ELSMOR

Towards European Licensing of Small Modular Reactors

International Summer School on Early-Deployable SMRs

2022

HOW TO DESIGN AN EXPERIMENTAL FACILITY

SIET S.p.A.

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NEED OF EXPERIMENTAL FACILITIES

The design and certification of a new nuclear power plant, be it a SMR, requires the execution of experimental tests for different goals:

- the independent verification of the functionality of systems devoted to the safety of the plant, e.g. DHRS. In this case, Separate Effect Test (SET) facilities are necessary;
- the verification of the behavior of the integral system, e.g. primary loop, secondary loops and also containment. In this case, Integral Test Facilities (ITF) are necessary;
- the validation of system codes, e.g. Relap5, Cathare, etc., on qualified experimental data to perform Reactor system analyses versus postulated accidents devoted to obtain the final reactor certification.

NEED OF AN EXPERIMENTAL FACILITY IN THE ELSMOR PROJECT

The need of an experimental facility in the ELSMOR project has basically three goals:

- Indicate the route on how to perform an experimental campaign to the European Regulator called to certify SMRs in Europe;
- test a passive decay heat removal system, to be potentially installed on the E-SMR, based on a compact plate-type heat exchanger included in a natural circulation loop that rejects heat into a water pool;
- validate different codes in pre-test and post-test analyses.

DESIGN OF AN EXPERIMENTAL RIG: THE ELSMOR FACILITY

The ELSMOR facility is a SET loop devoted to test a PDHR system that includes a plate-type heat exchanger (S-CSG Safety-Compact Steam Generator) installed in a natural circulation loop that rejects heat into a water pool by means of a vertical tube heat exchanger.

The potential use of a plate-type heat exchanger in an integral type SMR has the advantage of high power transfer in an extremely compact configuration. It is the first time this kind of heat exchanger is proposed to be part of a nuclear power plant for civil use, so it may require a wide experimentation before the application for licensing.

In general, the design of a facility starts from a technical specification indicating:

- the goal of testing;
- the scaling factors (elevation, volume, power scale);
- the phenomena of interest to be reproduced and investigated;
- the required characteristics of instrumentation and Data Acquisition System (e.g. accuracy, sampling frequency, etc.);
- the Test Matrix.

THE ELSMOR FACILITY: SCALING

Reference reactor E-SMR
Electric power ~170 MW
Thermal Power ~515 MW
2 Loops EHRS
Decay power per loop ~30 MW (decay power ~10% reactor power/2 ~26 MW)

The scaling for the ELSMOR facility mainly focuses on two aspects:

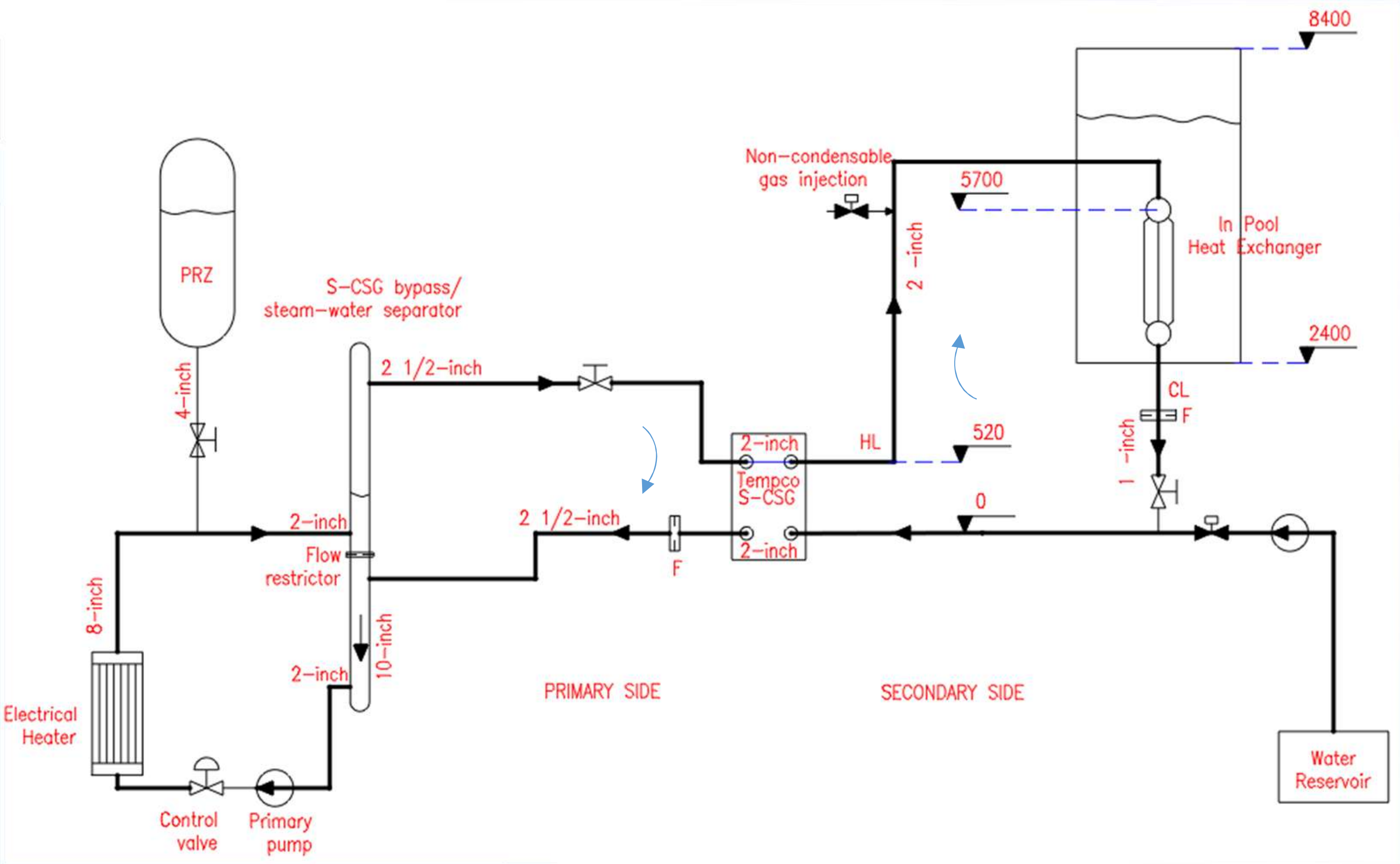
- heat exchanger power and pressure drops;
- loop pressure drops.

Type-plate heat exchanger specification
HX power ~500 kW
HX primary side pressure drops ~12 kPa (at 2.8 kg/s nominal flowrate)
HX secondary side pressure drops ~30 kPa (at 0.4 kg/s nominal flowrate)

Natural circulation loop specified height ~6 m.

ELSMOR facility scaling factors:
Elevation 1:1
Power ~1: 50

ELSMOR FACILITY SIMPLIFIED SCHEME



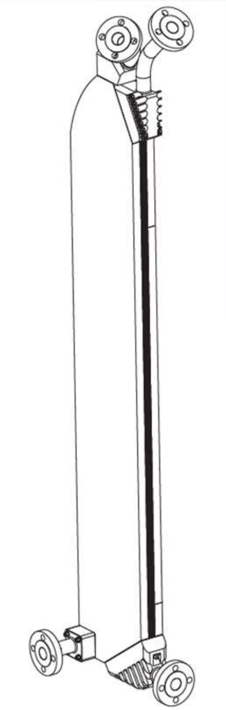
Total height: ~ 15 m
Power ~ 1 MW
(Plate-type HX power ~600 kW)
Primary side P 15.5 MPa; T 310 °C
Secondary side P: 10 MPa; T 315 °C
In-pool HX: 5 tubes, 2-inch diameter, ~2 m lenght

Cylindrical water pool:
~ 5 m^3 volume,
~ 6 m height,
atmospheric pressure

ELSMOR facility HEAT EXCHANGER

HX Specification

Design conditions	Primary side	Secondary side
Pressure (bar abs)	130	100
Temperature (°C)	325	325
Operating conditions	Primary side	Secondary side
Pressure (bar abs)	1 - 116	0.023 - 80
Temperature (°C)	20 - 320	20 - T_prim
Mass flow (kg/s)	~2.8	~0.4
Pressure drops (kPa)	12 (at 2.8 kg/s)	30 (at 0.4 kg/s)
Primary and secondary side volume ~15 - 20 l (each side)		
Nominal power 500 kW (with ~11 plates)		
Height (m) ~ 2.70 (exchanging part)		
Width (m) ~ 0.45		
Thickness (m) ~ 0.11 (of which about 1/3 occupied by plates)		
Heat transfer surface ~13 m^2		



Commercial HX chosen

TEMPCO Model TCBC2102H*130

Design conditions	Primary side	Secondary side
Pressure (bar abs)	140	100
Temperature (°C)	310	310
Operating conditions	Primary side	Secondary side
Pressure (bar abs)	1 - 116	0.023 - 80
Temperature (°C)	20 - 310	20 - T_prim
Mass flow (kg/s)	~3.9 (Note 1)	~0.4
Pressure drops (kPa)	31.6 (at 3.9 kg/s)	14.4 (at 0.4 kg/s)
Primary and secondary side volume ~10 l (with 130 plates) each side		
Power ~600 kW (with 130 plates)		
Height (m) ~ 0.5 (exchanging part)		
Width (m) ~ 0.2		
Thickness (m) ~ 0.30 (with 130 plates)		
Heat transfer surface ~12.16 m^2 (with 130 plates)		
Realization with 8 nozzles (double inlet/double outlet) to have spare ones for instrumentation installation		
Note 1: Primary side mass flow increase with respect to TA to have adequate PS outlet temperature higher than SS saturation temperature at 70 bar.		

HX HEAT TRANSFER COEFFICIENT verification BY TEMPCO CALCULATIONS

An estimation of the heat transfer coefficients was performed on the basis of the results of TEMPCO calculations for different cases: the h*liq* was obtained from the symmetric case and used to calculate both the h*stm* in the superheated steam case and the h*ss* in the base case. The h*stmcnd* was obtained by the h*ss* from the base case.

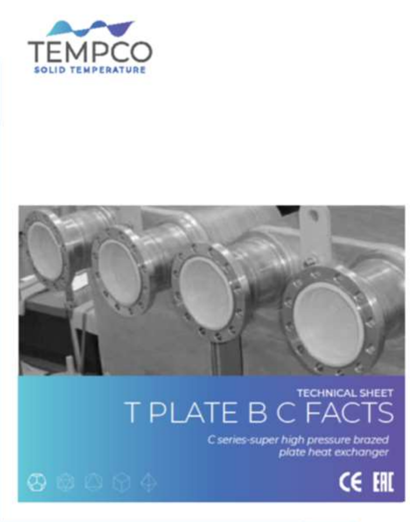
	Symmetric case	Superheated steam case	Base case	Two-phase Case
	PS Liquid - SS Liquid	PS liquid - SS Superheated steam	PS Liquid - SS evaporating	PS condensig - SS evaporating
Heat transfer coefficient				
Power (kW)	1402.24	6.85	602.4	606.8
DT log mean (°C)	19.915	1.477	9.276	34.20
Heat transfer area (m2)	12.16	12.16	12.16	12.16
Plate thickness (m)	0.001	0.001	0.001	0.001
AISI 316 themal conductivity (W/(mK))	16.2	16.2	16.2	16.2
Global heat transfer coefficient (W/(m^2K))	5790.4	381.4	5340.6	1459.1
	$\frac{1}{htot}=\frac{1}{hliq}+\frac{s}{k}+\frac{1}{hliq}$	$\frac{1}{htot}=\frac{1}{hliq}+\frac{s}{k}+\frac{1}{hstm}$	$\frac{1}{htot}=\frac{1}{hliq}+\frac{s}{k}+\frac{1}{hss}$	$\frac{1}{htot}=\frac{1}{hstmcnd}+\frac{s}{k}+\frac{1}{hss}$
	Heat transfer coefficient hliq is equal both sides	Heat transfer coefficient hstm obtained by hliq previouly calculated	Heat transfer coefficient hss obtained by hliq previouly calculated	Heat transfer coefficient hstmcnd obtained by hss previouly calculated
hliq (W/(m2K))	18022.7			
hstm (W/(m2K)) superheated		399.2		
hss (W/(m2K)) (evaporating)			14279.5	
hstm cnd (W/(m2K)) (condensing)				1806.4

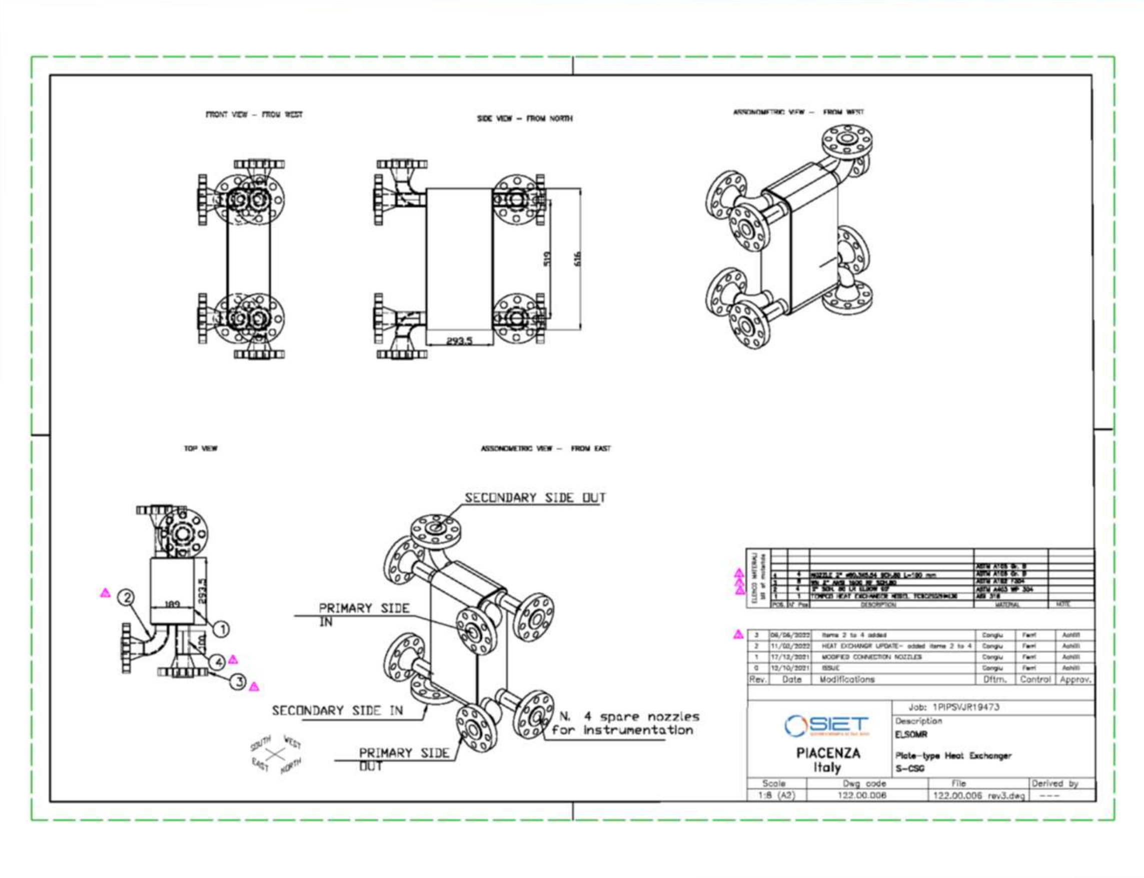
DETAILS of TEMPCO HEAT EXCHANGER

Drawing SIET 122.00.006 Rev.3

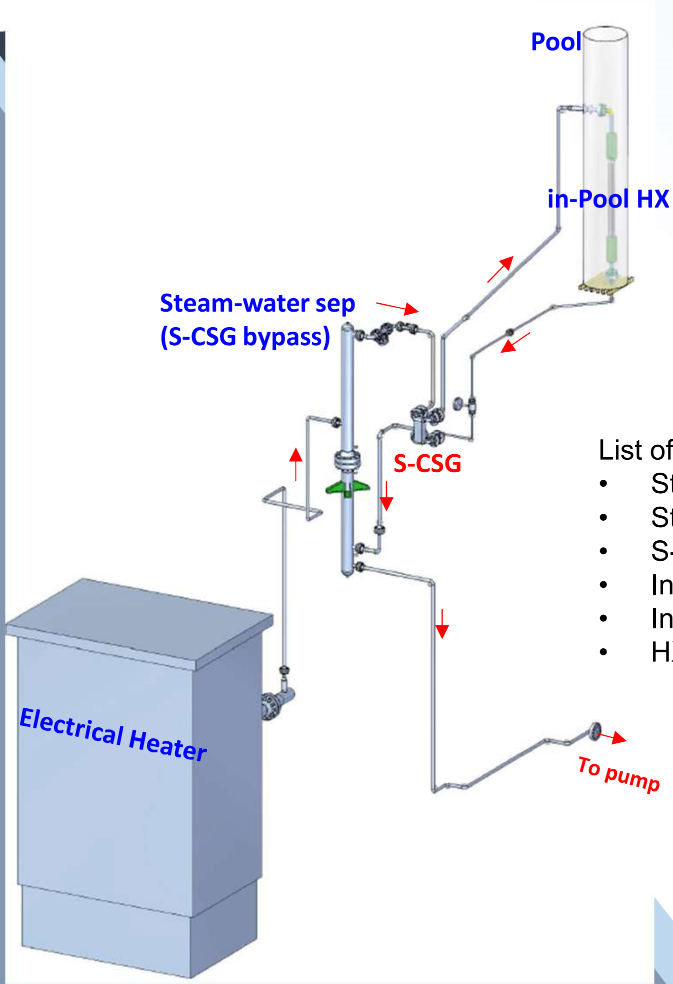
TEMPCO HX configuration:
- 4 nozzles for fluid (PS+SS)
- 4 nozzles for instrumentation insertion

TEMPCO HX technical sheet





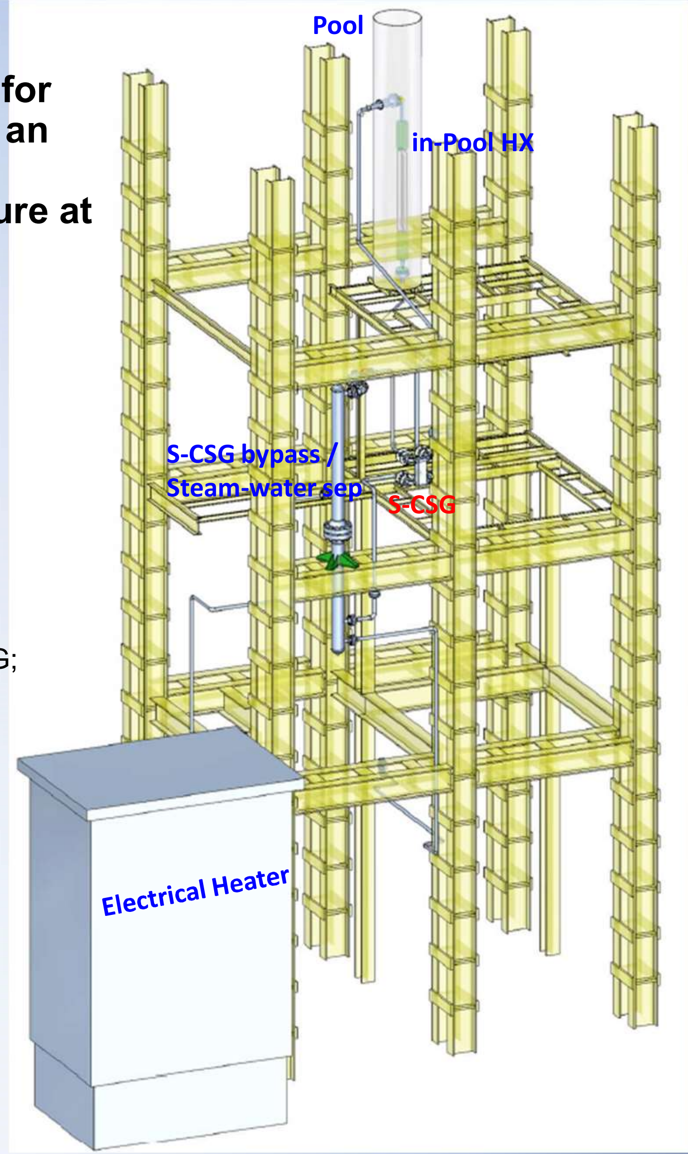
PIPING DESIGN



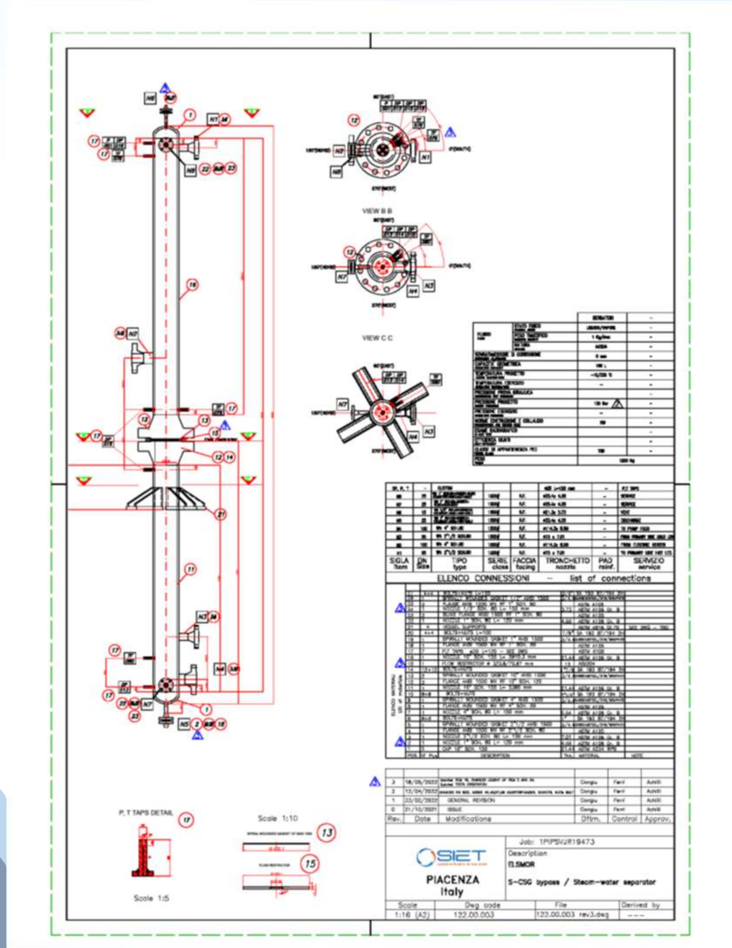
Piping drawings and mechanical verifications versus maximum pressure and temperature

List of main components/piping
- Steam-water separator (S-CSG bypass);
- Steam-water separator piping to and from the CSG;
- S-CSG (outer dimensions);
- In-pool heat exchanger;
- In-pool HX piping to and from the CSG;
- HX pool

Facility layout for installation on an existing load bearing structure at SIET



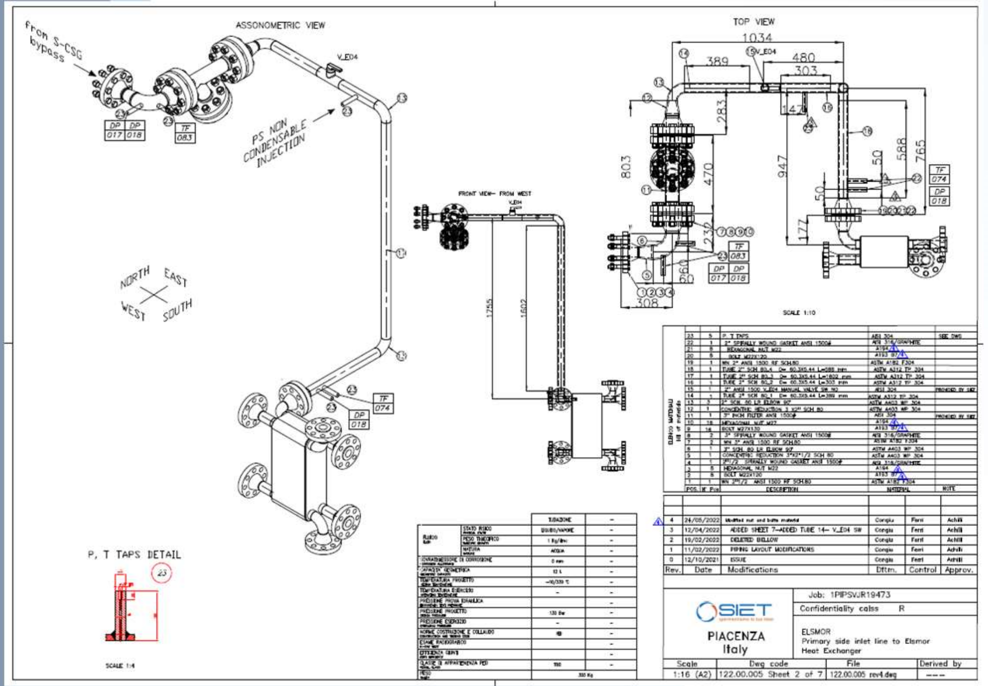
MECHANICAL DESIGN Steam-Water separator (S-CSG bypass)



Drawing SIET 122.00.003 Rev.3

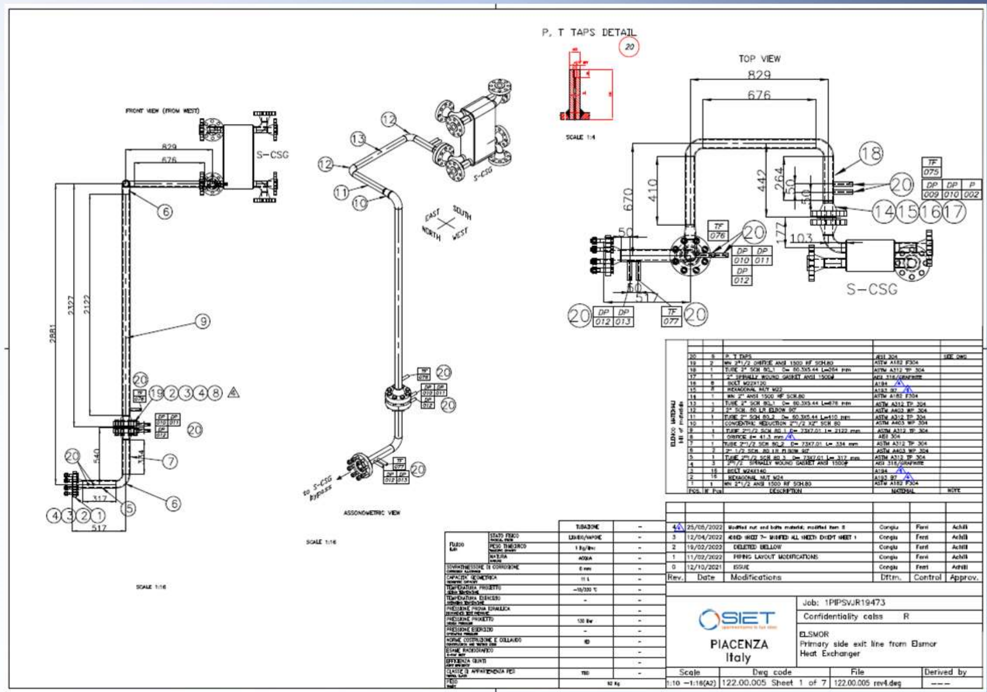
MECHANICAL DESIGN Primary side piping

TEMPCO PS HX inlet pipe



Drawing SIET 122.00.005 Rev.4 Sheet 2 of 7

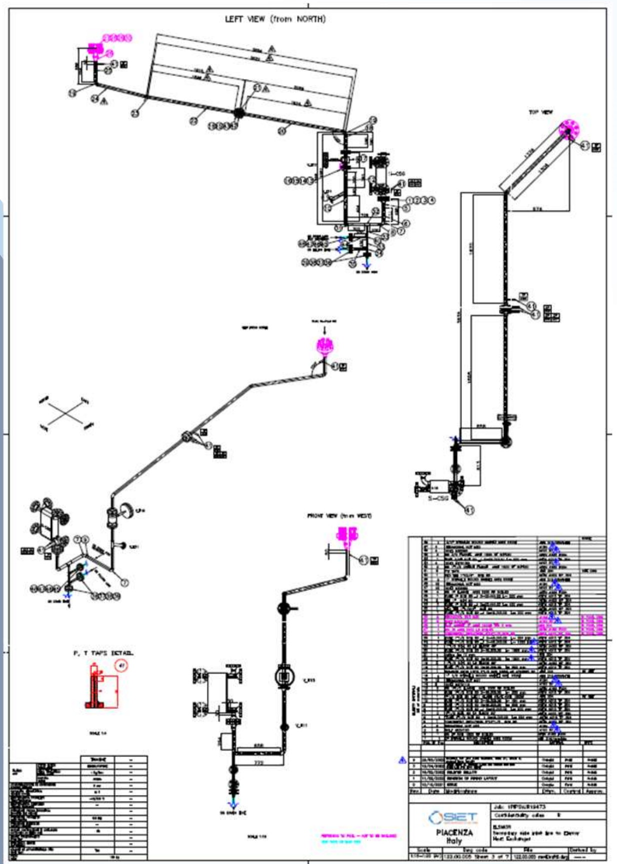
TEMPCO PS HX outlet pipe



Drawing SIET 122.00.005 Rev.4 Sheet 1 of 7

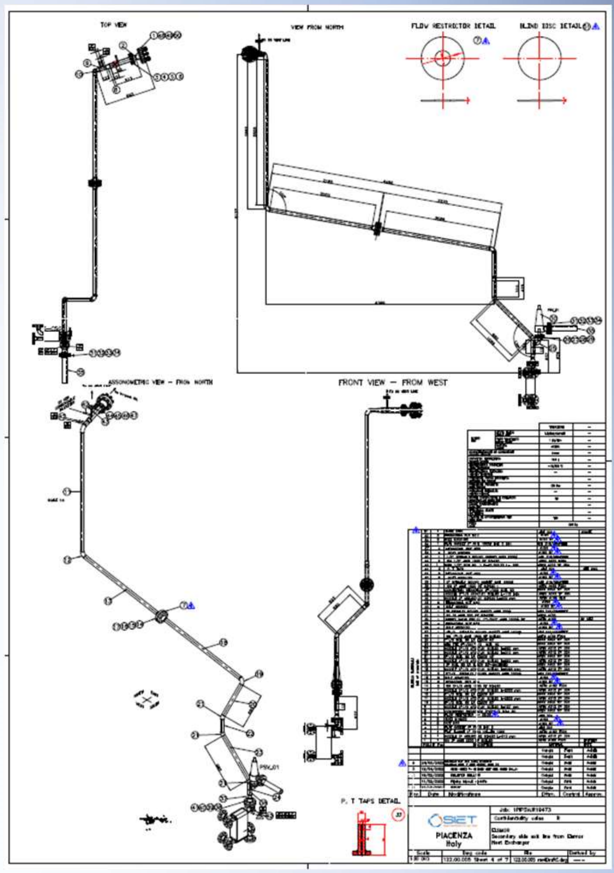
MECHANICAL DESIGN Secondary side piping

TEMPCO SS HX inlet pipe



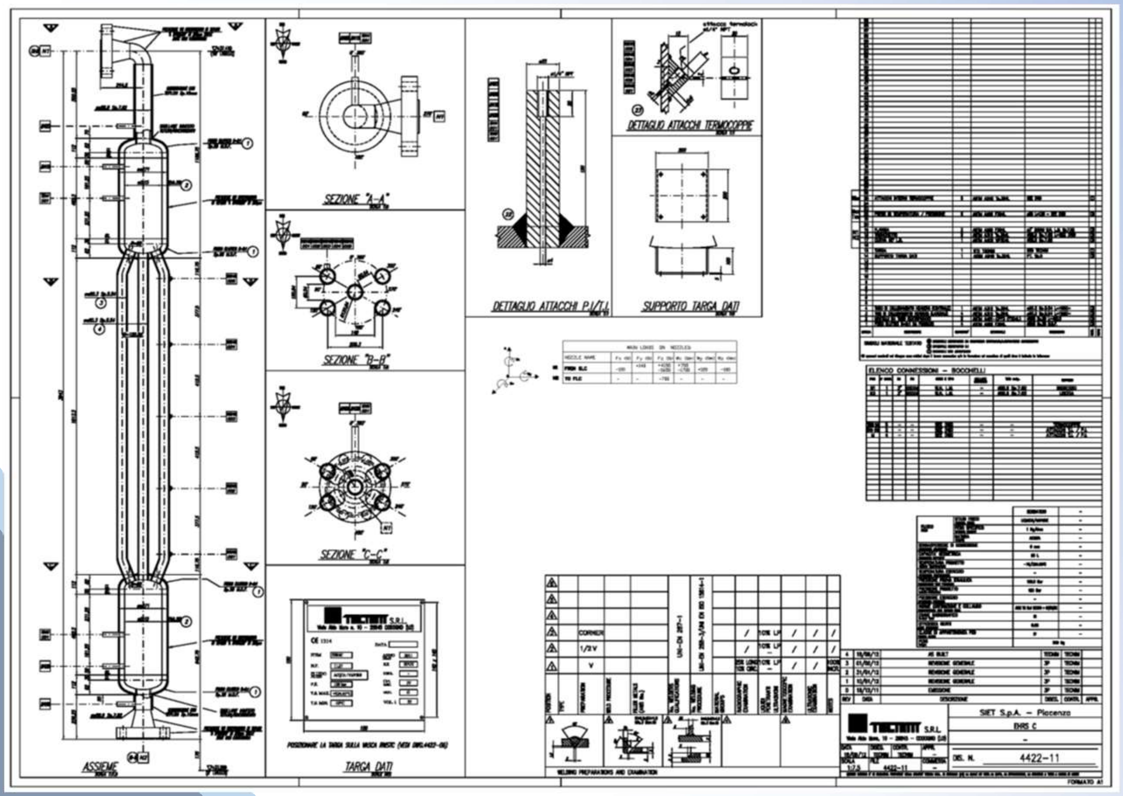
Drawing SIET 122.00.005 Rev.4 Sheet 3 of 7

TEMPCO SS HX outlet pipe



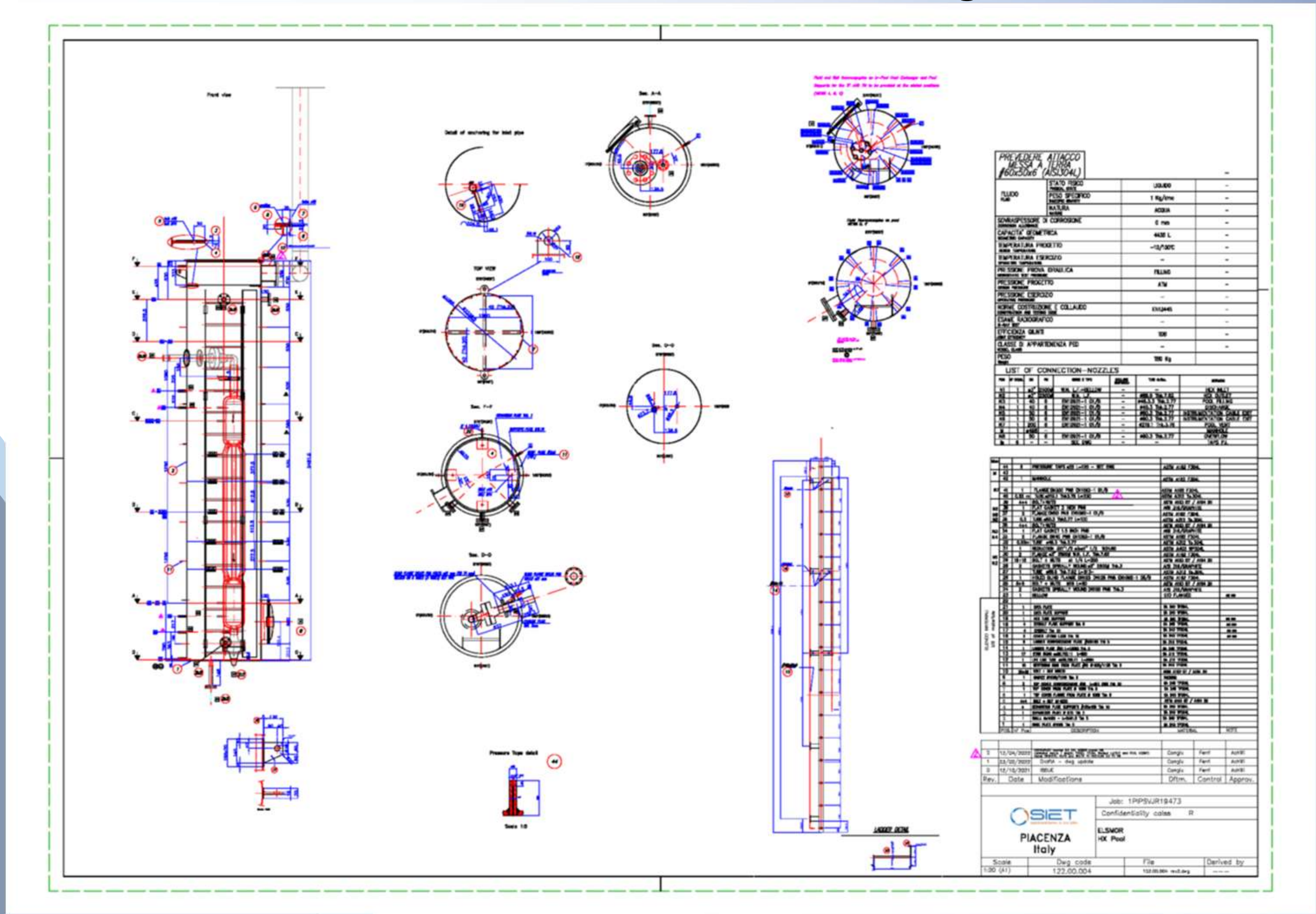
Drawing SIET 122.00.005 Rev.4 Sheet 4 of 7

MECHANICAL DESIGN In-pool heat exchanger



Drawing TECNIM 4422-11 Rev.04

MECHANICAL DESIGN Heat exchanger Pool



Drawing SIET 122.00.004 Rev.2

FACILITY LAYOUT VERIFICATION BY CODE SIMULATIONS

The RELAP5 code was used for the simulation of the natural circulation loop at the nominal operating conditions with the main goal of:

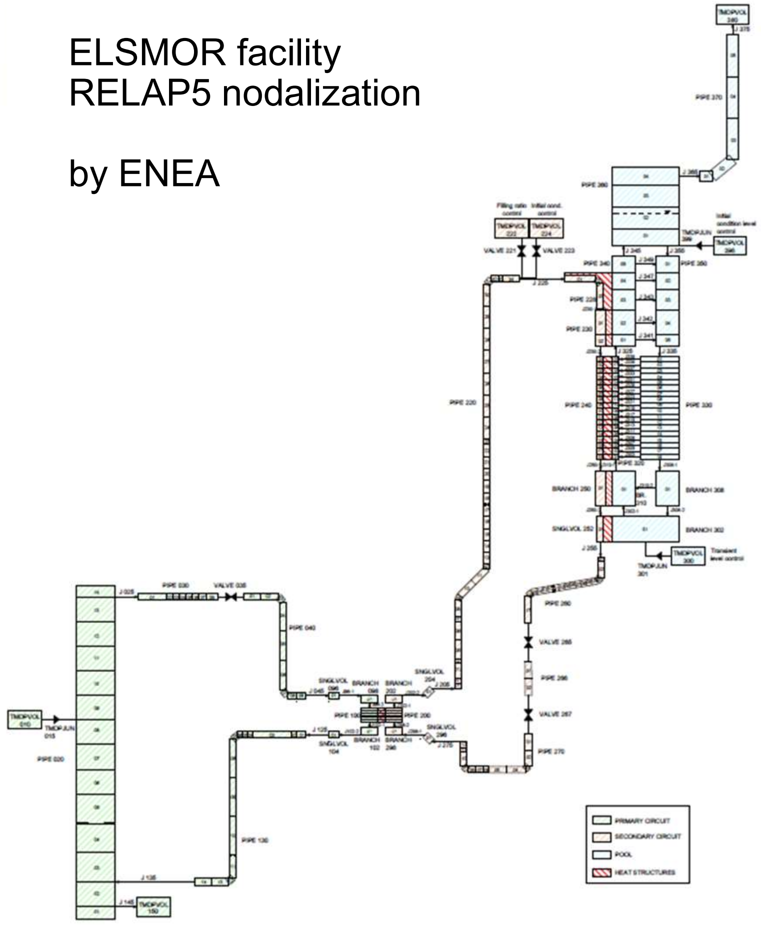
- verifying the size of the pipes;
- verifying the heat transfer capability of the loop.

Critical parameters in the simulation:

- Pressure drops in the piping;
- Heat transfer coefficients for both HXs;
- Filling ratio of the loop.

ELSMOR facility
RELAP5 nodalization

by ENEA



FACILITY LAYOUT VERIFICATION BY CODE SIMULATIONS

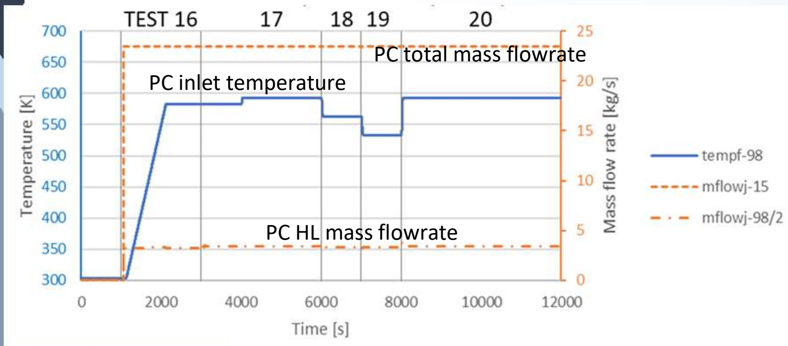
RELAP5 simulation of a transient included in the Test Matrix

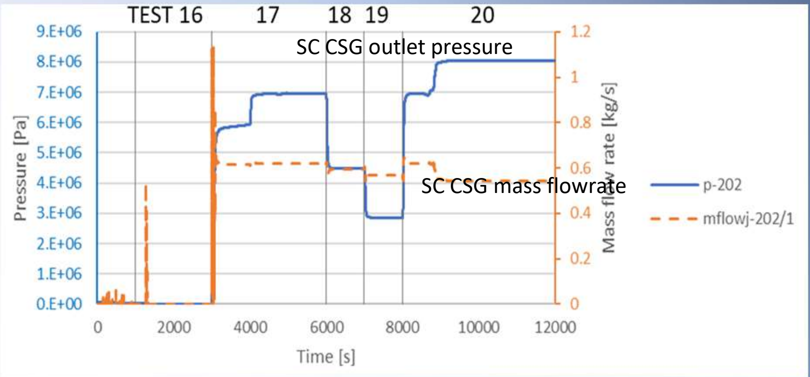
Group	Test N.	PC pressure	PC temp.	PC total flow rate	PC conditions	PC HL flow rate	SC FR	SC initial temp.	Pool temp.	Pool initial level	Orifice on PC HL	SC CL valve position	SC N_2 injection	Notes
N.	N.	bar	°C	kg/s	single/two-phase	kg/s	%	°C	°C	m	b (d/D ratio)	closing turns	Nl	
4	16	120	310	23.5	1-P	3.4	30	30	30	5	1	0	0	Start-up
	17	120	320	23.5	1-P	3.4	30	TBD	30-100	5	1	0	0	Transient + steady state
	18	120	290	23.5	1-P	3.4	30	TBD	100	5	1	0	0	Tests at reduce PS temperature (power)
	19	120	260	23.5	1-P	3.4	30	TBD	100	5	1	0	0	Tests at reduce PS temperature (power)
	20	120	320	23.5	1-P	3.4	30	TBD	100	2.3	1	0	0	Test at reduced level in the Pool

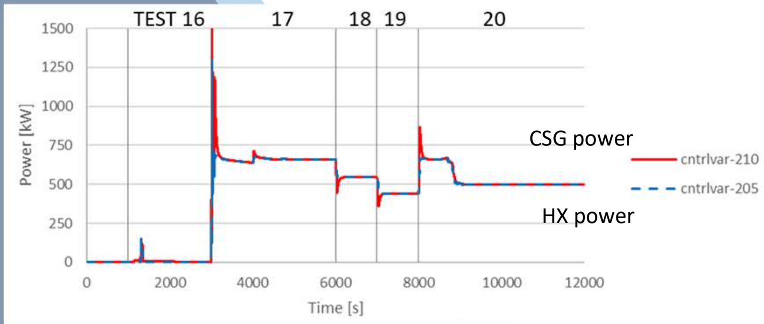
Time [s]	Test - event
0-1000	Initial cold conditions, mass reduction in the SC to obtain the FR
1000-3000	Test 16: start-up with PC temperature 310°C
1050	Start PC mass flow rate
1100	Start PC temperature ramp
3000	Opening SC control valve
3000-6000	Test 17: transient+steady state with PC temperature 320°C
4000	PC temperature rise from 310°C to 320°C
6000-7000	Test 18: test at reduced PS temperature (290°C)
7000-8000	Test 19: test at reduced PS temperature (260°C)
8000-12000	Test 20: Test at reduced level in the Pool (2.3 m)
8500	Opening pool discharge valve

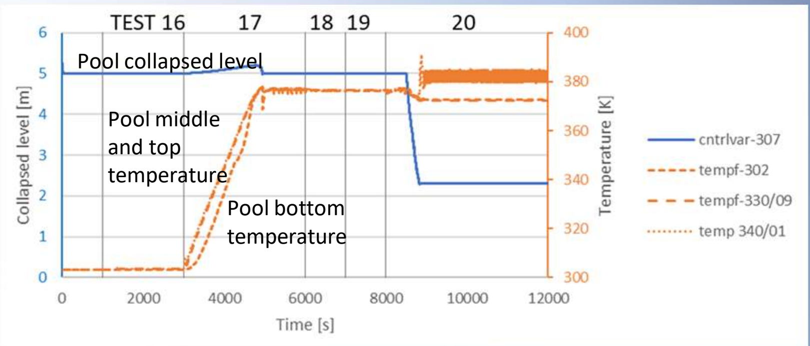
FACILITY LAYOUT VERIFICATION BY CODE SIMULATIONS

RELAP5 results of the simulation of a transient included in the Test Matrix









The results show that the natural circulation develops in the secondary side and no criticalities are evidenced in the design.

INSTRUMENTATION

The choice of instrumentation to be installed on a facility is made on the basis of:

- Measurement range;
- Instrument accuracy.

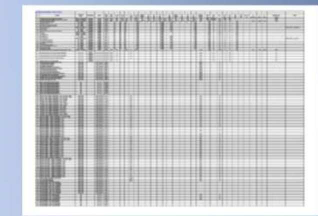
All the instruments must be calibrated in a calibration laboratory and calibration certificates must be checked and confirmed by qualified personnel before the installation on the loop.

Example of instrument table and needed information.

N.	Location	Instrument type	Manufacturer	Model	Plant code	SIET code	HP tap	LP tap	P1	P1 Azth.	P1 elev.	Nozzle elevation	P1 hsl	P1 hss	P1 hcl	P2	P2 elev.	Nozzle elevation	P2 hsl	P2 hss	P2 hcl	Instrum. Elevation	Head	Span	M.U.	LRV	URV	hcl net	hsl net	hss net	M	Q	K	Manufact.Error	Notes
							(+)	(-)		(°)	(m)	(m)	(m)	(m)	(m)		(m)	(m)	(m)	(m)	(m)	(m)	(m)	M.U.		M.U.	M.U.	(m)	(m)	(m)	(M.U./mV)	(M.U.)	(M.U.)	(+/- M.U.)	
1	SG Bypass (pump side) feedwater inlet mass flow	Orifice+ DP transmitter	Honeywell	STD830	F1001A	18166	M18	M19	M18	n.a.	-0.257	NA	NA	NA	1.203	M19	-0.257	NA	NA	NA	1.203	-1.460	0.000	#VALORE!	kPa	TBD	TBD	0						0.280	
2	SG Bypass (pump side) feedwater inlet mass flow (Low Span)	Orifice+ DP transmitter	Honeywell	STD120	F1001B	14722	M18	M19	M18	n.a.	-0.257	NA	NA	NA	1.203	M19	-0.257	NA	NA	NA	1.203	-1.460	0.000	#VALORE!	kPa	TBD	TBD	0						0.010	
3	Primary side pressurizer pressure	relative P transmitter	Honeywell	STG870	P1004	22831	M24		M24	n.a.	11.720				9.045							2.675	9.045	13	MPa	0	13	9.045	0	0	3.24982	-3.24942	0.1013	0.010	
4	Total DP across the pool (Pool Level)	DP - Transm.	Honeywell	STD820	DP-001		M20	M21	M20		20.978				20.978	M21	15.595				15.595		5.383	90	kPa	-10	80	5.383							
5	IN POOL HEX TOTAL DP	DP - Transm.	Honeywell	STD820	DP-002		M15	M14	M15		19.071				19.071	M14	15.759				15.759		3.312	60	kPa	-10	50	3.312							

The instruments in the ELSMOR facility are ~150.

Intrument table



The Data Acquisition System consists of Data acquisition boards cabled to each instrument that transmit the signals via ethernet to a PC.
The DAS boards for the ELSMOR facility are manufactured by National Instruments and the DAS program running on the PC is developed in NI-LabView ambient.

Data Acquisition System

The choice of DAS components and boards is made on the basis of:

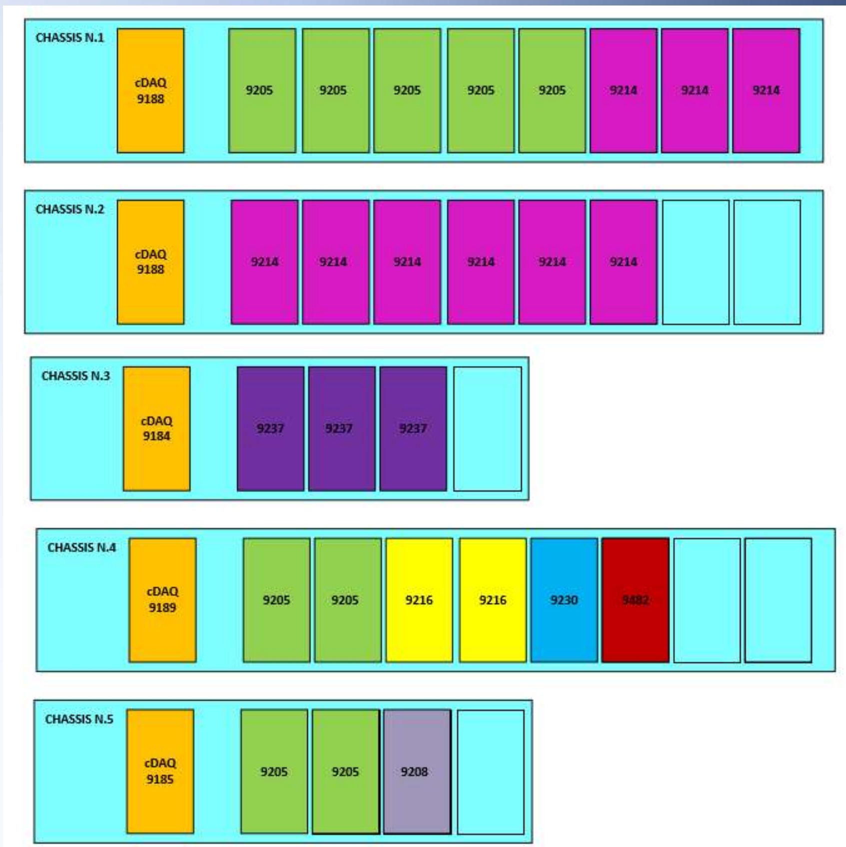
- DAS board accuracy;
- Type to signal to be recorded (e.g. high level 1 - 10 V; low level ± 50 mV);
- Sampling frequency.

All the DAS boards must be calibrated in a calibration laboratory and calibration certificates must be checked and confirmed by qualified personnel before the installation and cabling.

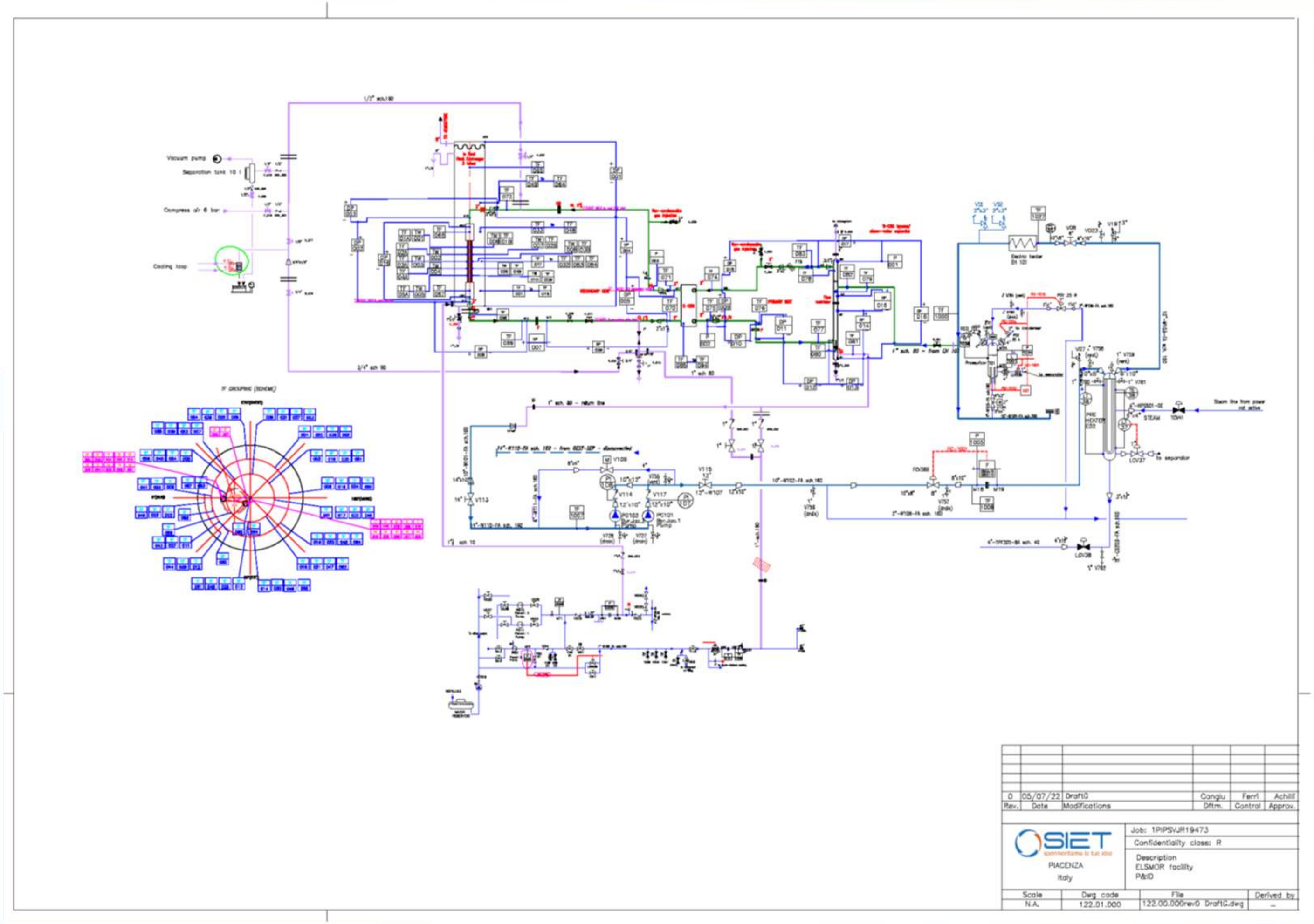
The Data Acquisition System consists of Data acquisition boards hosted in Chasses each cabled to instruments and the signals are transmitted via ethernet to a PC.
The Chassis and board manufacture is National Instruments.

The DAS program that runs on the PC is developed in NI-LabView ambient.
It performs the raw data acquisition (Volt), the conversion to Engineering units (e.g. Pa) and to derived quantities (e.g. Kg/s).

Scheme of a DAS based on NI components



PROCESS and INSTRUMENTATION DIAGRAM

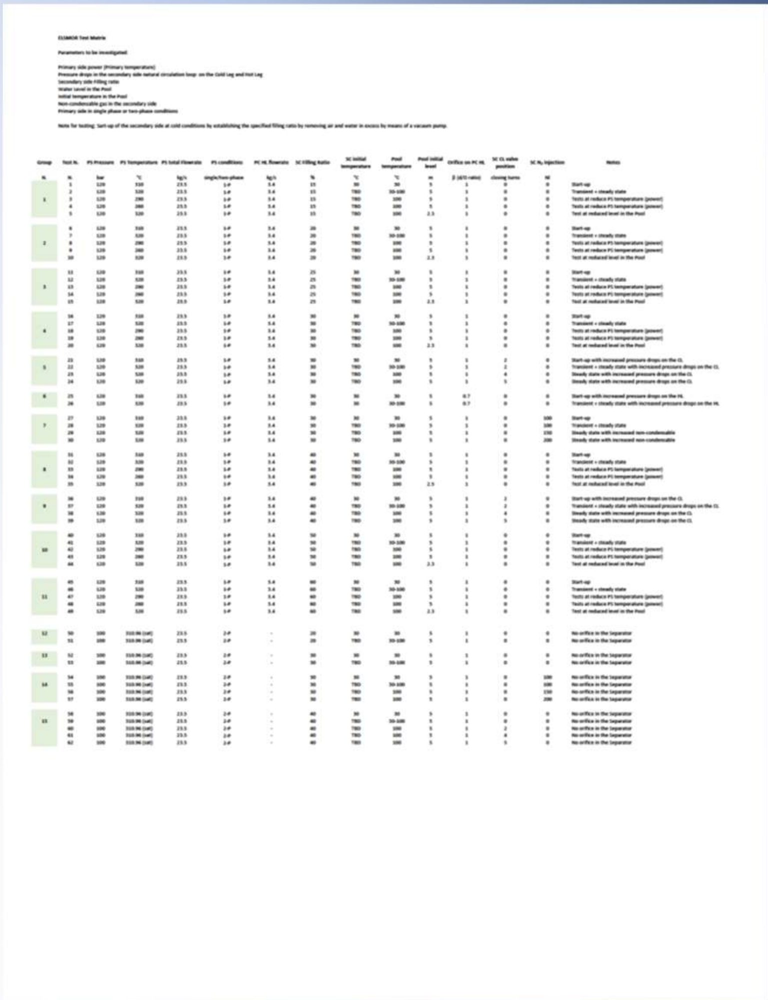


TEST MATRIX

The definition of the Test Matrix is done on the basis of:

- the phenomena to be investigated;
- the optimization of the facility operation;
- the need of specific experimental data for code validation;
- The energy cost optimization.

The Test Matrix for the ELSMOR facility consists of 62 test points grouped in 8 sections to optimize the operation.
They include tests at different filling ratios of the secondary loop and at different Primary Side temperature and flowrate conditions.
The non-condensable gas injection is also foreseen.



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TEST EXECUTION, DATA ANALYSES AND CODE VALIDATION

The tests execution can start only after the instrument check is performed at the beginning of the testing day and it is verified all of them are within certain specified limits (Hydro-zero check).

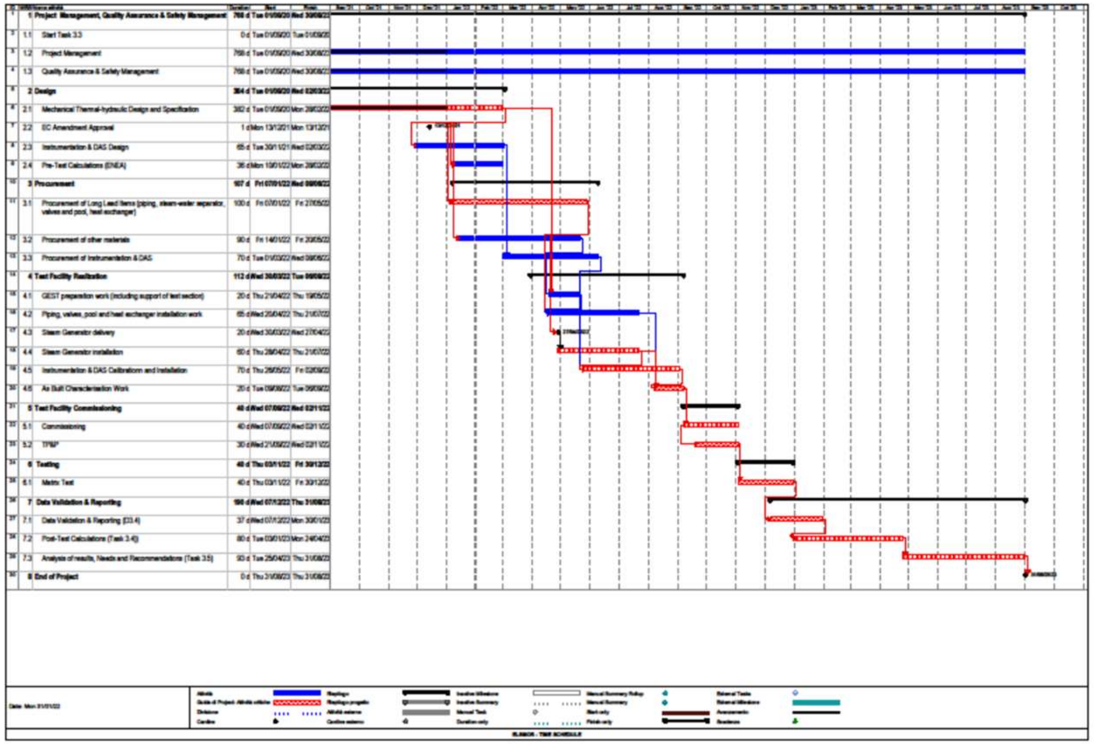
Once experimental data are available, first a data analysis is performed to verify that the phenomena of interest are captured.

Then, data can be used for code validation with the execution of post-test analyses.

Time Schedule for ELSMOR Facility Realization and Testing

- Design review and finalization (by February 2022)
- Procurement (by May 2022)
- Test facility realization (by August 2022)
- Test facility Commissioning (by October 2022)
- Testing (by December 2022)
- Data validation and reporting (by January 2023)

- Gantt chart



- THANK YOU!
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ELSMOR

Towards European Licensing of Small Modular Reactors

This project has received funding from the Euratom research and training programme 2014-2018 under Grant Agreement No. 847553.