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

2. ABSTRACT

The Dipole SHMS helium vessel mechanical stress is calculated by finite element analysis (FEA)
The calculation considers the worst case scenario, including the combination of the cool down from room temperature to liquid helium temperature, the dead weight, the horizontal acceleration provided by the magnet moving girder, the maximum unbalanced magnetic forces when the coil is off center related to the iron yoke, the helium maximum pressure during a quench.
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 and built according the ASME BPVC Section VIII Division 1.
This report presents the FEA analysis made by Sigmaphi. The shells thickness are optimized wherever it is possible to reduce the weight and ease the welding. The main modifications are the outer shell thickness 20 mm (JLAB Reference design) which becomes 15 mm and the inner shell thickness 12 mm (JLAB reference design) which becomes 10 mm. The details of the suspension links attachment are also modified compared to the JLAB reference design in order to reduce the bending effect through the end plates.

The helium vessel mechanical design as proposed by this report complies with the ASME BPVC requirement and is validated.

3. FEA Software

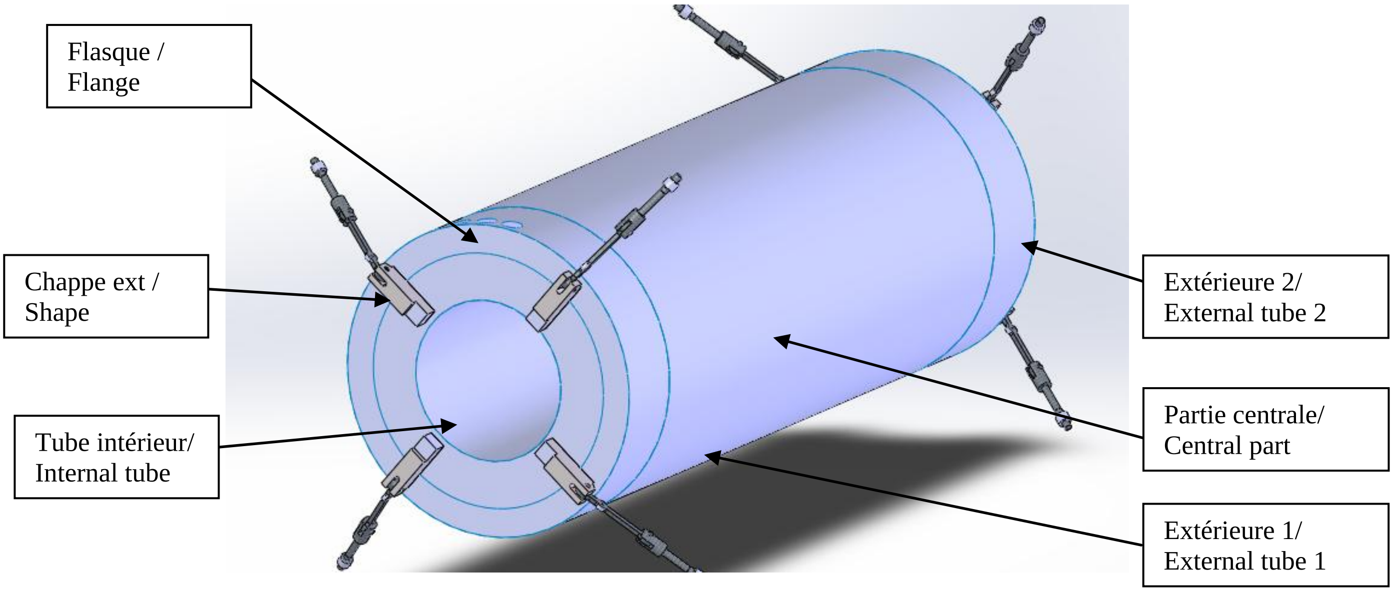
The FEA software used is ANSYS 14.0 Mechanical (Ansys Professional NLS)

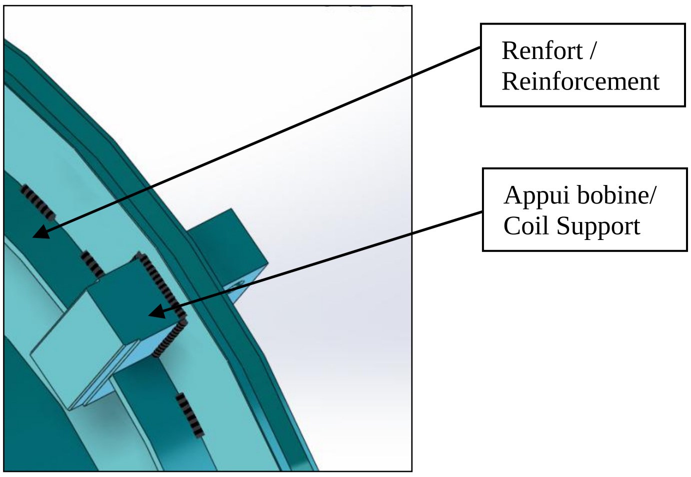
4. USER'S DESIGN SPECIFICATION

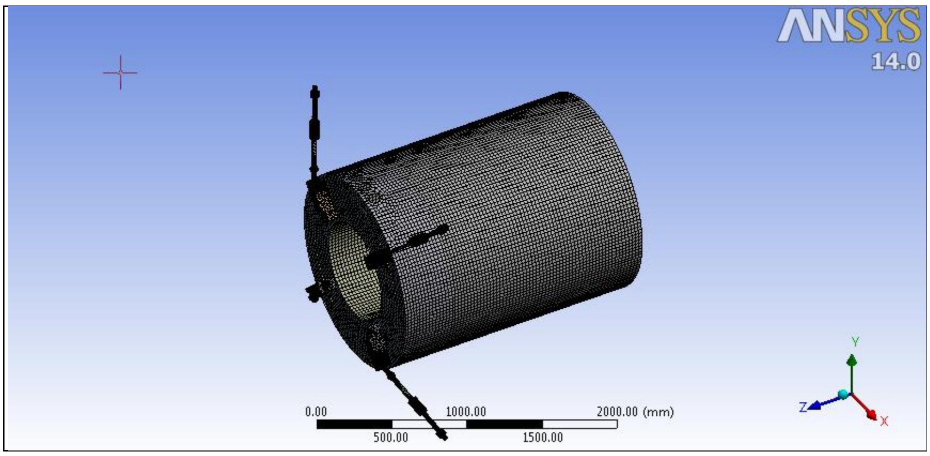
The user's specification is given below.

- ❑ Fluid: liquid 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
  - Lateral acceleration: 152 000 N (1g)
  - Magnetic forces: Horizontal 69000 N, Vertical 77 000 N (coil off centre 3 mm at 45° related to the yoke)

5. FEA MODEL GEOMETRY AND MESHING



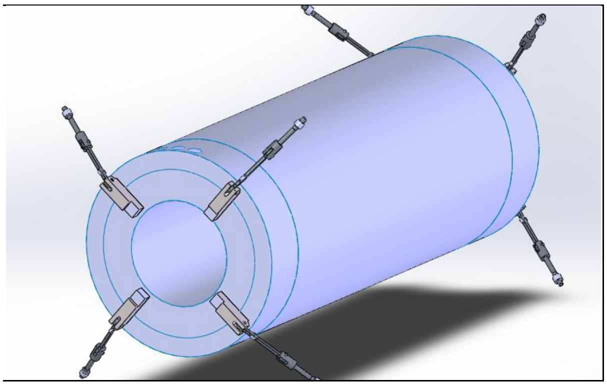


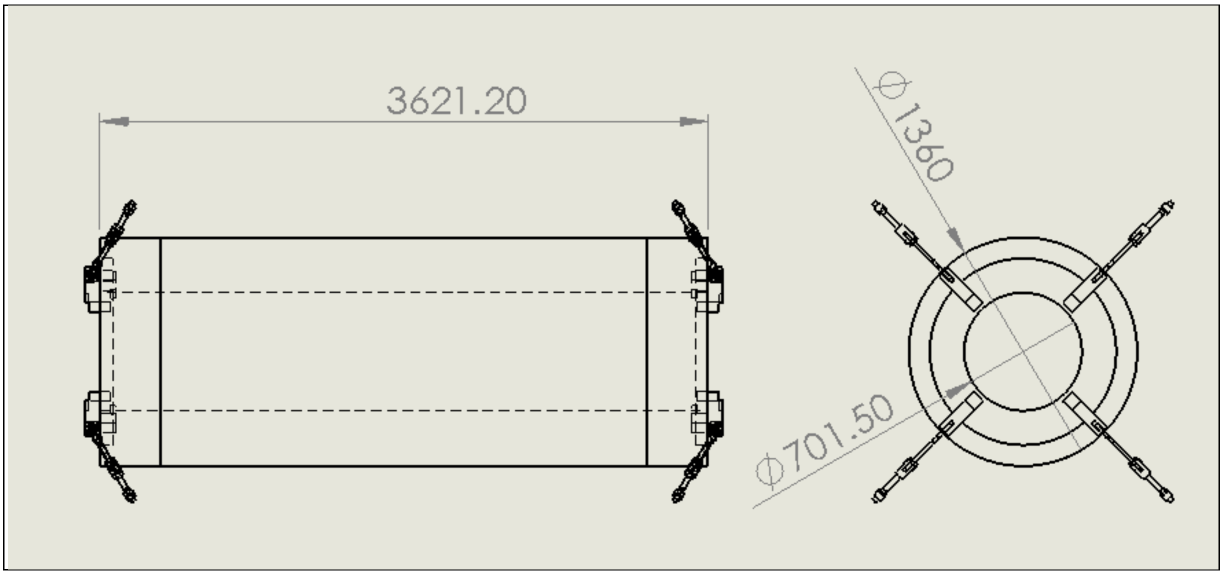


Mesh

Dimensions

Part	Material	Thickness	Weigth (Kg)
tube interieur	SS304	9.5	293.42
renfort	SS304	9.5	4.3632
renfort	SS304	9.5	4.3632
renfort	SS304	9.5	4.3632
renfort	SS304	9.5	4.3632
Flasque	SS304	29.5	242.54
Exterieure 1	SS304	14.5	170.85
Partie centrale	SS304	14.5	695.32
chappe ext	SS304		13.586
appui bobine int	SS304		13.611
NETRONIC50	nitronic 50		3.9877
Axe titane inferieur	TI6V		0.1584
Axe titane superieur	TI6V		0.1584
tirant titane	TI6V		1.0968

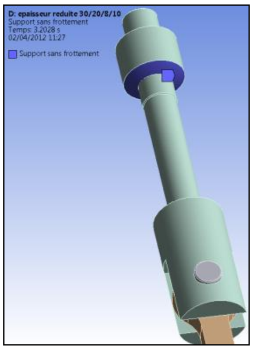




All dimensions are a membrane dimensions

6. FEA MODEL CONTACT AND BOUNDARIES CONDITIONS

We apply a support without frictionless to the spherical part of the suspension links (4 times) and a symmetry to the plan XY

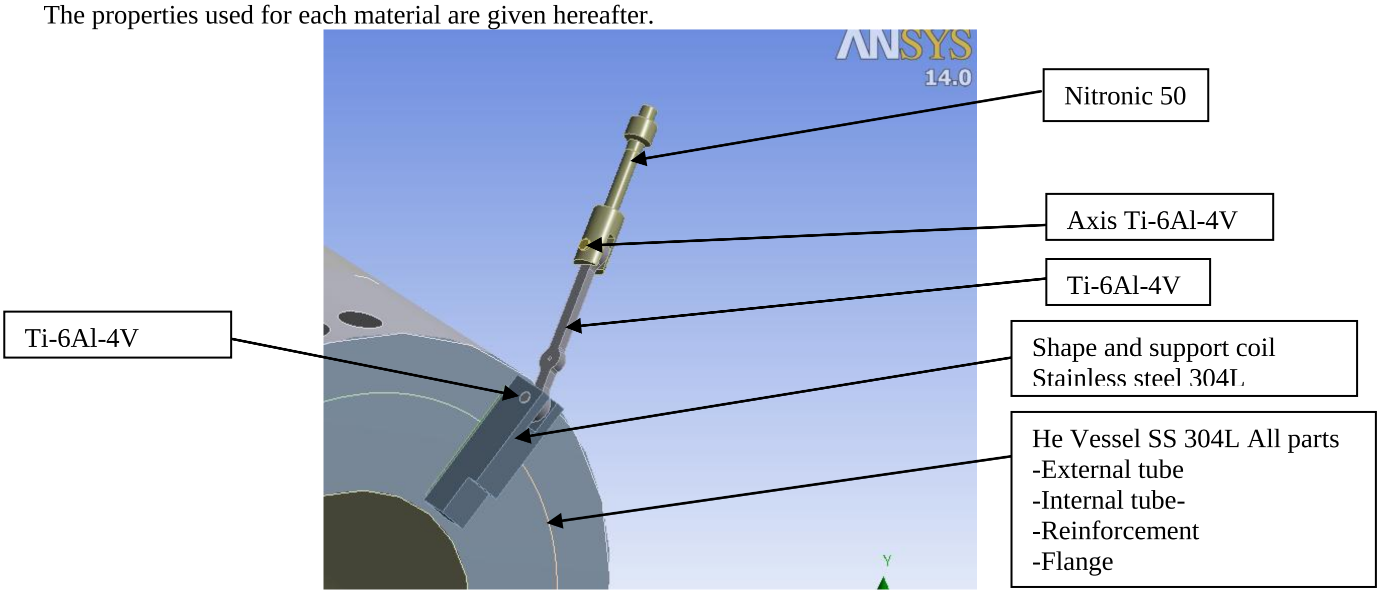


He Vessel / shape: Bonded
Suspension / axis (inferior and superior): Bonded
Nitronic 50 / superior axis: frictional (coef: 0.1)
Shape/inferior axis: frictional (coef: 0.1)

7. FEA MODEL MATERIALS

The material properties used are temperature dependant between 300 K and 4 K and are based on published data. The maximum allowable stress S 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 .
S is defined as 50% of the yield stress at 4 K for the Nitronic and Titanium parts which are not in contact with the pressure.

The properties used for each material are given hereafter.



- *Vessel 304L*

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

- Plates: SA-240
- Welded tube: SA-249, SA-688,
- Seamless pipe: SA-312
- Welded pipe: SA-312, SA-358,SA-409, SA-813, SA-814
- Bar: SA-479
- Note: Forging product form is not used for this vessel

Max Allowable Stress S at 20°C : S=115 MPa (16,7 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.

Expansion coefficient and young modulus according to the temperature:

Stainless steel 304 L

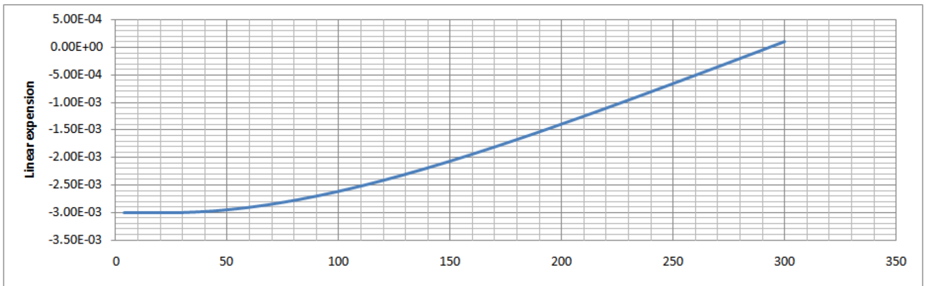
		SS 304	SS 304
	DL/L*10^5	units: GPa	units: GPa
a	-2.96E+02	2.10E+02	2.10E+02
b	-3.98E-01	1.22E-01	1.53E-01
c	9.27E-03	-1.15E-02	-1.62E-03
d	-2.03E-05	3.61E-04	5.12E-06
e	1.71E-08	-3.02E-06	-6.15E-09
T	23	5-57	57-300

Density	7900 Kg/m3

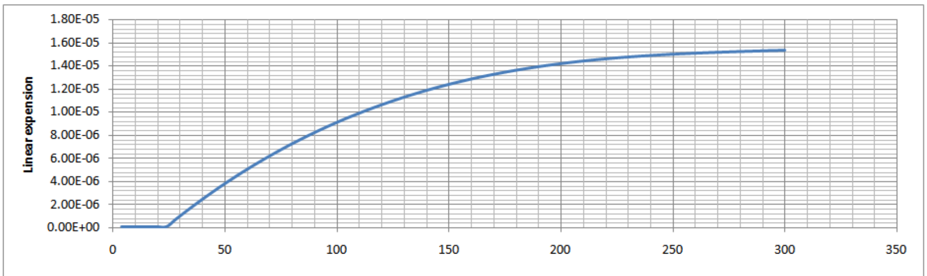
Equation of the form	
$y = a + bT + cT^2 + dT^3 + eT^4$	T≥Tlow(23°K)
y=f	T<Tlow(23°K)

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

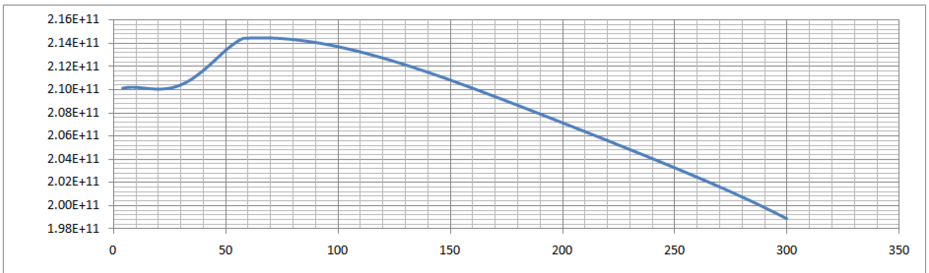
Equation of the form - Integrated coefficient	
$dy/dT = b + 2.cT + 3.dT^2 + 4.eT^3$	T≥Tlow(23°K)
dy/dT=0	T<Tlow(23°K)



Integrated Linear expansion of SS 304L



expansion coefficient of SS 304L



Young Modulus SS 304

- *<u>Suspension links lower part: Titanium</u>* Ti-6Al-4V

Young modulus at 20°C: E= 96000 Mpa
Yield stress at 20°C: Re=930 Mpa
Max Allowable Stress S considered: S= 744 MPa
Note: strength enhancement at low temperature are not considered for design contingency

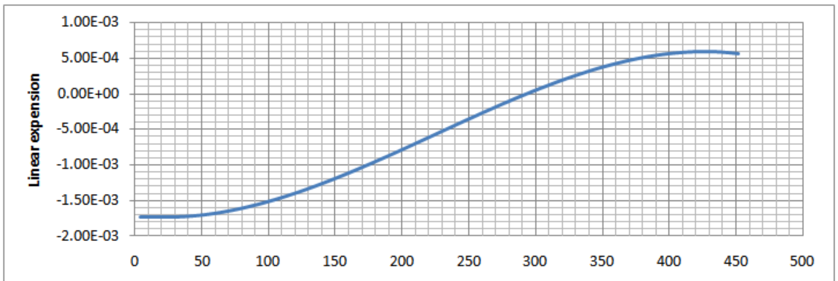
TITANE TI 6AL V

	*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*

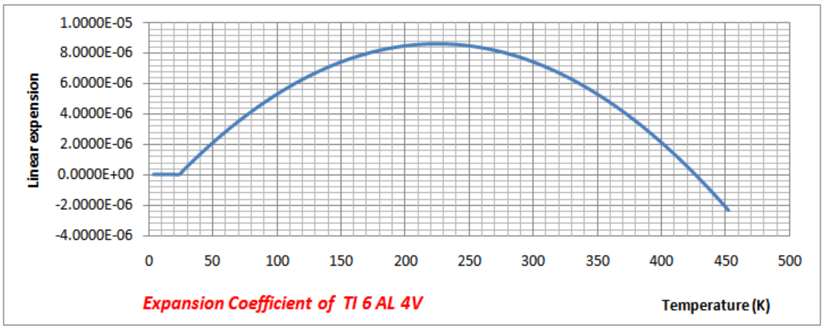
Equation of the form - Integrated coefficient	
$y = a + bT + cT^2 + dT^3 + eT^4$	T≥Tlow(24°)
y=f	T<Tlow(24°C)

**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(24°)
dy/dT=0	T<Tlow(24°C)



Integrated Linear expansion of TI 6 AL 4V



<u>Suspension links upper part : Nitronic 50</u>

Young modulus at 20°C: E=199000 MPa
Yield stress MPa at 20°C: Re=345Mpa
Max Allowable Stress S at 20°C : S= 276 MPa
Note: strength enhancement at low temperature is not considered for design contingency and take account the temperature gradient between 295 K and 77 K along the link upper part.

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.

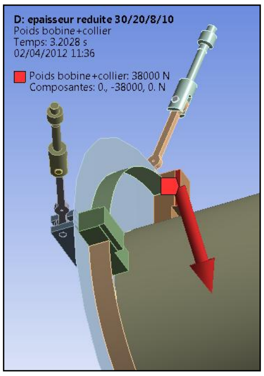
**Nitonic-50-technical-data (ELECTRALLOY –UNS S 209 10)*

8. FEA MODEL LOADING

(The loading 1 to 4 are applied to the step 1 of the model)

1. Weight collar + coil :

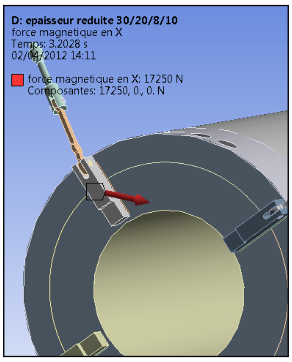
We simulate the weight of the coil and the collar to the superior coil support in the He Vessel (4 Times).
The total force is 152000 N (15500 Kg), we apply 38000 N per contact on the –Y axis



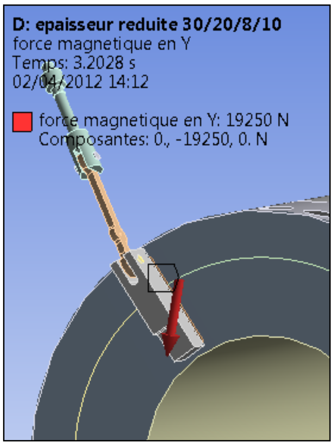
2. Magnetic forces on two direction –X axis and Y axis:

We simulate a magnetic force (the imbalanced magnetic forces extracted of the opera simulation-file 317111-Vers20 Rev D + displace yoke 3mm X and Y.OP3) to the He Vessel , this forces is applied on 4 lateral coil support for X forces and 4 superior coil support for the X axis.

The total force is 69000N for X axis, we apply 17250N per contact on the X axis.

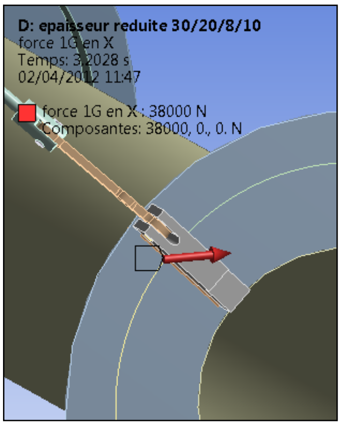


The total force is 77000N for Y axis, we apply 19250N per contact on the -Y axis.



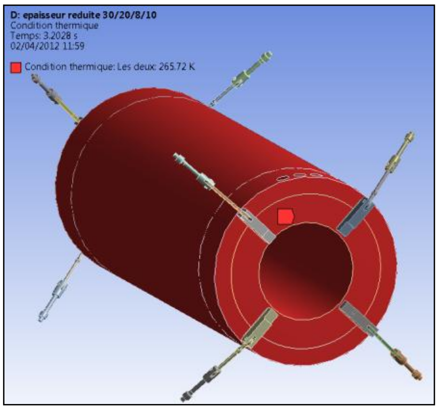
3. <u>Acceleration 1G on the Y axis:</u>

We simulate an acceleration (1G) to the He Vessel, this forces is applied on 4 lateral coil support .
The total force is 152000 N (coil + collar weight), we apply 38000 N per contact on the Y axis.



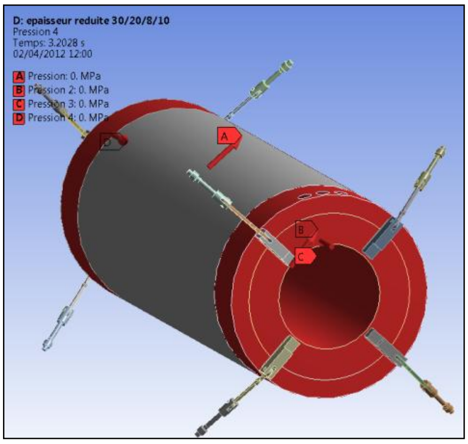
4. <u>Thermal contraction:</u> 295.15K to 4K

We apply a thermal condition 295.15K to 4K



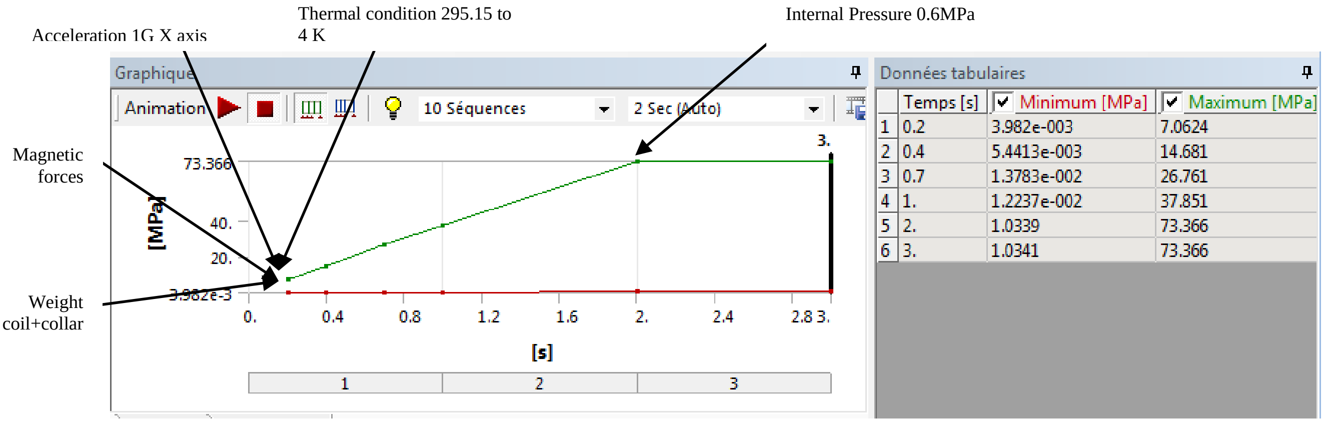
5. <u>Pressure 0.6 MPa in the HeVessel (simulation of quench)</u>

We apply a internal pressure in the Helium Vessel 0.6 MPa (6 atm)



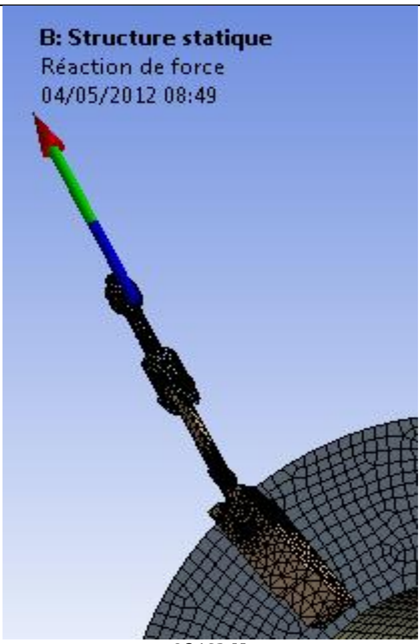
9. FEA MODEL SOLVING

The model is solved by successive steps as depicted by the plot below:

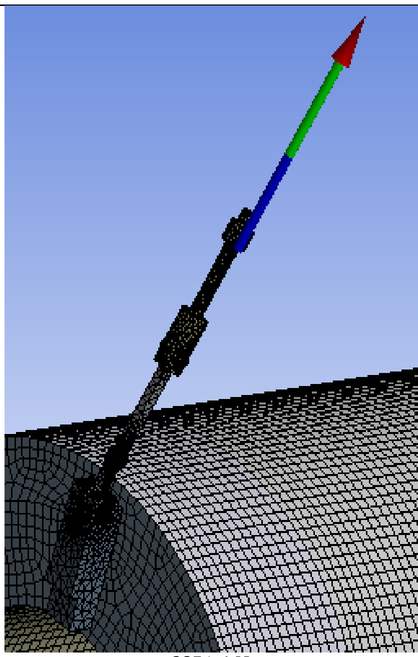


	Temps [s]	Minimum [MPa]	Maximum [MPa]
1	0.2	3.982e-003	7.0624
2	0.4	5.4413e-003	14.681
3	0.7	1.3783e-002	26.761
4	1.	1.2237e-002	37.851
5	2.	1.0339	73.366
6	3.	1.0341	73.366

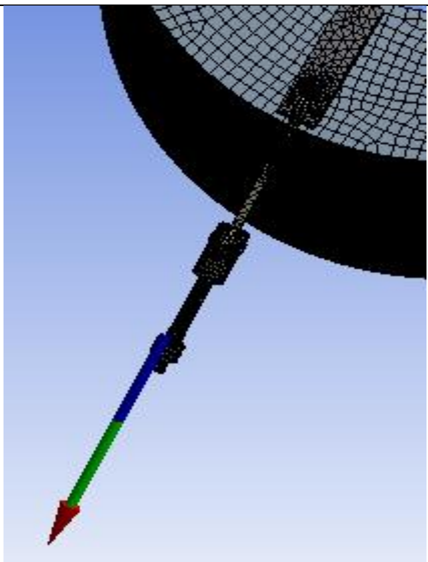
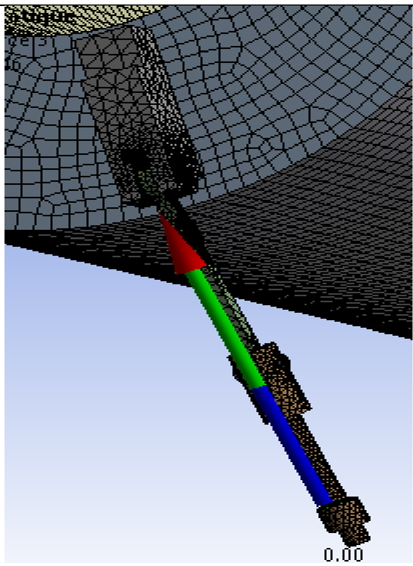
The model allows us to control the forces on each suspension links. Reaction forces are between 98462N and 8851.4N according to the suspension link locations



98462 N



8851.4 N

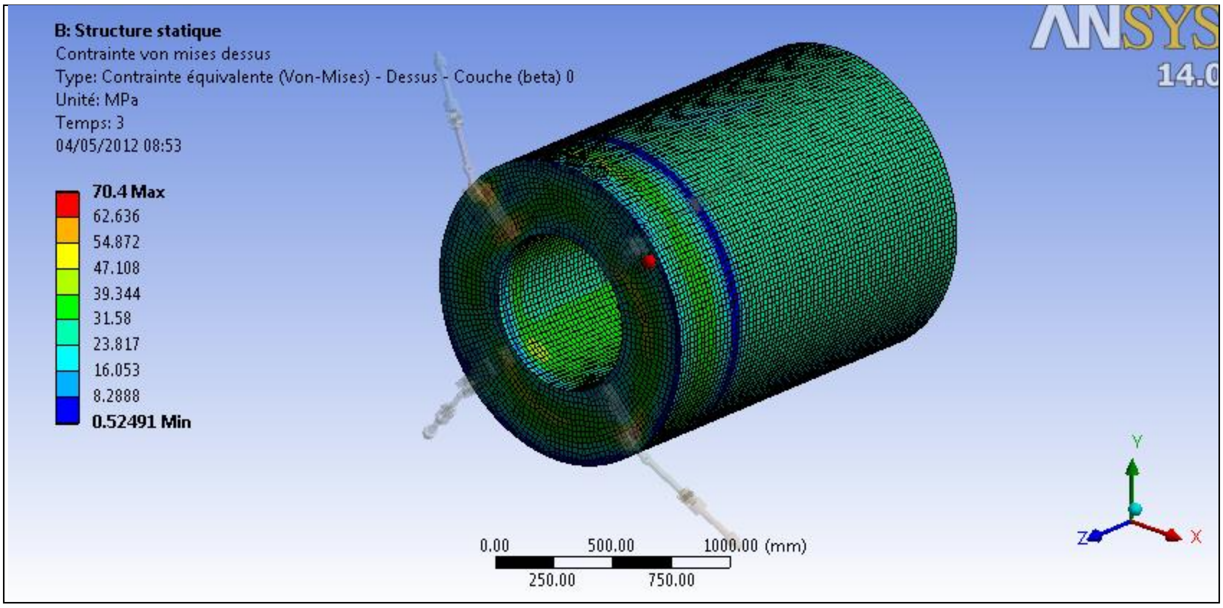
	
16122 N	*62560 N*

10. STRESS ANALYSIS

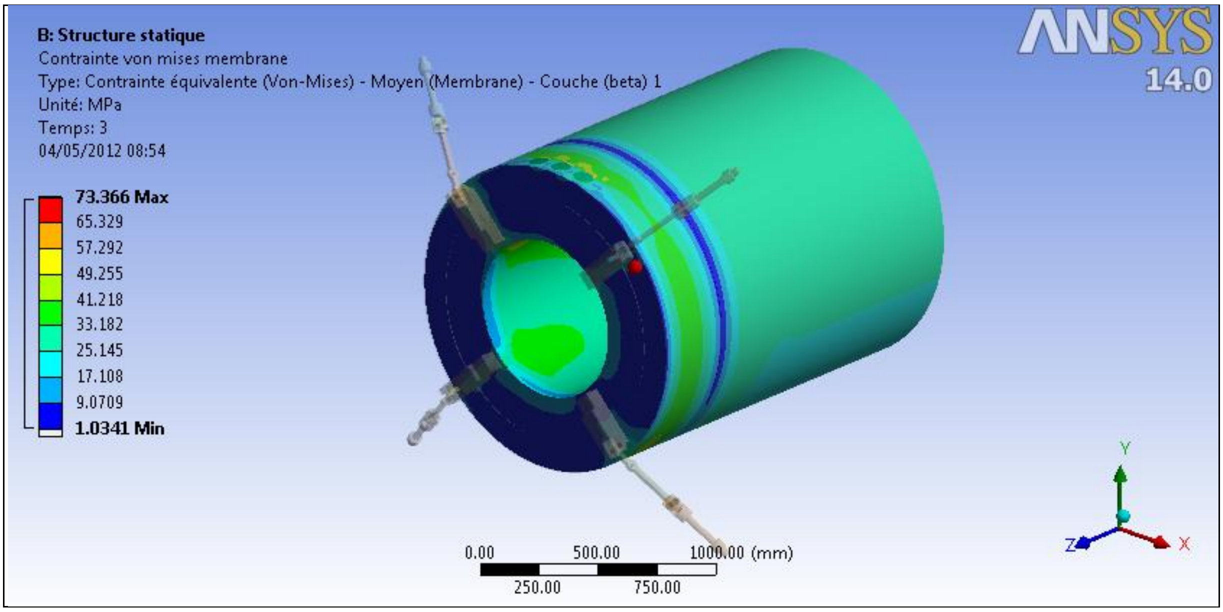
Considering the design contingency the peak stresses are below S for the parts in contact with the pressure.
We consider all stresses as primary and general stress which disregard the need to classify and linearize the stresses. The stress analysis is based on the Von Mises criteria and considers S as the maximum allowable stress for all locations.
The table below gives the peak stress for each material. The Von Mises stresses are below the allowable stress S in all locations.

Material	Von Mises Peak stress	Max Allowable stress S
Stainless steel 304L	79 Mpa	115 MPa
Nitronic 50	317 Mpa	345 MPa
Titanium Ti 6 V Al	521 Mpa	744 MPa

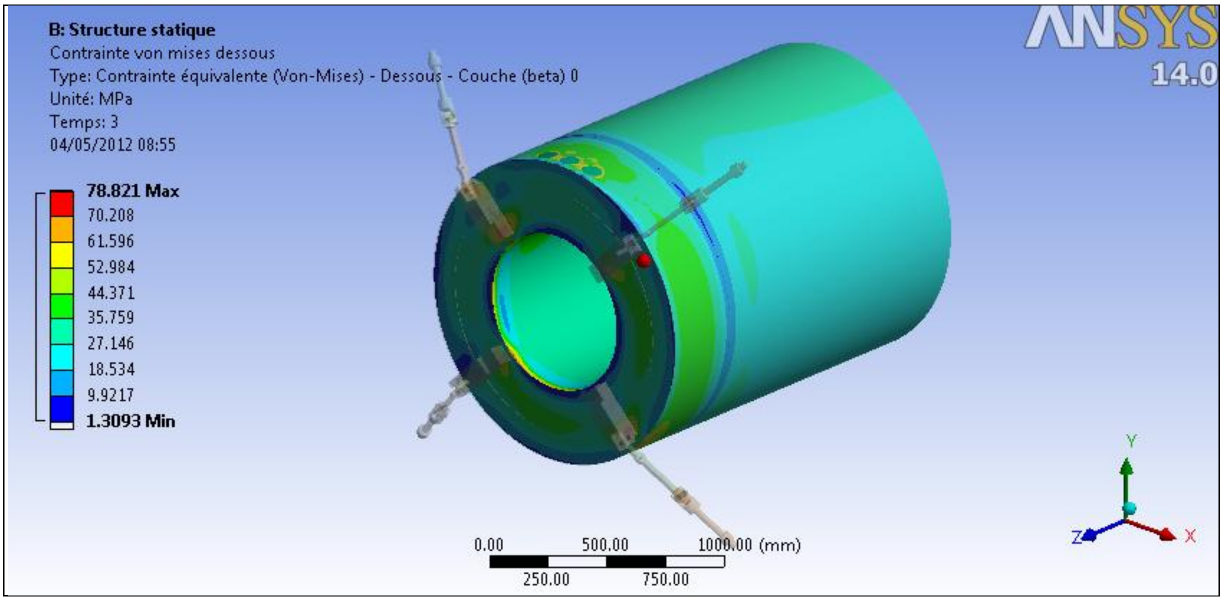
The pictures hereafter provide some VonMises screenshot.



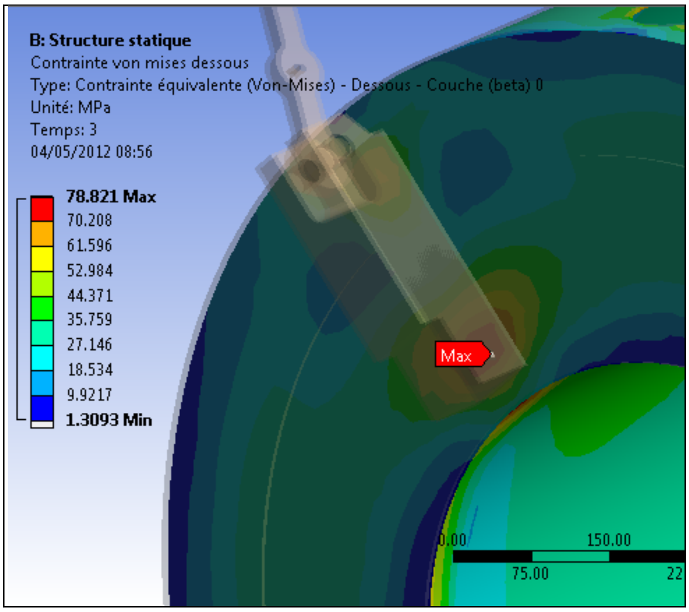
Equivalent (Von Mises) Stress Top - without a shape

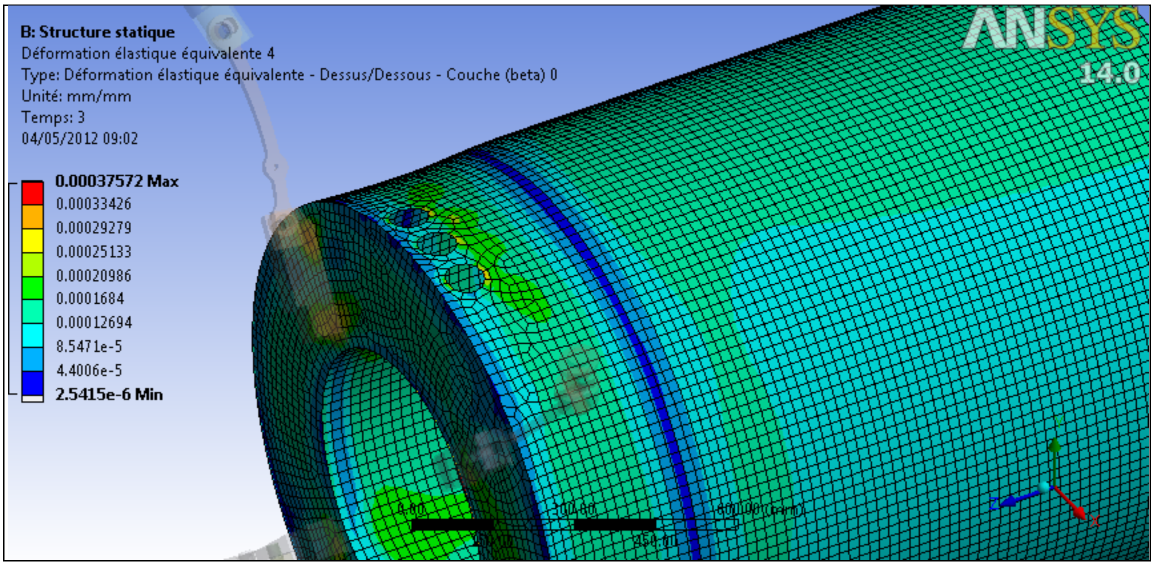


Equivalent (Von Mises) Stress Membrane - without a shape

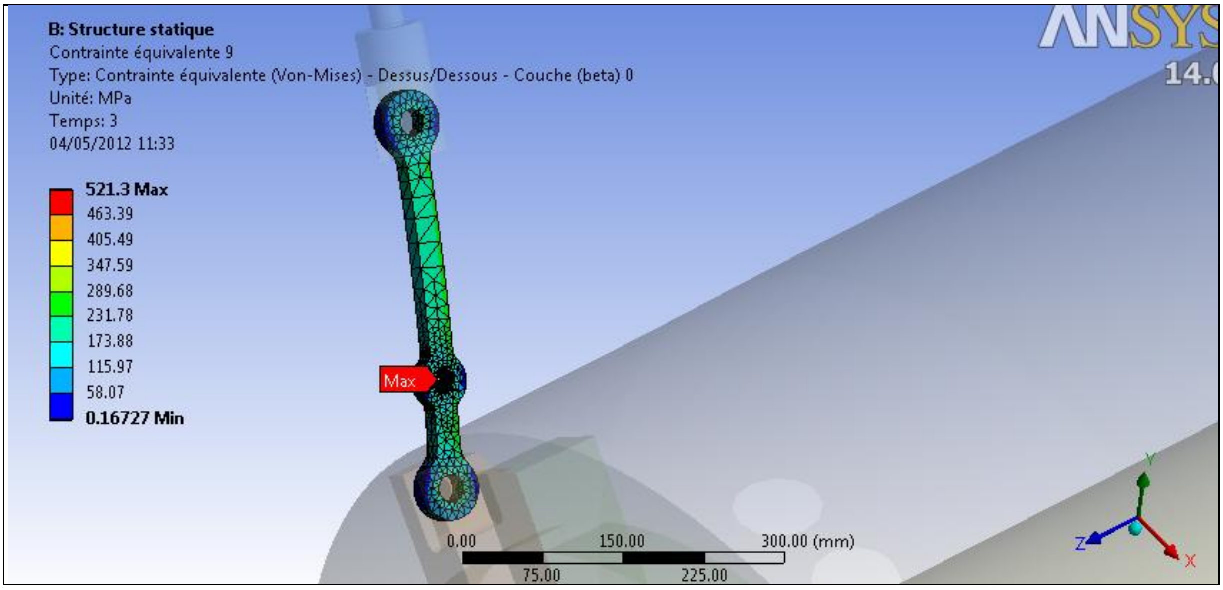


Equivalent (Von Mises) Stress Bottom – without a shape

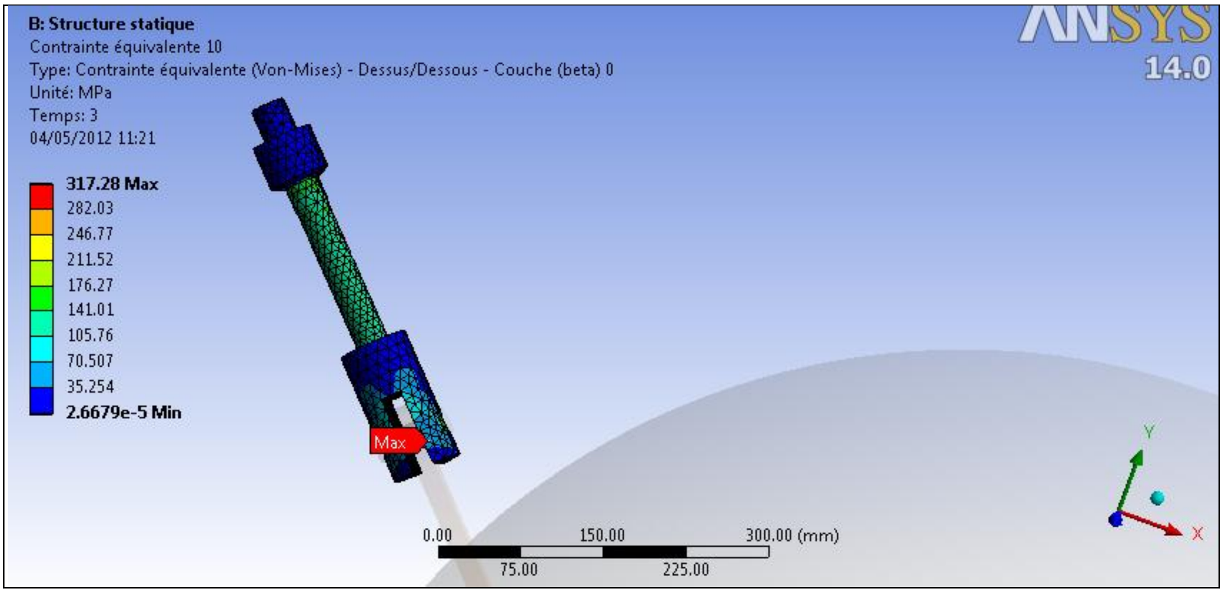




Distorted model



Stress -Suspension links Ti6-V-Al part-



Stress -Suspension links Nitronic 50 part-