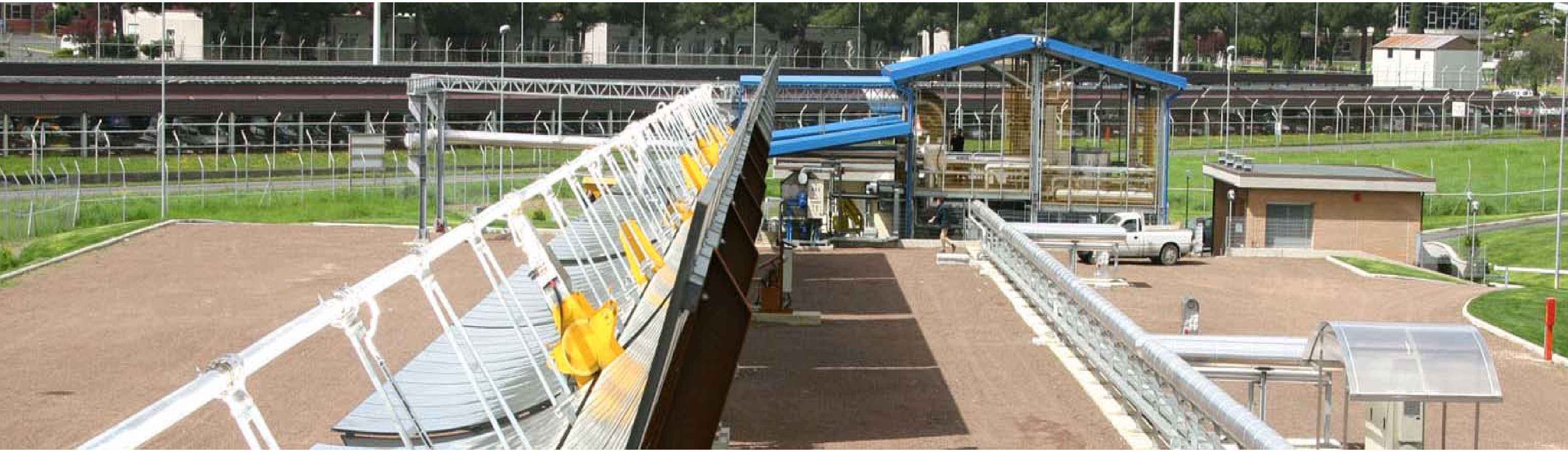
Trough Molten Salt HTF Field Test Experience

Experimental remarks on behaviour during operation and thermal fluid dynamics in transition states of molten salt mixtures



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ENEA
Solar Thermodynamic Energy
ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND THE ENVIRONMENT

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CSP Trough Molten Salt HTF Field Test Experience

This presentation deals with:

- Laboratory tests for molten salts characterization in the respect of corrosion and stability at high temperature.
- Experimental facilities and laboratory equipments with molten salts as HTF (Heat Transfer Fluid).
- Thermal Fluid Dynamics of molten salt mixtures (Transition state behaviour).
- R&D on molten salt Steam Generator.
- R&D on Thermal Storage systems.
- Molten salt HTF: instrumentation, piping and components (valves, pumps, etc.).

Laboratory tests for molten salts characterization in the respect of corrosion and stability at high temperature.

Chemical characteristics of molten salt in PCS facility		
Denomination	Mixture of sodium nitrate and potassium nitrate	
Weighed composition	*Sodium Nitrate $NaNO_3$*	60 %
	Potassium Nitrate KNO_3	40 %
Minimum concentration of nitrates		99 %
Maximum concentration of impurities	Nitrite	0,20 %
	Chloride	0,03 %
	Carbonate	0,05 %
	Sulfate	0,15 %
	Idrossile alkalinity	0,04 %
	Perchloride	0,04 %
	Magnesium	0,04 %
	Calcium	0,04 %
	Insoluble	0,06 %
Methods of analysis	nitrites, chlorides, sulfates, perclorates	Ionic chromatography
	carbonates and idrossile alkalinity	Potenziometric tiration
	magnesium and calcium	Atomic absorption to flame (FAAS)
		Spectrometry of atomic emission to induced plasma (ICP-AES) (ICP-AES)

Laboratory tests for molten salts characterization in the respect of corrosion and stability at high temperature.

The tests have been carrying out since four years on laboratory equipments in Brasimone and Casaccia ENEA Centres.

➔ Corrosion tests in static conditions have been carried out up to now on samples of various steels (carbon and s.s. both original and welded) at various temperatures (up to 550 °C) and durations (up to 8000 hours). The analysis of results (still in progress) seam to confirm the choice of AISI 321H and 316T stainless steel as reference material for the foreseen applications (solar energy collection and storage at high temperature).

➔ Corrosion tests in dynamic conditions are going to start on MOSE (MOlten Salts Experiments) Facility for similar samples with HTF circulation at about 1 m/s velocity at the same test conditions: 550 °C temperature and 8000 hours duration.

➔

Laboratory tests for molten salts characterization in the respect of corrosion and stability at high temperature.

MO.S.E. (MOlten Salts Experiments) Facility operating conditions:

➔ LOOP CHARACTERISTICS:

- PRESSURE 0.5 MPa
- TEMPERATURE (in the test section): 550 °C
- TEMPERATURE (in the other parts of loop) 450 °C
- MOLTEN SALTS MASS FLOWRATE: 1 kg/s

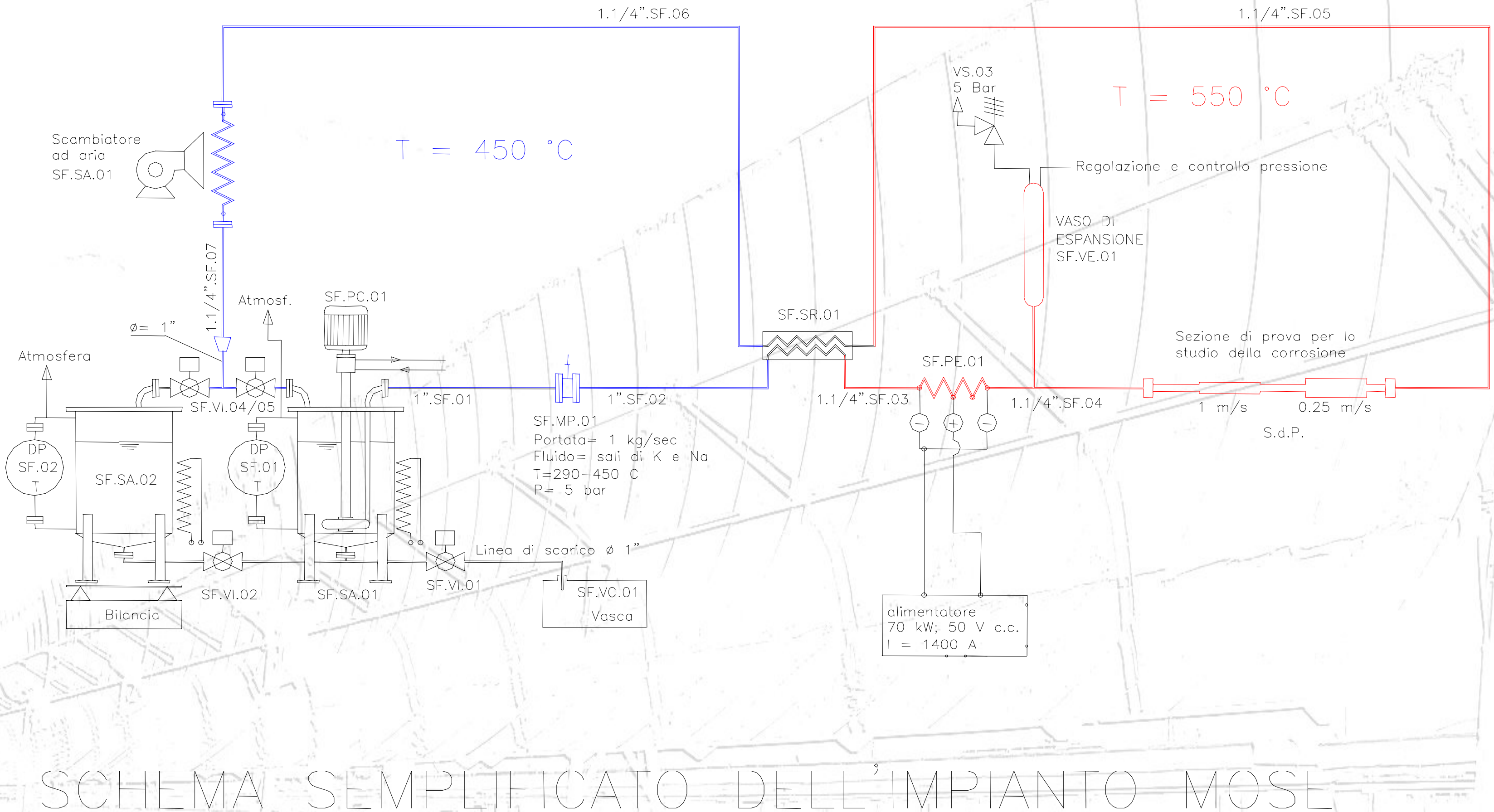
➔ TEST SPECIFICATIONS:

- DURATION: 8000 HOURS
- SAMPLES: AISI 321 H and AISI 316 T
- Test temperature: 540 ÷ 550 °C
- Velocity of fluid: 0.25 ÷ 1 m/s
- Sampling of molten salts: each 1000 hours
- 4 set of s.s. samples, to be extracted at periods of about 2000 hours

Laboratory tests for molten salts characterization in the respect of corrosion and stability at high temperature.

MO.S.E. (MOlten Salts Experiments) Facility

operating conditions:



Laboratory tests for molten salts characterization in the respect of corrosion and stability at high temperature.

MO.S.E. (MOlten Salts Experiments) Facility

Laboratory tests for molten salts characterization in the respect of corrosion and stability at high temperature.

During the previous tests on MOSE facility (2003) an accident took place: due to the corrosion of the carbon steel shaft, the impeller of molten salts pump detached from shaft causing serious damages. This fact was caused by the inadequate material choice made by pump manufacturer, that changed the material of shaft in stainless steel without any other problem.

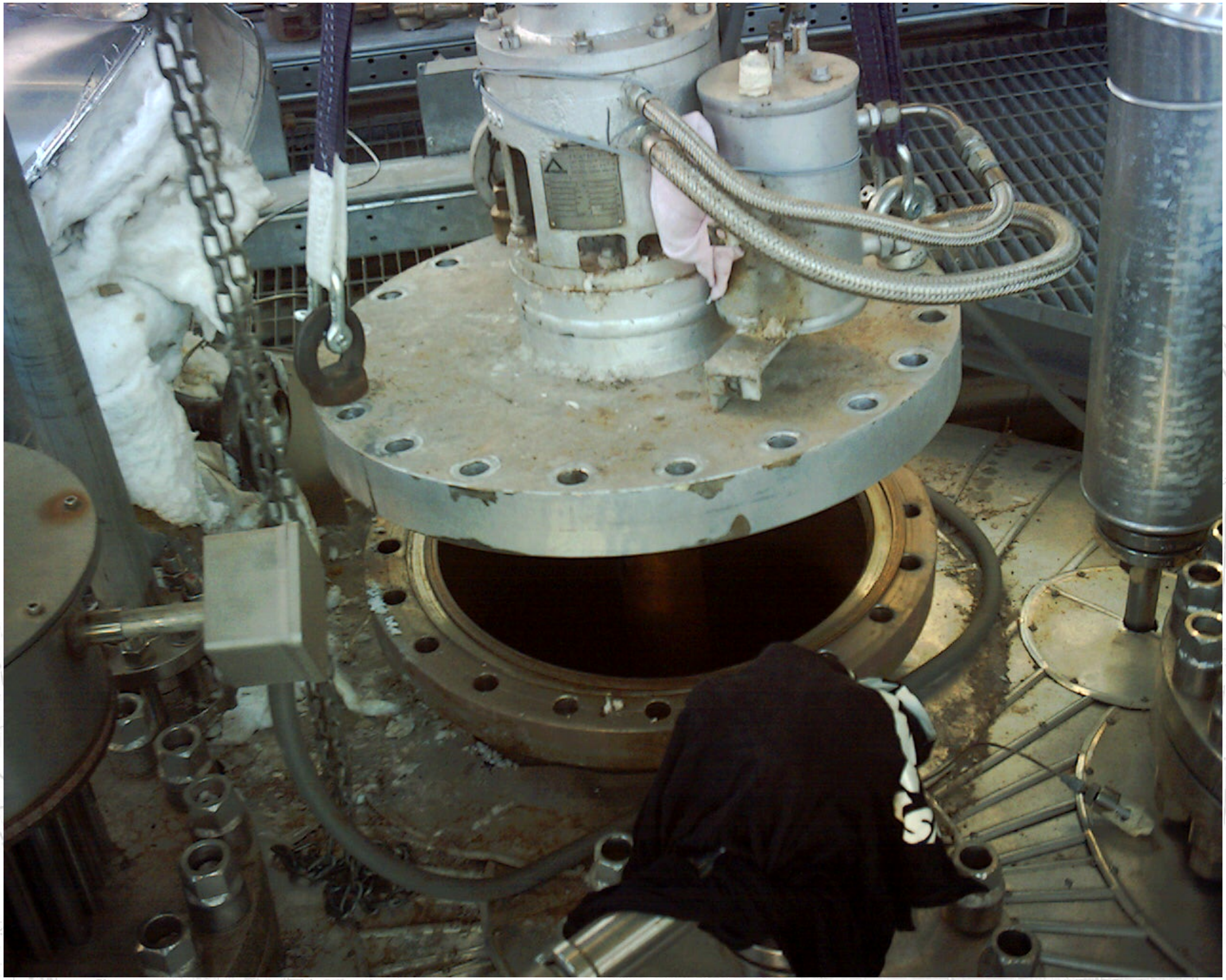
This fact is demonstrated by the following pictures of a similar molten salts pump during maintenance operation (2006, after two years of operation on PCS Facility).

Laboratory tests for molten salts characterization in the respect of corrosion and stability at high temperature.

Pump extraction from molten salt storage tank _ 1

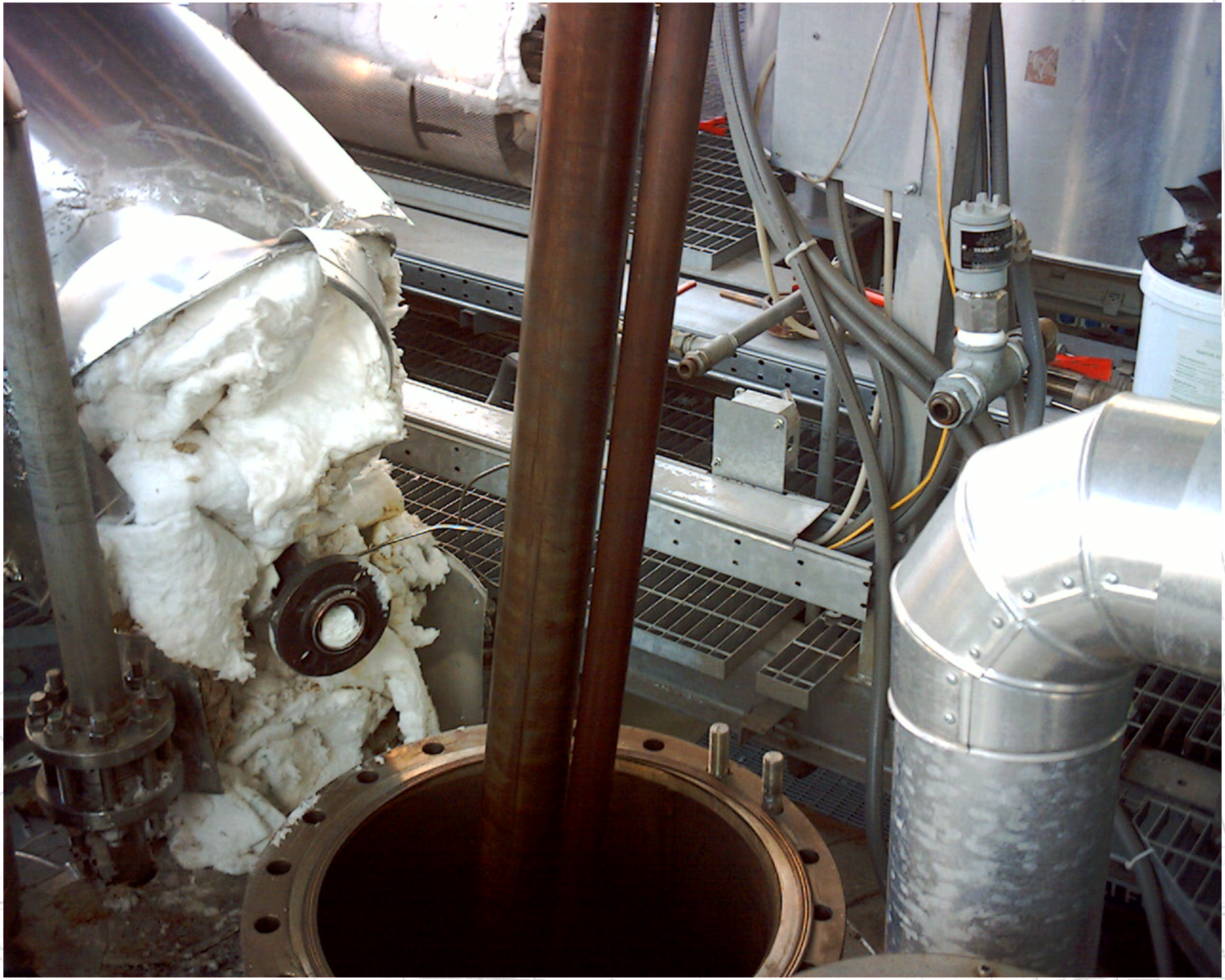
Laboratory tests for molten salts characterization in the respect of corrosion and stability at high temperature.

Pump extraction from molten salt storage tank _ 2



Laboratory tests for molten salts characterization in the respect of corrosion and stability at high temperature.

Pump extraction from molten salt storage tank _ 3

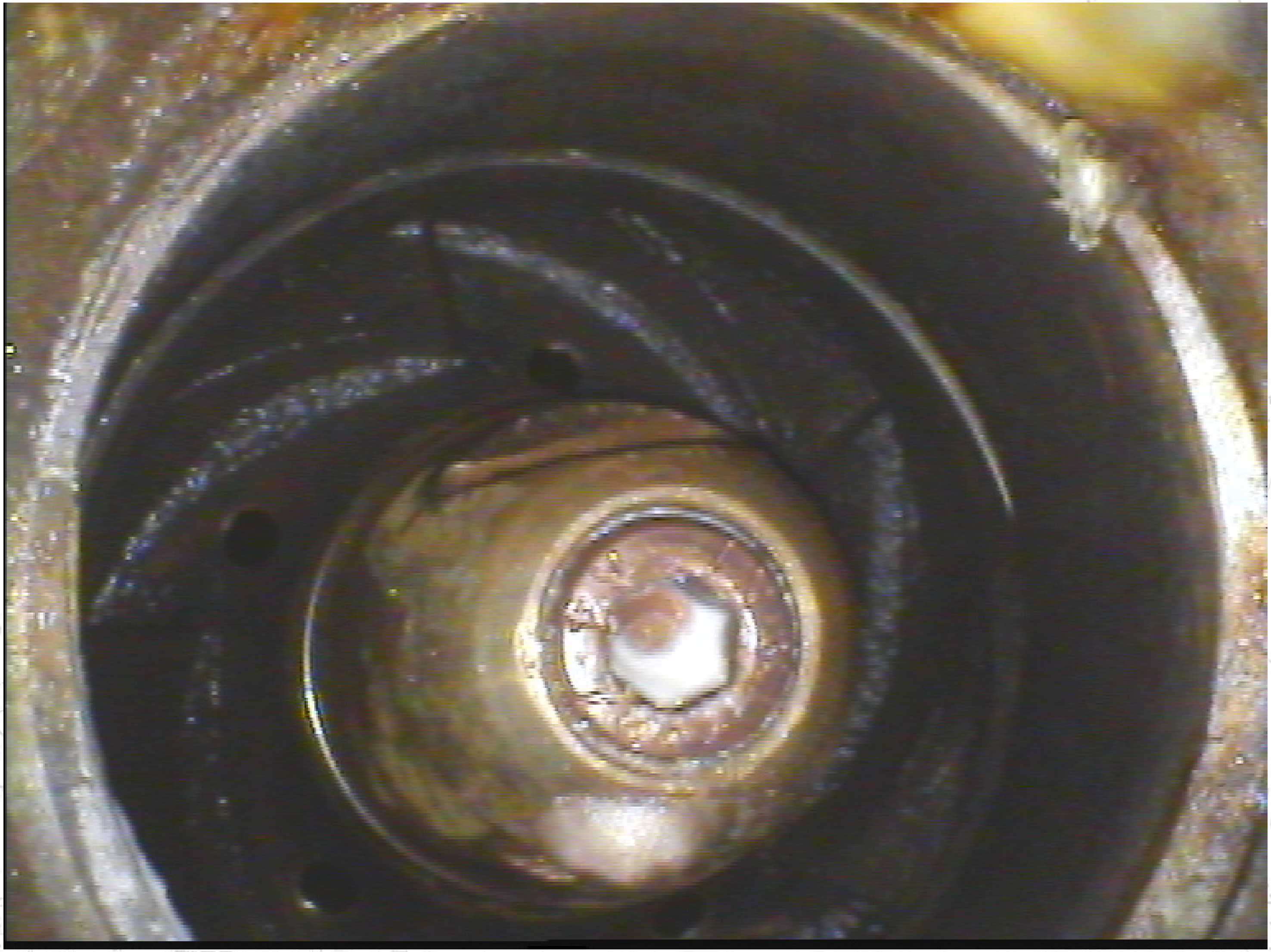


Laboratory tests for molten salts characterization in the respect of corrosion and stability at high temperature.

Pump impeller examination by endoscope _ 1

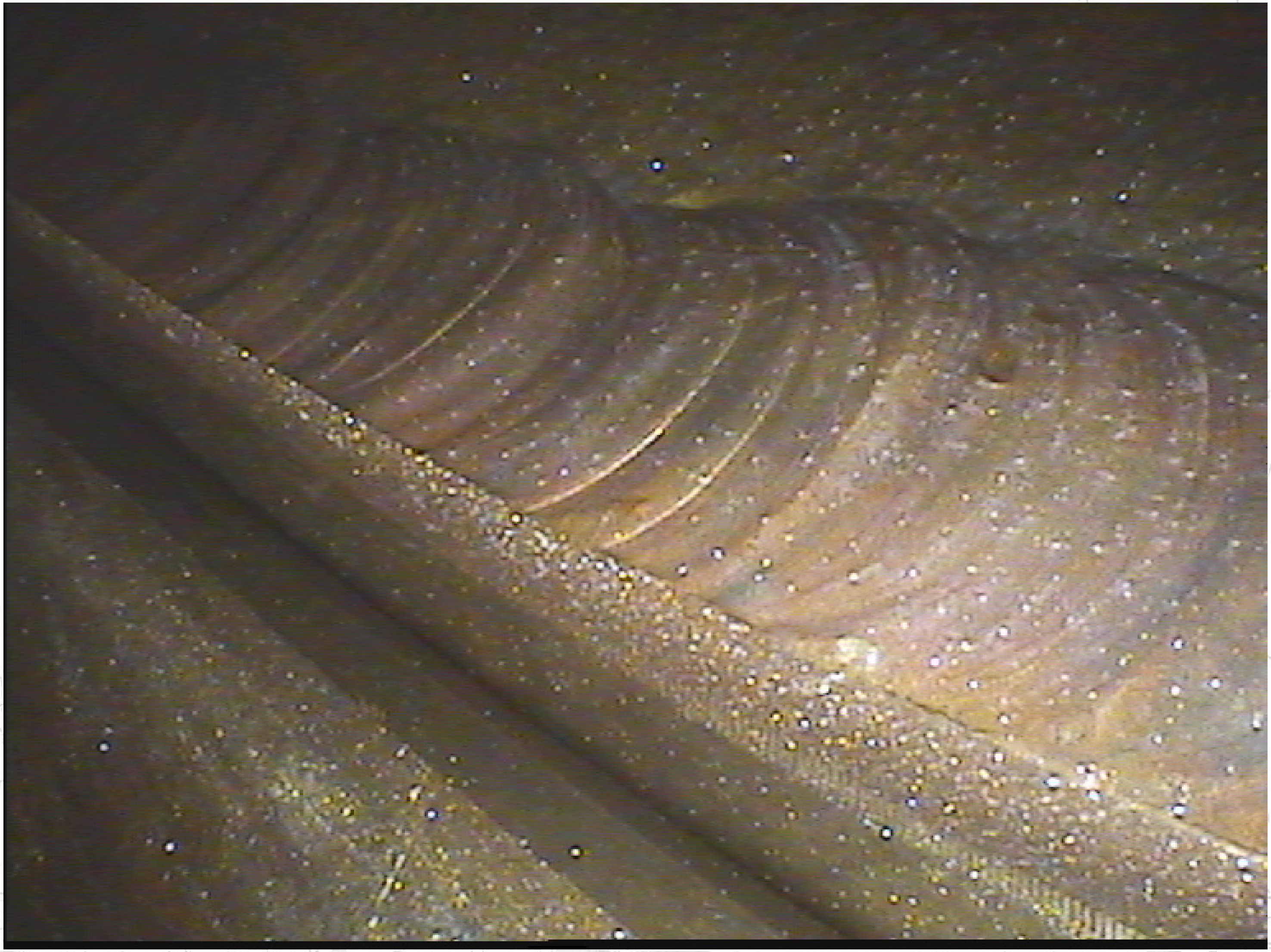
Laboratory tests for molten salts characterization in the respect of corrosion and stability at high temperature.

Pump impeller examination by endoscope _ 2



Laboratory tests for molten salts characterization in the respect of corrosion and stability at high temperature.

Pump impeller examination by endoscope _ 3



Laboratory tests for molten salts characterization in the respect of corrosion and stability at high temperature.

Pump impeller examination by endoscope _ 4

Laboratory tests for molten salts characterization in the respect of corrosion and stability at high temperature.

Stability tests in fluxed or not pressurized recipient conditions have been performed up to now on samples of molten salts at temperature up to 600 °C and duration up to 10000 hours. The analysis of results (also in progress) seam to confirm that molten salts nitrates degrade significantly in nitrite over 550 °C in fluxed conditions, without recovering at following cooling; while in not fluxed conditions after the cooling process a partial amount of nitrites reconverts to nitrates.

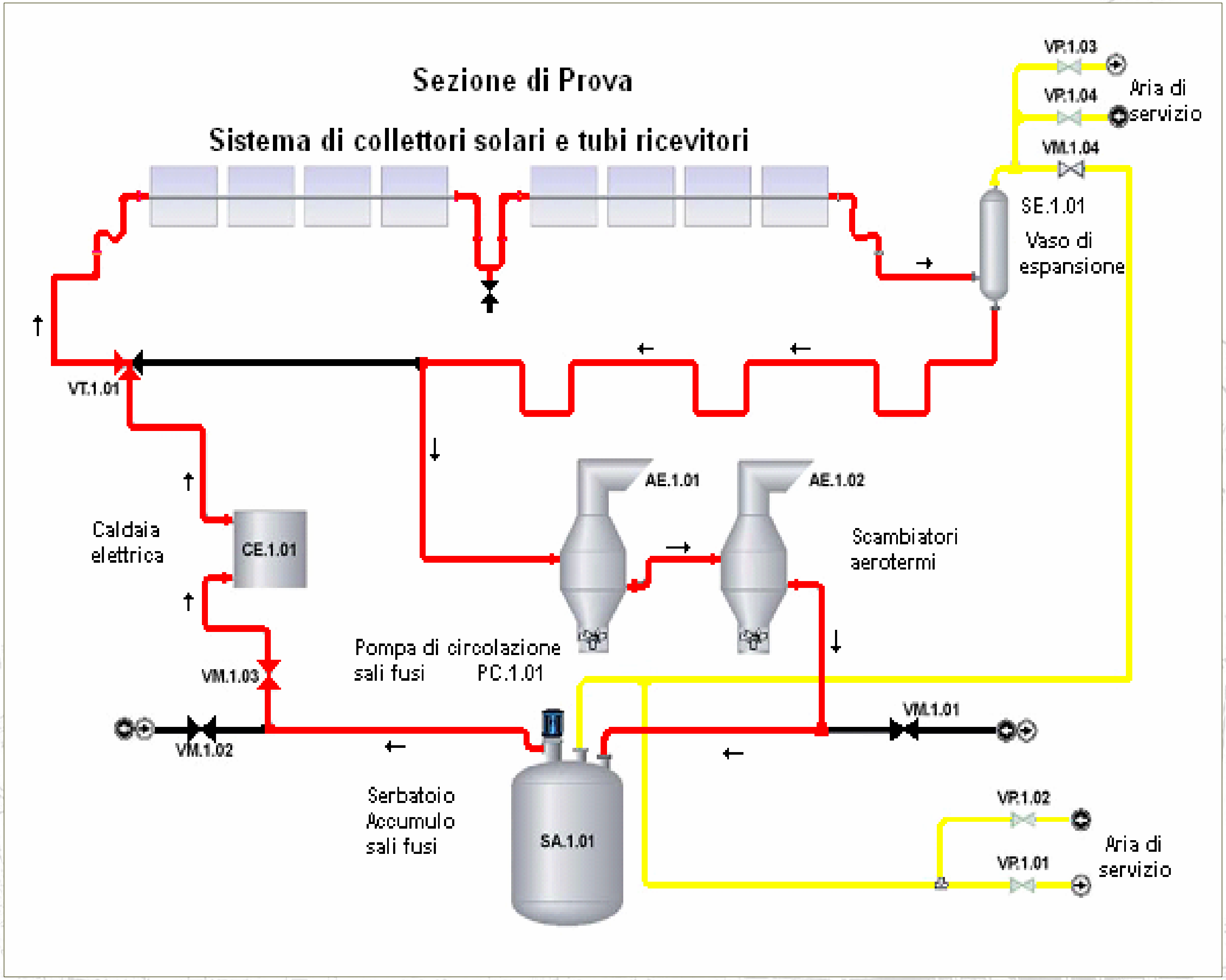
Experimental facilities and laboratory equipments with molten salts as HTF.

The most significant application in ENEA for molten salts as HTF is the PCS (solar collectors test) Facility that has been operating since about three years with these main results:

- full validation of concepts and technologies (as usual) adopted for the earlier design of the experimental facility;
- suggestion of some corrections in order to avoid any rising defects of components, to improve the operation reliability of the plant and to reduce the costs of manufacture;
- suggestion of new concepts and technologies (innovative) for a better design of trough CSP power plants, both large scale and small/medium scale co-generative.

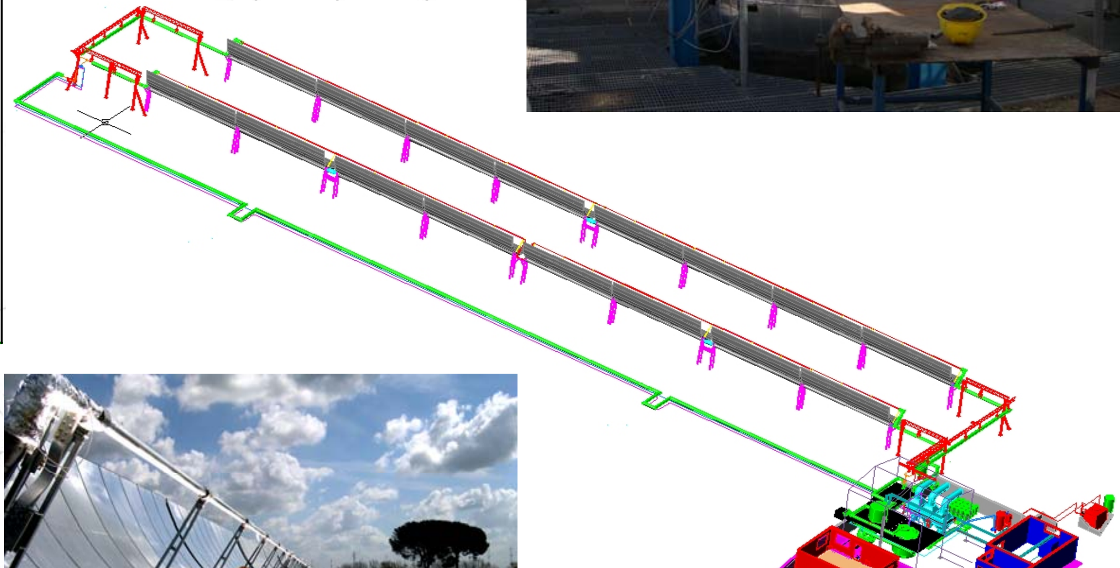
Experimental facilities and laboratory equipments with molten salts as HTF.

Diagram of PCS facility



Experimental facilities and laboratory equipments with molten salts as HTF.

Parameters	values	m.u.
Heat Transfer Fluid	mixture of salts: 40% KNO_3–60% $NaNO_3$	
Mass flow rate, min / max	2.5 / 6.6	kg/s
Temperature, min / max	270 /550	°C
Pump discharge pressure	0.80	MPa
Thermal storage tank:		
- diameter	2.0	m
- height	2.8	m
- design pressure	0.25	MPa
- auxiliary electrical heaters power	120	kW
- stored molten salts	12	Mg
Electrical pre-heater power, max	400	kW
Air coolers power, max	1000	kW
CSP Trough Test Section:		
- nominal length	100	m
- net useful mirror surface	~ 540	m^2
- design solar peak power	~ 540	kW



PCS facility

Thermal Fluid Dynamics of molten salt mixtures (Transition state behaviour)

Main targets of the thermal fluid dynamic experimental tests are:

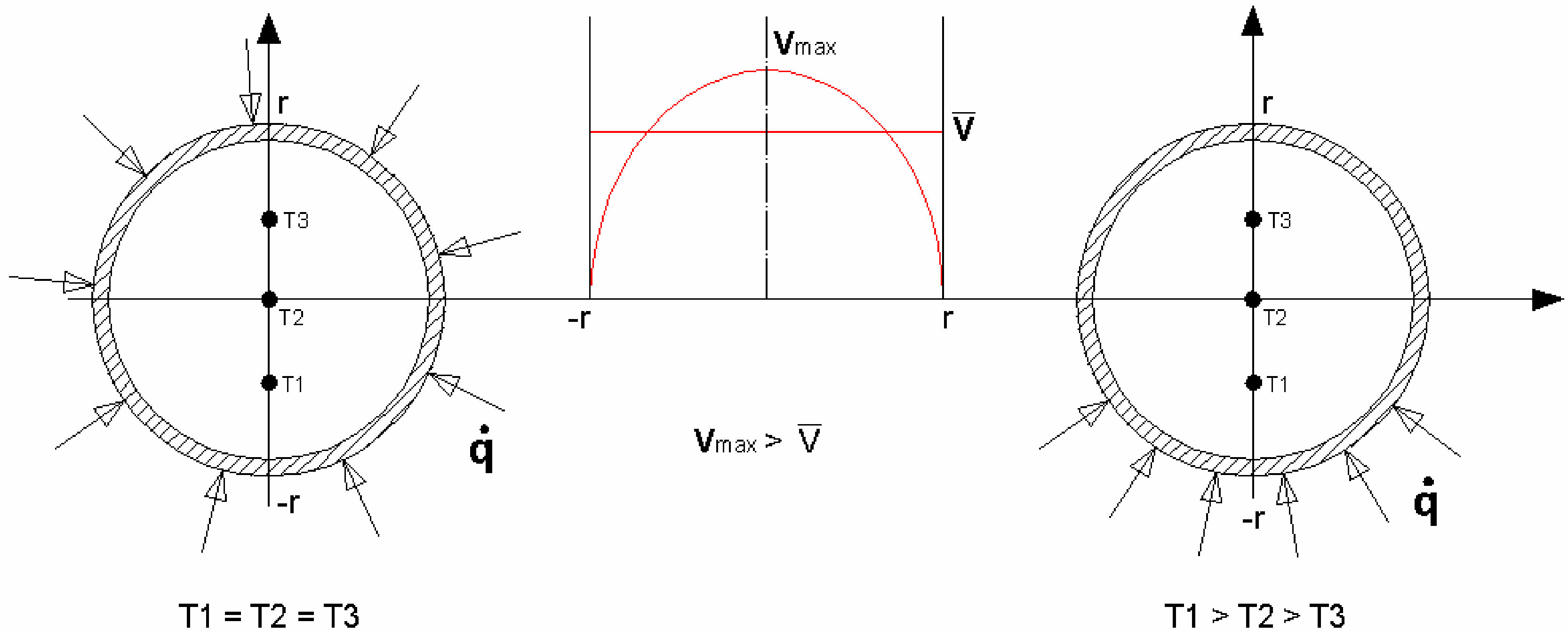
- to reduce plant management costs, especially in stand-by or extraordinary maintenance phases (plant long stops), in order to minimize heat losses and electric power supply (using only thermal power if possible),
- to have always full piping,
- to perform ‘pulsed’ salt circulation in order to maintain piping in hot conditions,
- to get medium scale plants having poor service
- to get self-sufficient systems by means of thermal storage, also as to electric power supply,
- to build high performance systems in very wide variable conditions (e. g., the SG),
- to lower the costs of thermal storage system construction.

Thermal Fluid Dynamics of molten salt mixtures (Transition state behaviour)

The focused thermal fluid dynamic transition states of molten salt flow rate (single-phase flow in a pipe) are:

◆ **<u>single-phase flow (motion) outside pipe</u>**

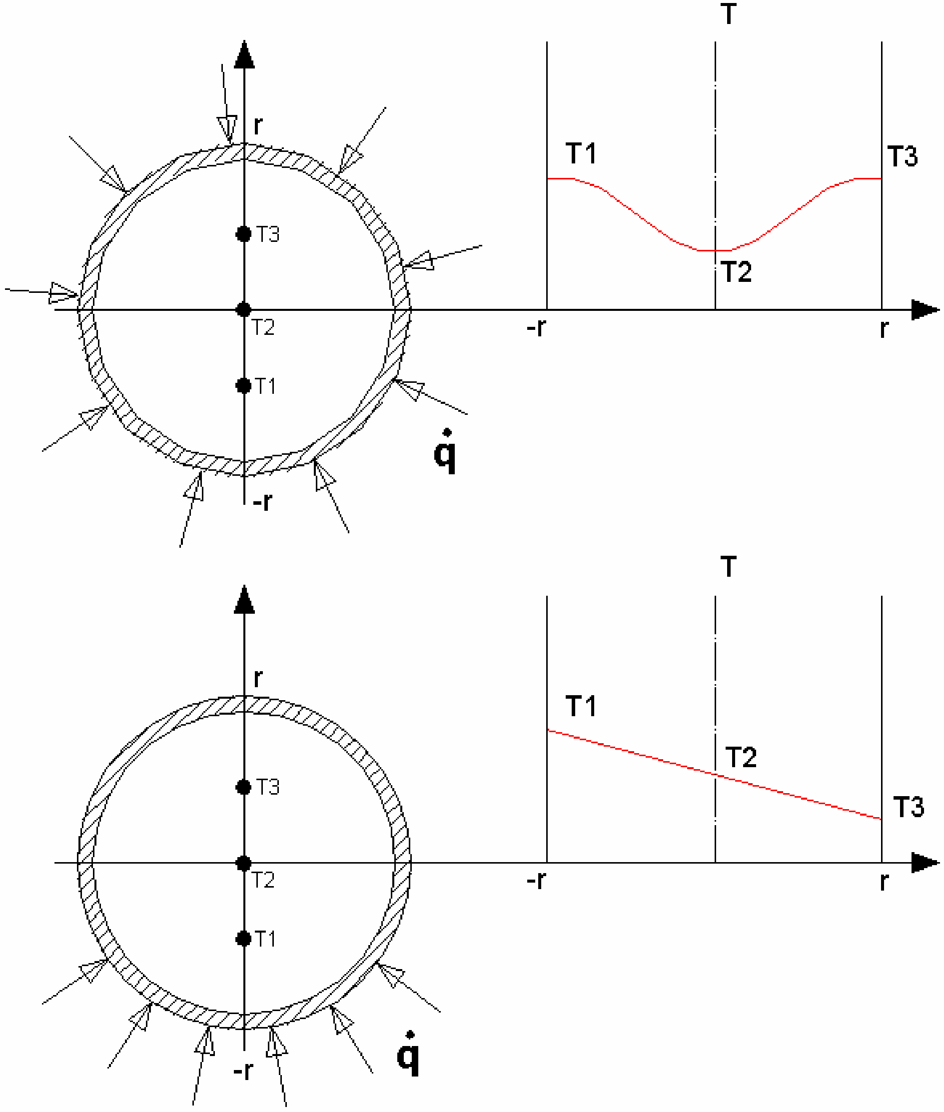
➔ fluid dynamic stratification in laminar conditions, with uniform and non-uniform heat flux on pipe surface (receiver (Heat Tube Unit, HTU) and piping),



Thermal Fluid Dynamics of molten salt mixtures (Transition state behaviour)

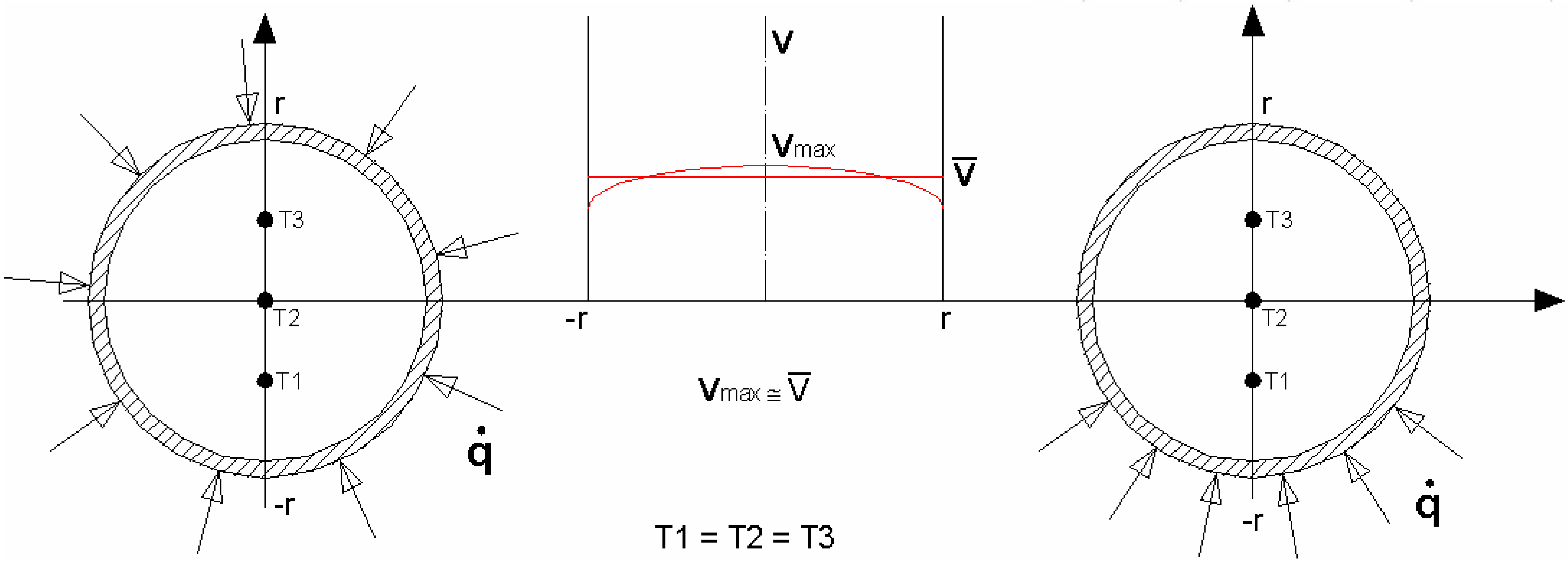
➔ Stagnant fluid:

thermal stratification with uniform and non-uniform heat flux up to freezing or melting of the salt



Thermal Fluid Dynamics of molten salt mixtures (Transition state behaviour)

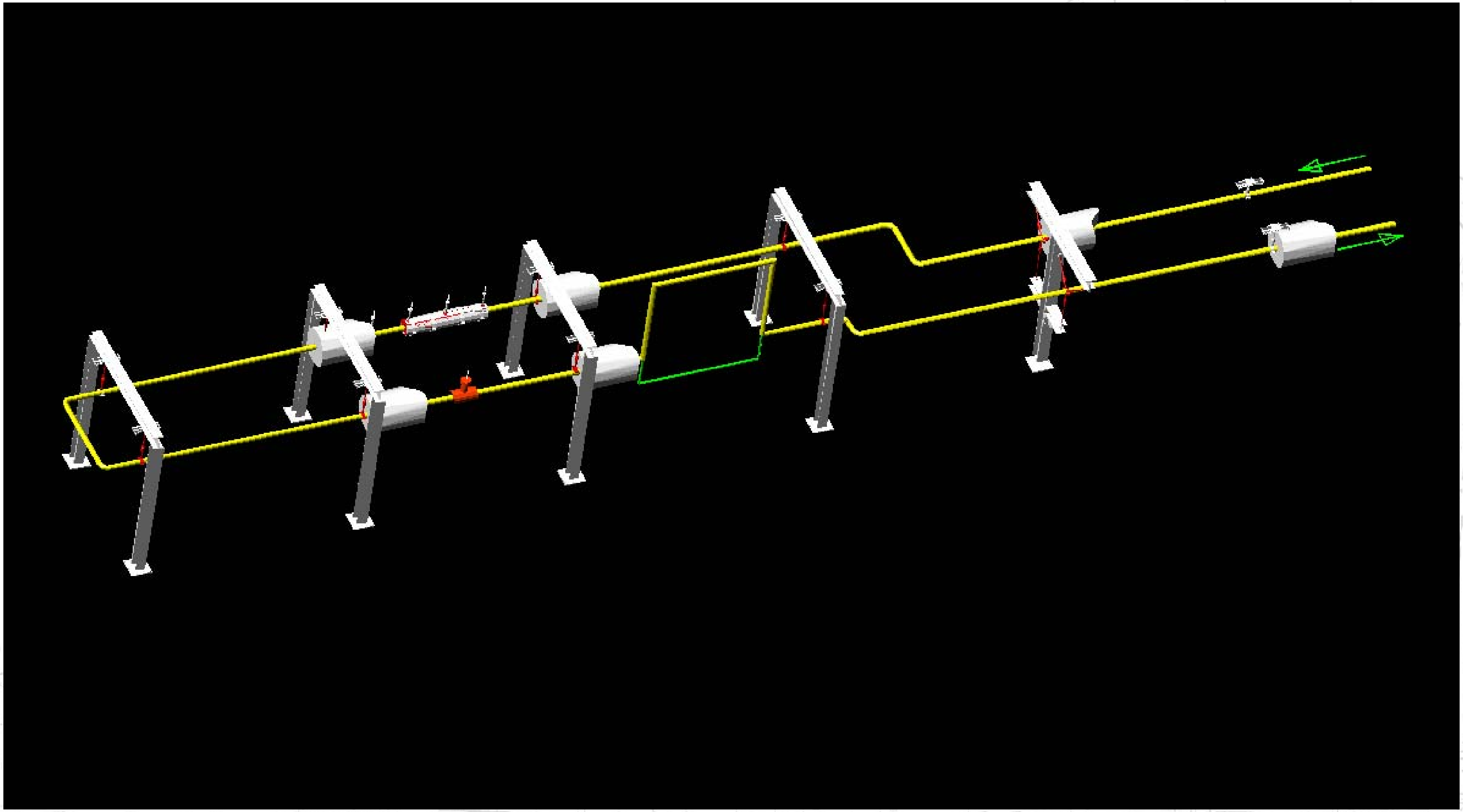
- study of the laminar → turbulent transition state with effect on the thermal stratification, with uniform and non-uniform heat flux



- study of the average heat transfer coefficient: $\alpha = f\,(T, v)$

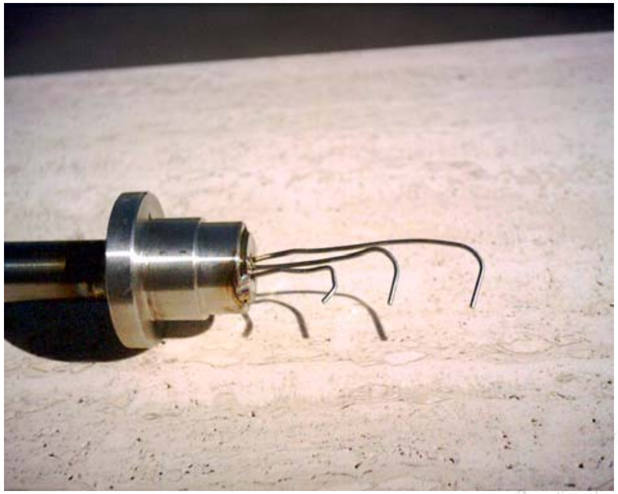
Thermal Fluid Dynamics of molten salt mixtures (Transition state behaviour)

- test section with Joule effect direct heating for thermal fluid dynamics experiments



Thermal Fluid Dynamics of molten salt mixtures (Transition state behaviour)

Details of the test section during construction

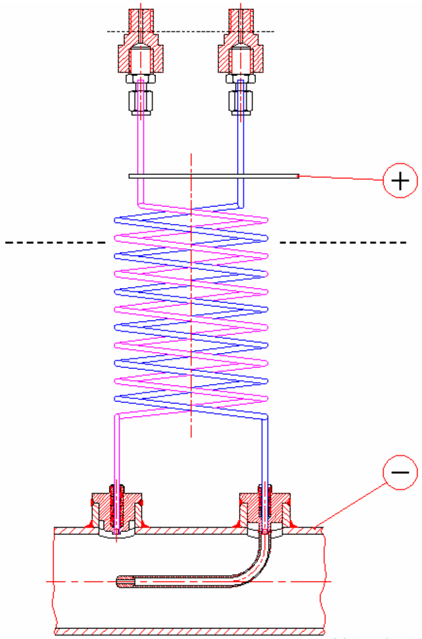


Thermocouples

(immersed in the fluid)

Thermal Fluid Dynamics of molten salt mixtures (Transition state behaviour)

Details of the test section during construction



PITOT TUBE

(joule effect heated)

Thermal Fluid Dynamics of molten salt mixtures (Transition state behaviour)

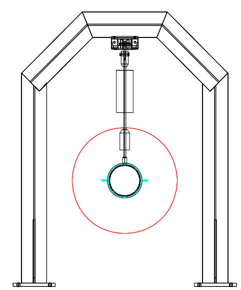
Details of the test section during construction

Piping without insulation

Special equipment for piping operation

Piping with complete insulation

Electrical/thermal insulated hangers for Joule effect direct heated piping

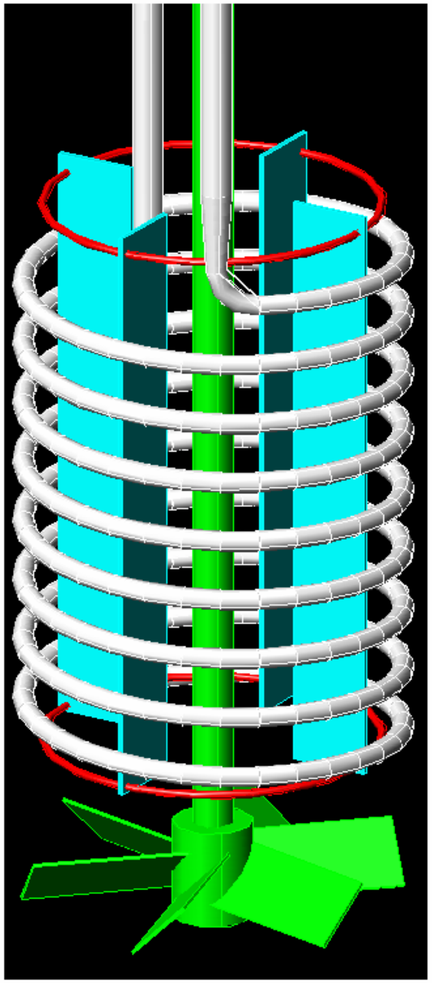


- **<u>single-phase flow (motion) outside pipe</u>**

  - ➔ study of the outside pipe motion of molten salt in extended medium (into a tank), also with baffles and impeller

  - ➔ study of the heat transfer coefficient in molten salt, coil external side: $\alpha = f\,(T, v_{salt}, \text{geometry})$, also with variation of temperature conditions inside the tubes (both single-phase or two-phase), up to incipient or occurred salt solidification with eventual heat flux re-balancing. Experiments useful in SG design.

Thermal Fluid Dynamics of molten salt mixtures (Transition state behaviour)

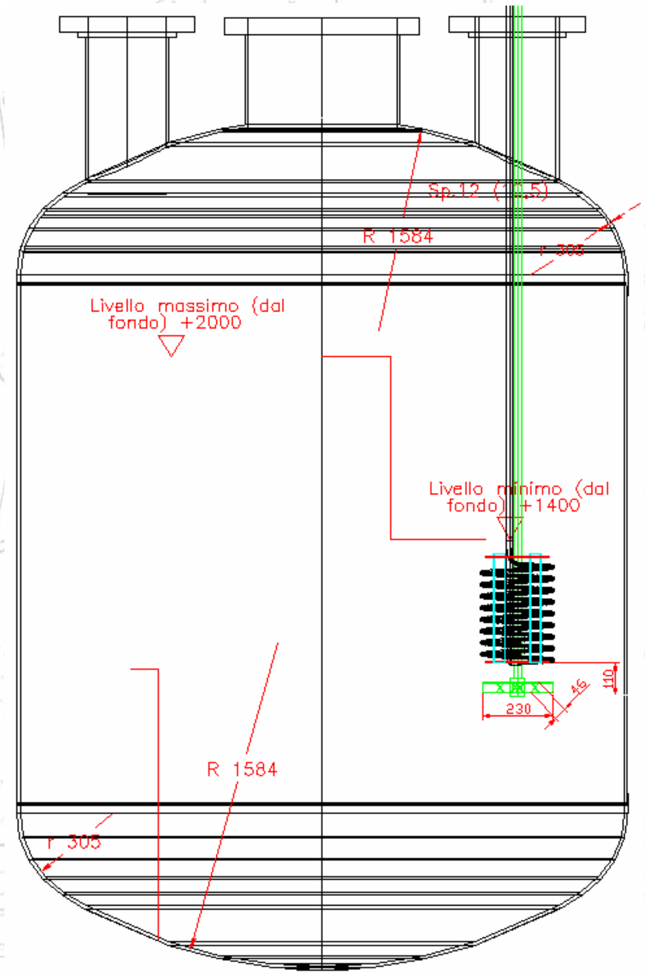


Test section main parameters:

- pipe diameter	1/2”
- coil diameter	0,23 m
- height	~ 0,35 m
- design pressure	6,0 MPa
- design temperature	290 °C
- steam mass flow rate	0,25 kg/s
- rated thermal power	30 kW

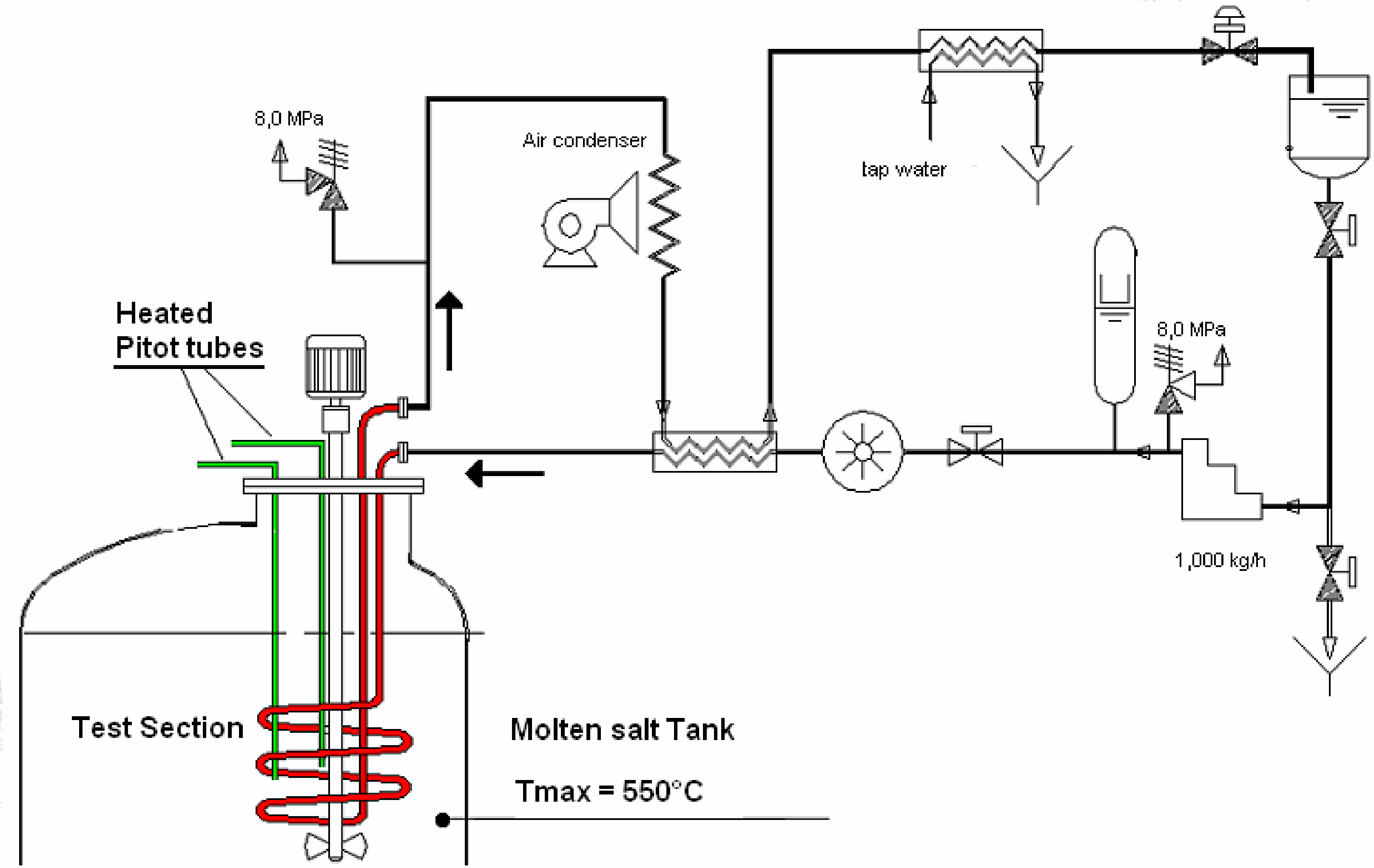
Scheme of the Test Section for the study of the basic parameters of a helicoidal coil SG

Scheme of the PCS facility storage tank with the Test section for measurement of the characteristic parameters of an helicoidal coil SG



Thermal Fluid Dynamics of molten salt mixtures (Transition state behaviour)

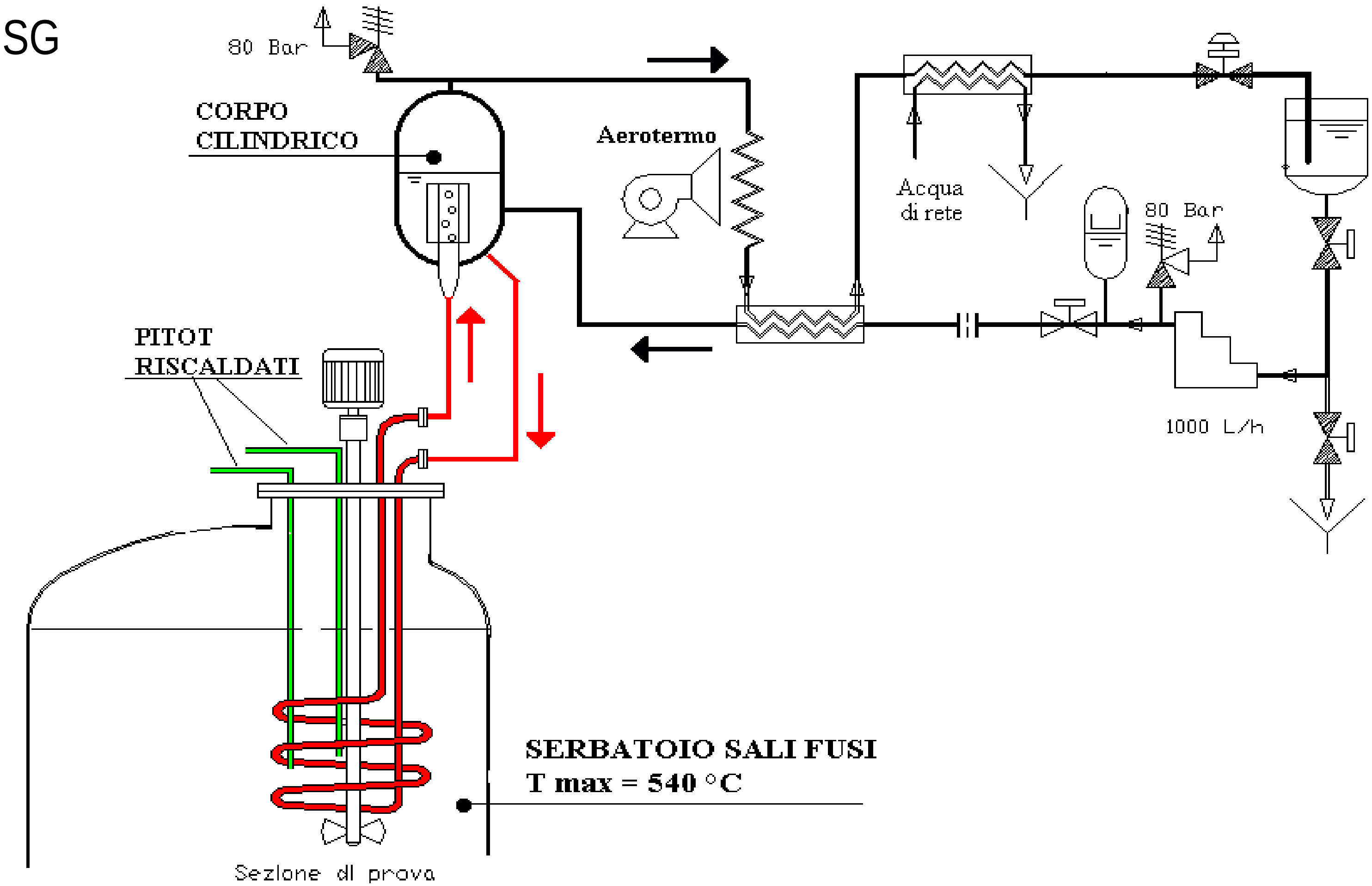
➔ experimental facility for 'once-through' SG



Thermal Fluid Dynamics of molten salt mixtures (Transition state behaviour)

- experimental facility for 'natural recirculation' SG with steam drum

- Tests conditions:
  - P = 0,8 ÷ 6,0 MPa
  - T = 170 ÷ 275°C
  - saturated steam



Thermal Fluid Dynamics of molten salt mixtures (Transition state behaviour)

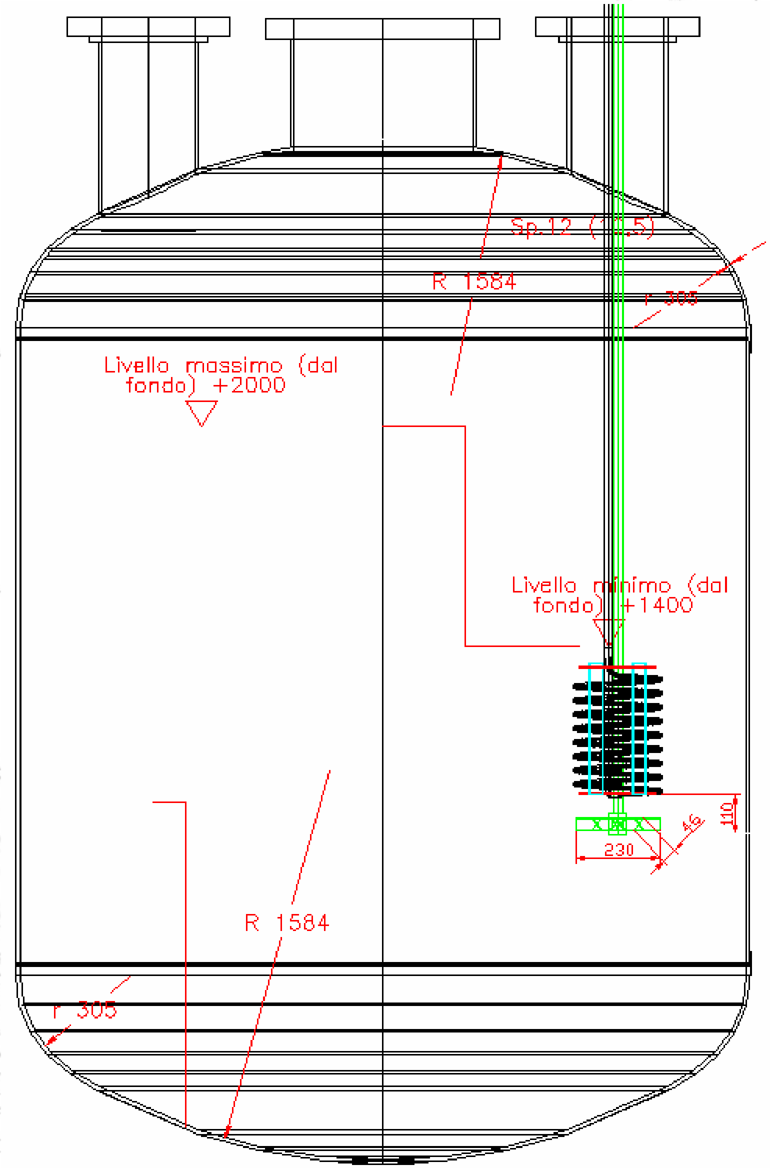
- **<u>Molten salt behavior and stratification inside tanks in condition of:</u>**
  - ➔ cooling control by means of central heater,
  - ➔ natural cooling, up to incipient freezing on the wall,
  - ➔ temperature maintenance by means of central heater,
  - ➔ influence of impeller induced agitation,
  - ➔ influence of both pump induced and incoming hot reflux mixing.

Thermal Fluid Dynamics of molten salt mixtures (Transition state behaviour)

PCS facility storage tank:

- diameter	2.0 m
- height	2.8 m
- design pressure	2.0 MPa
- electric heaters power	100 kW
- stored salt	~12,000 kg

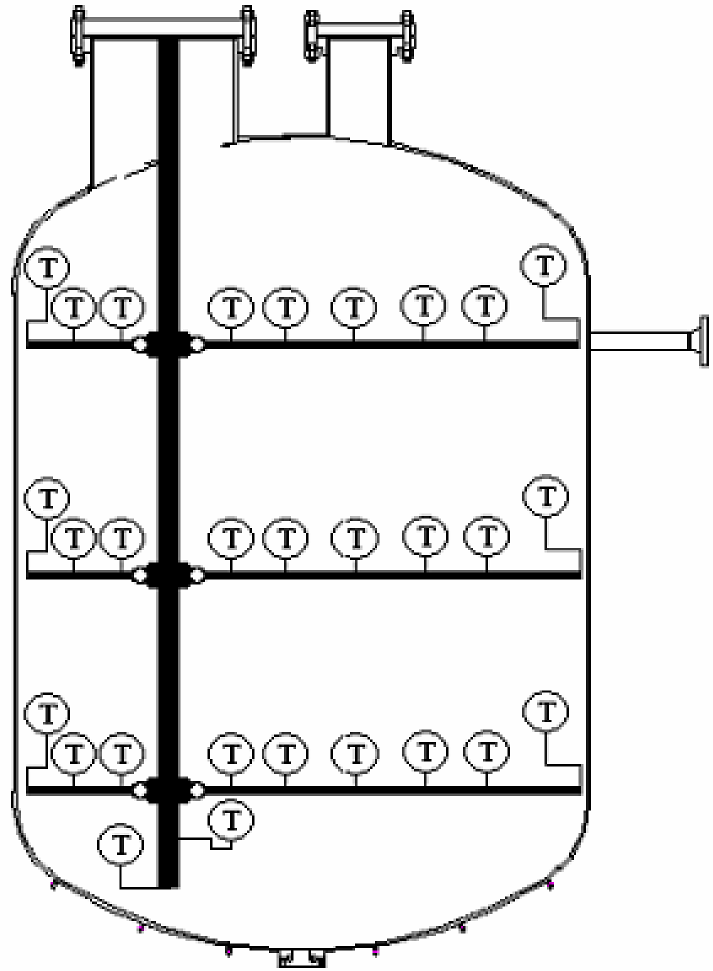
The PCS facility storage tank with the Test section for measurement of the characteristic parameters of an helicoidal coil SG



Thermal Fluid Dynamics of molten salt mixtures (Transition state behaviour)

Foreseen experimental tests:

temperature profiles measurement during heating and cooling phases, for the correct management of the tank with partial salt freezing



The PCS facility storage tank with the Test section for measurement of temperature profiles

disposition of thermocouples inside the tank

R&D activities on molten salt Steam Generator in ENEA

The experience of over three years qualification tests on PCS Facility suggests the application of the ENEA technology not only to large size power plants, but also to smaller size cogenerative power plants. These smaller plants, characterized by high efficiency in primary energy utilization allowed by the high temperature thermal storage of molten salt, are a solution technologically efficient and versatile for a large variety of industrial/civil heat processes.

R&D on molten salt Steam Generator

In medium/small size plants, in order to obtain competitive costs comparable to conventional cogenerative plants, it is necessary:

- to assure an adequate amount of simplifications to the thermal cycle of molten salt,
- to design components of not expensive manufacture,
- to get a simple plant operation.

R&D on molten salt Steam Generator

The two main components of the thermal cycle, not considering the solar field, are the Steam Generator and the Storage tanks:

- a simplification both of the cycle and of the plant operation can be obtained through integration of these two components, inserting the SG inside one of the two tanks,
- in the small/medium size plants, where it is chosen to carry out storage only in sensible heat and not also in mass, the SG is inserted in the only existing tank.

R&D on molten salt Steam Generator

Main characteristics of this type of SG:

- realization with helicoidal coils, with consequent simplicity in construction and management:
  - natural recirculation with steam drum, with dry saturated steam production and following overheating,
  - ‘once-through’, with direct steam production at the required quality,
- foreseen advantages:
  - possible salt freezing in distribution heads avoided,
  - high thickness shell for high pressure avoided,
  - possibility to maintain warm the SG during plant stand-by.

R&D on molten salt Steam Generator

- possibility to vary the conditions of produced steam by operating on the thermal exchange parameters

$$\dot{Q} = U * S * \overline{\Delta T}_{ln}$$

$$U = \frac{1}{(D_e/D_i)1/\alpha_{H2O} + D_e/2*\ln(D_e/D_i)/k_{ss} + 1/\alpha_s}$$

R&D on molten salt Steam Generator

- other safety advantages :
  - ➔ in case of a pipe failure with water/steam leakage in the shell, accident does not give serious consequences, if tank dome and vent pipes are suitably designed,
  - ➔ intrinsic modularity of the system,
  - ➔ possibility of system maintenance by operating from the top of the tank.

R&D on molten salt Steam Generator

Scheme of the helicoidal coil SG

H_{coil} = 5.5 m

D_{coil} = 3 m

H_{tot} = 14 m

N_{coils} = 16

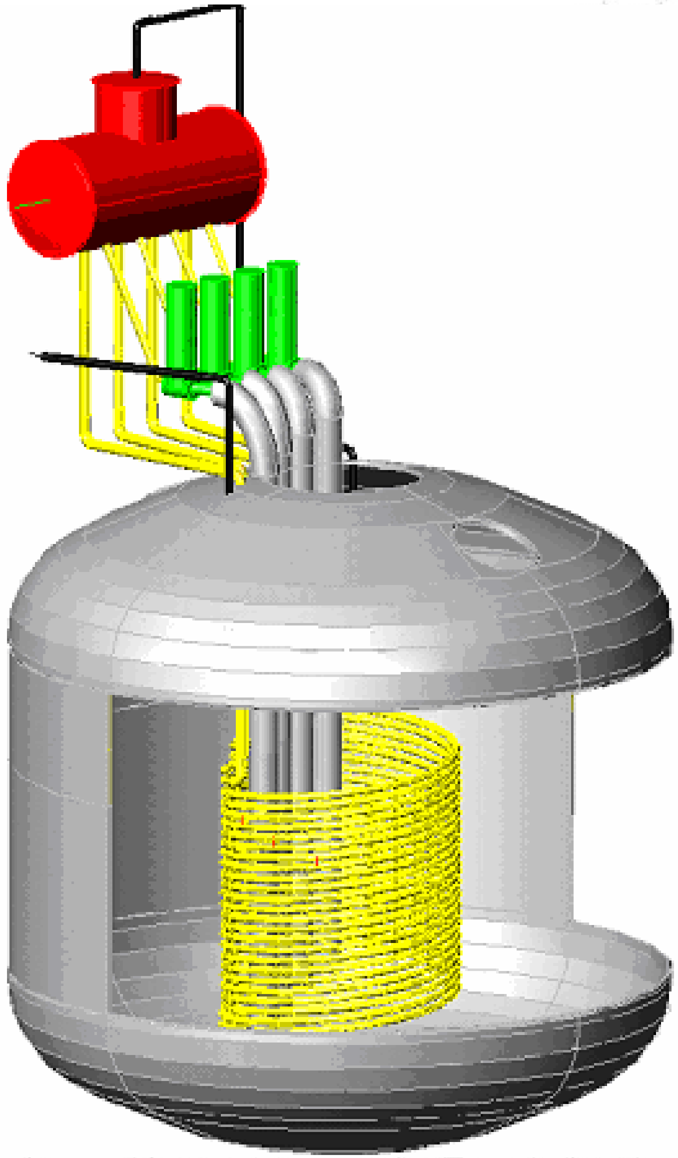
Weight ≅ 3,000 kg

D_t = 2” sch 40

p = 0.8 ÷ 6.0 MPa

T_{sat} = 170 ÷ 275°C

M’ = 1.5 ÷ 4.5 kg/s



R&D on molten salt Steam Generator

Proposed experiments with the tests section (see above) assembled on PCS facility:

- measurement of outside coil wall heat exchange coefficient at various salt conditions (indispensable design parameter);
- check of impeller type / power and of baffles, with check of salt motion;
- study of salt freezing on outside coil wall, in case of water temperature lower than salt freezing temperature;

R&D on Thermal Storage systems

As talking about the Steam Generator, a simplification both of the cycle and of the plant operation can be obtained through integration of the SG e STs, inserting the SG inside one of the two thermal Storage Tanks.

The further simplification proposed, in order to reduce the costs in the medium/small scale plants, is to consider only one tank.

R&D on Thermal Storage systems

In medium/small size plants (5 ÷ 15 MWt), the only one tank:

- works at a constant molten salt level;
- stores energy by the sensible heat of the working fluid;
- in particular cases (long plant stops) allows possible salt freezing on the tank wall;

R&D on Thermal Storage systems

- is equipped with a central heating system controlling the maintenance of salt in liquid phase; this safety 'hot cell' is realized by immersed heaters, in order to:
  - ➔ to define an internal cell where salt remains always liquid,
  - ➔ to control the possible development of solid salt thickness on the shell,
  - ➔ to utilize the solar energy to melt the possible solid salt at the plant start-up, so avoiding to utilize auxiliary energy of other type;

R&D on Thermal Storage systems

- during the operation, needs of suitable inner agitation systems in order to:
  - ➔ to homogenize salt temperature;
  - ➔ to prime a cross-sectional fluid motion regarding the boiler coils, in order to vary the thermo-fluid-dynamic parameters of the thermal exchange in the SG (coil external side);
  - ➔ to avoid the stratification of the salt;

R&D on Thermal Storage systems

- requires the insertion of the salt circulation pump inside of the safety 'hot cell', where the salt is surely always liquid (coinciding with the zone in which the SG is inserted);
- allows to avoid use of expensive systems (electric energy or steam) to maintain totally liquid the salt, due to the presence of the safety 'hot cell';
- requires the use of a back-up molten salts heater.

R&D on Thermal Storage systems

In the plants with two tanks:

- like already seen dealing the SG, the tanks will be both equipped of a safety hot central system, against salt freezing and for the control of the salt temperature when plant is in stand-by;
- in the tank containing the SG, the SG zone coincides with the safety ‘hot cell’;
- in the other tank, the pump will be positioned near the safety hot central system, to ensure always the salt circulation by exploiting only the solar energy from the solar collectors without additional energy systems.

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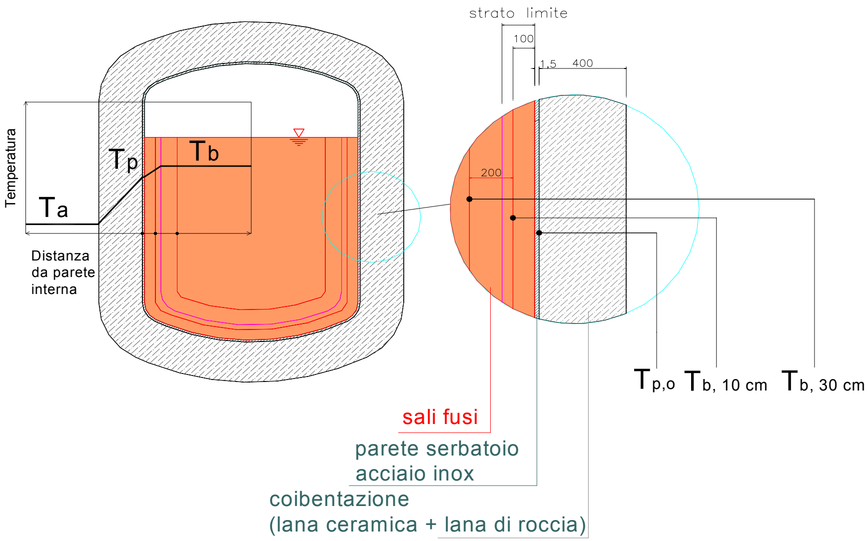
R&D on Thermal Storage systems

Proposed experiments on the PCS facility:

- measurement of horizontal/vertical stratification of the salt, when salt is allowed to waste heat and/or to solidify on the shell;
- check of the defrosting modality of solidified salt on the shell;
- study of motion of molten salt inside the tank.

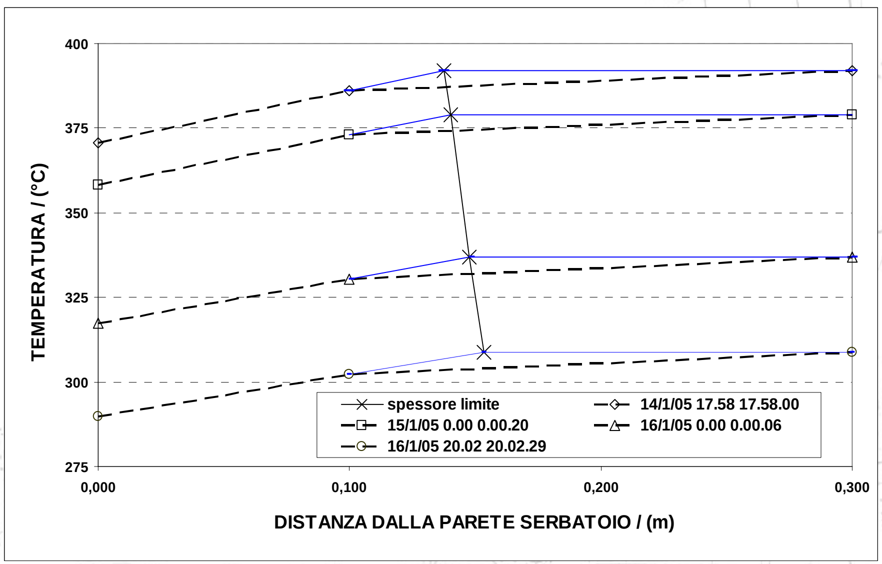
R&D on Thermal Storage systems

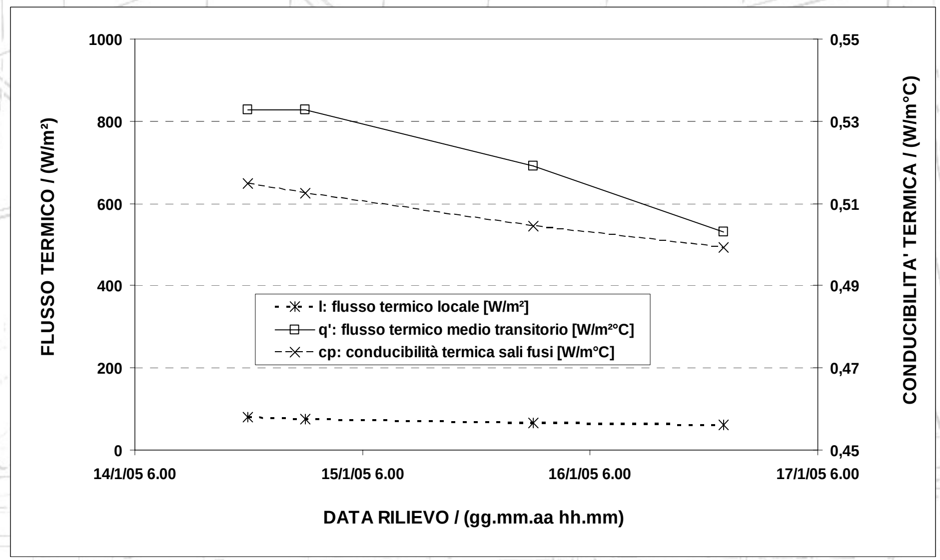


Some experimental results

Stratification trend vs time of molten salts into the storage tank

$$s_{p,\lim} = 0{,}1\left(T_{sali,0.3m} - T_{p,i}\right)/\left(T_{sali,0.1m} - T_{p,i}\right)$$



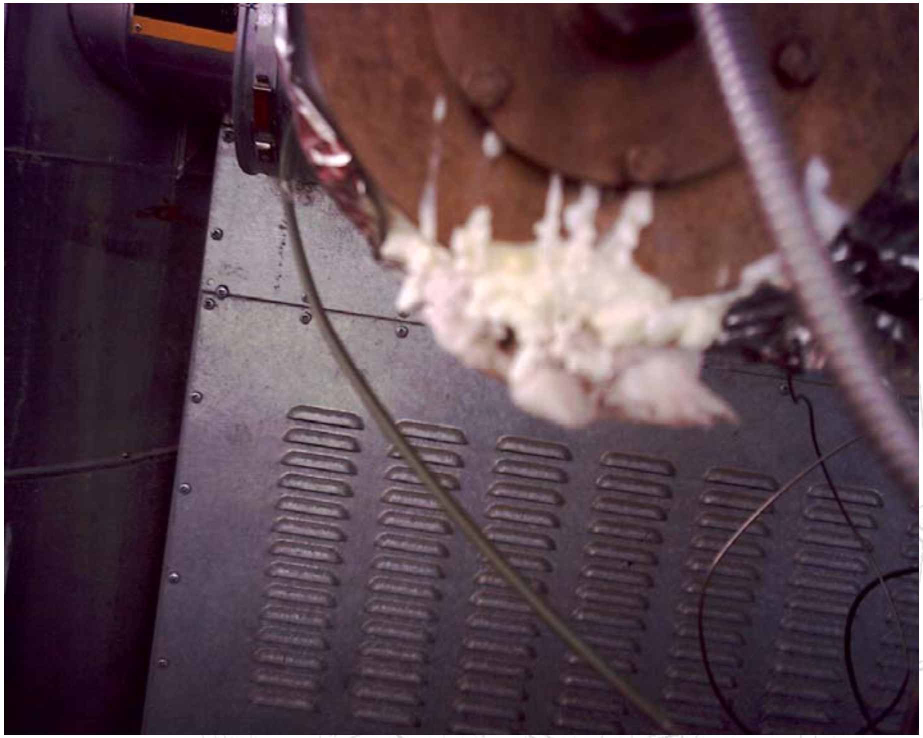


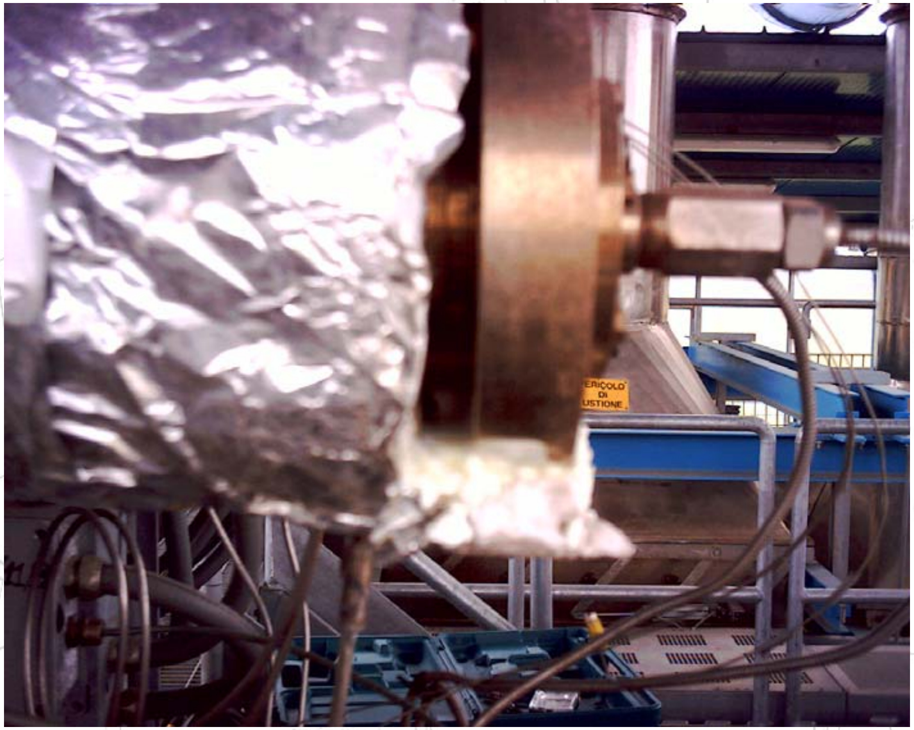
Molten salts HTF: instrumentation, piping and components (valves, pumps, etc.)

Main characteristics of piping design, “as usual” and improved (reference material AISI 321H):

- Electrical heating by means of:
  - mineral-insulated cables for tubes and line components (valves, flanges, other equipments)
  - direct Joule effect for solar tube receivers;
- Flanged joints especially equipped for minimizing the effects of molten salt leakages;
- Valves with sealing bellows (to avoid hardening of sealing stripes and resulting leakages from shaft) and very careful heating;
- Flexible metallic hoses, electrically heated by mineral-insulated cables or direct Joule effect, for connection between fixed pipes and moving solar tube receivers;
- Piping supports and hangers especially manufactured for minimizing cold spots and heat losses;
- Complex and especially manufactured fittings for process instrumentation (e.g., diaphram seal filled with silicon oil at the end of special thermostatic nozzle for pressure measurement in molten salts).

Molten salts HTF: instrumentation, piping and components (valves, pumps, etc.)





Molten salt leakage (solidified) at diaphragm seal flanged connection

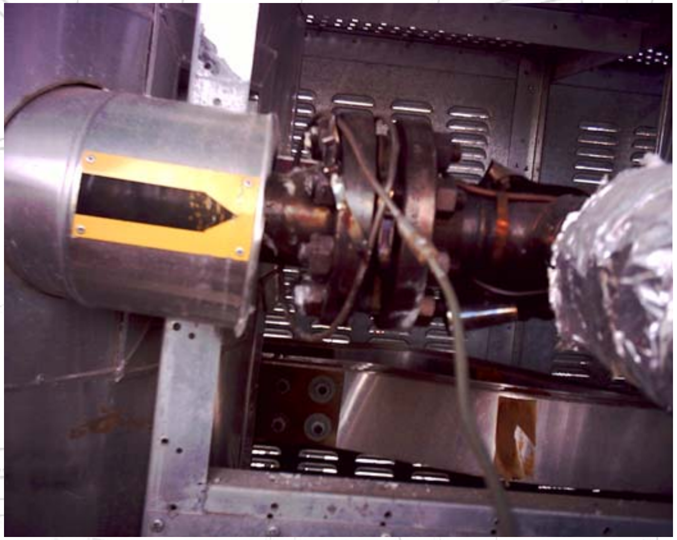
Molten salts HTF: instrumentation, piping and components (valves, pumps, etc.)

Molten salt leakage (solidified) at flanged connection: removal of the solidified salt pasted with ceramic fibers insulation

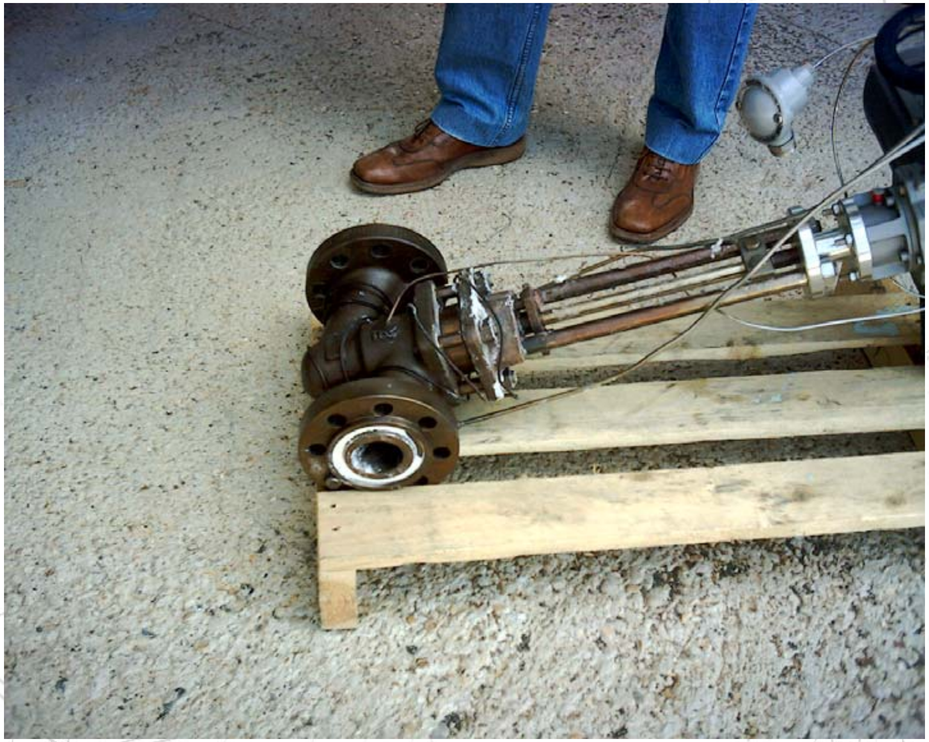
1_ solidified salt pasted with ceramic fibers insulation

2_ partial removal of solidified salt

3_ total removal of solidified salt

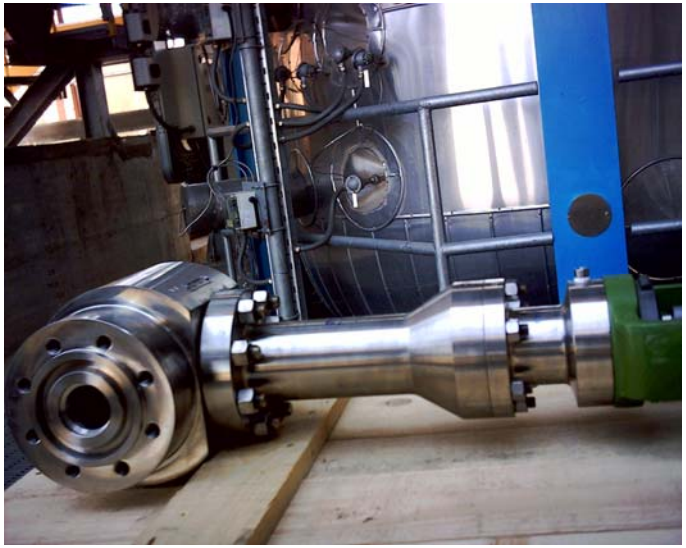


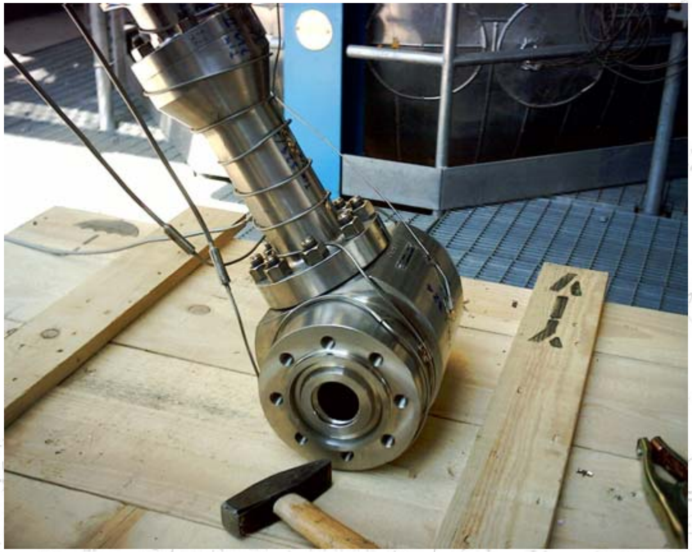
Molten salts HTF: instrumentation, piping and components (valves, pumps, etc.)

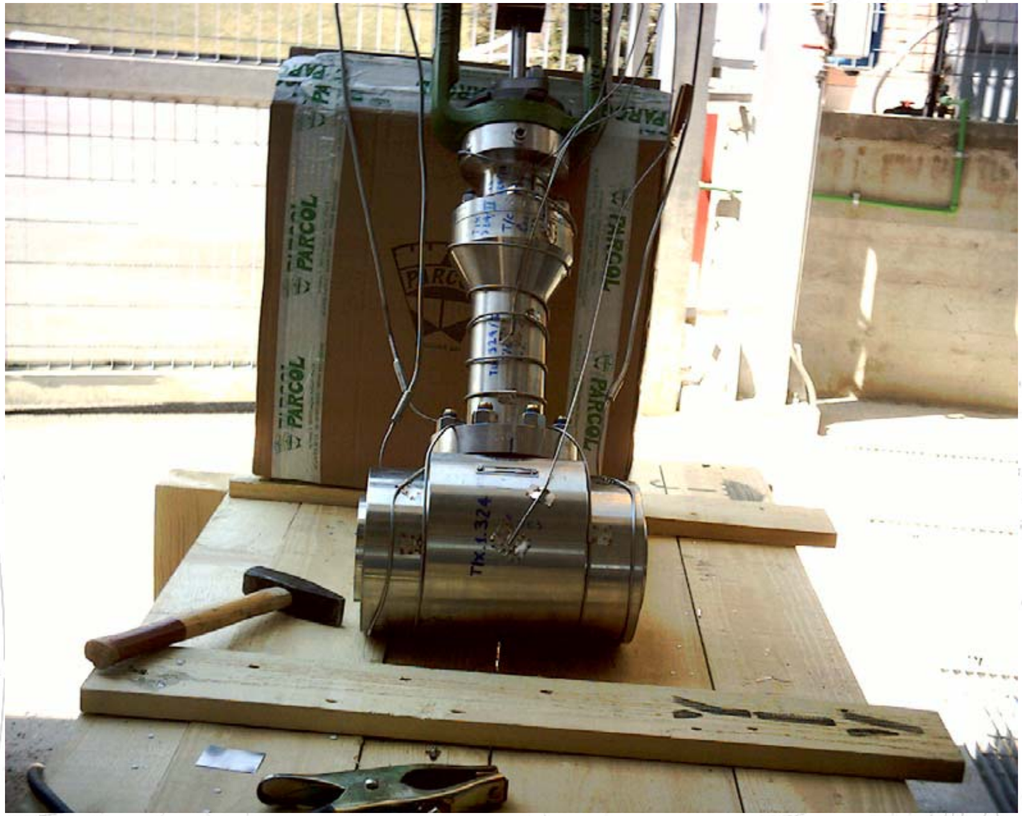


Disassembly of a control valve with
ceramic sealing strips packing on shaft

Molten salts HTF: instrumentation, piping and components (valves, pumps, etc.)





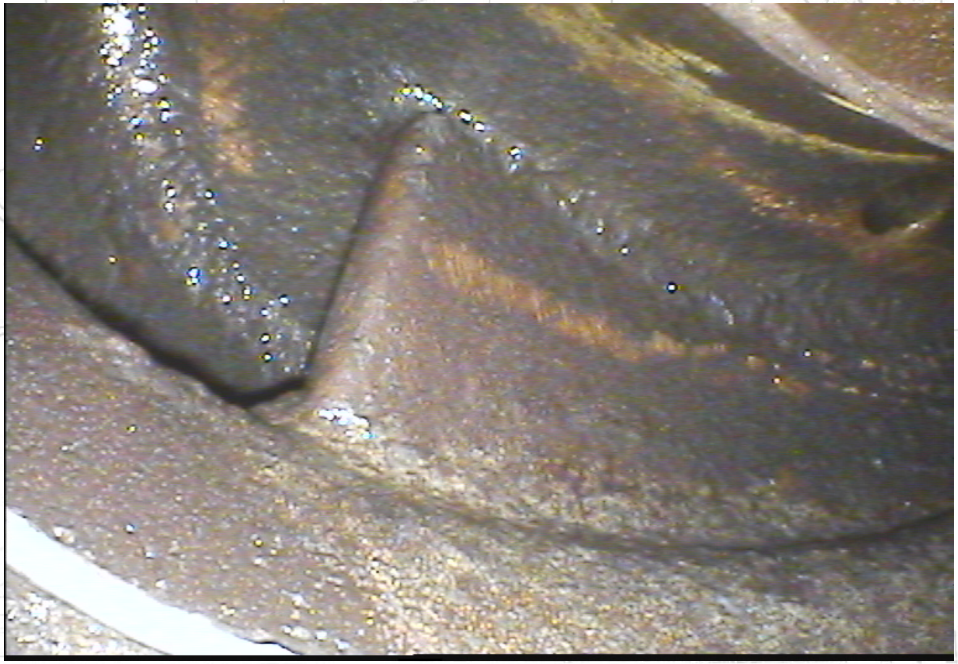


Preparation of auxiliary heating system by mineral insulated cable on a control valve with shaft bellows seal

Molten salts HTF: instrumentation, piping and components (valves, pumps, etc.)

Some experimental results about molten salts FRIATEC pump

- Reliability of the construction materials after some early failure;
- Performed a lot of operation cycles of the pumps;
- Non-destructive tests by endoscope have verified absence of corrosion.



Main characteristics of piping design, “innovative” (reference material AISI 321H):

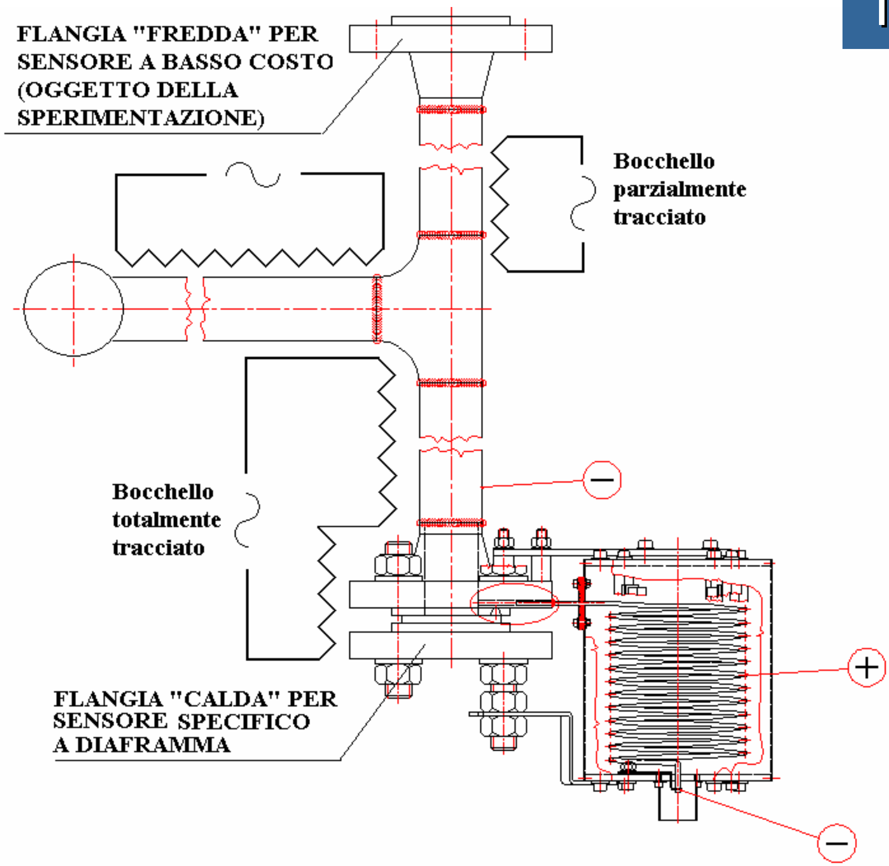
- Electrical heating only by means of direct Joule effect;
- Welded joints everywhere it is possible;
- Special equipment, ENEA patented, instead of usual valves, named “service molten salt valve” with assignments of thermostatic check and on/off valve;
- Flexible metallic hoses, electrically heated by direct Joule effect, for connection between fixed pipes and moving solar tube receivers;
- Special piping supports and hangers (ENEA concept), electrical and thermal insulated;
- Special fittings, ENEA patented, for application of “as usual” instrumentations at lower costs.

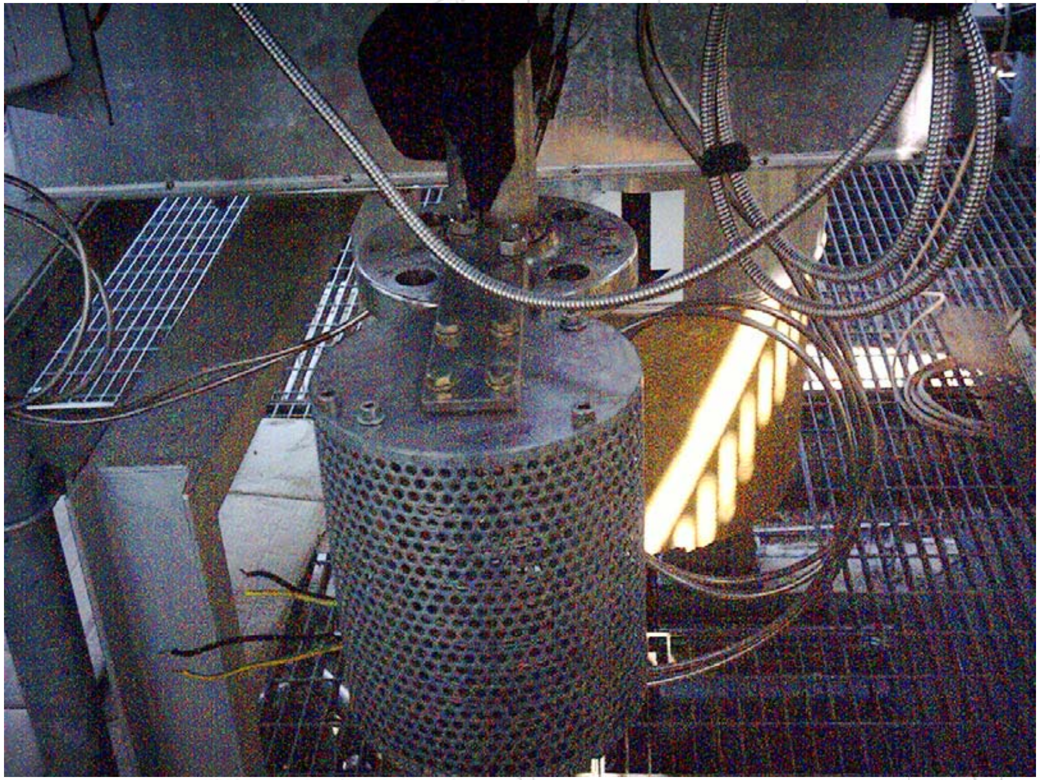
Instrumentations

- Measurement of P and ΔP in air (instrument with intrinsic safety)
- Measurement of ΔP: patented heated fittings for orifices, diaphragm, calibrated flanges, Pitot tube, for evaluating mass flowrate and velocity in molten salts processes;
- Measurement of T with patented fittings.

Molten salts HTF: instrumentation, piping and components (valves, pumps, etc.)

Instrumentations and special equipments





Test apparatus for comparison of pressure measurement with and without diaphragm seal (siliconic oil) and thermostatic drainage valve (joule effect operated)