



Agenzia nazionale per le nuove tecnologie, l'energia  
e lo sviluppo economico sostenibile



*Ministero dello Sviluppo Economico*

## RICERCA DI SISTEMA ELETTRICO

# Rapporto di dettaglio sulla progettazione e realizzazione dell'impianto LiFus6 per prove di corrosione da litio

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CORROSIONE DA LITIO

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Settembre 2012

Report Ricerca di Sistema Elettrico

Accordo di Programma Ministero dello Sviluppo Economico - ENEA

Area: Governo, gestione e sviluppo del sistema elettrico nazionale

Progetto: 1.3.2 Fusione nucleare: attività di fisica e tecnologia della fusione complementari a ITER

Responsabile del Progetto: Aldo Pizzuto, ENEA

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## Abstract

This document describes the engineering design of the LiFus6 experimental loop under construction in ENEA Brasimone.

It deals with the following topics:

- Background of the ENEA in corrosion experiments in lithium;
- Design description of the LiFus6 loop;
- Hydraulic, thermal and mechanical analysis of the loop.

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## Introduction

The evacuation of a large amount of heat (10 MW deposited beam power on a section of 0.01 m<sup>2</sup>) from the beam foot print area and the prevention of the lithium boiling necessitates a flow of lithium at a velocity of 10 to 20 m/s in the IFMIF target. The investigation of a possible subsequent corrosion/erosion effect is of importance for the EVEDA phase in order to assess the lifetime of the exposed target components; in particular of the nozzle and the backplate. Local shape modifications due to erosion/corrosion could give rise to flow instabilities leading to uncontrolled Li film thickness or massive spills, leading to a beam trip off and stop of IFMIF's operation.

In the reference design for the IFMIF target [1] limits of the erosion/corrosion rate have been specified as:

- 1 µm per year in the target
- 50 µm over 30 years in the loop

The goal of the current PA is to measure the erosion and corrosion rates of selected materials in relevant conditions, with the aim to provide evidence that these values can be achieved with the materials and operating conditions selected.

## Past experience

The Lifus 3 loop (fig. 1) was designed and constructed in 2001/2002 in ENEA, to evaluate the corrosion behaviour of Fusion reference structural materials, and in particular AISI 316 and Eurofer, in lithium environment in IFMIF relevant conditions. The original mission was to examine how the corrosion behaviour of the selected materials is affected by the impurities (C, N, H, etc.) which were said to be capable of playing a significant role in influencing the corrosion rate [1].

The LIFUS 3 loop work was focused on corrosion tests over EUROFER 97 and AISI 316L steels, as well as on lithium purification and monitoring experiments.

The operation of the loop was affected by several problems, mainly due to the complexity of system hydraulics, with the main circuit and the purification circuit working in parallel using only one pump, and the original commitments were not fully accomplished.

For this reason it was decided in 2010 to build a new experimental facility, simplified from the hydraulic point of view, capable to perform the set of tests required by the IFMIF community. This new loop, named Lifus 6, is hereafter presented.



Figure 1: Lifus 3 loop front view with the original canned pump

## Loop configuration and test setup

A series of erosion/corrosion tests shall be performed in the LIFUS 6 test loop (see Figg. 2, 3 and 4) at constant temperature of 350°C and Li flow velocity up to 16 m/s, impurity level, temperature, exposure duration and specimen materials with the goal to validate the choice of material made in the IFMIF reference design. The materials to be tested are mounted in a test section specially designed to achieve the specified Li flow velocities.

The Lifus 6 loop, in its operational configuration appears as a ring installed on a steel frame. The loop is not accessible during the operational phases and it is made of the following components:

- Drain/storage tank mounted on mobile supports to compensate the thermal expansion of the pipes. It is complete of electric tracing, thermocouples for regulation, safety and measure of the wall temperature, nozzles for connection to the piping. The tank also acts as hot trap at a temperature of 600°C during the off line purification of lithium from nitrogen impurities. In normal operation the storage lithium is maintained melted at about 300°C.
- Electromagnetic pump type GAAA IP 121 provided of air cooling system.
- Two flow meters:
  - The first one is a Vortex volumetric type, calibrated for a minimum flow velocity of 0.08 m/s and maximum 2.7 m/s corresponding to 0.40 – 5.4 m<sup>3</sup>/h
  - The second one is a Coriolis mass flow meter, with a range of 0-4000 kg/h of liquid metal.

Test section, in which the liquid metal reaches the foreseen testing conditions of velocity.

The Lifus6 loop is designed to perform corrosion/erosion tests in the following conditions:

- Lithium velocity up to 16 m/s
- Constant temperature along the loop of 350°C

According to fig.2, the Lithium flow at the pump outlet is divided in two parts. The main flow is driven to the test section and come back to the pump. A limited flow, about 1% of the total flow, enters instead the dedicated purification loop (subject of the Deliverable LF 4.4.1), where it passes through the Cold Trap (operated ad 200°C) to be continuously purified, essentially from carbon and oxygen. Materials to be tested are Eurofer 97 and AISI 316 Stainless Steel.

In the next paragraphs the design of the loop is presented.

## Lifus 6 loop design

As mentioned, the plant has a ring structure whose layout is shown in figure 2.

Two separate circuits can be easily identified: the liquid metal circuit, piping 1" and the gas lines made entirely with Swagelok pipes ½".

The liquid metal circuit is characterized by the following components:

- Electromagnetic pump model IP 121 manufactured by the GAAA Company. The best operational point is reached at 12 m<sup>3</sup>/h of volumetric flow rate with a head of 2.5 bar;
- Pneumatic Control Valve 1 ";
- Vortex Flowmeter, Rosemount model 8800;
- Test section, in which are reached the test conditions of fluid velocity;
- Coriolis mass flowmeter, Emerson Micro Motion DT65;
- Pressure gauges Gefran FO53732 in direct contact with liquid metal;
- Piping in AISI 316 L 1" Schedule 40;
- Storage tank.

The main purpose of the gas circuit is to maintain safety conditions during operation and plant stops, and therefore the strong control of oxygen and water in all possible loop conditions and in particular in loading and drainage phases. The liquid metal circuit is electrically heated and thermal insulated to guarantee a constant and uniform temperature of 350°C during operation.

LIFUS6 – P&ID

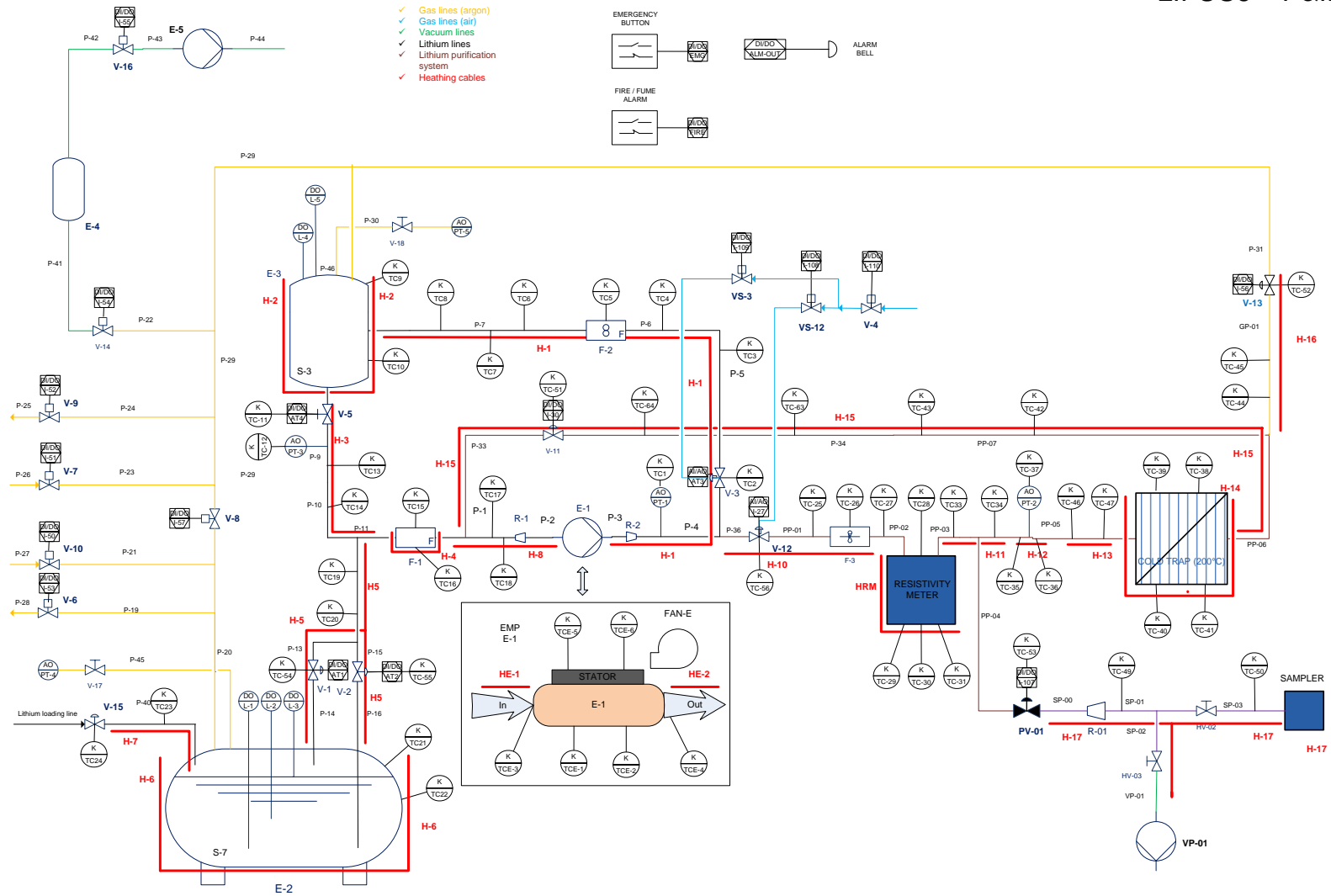


Figure 2: general layout of Lifus 6 loop



## Thermal Dimensioning

The system is entirely electrically traced to ensure the operating temperature and prevent freezing of the liquid metal in the circuit in any possible accidental and ordinary condition. The installed thermal power and thermal insulation have been determined as follow.

### Thermal insulation

To reduce as much as possible thermal losses the loop is thermal insulated. The thermal insulation is designed to maintain a maximum surface temperature lower than 50°C.

The general equation to determine the surface temperature is:

$$T_{es} = T_{is} - \frac{P_{th}}{S \cdot U^*}$$

In which:

- $U^* = ((s_{acc} / k_{acc}) + (s_{thi} / k_{thi}))^{-1}$
- $P_{th}$  is the thermal power globally exchanged with the environment
- $T_{is}$  is the temperature of the pipe surface, assumed as equal to the one of flowing lithium (conservative assumption) 350°C.

The thermal power  $P_{th}$  can be estimated using the formula:

$$P_{th} = U \cdot S \cdot \Delta T$$

In which:

$$U = ((1/h_{ext}) + (s_{st} / k_{st}) + (s_{thi} / k_{thi}))^{-1}$$

$$S = \pi \times d_{ext} \times h$$

$$\Delta T = (T_s - T_r)$$

Considering that the largest part of the loop is realized with 1" steel pipes, the evaluation can be conducted assuming a uniform pipe diameter.

The general parameters adopted are:

$T_r$ : 10°C

$h_{ext}$ : 7,5 W/m<sup>2</sup> K

$k_{st}$ : 25 W/m K

$k_{thi}$ : 0,05 W/m K

Using an iterative calculation procedure, the minimum thermal insulation thickness to respect the imposed outer temperature is 30 mm. To further reduce the thermal losses a thickness of 70 mm is selected.

The same procedure can be applied to the thermal insulation of the storage tank, that will be operated at 600°C during the purification phase. In this case, using the same equations, the thickness of the thermal insulation is 150 mm.

### Heating power

Fixed the thermal insulation, the thermal power dispersed in the environment can be determined using the general correlations reported in the previous paragraph.

Per 1 meter length of tube the surface to be heated is about 0.5 m<sup>2</sup>.

Assuming that the insulator surface is at 50°C and the air constantly at 10° C it can be assumed, simplifying, that each meter of pipe has a dispersion of about 100 W. This value represents the minimum power that should be provided to the tube, per unit length, to maintain the pipe surface at 350°C with the selected insulation and the surface of the insulating material at 50°C.

To operate the loop in the best conditions of safety and reliability and to reduce the risk of breakage of the heating cables, the installed thermal power is more than doubled, thus limiting the maximum power

required to compensate dispersions below 50% of the one available, and giving an adequate reserve to be used in abnormal conditions.

Performing the same evaluation on the storage tank, the minimum thermal power results about two times higher, per surface unit, with respect to pipe, coherently with the maximum storage temperature of 600°C during purification.

### Pre heating time

To reduce the thermal stresses on pipes during the heating phase, the temperature increase is usually fixed to a value of 10°C/h. To verify the respect of this condition, the heating time can be determined with the equation:

$$t = \frac{M_i \cdot c_p \cdot (T_f - T_r)}{P_{elet,i} - P_{disp,i}}$$

where

$M_i$  mass of the i pipe

$c_p$  specific heat of steel: 460 J/Kg °C

$T_f$  final temperature to be reached: 350°C

$T_r$  room temperature: 10°C

$P_{elet, i}$  electrical power of the heating cable;

$P_{disp, i}$  thermal power dispersed in the environment.

Considering the installed thermal power, the preheating time is lower than 4 hours, corresponding to a ramp of almost 100°C/h. The thermal power available allows to have times of pre heating much lower than required.

The same evaluation should be made for the storage tank, filled of lithium before charging the loop. Also in this case the condition is perfectly respected, considering the low density of lithium and the fact that about 50 kJ are necessary to increase the temperature of lithium up to 350°C, negligible with respect to the dispersed thermal power.

## Fluid dynamic analysis of the loop

### Pressure drops

The general equation to determine pressure drops in a hydraulic system is:

$$\Delta p = K \frac{\rho v^2}{2} \tag{1}$$

In which:

$$K = f_M \frac{L}{D} + K_r + K_a + K_c + K_T \tag{2}$$

$$\frac{1}{\sqrt{f_M}} = -2 \log_{10} \left( \frac{\varepsilon}{3.7} + \frac{2.51}{Re \sqrt{f_M}} \right) \tag{3}$$

(Colebrook equation)

$$Re = \frac{\rho \times v \times D}{\mu} \tag{4}$$

$\mu$  Reynolds number  
 $K$  → Total pressure drop coefficient

$f_M$	→	Distributed pressure drops
$K_r$	→	Pressure drop coefficient in case of reduction of pipe section = 0.5
$K_a$	→	Pressure drop coefficient for pipe enlargement = 1
$K_c$	→	Pressure drop coefficient for bended tube = 0.75
$K_T$	→	Pressure drop coefficient in a T joint = 0.4
D	→	Pipe internal diameter
$\mu$	→	Fluid viscosity
$\rho$	→	Fluid density
Re	→	Reynolds number
L	→	Pipe length
$\varepsilon$	→	Pipe roughness

Dividing the loop separating each part with different pressure drop characteristics, the fluid pressure in the loop can be draftly evaluated:

Bent C1			$\Delta p$	[Pa]	8,6605E+01		kc1	0,49435
Bent C2			$\Delta p$	[Pa]	8,6605E+01		kc2	0,49435
Bent C3			$\Delta p$	[Pa]	8,6605E+01		kc3	0,49435
Bent C4			$\Delta p$	[Pa]	8,6605E+01		kc4	0,49435
Bent C5			$\Delta p$	[Pa]	8,6605E+01		kc5	0,49435
Bent C6			$\Delta p$	[Pa]	8,6605E+01		kc6	0,49435
Bent C7			$\Delta p$	[Pa]	8,6605E+01		kc7	0,49435
Bent C8			$\Delta p$	[Pa]	8,6605E+01		kc8	0,49435
Bent C9			$\Delta p$	[Pa]	8,6605E+01		kc9	0,49435

	P [Pa]	T [°C]	$\rho$ [ kg/m <sup>3</sup> ]	Internal Diameter [m]	Velocity [m/s]
Point 1	4,0000E+05	350,00	499,85	0,02664	0,8372
Point 2	3,9997E+05	350,00	499,85	0,02664	0,8372
Point 3	3,9988E+05	350,00	499,85	0,02664	0,8372
Point 4	3,9981E+05	350,00	499,85	0,02664	0,8372
Point 5	3,9973E+05	350,00	499,85	0,02664	0,8372
Point 6	3,9969E+05	350,00	499,85	0,02664	0,8372
Point 7	3,7874E+05	350,00	499,85	0,02664	0,8372
Point 8	3,7863E+05	350,00	499,85	0,02664	0,8372
Point 9	3,7806E+05	350,00	499,85	0,02664	0,8372
Point 10	3,7783E+05	350,00	499,85	0,02664	0,8372
Point 11	3,7775E+05	350,00	499,85	0,02664	0,8372
Point 12	3,7768E+05	350,00	499,85	0,02664	0,8372
Point 13	3,7759E+05	350,00	499,85	0,02664	0,8372
Point 14	3,7755E+05	350,00	499,85	0,02664	0,8372
Point 15	3,1471E+05	350,00	499,85	0,02664	0,8372
Point 16	3,1470E+05	350,00	499,85	0,02664	0,8372

Point 17	2,9375E+05	350,00	499,85	0,02664	0,8372
Point 18	2,9373E+05	350,00	499,85	0,02664	0,8372
Point 19	2,9365E+05	350,00	499,85	0,02664	0,8372
Point 20	2,9362E+05	350,00	499,85	0,02664	0,8372
Point 21	2,9354E+05	350,00	499,85	0,02664	0,8372
Point 22	2,9348E+05	350,00	499,85	0,02664	0,8372
Point 23	2,9339E+05	350,00	499,85	0,02664	0,8372
Point 24	2,9337E+05	350,00	499,85	0,02664	0,8372
Point 25	2,9328E+05	350,00	499,85	0,02664	0,8372
Point 26	2,9324E+05	350,00	499,85	0,02664	0,8372
Point 27	2,9315E+05	350,00	499,85	0,02664	0,8372
Point 28	2,9312E+05	350,00	499,85	0,02664	0,8372
Point 29	2,8157E+05	350,00	499,85	0,02664	0,8372
Point 30	2,8156E+05	350,00	499,85	0,02664	0,8372

Pipe	Nodes	Length [m]	Intern. Diameter [m]	Extern. Diameter [m]	Roughness [m]	Average Pressure [Pa]	Average T [°C]	Average Density [kg/m <sup>3</sup> ]	Average Viscosity [Pa*s]	Velocity [m/s]	Re	Friction coeff.	Pressure drop [Pa]
P-3	1-2	0,22	0,02664	0,03340	5,0E-05	4,00E+05	350	499,85	4,08E-04	0,8372	2,7345E+04	2,3466E-02	33,950
	3-4	0,43833	0,02664	0,03340	5,0E-05	4,00E+05	350	499,85	4,08E-04	0,8372	2,7345E+04	2,3466E-02	67,642
	5-6	0,22912	0,02664	0,03340	5,0E-05	4,00E+05	350	499,85	4,08E-04	0,8372	2,7345E+04	2,3466E-02	35,357
	7-8	0,69734	0,02664	0,03340	5,0E-05	4,00E+05	350	499,85	4,08E-04	0,8372	2,7345E+04	2,3466E-02	107,612
	9-10	1,50625	0,02664	0,03340	5,0E-05	3,79E+05	350	499,85	4,08E-04	0,8372	2,7345E+04	2,3466E-02	232,440
	11-12	0,448	0,02664	0,03340	5,0E-05	3,78E+05	350	499,85	4,08E-04	0,8372	2,7345E+04	2,3466E-02	69,13
	13-14	0,28292	0,02664	0,03340	5,0E-05	3,78E+05	350	499,85	4,08E-04	0,8372	2,7345E+04	2,3466E-02	43,659
	15-16	0,1	0,02664	0,03340	5,0E-05	3,78E+05	350	499,85	4,08E-04	0,8372	2,7345E+04	2,3466E-02	15,432
	17-18	0,1	0,02664	0,03340	5,0E-05	2,94E+05	350	499,85	4,08E-04	0,8372	2,7345E+04	2,3466E-02	15,432
	19-20	0,14943	0,02664	0,03340	5,0E-05	3,78E+05	350	499,85	4,08E-04	0,8372	2,7345E+04	2,3466E-02	23,0596
	21-22	0,36887	0,02664	0,03340	5,0E-05	3,15E+05	350	499,85	4,08E-04	0,8372	2,7345E+04	2,3466E-02	56,9230
	23-24	0,14943	0,02664	0,03340	5,0E-05	2,94E+05	350	499,85	4,08E-04	0,8372	2,7345E+04	2,3466E-02	23,0596
	25-26	0,26897	0,02664	0,03340	5,0E-05	2,94E+05	350	499,85	4,08E-04	0,8372	2,7345E+04	2,3466E-02	41,5067
	27-28	0,19924	0,02664	0,03340	5,0E-05	2,93E+05	350	499,85	4,08E-04	0,8372	2,7345E+04	2,3466E-02	30,7462
	29-30	0,07591	0,02664	0,03340	5,0E-05	2,93E+05	350	499,85	4,08E-04	0,8372	2,7345E+04	2,3466E-02	11,7142
	Total	5,23381											8,0767E+02

Pressure drops are concentrated in the test section and in valves. Applying the same procedure to valves on the main loop, the results are:

Valve V2							Valve V4					
Cv		3	$K_1$				Cv		3	$K_1$		
$G_f$		0,49985	$K_2$				$G_f$		0,49985	$K_2$		
$N_1$		0,865	$K_{B1}$				$N_1$		0,865	$K_{B1}$		
d	[mm]	26,64	$K_{B2}$				d	[mm]	26,64	$K_{B2}$		
$N_2$		0,00214	$\Sigma k$				$N_2$		0,00214	$\Sigma k$		
$F_p$		1,0000	$\Delta p$	[Pa]	2,0950E03		$F_p$		1,0000	$\Delta p$	[Pa]	2,0950E03
Max flow rate							Max flow rate					
$F_F$		0,96000	$K_1$				$F_F$		0,96000	$K_1$		
$F_L$		0,90000	$F_{LP}$				$F_L$		0,90000	$F_{LP}$		
$F_{LP} / F_P$			$q_{max}$	[l/min]	174,08		$F_{LP} / F_P$			$q_{max}$	[l/min]	143,77

Pressure drops in the loop, excluding the test section, are lower than 0.5 bar. The test section is the main source of pressure drops as hereafter calculated:

Test section									
Pipe internal diameter	$D_{sp}$	[m]	0,021	$A_{sp}$	[m <sup>2</sup> ]	3,4636E-04	$v_{sp}$	[m/s]	1,34734
Specimen diameter	$D_p$	[m]	0,02	$A_p$	[m <sup>2</sup> ]	3,2201E-05	$v_p$	[m/s]	14,49216
Test section inlet	$k_i$	0,49435	$\Delta p$	[Pa]	8,6605E+01				
Test section outlet	$k_{ip}$	4,5351E-01	$\Delta p$	[Pa]	2,0576E+02				
Specimens inlet	$k_{ip}$	8,2270E-01	$\Delta p$	[Pa]	4,3184E+04				
Specimens outlet	$k_{ip}$	-3,0464E-01	$\Delta p$	[Pa]	-1,3821E+02				
Distributed pressure drop									
Length [m]	Intern. Diameter [m]	Roughness [m]	Average Temperature [°C]	Average Density [kg/m <sup>3</sup> ]	Average Viscosity [Pa*s]	Velocity [m/s]	Re	Friction coeff.	Pressure drop [Pa]
0,075	0,021	5,0000E-05	350,0	499,85	4,08E-04	1,3473	3,4689E+04	2,2030E-02	3,5697E+01
0,12	0,001	5,0000E-05	350,0	499,85	4,08E-04	14,4922	1,7767E+04	2,3194E-02	1,4609E+05
0,075	0,021	5,0000E-05	350,0	499,85	4,08E-04	1,3473	3,4689E+04	2,2030E-02	3,5697E+01
			$\Delta p_{tot}$	[Pa]	1,8950E+05				

Pressure drops in the circuit are lower than 2,5 bars, compatible with the pump head, giving an adequate margin to operate the cold trap branch.

## Mechanical design

In fig. 3 the entire loop is represented, while in fig. 4 the supporting structure is shown.

The reference design parameters of the loop are:

T= 400°C (650°C for the storage tank)

P= 0.4 MPa

The dimensioning of pipes has been made according to ASME B31.3 while the storage tank has been designed applying PED rules.

According to 1" pipe diameter, the reference schedule value given by ASME B31.3 is 10. We decided to use only sched 40 pipes, with a very high safety margin.

The same evaluation can be made for the storage tank. Also in this case the thickness is largely higher than the minimum allowed value.



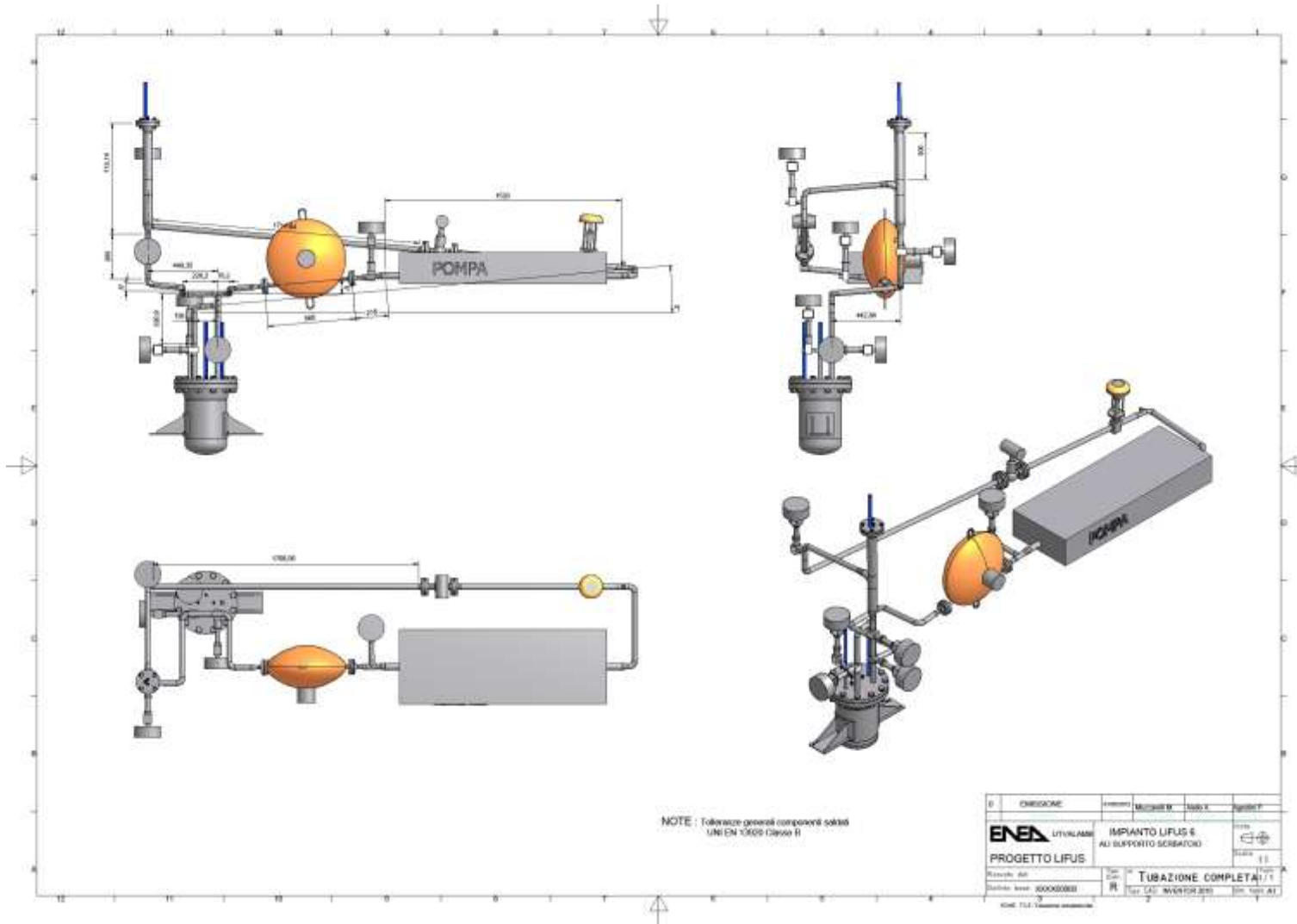


Figure 3: Lifus 6 piping and components

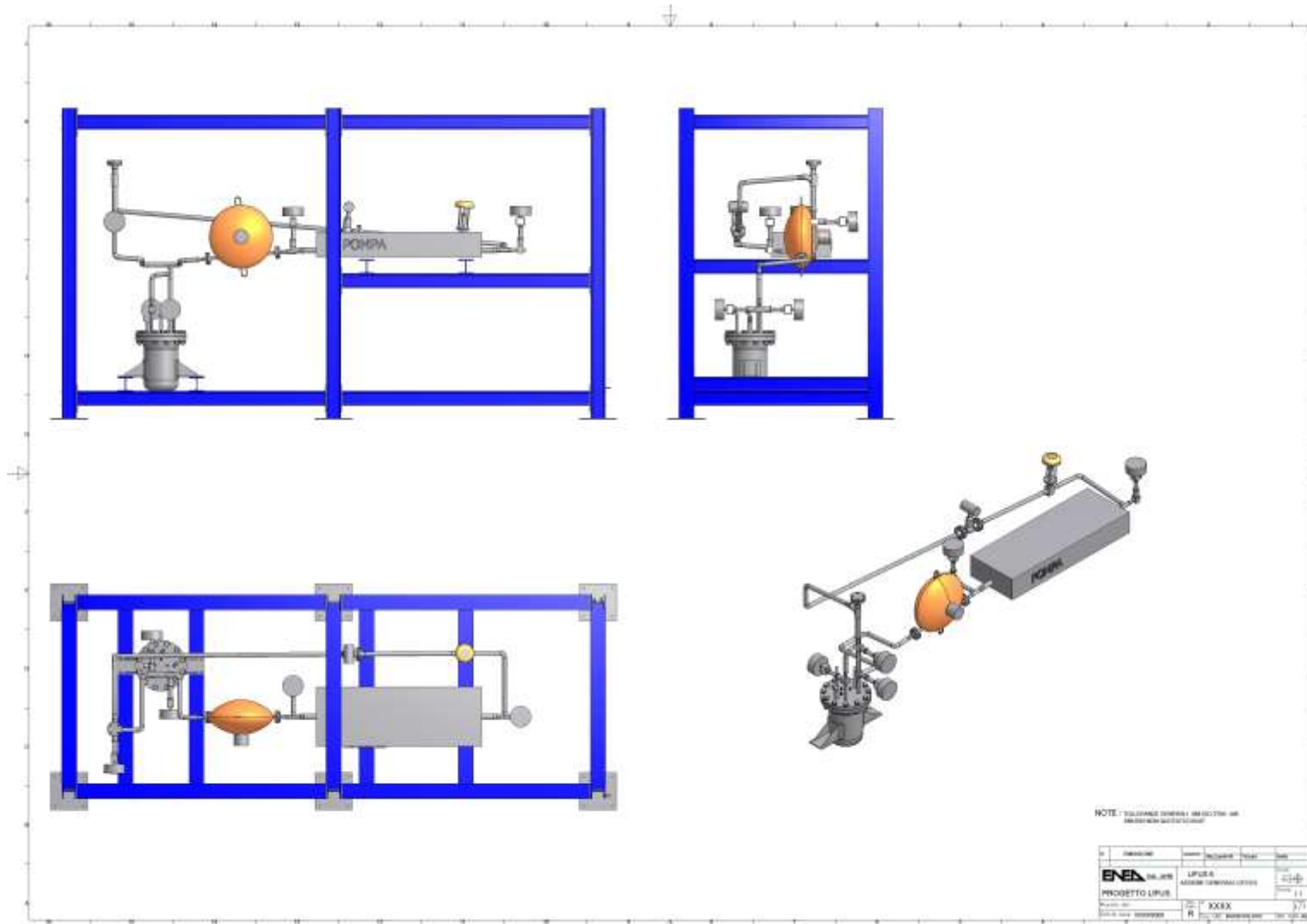
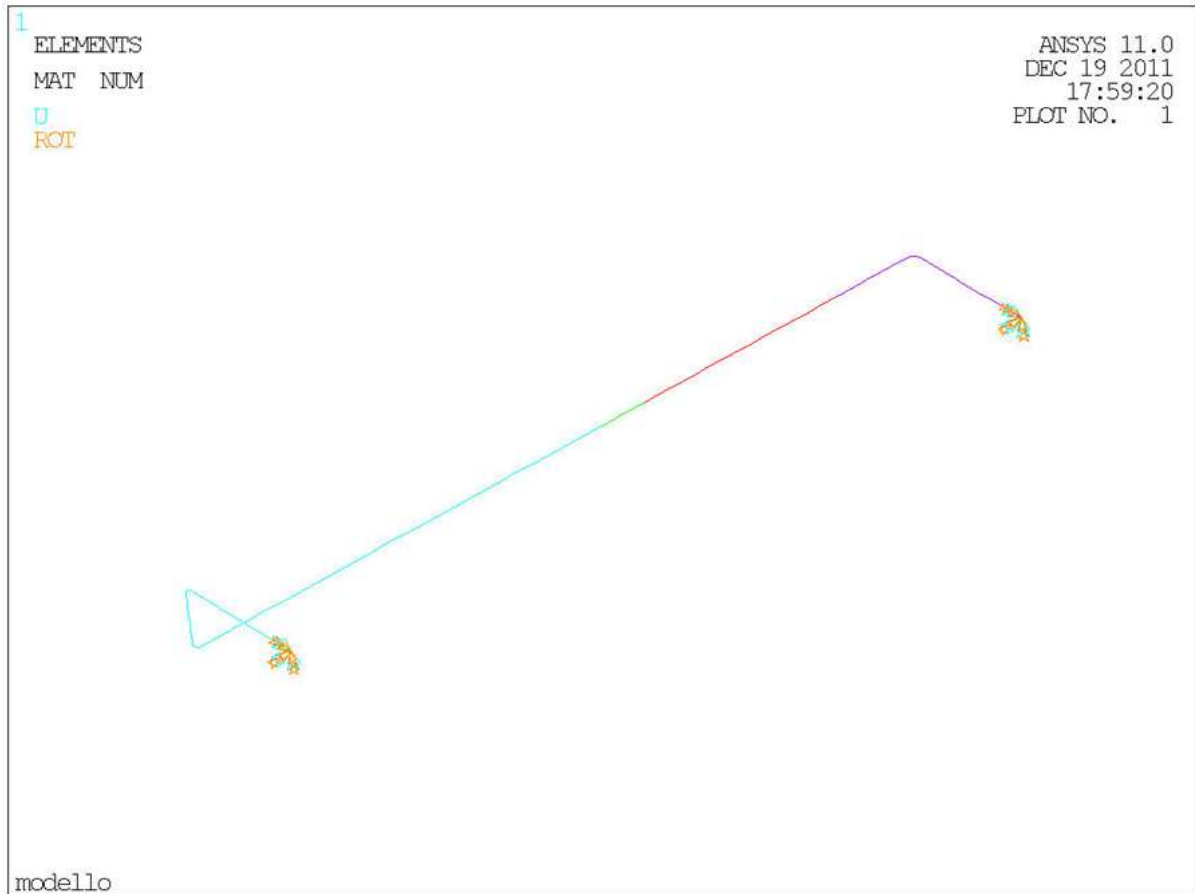


Figure 4: loop and support skid

## Thermomechanic analysis

The only fixed points of the loop are represented by the pump and the storage tank. Therefore, the pipes are free to expand, and mechanical stresses are negligible. To check in any case the real stress/strain situation a analysis of the longest pipe using Ansys was performed and results are show in figg. 5 to 9.



**Figure 5: nodalisation of the longest pipe, with material selection**

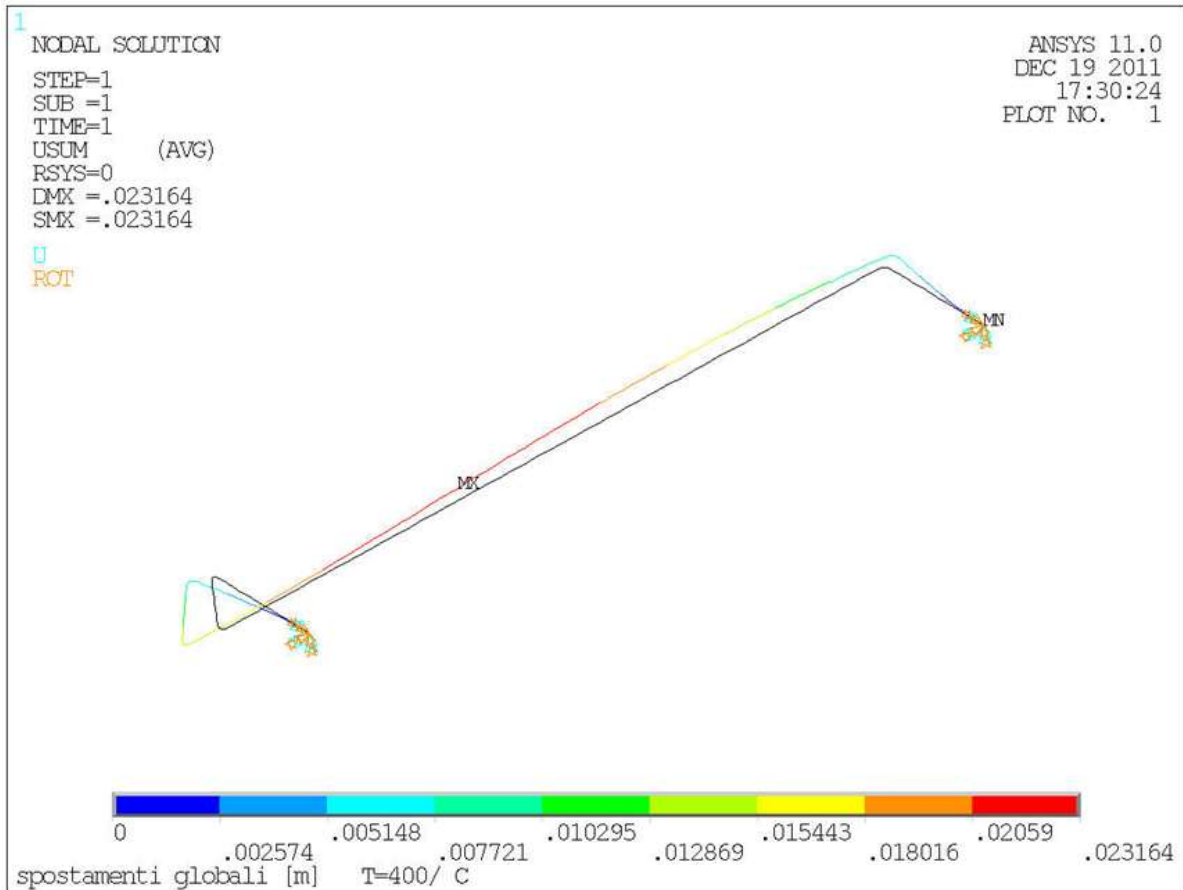


Figure 6: displacement of pipe at 400°C

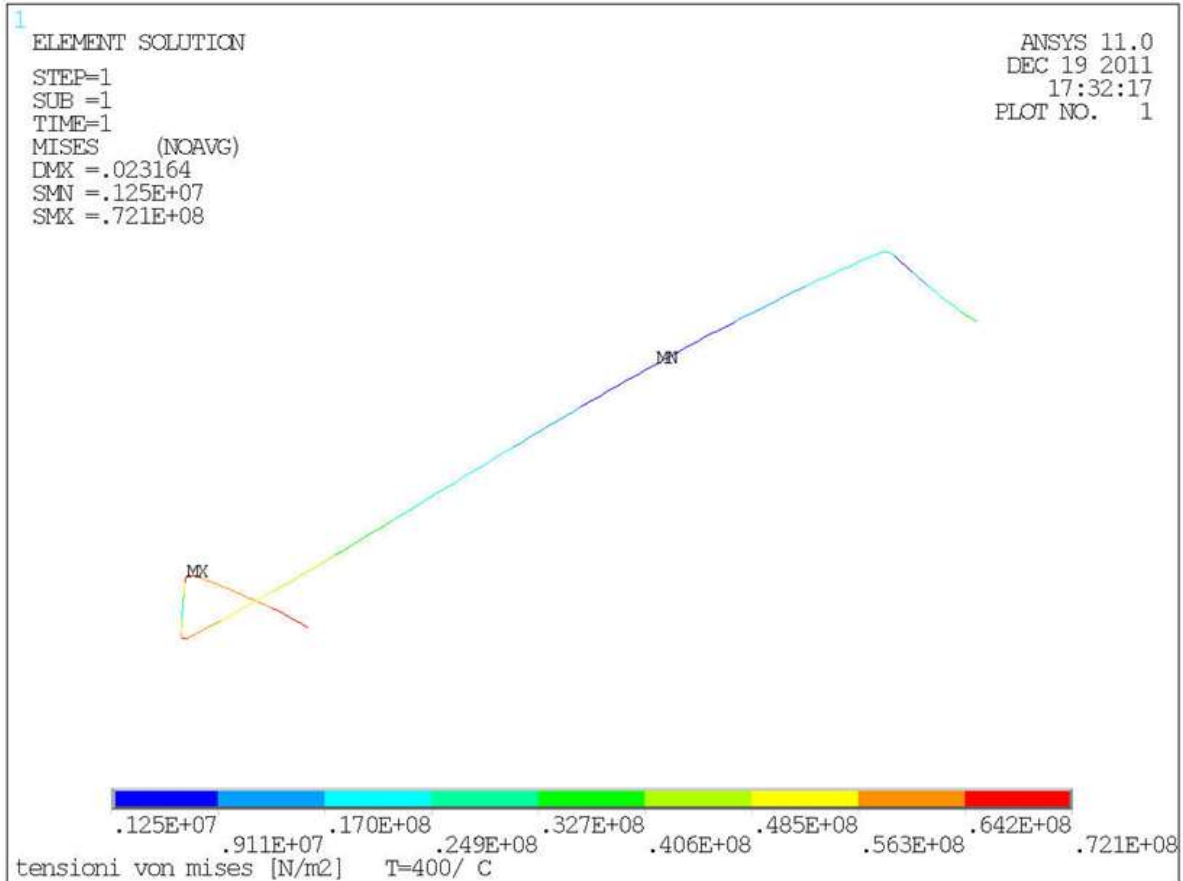


Figure 7: stress configuration at design temperature (400°C)

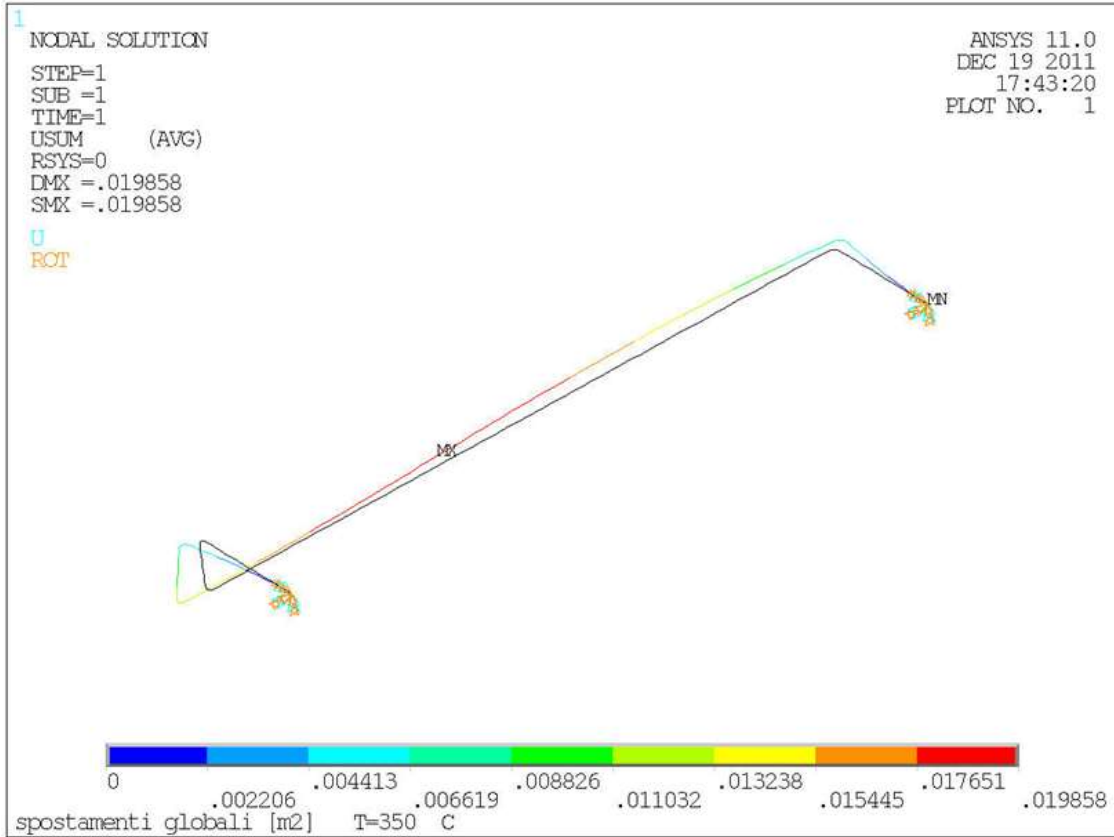


Figure 8: displacement of pipes at 350°C

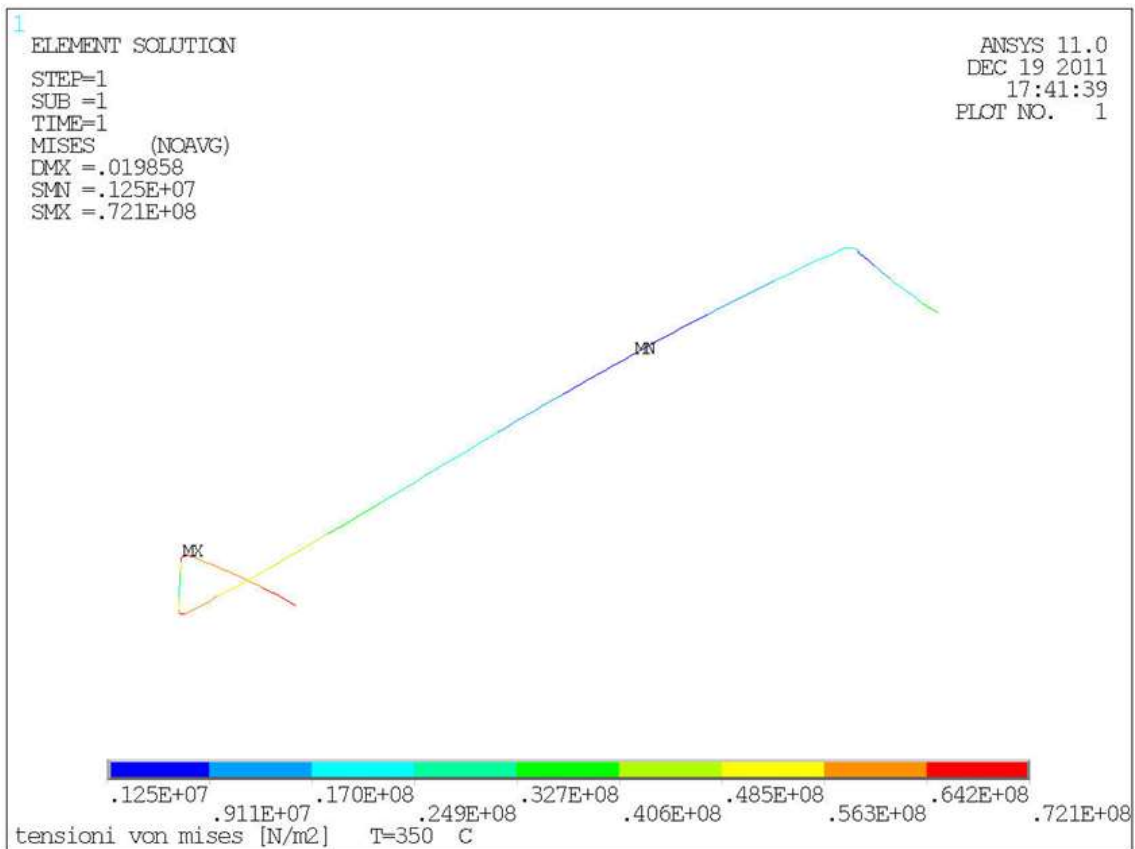


Figure 9: stress configuration at 350°C

## Anslys input parameters

Material: AISI 316 STEEL

TEMPERATURE [°C]	EXPANSION COEFFICIENT [1/°C 10 <sup>-6</sup> ]	YOUNG MODULUS [GPa ]	POISSON
25	15.97	192.0	0.3
100	16.40	185.9	0.3
200	16.95	177.7	0.3
300	17.45	169.6	0.3
400	17.91	161.4	0.3
500	18.33	153.3	0.3
600	18.17	145.2	0.3

In fig. 5 the geometry and nodalization of the system is represented, at room temperature, with the assumed knots of no rotation or translation at the ends.

In fig. 6 the total elongation passing from room to 400°C temperature, the reference for design, is represented while in fig. 7 the stress is reported. The total elongation is about 23 mm with a stress of 7,21 MPa. At 350°C, fig. 8, the elongation is 19.8 mm with a stress of 7,21 MPa in fig. 9. The stress is almost the same due to the decrease of Young modulus increasing the temperature.

This value is very low, one order of magnitude lower than the basic allowable stress given by ASME B31.3, and in any case pipes are free to move thanks to flexible suspensions.

## Test section design

For what concerns the test section, a detail of this is shown in fig. 10, while the assembly is in fig.11. The specimens have a cylindrical shape and are mounted on a rod fixed in the upper part to a removable centering plate, and supported on top and bottom of specimens assembly with centering systems. The centering plate is completely uncoupled with respect to the upper flange, to maintain the possibility to easily remove the upper flange and to use an extraction system to remove the specimen assembly, that will be surely stuck due to the presence of lithium.

With this solution it is realized a meatus in which the lithium flows at the design speed of at least 15 m/s. The triple anchoring of the support rod prevents the occurrence of vibrations in turbulent flow conditions. The outer diameter of the specimens is 20 mm, with a central hole of 3 mm, for the rod, and a height of 8 mm. The channel that hosts them has a diameter of 21 mm, with an external diameter corresponding to the one of a 1" standard pipe. The upper part of the test section, for a height of about 300 mm, is filled with Ar, in order to prevent any contact between the lithium and the sealing area of the flange. The pressure during operation will be about 2 bar, to compensate the pump head at test section inlet maintaining a constant level of lithium also during the start up of the pump. A double-level sensor is installed in the test section to control any accidental level climbs. The samples can be extracted by draining the system, opening the flange while maintaining the circuit in an inert atmosphere and removing the rod sample holder. This procedure ensures a limited contamination of the circuit and the maximum safety for the operators, reducing downtime for the replacement operations.

There is the possibility that lithium will reach the sealing area. That is the reason why the use of spiral wound sealing was preferred to ring joint, giving a higher guarantee on the clearness of the sealing area.

The connection with the circuit piping at inlet is made with a saddle-shaped coupling with 2" diameter to reduce the fluid velocity and the turbulence in the upper part of the test section about 5 cm of lithium are foreseen upper the joining to realize as much as possible calm fluid conditions and static free surface. This is necessary to avoid the transport of gas bubbles that should promote specimens erosions and pump cavitation.

The gas volume will act also as expansion tank in case of thermal expansion of lithium increasing the temperature or when launching the pump.

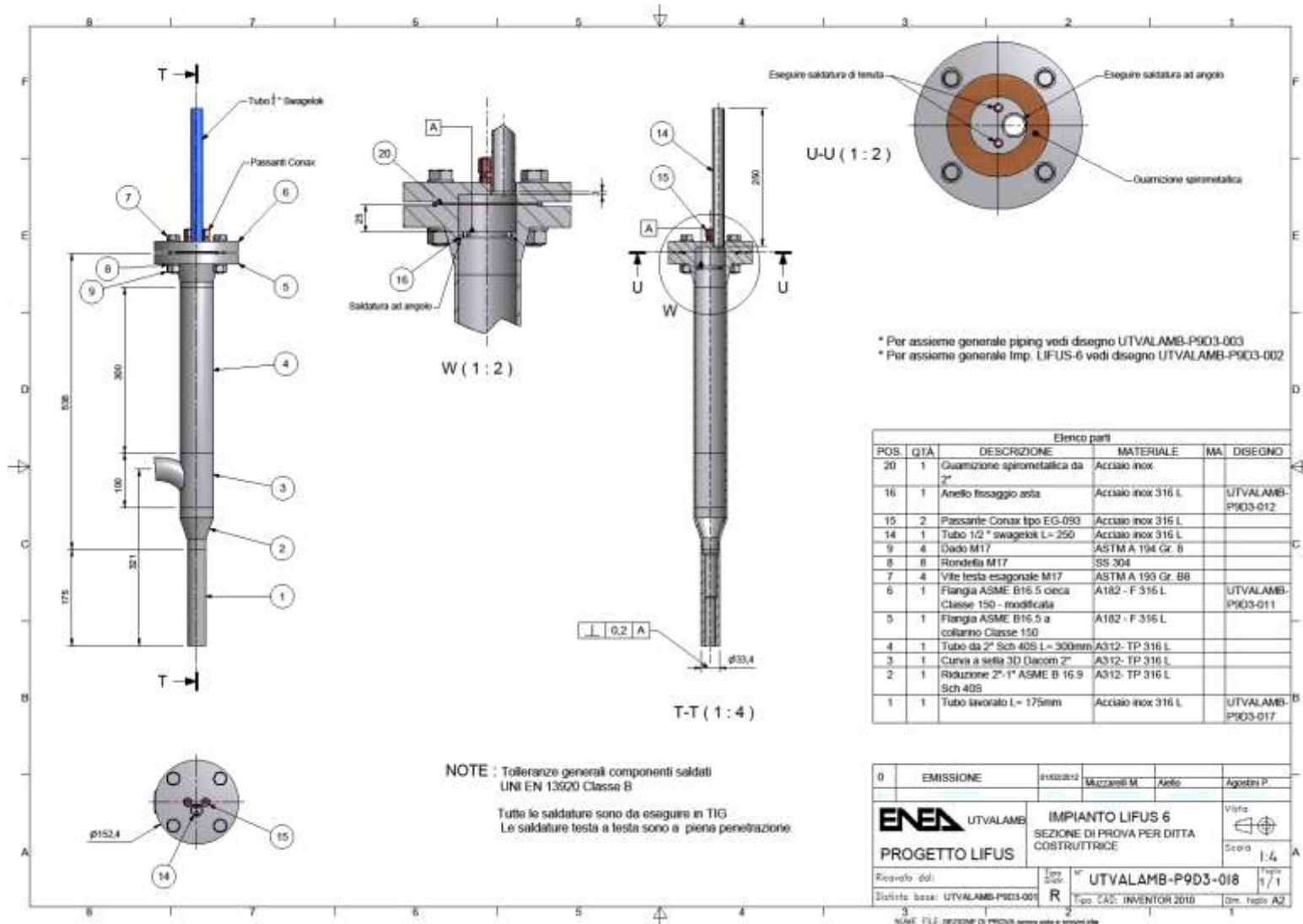


Figure 10: test section external view



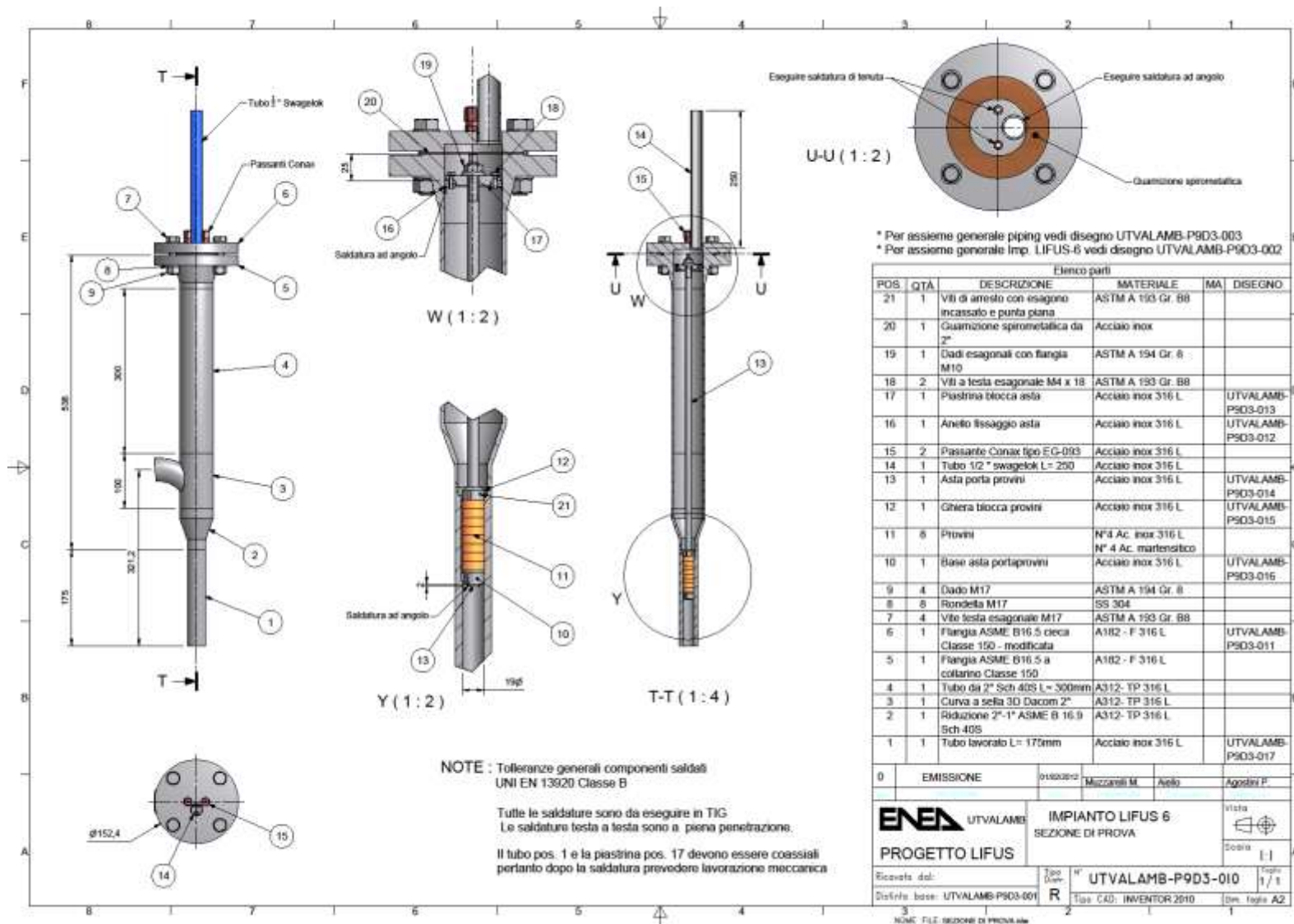


Figure 11: test section internal view with specimens

## Instrumentation

The instrumentation system consists of:

- Standard type K thermocouples, mounted on pipes surface;
- Vortex Flowmeter Rosemount Model 8800, Scale 0.08 - 2.7 m/s;
- Mass Flow Meter Coriolis type Micro Motion DT 65, scale 0-4000 kg/h
- Liquid metal pressure gauge Gefran IE2-S-6-M-B01D-4-4-D-0-0, piezoelectric type, scale 0-10 bar;
- Conductive level sensors in the storage tank and test section.

Instruments have been selected to be safe and suitable for use in lithium, at temperatures up to 350 ° C, and are provided with analog or Modbus type output, obviously excluding the thermocouples, or digital output.

## Control System

The control system is based on National Instruments products. In particular for the PLC have been selected modules of the family CompactRIO able to guarantee the required performances.

The CompactRIO system is comparable to the market standard Siemens S7 on small systems such Lifus6, in which it is requested the management of a limited number of points. It has a greater ease of use being able to be fully programmed by NI LabView Real Time.

The loop will be remote controlled connecting the PLC via a standard TCP-IP address. Moreover, as happens on all PLC systems, in case of loss of network connection the system will maintain the last safe configuration set with a full management of abnormal situations and alarm.

The accurateness of the control system will be verified performing a series of tests in water, to determine the time of response of the pump/test section/ flow meter system.

## Safety systems

To prevent injuries to personnel due to lithium leaks several safety measures have been adopted:

1. The experimental hall is completely isolated with safety doors during loop operations. The presence of personnel is not foreseen when the lithium is circulating, and the loop is remotely controlled.
2. A smoke reveal system can fastly identify the gaseous products of a reaction between lithium and environment.
3. Pipes are protected with a leak detection system based on the use of electrical contacts.
4. Valves are protected with a leak detection system.
5. Steel tanks are installed under the loop to avoid contact between lithium and concrete.

## Test and Evaluation Program

The test section is designed to perform three different corrosion test durations, hereafter presented:

### Short term test

The first experimental campaign will have a duration of 2000 hours. The test matrix is given below. Four specimens, two per each material, will be extracted, while four will be leaved in the test section.

Run	Material	Velocity [m/s]	Temperature [°C]	Time [h]	Nitrogen [wppm]	Roughness Ra [µm]
1	SS/EF	16	350	2000	< 30	< 0.3

Analysis of the specimens comprises:

- Cleaning of one sample and determination of the weight loss per unit of exposed surface (resolution 0.1 mg)
- Cutting and metallography of the specimen surfaces, not cleaned, by optical and scanning electron microscopy, measuring the variation in inner diameter and roughness at three different heights along the specimen;
- Elemental analysis of the residual metallic matrix by EDX;

Li will be analyzed at the end of the first run for impurity content determination.

### *Mid and Long term tests*

After the end of short term test one half of the specimens will be substituted and a 4000 hours run will be performed. The total test duration in this phase will be about 6,000 hours. The test program is given below.

Run	Position	Velocity [m/s]	Temperature [°C]	Time [h]	Nitrogen [wppm]	Roughness Ra [ $\mu\text{m}$ ]
2	SS/EF	16	350	4000	< 30	< 0.3
3	SS/EF	16	350	6000	< 30	< 0.3

## Loop operations

### *Lithium filling*

The Lifus6 loop will be full of lithium in its storage tank connected to the circulation pipes by two lines, one for the ordinary charging of the loop and the second one for the drainage. The tank is partially filled with titanium acting as nitrogen getter. To perform the purification of lithium before each charging the storage tank will be heated at 600°C. After this purification phase the storage tank will be cooled down at 300°C, and the system will be ready to be charged. The loop will be filled under vacuum. This is necessary to avoid the presence of gas in contact with pressure sensors. For this reason the inert gas in the loop will be evacuated using a vacuum pump. When the pressure is significantly lower than the atmospheric one, at least  $10^{-1}$  mbar, the connection valve V2 between the storage tank and the loop will be opened. If necessary, to speed up the loop charging inert gas will be gradually injected in the storage tank until a complete filling is reached. The loop will be considered fully filled when the level sensor in the test section will be reached by liquid metal. The V2 valve will be closed. At the end of this phase the test section will be filled with high purity Ar gas at over atmospheric pressure to prevent lithium contamination form external atmosphere.

### *Start of Li circulation*

After the lithium filling, the inner pressure in the test section is set at 2.05 bar.

Then the pump will be started at the lower possible power to start the circulation. The EMP voltage is progressively raised up to 235 V in order to assure a minimum flow rate of 28 l/m in the main loop. After temperature stabilization, it is necessary to verify the pump current. Since the current of each phase of the pump must not exceed 20 A, it is necessary to perform a check of all the three phases of the pump at regular time intervals. The operational pressure in the storage tank is regulated at 1.05 bar, the pressure in the loop is set at 1.1 bar to obtain a fast drainage in emergency.

At the same time the circulation in the main loop is started, the flow-rate in the purification line (in parallel) should be regulated to 5 cc/s. In order to respect the minimum residence time in the trap, the bypass flow rate can be regulated by operating the inlet pneumatic valve.

### *Draining of the loop*

The operation should be necessary in normal operations or in emergency case. In the first case, after pump stopping, the intercepting valve V2 is opened remotely by the operator, and the test section and the storage tank are connected to have a continuous pressure equilibrium and the drainage by gravity of the loop. Then the heating cables of the loop are switched off. In case of emergency, the drain operation is automatically activated and the test section pressurized to have a fast drainage. The drain conditions are: lithium leak and smoke detection.

## Conclusion

The construction of the loop is being completed, coherently with the presented design. The first tests with water are scheduled in November 2012, while the charging of lithium is foreseen in January 2013. Experimental activities will start at the end of the start up phase, approximately in March 2013.

## References

1. IFMIF- KEP International Fusion Materials Irradiation Facility key element technology phase report, JAERI (2003)
2. A. Aiello, 'Selection and development of materials for the monitoring and control of non-metallic impurities in liquid lithium', ENEA Report IM-A-R-02 (2003)

## List of Acronyms

Lifus 6	Experimental lithium flowing loop
DACS	Data Acquisition and Control Systems
IFMIF	International Fusion Materials Irradiation Facility
PLC	Programmable logic controller
$h_{ext}$	Convective
$k_{st}$	Thermal conductivity of steel
$k_{thi}$	Thermal conductivity of thermal insulation
$h$	Convection factor
$T_s$ e $T_r$	Surface and room temperature
$T_{es}$ e $T_{is}$	External and internal surface temperature
$s_{st}$	Steel thickness
$s_{thi}$	Thermal insulation thickness