sCO2-4-NPP: Innovative sCO_2-Based Heat Removal Technology for an Increased Level of Safety of Nuclear Power Plants

Deliverable D7.2
sCO2-4-NPP exploitation plan

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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	

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1 List of acronyms

Abbreviation / Acronym	Description / meaning
AFCEN	Association Française pour les règles de Conception, de construction et de surveillance en exploitation des matériels des Chaudières Electro Nucléaire
AFNOR	Association Française de Normalisation
ASME	American Society of Mechanical Engineers
ASN	Autorité de Sûreté Nucléaire
CCPN	Comité de Coordination et de Pilotage de la Normalisation
CDF	core damage frequency
Cenelec	Comité Européen de Normalisation Electrotechnique (European Committee for Electrotechnical Standardization)
CFD	Computational Fluid Dynamics
CNRA	Committee on Nuclear Regulatory Activities
CSP	Concentrated Solar Power
DEC	Design Extension Condition
DUHS	Diverse Ultimate Heat Sink
EIMT	Exploitation and Innovation Management Team
EN	Europäische Norm (in English 'European Standard')
EQ	Equipment Qualification
ETSON	European Technical Safety Organization Network
EU	European Union
GSR	General Safety Requirement
HX	Heat eXchanger
I&C	Instrumentation and Control
IAEA	International Atomic Energy Agency
IAEA-TECDOC	IAEA Technical Document
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IP	Intellectual Property
IPR	Intellectual Property Rights
KTA	Kerntechnischer Ausschuss (in English 'German Nuclear Standard Committee')

Abbreviation / Acronym	Description / meaning
NEA	Nuclear Energy Agency
NPP	Nuclear Power Plant
OECD	Organisation for Economic Co-operation and Development
OLC	operational limits and conditions
PCHE	Printed Circuit Heat Exchanger
PFHE	Plates and Fins Heat Exchanger
PIE	postulated initiating event
PSA	Probabilistic Safety Assessment
RCC-E	Règles de Conception et de Construction des matériels Electriques des îlots nucléaires REP (in English 'Design and construction rules for electrical equipment of PWR nuclear islands')
RCC-M	Règles de Conception et de Construction des Matériels mécaniques des îlots nucléaires REP (in English, 'Design and Construction Rules for the Mechanical Components of PWR Nuclear Islands')
RL	Reference Level
RWE	Rhine-Westfalia Electricity Factory
SC	safety class
SL	seismic level
SNETP	Sustainable Nuclear Energy Technology Platform
SSCs	Structures, Systems and Components
SSG	Specific Safety Guide
SSR	Specific Safety Requirement
TRL	Technology Readiness Level
VVER	Vodo-Vodyanoi Energetichesky Reaktor (Water-Water Energy Reactor)
WENRA	Western European Nuclear Regulators Association

2 Executive Summary

The D7.2 is the last version of the sCO2-4-NPP exploitation plan. This report describes the exploitation plans for the sCO2-4-NPP system and its components including the technological, regulatory, financial and organisational (business plan) roadmaps for reaching TRL9.

The development of the sCO2 system and its commissioning will only be successful if the different roadmaps (technological, regulatory and financial) are carried out in parallel. Indeed, it will not be possible to technologically develop a component that can be qualified if the qualification procedures are not established and if the standards for this type of equipment do not exist.

3 Introduction

The objective of the sCO2-4-NPP project is to continue the development of the sCO2 system, initially launched in the Euratom sCO2-HeRo project. For that, the consortium has worked on different topics such as simulation, development of the main components or analysis of the nuclear regulations necessary for the sCO2 system. This work has been integrated into an operating strategy presented in deliverable D7.1 of the project.

As the sCO2-4-NPP project ends in 2022, this deliverable summarizes the reflections and work of the sCO2-4-NPP project consortium, with the objective of preparing the next steps to increase the level of technological maturity of the sCO2 system and to achieve its real deployment in the nuclear sector.

In a first step, we review the strategy implemented by the partners, then we present the results obtained in terms of intellectual property.

Secondly, we present the different technological, regulatory, financial and organizational roadmaps that should enable the sCO2 system to reach TRL 8 - 9 level, which is synonymous with a production lead.

4 Overall strategy for exploitation of the sCO2-4-NPP technology

The main strength of sCO2-4-NPP was to bring together stakeholders covering the entire value chain (e.g.: EDF as plant operator/end-user, NRI as boiler designer, NP TEC as turbomachinery manufacturer, FIVES as heat exchanger manufacturer) as well as complementary experts in research and technology development (UDE for turbomachinery behaviour, CVR for cycle testing) with background and expertise to help the industry move forward. Synergies detected among players lead to new research activities and new business opportunities.

Bringing the technology from TRL 5 (end of sCO2-4-NPP) to TRL9, requires a step-by-step approach to the different requirements for a nuclear technology. The technological, regulatory, financial, and commercial roadmaps are developed to support this objective. An outline of this plan is presented below.

a) Technological roadmap:
   - Robustness and reliability: The different materials and components of the sCO2-4-NPP system must demonstrate their robustness and reliability for the entire operating life of the system. The work carried out within the project will make it possible to integrate this approach. To do this, the entire system and each of these components must be qualified for use in a nuclear environment (cf. regulatory approach). Risk assessment (probabilistic, deterministic) will also have to be carried out. The interaction of the sCO2-4-NPP system with specific operational and emergency systems of Nuclear Power Plants (NPPs) will be assessed.
   - Large scale testing availability: A pilot site will have to be identified for the installation of a technology pilot. This installation can only be considered once the system has been qualified. An MW scale prototype will also have to be built for long term testing. The Chinese Academy of Science is currently setting up a test loop for components running with sCO2. By purpose, this test loop shall be open to companies and research organisations around the world. The main performance data (max. 700 °C, max. 25 MPa, max. 5 MWth, and max. 26 kg/s sCO2) allow for testing equipment and components on MW scale.

b) Regulatory roadmap:
   - Equipment qualification (EQ): The safety function of a piece of equipment is generally established in terms of its required behaviour (active or passive) and its duration. The EQ is a process adopted to confirm that the system is capable of meeting, throughout its operational design life, the demands for performing its functions while being subject to the environmental conditions (vibration, temperature, pressure, jet impingement, electromagnetic interference, irradiation, humidity or any likely combination thereof) prevailing at the time of need. Environmental conditions to be considered include the variations expected in normal operation, anticipated operational occurrences, design basis accidents and design extension conditions without significant fuel degradation. Moreover, consideration shall be given to ageing effects caused by various environmental factors (such as vibration, irradiation and extreme temperature) over the expected lifetime of the equipment. The qualification programme shall replicate as far as practicable the conditions imposed on the equipment by the natural phenomenon, either by test or by analysis or by a combination of both.
   - Approval of the safety authorities: once the technology has been qualified, the operator who wishes to install the technology must have the approval of the national safety authority on which he depends. This approval is based on probabilistic safety studies, and deterministic studies

confirming the improvement or non-degradation of reactor safety. Preparatory work has been done during the project with WP3 studying the requirements and other WPs taking them into account in the design of the system.

c) Standardisation roadmap: In order to obtain their qualification, each element of the technology must be developed according to the reference standards. As part of the sCO2-4-NPP system, the consortium has already identified that the standards for compact heat exchangers for nuclear and turbomachines for sCO_2 are not finalised. For this reason, it has included in its dissemination plan an important communication with the various standardisation organisations.

d) Intellectual property: The technology of sCO2-4-NPP and the improvements that will be made up to its exploitation can be part of a patent process. Given the history of patents already existing for the concept of the technology or for the different components, technology developers will have to be careful to respect these IP rights. These include citing the existing patents to avoid future conflicts and to show that the sCO2-4-NPP patent is a real improvement of the former patent. Also, with regards to the current patent of RWE, specific conditions will be negotiated when the patent application is submitted (see table on key project results).

e) Sustainability of financing after the EU funding: To ensure sustainability of financing, the partners will seek funding through joint ventures and direct investment through venture capital to make the system robust and reliable, pilot plan development, large-scale testing and bringing the system to industrial scale. On the basis of the amounts allocated to other international projects related to the sCO_2 cycle, and taking into account the need to qualify this type of system for nuclear energy, at least €100 million would be needed to provide the necessary test benches and first test loops.

Securing an industrial integrator to adapt the sCO2-4-NPP technology to industrial scale: During the project, the solution was presented to different integrators, such as Framatome, to create partnerships for future industrialisation.

Besides the preparation of the exploitation plan and the different roadmaps mentioned above, sCO2-4-NPP partners carried out several activities during the project which prepare the future exploitation:

- An IP portfolio was set up and managed by the EIMT and a strategy for patenting and publications was be proposed
- Workshops with end-users to validate the technology and make them aware about the developments
- Contacts with potential investors to finance the next steps

4.1 Expected results to be exploited

The key project results which can be exploited are shown in [3].

Table 1: Key project results

RESULT	PARTNER	Specific EXPLOITATION ROUTES and STRATEGIES
sCO2-4-NPP sCO_2 heat removal system for nuclear power plants	Consortium (led by EDF)	The consortium studied whether patent possibilities are possible depending on the development of equipment and related innovations.
TURBOCOMPRESSOR	NP TEC	NP TEC used sCO2-4-NPP results to validate market assumptions and create an industrialisation program to improve its commercial

RESULT	PARTNER	Specific EXPLOITATION ROUTES and STRATEGIES
New integral turbocompressor design for sCO_2 power generation	UDE	offers (global cycle solution, turbomachinery alone for integrators) for any energy sector (including nuclear).
HEAT EXCHANGER solutions based in PCHE/PHFE (in stainless steel and nickel-based alloys) for sCO2	FIVES	FIVES opened new business lines for innovative HX for sCO_2 cycles suitable for conventional plant, CSP, biomass, etc. (global cycle solution, HX alone as main equipment for integrators). The exploitation routes are guided by market needs which are mainly compactness, robustness, and efficiency at a reasonable cost.

In addition to these main results, other partners exploited their results in the following ways (see [3]).

Table 2: Secondary results

Partner	Planned Result	Planned Use of Project Result	Main User(s)
USTUTT	Improved ATHLET code, improved ATHLET input deck.	The new code version will be presented to GRS (Gesellschaft für Reaktorsicherheit, code developer) at project end for inclusion in the next code release.	GRS or other users, who want to include sCO_2 systems in their plant or studies (for codes benchmarks for example)
GfS	Running various sCO2-cycle scenarios	Experience for demonstration of the sCO_2 cycle	• Nuclear technology experts • Students • Engineers • Nuclear operators
KSG	Robust HeRo-Loop on Glass Model, PWR simulator equipped with sCO_2 system	Presentation by KSG/GfS during Glass Model training and during expert courses	• Authorities • Technical expert groups • Nuclear personnel
CVR	• Transient (accident) simulations of the whole system (PWR with sCO_2 heat removal) (coupling ATHLET/CATHARE with Modelica). • The thermodynamic cycle design of the sCO_2 heat removal system. • Testing of the natural circulation and condensation of the steam cycle cooled by sCO2. • Optimisation and testing of the sink HX.	• Offer services in design (optimising the design and control system of sCO_2 units) and operation of sCO_2 units. • Offer customised thermal hydraulic software for sCO_2 applications. • Share general know-how in sCO_2 technology with other experts. • Broaden the sCO_2 interest and sCO_2 market. • Provide feedback to the developer of heat exchangers.	• NPP designers • NPP operators • NPP regulators

Partner	Planned Result	Planned Use of Project Result	Main User(s)
JSI	New knowledge and experience gained in independent review of licensing documents.	Experience used in other independent reviews.	• Krško NPP • Slovenian Nuclear Safety Administration • International Nuclear Safety community
UDE	• Increased expertise in sCO2-turbomachinery design and operation • New educational content	• sCO_2 turbomachine design integrated in different lectures (CFD and Gas Turbine Technology) • Support industry in the design of turbomachines for sCO_2 cycles for energy production (waste heat recovery, solar power). • Knowledge used in new project CO2OLHEAT – EU Project started June 1st, 2021)	• Students • Engineers • Industry
CVR	Transient (accident) simulations of the whole system (PWR with sCO_2 heat removal, coupling ATHLET/CATHARE with Modelica) responsible for the ATHLET part Review of licensing documents Design heat removal system from containment	• Offer services focused on licensing and safety requirements • Offer operators with technology VVER	• Nuclear regulators • NPP (VVER) operators

Each technical partner will be the owner of its developments and will own the exploitation rights, under the legal constraints.

5 Exploitation planning and management of intellectual property

An "Exploitation and Innovation Management Team" (EIMT) has been setup and is composed of representatives of the partners concerned by the exploitation of key results and involved in preparing the roadmap to TRL9 (EDF, USTUTT, NP TEC, FIVES CRYO, JSI, UDE, ARTTIC). The EIMT was tasked with development of the sCO2-4-NPP Exploitation Plan that covers the specific results of the sCO2-4-NPP project and the coordination of efforts to implement the exploitation. In addition, the EIMT also managed the Intellectual Property and exploitation of sCO2-4-NPP results, in accordance with the sCO2-4-NPP Consortium Agreement. This included the setup of an IP portfolio, strategy for patenting, strategy for publications, management of the evolution of the Consortium Agreement and market watch.

The technology of sCO2-4-NPP is part of a patents process. Given the history of patents already existing for the concept of the technology or for the different components, technology developers in the project are careful to respect these IP rights. These include citing the existing patents to avoid future conflicts and showing that the sCO2-4-NPP patent is a real improvement of the former patent.

5.1 IP Portfolio

The purpose of the IP Portfolio was to clarify ownership of project results to facilitate future exploitation. sCO2-4-NPP Consortium partners could submit results at any time for approval of the General Assembly. Once approved, the IP Portfolio was updated. The sCO2-4-NPP IP Portfolio should be considered as a tool to implement the provisions of the Consortium Agreement.

5.1.1 Approval process

To secure and guarantee the evidence that the Result belongs to the partner, a partner should register their Result to the IP Portfolio.

The process was as follows:

1. IP Registration Form to be completed by the partner claiming the Result.
2. Completed form to be sent by email to the Project Coordinator, copy the Project Office.
3. Project Coordinator to invite by email the General Assembly to approve the registration.
4. From receipt of the invitation, the General Assembly has 15 calendar days to raise objections. Objections shall be made to the partner claiming registration with a copy to the Project Coordinator. Allowable objections are those invoking legitimate interest with evidence attached (as stated in the EC Grant Agreement, when invoking legitimate interest, a Partner must show they will suffer disproportionately great harm).
5. After 15 days and if no objection, the Result is registered by the Project Office in the IP Portfolio to secure evidence that the Result belongs to the partner which claims it.

5.1.2 IP Registration Form

Table 3: IP Registration Form

Result	
Name of the Party	Name of organisation responsible
Owner(s)	Partner name(s)
Nature	Patent, design, software, etc.
Registration / Protection	Patent number, copyright, etc.
Title / Description	1/ Provide title of Result
	2/ Identify the task or WP where the Result has been produced
	3/ Description of the Result and when relevant, if the Result is co-owned by several participants
	4/ Background required to use the Result if Background needed
Access conditions for research in the project / Limitations	Description of the access conditions and if access is conditional to a specific licence agreement, agreement of co-owners, etc.
Access conditions for use / Limitations	Description of the access conditions for use, including for purpose, (i.e., further research, internal usage or commercial usage), and rights granted
Licensee(s) in the project	Name of the licensee (add additional licensees as necessary)
	Date of allocation:
	Type of licence:
Licensee(s) for use	Name of the licensee (add additional licensees as necessary)
	Date of allocation:
	Type of licence:
Dissemination	Dissemination undertaken for the Result outside licensing (publications, technology transfer, etc.)

5.1.3 Project results

CHX design:

A first patent was submitted for the CHX design. This first patent was submitted in France jointly between Fives, USTUTT and KSG/GFS. The consortium is now waiting for the anteriority research report from the INPI which is the French National Institute for Industrial Property.

Once received, the consortium will be able to submit the international patent until August 2022 if the research report does not reveal any anteriority to this work.

Therefore, several design details will be omitted from this report to guarantee confidentiality of this work while the patenting procedure is still ongoing.

Turbomachinery design:

Some of the results obtained were initially analyzed for a potential patent and thus led to the decision not to submit deliverable D4.1 within the planned timeframe, as the deliverable was public and would not have allowed the possible patenting of the results. After a period of biographical and anteriority research, it was decided by the responsible partner to favor the scientific publication way and not patenting.

5.2 Project activities to prepare for the exploitation of results

In addition to the preparation of the exploitation plan and the different roadmaps mentioned above, sCO2-4-NPP partners carried out several dissemination activities during the project to prepare the future exploitation.

The strategy for publication is described in D8.1 Dissemination and Communication Plan. The results of this strategy are detailed in the interim and final reporting of the project.

- **Joint event with sCO2-Flex**

The sCO2-4-NPP project participated in an event organized by the sCO2-flex project in June 2021, together with other European projects working on supercritical CO2. This online event had an audience of more than 100 people.

- **International conferences**

Participation in several international industrial conferences allowed the project results to be presented to a panel of potential users.

The online European sCO_2 Conference took place on March 23rd & 24th 2021 and was hosted by UDE and supported by the project partners. Four papers are related to the project and were published.

During the project, the partners have presented several scientific papers at conferences such as ASME Turbo-Expo, ASME FEDSM 2020.

The sCO2-4-NPP project has been presented in a panel at the international symposium sCO2 (USA).

The project has also participated in European events related to the European community such as FISA 2022 (joint paper with APAL and CAMIVVER projects), SNETP forum, SFEN forum).

- **End-user Workshop**

The End-user Workshop held online over two afternoons on 25th and 26th January 2022. The purpose of the workshop was to share intermediate project results with the public, particularly with potential end-users of the supercritical CO2 (sCO2) heat removal system. The workshop was originally foreseen as an in-person event at Month 24 of the project with demonstration of the sCO2 loop in the Glass Model at the premises of partner KSG in Essen, Germany. Due to the pandemic situation, the event was postponed to Month 29 and then modified into a fully remote event.

The first session on 25th January was held with the sCO2-4-NPP Advisory Board members only, to allow more detailed discussion of the specific application of the sCO2 system in the nuclear power plant. The second session was held on 26th January for the general public, to allow broad dissemination and consideration of the utilisation of the sCO2 system in other applications.

- **sCO2-4-NPP Symposium and Demonstration**

The sCO2-4-NPP Final Symposium held 8th and 9th June 2022, in Essen, Germany. The symposium was originally foreseen as an in-person event with demonstration of the sCO2 loop in the Glass Model and demonstration of the KONVOI simulator with the sCO2 system included at the premises of partner KSG in Essen, Germany.

The first day was dedicated to work presentations and was a hybrid event, in-person and online. The second day was only an in-person event, dedicated to the two demonstrations. This event helped the consortium to find new interlocutors to help develop the perspectives put forward in the roadmaps.

6 Technological roadmap to reach TRL9

The long and mid-term planning of necessary technological and scientific steps for bringing sCO2-4-NPP from TRL 5 to TRL 9 will be further detailed in this chapter.

The results from WPs 4, 5 and 6 are the starting point. Technological developments on both component scale and system architecture, as well as necessary steps for testing, validation, qualification as well as integration in existing and future NPPs were be studied, taking into account regulatory and licensing aspects and market and organisational factors in the project.

The technological roadmap defined in the sCO2-4-NPP project aims to provide a macroscopic and as exhaustive as possible view of the locks to be lifted and the next steps needed to develop the technology. Thus, the consortium worked to:

- Identify the technological locks to be lifted.
- Define the steps needed to take the technology from TRL 4-5 (end of project sCO2-4-NPP) to TRL 8-9.
- Establish the needs relating to the qualification, testing and acceptance of the sCO_2 system by the nuclear community (from the manufacturers associated with the components to the safety authorities).

Particular attention was also be paid in the roadmap to the potential use of the system and its components for areas other than nuclear safety.

Indeed, the system's components, such as turbomachines or heat exchangers, are components that can be used in fields such as the chemical industry, oil & gas and the progress in cycles using supercritical CO_2 in recent years could be of interest to these industries.

6.1 Identification of technological obstacles

Although the objectives of the sCO2-4-NPP project are to remove many technological obstacles, some issues remain to be validated, as they could not be dealt with during the project. These include issues related to the ageing, maintenance and reliability of the system. The technological roadmap proposed by the consortium will try to identify them in order to propose ways to improve the system.

6.2 System and components improvement

Based on the identified obstacles, the consortium is able to propose a roadmap for making the necessary improvements to the system and its components. In addition to the improvements aimed at increasing the reliability and robustness of the components (choice of materials, back-up systems, etc.), the consortium also examined aspects related to risk management (need for deterministic and probabilistic studies, etc.) and safety (measurement methods, risk of leakage, etc.).

6.2.1 Heat exchangers improvements

The heat exchangers are important components of the sCO2 system, because on the one hand the compact exchangers ensure the connection between the nuclear power plant to be cooled and the sCO2 system and

on the other hand the second exchangers ensure the heat removal towards the ultimate source (in the sCO2-4-NPP project, only the atmosphere is considered). During the project, these two types of exchangers have been the subject of significant developments (see the work of WP4 of the sCO2-4-NPP project and the associated patent), but cannot yet be considered at TRL 7 or 8 to envisage a use in the sCO2 system as is.

The project partners have therefore considered the next steps necessary to bring the exchangers to a higher TRL level.

Compact heat exchangers

A new compact heat exchanger design was developed and patented during the project. Nevertheless, this new design still needs some development in order to be qualified and used on an sCO2 system.

The tests performed on the SUSEN loop of the CVR partner show a slight deviation between the simulations and the results obtained for the heat exchange correlation. The uncertainties related to this deviation deserve to be studied in more detail, with new tests and optimizations of the design of the plates of this exchanger.

Questions concerning the heat resistance and the reliability of this exchanger on the long term were also raised, with the evocation of using another type of material, and to push the tests over a longer period.

Heat Sink Exchangers

The DUHS thermal-hydraulic design was experimentally and numerically verified by testing a small mockup unit. The experimental data were used to determine the heat transfer and Fanning friction factor correlations. These correlations were utilized to find an optimal channel geometry with a balance between the heat transfer and the pressure drop on the air side.

The final design of the DUHS was established regarding the results of the optimization work on both the sCO_2 and the air side. A compromise needed to be achieved to take into account not only the thermal and hydraulic optimization part but also the mechanical resistance of the device according to what is expected by the regulation, the manufacturability and the cost reduction optics. As with the compact heat exchangers, a program to test a prototype on a more representative scale, including improvements for mechanical strength will be required.

Although major achievements on heat exchanger technology were made during this project, there are still some technological gaps on manufacturing to be addressed. In fact, on one hand, for the compact heat exchangers, efforts are still required to elaborate fins stamped mechanically from a very resistant material such as Nickel based alloy Inconel 690. On the other hand, regulatory aspects were raised and detailed process propositions were made, to be followed for an integration of the brazing technology in the nuclear power plant regulations. These additional developments are mandatory to allow the integration of this compact and efficient heat exchanger technology in existing and future power plants.

6.2.2 Turbocompressor improvements

During the sCO2-4-NPP project, the partners developed a new turbocompressor to improve its performance and to test the use of new types of bearings such as magnetic bearings.

This new prototype has been successfully tested on the sCO2 loop located at KSG.

However, additional developments will be necessary to ensure the reliability of the turbocompressor and to establish the off-design operating conditions, as this will be required for the various qualification and safety files.

These necessary developments have been identified by the consortium partners and are as follows:

- Continuation of the simulations in order to quantify and reduce the uncertainties on the current models and to progress on the regulations to be set up to correctly operate the turbocompressor.
- Study the off-design behaviour of the turbocompressor from tests performed either on the current prototype or on a new prototype at a larger size, and by simulations, in order to develop the models that will allow to establish the most accurate performance maps possible.
- Optimize the choice of sub-components, such as bearings, materials used to increase the reliability in operation and start-up of the turbocompressor and eventually reduce the cost of the latter
- Determine the maintenance, non-destructive inspection, testing and qualification program for the turbocompressor integrated into the overall sCO2 system. This step is necessary to ensure that the turbocompressor is qualified for this use. Without a maintenance program and without the possibility to guarantee the proper functioning of the turbocompressor before its installation in the sCO2 system, this qualification will not be possible
- Build a prototype of the turbocompressor on a scale of 1 or at least more representative for certain choices of equipment and regulation of the turbocompressor. We know, for example, that rotation speeds change according to the size and power of the turbocompressor. These speeds can have an impact on other equipment in the system, such as the alternator and the monitoring instrumentation.... The current models allow us to establish initial hypotheses, but a prototype on a larger scale will be necessary to test the choices made (such as non-destructive testing systems, qualification tests, etc.)

6.2.3 Overall system improvements

The improvements to be made to the sCO2 system to increase its TRL level do not only concern the main equipment, but also the entire system.

Indeed, during the sCO2-4-NPP project, the consortium worked on the development of the main equipment and on the operation of the system in its entirety and its integration within a power plant, but to guarantee qualification (as presented in the regulatory roadmap in the following chapter), work on the entire sCO2 system is still necessary.

As a first step, in parallel with improvements on the main components such as the heat exchangers and the turbocompressor, it is necessary to:

- Determine and test different start-up procedures:

  In the framework of the sCO2-4-NPP project (cf. work of WP5 and WP6), the consortium has mainly focused on a push start, triggered automatically (or manually) at the time of the accident and the loss of the other safety systems. This procedure has the advantage of not requiring additional equipment such as batteries, pressurizer, valves, piping, etc. but is not yet optimized for integration into the operating rules of a plant. In order to accelerate the development of the sCO2 system (and depending on the progress of the regulatory roadmap), it is necessary to work on other possible start-up procedures such as, for example, maintaining the system in a standby state throughout the operation of the power plant in normal conditions, using batteries to start the turbocompressor and possibly increase start-up reliability, etc. These different procedures must be modelled and tested, as was the case for the push-start procedure in power plant simulators. This type of simulations will allow to adapt the start-up procedure according to the type of plant, to the current operating rules and to the operator's safety systems call strategies. This

will also allow to test different possible scenarios and thus to establish operating procedures limiting to the maximum the risks related to a human error, and to enrich the data used for the various safety studies.

- Establish the operating rules of the sCO2 system

The integration and use of the sCO2 system in nuclear power plants cannot be achieved without establishing its operating rules. These rules are also necessary to advance in the regulatory roadmap (to complete the necessary files for the safety authorities).

In addition, the integration of the simulator to define the start-up procedures will also allow the operator to train the operators in the operation of the sCO2 system and to collect their feedback in order to improve the operating rules.

The operating rules must also include all the necessary information on maintenance and periodic tests required to ensure proper operation of the sCO2 system. The maintenance rules defined for the main equipment (heat exchangers, turbocompressor, etc.) will be integrated into those of the sCO2 system as a whole. The periodicity of the controls of the piping, the components such as the valves, the instrumentation will also be determined. As sCO2 can be more corrosive than steam, it will be necessary to take this into account in the definition of this periodicity and in the choice of the control means.

The routine and periodic tests of the sCO2 system will also have to be defined, so that they can be integrated into the overall test procedures, and to ensure that these tests do not disturb the normal operation of the plant.

- Define more precisely the auxiliary equipment required for the sCO2 system:

In the work of the sCO2-4-NPP project (mainly the work of WP5 and WP6), the consortium has established initial hypotheses on the CO2 supply and circulation circuit within the system, on the electrical auxiliaries and instrumentation of the control command, and also on the connections with the steam circulation circuits of the plant. The developments carried out for the main equipment, regulation and safety requirements (such as the necessary redundancy of certain emergency equipment, or valves, etc.), as part of the ongoing work, should make it possible to establish a more precise mapping of the requirements for the auxiliary equipment.

In a second phase, the improvements to be made to the sCO2 system will be, once the first phases of qualification of the main equipment have been launched, to obtain the data necessary to carry out the various studies required to obtain qualification and authorization for the installation of the sCO2 systems within the nuclear power plant. Several types of studies will be necessary to satisfy the regulatory roadmap:

- Functional analysis of the sCO2 system:

As part of the dossier to be submitted to the safety authorities, the operator will have to provide a functional analysis of the system i.e. to identify all the functions involved in the operation of the sCO2 system (which equipment starts, which equipment exchanges heat, valves that have to operate, etc.) in order to establish as exhaustive a list as possible of all possible failures and to identify the means to remedy these failures (by preventive and/or corrective maintenance, by inspections, by tests, by equipment redundancy....)

- Safety analysis and potential integration into Probabilistic Safety Assessments (PSAs):

Data from the functional analysis and potential event data (failure rate in operation, at start-up, etc.) for the sCO2 system will need to be integrated into the plant safety analysis, as the system is designed to be

a safety system. It will also be necessary to plan a possible update of the plant's PSAs, integrating the risk associated with the sCO2 system.

6.2.4 Improvement of real time modelling

As stated in the previous chapters, simulation is a powerful tool for functional and safety analysis, to establish operational rules, to verify start-up conditions and response times and to identify conflicts in between the response of the sCO2 based heat removal system and other operational or safety systems. The FMU approach, demonstrated in WP6, allowed to connect the functionality of the retrofitted systems, modelled in Dymola, to an existing full scope NPP simulator as a most complete systems environment, not affecting the training capabilities of this facility.

For further use as an accepted tool, some improvements are necessary:

- For better flexibility regarding code development, bug fixing, monitoring and operational issues of the sCO2-part, license related issues of this technology will have to be addressed.
- Furthermore, limitations from the substance database concerning two-phase state of CO2 must be overcome to model off-design operation.
- Last but not least, the thermal hydraulic behaviour of the heat exchangers and the dynamic behaviour of the turbomachinery, again in off-design, start-up or stand-by conditions, will have to be refined continuously, reflecting the experience and numerical results from previous component testing in real time models.

These improvements should aim to fulfil basic criteria for a qualified tool in safety and operational analysis, e.g. by regularly benchmarking with qualified codes, like ATHLET and CATHARE.

6.3 Qualification and test

The various requirements for the qualification of components and a nuclear safety system include a part of tests on components (and/or on the system if possible) and a part of simulations.

Concerning the tests to be carried out, the work of WP3 and the regulatory roadmap present in detail the expectations, but for them to be implemented, the use of various prototypes will be necessary:

- For the main components, we have seen that the necessary future developments will require the use of prototypes at more representative scales. The construction of these prototypes on a larger scale will also allow the industrialists concerned to confront the industrial manufacturing constraints that will be necessary to satisfy for the qualification of these components.
- A pilot of the sCO2 system would also be a plus for the partners involved in its technological development. This pilot would allow to confirm the simulations and modelling of the behavior of the sCO2 system with test data. It would also allow the qualification files to be enriched by providing data demonstrating that the operation of the sCO2 system can ensure its functions under accident conditions, and also respects the various constraints of resistance to external events such as earthquakes, and events linked to the ageing of the system and its components.
- A pilot site will be interesting for the qualification and test of a pilot. This installation can only be considered once the system has been qualified. An MW scale prototype will also have to be built for long term testing. The architectural integration within an existing power plant (for retrofitting) can thus be tested and allow to enrich the associated feedback. The Chinese Academy of Science is currently setting up a test loop for components running with sCO2. By purpose, this test loop shall be

open to companies and research organisations around the world. The main performance data (max. 700 °C, max. 25 MPa, max. 5 MWth, and max. 26 kg/s sCO2) allow for testing equipment and components on MW scale.

7 Regulatory roadmap to reach TRL9

According to IAEA SSG-12[12], the licensing process for a nuclear installation will normally include the following steps, depending on national legislation:

- siting and site evaluation (which may include the environmental impact assessment),
- construction,
- design,
- commissioning,
- operation,
- decommissioning and
- release from regulatory.

For the purpose of this report, which relates both to existing nuclear power plant modification on installation of passive heat removal system (retrofit) and of the preparation of an installation on a new nuclear power plant design, in the focus are design, commissioning and operation steps of licensing (here it should be noted that for new design all other steps are also relevant, as sCO2-4-NPP system will be included in the design phase of the nuclear power plant). After introduction in Section 7.1 requirements for nuclear power plant modification are explained in Section 7.2. Next, design step of licensing process is described in Section 7.3 and finally, commissioning and operation step of licensing process is described in Section 7.4.

7.1 Introduction

The European Technical Safety Organization Network (ETSON) Safety Assessment Guide [4] provides fundamental recommendations to expertise bodies on reviewing and assessing safety questions raised in nuclear activities. This document states that safety objectives and requirements developed for new designs should be used as reference guidance for the evaluation, planning and implementation of plant modifications to older nuclear installations which can be shown to provide significant safety improvements while remaining practically achievable. Therefore, the IAEA requirements, presented in D3.5 [2], are input to this licensing roadmap.

IAEA safety standards are primarily addressed to national regulatory authorities and cover all regulatory and operational aspects of nuclear and radiation safety. They cover all facilities and activities that can give rise to radiation exposure (only peaceful facilities and activities are covered).

The following areas of regulatory treatment, which were in the scope of D3.5 [2], are of interest for this report:

- Requirements for the nuclear power plant modifications;
- Requirements for the structures, systems and components (SSCs);
- Safety classification of SSCs;
- Requirements for design basis;
- Requirements for equipment qualification;
- Requirements for operation and maintenance.

The OECD/NEA/CNRA survey on the regulatory practice to assess passive safety systems used in new nuclear power plant design [5], presented in D3.1 [1], cover also requirements for passive safety systems.

Regarding requirements for passive safety systems, it was observed that many countries do not have specific requirements. The survey showed that there are no differences in the regulatory treatment of systems irrespective whether they are passive or active in the following areas:

- providing system descriptions in the safety analysis report;
- protection from tampering;
- establishing operational limits and conditions;
- safety classification;
- protection against external events;
- functional failures identification and consideration;
- substantiation of system parameters;
- instrumentation and control;
- demonstration of the maximum number of passive safety system actuations (including false actuations), and consideration of the equipment design life and environment that it is operating in;
- false actuation considerations and system starting considerations;
- testing during commissioning;
- testing during operation.

Finally, the safety assessment process is performed in accordance with IAEA GSR Part 4 (Rev. 1) [6], which also requires that safety assessment is performed at different stages in the lifetime of a facility, including modification of the design (i.e., plant modification). For details refer to Section 4 of D3.5[2].

7.2 Requirements for nuclear power plant modifications

Requirement 11 of IAEA SSR-2/2 (Rev. 1) [8] standard on management of modifications requires that the operating organization shall establish and implement a programme to manage modifications.

IAEA DS497B [17] gives specific recommendations on controlling activities relating to modifications to nuclear power plants. In the interest is specially Section 4 entitled "Modifications relating to plant configuration".

For the purposes of IAEA DS497B [17], modifications relating to plant configuration are defined as any permanent or temporary alterations to structures, systems and components, process software, operational limits and conditions, operating procedures, or plant configuration documentation. This includes any replacement or refurbishment of existing structures, systems and components. In the context of sCO2-4-NPP system installation we deal with permanent modification, where besides new system also new operational limits and conditions would be introduced, operating procedures would be added and modified, and finally also plant configuration documentation would change.

Configuration management is the process of identifying and documenting the characteristics of a facility's structures, systems and components (including computer systems and software), and of ensuring that changes to these characteristics are properly developed, assessed, approved, issued, implemented, verified, recorded and incorporated into the facility documentation [20]. IAEA SSR-2/2 (Rev. 1) [8] Requirement 10 emphasises the need to maintain the configuration documentation in strict accordance with the actual physical configuration.

Facility configuration information is record information that describes, specifies, reports, certifies, or provides data or results regarding the design requirements or design basis, or pertains to other information attributes associated with the facility and its structures, systems and components.

Section 4 of IAEA DS497B [17] provides guidance on categorization of modifications, safety assessment, review of proposed modifications, design considerations (in particular, the capability to fulfil the fundamental safety functions), modifications to operational limits and conditions, modifications to procedures and documentation, modifications to computer based systems, and configuration control.

Categorization of modifications: IAEA DS497B [17] in Section 4 recommends that the proposed modifications should be categorized in accordance with their safety significance. Three categories are proposed (i.e., Category 1, Category 2 and Category 3). Modifications in Category 1 are capable of having a significant effect on safety, or involve an alteration of the principles and conclusions on which the design and the licensing of the plant were based. Modifications in Category 2 include changes in items important to safety, and in associated operational approaches and/or procedures, and usually necessitate an update of the safety analysis report or other licensing documents. Modifications in Category 3 are minor modifications.

Safety assessment: In accordance with paragraphs 4.6 and 5.2 of IAEA GSR Part 4 (Rev. 1) [6], the safety assessment of a nuclear power plant is required to be updated as necessary so as to take into account the modifications to the design or operation of the plant. Human and organizational factors are also required to be considered when assessing the modification: see 4.40 of SSR-2/2 (Rev. 1) [6]. The comprehensive safety assessment should demonstrate that the modified plant can be operated safely and that it complies with the system specifications and relevant safety requirements.

The overview of IAEA safety assessment process is shown in Figure 1. As can be seen, part of the assessment process is also (general) safety approach with requirements for defence in depth, multiple barriers and safety margins (Requirement 13). The safety assessment includes safety analysis, which consists of a set of different quantitative analyses for evaluating and assessing challenges to safety by means of deterministic and also probabilistic methods (Requirements 14 through 19). On the left side of Figure 1, features to be assessed are shown (Requirements 6 through 12). At the end of assessment process, safety analysis report should be prepared and submitted to the regulatory body (Requirement 24).

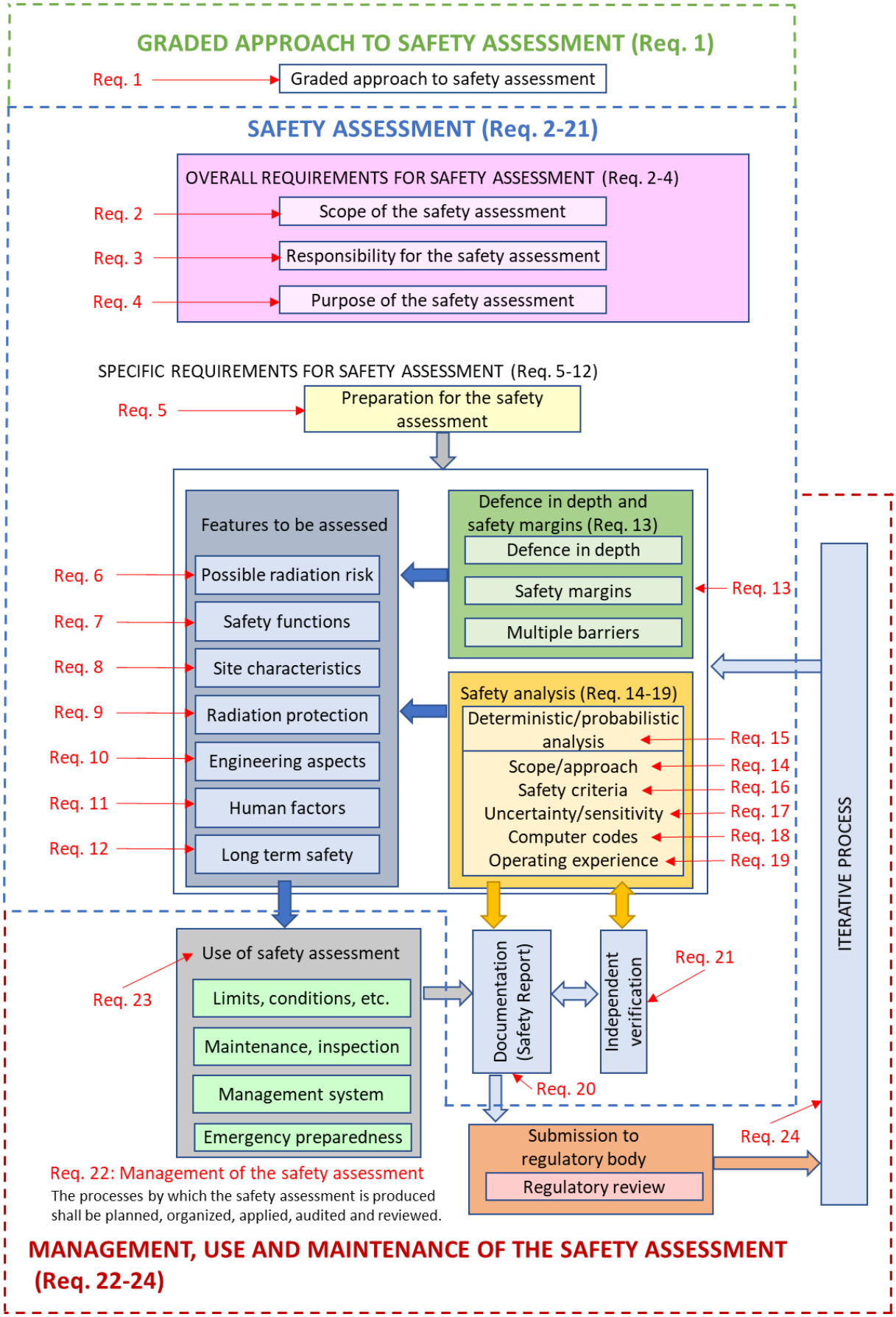

Figure 1: Overview of IAEA safety assessment requirements in accordance with GSR Part 4 (Rev. 1) standard [6] (extended Fig. 1 of IAEA GSR Part 4 (Rev. 1) [6])

According to IAEA DS497B [17] special consideration should be given to demonstrating the following:

(a) *The modification complies with all relevant requirements established in IAEA SSR-2/1 (Rev. 1) [7] and IAEA SSR-2/2 (Rev. 1) [8] for all relevant plant states;*
(b) *Interfaces with nuclear security have been taken into account;*
(c) *New or modified systems will not adversely affect the safety of other items important to safety under all plant states;*
(d) *Due account has been taken of the potential consequences if the modification is inadequately implemented;*
(e) *The occupational exposures from the implementation of the modification, and the occupational exposures and public exposures (including potential exposures due to accidents) as a result of the modification are below approved limits and as low as reasonably achievable. In considering this, the need for the modification and any associated benefits to safety should be taken into account;*
(f) *The modification can be performed without adversely affecting the safety of the plant and will not introduce new hazards;*
(g) *The technical or operational effect of the modified system on each of the accident sequences considered in the safety analysis report has been adequately assessed;*
(h) *Each identified failure mode of the modified system has been assessed by appropriate evaluation methods. In addition to the direct effects on the plant, the effects on items important to safety should also be considered in the assessment;*
(i) *The impact of potential external events and the consequences of inadequate qualification of the structures, systems and components to withstand them has been assessed and/or analysed;*
(j) *The environmental impact has been evaluated and considered;*
(k) *The safety consequences of implementing the modifications (and of any temporary equipment used), and the ability to withstand anticipated operational occurrences and accident conditions during the implementation, have been considered;*
(l) *The potential interaction with other design changes has been reviewed to ensure control of the plant configuration after implementation of the modification (e.g. because a later change might depend upon whether an earlier proposed change has already been made);*
(m) *The scope of commissioning testing meets system specifications;*
(n) *The radioactive waste arising from the plant modification will be properly managed;*
(o) *The need to temporarily disable any safety related plant interlocks, or to suspend any operating restrictions, has been fully assessed before implementation, and that steps are in place to ensure the prompt reversal and reinstatement of such measures;*
(p) *In the case where a modification has already been implemented in a similar plant, any differences between the plants has been properly assessed before design documentation, implementation procedures or test procedures have been duplicated.*

Design considerations: When modifications, including installation of new and additional SSC's, are first proposed, their compatibility with the original design bases should be assessed. Modifications relating to plant configuration should meet the requirements for the design of nuclear power plants established in IAEA SSR-2/1 (Rev. 1) [7]. The detailed design of modifications should include specifications for construction, installation, commissioning, equipment qualification and testing (including test acceptance criteria), ageing control and for maintenance during operation and decommissioning.

Modifications to operational limits and conditions: Paragraph 4.8 of SSR-2/2 (Rev. 1) [8] requires review and revision as necessary in consideration of changes. Where alterations to the operational limits and conditions

become necessary, they should be considered to be modifications of high safety significance (e.g. Category 1 modifications).

Modifications to procedures and documentation: Modifications to procedures and documentation should be categorized in accordance with their safety significance. Any modifications to procedures and documentation are required to be approved: see para. 7.4 of SSR-2/2 (Rev. 1) [8]. Modified documents should be verified and validated before use. Any other documents affected by the modifications are required to be revised and operating personnel are required to be appropriately trained: see paragraph 4.43 of SSR-2/2 (Rev. 1)[8].

Modifications to computer based systems: Recommendations on the design and control of software for nuclear power plants are provided in IAEA SSG-39 [14]. For modifications to be carried out on computer systems, in particular software, a comprehensive validation and verification process should be implemented to ensure the suitability of the changes.

Configuration control: Consistency is required between modifications, design requirements and plant documentation: see Requirement 10 and paragraph 4.38 of SSR-2/2 (Rev. 1) [8]. When modifications are made to SSCs and process software, the relevant plant documentation should be modified accordingly. When modifications are to be made to OLCs (see paragraphs 4.19–4.21), the associated operating instructions and procedures should be modified accordingly (see paragraphs 4.22 and 4.23), and in some cases the associated SSCs might also be subject to modification. Configuration management should also be used to ensure that the implementation of the modification is in accordance with the design requirements as established in the design documentation. Consideration should be given to the need to revise procedures, training and plant simulators or training facilities as part of the implementation of the modification (see also paragraph 4.21 of SSR-2/2 (Rev. 1) [8]. Training is required to be provided for plant personnel on the modified plant structures, systems and components: see paragraph 4.43 of SSR-2/2 (Rev. 1) [8]. Any updates to the configuration of the plant simulator or training facilities should be included within the modification programme, to ensure that this programme accurately reflects all modifications and changes made to the plant.

For further details on above information refer to IAEA DS497B [17]. IAEA requirements for plant modifications are presented also in Chapter 5.4.1 of D3.5 [2].

7.3 Design step of licensing process

7.3.1 Requirements for SSCs

Once the safety classes of the SSCs have been established, corresponding engineering design rules will have to be specified and applied. Engineering design rules are the relevant national or international codes, standards and proven engineering practices that are applied, as appropriate, to the design of SSCs to meet the overall objective that the most frequent postulated initiating events yield little or no adverse consequences, while more extreme events (those having the potential for the greatest consequences) have a very low probability of occurrence. Depending on its safety significance, reflected by its safety class, each SSC is designed, manufactured and operated according to appropriate engineering rules defined to give confidence that its capability, reliability and robustness will be adequate.

It is reasonable to distinguish between design requirements that apply at the system level and those that apply to individual structures and components:

- Design requirements applied at the system level may include specific requirements, such as single failure criteria, independence of redundancies, diversity and testability, but also general requirements for environmental, seismic and hazard qualification.

- Design requirements applied for individual structures and components precise the needs with regard to environmental and seismic qualification, and manufacturing quality assurance procedures. They are typically expressed by specifying the codes or standards that apply.

For further details and guidance documents refer to Section 5.3.1 of D3.5 [2].

7.3.1.1 Requirements applicable to system

Document IAEA TECDOC-1787 [18] gives as example a set of typical generic design requirements for systems, as shown in Table 4.

Moreover, seismic requirements and environmental qualification are essential to ensure the integrity of buildings and structures or the operability of components if required in case of an earthquake or during accident conditions with harsh ambient conditions. Any system designed to mitigate the consequences of an accident is expected to be designed according to requirements ensuring its operability when challenged. Nevertheless, qualification requirements are defined at the individual component level taking into account the relevant environmental conditions at the component location and its mission time.

Table 4: Example of typical safety requirements for systems (TABLE 17 of [18]Error! Reference source not found.**)**

System safety class	Single failure criterion	Physical & electrical separation	Emergency power supply	Periodic tests	Protected against or designed to withstand hazard loads	Environmental qualification
SC1	Yes	Yes	Yes	Yes	Yes	Yes
SC2 (1)	Yes (1)	Yes	Yes	Yes	Yes	Yes
SC2 (2)	Not required (3) (4)	Yes for redundant equipment	Yes	Yes	Yes	Yes
SC3 (5)	Not required (6)	Yes for redundant equipment	Yes	Yes	Yes	Yes
SC3 (7)	Not required	Not required	According to functional analysis	Yes (8)	According to functional analysis	According to functional analysis

(1): Systems necessary to reach and maintain a safe state. Reaching a safe state should be possible despite one single failure.

(2): Systems designed for design extension conditions as a backup of a system assigned to safety class 1. Independence from the safety class 1 system is necessary.

(3): System designed as a backup of a system assigned to safety class 1 already provides an alternate means to accomplish the same safety function as that performed by the safety class 1 system. Nevertheless, reliability of such system needs to be adequate to meet the total core damage frequency (CDF) target.

(4): Might be needed for I&C backup system to prevent spurious actuation (e.g., for the diverse actuation system).

(5): Systems designed to mitigate the consequences of design extension conditions but not assigned to safety class 2.

(6): Compliance with the single failure criterion is not required in design extension conditions. However redundant active components might be necessary to achieve the reliability expected for the function to be accomplished by the system (e.g., active components of systems required to preserve the containment integrity in case of a severe accident with core melt).

(7): Systems not required meeting the acceptance criteria established for design basis accidents or design extension conditions but that are in the group of systems important to safety according to the IAEA Safety Glossary. A common set of requirements to be systematically applied cannot be established, but the relevant and specific requirements are generally defined on the basis of a functional analysis supplemented by probabilistic insights.

(8): Unless necessary for normal operation. Redundant divisions of a single safety system need to be independent and separated from each other to prevent a failure in one redundancy from propagating to the non-affected redundancies, or the loss of all of the redundancies caused by a hazard. Independence and separation of systems belonging to different levels of defence are also

fundamental design elements for achieving a high level of safety, and are therefore expected to be implemented adequately between the different levels of defence. However, independence of levels of defence is a complex issue taking into account that full independence is not practically feasible, and is therefore not addressed in TECDOC-1787 [18].

7.3.1.2 Requirements applicable to individual structures and components

Generic consideration: Document IAEA TECDOC-1787 [18] explains that by assigning a safety class to every individual SSC, a set of design and manufacturing requirements needs to be established to meet the requested quality and reliability objectives. Adequate and proven codes or standards need to be used for the design and manufacturing of the structures and components to ensure that they will be designed, manufactured, constructed, installed, commissioned, quality assured, maintained, tested and inspected according to their safety significance. These industry codes and standards indicate the methodologies, rules and criteria to be used for procurement, design, construction, inspection and testing of components.

Seismic requirements: Document IAEA TECDOC-1787 [18] explains that apart from the safety classification, it is also important to factor in the requirements related to classification of SSCs with respect to the importance of their integrity/performance/failure during a seismic event.

Environmental qualification: Document IAEA TECDOC-1787 [18] explains that qualification of equipment contributes to provide evidence that safety classified equipment is able to fulfil its required function(s) during accident conditions (design basis accidents or design extension conditions), despite the harsh environmental conditions (pressure, temperature, moisture, irradiation) prevailing prior to or at the time they are requested to operate. Specifications need to be defined taking into the following factors:

- The location of the item (environmental conditions are building dependent);
- The mission(s) of the item in accident conditions.

Pressure retaining equipment: Document IAEA TECDOC-1787 [18] gives examples of well-established codes defining design and manufacturing requirements for pressure retaining equipment the following:

- ASME Boiler and Pressure Vessel Code, Section III, Division 1
- French Association for Design, Construction and In-Service Inspection Rules for Nuclear Island Components (AFCEN) (RCC-M)
- Safety Standards of the German Nuclear Safety Standards Commission (KTA).

All the above standards are explained in more detail in Section 6.4.1 of D3.1 [1] Table 5 shows relationship between safety classes SC2 and SC3 and code requirements for pressure retaining equipment.

Table 5: Relationship between safety class and code requirements for pressure retaining equipment (adapted per Table 18 of [18])

Safety Class	Safety classified pressure retaining equipment items	Code requirement	Example of SSCs
SC2	Components providing Cat. 3 functions with a safety barrier class 2	ASME Code, Section III, Division 1, Subsection NC RCC-M2	Residual heat removal system
	Components providing Cat. 2 functions	ASME Code, Section III, Division 1, Subsection ND RCC-M3	Spent fuel pool cooling system
SC3	Components providing Cat. 3 functions with a safety barrier class 3	ASME Code, Section III, Division 1, Subsection ND RCC-M3	Systems containing radioactive fluids in normal operation, e.g. chemical volume and control system, waste processing systems
	Components providing Cat. 3 functions unless specific codes and requirements are applied for specific reasons	Conventional codes like: • European Pressure Directive 97/23/EC • ASME Code, Section VIII, Division 1 for pressure vessels • ANSI B31.1 for piping	Systems providing make-up to feedwater tanks in postulated design extension conditions

7.3.1.3 Requirements for design basis

The design and construction of the sCO2-4-NPP system must meet certain requirements and regulations. The IAEA requirements for design are given in IAEA SSR-2/1 (Rev. 1) [7] and recommendations to satisfy design requirements in IAEA SSG-56 [15]. According to paragraph 3.7. of IAEA SSG-56 [15], the design basis for every SSC should specify items as shown in Figure 2.

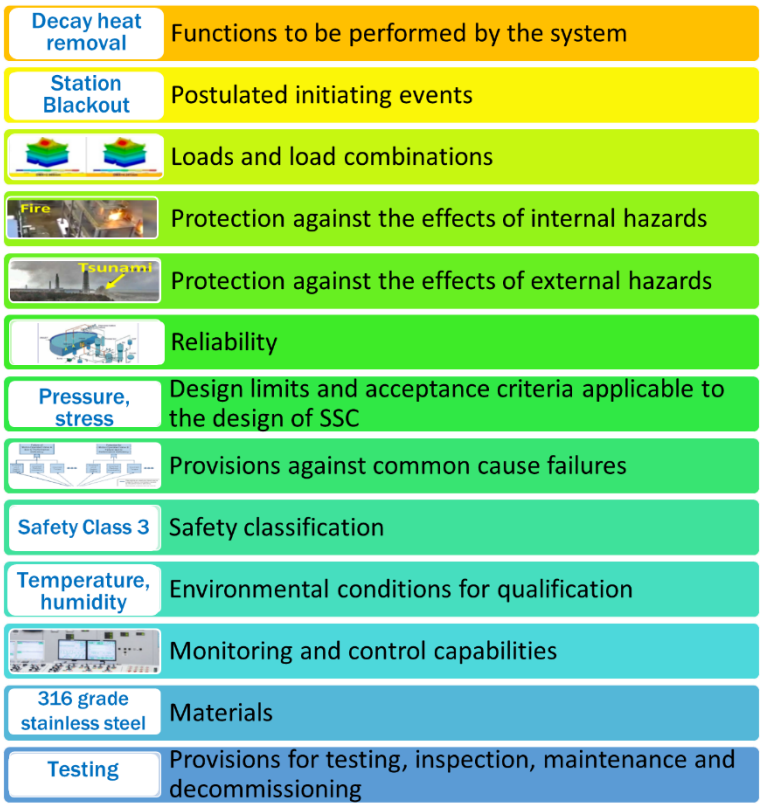

Figure 2: Design basis items to be specified

Requirement 10 of IAEA SSR-2/1 (Rev. 1) [7] standard on assessment of engineering aspects requires it shall be determined in the safety assessment whether a facility or activity uses, to the extent practicable, structures, systems and components of robust and proven design.

Engineering aspects according to IAEA include implementation of defence in depth, operating experience, radiation protection, safety classification of SSCs, aging and wear-out mechanism, protection against internal and external hazards, materials, equipment qualification.

Requirement 12 of IAEA SSR-2/1 (Rev. 1) [7] standard on features to facilitate radioactive waste management and decommissioning requires that special consideration shall be given at the design stage of a nuclear power plant to the incorporation of features to facilitate radioactive waste management and the future decommissioning and dismantling of the plant.

Requirement 14 of IAEA SSR-2/1 (Rev. 1) [7] standard on design basis for items important to safety requires that the design basis for items important to safety shall specify the necessary capability, reliability and functionality for the relevant operational states, for accident conditions and for conditions arising from internal and external hazards, to meet the specific acceptance criteria. The requirements for design basis items shown in Figure 2 are specified below.

Functions – Requirement 4 of IAEA SSR-2/1 (Rev. 1) [7] standard on fundamental safety functions requires fulfilment of fundamental safety functions to be ensured.

The sCO2-4-NPP system will participate in the following three fundamental safety functions:

- the control of nuclear chain reactions,
- the evacuation of thermal power from the reactor core,
- the prevention of radioactive releases.

Compliance with the latter makes it possible to ensure the fourth fundamental safety function, which is the protection of people and the environment against ionizing radiation.

Postulated initiating events (PIEs) – Requirement 16 of IAEA SSR-2/1 (Rev. 1) [7] standard on postulated initiating events requires to identify a comprehensive set of postulated initiating events.

sCO2-4-NPP will provide a heat removal solution for Nuclear Power Plants that will increase the grace period in case of station blackout and loss of ultimate heat sink PIEs to beyond 72 hours.

Load and load combinations – Requirement 17 of IAEA SSR-2/1 (Rev. 1) [7] standard on internal and external hazards requires that hazards shall be considered in the determining the generated loadings for use in the design of relevant items important to safety for the plant.

The sCO2-4-NPP system and its components must be able to handle various loads and load combinations.

Protection against the effects of internal hazards – Requirement 17 of IAEA SSR-2/1 (Rev. 1) [7] standard on internal and external hazards requires that all foreseeable internal hazards and external hazards, including the potential for human induced events directly or indirectly to affect the safety of the nuclear power plant, shall be identified and their effects shall be evaluated. Hazards shall be considered in designing the layout of the plant and in determining the postulated initiating events and generated loadings for use in the design of relevant items important to safety for the plant.

The sCO2-4-NPP system will need to be protected against internal hazard that could induce a DEC event for which the system would be required.

Protection against the effects of external hazards – See Requirement 17 of IAEA SSR-2/1 (Rev. 1) [7] above.

Protection will depend greatly on the location of the various modules of the sCO2-4-NPP system.

Design limits and acceptance criteria applicable to the design of SSC – Requirement 15 of IAEA SSR-2/1 (Rev. 1) [7] standard on design limits requires that a set of design limits consistent with the key physical parameters for each item important to safety for the nuclear power plant shall be specified for all operational states and for accident conditions.

The design limits and acceptance criteria for the sCO2-4-NPP system will have to be determined from the power plant where the system is installed.

Reliability – Requirement 23 of IAEA SSR-2/1 (Rev. 1) [7] standard on reliability of items important to safety requires that the reliability of items important to safety shall be commensurate with their safety significance.

sCO2-4-NPP system will have to be dimensioned to be able to accomplish its mission in the event of failure of one of the modules.

Provisions against common cause failures – Requirement 24 of IAEA SSR-2/1 (Rev. 1) [7] standard on common cause failures requires that the design of equipment shall take due account of the potential for common cause failures of items important to safety, to determine how the concepts of diversity, redundancy, physical separation and functional independence have to be applied to achieve the necessary reliability.

This requirement is applicable to system as a whole (e.g., several modules of sCO2-4-NPP) and not to the components of the sCO2-4-NPP.

Safety classification – Requirement 22 of IAEA SSR-2/1 (Rev. 1) [7] standard on safety classification requires that all items important to safety shall be identified and shall be classified on the basis of their function and their safety significance.

Due to its function, the sCO2-4-NPP system will have to be classified as safety equipment.

Environmental conditions for qualification – Requirement 30 of IAEA SSR-2/1 (Rev. 1) [7] standard on qualification of items important to safety requires that a qualification programme for items important to safety shall be implemented to verify that items important to safety at a nuclear power plant are capable of performing their intended functions when necessary, and in the prevailing environmental conditions, throughout their design life, with due account taken of plant conditions during maintenance and testing.

The sCO2-4-NPP system components are required to be qualified to perform their functions in the entire range of environmental conditions.

Monitoring and control - Requirement 59 of IAEA SSR-2/1 (Rev. 1) [7] standard on provision of instrumentation requires that instrumentation shall be provided for: determining the values of all the main variables that can affect the fission process, the integrity of the reactor core, the reactor coolant systems and the containment at the nuclear power plant; for obtaining essential information on the plant that is necessary for its safe and reliable operation; for determining the status of the plant in accident conditions; and for making decisions for the purposes of accident management.

Requirement 60 of IAEA SSR-2/1 (Rev. 1) [7] standard on control systems requires that appropriate and reliable control systems shall be provided at the nuclear power plant to maintain and limit the relevant process variables within the specified operational ranges.

Monitoring and control of the sCO2-4-NPP system will be carried out by the Instrumentation and Control (I&C) architecture, which consists of several sub-systems and their associated electrical and electronic equipment.

Materials – Requirement 47 of IAEA SSR-2/1 (Rev. 1) [7] standard on design of reactor coolant systems requires that the components of the reactor coolant systems for the nuclear power plant shall be designed and constructed so that the risk of faults due to inadequate quality of materials, inadequate design standards, insufficient capability for inspection or inadequate quality of manufacture is minimized.

The materials used for the sCO2-4-NPP system must be chosen taking into account their chemical composition and the phenomena to which they are likely to be subjected.

Provisions for testing, inspection, maintenance and decommissioning – Requirement 29 of IAEA SSR-2/1 (Rev. 1) [7] standard on calibration, testing, maintenance, repair, replacement, inspection and monitoring of items important to safety requires that items important to safety for a nuclear power plant shall be designed to be calibrated, tested, maintained, repaired or replaced, inspected and monitored as required to ensure their capability of performing their functions and to maintain their integrity in all conditions specified in their design basis.

In order to guarantee an adequate level of reliability during reactor operation, the sCO2-4-NPP system shall be maintained under suitable conditions in order to be available and ready to operate correctly.

For further details and guidance documents refer to Section 5.5 of D3.5 [2].

7.3.2 Requirements for safety analysis

IAEA GSR Part 4 (Rev. 1) [6] requirements for safety analysis are Requirements 14-21 (see Figure 1). Both deterministic and probabilistic approaches shall be included in the safety analysis. The aim of the deterministic approach is to specify and apply a set of deterministic rules and requirements for the design and operation of facilities or for the planning and conduct of activities. The objectives of a probabilistic safety analysis are to determine all significant contributing factors to the radiation risks arising from a facility or activity, and to evaluate the extent to which the overall design is well balanced and meets probabilistic safety criteria where these have been defined.

Requirement 42 of AEA SSR-2/1 (Rev. 1) [7] standard on safety analysis of the plant requires that a safety analysis of the design for the nuclear power plant shall be conducted in which methods of both deterministic analysis and probabilistic analysis shall be applied to enable the challenges to safety in the various categories of plant states to be evaluated and assessed.

The guidance for deterministic safety analysis is given in IAEA SSG-2 (Rev. 1) [9] and probabilistic safety analysis in IAEA SSG-3 [10] and IAEA SSG-4 [11].

7.3.3 Other requirements

Requirement 32 of IAEA SSR-2/1 (Rev. 1) [7]) standard on human factors requires that systematic consideration of human factors, including the human–machine interface, shall be included at an early stage in the design process for a nuclear power plant and shall be continued throughout the entire design process.

7.4 Commissioning and operation step of licensing process

Relevant requirements of IAEA SSR-2/2 (Rev. 1) [8]) for commissioning and operation are the Requirements 6, 10, 11, 13, 14, 18, 25, 26, 27, 28, 31 and 32. The Requirements 6 and 28 of IAEA SSR-2/2 (Rev. 1) [8]) are described in Section 7.4.1, which deals with operational limits and conditions, while Requirements 25, 31 and 32 of IAEA SSR-2/2 (Rev. 1) [8]) are described in Section 7.4.3 dealing with plant commissioning, and maintenance, testing, surveillance and inspection. Requirements 17 through 24 of IAEA SSR-2/2 (Rev. 1) [8]) deal with the following operational safety programmes: Consideration of objectives of nuclear security in safety programmes, Emergency preparedness, Accident management programme, Radiation protection, Management of radioactive waste, Fire safety, Non-radiation-related safety, and Feedback of operating experience.

Requirement 10 of IAEA SSR-2/2 (Rev. 1) [8]) on control of plant configuration requires that the operating organization shall establish and implement a system for plant configuration management to ensure consistency between design requirements, physical configuration and plant documentation.

Requirement 11 of IAEA SSR-2/2 (Rev. 1) [8]) gives requirements for management of modifications. Modifications can be done on the original design (new advanced reactor) and on existing operating reactors. Refer to Section 7.2, where plant modifications have been already considered.

Requirement 13 of IAEA SSR-2/2 (Rev. 1) [8]) standard on equipment qualification is explained in Section 7.4.2.

Requirement 14 of IAEA SSR-2/2 (Rev. 1) [8]) standard on ageing management requires that the operating organization shall ensure that an effective ageing management programme is implemented to ensure that required safety functions of systems, structures and components are fulfilled over the entire operating lifetime of the plant.

Requirement 18 of IAEA SSR-2/2 (Rev. 1) [8]) standard on emergency preparedness requires that the operating organization shall prepare an emergency plan for preparedness for, and response to, a nuclear or radiological emergency.

Requirement 26 of IAEA SSR-2/2 (Rev. 1) [8]) standard on operating procedures requires that the operating procedures shall be developed that apply comprehensively (for the reactor and its associated facilities) for normal operation, anticipated operational occurrences and accident conditions, in accordance with the policy of the operating organization and the requirements of the regulatory body.

Requirement 27 of IAEA SSR-2/2 (Rev. 1) [8]) standard on operation control rooms and control equipment requires that the operating organization shall ensure that the operation control rooms and control equipment are maintained in a suitable condition.

For further details and guidance documents refer to Section 5.7.1 of D3.5 [2].

7.4.1 Operational limits and conditions

Requirements for operational limits and conditions (OLCs) are given both for design and operation of nuclear power plant.

Requirement 28 of IAEA SSR-2/1 (Rev. 1) [7] standard on operational limits and conditions for safe operation requires that the design shall establish a set of operational limits and conditions for safe operation of the nuclear power plant.

Requirement 6 of IAEA SSR-2/2 (Rev. 1) [8]) standard on operational limits and conditions requires that the operating organization shall ensure that the plant is operated in accordance with the set of operational limits and conditions.

For further details and guidance documents refer to Section 5.7.1.1 of D3.5 [2].

7.4.2 Requirements for equipment qualification

Requirement 13 of IAEA SSR-2/2 (Rev. 1) [8]) standard on equipment qualification requires that the operating organization shall ensure that a systematic assessment is carried out to provide reliable confirmation that safety related items are capable of the required performance for all operational states and for accident conditions.

Equipment qualification (EQ) includes e.g., seismic qualification, environmental qualification, electromagnetic qualification. The safety function of a piece of equipment (electrical or mechanical or I&C equipment) is generally established in terms of its required behaviour (active or passive) and its duration. The EQ is a process adopted to confirm that the system is capable of meeting, throughout its operational design life, the demands for performing its functions while being subject to the environmental conditions (vibration, temperature, pressure, jet impingement, electromagnetic interference, irradiation, humidity or any likely combination thereof) prevailing at the time of need. Environmental conditions to be considered include the variations expected in normal operation, anticipated operational occurrences, design basis accidents and design extension conditions. Moreover, consideration shall be given to ageing effects caused by various environmental factors (such as vibration, irradiation and extreme temperature) over the expected lifetime of the equipment. The qualification programme shall replicate as far as practicable the conditions imposed on the equipment by the natural phenomenon, either by test or by analysis or by a combination of both.

In Section 3 of IAEA SSG-69 [16] it is stated that the design inputs that are necessary for equipment qualification should be established and documented in a specification that includes the following:

(a) The performance requirements necessary to accomplish the intended safety functions;
(b) The specified environmental conditions and operating conditions expected in operational states and accident conditions, including for seismic events;
(c) The safety class (see IAEA SSG-30 [13]) assigned to the equipment and the corresponding supplemental classifications (e.g., seismic classification, quality classification);
(d) The acceptance criteria for equipment qualification.

Examples of performance requirements include requirements for accuracy, resolution, range, sample rate and response time. Relevant environmental conditions for operational states typically ambient temperature and pressure, humidity and steam, radiation level, submergence, chemical leakages (e.g., boric acid, steam spray), chemicals in the atmosphere (e.g., salt mist, oil aerosols, dust), induced vibrations from neighbouring equipment or from a seismic event and SL-1 vibration.

Relevant operating conditions for operational states are typically power surges, operating cycles (e.g. electrical, mechanical, water hammer), electrical loading parameters (e.g. voltage, frequency, current), mechanical loads (e.g. thrust; torque; displacement; non-seismic vibration including flow induced vibration, condensing mode vibration and quenching vibration), process fluid conditions (e.g. pressure, temperature, chemical composition, flow rate, water hammer), chemical composition, loads and duty cycles, self-heating, submergence, electromagnetic interference and electromagnetic fields.

Service conditions recommendations are specified for equipment located in mild environments, for harsh environments resulting from design basis accidents and conditions resulting from design extension conditions with core melting.

As explained in D7.1 [3], service conditions include many considerations for equipment qualification: environmental, loading, power, and signal conditions expected during normal operation; expected abnormal extremes in operating requirements; and postulated conditions for design-basis events (similar conditions are expected for design extension conditions without core melting). Postulated design-basis events are those used during the design of the plant to establish the requirements for the acceptable performance of structures, systems, and components. They include large-break loss-of-coolant accidents, high-energy line breaks, main steam line breaks, and similar events that can cause high-temperature, high-pressure fluid sprays, flooding, or pipe whip. Design-basis events can also be caused by natural phenomena such as an earthquake. Service conditions also include operating conditions such as self-heating, cycling, process fluid conditions, and electromagnetic interference.

Qualification of equipment shall be accomplished by test, analysis, documented operating experience, or some combination of these methods. Type testing is the preferred method for qualification of equipment. In Section 4 of IAEA SSG-69 [16], the following equipment qualification methods are recommended:

(a) Type tests;
(b) Analysis;
(c) Evaluation of operating experience;
(d) Where appropriate, an assessment of equipment capability for design extension conditions;
(e) A combination of the above methods.

For type testing the recommendations are given on the following:

- General recommendations,
- Test specification for equipment qualification by type testing,
- Test specimens for equipment qualification by type testing,
- Simulation of aging effects (pre-aging) in type tests for equipment qualification,
- Simulation of seismic conditions in type testing for equipment qualification,
- Simulation of specified service conditions in type testing for equipment qualification, and
- Margins for test profiles in type testing for equipment qualification.

As explained in D7.1 [3], the ageing of systems and components is a potential common cause failure mechanism. Equipment qualification testing for the effects of aging typically applies techniques that use

accelerated aging methods on test specimens to simulate years of service under the expected operating conditions.

Information on suitable margins for conducting type tests on electrical equipment important to safety is provided in EN 60780-323 [19]. This standard describes the basic requirements for qualifying electrical equipment important to safety and interfaces (electrical and mechanical) that are to be used in nuclear facilities. The principles, methods, and procedures described are intended to be used for qualifying equipment, maintaining and extending qualification, and updating qualification, as required, if the equipment is modified. The qualification requirements in this standard, when met, demonstrate and document the ability of equipment to perform safety function(s) under applicable service conditions, including design basis events and certain design extension conditions, and reduce the risk of environmentally induced common-cause equipment failure.

For further details and guidance documents refer to Section 5.6.1 of D3.5 [2].

7.4.3 Plant commissioning, and maintenance, testing, surveillance and inspection

Requirement 25 of IAEA SSR-2/2 (Rev. 1) [8]) standard on commissioning programme requires that the operating organization shall ensure that a commissioning programme for the plant is established and implemented.

Requirement 31 of IAEA SSR-2/2 (Rev. 1) [8]) standard on maintenance, testing, surveillance and inspection programmes requires that the operating organization shall ensure that effective programmes for maintenance, testing, surveillance and inspection are established and implemented.

Requirement 32 of IAEA SSR-2/2 (Rev. 1) [8]) standard on outage management requires that the operating organization shall establish and implement arrangements to ensure the effective performance, planning and control of work activities during outages.

For more details and guidance documents refer to Section 5.7.1.2 of D3.5 [2].

7.5 Contacts with regulatory bodies

Any new safety systems need to go through specific qualifications on a nuclear regulatory level. An independent review of the acceptability of set requirements and criteria to be considered in the licensing process has been carried out (WP3). The project also collaborated with an external regulatory advisor. The results provided input for defining the regulatory roadmap to reach TRL9.

7.6 Contacts with standards bodies

To understand the potential need and opportunities for standardisation of the sCO2-4-NPP technology, the project monitored and align with any evolution of relevant standards in NPP safety. Partners alerted standards bodies on the need for evolution of standards for the main components of the sCO2-4-NPP system. The standards for compact heat exchangers for nuclear applications and turbomachines for sCO_2 are not finalised.

Participation in standardisation committees relating to system components (or contact) can be envisaged for the industrial partners directly concerned. At present, the existing standards on sCO_2 equipment are mainly for use in the chemical industry and not for power generation.

The main standardisation committees that may be interested are CCPN, AFNOR, IEC and CENELEC.

8 Financial and organisational roadmap to reach TRL9

In sCO2-4-NPP, the partners worked on financial, organisational and marketing roadmaps for bringing the sCO2-4-NPP system to TRL9 with the technological and regulatory roadmaps developed. These roadmaps can be used to contact different stakeholders (financial, industrial partners) to establish partnerships so as to ensure the continuation of the developments on a financial and industrial level.

- Standardisation roadmap: In order to obtain their qualification, each element of the technology must be developed according to the reference standards. As part of the sCO2-4-NPP system, the consortium has already identified that the standards for compact heat exchangers for nuclear and turbomachines for sCO_2 are not finalised. For this reason, it has included in its dissemination plan an important communication with the various standardisation organisations.
- Sustainability of financing after the EU funding: To ensure sustainability of financing, the partners will seek funding through joint ventures and direct investment through venture capital to make the system robust and reliable, pilot plan development, large-scale testing and bringing the system to industrial scale. On the basis of the amounts allocated to other international projects related to the sCO_2 cycle, and taking into account the need to qualify this type of system for nuclear energy, at least €100 million would be needed to provide the necessary test benches and first test loops.
- Securing an industrial integrator to adapt the sCO2-4-NPP technology to industrial scale: During the project, the solution will be presented to different integrators, such as Framatome, to study the relevance and possibility of continuing work on the development of the NPP system with nuclear manufacturers.

8.1 Preliminary Business Model

A sketch of the main elements of the smart system business model is presented in Figure 3, following the CANVAS method.

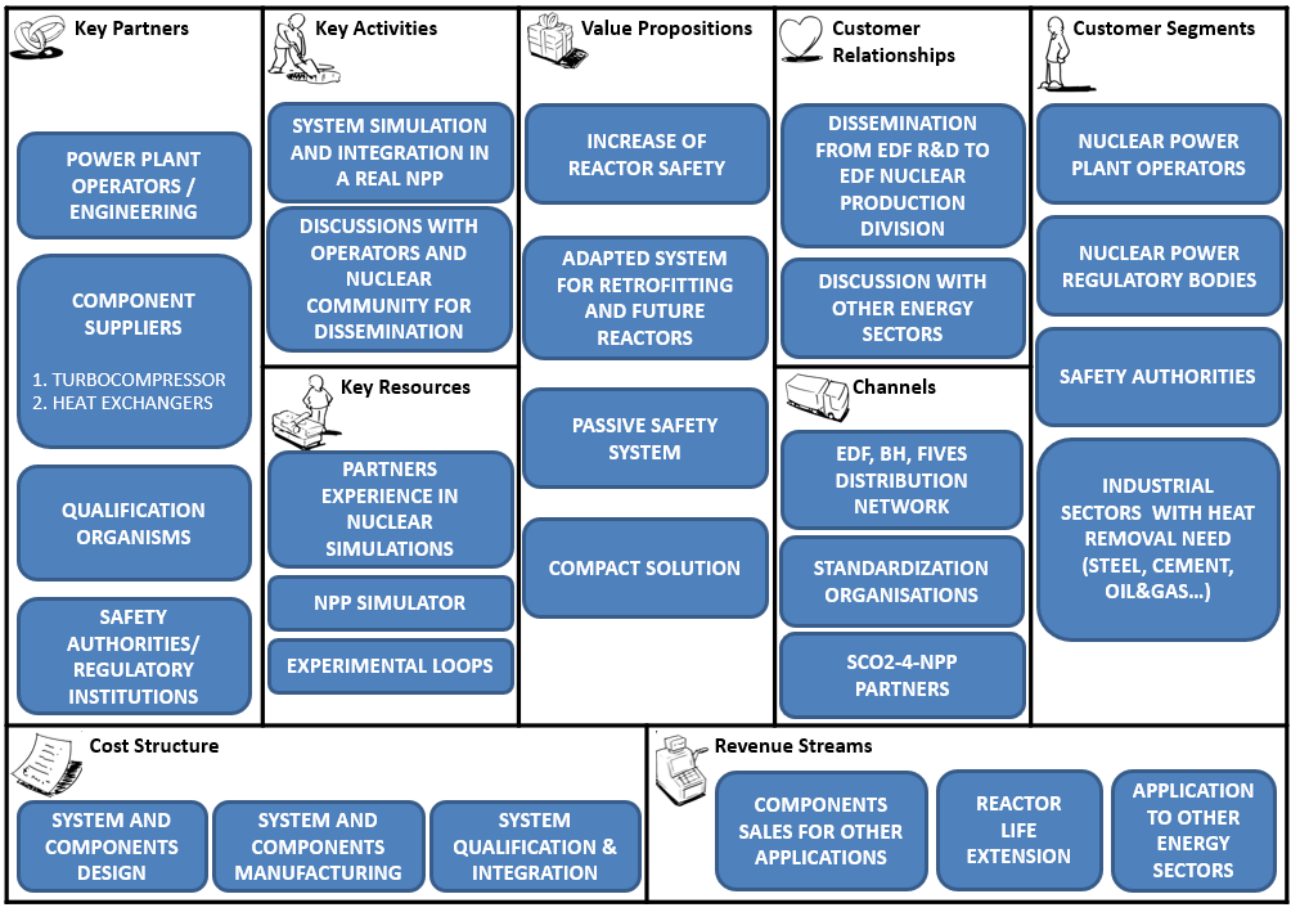

Figure 3: sCO2-4-NPP business model (CANVAS methodology diagram)

8.2 Financial roadmap

In view of the safety and security issues related to nuclear power plants, the next steps in the development of the NPP system will have to be taken in collaboration or with the agreement of the safety authorities (and thus legislators in some countries). This type of technological development project requires very significant investment and strong collaboration between partners.

The next steps related to technological development could be carried out through collaborative projects (subsidized or not). Indeed, as identified in the technological roadmap, these next steps mainly concern the continuation of the modeling of the behavior of the main components, the simulations of the behavior of the sCO2 system and the tests of different options for the components (new materials, design improvements, etc.) and for the system as a whole (start-up modes, first observations and first operating rules). This work requires a lower financial investment than the test loop of the entire sCO2 system or full-scale prototypes of the main components. This stage would allow the main components of the sCO2 system to reach TRL 6 to 7 and thus provide a better basis for discussion with the various safety authorities.

Secondly, the technological and regulatory roadmaps show that an integrated and integrable vision of the system will be necessary to finalize the last developments and also that the financing of prototypes at representative scales will be necessary to ensure the qualification of the equipment and to respond to the last steps of the technological roadmap for the whole system. This vision should be carried by a nuclear integrator, thus capable of working on all aspects of the sCO2 system: improvement of equipment, definition of operating

rules, and therefore of producing qualification and safety files, carrying out the necessary tests, and integrating this system into all existing safety systems. The investment will be substantial (several tens of millions of euros), so the nuclear integrator will also have to look for potential end Users, or national investment funding.

8.3 Organisational roadmap

The development of the sCO2 system and its commissioning will only be successful if the different roadmaps (technological, regulatory and financial) are carried out in parallel. Indeed, it will not be possible to technologically develop a component that can be qualified if the qualification procedures are not established and if the standards for this type of equipment do not exist.

To achieve this, the actors involved in the development of the sCO2 system must develop a strong network to ensure the financing of developments and the involvement of all the actors in the nuclear industry.

At the end of the sCO2-4-NPP project, the consortium has succeeded in creating relationships with different actors (nuclear developers, safety authorities, TSO, industrialists, academics...) of the sCO2 technology and of the nuclear industry. But to ensure the system's TRL rise, it is now necessary for this technology to be taken over by an industrial player capable of making progress on the system as a whole, with the support of more specialized players such as the developers of main components, nuclear operators, etc., in order to remove the last remaining barriers.

During the project, the consortium had regular contacts with industrial integrators in order to present them the work of the project, the results obtained and the possible perspectives. These meetings took place either within the framework of exchanges with the Advisory Board of the project, or End-users, but also within the framework of international conferences and workshops of the nuclear sector.

The partners of the project have therefore thought about the possible articulation of the different roadmaps and have managed to synthesize the parallel development in the following figure:

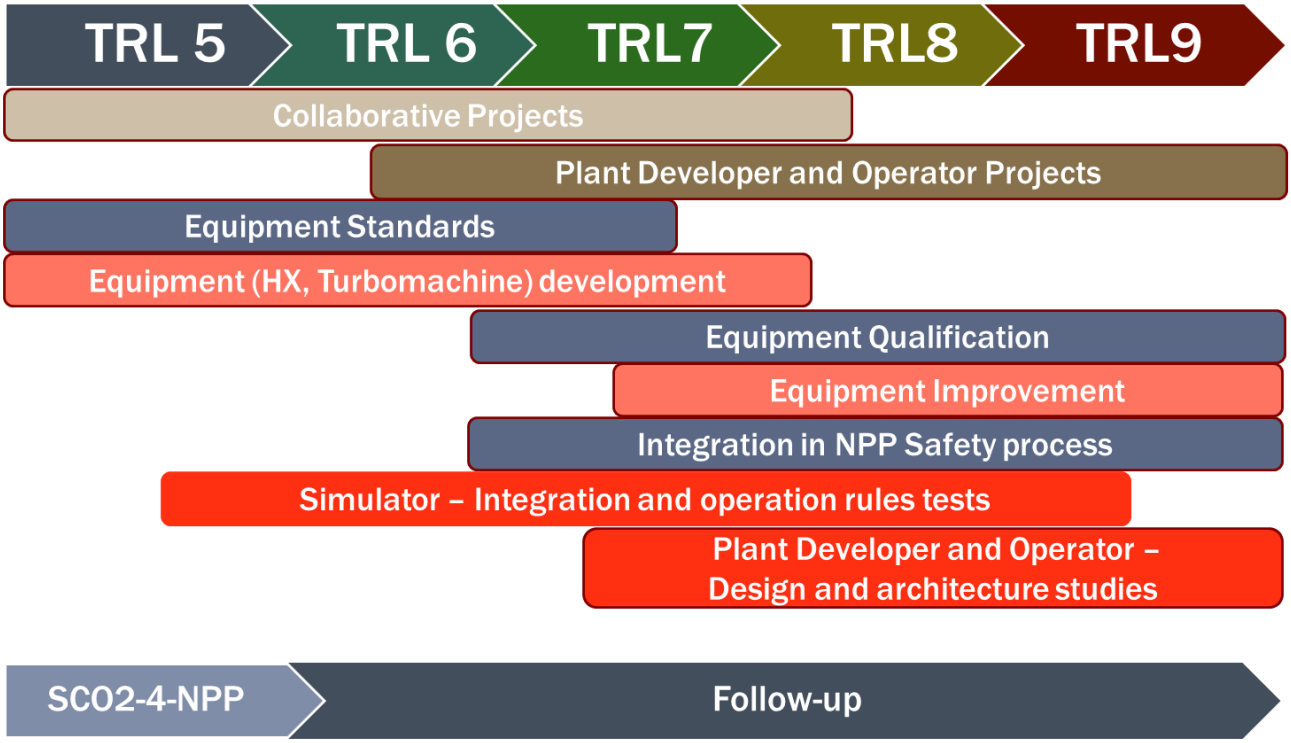

Figure 4: General roadmap to TRL 9

The brown boxes represent the stages of the financial roadmap. As we have explained, a first step could be through collaborative projects, research and innovation. The development of the main equipment (in light red), the first steps towards standardization (in blue) and the reflections on the whole system (in red) and its operation could be carried out during this period.

In a second phase, it will be necessary to continue the development of the system through industrial projects, supported by a nuclear integrator. It is during this period that it will be possible to finalize the qualification of the equipment (and the system) - in blue on the figure - while making some final improvements to the equipment, based on the results of the qualification tests. It will also be the opportunity to integrate the sCO2 system into the whole safety process of the plant, and to set up the projects for writing all the necessary safety and engineering files.

9 Conclusion

This report describes the exploitation plans for the sCO2-4-NPP system and system components including the technological, regulatory, financial and organisational (business plan) roadmaps for reaching TRL9.

The overall strategy for exploitation is described, together with steps to be taken during and following the project for the technology to reach TRL9. Challenges to be overcome in order to reach these objectives are also identified.

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