sCO2-4-NPP: Innovative sCO2-Based Heat Removal Technology for an Increased Level of Safety of Nuclear Power Plants

Deliverable 5.3

Summary of modifications on the reference plant after integration of the heat recovery system

Work programme topic addressed: NFRP-2018-10: Encouraging innovation in nuclear safety for the benefit of European citizen

Type of action: Innovation action

Grant Agreement number:	847606
Start date of project: 1 September 2019	Duration: 36 months
Lead beneficiary of this deliverable:	EDF
Due date of deliverable: 28/02/2022	Actual submission date: 19/08/2022
	Version #: R1.0

Type		
R	Document, report excluding the periodic and final reports	X
DEM	Demonstrator, pilot, prototype, plan designs	
DEC	Websites, patents filing, press & media actions, videos, etc.	
OTHER	Software, technical diagram, etc.	
Dissemination level		
PU	PUBLIC, fully open, e.g. web	X
CO	CONFIDENTIAL, restricted under conditions set out in Model Grant Agreement	

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 847606.

Revision History

Release	Date	Reason for Change	Author	Distribution
R0.1	18/07/2022	Draft to review	A. Cagnac	Consortium
R1.0	19/08/2022	Final version	A. Cagnac	Public

Deliverable Contributors

Authors

Partner	Name
EDF	Albannie Cagnac

Contributors

Partner	Name
JSI	A. Prošek

Internal Reviewers

Partner	Name
USTUTT	J. Starflinger

Table of contents

List of Tables

List of Figures

1 List of Acronyms

Abbreviation / Acronym	Description / meaning
ASG	Steam generator supply system
ASN	Autorité de Sûreté Nucléaire
BAS	Bâtiments d'auxiliaires (in English ‘auxiliary building’)
CHX	Compact Heat Exchanger
EIP	Élément important pour la protection (in English 'element important for protection')
HF	Conventional Island Electrical Building
HK	Hall Fuel Building
HR	Reactor building
INB	installations nucléaires de base (in English, 'basic nuclear installations')
NPP	Nuclear Power Plant
UHS	Ultimate Heat Sink
VDA	Ventilation to Atmosphere
VVP	Main Steam Supply System

2 Executive Summary

In the framework of the sCO2-4-NPP project, the consortium aims to continue the development of the sCO2 system, developed in the sCO2-HeRo project. The role of WP5 is to study the full scale-up of the sCO2 system and its possible integration in a nuclear power plant.

The aim of this report is to summarise, on the basis of the work carried out in WP5 of the sCO2-4-NPP project, the main modifications required in a power plant in order to install the sCO2 system.

Firstly, it presents the structural modifications, then the organisational modifications and finally the regulatory modifications.

It should be noted that as the sCO2 system is still at TRL 5 level, the detailed description of all necessary modifications is not exhaustive. This can only be done in the context of a concrete installation project, so that it can be adapted to the design of the nuclear power plant, and thus to the different equipment and their operating parameters that will be impacted.

3 Introduction

In the framework of the sCO2-4-NPP project, the consortium aims to continue the development of the sCO2 system, developed in the sCO2-HeRo project. The role of WP5 is to study the full scale-up of the sCO2 system and its possible integration in a nuclear power plant.

The aim of this report is to summarise, on the basis of the work carried out in WP5 of the sCO2-4-NPP project, the main modifications required in a power plant in order to install the sCO2 system.

Firstly, it presents the structural modifications, then the organisational modifications and finally the regulatory modifications.

4 Methodological approach

In order to identify and establish the list of modifications required to allow the installation of an sCO2 system in a nuclear power plant, we have relied on the work carried out in WP2, WP4, WP5 and WP6 of the sCO2-4-NPP project to identify the architectural modifications and procedures related to the operation of a power plant, and on the current regulations (work of WP3) to identify the regulatory procedures.

In a first step, the works of WP2, WP4 and WP5 will be used to present the architectural modifications to be carried out at the level of the power plant, within the framework of a retrofit installation (thus on an already existing power plant) and of the preparation of an installation on a new power plant design.

We will then present the modifications to the operating procedures to be implemented, and finally we will conclude with the regulatory modifications that will be necessary to obtain the approval of the safety authorities to install and operate the sCO2 system.

5 Architectural modifications

In deliverable 5.2, we studied the installation of sCO2 modules in an existing power plant (retrofit), this work will allow us in this deliverable to establish the list of architectural modifications to be carried out within a power plant, for the case of retrofit, but also for the case of an installation in a new power plant (and thus taking into account and the inclusion of the sCO2 system from the design phase of the power plant).

5.1 Architectural modifications in the context of a retrofit

Retrofitting the sCO2 system is the most difficult installation to carry out because it is necessary to find the right place for the modules, to couple with the existing installations, while trying to carry out as few structural modifications as possible and ensuring that the safety, security and proper functioning of all the equipment are guaranteed.

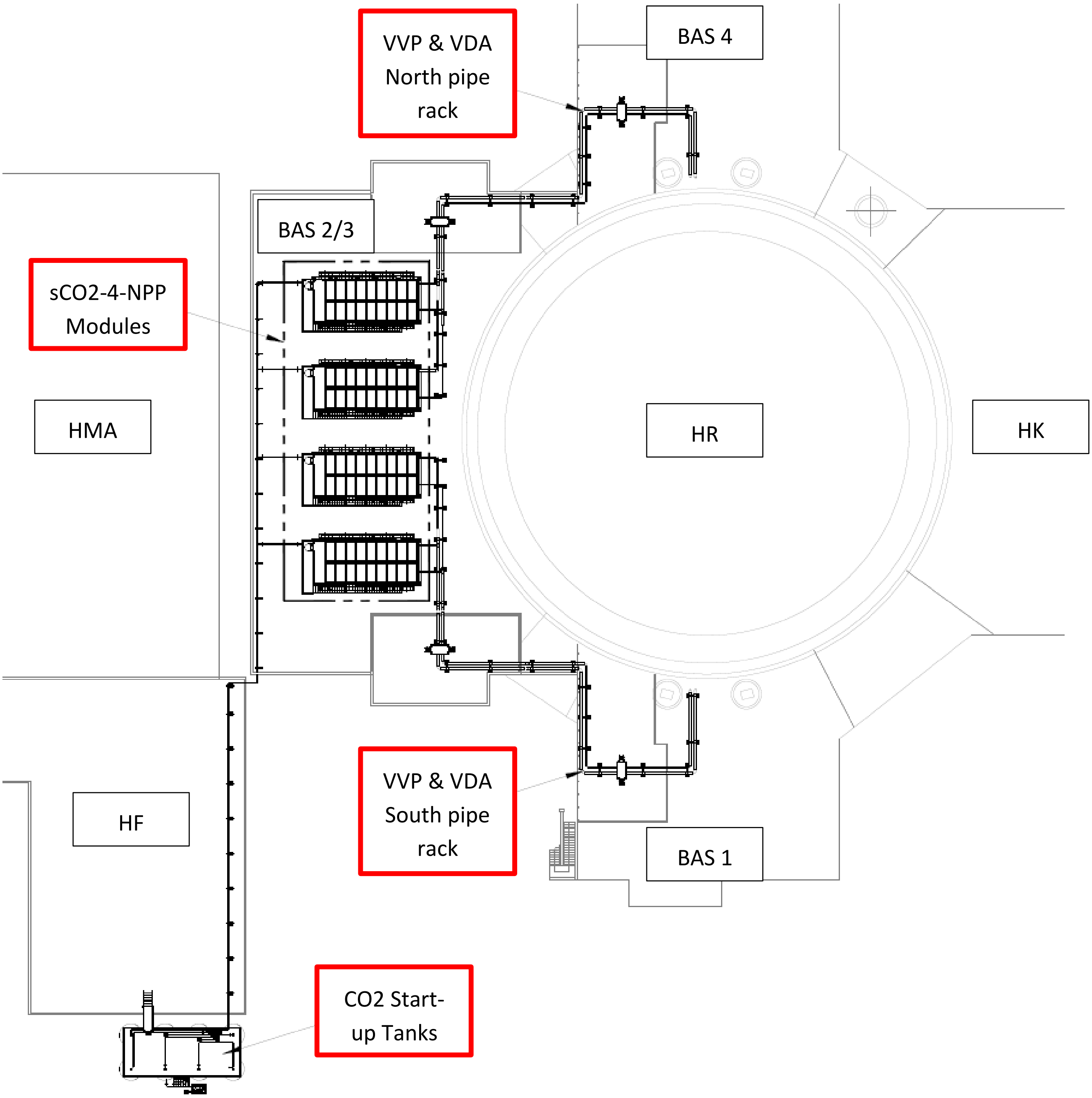


Figure 1: Proposition for installation on a rooftop (from sCO2-4-NPP D5.2)

5.1.1 Civil engineering modifications

The major changes for the civil engineering are related to two possibilities for installing the sCO2 systems.

To install the sCO2 system within the plant, it must first be determined whether the required number of sCO2 modules can be installed on a roof (as presented in deliverable D5.2), or within one of the plant buildings (outside the reactor building and the fuel building, as the lack of available space will probably not allow an installation of one or more modules and would require new safety demonstrations).

Installation on the roof of buildings:

The first modifications to be made will be to ensure that the roof of the building can support the total weight of the sCO2 modules, and the necessary protection against external events (e.g. earthquake resistant walls): Roof reinforcement and terracing will be required.

In the case of other equipment on the roof of the building (e.g. VDA systems on some PWR designs), it will be necessary to ensure that the modules installed do not interfere with their proper operation and maintenance (by checking that the circulation plans of personnel and vehicles are respected, or modified if necessary).

Installation outside existing buildings:

If the sCO2 systems are not installed within the power plant, but somewhat apart from it, the constraints on existing buildings will be much less.

The modifications to be made from a civil engineering point of view will be in the area of land preparation (earthworks, access road, installation of piping, etc.) and building construction (to current standards according to the safety classification of the sCO2 system).

5.1.2 Modification of existing water circuits

The modification of existing water circuits is one of the major changes in the installation of sCO2 modules, as the operator will have to ensure that this installation will not affect other plant circuits and safety systems that would be connected to the same water circuits.

Installation on a building roof:

In Deliverable D5.2 of the sCO2-4-NPP project, we presented the installation of the plant's auxiliary systems on a building roof. In order to maximise the proximity of the system to the primary loop of the plant (and thus maximise its ability to remove residual heat from the core), in deliverable D5.5 we studied the connection of the sCO2 system to the main steam and VDA piping on an EPR plant. The results of this work showed that the sCO2 system works well with the following configuration:

- Coupling of the sCO2 inlet piping to the main VVP piping, reusing the piping feeding the VDA system: The vapor side of the CHX corresponds to a subsidiary loop of the secondary loop of one steam generator of the EPR nuclear plant. As represented in Figure 2, the main pipe of the secondary loop filled with vapor coming from one steam generator (SG) and going to the turbine of the nuclear plant is divided to create an auxiliary loop.
- Coupling of the outlet pipe of the sCO2 system to the feeder pipe of the steam generators.

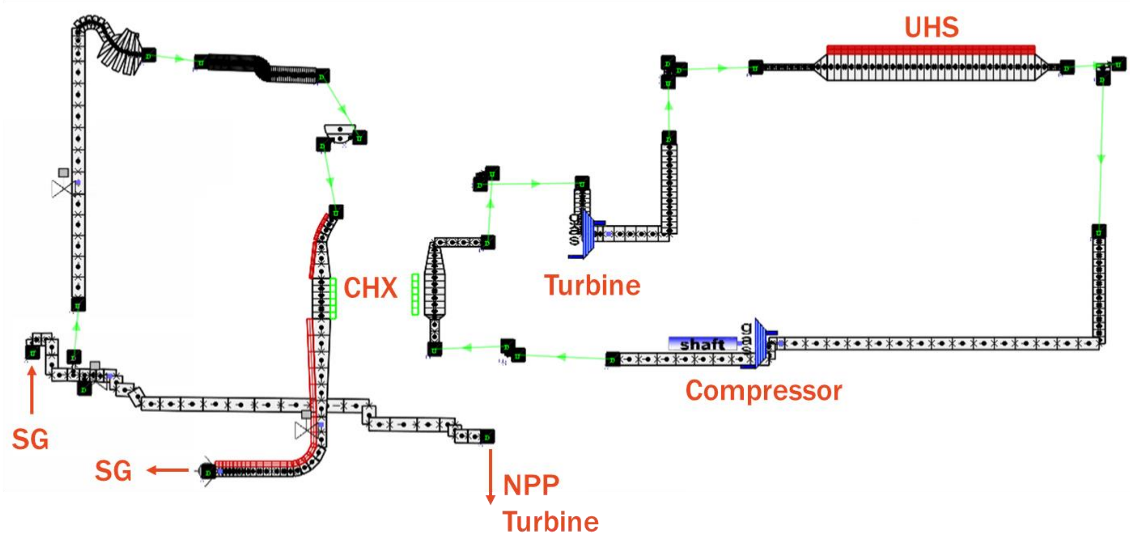


Figure 2: Integration of the sCO2 loop to the secondary loop of the EPR nuclear plant

There are therefore 2 major changes to consider for this installation:

- Creation of the supply pipework for the sCO2 system, by creating a connection to the VDA system pipework. The automatic or manual valves will also have to be provided, depending on the operating rules of the sCO2 system.
- Creation of a discharge pipe for the sCO2 system, with a connection to the steam generator supply pipe. This piping must comply with the standards and regulations of the ASG system piping and must also include valves to ensure the isolation of the sCO2 system if necessary.

The connections of these two pipes (inlet and outlet of the sCO2 system) must also be made outside the reactor building to avoid having to make a possible breakthrough in the building and thus avoid a modification of the safety file of the reactor building (and therefore a re-evaluation of all the associated studies).

A dedicated circuit for filling and managing the CO2 within the system is also required. This is shown in Figure 1 between the sCO2 storage tanks and the sCO2 modules. Installation of this piping on roofs is possible. Pipes and valves should be chosen to ensure the integrity of the piping (lifetime, reliability, control).

Installation outside existing buildings:

The modifications to the plant are the same as for a rooftop installation. The sCO2 system will need to be connected to the main steam circuits to supply the system. For a plant without a VDA circuit, as the modules will not be located close to the equipment, it will be necessary to connect directly to the VVP piping.

The outlet piping of the sCO2 system will also be connected to the piping of the Steam Generator supply system.

The sCO2 modules will be installed outside of the existing buildings, and therefore the modification of the pipework will need to make the necessary breakthroughs in the existing buildings.

5.1.3 Modification of auxiliary circuits / loops (electrical circuits, control command, etc.)

Auxiliary equipment such as instrumentation for control, operation and monitoring of the sCO2 system is also required.

The current development of the sCO2 system foresees a self-sufficient start-up, not requiring the use of systems such as batteries or stand-by operation during the operation of the plant, except in accidental situations. It is the pressure of the CO2, which allows the turbomachines to start up, without the need for an auxiliary source.

If future developments of the sCO2 system evolve towards another starting mode, it may be necessary to consider the installation of batteries (or even to plan for them as a precautionary measure, following a full risk analysis of possible start-up failures).

To ensure the operation and monitoring of the sCO2 system in good conditions, it will also be necessary to create the circuit with all the necessary instrumentation, as well as the implementation in the control room of the means to monitor and operate the system (start-up, shutdown, control of valves, regulation of the turbomachine, etc.).

The necessary instrumentation must also be provided to ensure the safety of the personnel and the sCO2 system. CO2 is an inert, non-flammable gas, but in the event of a leak it can cause anoxia, which is dangerous for the personnel in the building. It will therefore be necessary to integrate into the buildings of the various modules, sensors for monitoring the level of Carbon Dioxide, and the necessary ventilation systems in the event of a leak.

The supply and circulation circuit of the sCO2 system is also one of the auxiliary circuits that will need to be implemented. There may be a risk of condensation within the circuit, as explained in Deliverable D5.2. The high pressure of the system should limit this risk, but it is advisable for reasons of risk control and therefore safety to consider the installation of a draining system.

5.2 Architectural changes in a new plant

Integrating the sCO2 system into the design of the plant will allow the plant developer to install the sCO2 system in the most optimal way possible to optimise its operation and safety contribution. In addition, it will facilitate the work of connecting the various piping systems.

5.2.1 Civil engineering changes

The first step for the plant developers will be to establish the location of the sCO2 system in one of the plant buildings.

This location can be optimised on the basis of the final developments of the system (optimisation of certain equipment and determination of the system's control procedures may require maximum proximity to the steam generators, or proximity to the system's heat sink, etc.), the safety studies accompanying the regulatory dossier (need for a minimum distance to the reactor building, ...).

At present, we can assume that the sCO2 system can be integrated in an auxiliary building of the reactor, but several options are possible.

The civil engineering modifications, compared to the current designs, will therefore be directly integrated into the design.

5.2.2 Modifications of existing water system

As in the case of retrofit, the integration of the sCO2 system will require new piping and connections to the usual water circuits of a nuclear power plant.

The modifications to the original design will be the same as in the case of a retrofit. However, these connections will be optimised from the start.

5.2.3 Modification of auxiliary circuits / loops (electrical circuits, control command, etc.)

The modifications to be considered for all circuits and auxiliary equipment are the same as in the case of a retrofit. The arrangements will be optimised at the design stage, thus leading to a probable cost reduction compared to a retrofit.

5.3 Summary of structural modifications

Table 1: Summary of structural modifications

Category	Type of changes
Civil engineering	Identification of the location of the sCO2 system
	Reinforcement of building roofs
	Construction of the structure to house the sCO2 system
	Installation of piping
Piping of the sCO2 system	Installation of the sCO2 storage tanks
	Installation of piping and leakage and condensation prevention systems
Connecting piping to the plant	Connecting the sCO2 system inlet piping to the main steam piping or VDA system piping
	Connection of the sCO2 system outlet piping to the steam generator supply system piping
	Training of crews in sCO2 system safety
Auxiliary systems	Integration of instrumentation and control with plant control (control room)
	Installation of any emergency start-up systems

6 Plant Operation modifications

The installation of an sCO2 system as an additional safety system will also lead to changes in the operation of the NPP. Whether it is a retrofit installation, or an installation as part of a new plant design, the approach to modifying the general operating and maintenance rules will be the same.

Any change to the operating rules will have to be declared to and accepted by the safety authorities.

The teams concerned will also have to be trained, which implies the integration of the operation and maintenance of the sCO2 system in all the necessary training processes.

6.1 Operation of the plant and the sCO2 system

6.1.1 Modifications to the Operating Rules for normal operation

The current development of the sCO2 system assumes that the system will be shut down during plant operation, except in the case of an accident.

If future developments of the sCO2 system maintain this type of operation, the changes to the operating rules of the plant will mainly concern the rules related to periodic testing of the sCO2 system. The sCO2 system will have to be tested on a regular basis, in order to verify the correct start-up of the system and the correct operation. At present, the periodicity of these tests has not been determined (e.g. Deliverables D3.3 and D3.4), and can only be determined once the system is fully developed, qualified and safety categorised.

These tests should be incorporated into the plant's test procedures.

If future developments of the sCO2 system show an interest in using the sCO2 system in the operation of the power plant, in a normal situation (as for example the VDA system which is used during certain transients of the power plant, outside any accident situation), any operating process will have to be integrated into the general operating rules.

These processes will be established on the basis of simulations, studies and tests carried out on the system and on the coupling with the power plant, by the teams in charge of establishing and writing these rules. The values for monitoring and controlling the sCO2 system and the interactions with the power plant will be established on the basis of the various tests, studies and modelling.

6.1.2 Modifications to the Rules of Operation in Accident Situations

The sCO2 system was initially designed to be used in accident situations and to remove residual heat from the core, so the operating rules of the system will mainly be established for accident situations.

As indicated in deliverables D3.3, D3.4 and D5.5, the continuation of the work on the sCO2 system will make it possible to establish the conditions and therefore the chronology of use of the various safety systems of the power plant, but also the various regulations for the control of the various sCO2 modules (start-up of one or more modules, variations in the power of the modules, etc.).

The first step will be **to establish the chronology of use of the different safety systems**. Indeed, the sCO2 system has been designed to be used in an SBO scenario (Station Black-Out), and therefore to be the system that must remain operational when all the others are no longer operational. But it could also be used in other accident situations, where the other safety systems are still functional.

The engineering teams in charge of establishing the operating rules will therefore have to establish the different possible sequences of use of the safety systems.

From these different sequences, it will be possible **to establish the values of the operating parameters** to identify when to start up the system, to monitor the correct start-up of the sCO2 system and to ensure its operation. Similarly, the different plant parameters to be monitored will be identified, in order to be integrated into the procedures followed by the plant's operating teams.

All these new rules will have to be integrated into the General Operating Rules as well as into the training program of the teams.

6.2 Maintenance of the sCO2 system

Preventive and corrective maintenance operations will also lead to operational modifications.

Preventive maintenance actions (inspections, non-destructive testing, tests, etc.) will have to be scheduled according to a periodicity that will be established when the qualification file is drawn up, based on the first tests carried out and the knowledge of the degradation mechanisms for the main components (turbo-machines, compact heat exchangers, piping, small equipment such as valves, etc.). These actions must be integrated into the plant's maintenance schedule.

Corrective maintenance actions can only be carried out once a failure or degradation of one of the system components has been observed. Therefore, the establishment of a periodic test schedule is essential to detect any degradation or failure in the operation of the system. Similarly, regular inspections will reveal any degradation in the components of the sCO2 system.

Given the compactness of the sCO2 modules and the ease of transporting the components, some of the maintenance operations usually carried out at the plant site could be carried out at a location other than the sCO2 modules, by the component manufacturer or the operator, after a standard exchange of the component for a newly qualified one.

6.3 Summary of operational modifications

Table 2: Summary of operational modifications

Category	Type of changes
Normal operating rules	Operation/regulation process of the sCO2 system
	Periodic tests
Operating rules for accidental situations	Start-up sequence of the sCO2 system
	Operation/regulation process of the sCO2 system
Maintenance	Preventive maintenance operations
	Corrective maintenance operations
Human Resources	Training of staff in sCO2 operation
	Training of staff in sCO2 system safety

7 Regulatory modifications

Any modification of a nuclear power plant must be accompanied by a regulatory modification application to the safety authorities.

In deliverables D3.2, D3.3 and D3.4 we have identified the regulations for the sCO2 system and the modifications required for a nuclear power plant. In this deliverable we will use the information from these deliverables to summarise the regulatory changes required for the implementation of a sCO2 system in a nuclear power plant.

We will distinguish between 3 distinct issues: regulatory changes related to the sCO2 system itself, regulatory changes related to a retrofit installation and regulatory changes related to an integration of the system in a new plant.

7.1 Overview of regulations relating to the modification of a nuclear power plant

There are different categories of modifications relating to a nuclear power plant. These categories are as follows:

- documentary modification: modification of one of the documents constituting the files filed with the safety authorities concerning the authorization, the authorization for commissioning, the operation and the safety of the plant;
- physical modification: modification consisting of the addition, alteration or removal of one or more elements important for protection (EIPs), or the addition, alteration or removal of one or more items whose presence, operation or failure is likely to affect the operation or integrity of an EIP;
- significant modification: modification falling under II or III of Article L. 593-14 or Article L. 593-15 of the Environmental Code (change of operator, operating procedures, dismantling);
- organizational modification: modification consisting of the addition, change or deletion of elements of the organizational structure or integrated management system, elements relating to roles and responsibilities, interfaces between entities, assigned resources, control and decision-making processes, computer and document management tools, temporal organization of work;
- substantial modification: modification falling under II or III of article L. 593-14 of the environment code.

It is the responsibility of the operator to determine the category of the change and then to design the file accompanying the change.

Within the framework of the sCO2-4-NPP project, considering the function of the sCO2 system, a French operator will have to constitute a significant modification file, because the installation of the sCO2 system will lead to a documentary modification (new operating rules in case of accident), a material modification (the system can be considered as an EIP) and an organizational modification. This modification will be subject to authorization by ASN and not to declaration to ASN.

7.2 Regulatory changes related to the sCO2 system

The sCO2 system is a new safety system. In deliverable D3.2, we identified the system as a possible category 3 in the SSC classification.

For this category of the SSC classification, we have presented the details of the regulations that the sCO2 system must meet in order to be able to write the qualification and justification file to the safety authorities in Deliverable D3.3.

The development of the sCO2 system will therefore have to follow the regulations in force, but notwithstanding, as indicated in the work of WP3, some aspects of the sCO2 system are not present in the regulations and will therefore have to be addressed. The table below summarises these points to be addressed in order to have an sCO2 system that can be qualified and eligible for a power plant installation:

Category	Type of changes
Standards	Standardization for Compact Heat Exchangers in NPP
	Standardization for sCO2 turbomachines for power generation
Suppliers	Proven Quality assurance of the system
Operator	Ensure that the entire regulatory process is followed

7.3 Regulatory changes when retrofitting

Deliverable D3.2 reminds that the NPP operator is responsible for the safety aspects of the changes and for obtaining the appropriate assessment and approval of regulatory body in accordance with the state regulations.

The operator will be responsible for compiling the modification request file with all the necessary documents. It is possible to be exempted for the operator to present certain documents upon justification on his part and acceptance by the safety authorities.

As in the case of an installation application, the file for a substantial plant modification should include the following elements:

1. If the operator is a legal entity, its corporate name or denomination, its registered office and the capacity of the signatory of the application;
2. A document describing the nature of the modification of the installation, its technical characteristics, the principles of its operation, the operations that will be carried out and the different phases of its realization;
3. A detailed plan of the installation on a scale of at least 1/2500; however, this scale may be reduced due to the size of the installation;
4. The impact study;
5. The updated version of the safety report;
6. The updated risk management study;
7. Updating of the decommissioning plan, which presents the methodological principles and the steps envisaged for the dismantling of the installation as well as the rehabilitation and subsequent monitoring of the site;
8. Updating the general operating rules that the operator plans to implement,
9. In the event of modification of the internal emergency plan, the opinion of the Health, Safety and Working Conditions Committee in accordance with the French Labor Code.

In addition to the file, the operator must also ensure the management of physical changes (INB Order). Via the integrated management system (obligatory for any operator of a nuclear power plant), the operator must put in place provisions to ensure that the physical modifications are designed, validated and implemented in particular in compliance with the regulations applicable to the INB (INB Order). Concerning these provisions, they must include elementary actions. The operator shall ensure the traceability of these actions, keep the corresponding documents in such a way that they remain easily accessible and legible, protected, in good conditions, and archive them for an appropriate and justified period of time.

7.4 Regulatory changes when integration in a new plant design

The entire regulatory process for the sCO2 system will be carried out at the same time as the regulatory process for the application to build and operate the nuclear power plant.

As for a retrofit installation, the operation will have to demonstrate the contribution of the sCO2 system to the safety of the plant, and the non-increase in risk linked to this new system. The list of the documents is the same than for a retrofit application.

8 Conclusion

On the basis of the work of WP5, we have determined the main modifications to be implemented, within the framework of a retrofit of the sCO2 system or for a new plant design.

The modifications to be carried out will all have to be carried out in compliance with the regulatory procedure in force for the nuclear power plant (if retrofit) or the country (if new plant).

Some modifications cannot, at present, be developed in a more precise manner (notably operational modifications) as they are dependent on the design of the installation plant and the procedures applied by the operator. Nevertheless, this report provides an outline of the main areas affected by the modifications.

Appendix A General installation

In this appendix, we recall the equipment of the sCO2 module.

Figure 3: sCO2-Based Heat Removal Technology General Installation - Isometric view 2

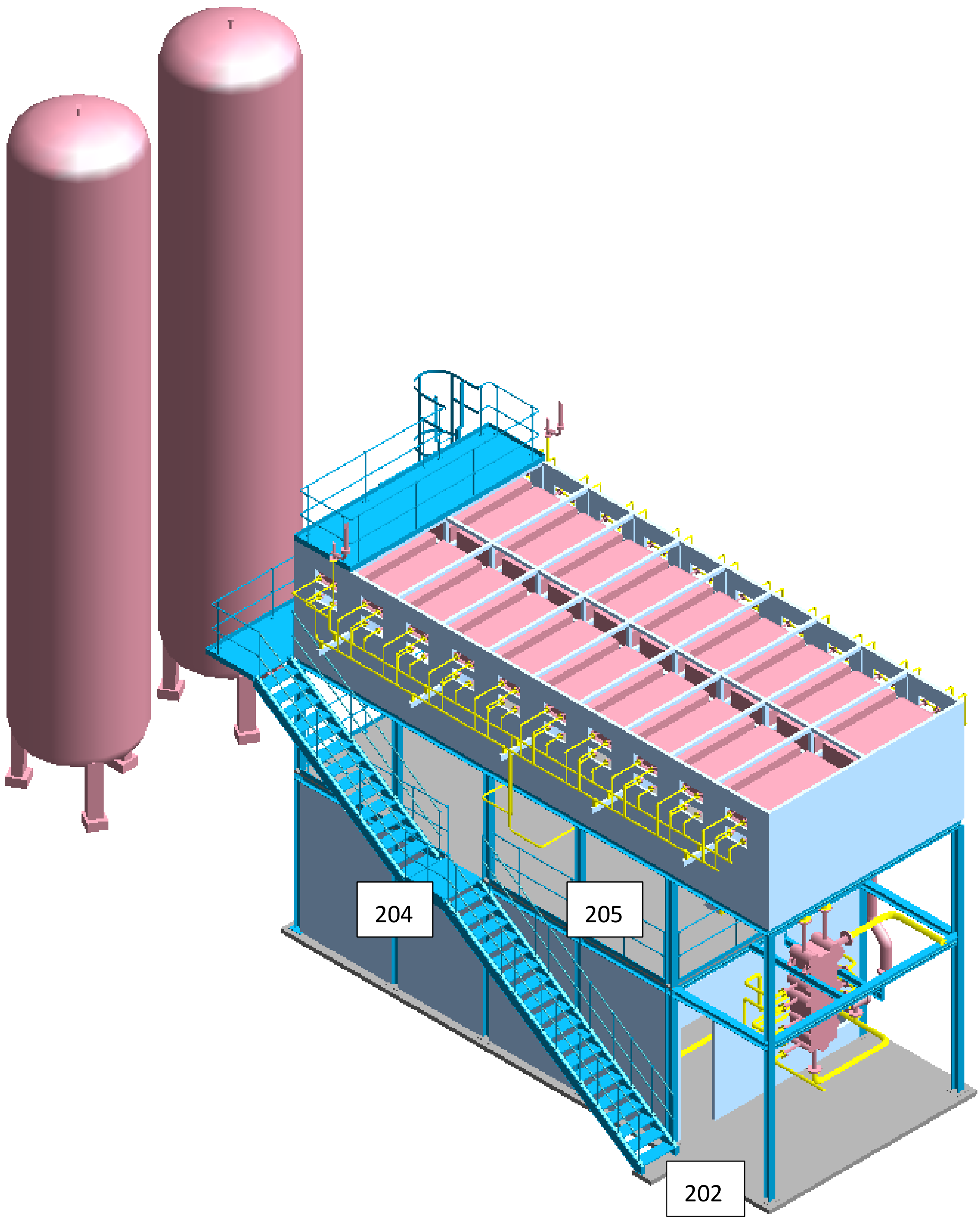
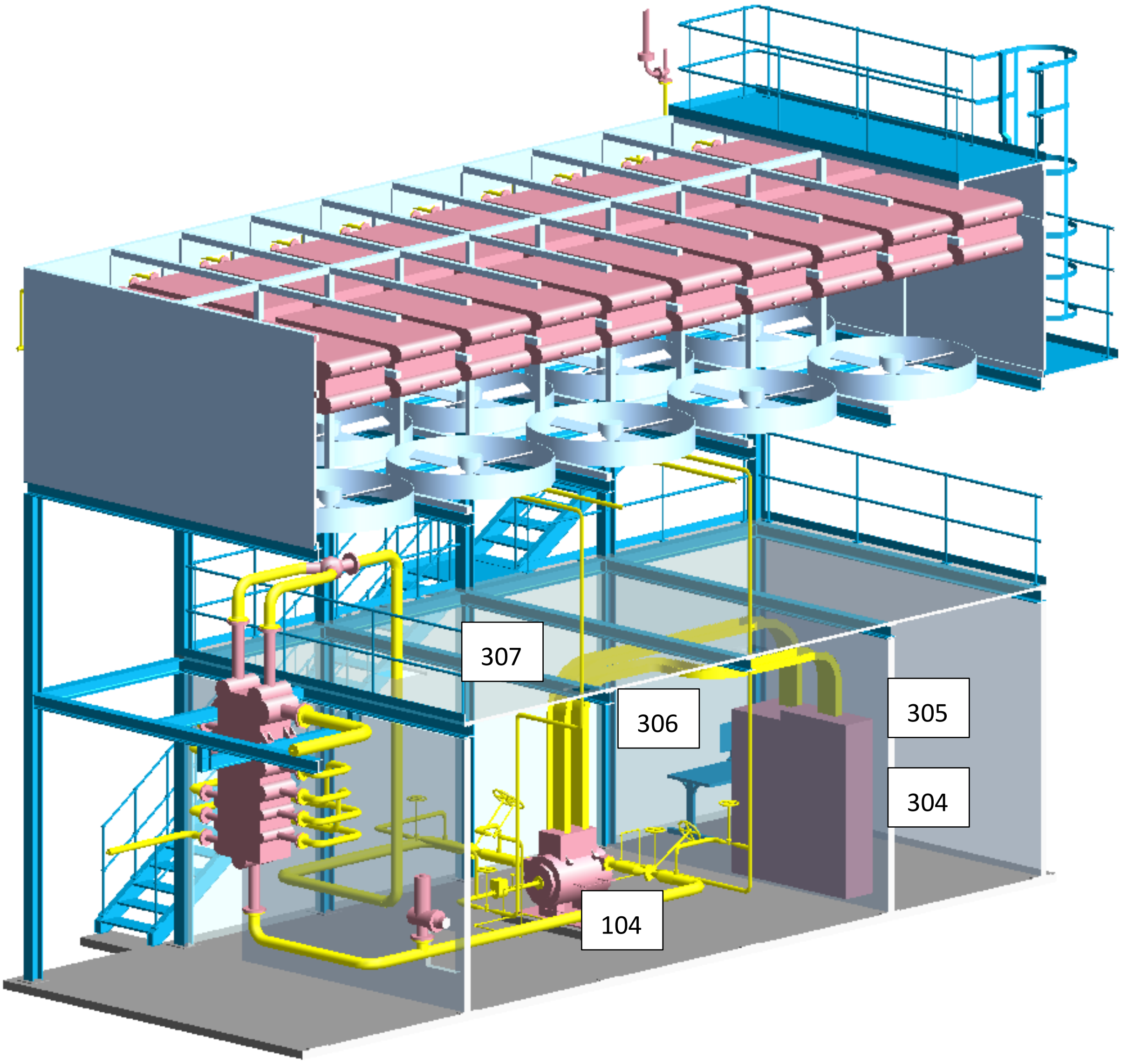


Figure 4: sCO2-Based Heat Removal Technology - General Installation - Interior section view



Main equipment:

- 101: CHX Exchanger
- 102: DUHS Exchangers
- 103: CO2 Start-up Tanks
- 104: Turbomachine

Auxiliary equipment:

- 301: Start-up CO2 vent
- 302 & 303: CO2 loop safety vents
- 304: Electrical & Batteries cabinet
- 305: Control & Command cabinet
- 306: Command & Command post
- 307: Turbomachine electrical interface

Access:

- 201: Mechanical room main access
- 202: Mechanical room secondary access
- 203: Electrical, Control & Command room main access
- 204: Stairs to intermediary and DUHS Platform
- 205: Intermediary platform
- 206: DUHS access platform