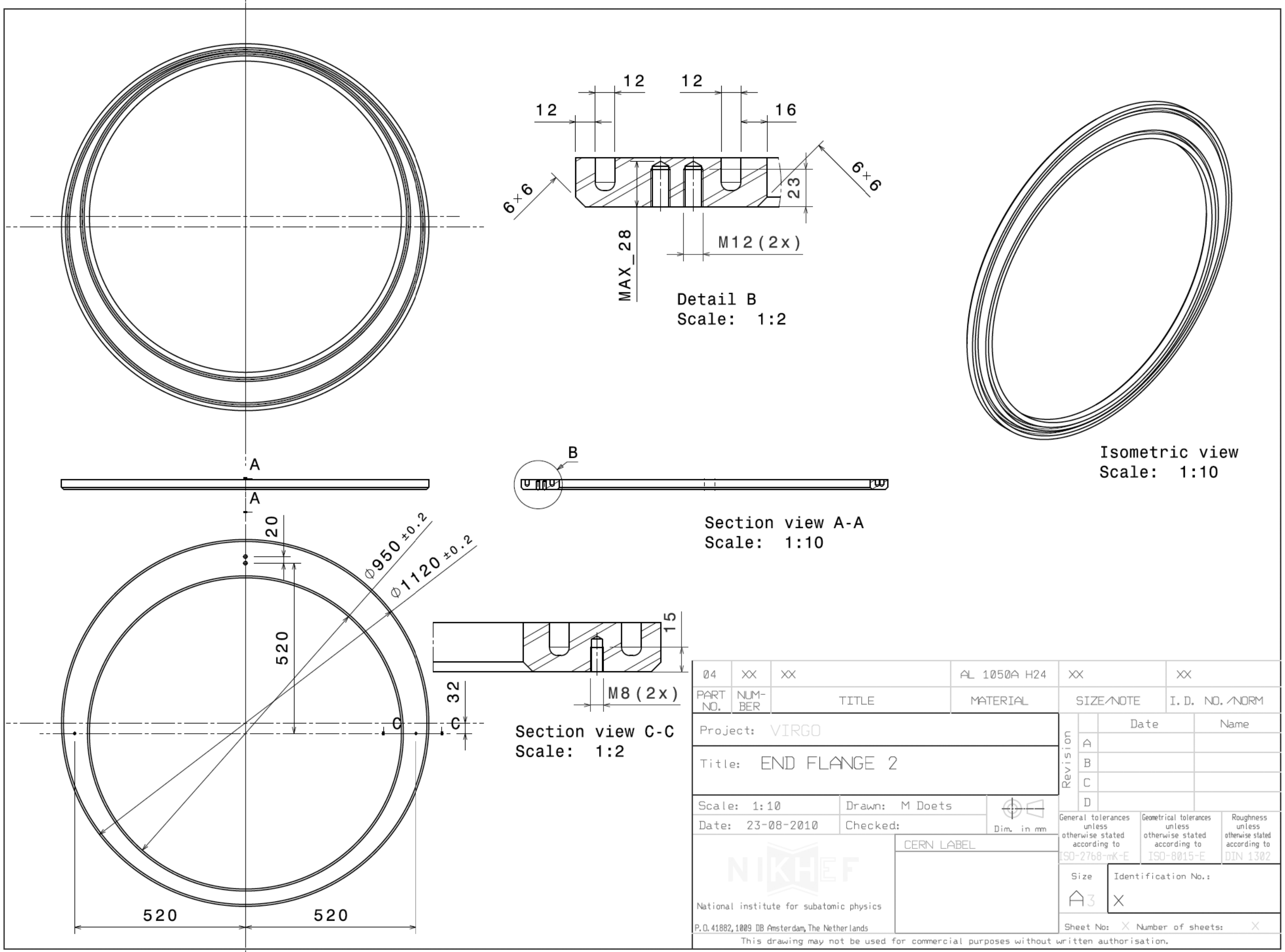
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12
16
6x6
6x6
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MAX_28
M12(2x)
Isometric view
Scale: 1:10
A
A
B
Section view A-A
Scale: 1:10
20
ø950 ±0.2
ø1120 ±0.2
520
32
C
C
15
M8(2x)
Section view C-C
Scale: 1:2
520
520
04
XX
XX
AL 1050A H24
XX
XX
PART NO.
NUM-BER
TITLE
MATERIAL
SIZE/NOTE
I.D. NO./NORM
Project: VIRGO
Title: END FLANGE 2
Revision
Date
Name
A
B
C
D
Scale: 1:10
Drawn: M Doets
Date: 23-08-2010
Checked:
Dim. in mm
General tolerances unless otherwise stated according to ISO-2768-mK-E
Geometrical tolerances unless otherwise stated according to ISO-8015-E
Roughness unless otherwise stated according to DIN 1302
CERN LABEL
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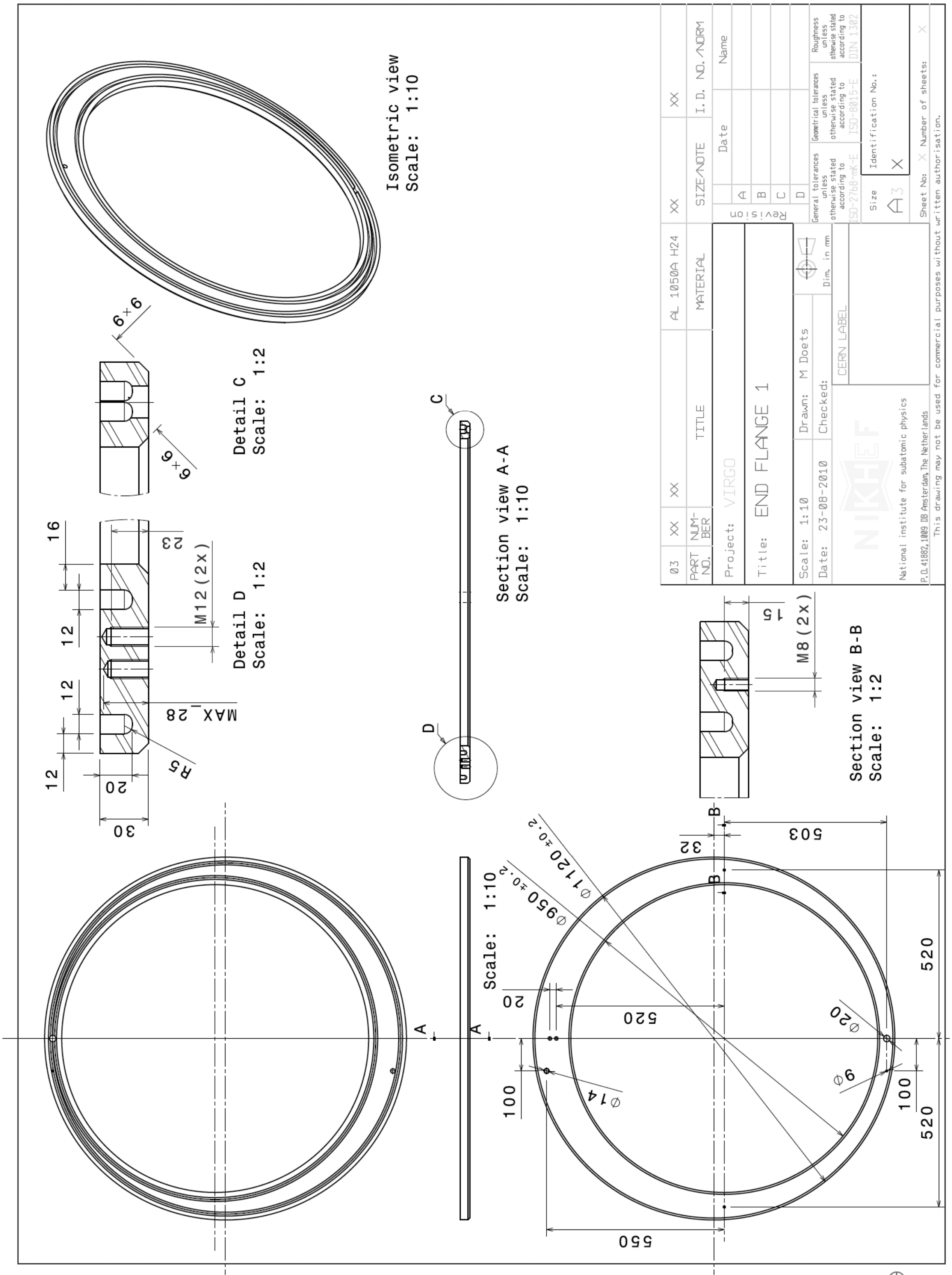
Isometric view
Scale: 1:10
Detail C
Scale: 1:2
6×6
6×6
Detail D
Scale: 1:2
16
23
M12(2x)
12
12
MAX_28
12
20
30
R5
Section view A-A
Scale: 1:10
C
D
Section view B-B
Scale: 1:2
15
M8(2x)
Scale: 1:10
A
A
B
B
503
32
Ø1120+0.2
Ø950+0.2
20
520
100
550
Ø14
Ø6
Ø20
100
520
520
03
XX
XX
XX
AL 1050A H24
XX
XX
PART NO.
NUM-BER
TITLE
MATERIAL
SIZE/NOTE
I. D. NO./NORM
Project: VIRGO
Title: END FLANGE 1
Scale: 1:10
Date: 23-08-2010
Drawn: M Doets
Checked:
CERN LABEL
Dim. in mm
Revision
A
B
C
D
Date
Name
General tolerances unless otherwise stated according to ISO-2768-mK-E
Geometrical tolerances unless otherwise stated according to ISO-8015-E
Roughness unless otherwise stated according to DIN 1302
Size A3
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Sheet No: X Number of sheets: X
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7.2 Contents of the PED modules

Module	Description
A	Manufacturers attend to internal manufacturing control, themselves producing and storing the documentation. The authorized body not involved.
A1	Manufacturers attend to internal manufacturing control, themselves producing and storing the documentation. The authorized body monitors the final verification through unannounced visits.
B	Manufacturers draw up the technical documentation and provide samples. The authorized body examines the technical documentation and undertakes the necessary testing of the samples and issues an EEC type testing certificate.
B1	The manufacturer draws up the technical documentation. The authorized body examines the technical documentation and issues an EEC construction testing certificate.
C1	Manufacturers ensure that production conforms to the specifications of the type approval. The authorized body monitors the final verification through unannounced visits.
D	Manufacturers use a documented quality assurance system that covers production, final inspection and testing. The authorized body audits, approves and monitors the quality assurance system.
D1	As D but manufacturers must also draw up and file technical documentation for the equipment.
E	Manufacturers use a documented quality assurance system that covers final inspection and testing. The authorized body audits, approves and monitors the quality assurance system.
E1	As E but manufacturers must also draw up and file technical documentation for the equipment.
F	Manufacturers ensure that production conforms to the specifications of the type approval or the construction testing certificate. The authorized body inspects each product. The authorized body issues a certificate of conformity.
G	The manufacturer draws up and submits the technical documentation. The authorized body examines the technical documentation, manufacture and each individual product. The authorized body issues a certificate of conformity.
H	Manufacturers use a documented quality assurance system that covers construction, production, final inspection and testing.
H1	As H but manufacturers must also apply for construction approval from the same authorized body that monitors the quality assurance system.