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Integration of sCO2-HeRo in to the PWR type of reactors

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ÚJV

sCO2 HeRo
The supercritical CO_2 heat removal system

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Basic design - integration to the NPP defense in depth concept IAEA

Levels of defense in depth	Associated plant condition categories	Objective		Essential means
DID 1	**DBC - Normal** operation	Prevention of abnormal operation and failures		Conservative design and high quality in construction and operation, control of main plant parameters inside defined limits
DID 2	**DBC** - Anticipated operational occurrences (**abnormal**)	Control of abnormal operation and detection of failures		Control, limiting and protection systems and other surveillance features
DID 3	**Design basis** accidents (postulated single initiating events)	Control of accident to limit radiological releases and prevent escalation to core melt conditions	LOCA	Reactor protection system, safety systems, accident procedures
DID 4a	**DEC** - Postulated multiple failure events		SBO LOCA (no emergency active cooling system available)	Additional safety features, accident procedures
DID 4b	**Beyond design basis** accidents Severe accidents	Control of accidents with core melt to limit off-site releases	Core melt, direct Con[illegible] heating, corium cooling	Complementary safety features to mitigate core melt, Management of accidents with core melt (severe accidents)
DID 5	-	Mitigation of radiological consequences of significant releases of radioactive material		Off-site emergency response

SBO-SG_HRS

Containment_HRS

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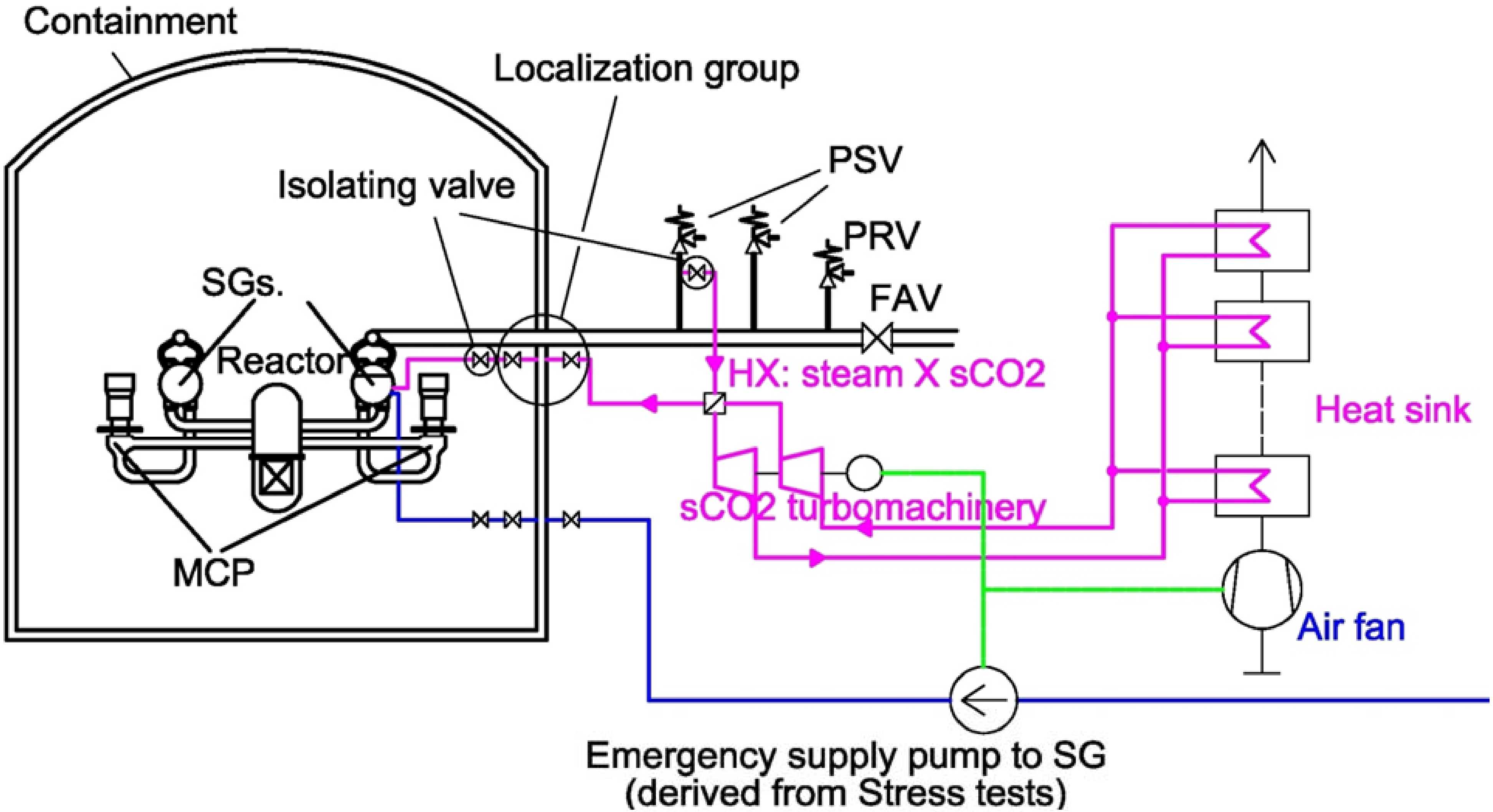
Basic design - integration to the NPP defense in depth concept IAEA

- **SBO-SG_HRS system should work in case of Station BlackOut, in defense in depth level DID 4a - design extension condition DEC - Postulated multiple failure events according IAEA or DID 3b Selected Multiple failures events according WENRA.**
- **Containment_HRS serves for removal of heat from containment and it should work in case of any rupture in primary circuit. It can be used in case of LOCA accident DID 3 - Design basis accidents (postulated single initiating events) according IAEA or DID 3a Postulated single initiated events according WENRA and in case of SA (Severe accidents) DID 4b - Beyond design basis accidents according IAEA or DID 4 – Postulated Core Melt Accidents according WENRA.**

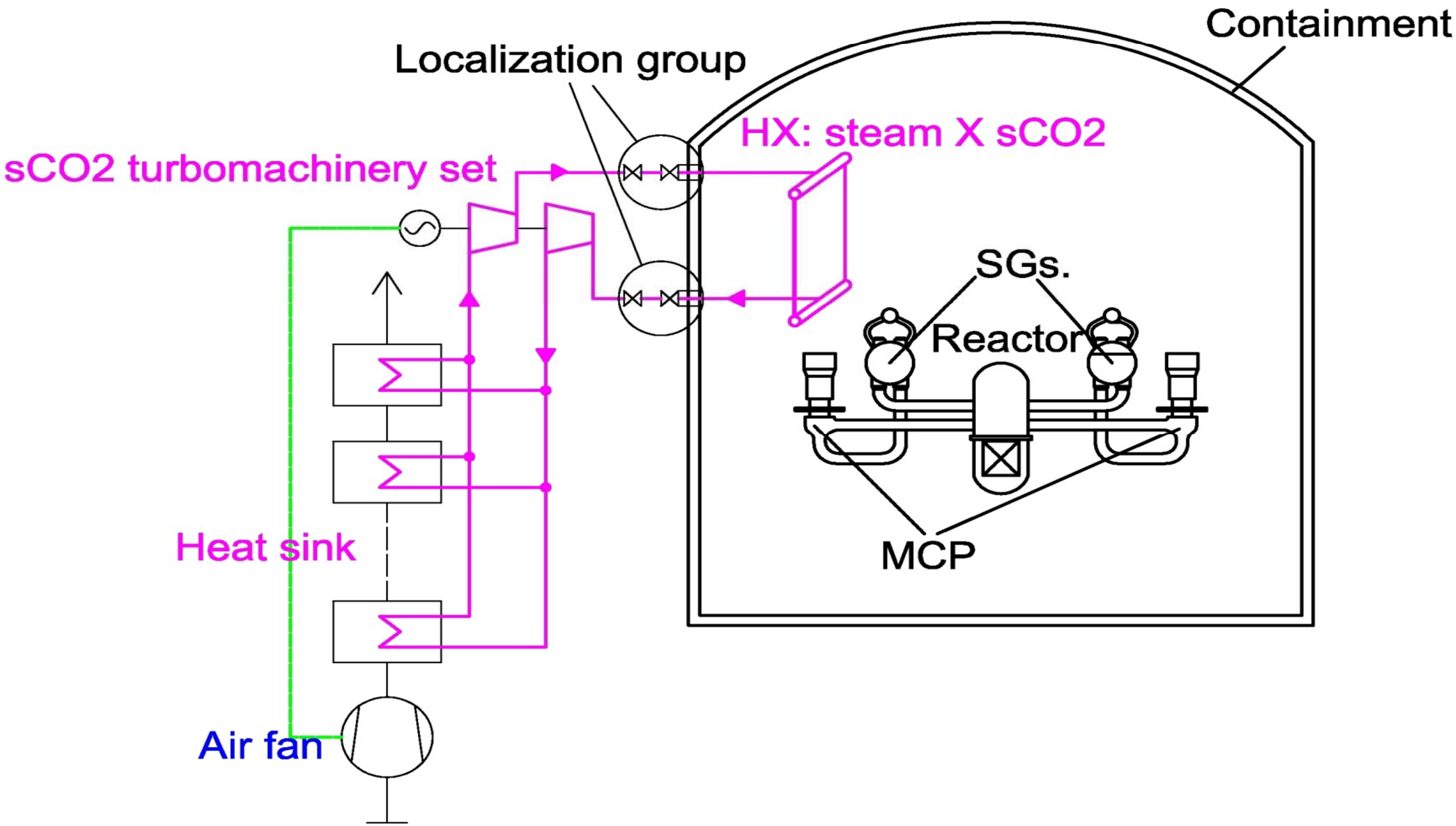
Basic design - SBO-SG_HRS



SBO-SG_HRS

- **SBO-SG_HRS is Self-propellant, self-launching. The self-launching system is conditioned for:**
  - Newly build NPP, is possible to integrate SBO-SG_HRS to DID logic sequence, because it's newly developed in the design phase of project.
  - Currently operated units, it's difficult to add SBO-SG_HRS system as self-launching - operator manually actuated systems needed.

Basic design - Containment_HRS



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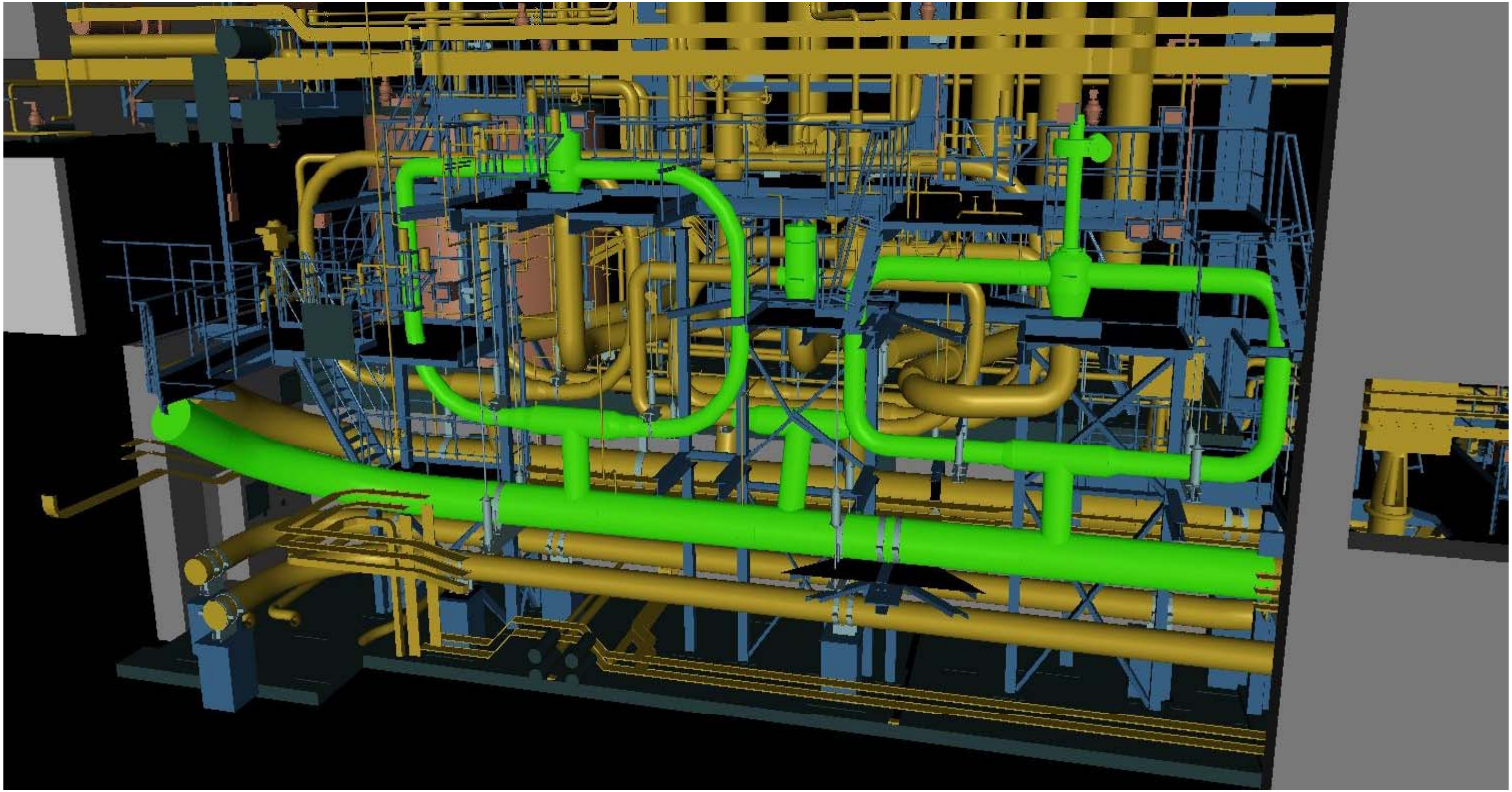
Basic design - Containment_HRS

- Design of Containment_HRS (Heat Removal System) can be self-propellant, but not self-launching because of changing conditions inside containment.

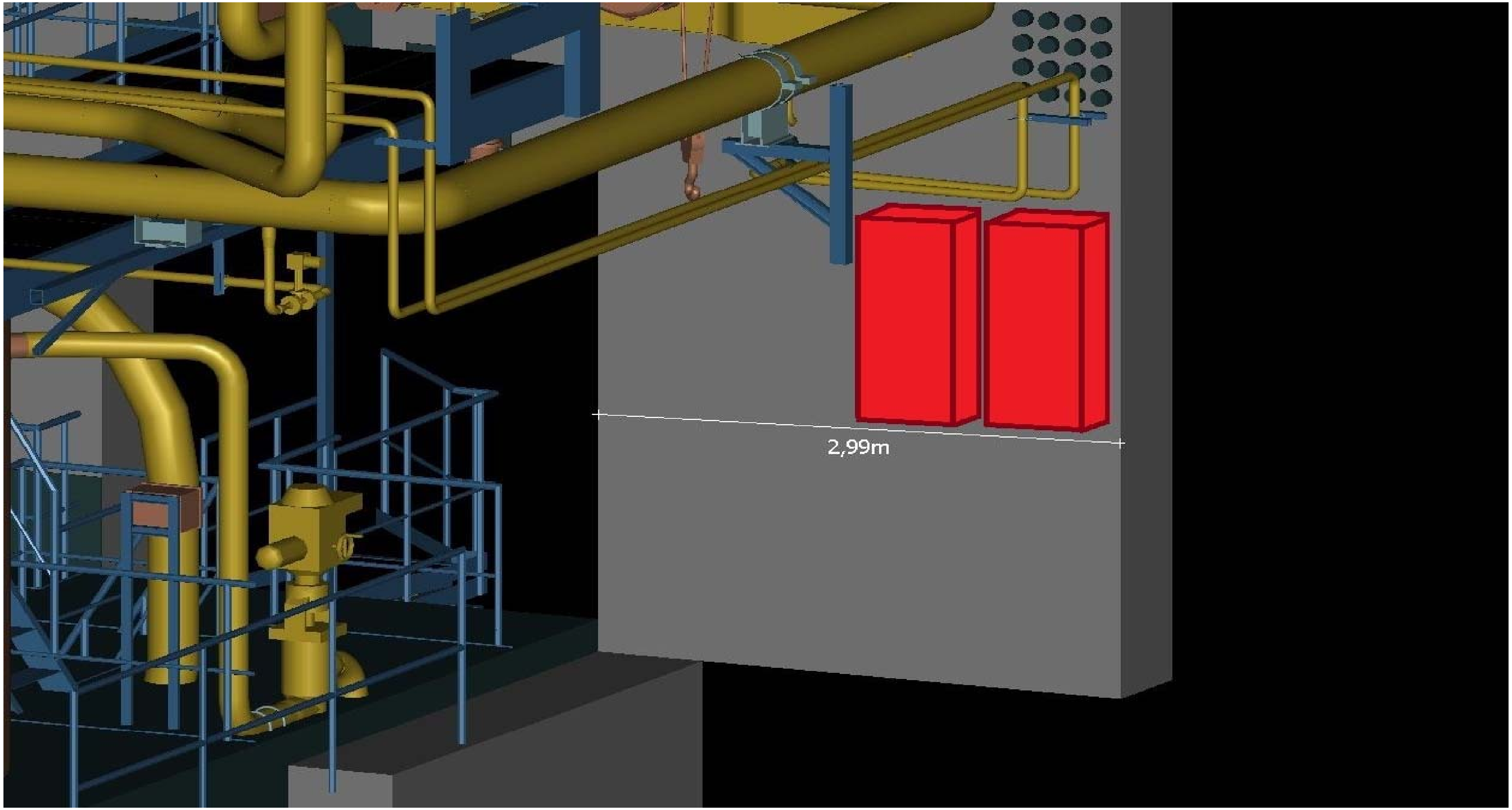
Basic design - HRS

- **Arrangement of four units in containment**
  - System consists of 4 individual unites
- **System components**
  - Pipelines, Isolation valve – vapor/ water, Containment localization group of valves, CO_2 loop turbo machinery, Breather valve, Heat exchanger CO_2 / air, Heat exchanger steam / CO_2, Air fan, Start up system, Storage and supply of CO_2 gas

System integration - SBO-SG_HRS

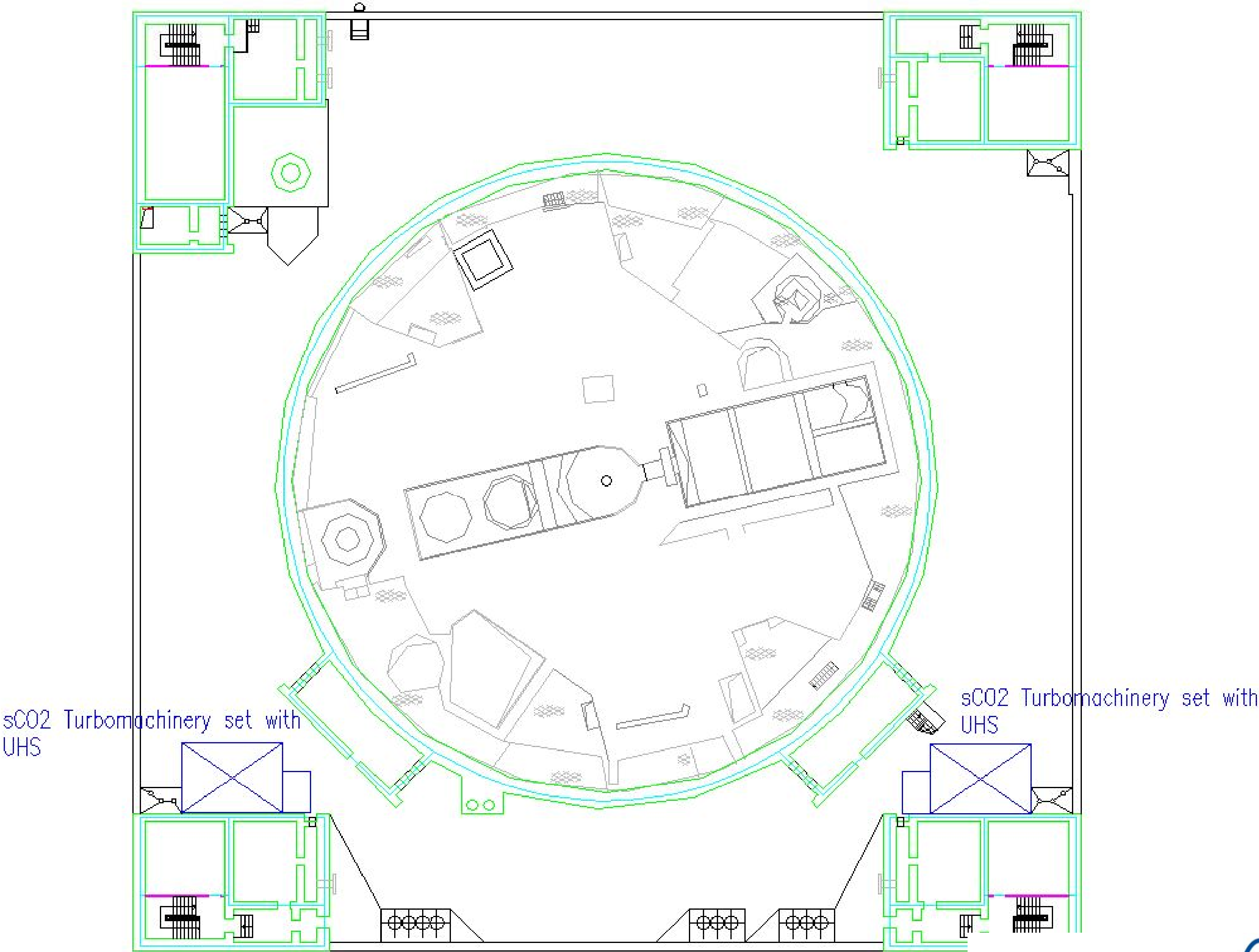


System integration - SBO-SG_HRS



sCO2 HeRo
The supercritical CO_2 heat removal system

System integration - SBO-SG_HRS



Thermodynamic analysis

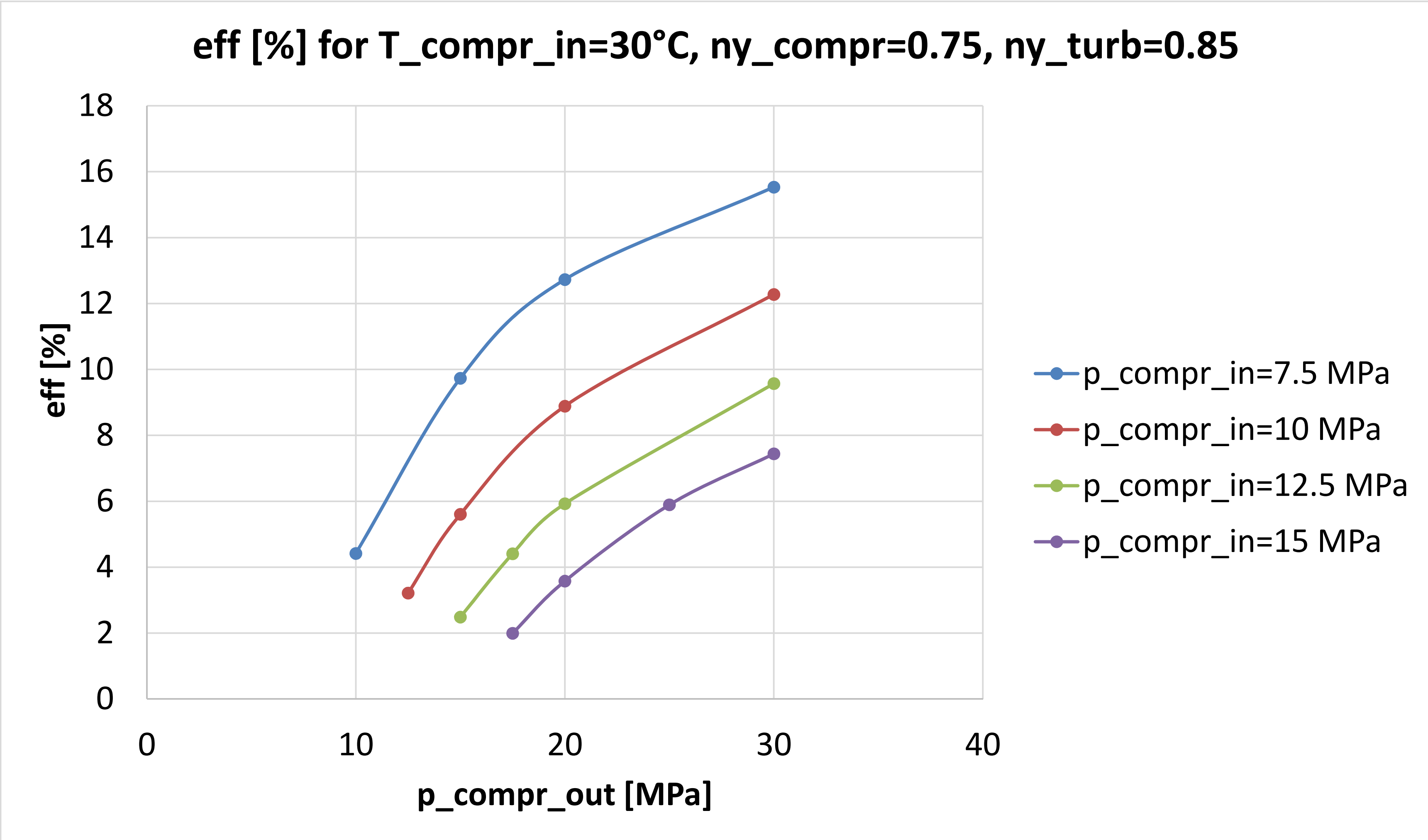
Cycle calculation – optimization of parameters

- The sCO_2-HeRo cycle is design as a simple Brayton cycle.
- The optimization is based on searching a compressor inlet and outlet pressure of cycle to receive the highest efficiencies of the cycle.
- thermodynamic values of the cycle which were considered.

Variable	*Value*	*Unit*
inlet temperature sCO2 to the compressor	30, 40 and 50	˚C
inlet temperature sCO2 to the turbine CONTAIMENT_HRS/SBO-SG_HRS	114.0/280.0	˚C
Inlet sCO2 pressure to the compressor	75, 100, 125 and 150	bar
inlet sCO2 pressure to the turbine	100, 150, 200 and 300	bar
thermal power of heat source	5000.0	kW
isentropic efficiencies of the compressor	0.65, 0.75 and 0.8	-
isentropic efficiencies of the turbine	0.75, 0.85 and 0.9	-

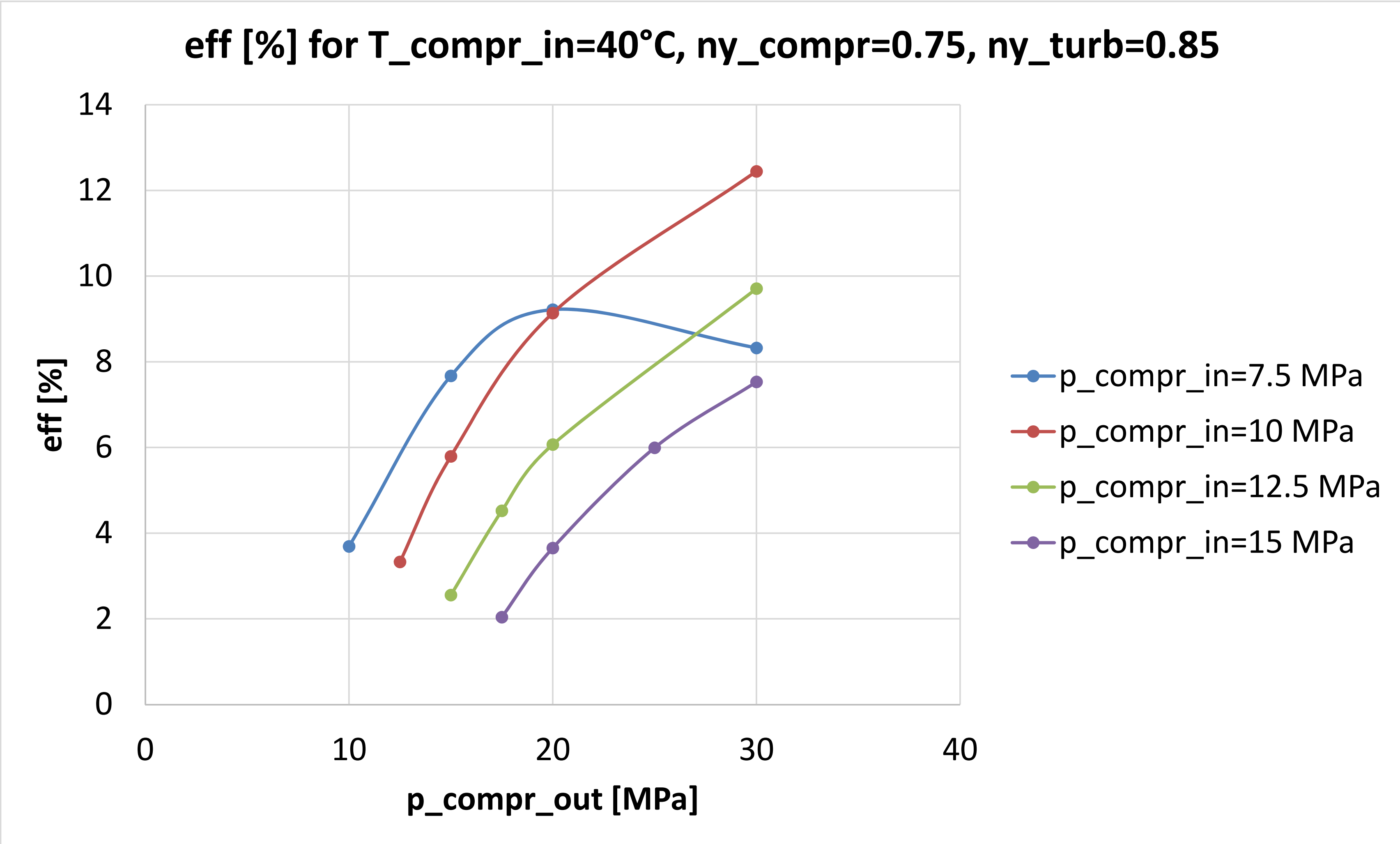
Thermodynamic analysis

Cycle calculation – optimization of parameters



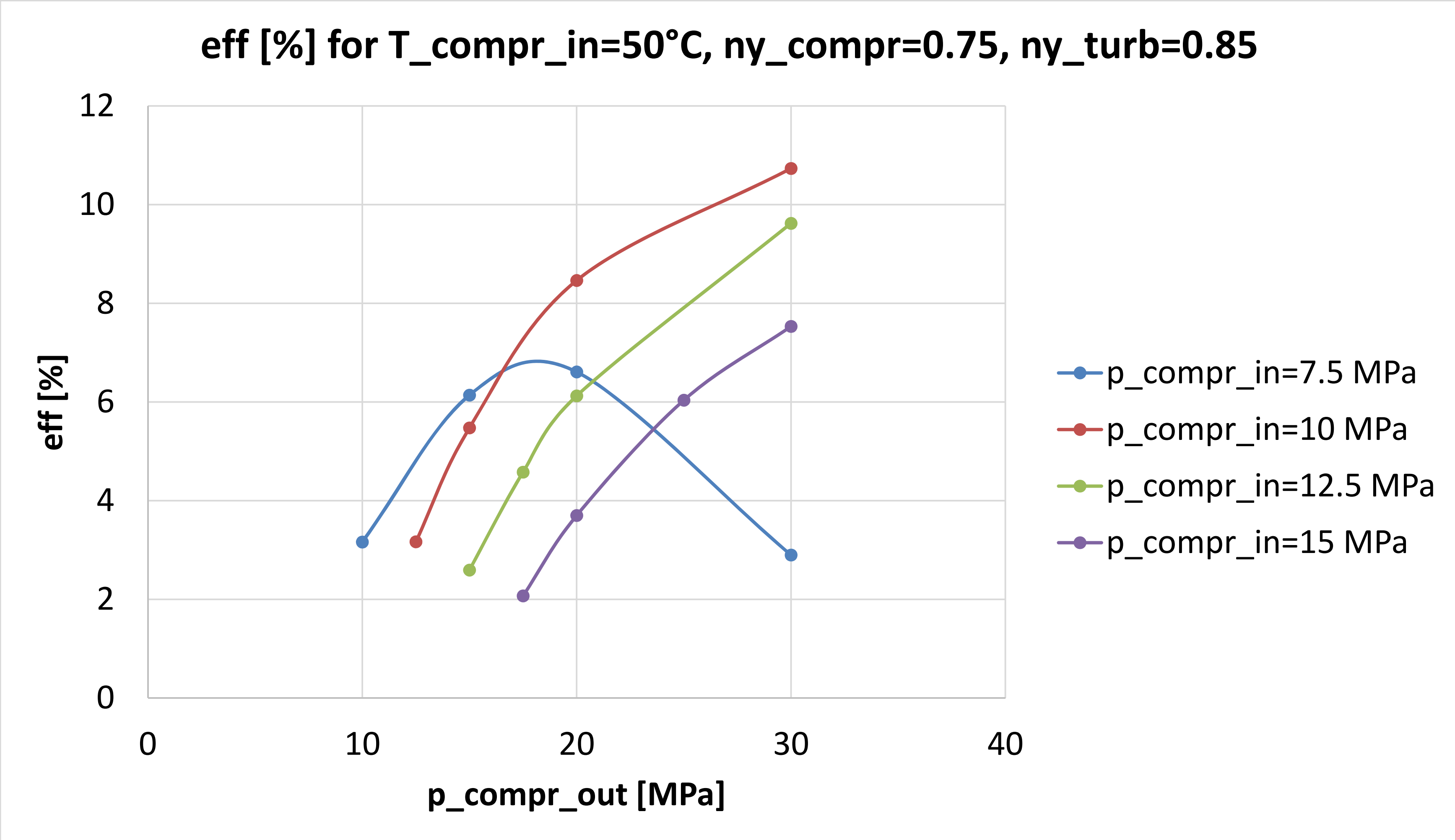
Thermodynamic analysis

Cycle calculation – optimization of parameters



Thermodynamic analysis

Cycle calculation – optimization of parameters



sCO2 The supercritical CO_2 HeRo heat removal system

Thermodynamic analysis

Cycle calculation – optimization of parameters

- According to Czech authority (SUJB) all safety systems needs to be designed for extreme climatic conditions, i.e. air temperature 45°C. On the other hand, the system should be able to work during winter temperatures below zero °C as well.
- A sensitivity study was performed in order to see the behavior of cycle in off-design inlet compressor temperature to prevent difficulties when setting improper nominal design conditions.

Thermodynamic parameters of cycle designed for 55°C of compressor inlet and influence on the cycle for 30°C

T1 [°C]	p1 [MPa]	p2 [MPa]	m [kg/s]	η_cycle [%]	P_cycle [MW]
55.00	11.67	17.51	15.36	5.39	0.27
30.00	11.67	17.51	11.58	5.33	0.27

Thermodynamic parameters of cycle designed for 30°C of compressor inlet and influence on the cycle for 55°C

T1 [°C]	p1 [MPa]	p2 [MPa]	m [kg/s]	η_cycle [%]	P_cycle [MW]
55.00	7.21	10.82	20.91	3.82	0.19
30.00	7.21	10.82	12.16	6.21	0.31

It is evident that the system designed for nominal conditions 30°C compressor inlet has a few percent higher power output than the system designed for 55°C during off-design 30°C. However, this system would shows worse performance at off-design 55°C which has the highest importance.

Thermodynamic analysis

Cycle calculation – optimization of parameters

SBO-SG_HRS system optimization

- Nominal thermodynamic values of the SBO-SG_HRS cycle which were selected as an optimum.
- The pressure ratio was limited to 1.5 so to keep one stage design of compressor and having acceptable low rpm.

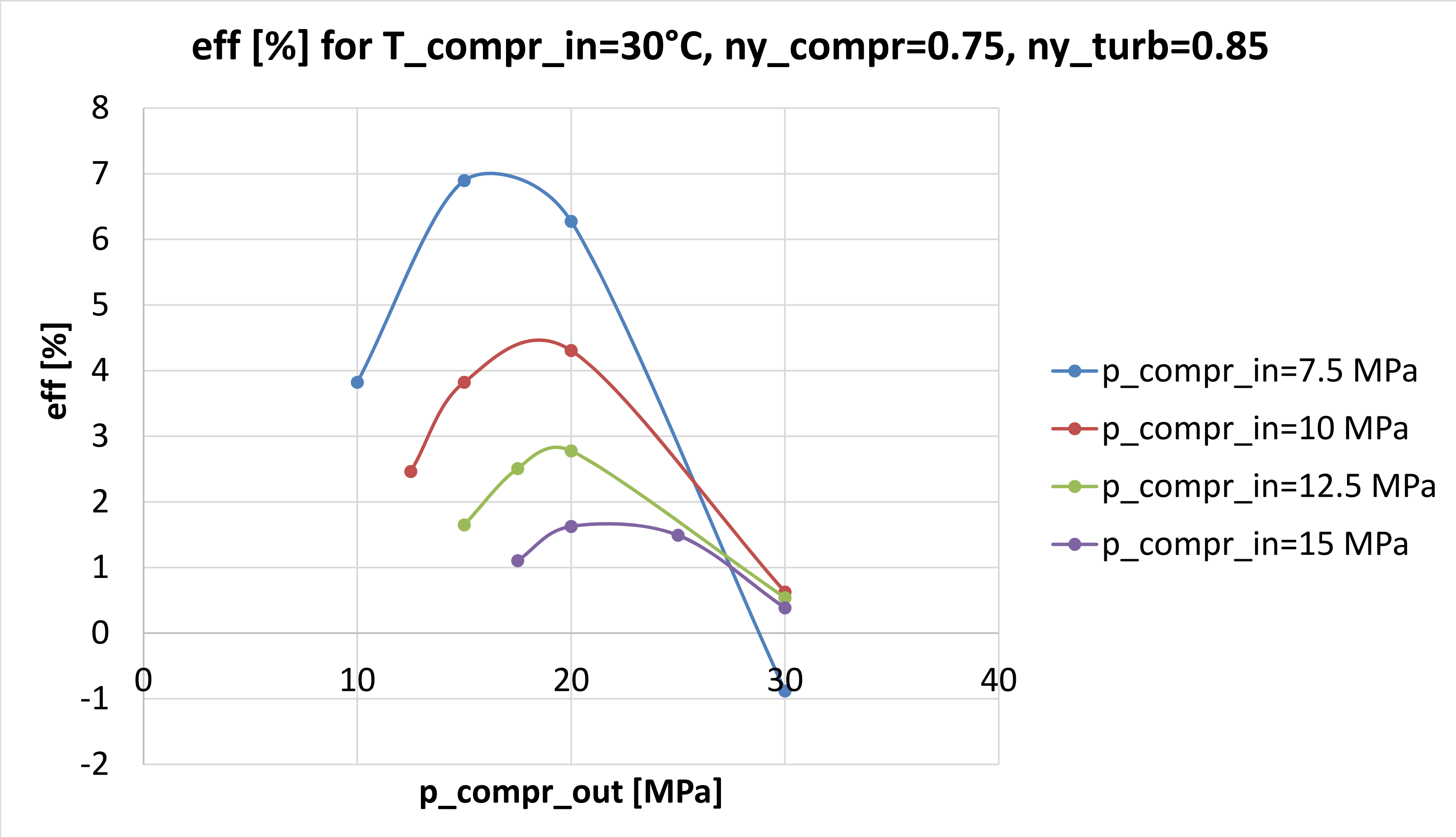
Variable	*Value*	*Unit*
inlet temperature sCO2 to the compressor	**55.0**	°C
inlet temperature sCO2 to the turbine	**280.0**	°C
outlet temperature sCO2 of the compressor	77.1	°C
outlet temperature sCO2 of the turbine	240.9	°C
inlet pressure sCO2 to the compressor	116.7	bar
inlet pressure sCO2 to the turbine	175.1	bar
mass flow rate of sCO2	15.4	kg/s
thermal power of heat source	**5000.0**	kW
thermal power of sink HX	4730.0	kW
isentropic efficiencies of the compressor	0.75	-
isentropic efficiencies of the turbine	0.85	-
power of turbine	500.0	kW
power of compressor	230.0	kW
power output of cycle	**270.0**	kW
cycle efficiency	**5.4**	%

The preliminary calculation of compressor and turbine sizing was performed according to Aungier (R. Aungier, Centrifugal compressor).

Thermodynamic analysis

Cycle calculation – optimization of parameters

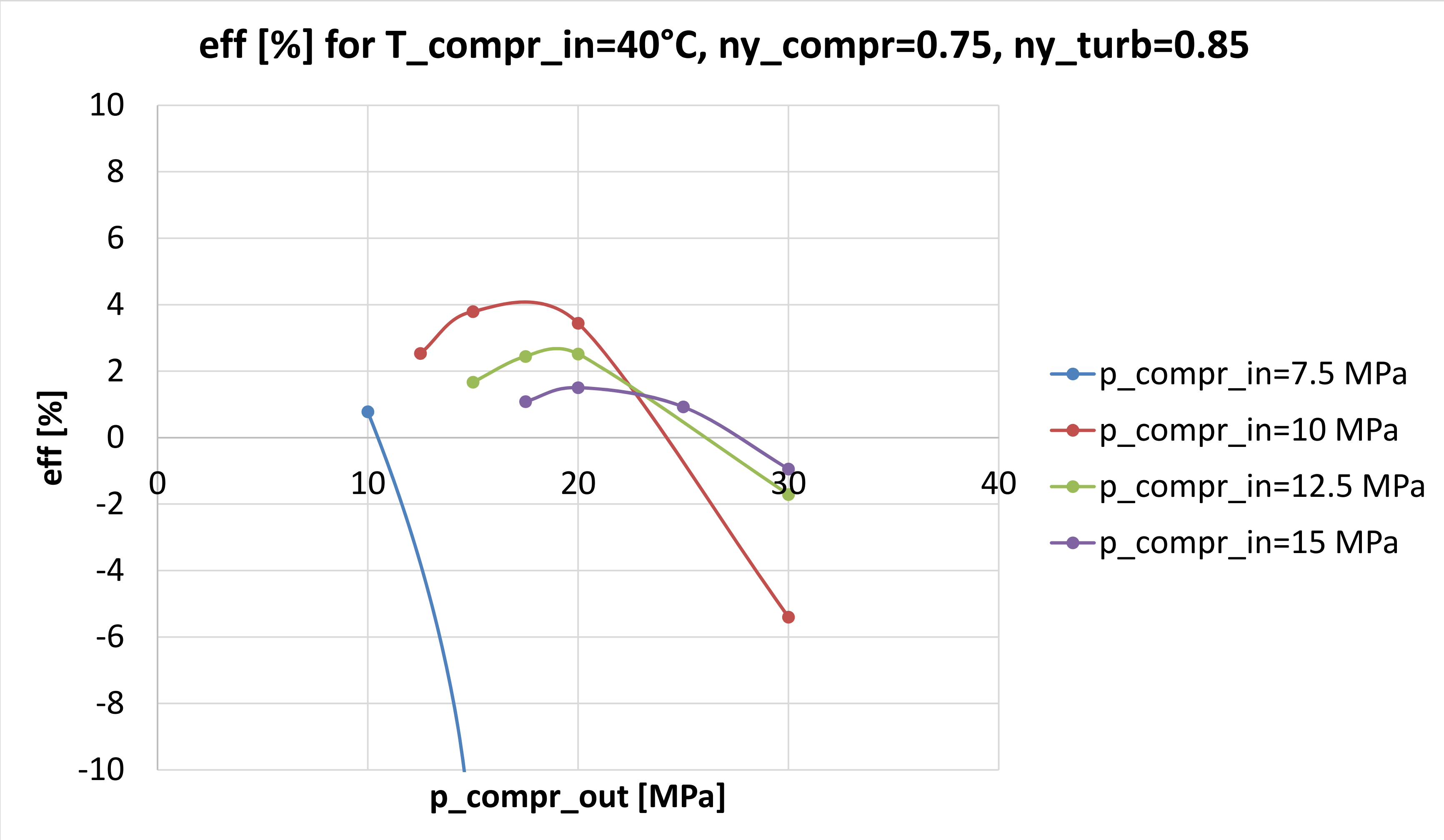
CONTAINMENT_HRS system optimization



Thermodynamic analysis

Cycle calculation – optimization of parameters

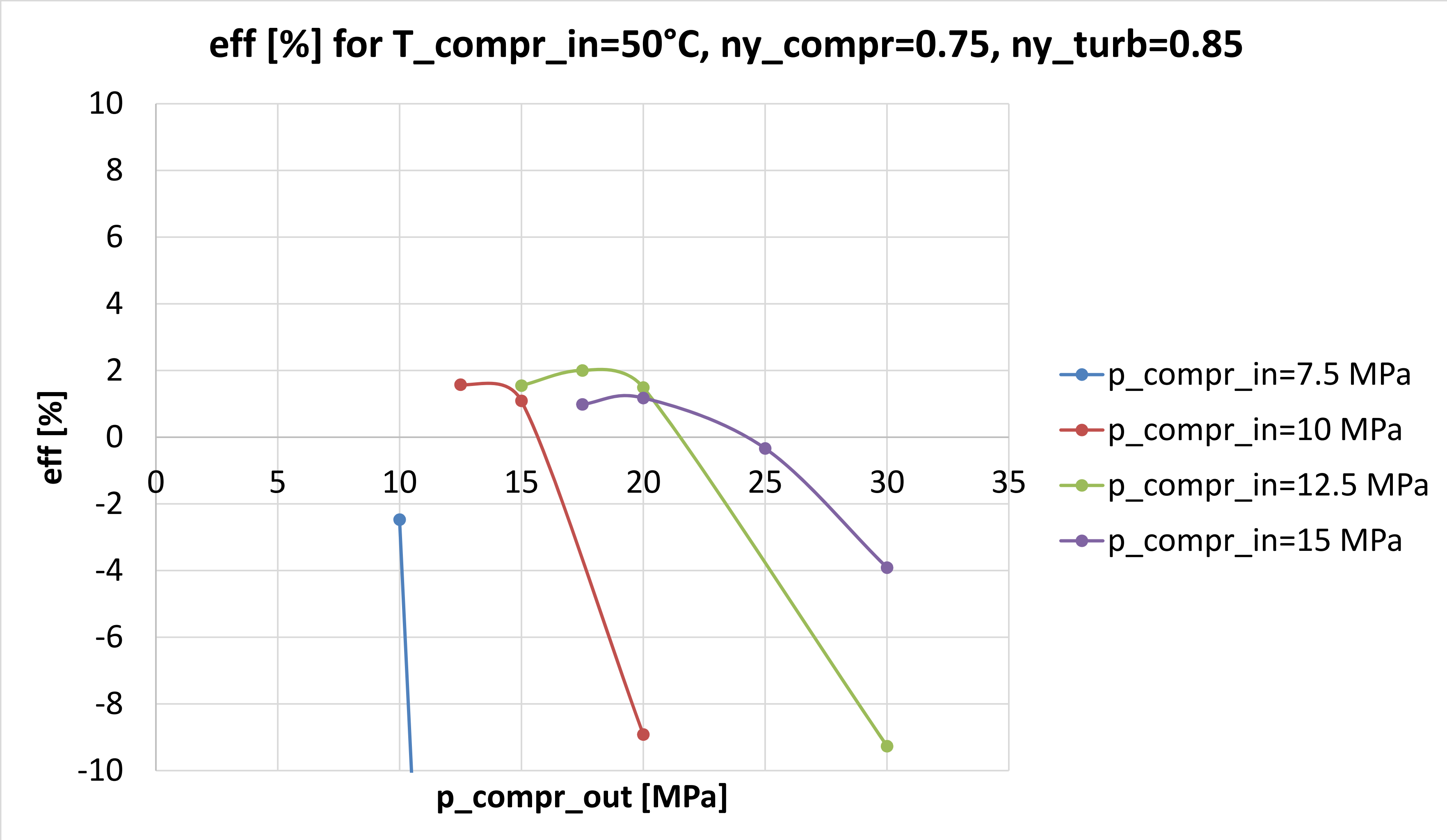
CONTAINMENT_HRS system optimization



Thermodynamic analysis

Cycle calculation – optimization of parameters

CONTAINMENT_HRS system optimization



Thermodynamic analysis

Cycle calculation – optimization of parameters

- According to Czech authority (SUJB) all safety systems needs to be designed for extreme climatic conditions, i.e. air temperature 45°C. On the other hand, the system should be able to work during winter temperatures below zero °C as well.
- A sensitivity study was performed in order to see the behavior of cycle in off-design inlet compressor temperature to prevent difficulties when setting improper nominal design conditions.

Thermodynamic parameters of cycle designed for 55°C of compressor inlet and influence on the cycle for 30°C

T1 [°C]	p1 [MPa]	p2 [MPa]	m [kg/s]	η_cycle [%]	P_cycle [MW]
45.00	10.28	15.85	38.22	3.24	0.16
30.00	10.28	15.82	24.56	3.82	0.19

Thermodynamic parameters of cycle designed for 30°C of compressor inlet and influence on the cycle for 55°C

T1 [°C]	p1 [MPa]	p2 [MPa]	m [kg/s]	η_cycle [%]	P_cycle [MW]
45.00	7.21	14.43	327.29	-69.73	-3.49
30.00	7.21	14.43	28.77	7.28	0.36

It is evident that the system designed for nominal conditions 30°C compressor inlet has higher power output, approximately double than the system designed for 45°C during off-design 30°C. However, this system would not be self-propellant during off-design 45°C which has the highest importance.

Thermodynamic analysis

Cycle calculation – optimization of parameters

CONTAINMENT_HRS system optimization

- Nominal thermodynamic values of the SBO-SG_HRS cycle which were selected as an optimum.
- The pressure ratio was limited to 1.5 so to keep one stage design of compressor and having acceptable low rpm.

Variable	*Value*	*Unit*
inlet temperature sCO2 to the compressor	**45.0**	°C
inlet temperature sCO2 to the turbine	**114.0**	°C
outlet temperature sCO2 of the compressor	63.6	°C
outlet temperature sCO2 of the turbine	79.3	°C
inlet pressure sCO2 to the compressor	102.8	bar
inlet pressure sCO2 to the turbine	158.5	bar
mass flow rate of sCO2	38.2	kg/s
thermal power of heat source	**5000.0**	kW
thermal power of sink HX	4840.0	kW
isentropic efficiencies of the compressor	0.75	-
isentropic efficiencies of the turbine	0.85	-
power of turbine	650	kW
power of compressor	490	kW
power output of cycle	**160**	kW
cycle efficiency	**3.2**	%

The preliminary calculation of compressor and turbine sizing was performed according to Aungier (R. Aungier, Centrifugal compressor).

Conclusions

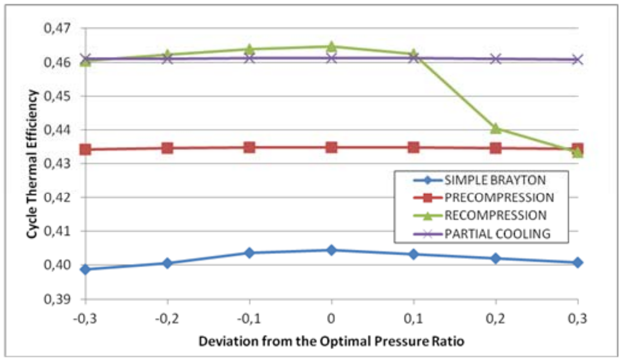
According to performed analyses for the PWR the aim of having integrated the sCO2-HeRo system into the real power plant is feasible as a safe, reliable and efficient residual heat removal system from the nuclear reactor vessel without the requirement of external power sources.

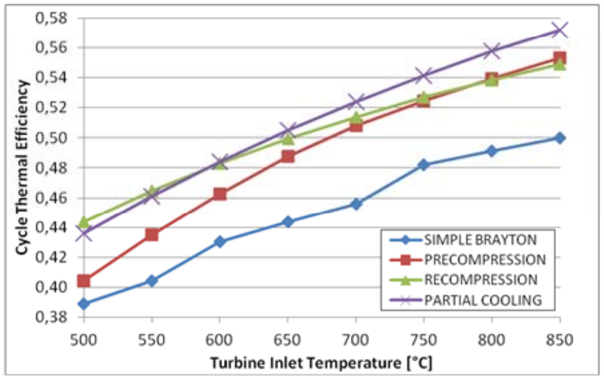
The project leading to this application has received funding from the *Euratom research and training programme 2014-2018* under grant agreement No 662116.

CVR CO_2 activities

S-CO_2 loop – main parameters

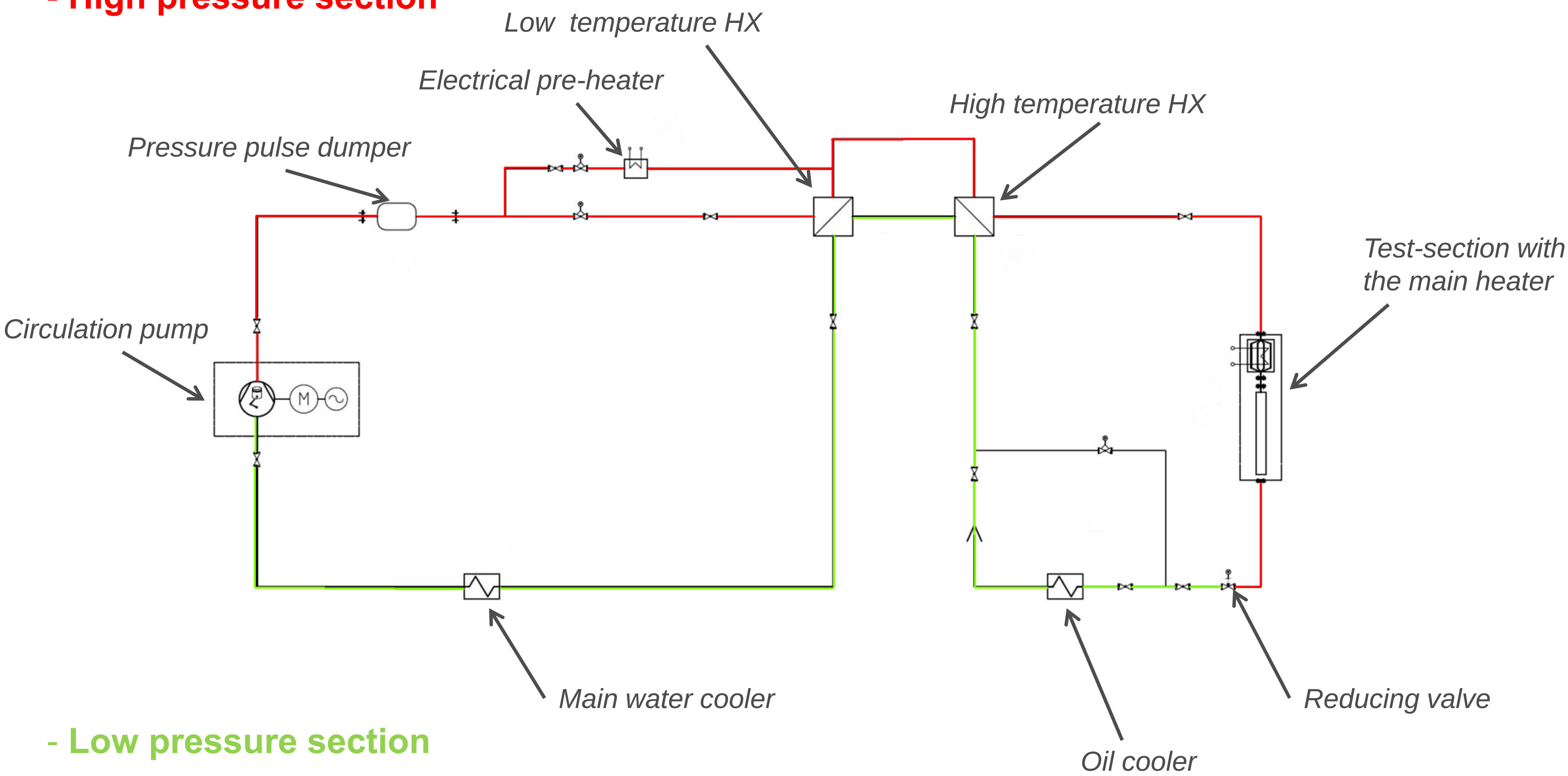
- Max. operating temperature: 550˚C
- Max. pressure at high pressure site: 25 MPa
- Max. pressure at low pressure site: 12,5MPa
- Max. flow rate: 0,4 kg/s
- Total heating power: 120 kW
- Power of the pre–heater : 20 kW
- Power of the main heater : 100 kW





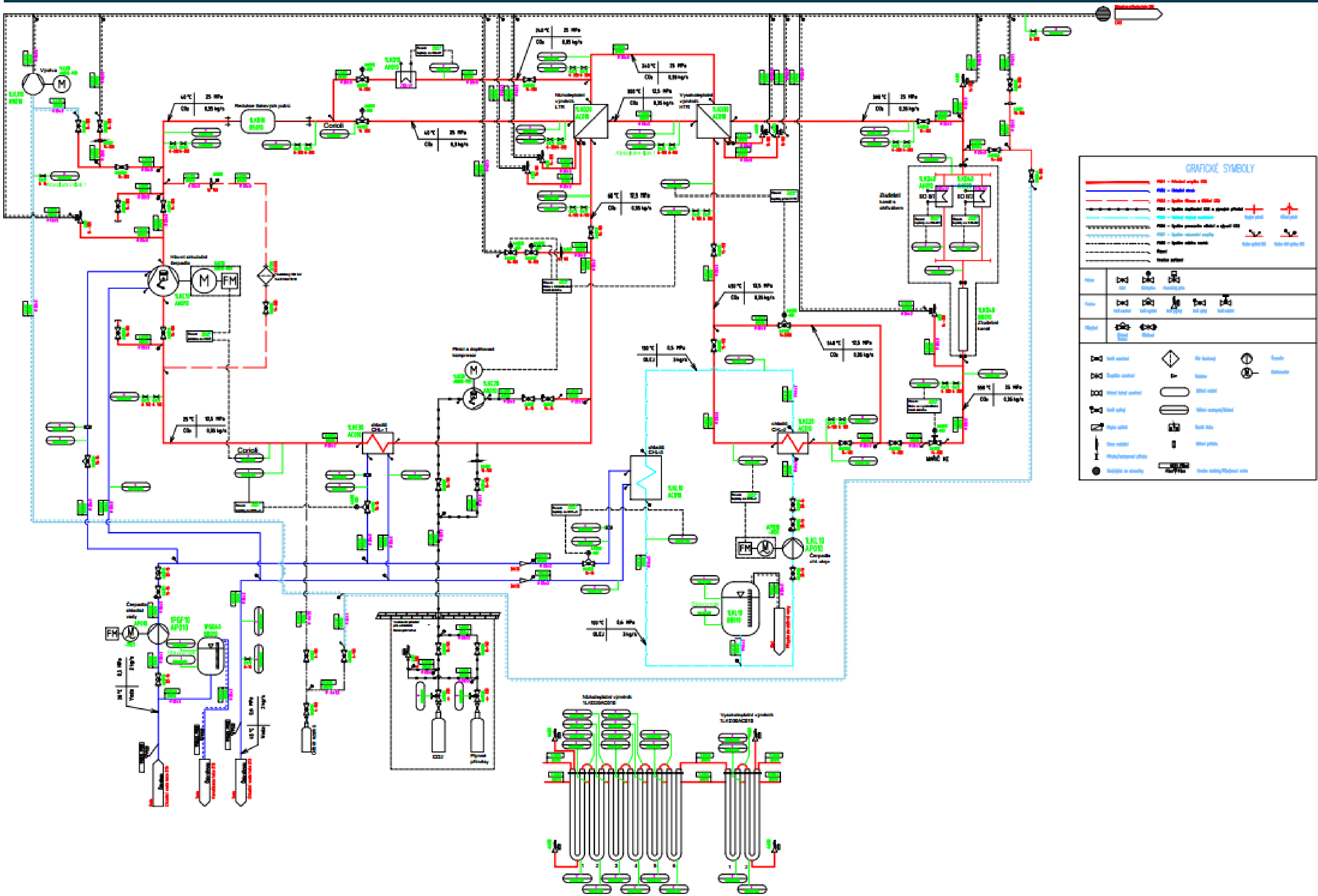
SCO2 loop – Primary circuit

- High pressure section

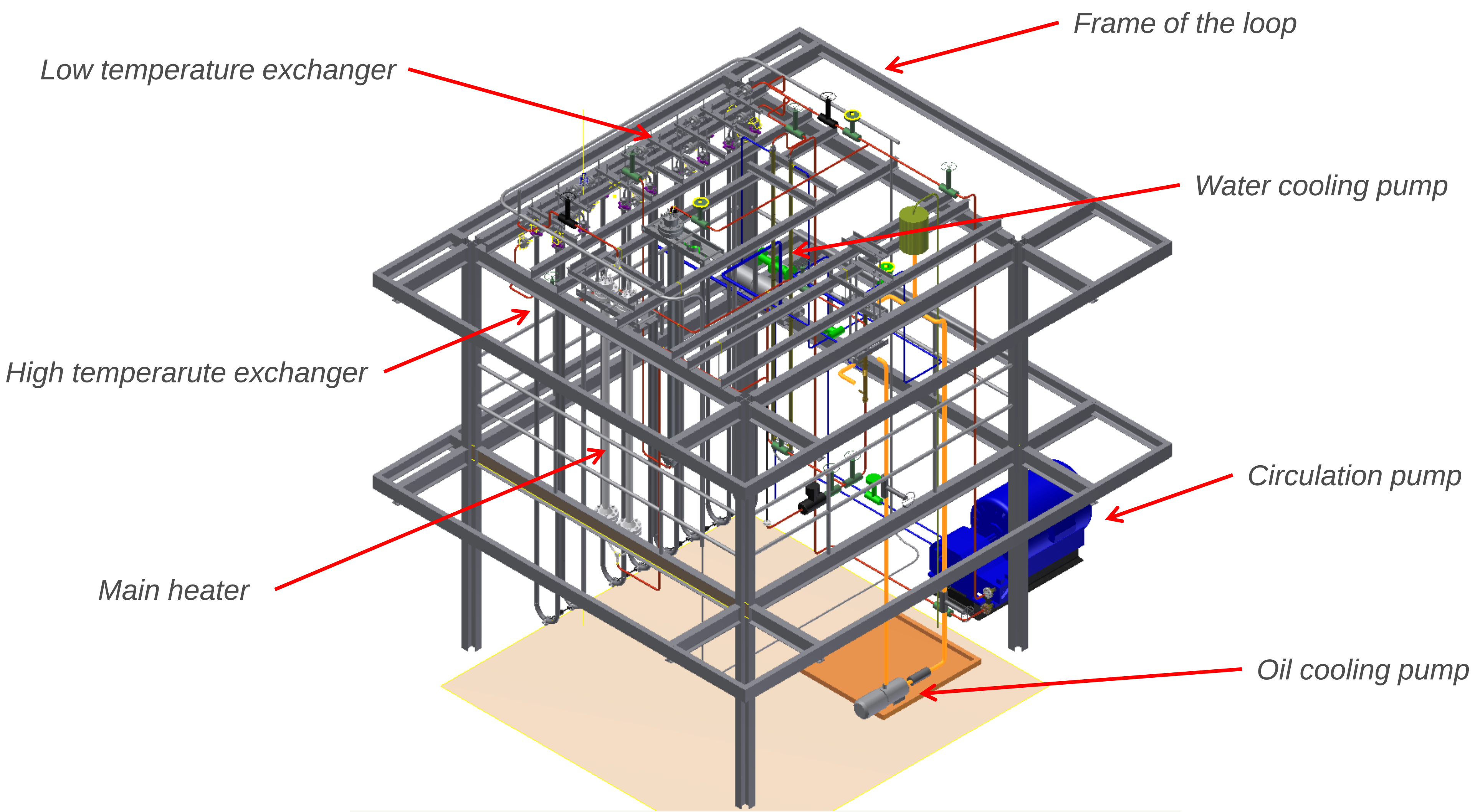


- Low pressure section

Experimental loop S-CO2 SUSEN



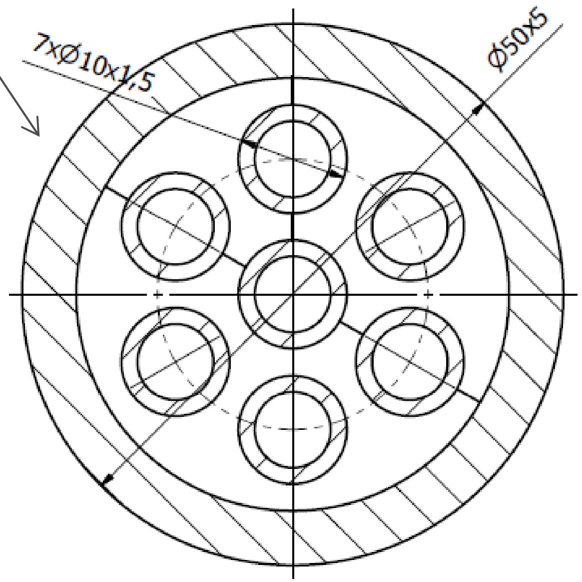
Design of the experimental loop



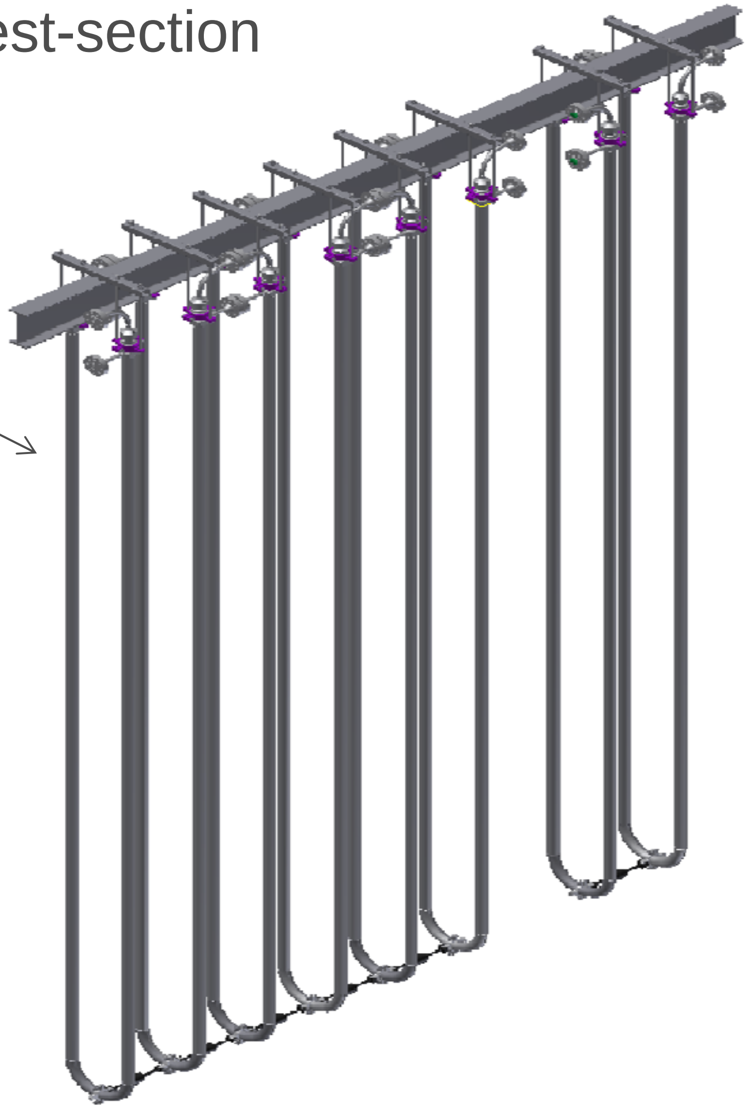
Experimental capabilities

- **Test-Section – corrosion, erosion on parameters**
  - Loop is built for easy change different Test-section
- **Heat exchangers**
  - Test of the poperties heat exchangers

Cross exchanger

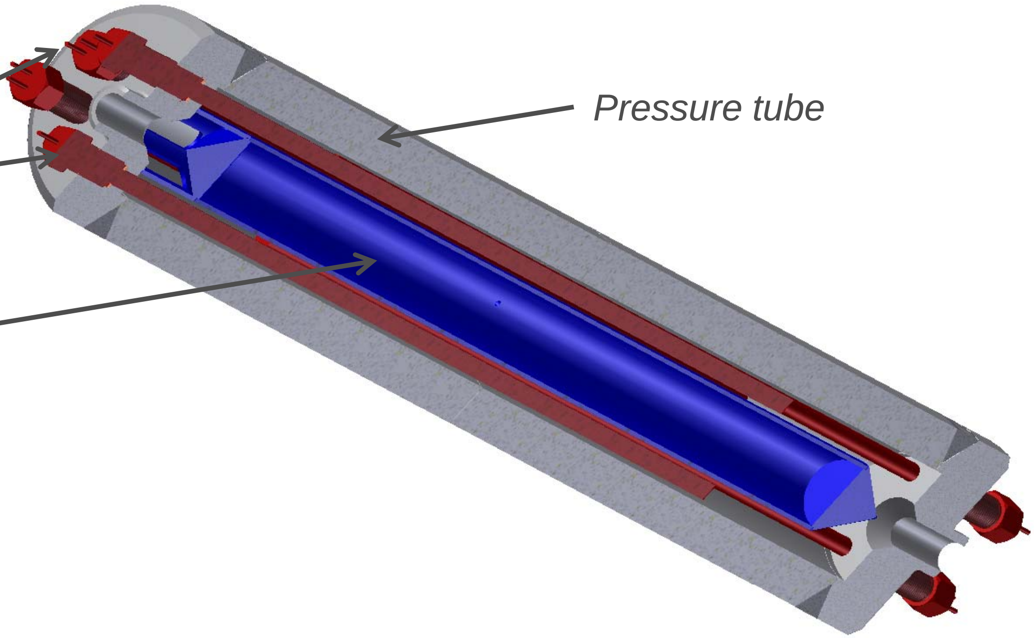


Exchangers assembly



Experimental capabilities

- **FIV – Flow induced vibration**
  - The loop is going to heated by two parallel channels, and is possible to heat each other



- **Turbomachinary**
  - the loop is able to test HeRo turbo set

Thank you

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