SUMMARY

1. REVISION RECORD

DESCRIPTION	REVISION	DATE and AUTHOR
Creation for version V11-2	A	10/04/2012 – SA
Add comments related to ASME Section 8 Div I and II	B	26/04/2012 – FF
Update with simulation V11-3	C	04/05/2012 – SA
Updated with simulation 317111-JLAB-He-Vessel-19-02-14	D	21/02/2014 – SA-AP

This revision of the report is in accordance with the following drawing of the helium vessel:

317111-JLA-703-001-revI

2. ABSTRACT

The Dipole SHMS helium vessel mechanical stress is calculated by finite element analysis (FEA).
This reports concerns only the helium vessel: suspension links and chimneys for helium supply and return will be studied in another report. The calculation considers two worst case scenarios:

- The first one includes:
    - Cool down from room temperature (293K) to liquid helium temperature
    - The dead weight
    - The gravity
    - The orientation of the He vessel
    - The horizontal acceleration provided by the magnet moving girder
    - The maximum unbalanced magnetic forces when the coil is off centered related to the iron yoke
    - The helium maximum pressure during a quench.
    - Preload applied by suspension links
- The second one concerns only the test pressure after welding.

The helium vessel is Designed by Analysis (DBA) according to the ASME Boiler and Pressure Vessel Code (ASME BPVC) Section VIII Division 2 Part 5 (version 2010) and built according the ASME BPVC Section VIII Division 1. This report presents the FEA analysis made by Sigmaphi. The shells thicknesses are optimized wherever it is possible to reduce the weight and ease the welding.

The helium vessel mechanical design as proposed by this report complies with the ASME BPVC requirements for the two studied worst cases.

3. FEA Software

The FEA software used is ANSYS 15.04 Mechanical (ANSYS Professional NLS)

4. USER'S DESIGN SPECIFICATION

The user's specification is given below:

- Fluid: liquid and/or gaseous helium
- Operating temperature: -268°C (4K)
- Thermal stress : Cool down from 20°C to -268°C (4K)
- Design pressure: 6 atm inner, vacuum outer

- External forces:
  - Collared coil weight: 152 000 N (gravity = 9806.6mm/s²)
  - The dipole is inclined at 9.2°
  - Lateral acceleration: 152 000 N (1g)
  - Magnetic forces: Horizontal 69000 N, Vertical 77 000 N (coil off centered of 3 mm at 45° related to the yoke)
  - Preload in suspension links: 45 500N
- 2 worst cases are studied:
  - All the external forces + design pressure
  - Test pressure only (7*1.43 = 10 bars)

5. FEA MODEL GEOMETRY AND MESHING

The following figure represents the helium vessel with chimneys and pipes for the helium supply and return:

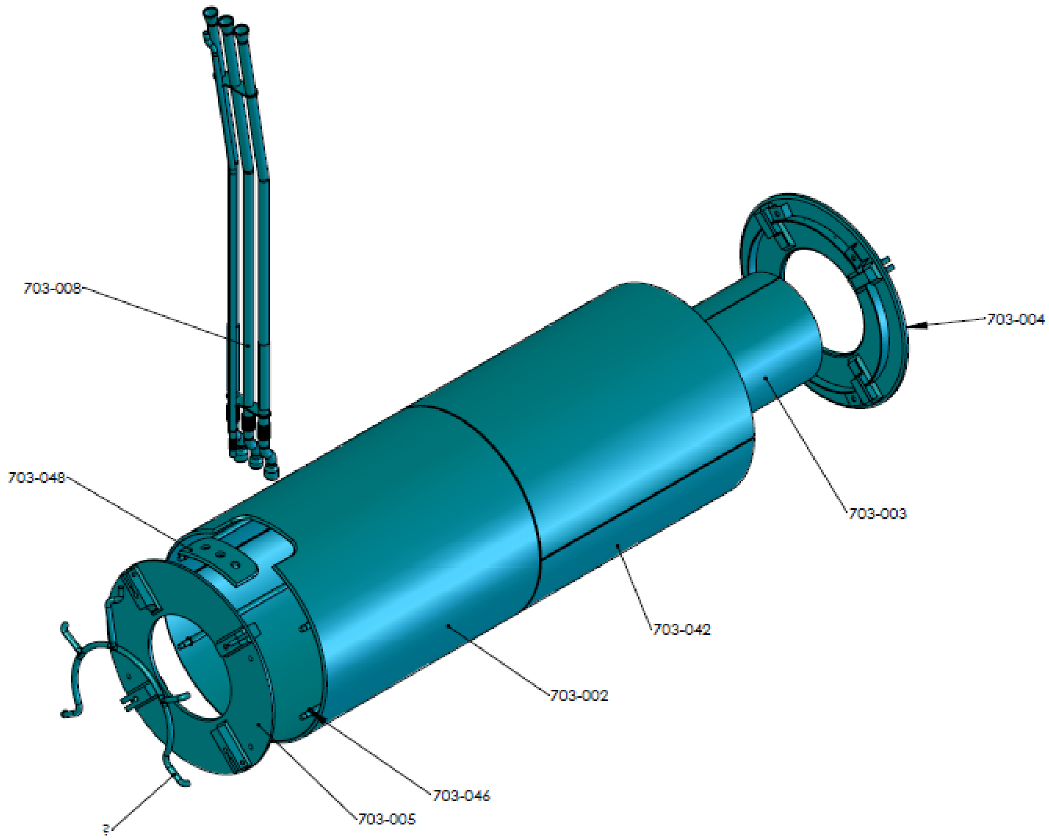


Figure 1: view of the helium vessel with pipes and chimney for the helium supply and return

Chimney, pipes and suspension links are not taken into account in this report. However suspension links are used in this FEA model because it implies stresses in the vessel. The following figure represents the parts which appear in the FEA model: Suspension links and Helium vessel without pipes and chimney.

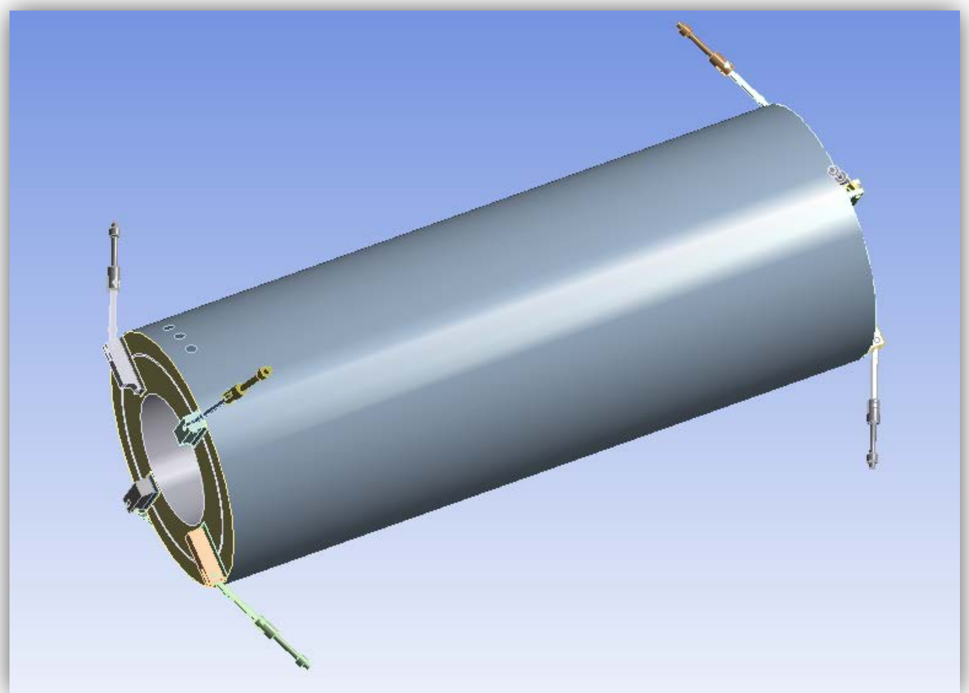


Figure 2: view of the helium vessel and suspension links

The following table summarizes materials, thickness and weight for each part of the helium vessel:

Part designation	Part number	Material	Thk (mm)	Tolerance	Minimal thickness	Weight (kg)
Outer tube 1/2	317111-JLA-703-002-rev H	UHA 23, SA 240 TP 304 L, UNS No.S30403, 1.4307	20	+/-0.5	19.5	1185
Inner tube	317111-JLA-703-003-rev F		12	+/-0.5	11.5	748
Flange side end	317111-JLA-703-004-rev I		30	+/-0.5	29.5	374
Flange side arrival	317111-JLA-703-005-rev I		30	+/-0.5	29.5	366
Outer tube 2/2	317111-JLA-703-042-rev B		20	+/-0.5	19.5	1203
Rustine	317111-JLA-703-048-rev A		20	+/-0.5	19.5	16

The following figure summarizes the main dimensions of the helium vessel:

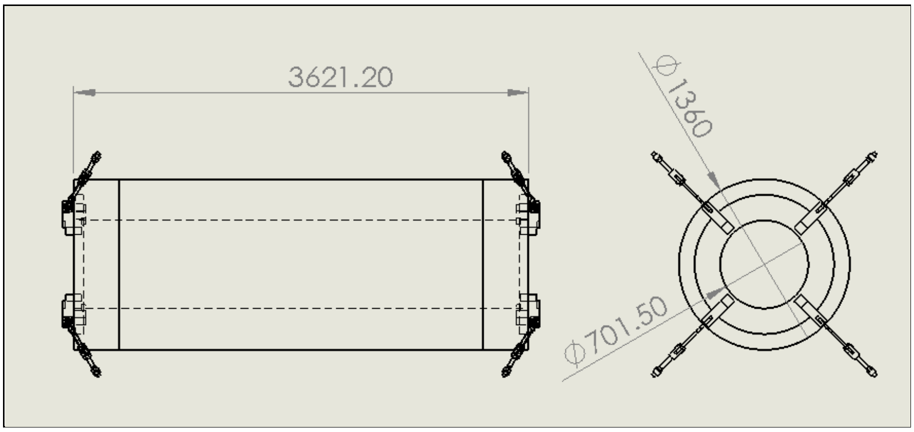


Figure 3: main dimensions of the helium vessel

The elements used for the meshing of the helium vessel are the following one:

- Shell elements for tubes and flanges of the helium vessel
- Volume elements for the other parts of the model (copes, reinforcements and suspension links)

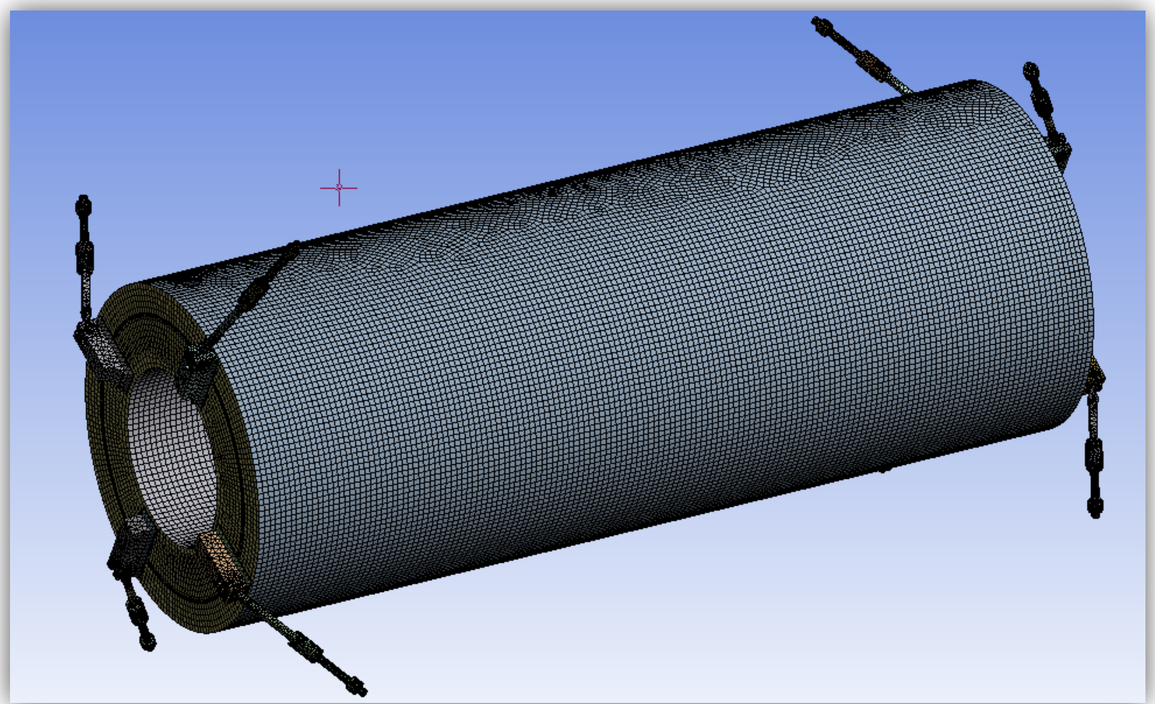


Figure 4: mesh of the helium vessel and suspension links

6. FEA MODEL CONTACT AND BOUNDARIES CONDITIONS

We apply a frictionless support on the spherical part of the suspension links and a frictional contact between suspension links and copes of the helium vessel (f=0.2).

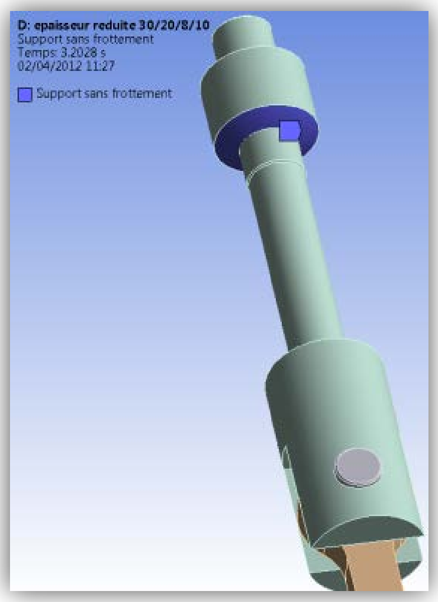


Figure 5: frictionless support on the blue area

Copes and flanges of the helium vessel are bonded together thanks to the weld. All the forces between copes and flanges are transmitted by the weld. All the parts of the helium vessel are considered bonded thanks to 100% penetration weld.

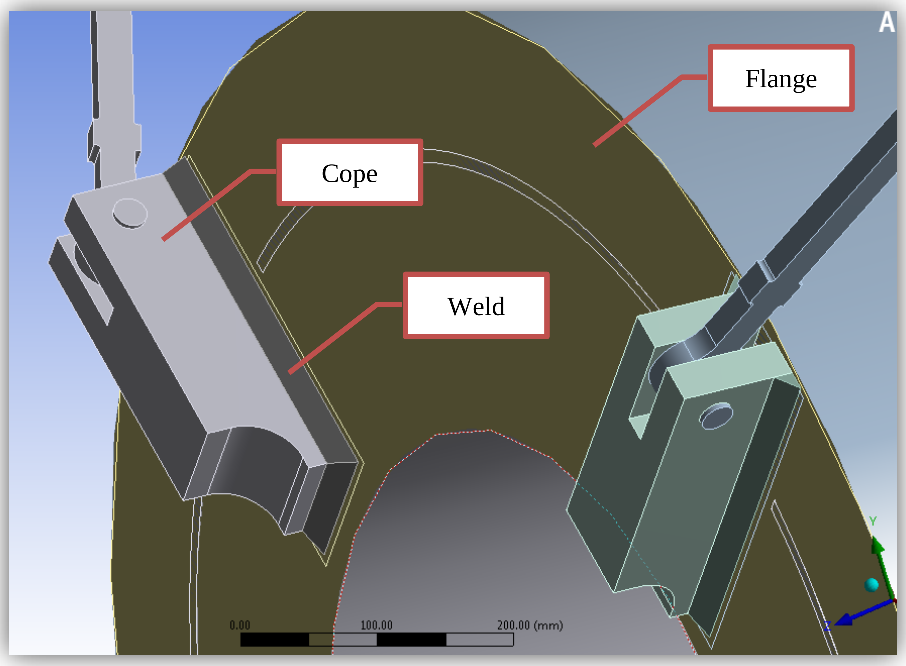


Figure 6: view of the weld between copes and flanges

7. FEA MODEL MATERIALS

Material properties depend on the temperature which varies between 300 K and 4 K: these mechanical properties are based on published data. The maximum allowable stress S for the helium vessel is based on ASME Section VIII UG23, UHA 23 and Section II Part D for the parts in stainless steel in contact with the pressure. Remember that suspension links are not considered in this report.

The following figure summarizes the materials used in this FEA model:

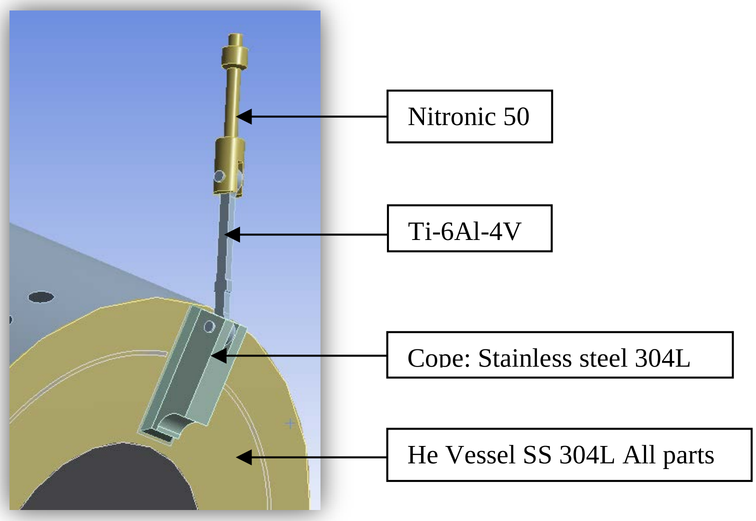


Figure 7: materials used in the FEA model

- *Helium Vessel 304L*

Material: 304L - UNS No. S30403 (SA 240 TP 304 L, 1.4307) - Nominal composition: 18Cr-8Ni According to ASME Section VIII Division I, UG23, High Alloy Steel UHA 23, Materials Section II Part D

Yield strength at 20°C = 172 MPa (25 ksi)
Max Allowable Stress S at 20°C for parts under pressure in normal operating: S=115 MPa (16.7 ksi)
Max allowable stress Sm for test under pressure at 10 bars: Sm=155 MPa (22 ksi)
Note: We disregard the yield stress enhancement at low temperature and consider only the S value given at 20°C for design contingency and material certification easiness.

The following tables and graphs give the coefficient of thermal expansion and the young's modulus as a function of the temperature for stainless steel 304L:

Stainless steel 304 L

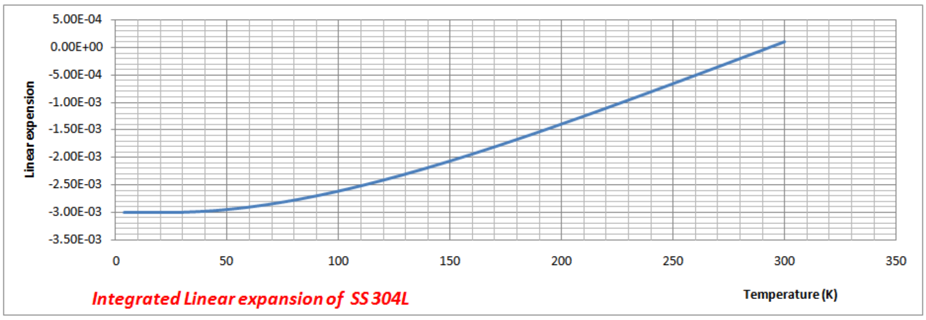
	DL/L*10^5	SS 304 units: GPa	SS 304 units: GPa
a	-2.96E+02	2.10E+02	2.10E+02
b	-3.98E-01	1.22E-01	1.53E-01
c	9.27E-03	-1.15E-02	-1.62E-03
d	-2.03E-05	3.61E-04	5.12E-06
e	1.71E-08	-3.02E-06	-6.15E-09
T	23	5-57	57-300

Density	7900 Kg/m3

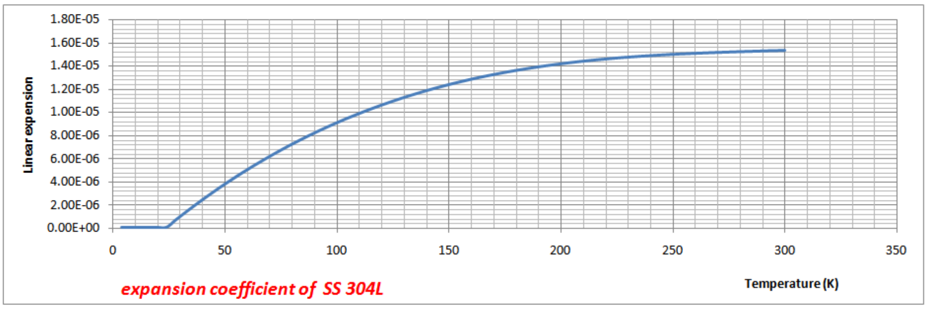
Equation of the form	
$y = a + bT + cT^2 + dT^3 + eT^4$	T≥Tlow(23°K)
y=f	T<Tlow(23°K)

Refrences for this material : http:// Cryogenics.nist.gov

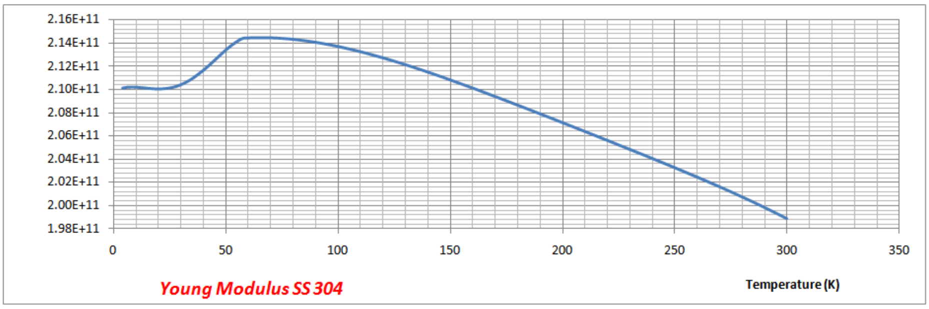
Equation of the form - Integrated coefficient	
$dy/dT = b + 2.cT + 3.dT^2 + 4.eT^3$	T≥Tlow(23°K)
dy/dT=0	T<Tlow(23°K)



Integrated Linear expansion of SS 304L



expansion coefficient of SS 304L



Young Modulus SS 304

- *Suspension links lower part: Titanium* Ti-6Al-4V
  Young modulus at 20°C: E= 96000 MPa

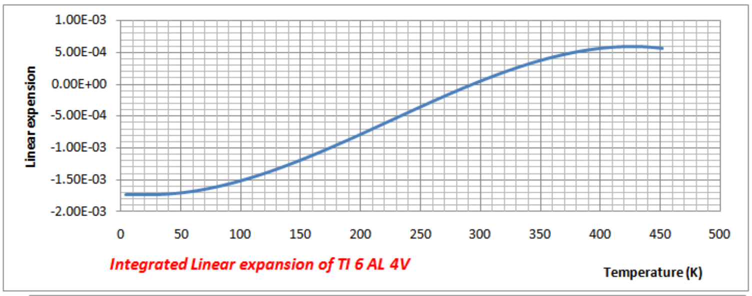
TITANE TI 6AL V

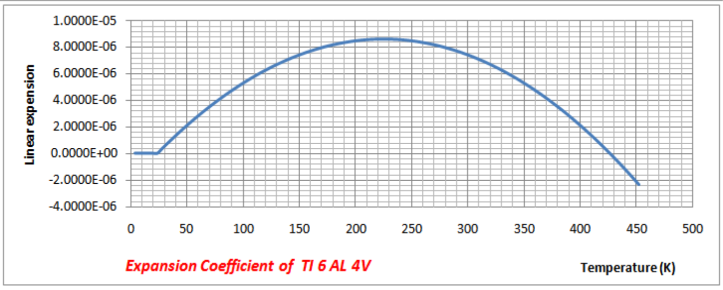
	DL/L*10^5
a	-1.7110E+02
b	-2.1400E-01
c	4.8000E-03
d	-7.1110E-06
e	0.0000E+00
T	24

Equation of the form - Integrated coefficient	
$y = a + bT + cT^2 + dT^3 + eT^4$	T≥Tlow(24°)
y=f	T<Tlow(24°C)

References for this material : http:// Cryogenics.nist.gov

Equation of the form - Integrated coefficient	
$dy/dT = b + 2.cT + 3.dT^2 + 4.eT^3$	T≥Tlow(24°)
dy/dT=0	T<Tlow(24°C)





Suspension links upper part : Nitronic 50
Young modulus at 20°C: E=199000 MPa

Coefficient of Thermal Expansion

Table 26

Coefficient of Thermal Expansion
Annealed Material*

Temperature Range F (C)	Coefficient of Thermal Expansion microinches/in/°F. (μm/m•K)	
70-200 (21-93)	9.0	(16.2)
70-400 (21-204)	9.2	(16.6)
70-600 (21-316)	9.6	(17.3)
70-800 (21-427)	9.9	(17.8)
70-1000 (21-538)	10.2	(18.4)
70-1200 (21-649)	10.5	(18.9)
70-1400 (21-760)	10.8	(19.4)
70-1600 (21-871)	11.1	(20.0)

* Average of duplicate tests.

Thermal Contraction

Temperature F (C)	Contraction Parts Per Million (ppm)	Mean Expansion Coefficient Between T and 75 F (24 C)	
		ppm/°F	ppm/°C
-41 (-41)	948	8.17	14.61
-51 (-46)	1016	8.06	14.53
-60 (-51)	1074	7.95	14.34
-80 (-62)	1237	7.98	14.40
-100 (-73)	1398	7.99	14.43
-125 (-87)	1560	7.80	14.07
-150 (-101)	1723	7.66	13.80
-178 (-117)	1951	7.71	13.84
-200 (-129)	2079	7.56	13.60
-225 (-143)	2231	7.44	13.37
-260 (-162)	2333	6.96	12.55
-320 (-196)	2542	6.44	11.56

Thermal Conductivity

Table 28

Temperature F (C)	Thermal Conductivity* BTU/hr/ft²/in/°F (W/m•K)	
70 (21)	—	—
300 (149)	108	(15.6)
600 (316)	124	(17.9)
900 (482)	141	(20.3)
1200 (649)	160	(23.0)
1500 (816)	175	(25.2)

* Average of duplicate tests.

**Nitonic-50-technical-data (ELECTRALLOY –UNS S 209 10)*

8. FEA MODEL LOADING

1. Gravity 9808.6mm/s²

2. Weight collar + coil :

We apply the weight of the coil and collars to the superior coil supports of the He Vessel (4 Times). The total force is 152000 N (15500 Kg), we apply 38000 N per contact on the –Y axis

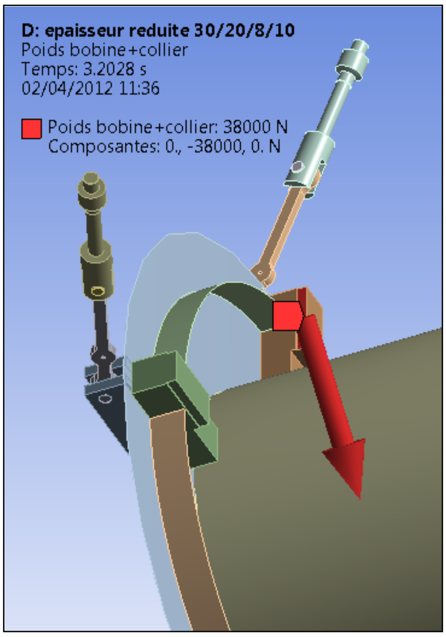


Figure 8: application of the weight on coil supports

3. Magnetic forces on two direction –X axis and Y axis:

We simulate a magnetic force (the imbalanced magnetic forces extracted from OPERA simulation-file 317111-Vers20 Rev D + displace yoke 3mm X and Y.OP3) to the He Vessel. This force is applied on 4 lateral coil supports for X forces and 4 superior coil supports for the Y axis. The total force is 69000N for X direction. So we apply 17250N per contact in this direction. The total force is 77000N for Y direction. So we apply 19250N per contact in this direction.

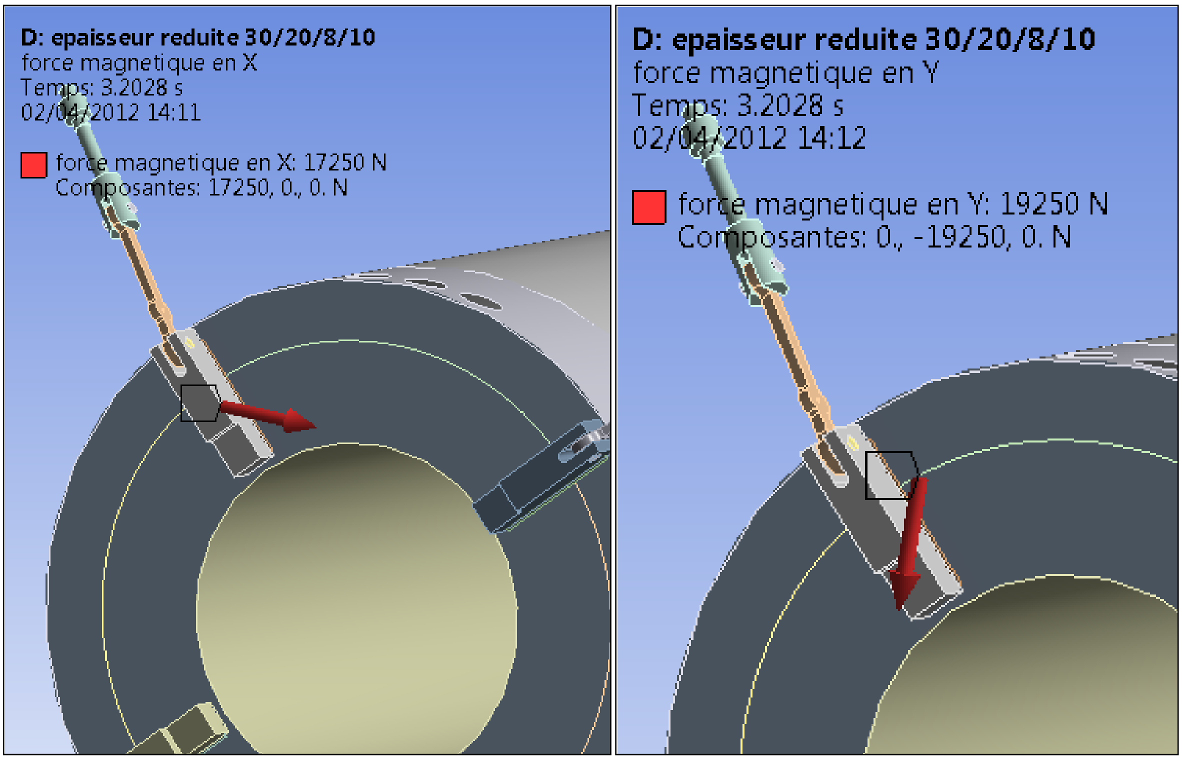


Figure 9: application of the magnetic forces in X & Y-direction

4. Acceleration 1G on the Y axis:

We simulate the acceleration (1G) of the He Vessel, this forces is applied on 4 lateral coil supports. The total force is 152000 N (coil + helium vessel weights). So we apply 38000 N per contact on the X axis.

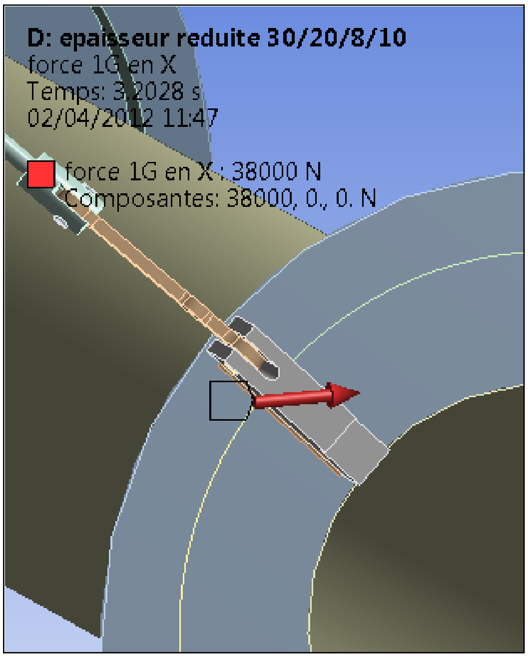


Figure 10: application of the lateral acceleration in X-direction

5. Thermal contraction:

We apply a thermal condition from 295.15K to 4K for the he Vessel and from 295.15K to 77K for Ti-6Al-4V parts. We consider that Nitronic 50 parts are at room temperature (295.15K).

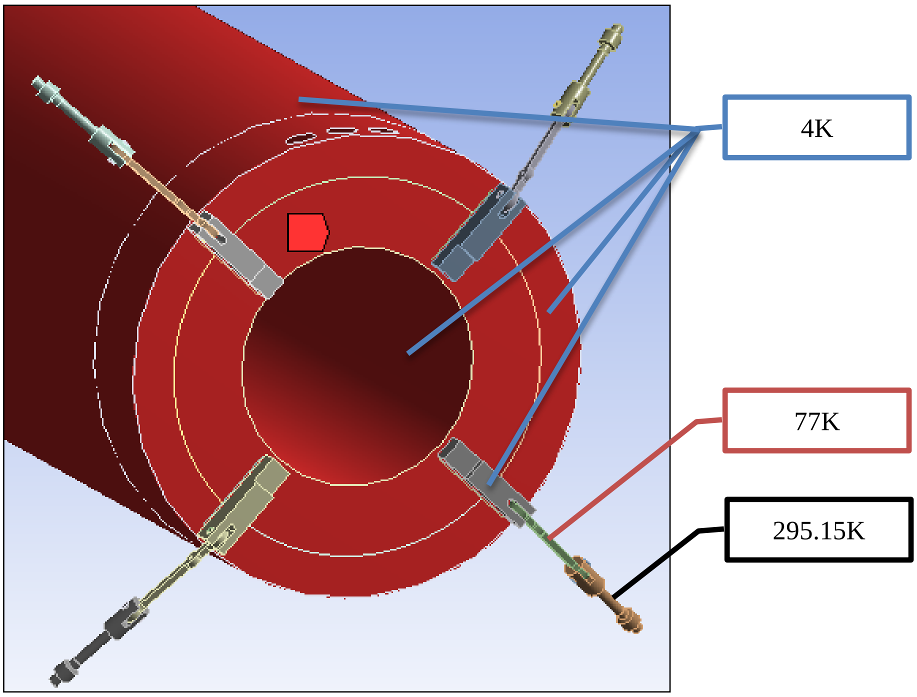


Figure 11: application of the thermal contraction

6. Pressure 0.6 MPa in the HeVessel (simulation of quench)

An internal pressure of 0.6 MPa (6 atm) is applied into the Helium Vessel. Helium is gaseous in this case. 0 atm is applied outside the helium vessel.

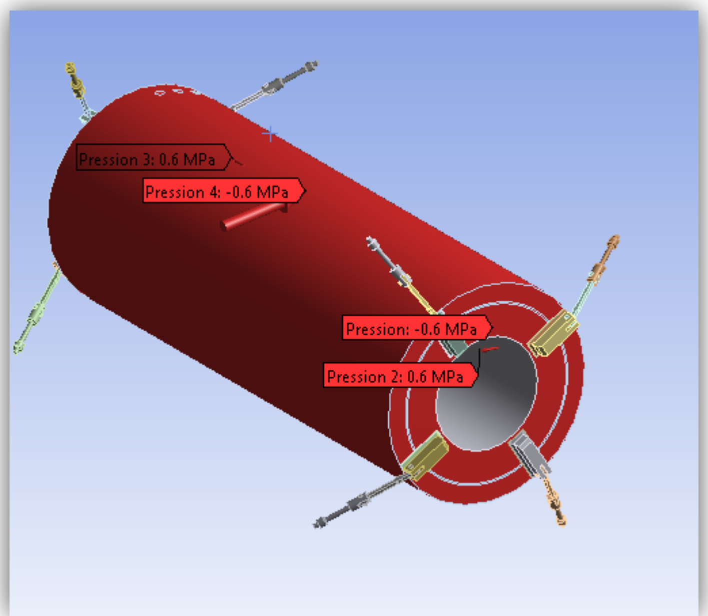


Figure 12: application of the internal pressure

7. Preload applied on suspension links

We apply a preload on suspension links in order to keep these all of these suspension links under tension even when all the external forces are applied. These parts are designed to support the mechanical stress induced by the worst case scenario. The preload applied on each suspension link is equal to 45500 N

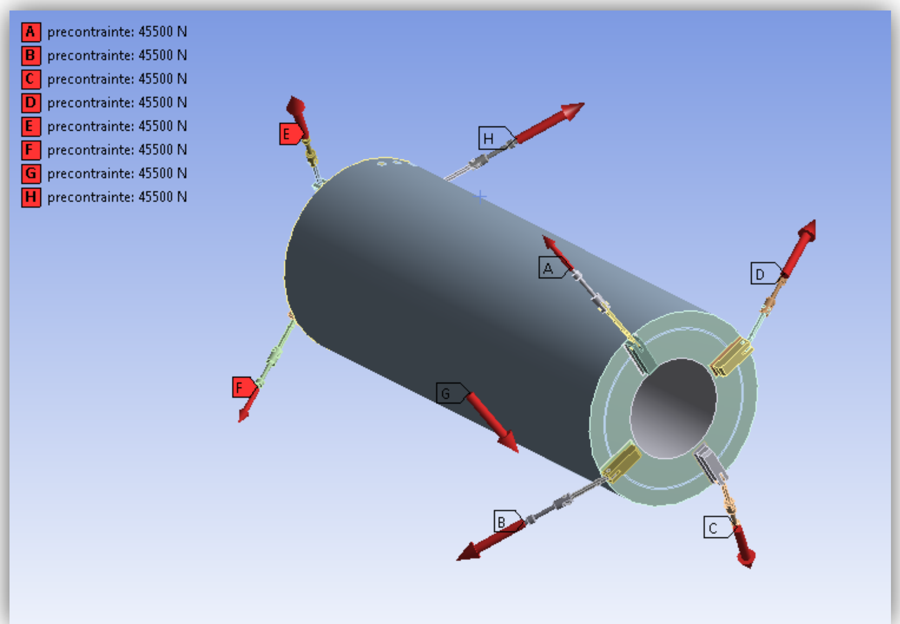


Figure 13: application of the preload on suspension links

9. FEA MODEL SOLVING

The model is solved by successive steps as defined in the following table. Each step corresponds to the application of one loading:

Propriétés	Etape 1	Etape 2	Etape 3	Etape 4	Etape 5	Etape 6
Contrôles d'incrément						
Temps final pour cet incrément	1.	2.	3.	4.	5.	6.
Incrément de temps automatique	Activé	Activé	Activé	Activé	Activé	Activé
Défini par	Sous-incréments	Sous-incréments	Sous-incréments	Sous-incréments	Sous-incréments	Sous-incréments
Reporter l'incrément de temps	N/A	Désactivé	Désactivé	Désactivé	Désactivé	Désactivé
Sous-incréments initiaux	10	10	10	10	10	10
Sous-incréments minimaux	10	10	10	10	10	10
Sous-incréments maximaux	100	1000	1000	100	100	100

10. WORST CASE N°1: OPERATING CONDITIONS

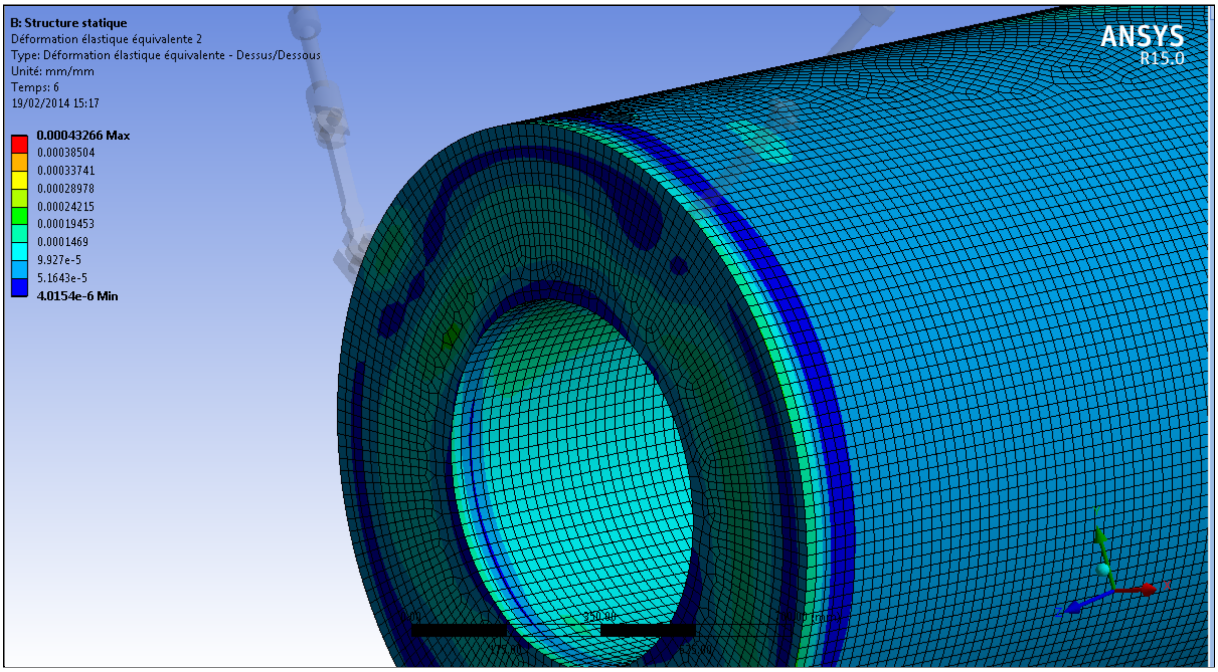
Considering the design contingency the peak stresses are below the maximum allowable stress at 20°C (S) for the parts in contact with the pressure.
We consider all stresses as primary and general stress which disregards the need to classify and linearize the stresses. The stress analysis is based on the Von Mises criteria and considers S as the maximum allowable stress for all locations.

The following table gives the peak stress in superior, mid and inferior skin for each part of the helium vessel. The Von Mises stresses are below the allowable stress S for all these parts except for a local stress in the weld outside the vessel: for this peak stress we consider an acceptance criterion at 100% of the yield strength = 172 MPa.

Part designation	Von Mises stress in superior skin	Von Mises stress in mid skin	Von Mises stress in inferior skin	S
Outer tube	62.8 MPa	32.5 MPa	90.8 MPa	115 MPa
Inner tube	66.8 MPa	36.5 MPa	54 MPa	115 MPa
Flange side end	51.6 MPa	31.5 MPa	50.9 MPa	115 MPa
Flange side arrival	39.6 MPa	37 MPa	42.2 MPa	115 MPa
Welds between copes and flanges	156 MPa			172 MPa

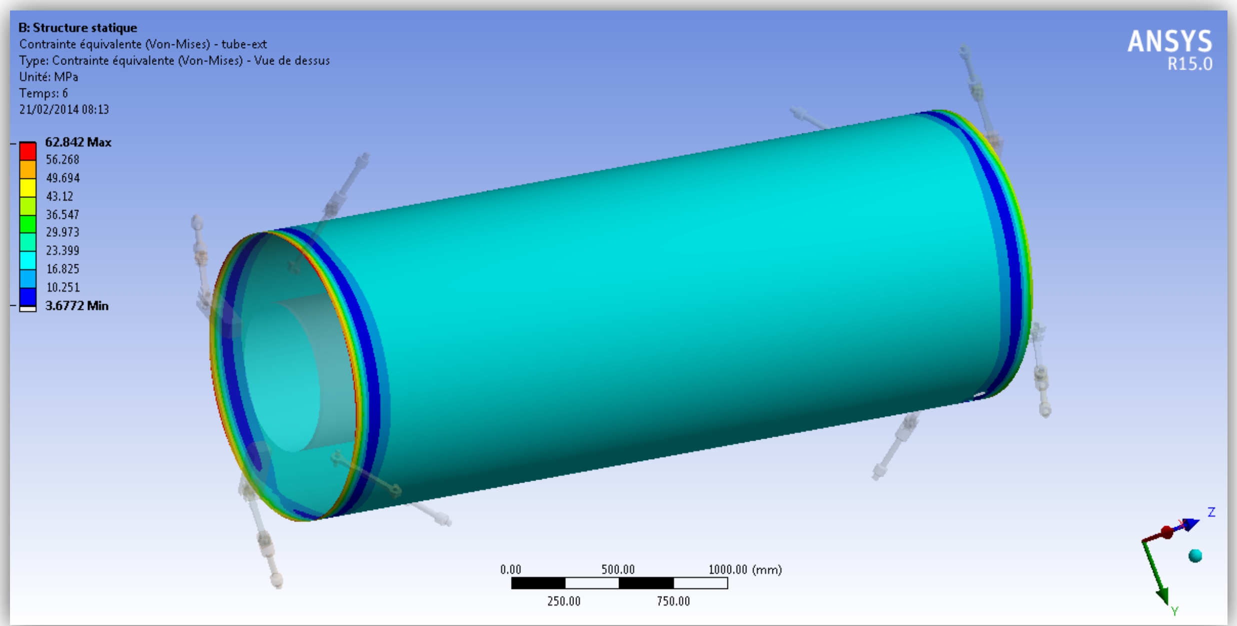
The following screenshots give more details on the area of maximum stresses:

- **<u>Deformation of the Helium vessel:</u>**

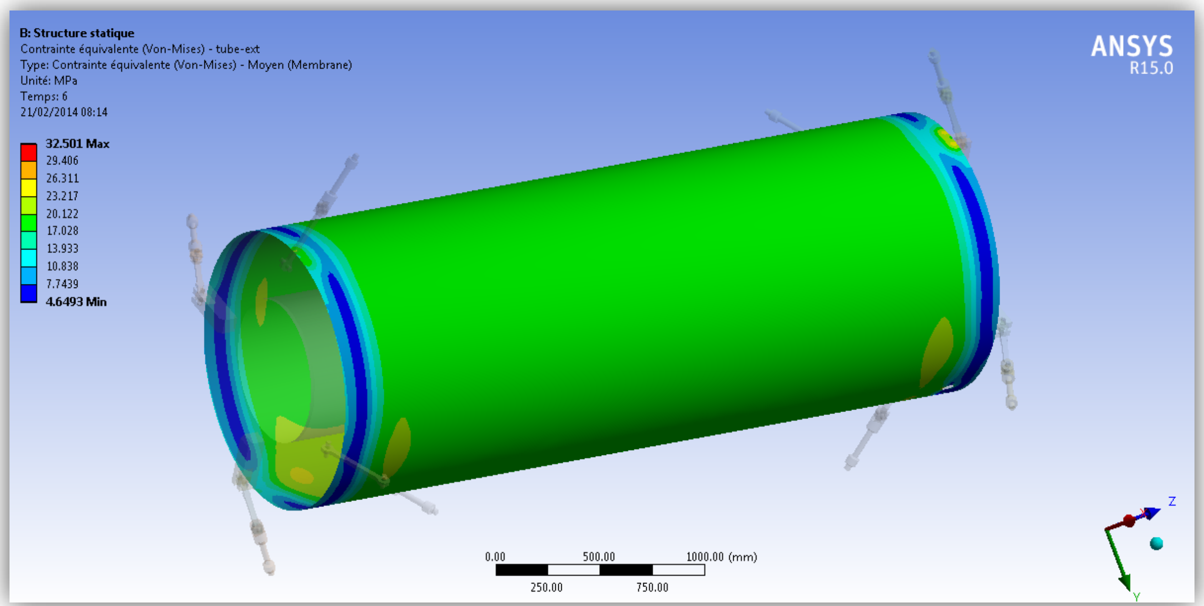


- **<u>Outer tube:</u>**

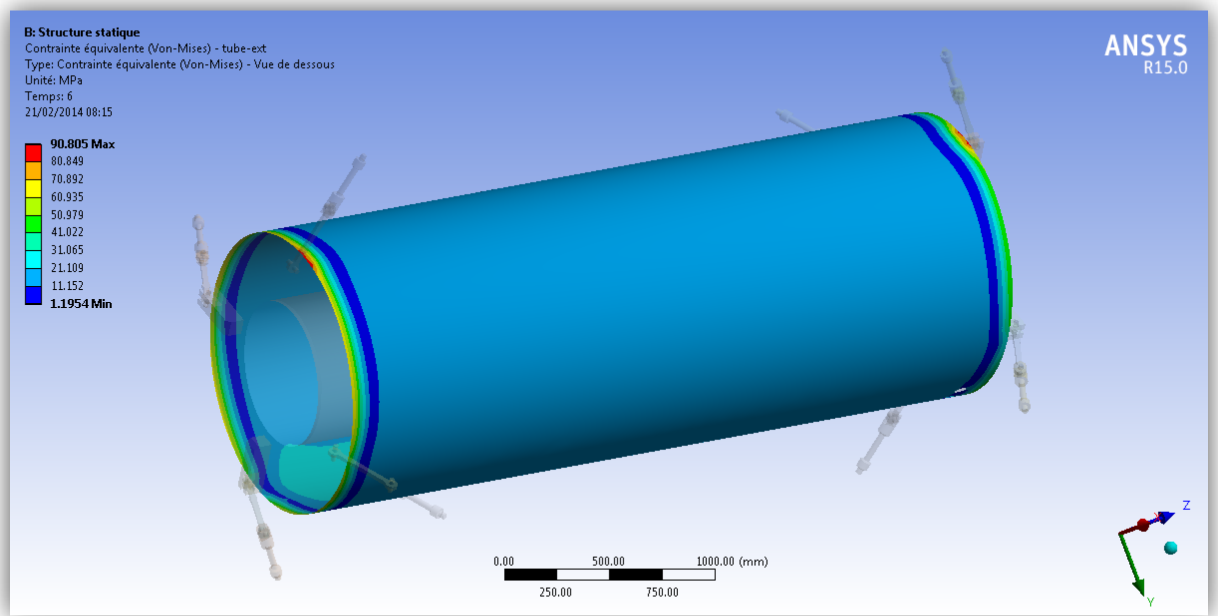
  - Superior skin:



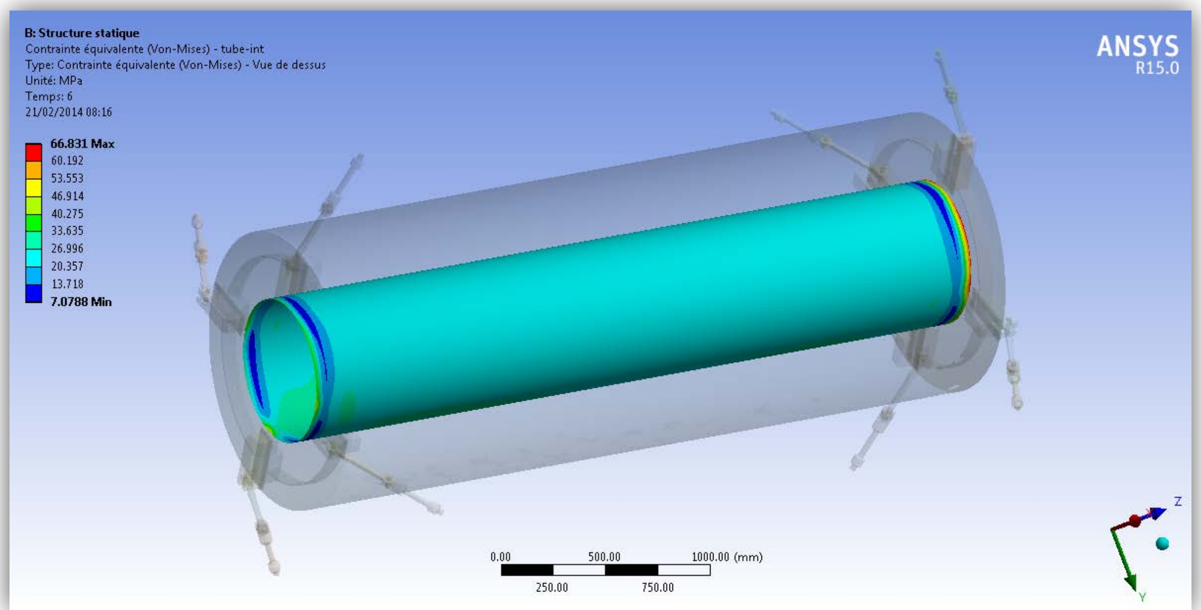
- Mid skin:



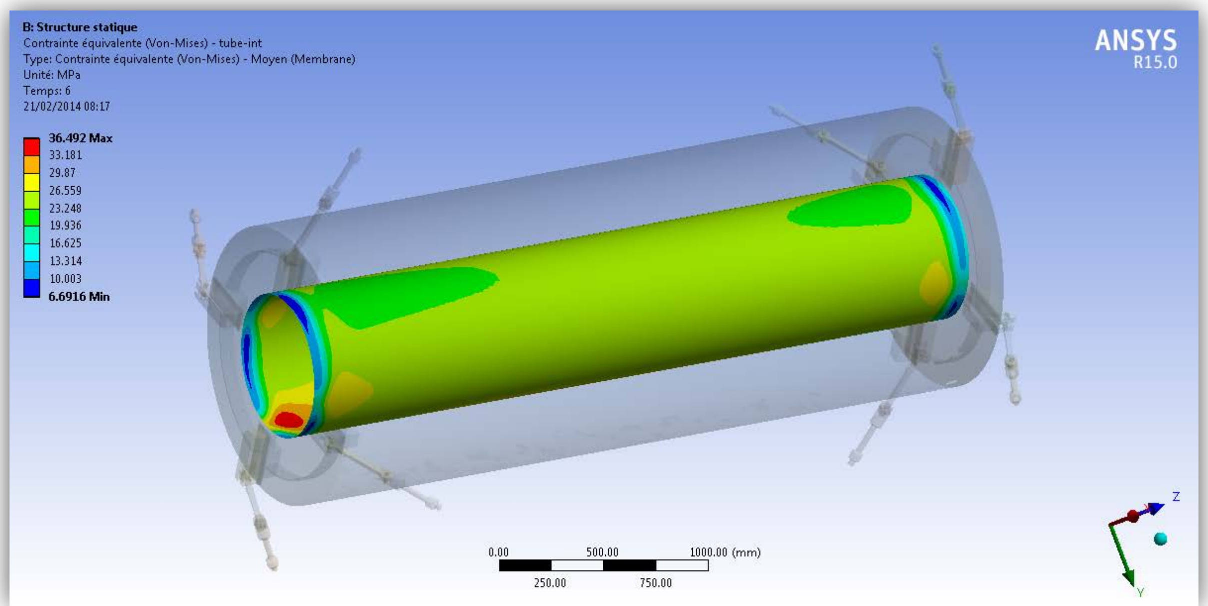
- Inferior skin:



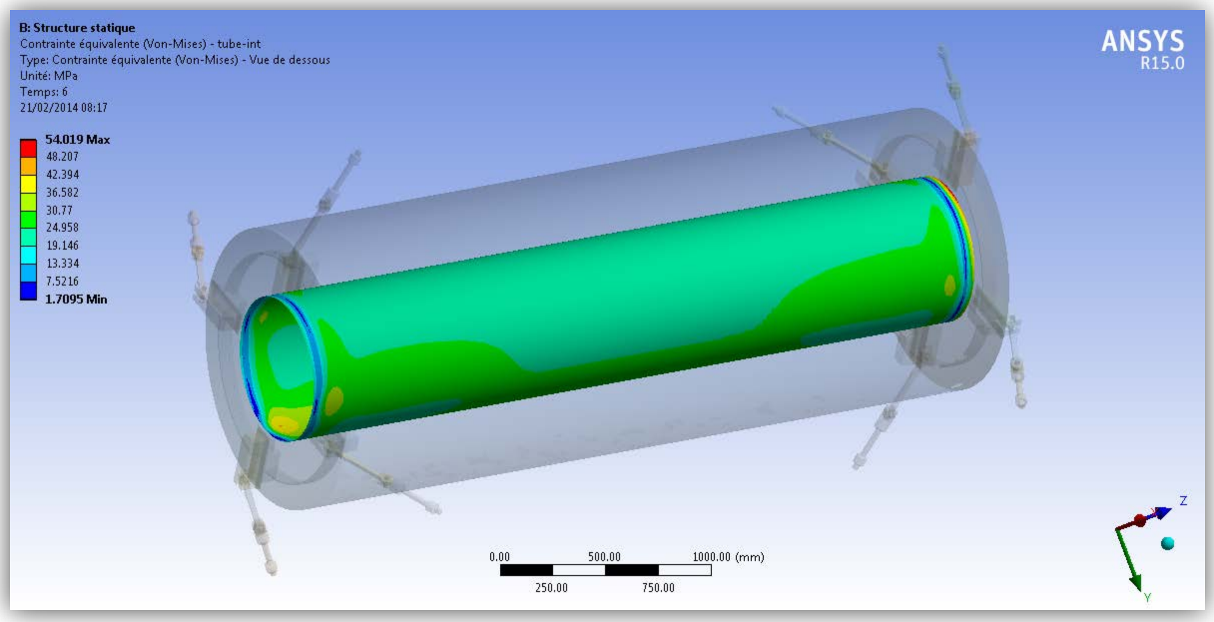
- **<u>Inner tube:</u>**
  - Superior skin:



  - Mid skin:

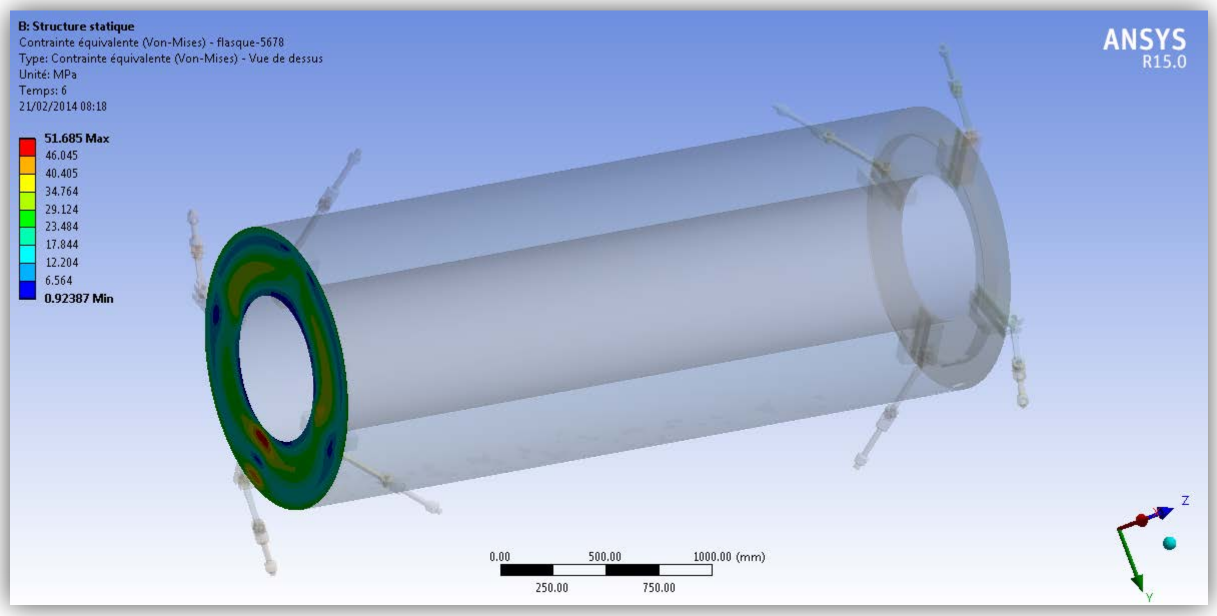


- Inferior skin:

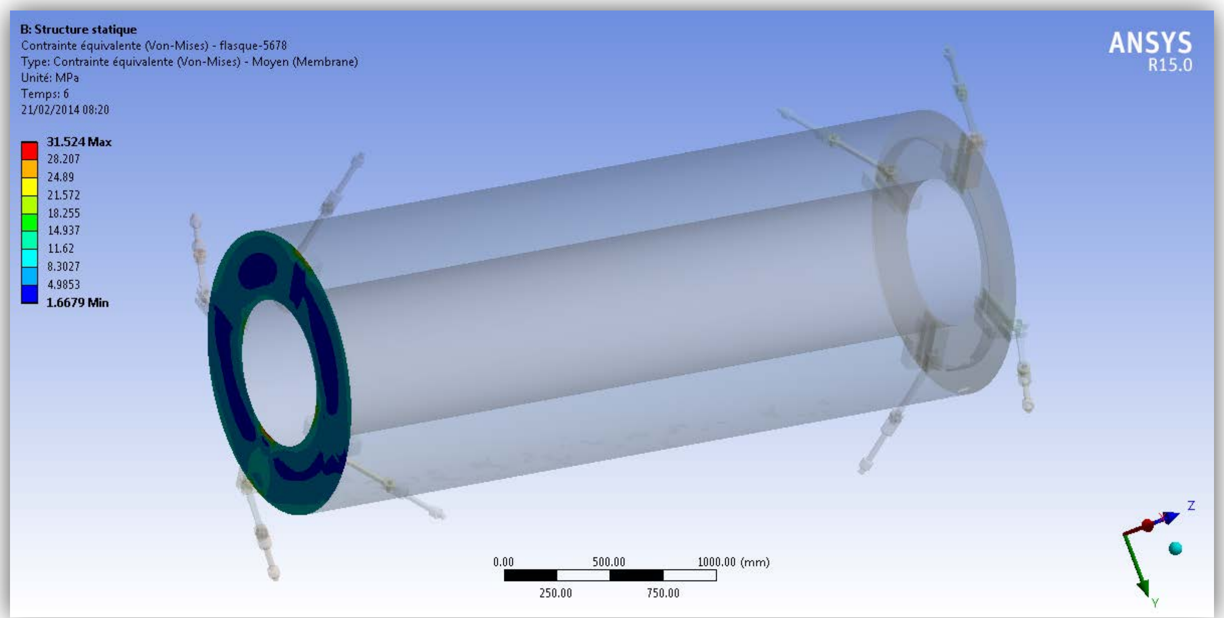


- **Flanges side end:**

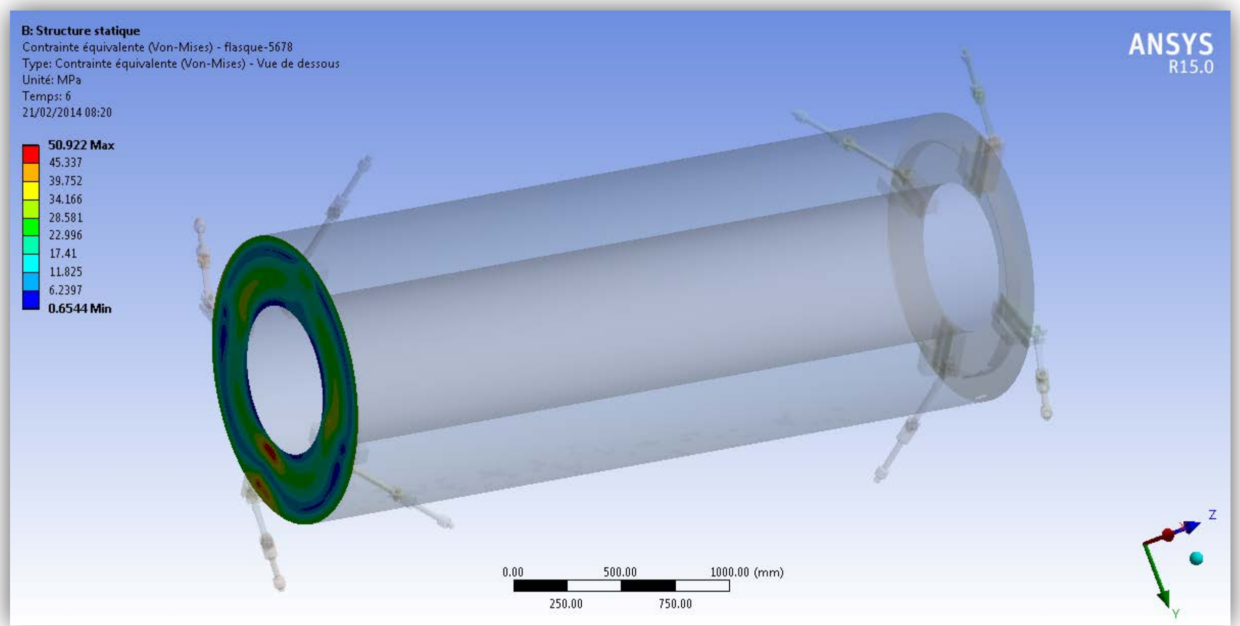
  - Superior skin:



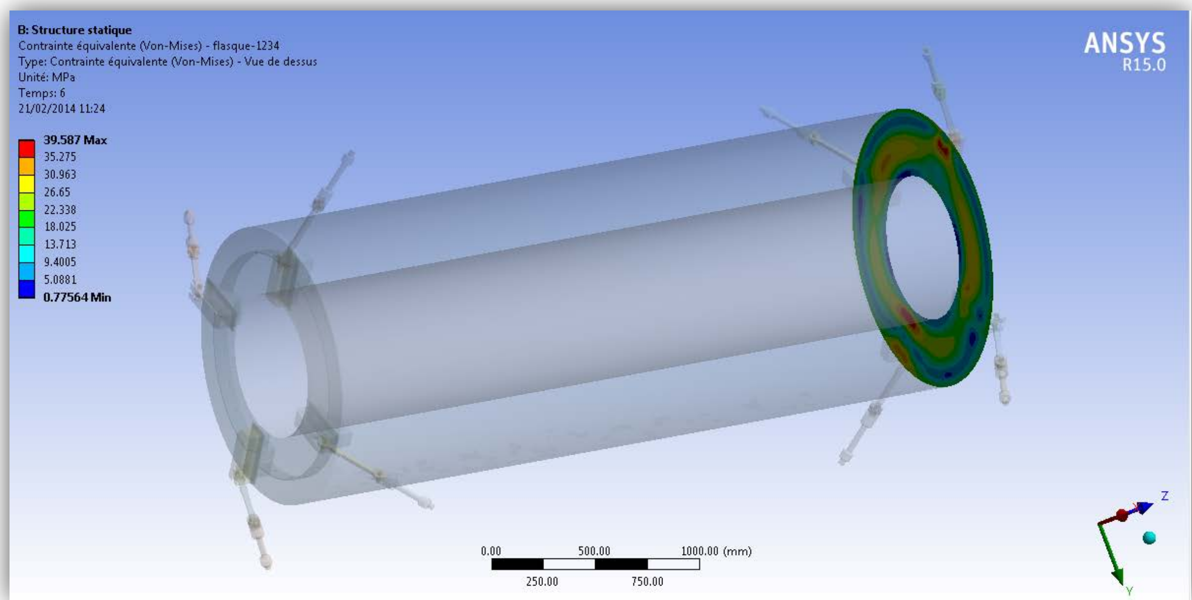
- Mid skin:



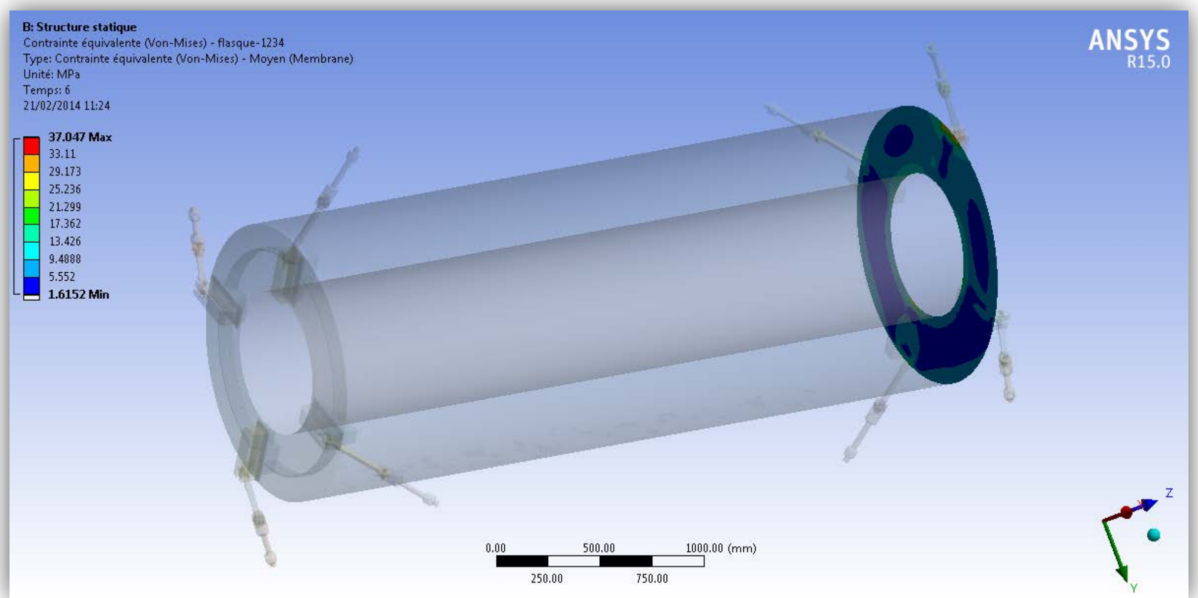
- Inferior skin:



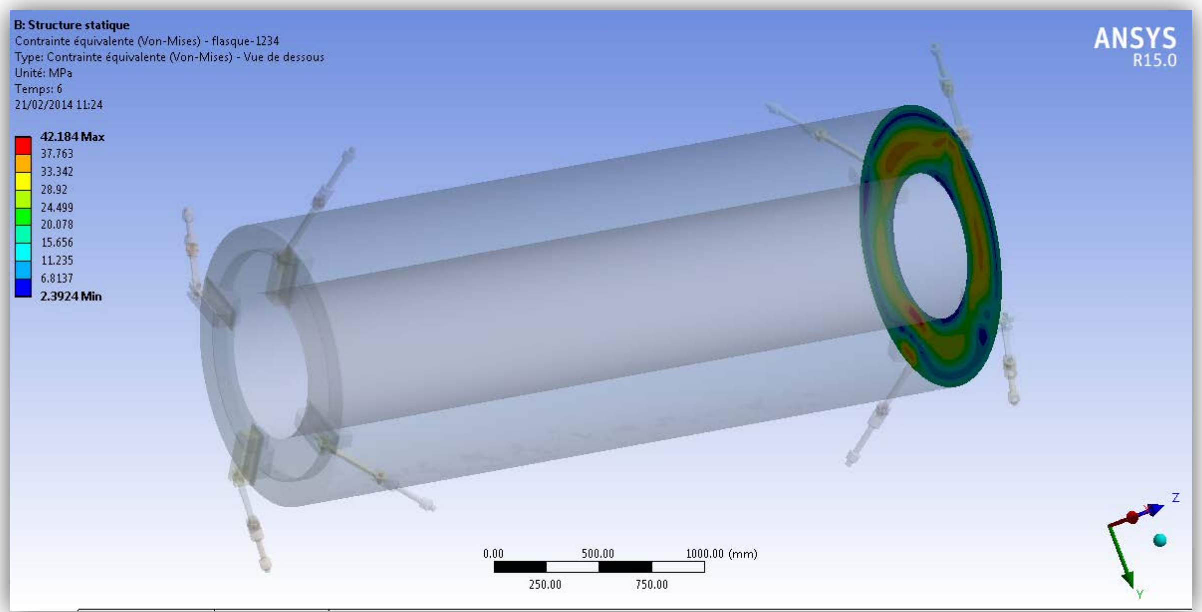
- **<u>Flanges side arrival:</u>**
  - Superior skin:



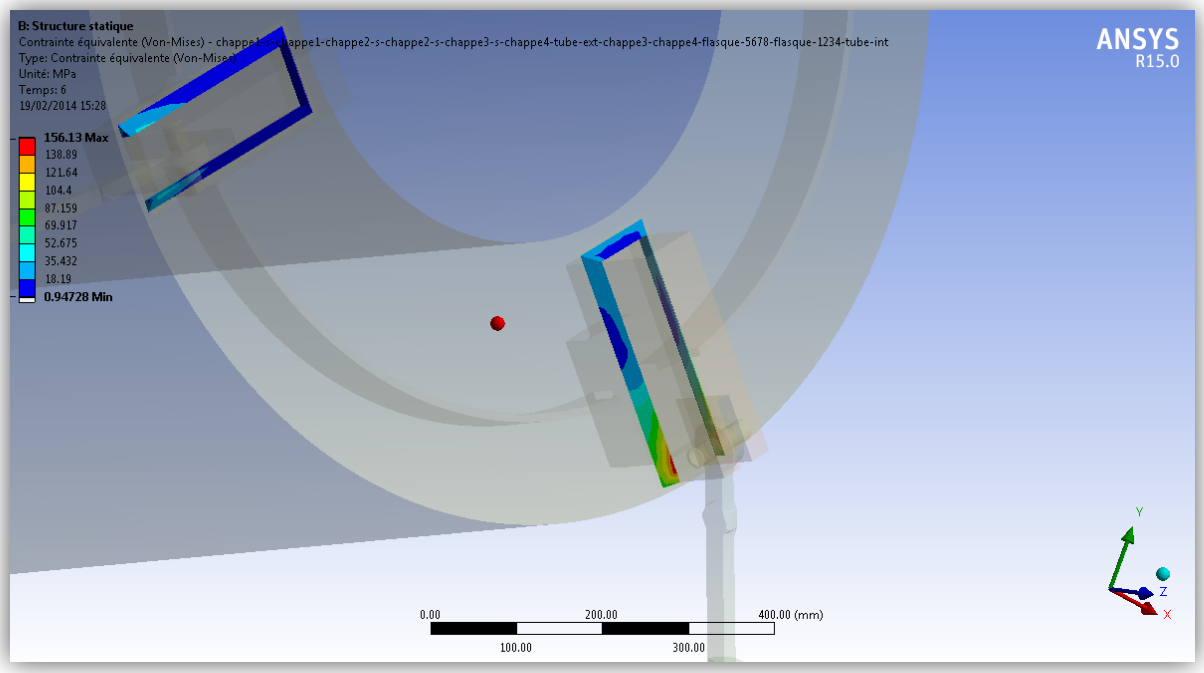
  - Mid skin:



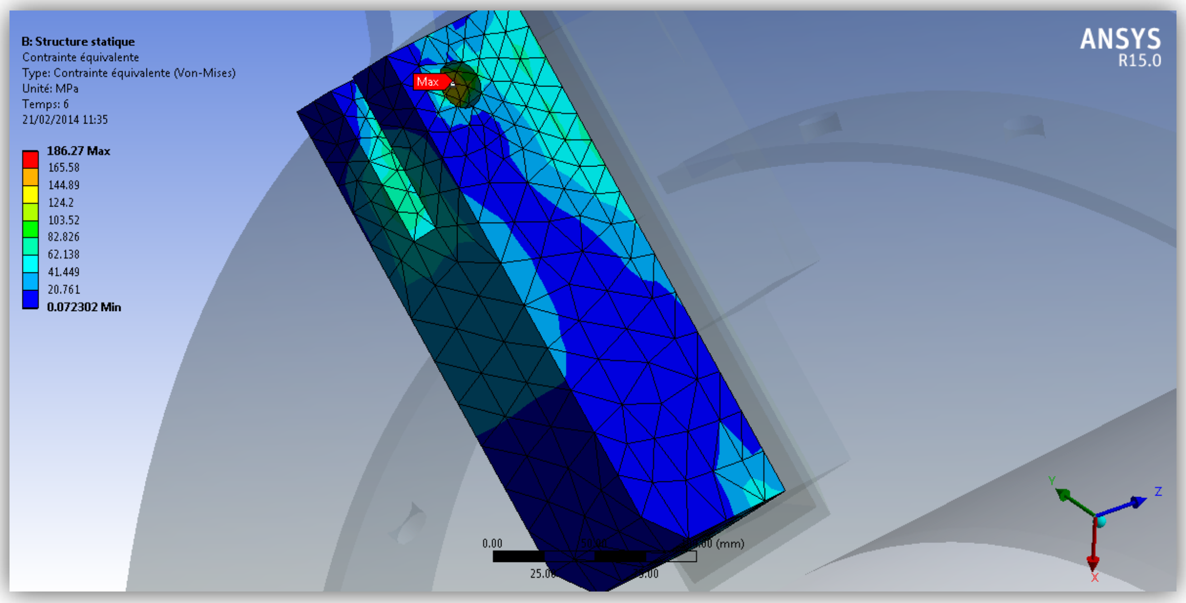
- Inferior skin:



- **<u>Welds between copes and flanges</u>**



- **Stress in copes**



The peak stress into the hole comes from the mesh. This part will be treated in details in the report on suspension links.

11. WORST CASE N°2: TEST PRESSURE

The second worst case concerns the pressure test at 10 bars after welding of the helium vessel. The maximum peak stress is equal to 117 MPa which is inferior to 155 MPa (90% of the yield strength).

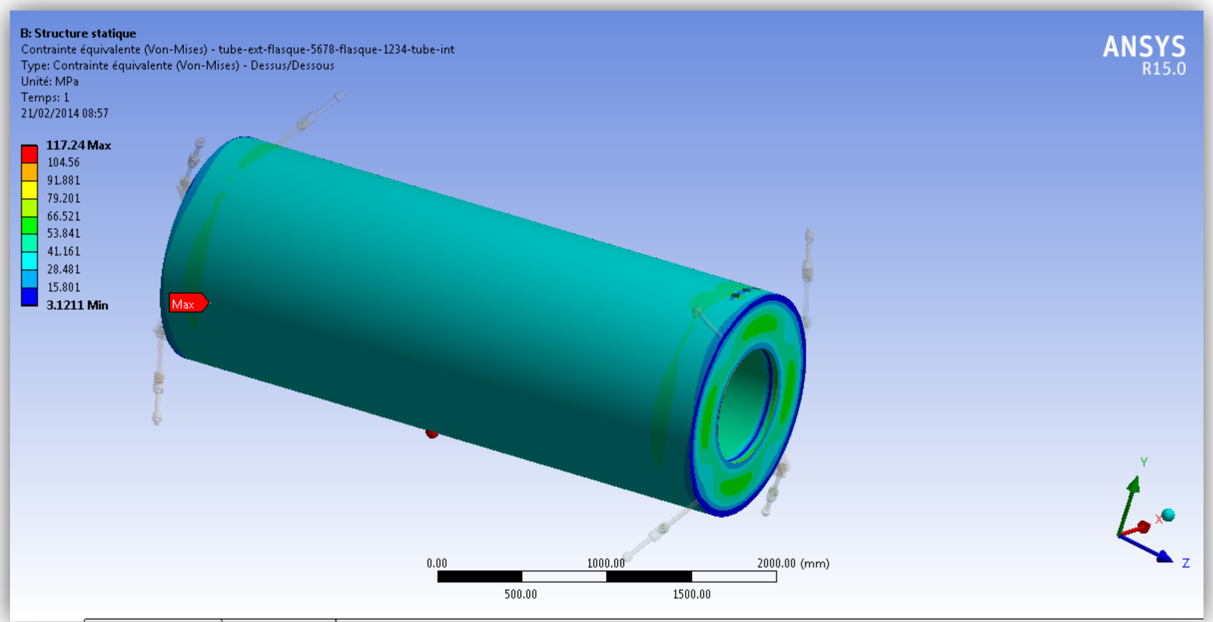


Figure 14: Von Mises peak stress (inferior & superior skin) during pressure test at 10 bars