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

# D9.3 Interim Technical Review

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

*Type of action: Innovation action*

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|---|---|
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| | Version #: R1.0 |

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

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# Revision History

| Release | Date | Reason for Change | Author | Distribution |
|---|---|---|---|---|
| R0.1 | 16/02/2021 | Draft based on M18 Technical Report | Susan Barreault | General Assembly |
| R1.0 | 26/02/2021 | Final version | Susan Barreault | Public |

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# 1 List of Acronyms

| Abbreviation / Acronym | Description / meaning |
|---|---|
| CHX | Compact Heat Exchanger |
| DUHS | heat sink exchanger (Diverse Ultimate Heat Sink) |
| ESPN | Equipment Sous Pression Nucléaire (Nuclear Equipment Under Pressure) |
| HX | Heat Exchanger |
| IAPI | Important Activities for the Protection of Interests |
| NDA | Non-Disclosure Agreement |
| NDESR | Necessary Dimensions to meet the Essential Safety Requirements |
| PED | Pressure Equipment Directive |
| PWR | Pressurized Water Reactor |
| RCC-M | Regles de Conception et de Construction des Materiels Mecaniques des Ilots Nucleaires PWR |
| SBO | Station Black Out |
| TISC suite | Software package for coupling simulation tools |
| ToR | Terms of Reference |
| TRL | Technology Readiness Level |
| VVER | Water-Water Energy Reactor |

# 2 Executive Summary

This deliverable D9.3 Interim Technical Review provides a comprehensive status of project progress against objectives as of M18 (February 2021), half-way through the project. The overall status is given in terms of project milestones, deliverables and risk management, followed by a detailed status per task, including progress toward objectives, exploitable results achieved to date, and challenges encountered. The project is largely on track, but with a few deliverables and milestones delayed by two or three months due to pandemic-related laboratory closures affecting the schedule for testing and manufacture of components.

# 3 Explanation of the work carried out by the beneficiaries and overview of the progress

## 3.1 Objectives

The project high-level objectives are shown in the table below and correspond with work packages 1 through 7. The work packages are roughly sequential, with some overlap, and results of one work package being used as input for the following workpackage.

| Objectives | Achievement (Yes/No, Comment) |
|---|---|
| Objective 1: Validation of $sCO_2$ models in thermal-hydraulic system codes on lab scale | YES, Measurements were taken, HeRo cycle was modelled in ATHLET, CATHARE and MODELICA for a benchmark test case. Benchmark test case was successfully simulated, and results were compared to measurements. |
| Objective 2: Specification of an upscaled system, boundary conditions and simulations for implementation of sCO2-4-NPP loop in a full-scale NPP (PWR) | NO (In progress, achievement expected in May 2021 – see WP2) |
| Objective 3: Preparation of a licensing roadmap of the sCO2-4-NPP system to ensure compliance with application regulation | NO (In progress – see WP3) |
| Objective 4: Design of components for the sCO2-4-NPP loop in the context of licensing requirements (turbomachinery, heat exchanger, auxiliary systems) | NO (In progress – see WP4) |
| Objective 5: Final design of the system architecture of sCO2-4-NPP integrated in a full-scale NPP | NO (In progress – see WP5) |
| Objective 6: Validation of sCO2-4-NPP loop in a virtual “relevant nuclear environment” PWR | NO, first test case model was exchanged with CVR and could be successfully connected to simulator (In progress – see WP6) |
| Objective 7: Prepare technical, regulatory, financial and organisational roadmaps to bring sCO2-4-NPP to Market | NO (In progress – see WP7) |

### 3.1.1 Milestones

| ML# | ML | WP# | Lead | Due | Due date | Means of Verification | Status | Achievement date | Comments |
|---|---|---|---|---|---|---|---|---|---|
| MS1 | Thermohydraulic codes validated | WP1 | UDE | M9 | 31/05/2020 | Initial experiment in $sCO_2$ loop finalised and results have been communicated to partners (D1.1 submitted) | Achieved D1.1 & D1.2 submitted | 29/05/2020 | |
| MS2 | Input to specifications for scaled-up system (test data from sCO2-HeRo loop, boundary conditions for SBO and specifications from licensing) | WP1, WP2, WP3 | USTUTT | M9 | 31/05/2020 | Initial experiment in $sCO_2$ loop finalised and results have been communicated to partners (D1.2, D2.1 and D3.1 submitted) | Achieved D1.2, D2.1 & D3.1 submitted | 29/05/2020 | |
| MS3 | Simulation of sCO2-4-NPP loop using scaled up component models ready | WP2 | USTUTT | M18 | 28/02/2021 | Simulation based on first specification for components finalised (D2.2 submitted) | Ongoing | | Rescheduled to May 2021, Delay due to the COVID situation |
| MS4 | Preliminary technical specifications of scaled-up sCO2-4-NPP loop ready | WP4 | UDE | M18 | 28/02/2021 | First specifications for scale-up of components available. | Ongoing | | Rescheduled to May 2021 (see MS3) |
| MS5 | Technical specification of components and system architecture of final design ready | WP4, WP5 | EDF | M26 | 31/10/2021 | Final specifications of the components and system architecture available (D4.3, D4.6, D5.2 submitted) | Started | | |
| MS6 | Fast running version for integration in KONVOI virtual NPP ready | WP5 | CVR | M26 | 31/10/2021 | Developments of fast running model finalised and delivered (D5.6 submitted) | Not started | | |
| MS7 | Validated system in KONVOI virtual NPP ready | WP6 | KSG | M29 | 31/01/2022 | Simulations in KONVOI NPP finalised and results reported (D6.2 submitted) | Started | | Test case was started ahead of schedule |

| ML# | ML | WP# | Lead | Due | Due date | Means of Verification | Status | Achievement date | Comments |
|---|---|---|---|---|---|---|---|---|---|
| MS8 | Simulation of sCO2-4-NPP loop using final design parameters ready | WP5 | EDF | M30 | 28/02/2022 | Simulations with real design parameters finalised (D5.5 submitted) | Not started | | |
| MS9 | Independent review of requirements for licensing | WP3 | JSI | M36 | 31/08/2022 | All safety and regulatory specifications for the system have been reviewed (D3.5 submitted) | Not started | | |
| MS10 | Roadmaps to TRL9 ready | WP7 | EDF | M36 | 31/08/2022 | All roadmaps are finalised (D7.2 submitted) | Not started | | |

### 3.1.2 Deliverables

| Del# | Deliverable name | WP # | Lead beneficiary | Dissemination level | Due delivery date from Annex I | | Status | Actual delivery date | Comments |
|---|---|---|---|---|---|---|---|---|---|
| D1.1 | Data on behaviour of the sCO2-HeRo-loop and the glass model | 1 | UDE | CO | M3 | 30/11/2019 | Delivered | 29/11/2019 | |
| D1.2 | Report on the validation status of codes and models for simulation of sCO2-HeRo loop | 1 | USTUTT | PU | M9 | 31/05/2020 | Delivered | 29/05/2020 | |
| D2.1 | Report on the definition of initial and boundary conditions for the SBO accident | 2 | EDF | PU | M6 | 29/02/2020 | Delivered | 29/02/2020 | |
| D2.2 | Analysis of the performance of the sCO2-4-NPP system under accident scenarios based on scaled-up components data | 2 | USTUTT | CO | M18 | 28/02/2021 | In progress | | Rescheduled to 31/05/2021 |
| D3.1 | Report on identification of the regulatory elements for design of components and system | 3 | JSI | PU | M9 | 31/05/2020 | Delivered | 29/05/2020 | |
| D3.2 | Requirements for reference plant modifications for installation of sCO2-4-NPP | 3 | NRI | PU | M14 | 31/10/2020 | Delivered | 30/10/2020 | |

| Del# | Deliverable name | WP # | Lead beneficiary | Dissemination level | Due delivery date from Annex I | | Status | Actual delivery date | Comments |
|---|---|---|---|---|---|---|---|---|---|
| D3.3 | Design bases and analyses for system and components | 3 | NRI | PU | M16 | 31/12/2020 | Delivered | 22/12/2020 | |
| D3.4 | Requirements for the preoperational and initial start-up test programmes for the system | 3 | NRI | PU | M20 | 30/04/2021 | Started | | |
| D3.5 | Independent review of the sCO2-4-NPP system licensing roadmap for real nuclear power plant | 3 | JSI | PU | M36 | 31/08/2022 | Not started | | |
| D4.1 | Test results of the improved small-scale turbomachine | 4 | UDE | PU | M18 | 28/02/2021 | Started | | Rescheduled to 31/05/2021 |
| D4.2 | Review turbomachine design for sCO2-4-NPP | 4 | UDE | CO | M20 | 30/04/2021 | Not started | | Rescheduled to 30/06/2021 |
| D4.3 | Conceptual design of the sCO2-4-NPP turbomachine | 4 | UDE | PU | M36 | 31/08/2022 | Not started | | |
| D4.4 | Preliminary design and models of the sCO2-4-NPP heat exchangers | 4 | FIVES CRYO | PU | M18 | 28/02/2021 | Delivered | 28/02/2021 | |
| D4.5 | Final conceptual design of the Heat Sink Exchanger | 4 | USTUTT | PU | M36 | 31/08/2022 | Not started | | |
| D4.6 | Final conceptual design of the Heat Recovery Exchanger | 4 | CVR | PU | M36 | 31/08/2022 | Not started | | |
| D4.7 | Qualification methodology for Heat Exchanger and turbomachinery according to NPP requirements | 4 | FIVES CRYO | PU | M34 | 30/06/2022 | Not started | | |
| D5.1 | Design concept with auxiliary systems | 5 | EDF | PU | M26 | 31/10/2021 | Started | | |
| D5.2 | Preliminary design of sCO2- 4-NPP system integrated in a real NPP | 5 | EDF | CO | M26 | 31/10/2021 | Started | | |
| D5.3 | Summary of modifications on the reference plant after integration of the heat recovery system | 5 | EDF | PU | M30 | 28/02/2022 | Not started | | |

| Del# | Deliverable name | WP # | Lead beneficiary | Dissemination level | Due delivery date from Annex I | | Status | Actual delivery date | Comments |
|---|---|---|---|---|---|---|---|---|---|
| D5.4 | Thermodynamic performance of the heat recovery system integrated into the plant | 5 | CVR | PU | M24 | 31/08/2021 | Not started | | |
| D5.5 | Integration of data from real design parameters into the CATHARE thermal-hydraulic code and simulations based on accident scenarios | 5 | EDF | CO | M30 | 28/02/2022 | Not started | | |
| D5.6 | Fast running version of the $sCO_2$ heat removal system for implementation in control logic of PWR simulator | 5 | CVR | PU | M26 | 31/10/2021 | Not started | | |
| D6.1 | Specification for interface | 6 | KSG | CO | M19 | 31/03/2021 | Started | | Interface specification has started. Test case is already successfully implemented. |
| D6.2 | $sCO_2$ System integrated in PWR-simulator | 6 | KSG | PU | M29 | 31/01/2022 | Not started | | |
| D6.3 | Representative transients of a European PWR equipped with sCO2-system monitored and assessed | 6 | GfS | PU | M36 | 31/08/2022 | Not started | | |
| D7.1 | First version of sCO2-4-NPP exploitation plan | 7 | EDF | PU | M18 | 28/02/2021 | Delivered | 28/02/2021 | |
| D7.2 | sCO2-4-NPP exploitation plan | 7 | EDF | PU | M36 | 31/08/2022 | Not started | | |
| D8.1 | Dissemination and communication plan | 8 | ARTTIC | CO | M3 | 30/11/2019 | Delivered | 29/11/2019 | |
| D8.2 | Data management plan | 8 | EDF | CO | M4 | 31/12/2019 | Delivered | 26/12/2019 | |
| D8.3 | Project public website | 8 | ARTTIC | PU | M6 | 29/02/2020 | Delivered | 29/02/2020 | |

| Del# | Deliverable name | WP # | Lead beneficiary | Dissemination level | Due delivery date from Annex I | | Status | Actual delivery date | Comments |
|---|---|---|---|---|---|---|---|---|---|
| D8.4 | End-user workshop | 8 | ARTTIC | PU | M24 | 31/08/2021 | Started | | Rescheduled to M27 |
| D8.5 | sCO2-4-NPP symposium | 8 | EDF | PU | M35 | 30/07/2022 | Not started | | |
| D9.1 | Management Plan | 9 | ARTTIC | CO | M3 | 30/11/2019 | Delivered | 29/11/2019 | |
| D9.2 | Collaborative web space | 9 | ARTTIC | CO | M4 | 31/12/2019 | Delivered | 30/12/2019 | |
| D9.3 | Interim technical review | 9 | EDF | PU | M18 | 28/02/2021 | Delivered | 28/02/2021 | |

### 3.1.3 Risks

The following risks have been identified and the status of mitigation plans are regularly monitored.

| Risk N° | Description | WP | Risk mitigation measures | Reporting Period | Mitigation measures applied? | Risk materialized ? | Comments |
|---|---|---|---|---|---|---|---|
| 1 | Problems with the system code CATHARE as a new version of the code will be used in the project so that code cannot be successfully validated and used within the scope of the project | WP1, WP2, WP5 | ATHLET will be used to provide necessary results for the sCO2-4-NPP system. If problems are identified early in the project, code developers and the CATHARE community will be contacted for support. As a last resort, support for the new version will be subcontracted. | 1 | Yes | No | The CATHARE3 library dedicated to “real gas” turbomachinery model is private and not accessible for now. The “perfect gas” turbomachinery model will then be used instead in the CATHARE3 simulations |
| 2 | Elimination of auxiliaries of sCO2-HeRo turbomachine is not successful | WP4 | Change the strategy/concept of accept auxiliaries. The acceptance of auxiliaries will | 1 | No | No | The turbomachinery with magnetic bearings is part of the |

| Risk N° | Description | WP | Risk mitigation measures | Reporting Period | Mitigation measures applied? | Risk materialized ? | Comments |
|---|---|---|---|---|---|---|---|
| | | | most likely require batteries as initial source of energy. | | | | tests in task 4.1 that we are about to start in Feb. 2021 |
| 3 | Current regulatory requirements are not sufficiently developed for consideration in system and component design | WP3 | Early involvement of regulatory bodies and the project advisors who are regulatory experts, as well as NPP operators (project partners and end user group members). | 1 | Yes | No | On track: WP3 meeting (remotely) with external advisors has been held on 18 March 2020 (during Consortium meeting 17-18 March 2020). |
| 4 | Delays in experimental results due to malfunctioning of heat exchangers | WP1 | Use best engineering estimates until equipment is available. Reallocation of project funds to cover potential repair costs. | 1 | No | No | |
| 5 | Delays in experimental results due to malfunctioning of existing turbomachinery | WP1, WP4 | The damaged parts of the turbomachine will be replaced by spare parts, which are available for the rotor and the bearings. In case of repeated malfunction of the turbomachine the new design can be used as additional mitigation measure which would cause a delay in D1.1. | 1 | Yes, turbomachine exchanged. D1.1 not delayed | Yes, increased leakage on compressor seal | Seal was damaged due to foreign object. The seal was replaced and tests continued. |
| 6 | Fast running model code not stable for running in KONVOI PWR simulator environment | WP5, WP6 | Early involvement of KSG in specifying the needs for real time modelling and interface | 1 | Yes | No | Proof of concept for data exchange was done successfully ahead of schedule. |
| 7 | Main results do not reach the main stakeholders of the project which would be an obstacle for further development and market introduction of the system | WP7, WP8 | Set up a detailed plan for dissemination and preparation of exploitation of results with concrete actions for reaching | 1 | Yes | No | On track but still relevant: D8.1 Dissemination Plan issued with concrete actions for reaching target audiences. Success criteria and schedule |

| Risk N° | Description | WP | Risk mitigation measures | Reporting Period | Mitigation measures applied? | Risk materialized ? | Comments |
|---|---|---|---|---|---|---|---|
| | | | target audiences. Review it regularly. | | | | monitored regularly in EB meetings. Participation to scientific and industry conferences delayed due to coronavirus. |
| ***Unforeseen risks*** | | | | | | | |
| 8 | Delays in experimental results will delay validation -> scaled-up simulations not based on (fully) validated codes. | WP1 | Use only partly validated codes for WP2; Improve in WP5. | 1 | Yes | Yes | Compressor measurements delayed (see risk No. 5) and high complexity of simulations required to reduce complexity for benchmark test case. Up to date approach from literature is used together with conservative assumptions as far as possible in respective codes. |
| 9 | Safety bearing failure during tests with magnetic bearings | WP4 | An additional set of safety bearings is supplied by the vendor. Additional set is available. | 1 | No | No | The safety bearing is the back-up of the magnetic bearing. In case of e.g. an overload of the magnetic bearing the safety bearing prevents damage to the shaft. Otherwise, the bearings will not be used. Due to the application of $sCO_2$ at the bearings the risk of such a touch-down and the wear of the safety bearing may increase. |

| Risk N° | Description | WP | Risk mitigation measures | Reporting Period | Mitigation measures applied? | Risk materialized ? | Comments |
|---|---|---|---|---|---|---|---|
| 10 | Delay of manufacturing/assembly of improved turbomachine for task 4.1 | WP4 | Time for test in the HeRo cycle can be shortened. | 1 | Yes but nevertheless delays are expected. | Yes | Reason: Closure of mechanical workshop at UDE from March to May 2020 due to Coronavirus. Manufacturing of parts outside UDE workshop is not possible due to limited budget. Further, delivery of parts of external suppliers for gas bearing test is delayed. |
| 11 | Gas bearing tests require more $CO_2$ as anticipated. Gas bearing test cannot be supplied by a tank of CO2. | WP4 | Gas bearing tests will be carried out at USTUTT in SCARLETT facility | 1 | Yes | Yes | If magnetic bearings are unsuitable (not working in $sCO_2$ or not allowed due to regulations), hydrostatic gas bearings will be applied for the design in task 4.2 as bearings in general have not been operated in sCO2. Operation has to be tested/validated. |
| 12 | More tests in the HeRo cycle are required as anticipated. | WP1 | Continue testing after end of May 2020. | 1 | Yes | Yes | Additional tests were carried out in June and July 2020 to be able to use measurements for validation. |
| 13 | Reduced testing time for improved turbomachine (task 4.1) | WP4 | Reduce amount of tests or extend task 4.1 and reschedule D4.1 to May 2021 | 1 | Yes | Yes | Commissioning of turbomachine might be delayed (risk - ID 10). Further, classes at the glass model at GfS are currently not possible due to Coronavirus and this provides more testing time. |

| Risk N° | Description | WP | Risk mitigation measures | Reporting Period | Mitigation measures applied? | Risk materialized ? | Comments |
|---|---|---|---|---|---|---|---|
| 14 | Optimization recommendations for turbomachine will be missed in deliverable 4.2 due to delays in task 4.1 | WP4 | The due date of deliverable 4.2 could be shifted to the end of June 2021, to guarantee the expected completeness of the report. | 1 | Yes | Yes | Since deliverable 4.1 is an input of task 4.2, several recommendations regarding the turbomachine from deliverable 4.1 must be considered in task 4.2, e.g. the conclusions obtained from the tests of the magnetic bearings and whether magnetic bearings or hydrostatic gas bearings should be applied in task 4.2. |
| 15 | Significant change in thermodynamic conditions of the cycle design will impact the design of the turbomachine | WP2, WP4 | The designs should be fixed before D2.2 by running the simulations in ATHLET, CATHARE or Modelica with current design parameters. | 1 | Yes | No | The tests in simulation codes can point out whether the current cycle design and the corresponding turbomachine design are appropriate for the requirements of sCO2-4-NPP. These tests should be performed first to ensure the designs and to avoid a big change of the designs in the future. |
| 16 | Cold start-up of the turbomachine (e.g. at ambient of -46°C) could fail | WP4, WP5 | Operation strategies like a constant inlet temperature (e.g. 55°C) of the compressor or warm-up of the compressor inlet should be considered. | 2 | No | No | Since the coldest temperature is mentioned as -46°C in Czech, the start-up process of the turbomachine could be a difficulty. The start-up strategy of the turbomachine should be developed and tested in the |

| Risk N° | Description | WP | Risk mitigation measures | Reporting Period | Mitigation measures applied? | Risk materialized ? | Comments |
|---|---|---|---|---|---|---|---|
| | | | | | | | simulation codes (ATHLET, CATHARE or Modelica). |
| 17 | Difficulties to complete architecture design due to new internal rules on the use of plans/visualization of EPR-type reactor designs at EDF | WP5 | Step-by-step process:<br>- Architecture of the $sCO_2$ module while waiting for the necessary authorizations<br>- Anticipated exchanges with the units responsible for new designs | 1 | Yes | No | |
| 18 | Delays of modelling of $CO_2$ loop scaled-up components and their testing in Dymola | WP2 | Strengthening the work team and increasing the allocated man-hours | 1 | Yes | Yes | CVR - run of test case model with NRI ATHLET was performed successfully. This task was done earlier than was planned so the more men-hours for scaled-up model is available. |
| 19 | CVR can't perform suitable approach to achieve real-time running of the model on its own without the help of an external supplier. | WP6 | Continuing of cooperation with a proven subcontractor (XRG). The need to increase CVR budget line for subcontracting and the need of partial reallocation of project funds is likely. | 2 | No | No | Preliminarily, there are three approaches to develop a real-time model<br>a) simplification of the original model<br>b) parallelization of the computational task<br>c) solution in frequency domain<br>An evaluation is currently underway which approach will lead to the goal and whether the CVR can implement it on its |

| Risk N° | Description | WP | Risk mitigation measures | Reporting Period | Mitigation measures applied? | Risk materialized ? | Comments |
|---|---|---|---|---|---|---|---|
| | | | | | | | own without the help of an external supplier in time. |
| 20 | Dymola-Model is not running in real-time | WP6 | Transfer of real-time model development to KSG (KSG to Develop real-time model with KSG-Tools) | 2 | No | No | Likelihood of the risk occurring depends on mitigation plan application of the above WP6 risk. It could be close to zero or 3 in case of risk #19, risk mitigation will not be applied.<br>(KSG: This will add significant effort to KSG) |
| 21 | Coupling of Dymola-Model to Konvoi-NPP Simulator not possible | WP6 | Develop realtime model with KSG-Tools; Start coupling test early. | 2 | No | No | Coupling of Dymola-Model has been tested successfully with a test case model delivered by CVR. |

## 3.2 Explanation of the work carried out per WP

### 3.2.1 WP1 Collection of data and validation of the thermal hydraulic system codes [Months: 1-9]

Leader: UDE

#### 3.2.1.1 Progress towards objectives

| WP Objectives | Achieved (Yes/No and comment) |
|---|---|
| To test the sCO2-HeRo system in the glass model at GfS to generate data on the performance and to validate the safety codes CATHARE and ATHLET. | Yes. D1.1 and D1.2 submitted.<br>Measurements in HeRo cycle in task 1.1 show operability of the loop and behaviour of components. Measurement data was used in task 1.2 to check cycle models. |

#### 3.2.1.2 Exploitable results

Validation of thermohydraulic codes: The generation of measurement data helps to understand the behaviour of $sCO_2$ cycles in general and the sCO2-HeRo cycle in particular. The design of the heat removal cycle for the NPP profits from these experiments. The validation of codes (ATHLET, CATHARE and MODELICA) against these measurements is used to understand challenges in modelling a $sCO_2$ cycle. Furthermore, the confidence level of the simulation results is gradually increased. Thus, simulation of the $sCO_2$ heat removal cycle for the NPP will deliver realistic results and bring the system to TRL5.

#### 3.2.1.3 Problems met and actions taken (if any)

| Deviation / Explanation | Impact on other WPs | Impact on resources | Impact on schedule |
|---|---|---|---|
| Additional tests were carried out in June and July 2020 with Turbomachine from sCO2-HeRo project to provide more measurements for validation of compressor design tools | Additional data was used for validation of design tools in WP4. No delay for other WPs. | Tests could not be done before M9 because of closure due to COVID19 from March to May 2020. | Additional tests were carried out after WP1 was concluded (in M10 and M11). |

#### 3.2.1.4 Details for each task

**Task 1.1 Testing and generating data on performance of sCO2-HeRo system (M1-M3) [UDE, GfS, KSG].**

Task leader: UDE

Task started in September 2019 and ended with D1.1, which was delivered on time, in November 2019. Some additional tests continued until March 2020, which is in line with the Description of Action that specifies that some test cases may be re-run if required.

The target of this task is to provide partners of task 1.2 with sufficient data to validate their thermohydraulic codes (ATHLET, CATHARE and MODELICA) for cycle simulation. Several tests were conducted according to the test plan agreed with partners of task 1.2 who are beneficiaries of the results of task 1.1. The following strategy was defined:

- Run tests and provide measurements starting with test cases of low complexity. Then, increasing the number of involved components continuously increases complexity.

Therefore, first tests exclude the turbomachine and focus on circulation with the piston pump over ultimate heat sink (UHS) only and then over the whole cycle with the compact heat exchanger and slave electrical heater (SEH). It was agreed to continue with turbomachine tests only after these were successfully completed.

To provide partners of task 1.2 with the means to carry out their validation, several files were shared providing the specifications of the cycle and the measurement data. D1.1 describes the provided data and supports the partners by specifying the content of each file.

D1.1 and additional tests (results are available on the project intranet) provide data regarding:

- Filling and start-up procedures
- Impact on component positions on cycle operation
- Pressure losses in pipes and components
- Heat transfer in compact heat exchanger (CHX), slave electrical heater (SEH) and ultimate heat sink (UHS) in stationary and transient experiments
- Circulation by piston pump and compressor of the turbomachine (stationary and transient)
- Flow behavior and its impact on cycle operation (e.g. pressure level)

Due to challenging cycle behavior which required additional time for initial tests (filling, start-up from subcritical to supercritical conditions) and an increased leakage on the compressor side of the turbomachine caused by a damaged seal (in turn caused by foreign objects) some tests are not reported in D1.1 and were not conducted until the end of WP1. The main reason is that mandatory tests for code validation (as agreed with partners of T1.2) were given priority over the analysis of the increased leakage. Later, the Corona outbreak did not allow partners to re-run tests with reduced leakage as testing in the last 2.5 months of WP1 was not possible. However, this did not interfere with validation of codes in task 1.2 as will be described later. Additional tests on the turbomachine were carried out in summer 2020 with a refurbished seal. They revealed the available auxiliary power of the turbine to be insufficient to reach design rotational speed of 50,000 rpm. This is caused by an unfavorable combination of pressure losses in the piping being higher than expected and a quite large ratio of leakage over compressor and turbine seals versus cycle main flow rate. It is expected that this issue will be overcome in tests in task 4.1 by improving cycle geometry by replacing certain valves to reduce pressure losses and the reduction of leakage flow rate due to higher pressure on the back side of the labyrinth seals at the hub of both compressor and turbine impeller. In any case, there is good agreement between the measured and predicted behavior of the turbomachine (compressor and turbine) in terms of pressure ratio and leakage flow rates.

In summary, task 1.1 gradually increased the knowledge and understanding of s$CO_2$ cycle behavior and provided the required data for task 1.2. Therefore, it is considered to be successfully completed.

Partner contributions:

GfS:

- Elaboration of test plan
- Support in operation
- Evaluation of measurement data

- Preparation of D1.1

KSG:

- Elaboration of test plan
- Providing sCO2-HeRo cycle facility and consumables
- Operation of sCO2-HeRo cycle for generation of measurement data

UDE:

- Elaboration of test plan
- Operation of turbomachine in sCO2-HeRo cycle for generation of measurement data
- Evaluation of measurement data
- Preparation of D1.1

**Task 1.2 Validating/improving safety codes (M2-M9) [USTUTT, EDF, CVR, GfS, UDE]**

Task leader: USTUTT

The task started in October 2019 and ended with submission of Deliverable D1.2 on schedule in May 2020.

The target of task 1.2 is the validation of the codes (ATHLET, CATHARE and MODELICA) with the measurements provided by task 1.1. Therefore, the test plan equivalent to the plan for validation was defined in collaboration with partners of task 1.1. It is based on the strategy to continuously increase the complexity of the model and validate it step by step. Thus, it was decided to focus on the circulation tests with the piston pump (excluding the turbomachine) first. During the implementation of the cycle in the different codes it became obvious that the cycle behavior is highly complex and the initial development status of each code for s$CO_2$ very different (see deliverable D1.2). The latter results in fundamental difficulties to implement the turbomachine, in particular. Therefore, it was decided to benchmark the codes on a circulation test with the piston pump only. The piping and instrumentation diagram for the benchmark is shown in Figure 1. The bold line shows the flow path for the benchmark (Valve TK02 S105 is closed). Thus, the $CO_2$ flows from the piston pump to the UHS, the CHX (no heat transfer in the CHX), the SEH and back to the inlet of the piston pump. During task 1.2, partners implemented the following components in their models visible in Figure 1 to do the benchmark (behavior of the s$CO_2$ loop in simulation for each code):

- Pipes
- Valves
- Piston pump
- Slave electrical heater (SEH)
- Ultimate heat sink (UHS)

For now, only the calibration of experimental data with CATHARE has been performed for the steady state. The simulation of the transient with CATHARE needs further work as multiple divergence issues occurred when varying the air temperature and heat exchange coefficient during the calculation. The next step is to model the entire s$CO_2$ loop. Significant work has to be performed on the turbomachinery modelling in CATHARE. The compressor and the turbine must be added in the loop. The modelling work will require the support of the code development team as the data setting is quite complex and the divergence issues are numerous for this recent application with supercritical $CO_2$.

The benchmark cycle has been modelled and simulated successfully with the help of ClaRaPlus MODELICA library within the Dymola environment. General agreement between simulation and measurement is observed, but also several shortcomings (e.g., valve modelling, UHS heat transfer coefficient at air side modelling, air mass flow rate calculation) were identified. Elimination of these shortcomings and continuation in modelling of the other still missing components shall be part of the future CVR effort.

With ATHLET the benchmark cycle has also been modelled and simulated successfully. Similar to CATHARE, instability issues were observed, but most of them were solved except the transition to subcritical states close to the critical point. Due to the detailed modelling of the SEH and UHS, the results are in good agreement with the measurements. The remaining deviations might be related to the oscillations in the cycle or to special heat transfer effects close to the critical point. In the future, the modelling and validation efforts must be continued, especially to improve the recently developed turbomachinery and compact heat exchanger models.

By the validation of the simulations presented in deliverable D1.2, the implementation of supercritical $CO_2$ in the codes ATHLET, CATHARE and MODELICA moved a big step ahead. Therefore, the confidence level for designing and simulating the heat removal cycle for the nuclear power plant is gradually increased and the goals of deliverable D1.2 are attained.

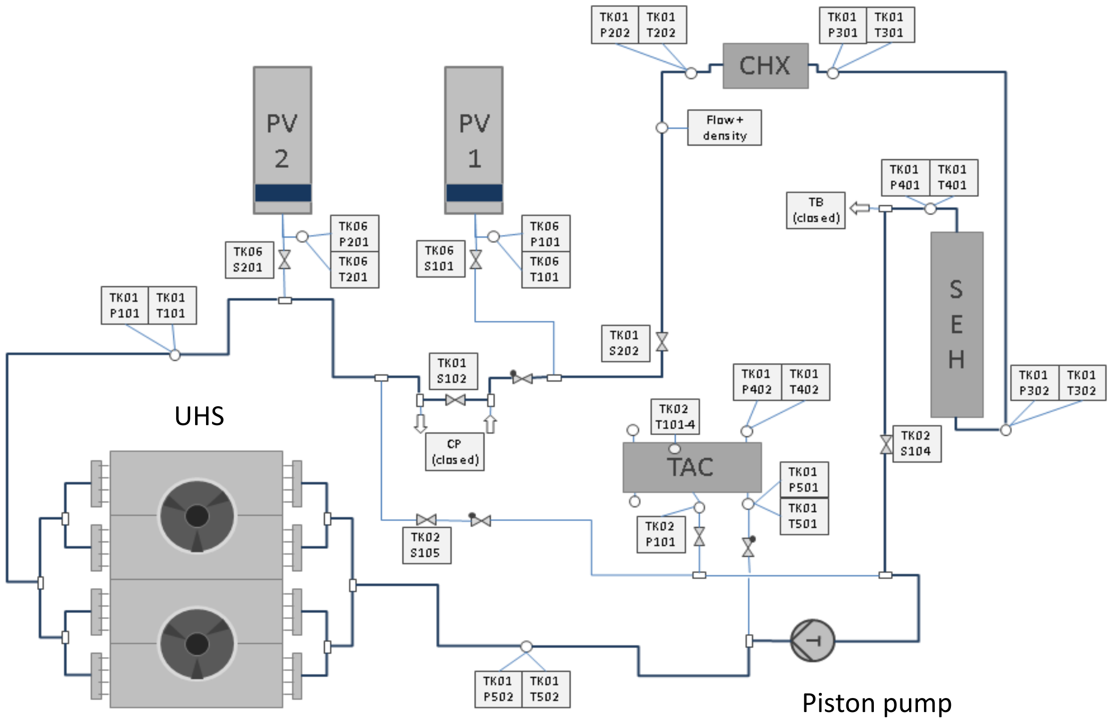



**Figure 1: Piping and instrumentation diagram for the benchmark test**

Preparations for implementation and validation of the other components were also done for:

- Turbomachine
- Compact heat exchanger (CHX, ATHLET only)

The validation of the latter will be done simultaneously with their implementation in the cycle in WP2.

Partner contributions:

CVR:

- Create model of HeRo cycle in MODELICA
- Validate model against measurements from HeRo cycle

- Preparation of D1.2 (MODELICA)

EDF:

- Create model of HeRo cycle in MODELICA
- Validate model against measurements from HeRo cycle
- Preparation of D1.2 (CATHARE)

GfS:

- Evaluation of measurement data
- Support in questions regarding HeRo cycle behavior for code validation
- Preparation of D1.2 (Cycle behavior and measurement corrections)

UDE:

- Support in questions regarding HeRo cycle behavior for code validation
- Preparation of D1.2 (HeRo cycle description)

USTUTT:

- Create model of HeRo cycle in ATHLET
- Validate model against measurements from HeRo cycle
- Preparation of D1.2 (ATHLET)

Workpackage 1 is finished.

### 3.2.2 WP2 Initial and boundary conditions of sCO2-4-NPP integrated in an NPP [Months: 3-18]

Leader: USTUTT

#### 3.2.2.1 Progress towards objectives

| WP Objectives | Achieved (Yes/No and comment) |
|---|---|
| Definition of accident scenarios | Yes, D2.1 submitted |
| Simulation of sCO2-4-NPP loop in a real NPP using scaled-up component models | No, in progress |
| Definition of technical specification of sCO2-4-NPP | No, in progress |

#### 3.2.2.2 Exploitable results

The definition and documentation (D2.1) of the accident scenarios for three different types of pressurized water reactors (EPR, VVER1000, KONVOI) provide important boundary conditions and guidance for the design and scaling of the plant-scale $sCO_2$ loops.

Further, the description of the accident progression (supported by simulation results) under the basic SBO scenarios (without $sCO_2$ loops), which develop into severe accidents with core melting in the time range of a few hours, is an important reference to assess and highlight the benefits of retrofitting a $sCO_2$ loop.

#### 3.2.2.3 Problems met and actions taken (if any)

| Deviation / Explanation | Impact on other WPs | Impact on resources | Impact on schedule |
|---|---|---|---|
| Simulation of sCO2-4-NPP loop using scaled up component models delayed due to<br>a) The COVID situation<br>b) The necessity to shift part of the work foreseen later in WP5 to WP2, specifically the thermodynamic design, in order to provide in time (i) the cornerstones for the design of components in WP4 and (ii) the basis and frame for developing and implementing scaled-up models in the codes in WP2. | Impact on WPs 4 and 5 was minimized by providing the thermodynamic design | No impact | MS3, MS4 and D2.2 rescheduled to 31 May 2021 |

#### 3.2.2.4 Details for each task

**Task 2.1 Definition of initial- and boundary conditions for an SBO accident (M3-M9) [EDF, GfS, KSG, JSI, USTUTT, CVR, NRI]**

The task started in September 2019 and ended with deliverable D2.1, which was delivered on time in February 2020.

In the task, the initial and boundary conditions of Station Blackout (SBO) scenarios for three important types of Pressurized Water Reactors (PWR) present in the European fleet of nuclear reactors, namely EPR, KONVOI and VVER 1000, were defined and documented. An important point was to discuss the accident scenarios not only from the perspective of code simulations, but also from an operator's point of view. The three reactor types under consideration naturally differ not only clearly by design, but also by accident management procedures. Nevertheless, the scenarios could be made convergent through the major common assumption that all electrically powered active systems are not available. Emphasis was on the clear specification of the assumptions and boundary conditions for SBO scenarios in the different reactors, including the steady state under normal operation conditions as initial condition for the accident transient.

In D2.1, a short presentation of the codes to be used for the reactor simulations (CATHARE, ATHLET, ATHLET/DYMOLA) was also provided, together with the plant model (nodalization, etc.). The accident sequences have been described in terms of sequence and timing of major events. In spite of the technical differences between the considered plant types, the sequences show common trends due to the fact that the residual power has to be removed through bleeding of the steam generators (SGs).

Partner contributions:

CVR:

- Scenario of a SBO for a VVER1000 PWR
- Description of ATHLET input model

- Simulation results of SBO accident
- Contribution to D2.1

EDF:

- Scenario of a SBO for a EPR PWR
- Description of CATHARE input model
- Preparation of D2.1

GfS:

- Scenario of a SBO for a Konvoi/pre-Konvoi PWR under an operator's view
- Contribution to D2.1

USTUTT:

- Scenario of a SBO for a EPR PWR
- Description of ATHLET input model
- Simulation results of SBO accident
- Contribution to D2.1

**Task 2.2 Simulation of sCO2-4-NPP loop in a real NPP using scaled-up component models (M10-M18) [USTUTT, EDF, CVR]**

An important first achievement in WP2 was the definition of the basic thermodynamic design of the $sCO_2$ heat removal system. Although this task was initially not foreseen within WP2 (only later in WP5), it turned out to be indispensable to provide in time (i) the cornerstones for the design of components in WP4 and (ii) the basis and frame for developing and implementing scaled-up models in the codes in WP2. The rationale behind the chosen design and its major parameters are as follows. The $sCO_2$ heat removal system is designed for the highest power input and the highest ambient temperature because this is the design point of the heat exchangers and the highest ambient temperature is the worst-case condition from a thermodynamic point of view. Some conditions in the $CO_2$ loop can be determined directly from the assumptions, which have been developed within this project and will be improved continuously. The remaining conditions in the $CO_2$ loop are determined through optimization, aiming for the highest excess power $\Delta P$, which is defined as the turbine power reduced by the power consumption of the compressor and the fan. The excess power is maximized because it will decrease with decreasing thermal power input and the system should be able to operate self-propelling as long as possible. The design procedure yields an excess power of 283 kW at a relatively high compressor inlet pressure of 126.3 bar. The high operating pressure is a consequence of the need of a high fluid density at the compressor inlet despite the high compressor inlet temperature of 55 °C, which results from the high ambient design temperature of 45 °C.

Based on the definition of the thermodynamic layout, simulations were carried out where the $sCO_2$ heat removal system was modelled in stand-alone mode in order to explore the performance in working range and possible limits. Figure 2 shows exemplarily for the CATHARE code a visualisation of the nodalisation used in the stand-alone simulation of the $sCO_2$ heat removal system. Here, the reactor loops are not simulated and replaced by a boundary condition representing the steam flow (coming from the steam generators) through the primary side of the CHX. The modelling of the scaled-up turbine and compressor has been designed, tested and implemented in CATHARE3. The modelling of CHX and UHS heat exchangers is still simplified for now but the development of accurate modelling is in progress. For the modelling with ATHLET and DYMOLA similar representations of the $sCO_2$ heat removal system are applied.

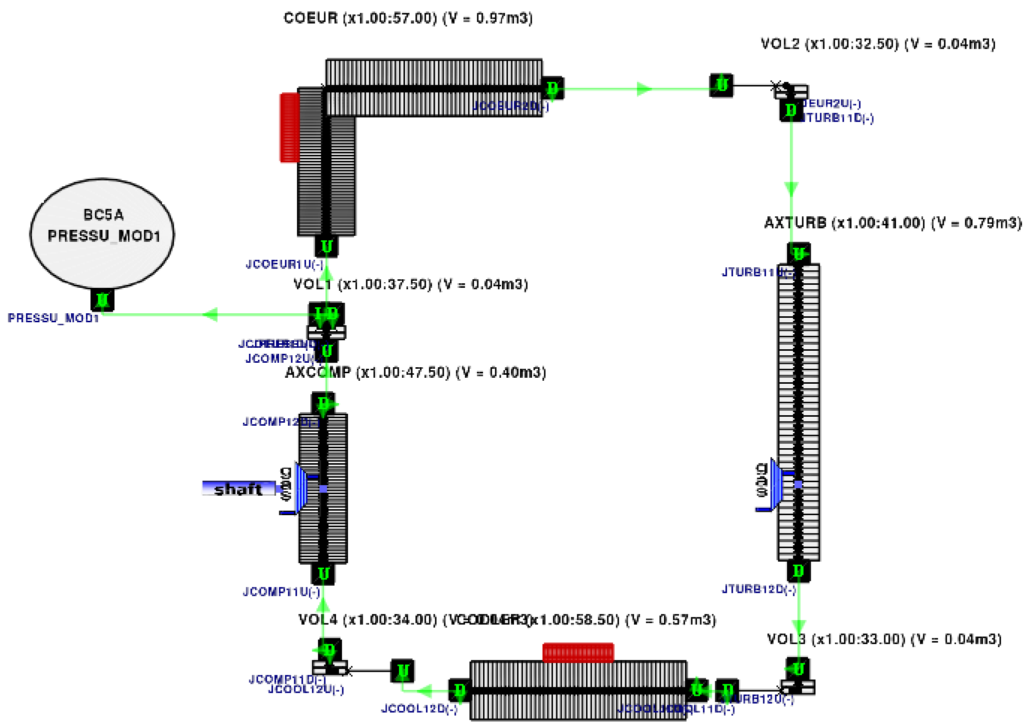



**Figure 2: Visualisation of the nodalisation used in stand-alone simulations of the $sCO_2$ system with CATHARE3**

The stand-alone simulations of the $sCO_2$ system indicated that the design compressor inlet temperature should be kept constant during operation by controlling the fan speed of the UHS. This control method can be used almost for the whole range of ambient temperatures. At very low ambient temperatures combined with low $CO_2$ mass flow rates, an UHS bypass may be required for the control of the compressor inlet temperature. Different heat fluxes from the steam-side can be handled by controlling the shaft speed of the turbomachinery. The shaft speed $n$ should be decreased with decreasing thermal power input $Q_{CHX}$ in order to keep the system self-propelling, as can be observed from Figure 3. The white regions indicate where the system is not able to operate. Therefore, the shaft speed is controlled in the reactor simulations to keep the turbine inlet temperature constant. This method successfully balances the heat removal by the $CO_2$ systems and the heat production by the decay heat.

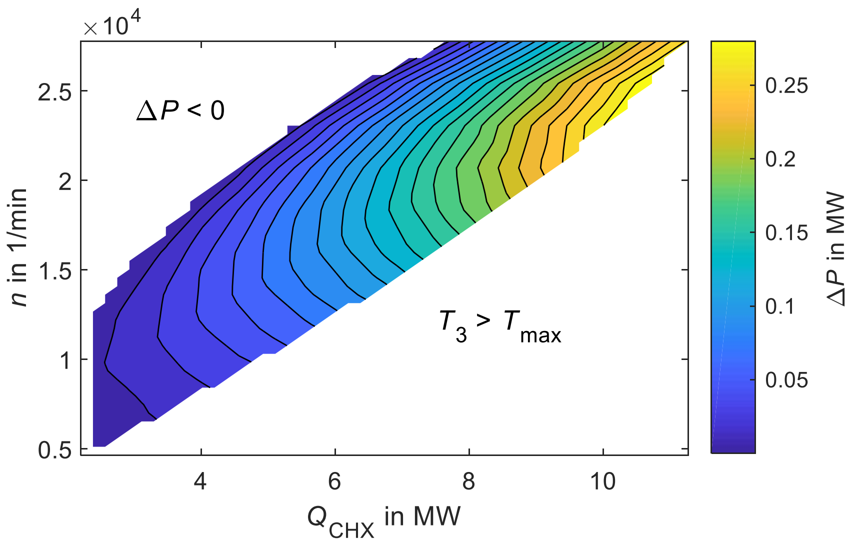



**Figure 3:** Excess power output of the cycle at $T_1 = 55$ °C and $T_{air,in} = 45$ °C with type 2 turbomachinery

Further working modes like reduced heat fluxes from the steam side and ambient air temperatures lower than 45° C were also tested, as well as alternative methods to control the $sCO_2$ system by means of the UHS fan speed or by means of partly bypassing the UHS or CHX on the $CO_2$ side, respectively.

After having verified by means of the stand-alone simulations of the $sCO_2$ system that the chosen thermodynamic design is feasible and provides a sufficiently large working range which can be adapted to the requirements of different reactors (by selection of a sufficient number of modules and adequate control strategy), the subsequent work concentrated on the preparation and execution of coupled simulations.

For this purpose, the calculations for reference station blackout (SB) scenarios (without $sCO_2$ heat removal system) for the three (generic) plant types under consideration (EPR, VVER-1000 and Konvoi) were consolidated and documented to serve as a basis for comparison and for evaluation of the benefits of the $sCO_2$ heat removal system. Concerning simulations for the EPR, the existing dataset of the reference SBO sequence (without $sCO_2$ system) was successfully translated from the CATHARE2 to the CATHARE3 version. This will allow to use the most up-to-date code version and models of CATHARE also for the coupled simulations. Figure 4 shows a visualisation of the reactor vessel of the EPR modelled in CATHARE 3. The ATHLET models used for the simulations of the VVER-1000 and Konvoi reactors were also reviewed and revised in order to comply with the code version to be used for the coupled simulations.

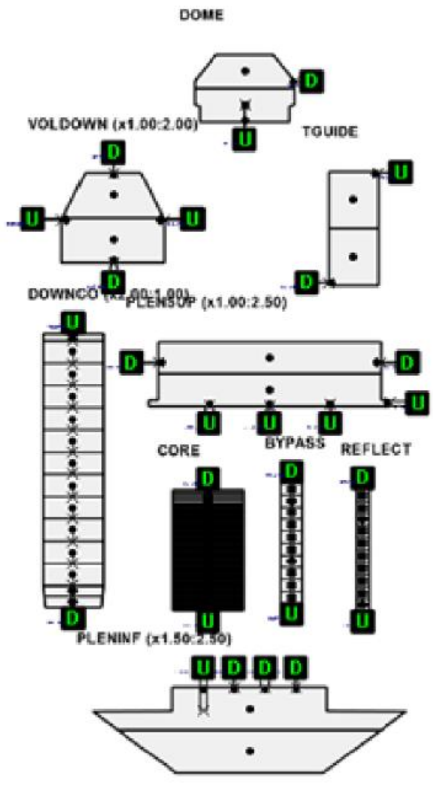



**Figure 4: Visualisation of the reactor vessel of the EPR modelled in CATHARE 3**

Further work comprised the preparation of the coupled simulations. Due to the different simulation tools used by the involved partners, this involved different steps and efforts.

Concerning simulations with scaled-up components of the sCO2-4-NPP loop attached to a VVER 1000 reactor, the overall model is based on coupling of DYMOLA ($sCO_2$ part) and ATHLET (steam/water part) models. The scaled-up model of the $sCO_2$ loop was developed and tested. In parallel, the ATHLET model of the VVER 1000 system supplemented with the CHX water/steam side was also prepared. The intermediate modelling system based on the TISC tool ensuring coupling between the two models was successfully tested on a simple case. In the next phase, the coupling of both models will be established, and simulations will be run.

Concerning simulations with scaled-up components of the sCO2-4-NPP loop attached to an EPR reactor, the $sCO_2$ system and the reactor components (vessel, primary and secondary loops, etc.) are fully integrated in the modelling within CATHARE3. Thus, no special numerical procedures have to be developed and coupled simulations are not an issue. Respective simulations are ongoing and will focus on investigating the general performance and suitable control strategies.

For the coupled simulations of the $sCO_2$ heat removal system attached to a Konvoi reactor with the ATHLET code, the reactor model has been extended to enable the separate and independent simulation of all four primary (and secondary) loops. This allows to capture correctly non-symmetrical effects resulting from switching off some of the $sCO_2$ units in order to adapt to the decreasing decay power. Extensive analyses have already been carried out, addressing several aspects of operation and control of the $sCO_2$ heat removal system.

In the reactor simulations two different decay heat curves resulting from a different operation history (low vs. high burnup and short vs. long operation period) were analysed. The first case, which considers high burnup (end of cycle) plus a margin due to uncertainties in order to provide a conservative estimate, is used to determine the number of $sCO_2$ units required to safely remove the decay power. The results of ATHLET simulations of a KONVOI PWR indicate that at least three units are required to cool the reactor over a long period of time. This can be observed from Figure 5 where the calculated temperatures $T_{prim}$ at the hot leg nozzles of the reactor pressure vessel are compared for different numbers of $sCO_2$ units. This temperature may be used as a first indicator to analyse if the cooling of the core can be guaranteed. For reference, also the case without $sCO_2$ system (0) is included. With less than three units, uncovering of the core and a temperature escalation leading into severe accident with core melting cannot be avoided. With three units, core melting can be prevented, however, the core is almost uncovered. Thus, at least four units of the heat removal system should be installed to be on the safe side.

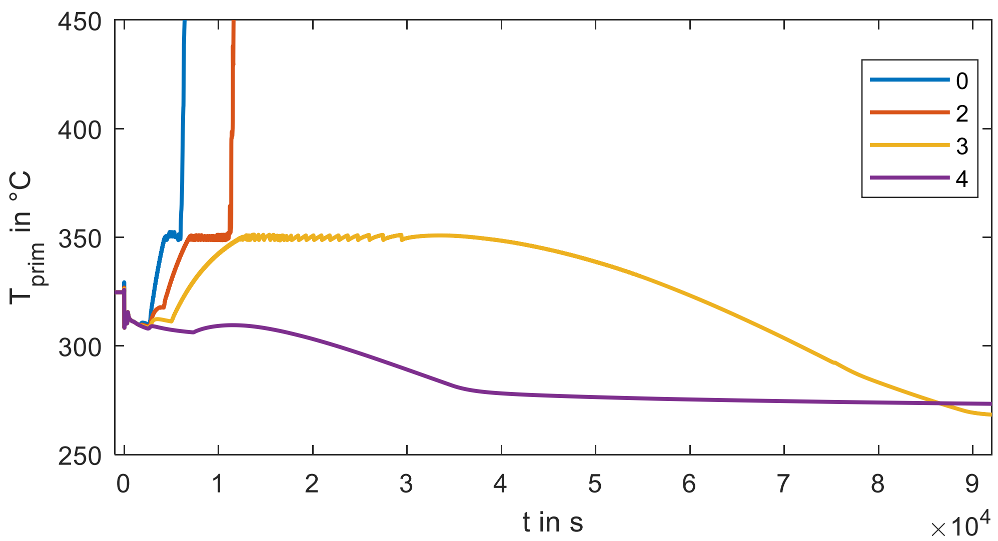



**Figure 5: Calculated temperatures $T_{prim}$ at the hot leg nozzles of the reactor pressure vessel after the start of the accident for different numbers of $sCO_2$-loops simulated with ATHLET for a KONVOI PWR**

In a second case with a lower burnup and an operation period of just one day before the accident, the decay heat curve is decreasing faster than in the first case and represents a conservatively low decay heat. This case is used to investigate the long-term operation of the heat removal system. Due to the faster decrease of the decay heat, this case is more challenging concerning controlling the $sCO_2$ system in a manner which guarantees long term operation with generation of excess electricity. The strategy with control of the shaft speed of the turbo-compressor and sequential shut-down of single units derived from the standalone simulations was applied and tested. Operability of the $sCO_2$ system with successful removal of decay power for more than 72 hours has been successfully demonstrated.

The deliverable D2.2 is under preparation and will document further results of the simulations for the different reactor types with the up-scaled $sCO_2$ system in more details.

**Partner contributions:**

EDF:

- Conversion from CATHARE2 to CATHARE3 version of existing dataset of reference SBO sequence (without $sCO_2$ system) in EPR done
- Simulations of reference SBO sequence (without $sCO_2$ system) in EPR carried out, evaluated and documented
- Modelling of scaled-up components of the $sCO_2$-system in CATAHRE3 in progress.
    - The modeling of the scaled-up turbine and compressor has been designed, tested and implemented in CATHARE3
    - The modeling of CHX and UHS heat exchangers is simplified for now, but the development of accurate modeling is in progress
    - Discussions with the team from Fives Cryo dedicated to the design of the heat exchangers have been performed
- Stand-alone simulations (NPP side replaced by simplified boundary conditions) of $sCO_2$ system with simplified CHX and UHS heat exchangers carried out and checked concerning functionality and plausibility
- The $sCO_2$ system and the SBO sequence in EPR are both modelled with CATHARE3, so coupled simulations are not an issue

NRI:

- Scaled – up model of the $sCO_2$ loop prepared in Dymola (Dymola scaled – up model)
- Dymola scaled-up model tested in stand-alone simulation mode (without ATHLET) with the help of simplified boundary conditions on the water side of the CHX
    - Working mode with the ambient air temperature +45°C successfully tested
    - Other working modes (low heat input and low ambient air temperature) tested
- Different control strategies (UHS fan speed, CHX bypassing on the $CO_2$ side, UHS bypassing on the $CO_2$ side) tested
- Initial realistic state for the VVER-1000 NPP tuned and SBO accident calculated (until the cladding temperature exceeds 1200 ° C (3.5 h)), analyzed and documented
- Coupling of Dymola and ATHLET successfully tested with the help of simple 2 pipes heat transfer model (coupling performed with the help of TISC software and Linux wrappers)
- Works in progress regarding the ATHLET VVER 1000 and Dymola scaled-up model coupling

USTUTT:

- Update of existing input decks for plant calculations to new ATHLET version
- Base case scenario (without $sCO_2$ loop): Revision of input deck and repetition of simulations with new ATHLET version
- Thermodynamic layout of plant scale loop finalized (also discussed with WP 4 & 5)

- Simulation of reference SBO sequence (without $sCO_2$ system) carried out, evaluated and documented
- Modelling of scaled-up components of the $sCO_2$-system designed, implemented and tested in ATHLET
- Stand-alone simulations (NPP side replaced by simplified boundary conditions) of $sCO_2$ system carried out and checked concerning functionality and plausibility
- Functionality of coupled simulations (using simplified/mock-up models, where appropriate) tested and verified
- Input deck for plant simulation of SBO sequence including $sCO_2$ system available, checked and executable
- Simulations of SBO scenario including $sCO_2$ system in progress (with and without control strategy)
- Two publications for the 4$^{th}$ European $sCO_2$ Conference (see chapter 3.2.8.2)

### 3.2.3 WP3 Licensing requirements "for relevant environment" [Months: 1-36]

Leader: JSI

#### 3.2.3.1 Progress towards objectives

| WP Objectives | Achieved (Yes/No and comment) |
|---|---|
| Setup of requirements for system components and functionality (Task 3.1) | Yes |
| Setup of requirements and criteria of modifications on the reference plant after integration of the heat recovery system (Task 3.2) | Yes |
| Design bases and safety analyses requirements for system and components (Task 3.3) | Yes |
| Setup of requirements for testing and operation (Task 3.4) | No, in progress |
| Independent review of the proposed sCO2-4-NPP system considering the international experience in licensing of similar systems (Task 3.5) | No, starts at M19 |

#### 3.2.3.2 Exploitable results

In the D3.1, the nuclear regulatory elements to be considered in the design of components and system for passive decay heat removal, called sCO2-4-NPP, have been identified. The design of components within the framework of nuclear licensing is an important step to enable the adoption of sCO2-4-NPP by nuclear authorities and nuclear power plant (NPP) operators. The detailed design of the sCO2-4-NPP components (turbomachinery, heat exchangers and auxiliary systems) will therefore be specified taking into account regulatory requirements provided in D3.1. Outputs of Task 3.1 are to be used in Task 4.2 for a conceptual design of a turbomachine, in Task 4.4 for proposing the best optimised design solutions for the heat sink exchanger and in Task 4.5 for performing a complete mechanical study in order to improve the mechanical integrity of the heat recovery exchanger.

Besides their use within the sCO2-4-NPP project, the results will also be exploited by nuclear power plant designers, operators and regulators, in particular, for performing safety assessments of passive safety systems.

In deliverable 3.2, NRI and EDF have identified the specific regulations in the Czech Republic and France for nuclear power plants. The objective of this identification was to lay the necessary foundations for understanding the regulations for safety systems, innovations, and modifications to nuclear power plants. Indeed, although nuclear safety is a common objective for all nuclear power plant operators, the regulations, and criteria to be met are set out at a national level. Deliverable 3.2 thus offers a comparison of the differences between the national regulations of the two main contributing partners in this task.

D3.2 covers a few main aspects of nuclear safety, namely the nuclear regulatory framework, the general approach to safety and the requirements for systems, structures and components in an NPP. Finally, the requirements for the plant modifications are discussed. All these topics are presented for both Czech Republic and France cases. Many regulations regarding nuclear safety are similar in these countries as they are based on the same international rules (IAEA, WENRA, ICRP, etc.). This fact makes it easier for the sCO2-4-NPP system designers to make it possible to implement the system in more European countries. D3.2, that will be independently reviewed in Task 3.5, will be used as input to WP7 for defining a regulatory roadmap to reach TRL9.

In deliverable D3.3, NRI and EDF used the results of D3.2 to identify the regulations and construction rules to be followed for the construction and qualification of the s$CO_2$ system and its components. Thus, criteria and rules relating to the materials of the components, parameters such as mechanical strength and the classification of the s$CO_2$ system components in terms of safety were defined. The steps for the qualification of the system were addressed. Regulatory changes for the modification of power plants in the Czech Republic and France if the s$CO_2$ system were to be integrated into existing power plants are also presented in the deliverable.

D3.3 provides detailed requirements for the design and operation of the s$CO_2$ system in Czech and French NPPs. The specific safety classification of the sCO2-4-NPP system in Czech and French legislation is presented. Requirements for the design basis of structures, systems and components (SSCs), such as functions to be performed, internal and external hazards, safety classification, reliability, environmental conditions for qualification monitoring and control, etc. are included. In general, it is much easier to clearly define the design basis for the SSCs in Czech Nuclear Power Plants than in French NPPs. Requirements for qualification (testing, qualification strategy, numerical qualification strategy and qualification quality requirements) of French NPPs and conformity assessment procedure for Czech NPPs have been also given. Finally, requirements for operation are specified (e.g. human factors, operating technical specifications, emergency plans). D3.3, that will be independently reviewed in Task 3.5, will also be used as input to WP7 for defining regulatory roadmap to reach TRL9.

#### 3.2.3.3 Problems met and actions taken (if any)

None to report.

#### 3.2.3.4 Details for each task

**Task 3.1 Identification of the regulatory elements to be considered in the design of components and system (M1-M9) [JSI]**

Task leader: JSI

The task started in September 2019 and ended with D3.1, which was delivered on time in May 2020. The starting point for identification of the nuclear regulatory elements was the setup of a hierarchy of regulatory requirements proposed to be used for the sCO2-4-NPP project. It consists of five levels of rules, where the first two levels are equivalent, consisting of European harmonized requirements for existing reactors and internationally established requirements for design of nuclear power plants.

Level I high level requirements of Western European Nuclear Regulators Association (WENRA) and the Level II requirements for nuclear power plant design of International Atomic Energy Agency (IAEA) are equivalent levels (highest requirements like country legislation), with the difference that WENRA presented harmonized European requirements for existing reactors and are therefore at the top (the report focuses on design requirements), while IAEA presented internationally established standards for design of nuclear power plants, but the scope is broader than that of WENRA and was therefore included as complementary.

Level III documents deal with process- oriented documents (quality assurance, regulatory guides on design, modification, etc.). For quality assurance, a few standards satisfying specific nuclear requirements may be used, including the IAEA management system. For design processes, the IAEA or U.S. Nuclear Regulatory Commission (NRC) again provide acceptable guidance, if national regulatory guides of a selected European country are not available. For nuclear civil structures, the design guide of the Swedish Radiation Safety Authority is given. Finally, plant modification process guides are also described.

Level IV presents documents, which are component-oriented for design and operation. For nuclear codes and standards for mechanical component design it was identified (based on literature) that although the French RCC-M and ASME Section III codes may contain different sets of requirements, they result in components of an equivalent level of quality. Similar conclusions could be drawn for the German KTA standard for the selected example. Nuclear codes and standards for civil structures and electrical equipment are also described.

Finally, Level V deals with the codes and standards used for conventional facilities. It is expected that primarily Level IV nuclear component-oriented documents will be used for the design of sCO2-4-NPP components.

The future key issue is that according to WENRA the current safety approach relies primarily on active safety systems. Therefore, achieving the same reliability as for active safety systems may challenge the existing safety strategy. In addition, the safety demonstration of reactor designs relying on passive safety features need to be developed to ensure safe operation of those designs in the future.

Partner contributions:

JSI: Preparation of D3.1

**Task 3.2 Requirements and criteria for reference plant modification on heat recovery system installation (M1-M14 [NRI, EDF]**

The task started in September2019 and ended with D3.2, which was delivered on time in October 2020. In this task, the requirements in Czech Republic and in France in order to approve nuclear power plant modification and installation of the heat recovery system have been described. The licensing requirements depend on the country regulations, design requirements and other factors that should be considered in the analysis. In parallel with T3.1 and T3.3, this task provides the set of requirements for the implementation of the system in the nuclear power plant in selected reactor types (VVER in Czech Republic and PWR in France).

The part regarding the Czech Republic case is based on the example of a VVER-1000 reactor and Temelín NPP. The French part uses the example of an EPR reactor. The nuclear regulatory framework in Czech Republic (see

Figure 6) and in France (see Figure 7) is described. The implementation of the international requirements has been presented as well as country specific legislation and hierarchy of the rules. The requirements in Czech Republic can be arranged into a 5-level "pyramid", which represents their hierarchy as shown in Figure 6. The first level contains the most important legal documents and the last one contains the normative and technical documentation.

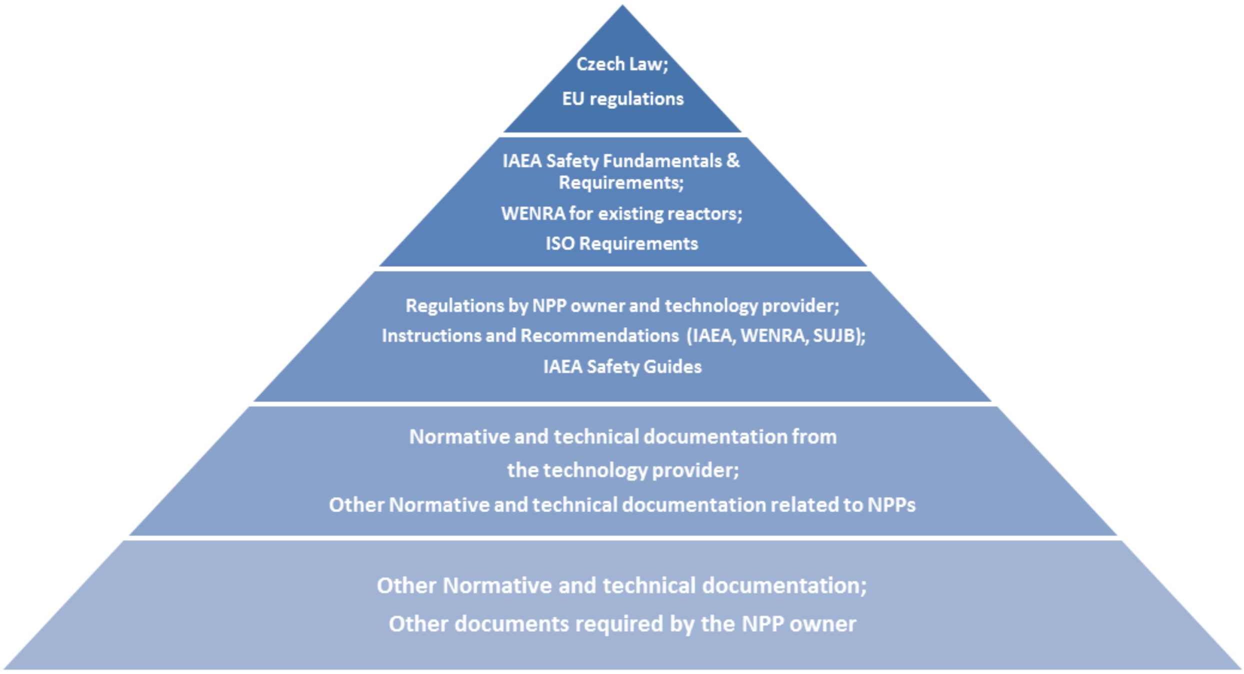



**Figure 6: Hierarchy of nuclear regulations in Czech Republic**

As shown in Figure 7, the French nuclear regulations and law are characterized by many sources, as in other countries with nuclear energy capacities. The original features of this legislation derive chiefly from international recommendations or regulations.

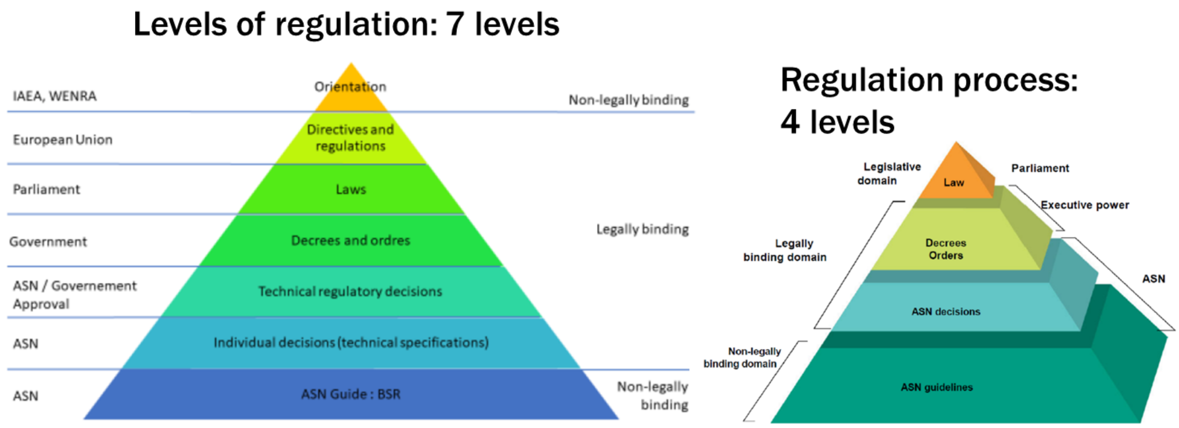



**Figure 7: Levels of regulation in the local nuclear field in France (left) and French nuclear regulation process (right)**

Then, the description of a general approach to nuclear safety was elaborated. The most important aspects have been considered, such as the Defense in Depth concept, classification of NPP states, safety analysis and acceptance criteria. The concepts and rules are similar in Czech and French legislation and some links between the two parts are given, where appropriate. Next, the requirements and classification of NPP systems, structures, and components (SSCs) have been identified, with special emphasis on the place of the $sCO_2$ system in the classification. Finally, the process of NPP modification in Czech Republic and in France has been given. All main steps and requirements regarding the process are presented briefly:

- Categorization of changes according to their significance
- Responsibilities
- Implementation of modifications
- Safety assessment (Description of the modifications, Impact study, Safety report, Risk management study)

It was concluded that it will be highly beneficial to install an alternative system for the emergency residual heat removal in Czech NPPs. However, it would require the regulatory body (SÚJB) approval along with the careful preparation of design documentation, safety assessment, personnel training, etc. All these steps should be consistent with the applicable national and international regulations currently in force. Concerning the requirements for licensing in France, the role of the operator of the power plant on which the $sCO_2$ system will be installed is crucial. Indeed, the French legislative texts are not very prescriptive, so it is up to the operator to design a modification application that meets the level expected by the Autorité de sûreté nucléaire (ASN) and Institut de radioprotection et de sûreté nucléaire (IRSN).

Partner contributions:

NRI:

- Introduction to nuclear industry in Czech Republic
- Nuclear regulatory framework in Czech Republic
- Safety general approach in Czech Republic
- Requirements for the SSC in Czech Republic
- Requirements for the plant modification in Czech Republic
- Preparation of D3.2

EDF:

- Introduction to nuclear industry in France
- Nuclear regulatory framework in France
- Safety general approach in France
- Requirements for the SSC in France
- Requirements for the plant modification in France
- Contribution to D3.2

**Task 3.3 Design bases and safety analyses for system and components (M6-M16) [NRI, EDF]**

The task started in February 2020 and ended with D3.3, which was delivered on time in December 2020. Within the framework of the sCO2-4-NPP project, the consortium has planned to establish a roadmap to inform and prepare the regulatory aspects related to the developed $sCO_2$ system. For this purpose, a multi-stage process has been initiated. In D3.3 the regulatory requirements for the development of the $sCO_2$ system, analyzing the expectations from the design phase to the operation phase (including the expectations for qualification by the relevant authorities) are presented in detail, both for Czech and French Nuclear Power Plants (NPP).

The standards regarding the main functions of the sCO2-4-NPP system (decay heat removal and heat transfer to the ultimate heat sink) have been given based on the International Atomic Energy Agency (IAEA) documents. The RCC-M, AMSE and KTA standards have been also considered. After that, the specific safety classification of the sCO2-4-NPP system in Czech and French legislation has been presented.

The following requirements (according to the IAEA SSG-56) for the design basis of Systems, Structures and Components have been discussed (with overview and both Czech and French specific requirements):

- Functions to be performed by the system (without country specific requirements)
- Postulated initiating events that the system must cope with (without country specific requirements)
- Loads and load combinations the system is expected to withstand
- Protection against the effects of internal hazards
- Protection against the effects of external hazards
- Design limits and acceptance criteria applicable to the design of SSC
- Reliability
- Provisions against common cause failures within a system and between systems belonging to different levels of defense in depth (without country specific requirements)
- Safety classification
- Environmental conditions for qualification
- Monitoring and control capabilities
- Materials

It has been concluded that, in general, it is much easier to clearly define the design basis for the SSC in Czech Nuclear Power Plants (NPPs) than in French NPPs. Czech Republic is a smaller country with no seacoast and very similar meteorological conditions over the entire area. There are only two NPPs and one of them (Temelín NPP) was taken as the example for establishing the conditions for the $sCO_2$ system. On the other hand, France is a much bigger country with varied meteorological and seismic conditions and the largest number of nuclear reactors in Europe. Therefore, the postulated loads and hazards differ depending on which site is considered. In most cases, the legislation and appropriate documents were described in the deliverable instead of specific values and parameters.

The requirements for the qualification of the SSC have been given separately for Czech and French NPPs. It gives an idea about how to prove the system's conformity with the requirements listed (tests, safety analysis etc.).

Finally, some of the most important requirements regarding the operation have been presented both for Czech and French NPPs.

Partner contributions:

NRI:

- $sCO_2$ system safety classification in Czech Republic
- Requirements for design basis in Czech Republic
- Requirements for qualification in Czech Republic
- Requirements for operation in Czech Republic
- Preparation of D3.3

EDF:

- $sCO_2$ system safety classification in France
- Requirements for design basis in France
- Requirements for qualification in France
- Requirements for operation in France
- Contribution to D3.3

**Task 3.4 Requirements for testing and operation (M10-M20) [NRI, EDF, CVR]**

The task started in June 2020 and is planned to end with D3.4 in April 2021. The D3.1 provides review ofpressure vessel codes and standards (both nuclear and conventional). In such standards, the requirements for testing and performance are also set. For example, ASME Operations and maintenance code of nuclear power plants establishes the requirements for preservice and in-service testing and examination of certain components to assess their operational readiness in the light-water reactor power plants.

In order to guarantee an adequate level of reliability during reactor operation, the $sCO_2$ system shall be maintained under suitable conditions in order to be available and ready to operate correctly. This implies being able to determine the periodic tests, preventive maintenance operations (and decommissioning if necessary) to be set up for the $sCO_2$ system. In the D3.3, it has been identified that in the state of development of the system, it is difficult to determine the maintenance operations that will depend on the characteristics of the final equipment. However, it is possible to determine whether periodic testing or inspections will be required. High-level requirements have already been identified for Czech and French NPPs. The work is in progress.

Partner contributions:

NRI:

- Identification of requirements for testing in Czech Republic

EDF:

- Identification of document Operating Technical Specifications with general requirements to define the equipment required in operation and the test programs.
- Based on the results of D3.2, determination of which procedures related to the operation and periodic testing of the plant would be impacted by the installation of the $sCO_2$ module. EDF is now in the process of determining, from the operating rules of the power plants, and from knowledge of the $sCO_2$ components and cycles, which could be the first rules to be applied.

**Task 3.5 Independent review of requirements (M19-M36) [JSI]**

N/A (Task 3.5 start is at M19 and depends on completion of D3.2, D3.3 and D3.4.)

### 3.2.4 WP4 Conceptual design of components (turbomachinery and heat exchangers) [Months: 1-36]

Leader: FIVES CRYO

#### 3.2.4.1 Progress towards objectives

| WP Objectives | Achieved (Yes/No and comment) |
|---|---|
| Scaling-up of component models from sCO2-HeRo to sCO2-4-NPP | No, in progress |
| Improvement of the sCO2-HeRo design regarding robustness | No, in progress |

| WP Objectives | Achieved (Yes/No and comment) |
|---|---|
| Conceptual design of turbomachinery for sCO2-4-NPP loop | No, in progress |
| Conceptual design of heat exchangers for MW-scale sCO2-4-NPP loop | Yes. Design of DUHS and CHX achieved. |
| Plan for qualification of heat exchangers and turbomachinery | No, in progress |

#### 3.2.4.2 Exploitable results

Validation of applicability of bearing technology in $sCO_2$ environment:

Task 4.1 designs and tests a turbomachine with magnetic bearings in $sCO_2$ and analyses the behaviour of hydrostatic gas bearings in $sCO_2$ environment. Hardly any experimental results on both bearing technologies are currently available. The task proves applicability of these technologies in $sCO_2$ environment so they may be applied in larger scale turbomachines.

#### 3.2.4.3 Problems met and actions taken (if any)

| Deviation / Explanation | Impact on other WPs | Impact on resources | Impact on schedule |
|---|---|---|---|
| Delays due to closure of mechanical workshops and delay in procurement of parts caused by Covid-19 situation | None expected | Three additional personnel months are required due to shift of deliverable D4.1 | Delays on turbomachinery manufacturing and gas bearing tests require shift of D4.1 by 3 months to M21 and D4.2 by 2 months to M22 |
| Material test on gas bearing material and preparation for gas bearing tests in SCARLETT facility (USTUTT) | No | USTUTT is carrying out experiments in WP4 (not foreseen) | No |

#### 3.2.4.4 Details for each task

**Task 4.1 Validation of the design procedures by means of testing an improved sCO2-HeRo-scale turbomachine with technology, which correlates to those of the sCO2-4-NPP technology (M1-M18) [UDE, NP TEC, GfS, KSG]**

The task started in September 2019 and is expected to end with D4.1 in May 2021, a three-month delay. The goal of task 4.1 is the design and testing of an improved turbomachine (compared to the one tested in WP1) for the sCO2-HeRo cycle to validate bearing technology as an input for task 4.2.

The status of task 4.1 is as follows:

- Design of magnetic bearings and turbomachine is finished.
- Manufacturing of turbomachine was completed in January 2021.
- Procurement of additional parts was completed in January 2021.
- Assembly of turbomachine with magnetic bearings was completed in January 2021.
- Commissioning of turbomachine with magnetic bearings started in January 2021 and is planned to be completed by end of February 2021.
- Possibilities for gas bearing tests have been checked with owners of $sCO_2$ loops (CVR, KSG and USTUTT). Tests will be carried out in April 2021 at the SCARLETT facility at USTUTT. Pre-tests on gas bearing material for compatibility with $sCO_2$ have been carried out in November 2020.

The turbomachine is an enhanced version of the one from the sCO2-HeRo project. The improvement is basically related to the exchange of bearings from ball bearings to magnetic bearings (subcontracted to MECOS AG). This allows to discard the piston pump in the cycle whose main task is the reduction of pressure in the central housing of the turbomachine indicated in Figure 8**Error! Reference source not found.**. This is required because lubricants in the used ball bearings are dissolved by $sCO_2$. Furthermore, the leakage over the seal on the hub of the compressor and turbine impeller is reduced by the higher backpressure of the seal. Figure 8**Error! Reference source not found.** further shows the compressor, generator, and turbine from left to right. The axial magnetic bearing consists of a disc (brown) on the rotor and two electromagnets (yellow & light grey). The radial bearings on both sides include the sleeves (brown) on the rotor, the electromagnets (orange), emergency ball bearings (without lubrication, blue) and sensor rings (light grey) with position sensors for the shaft.

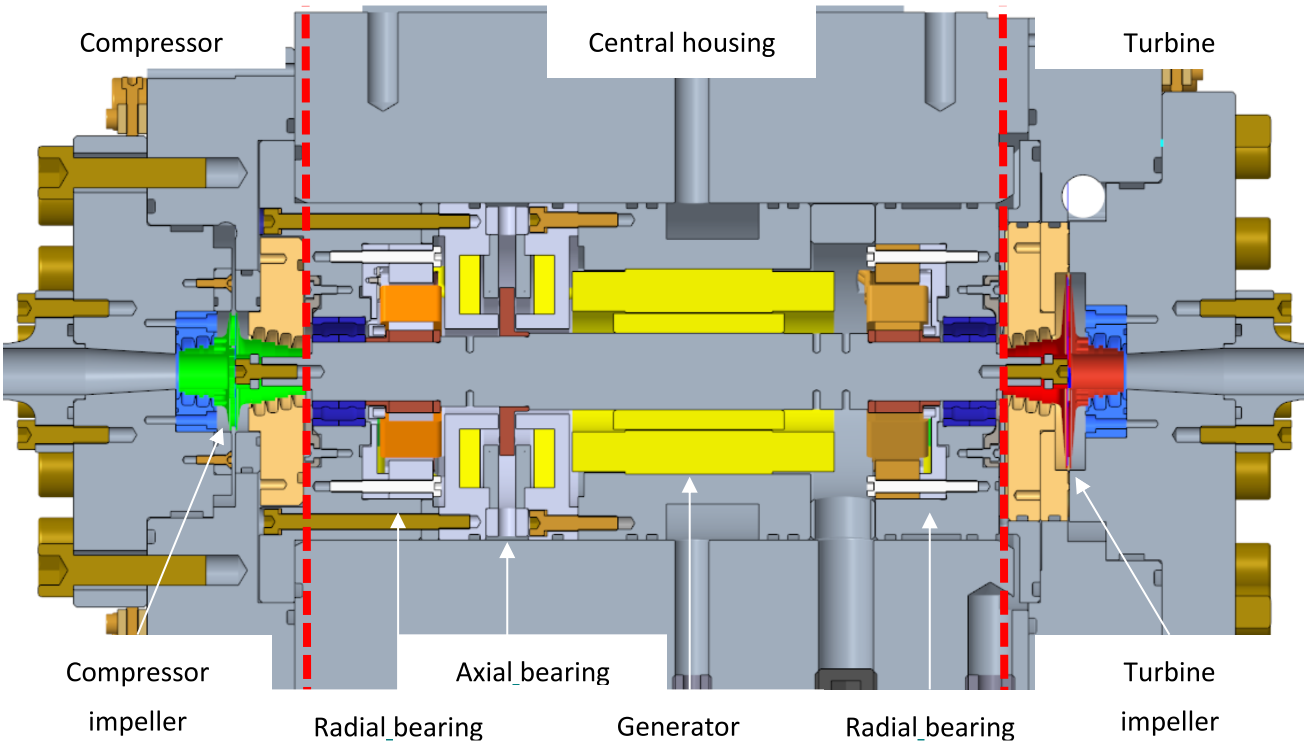



**Figure 8: Cross section of turbomachine design for task 4.1**

These parts may also be found on the right side of Figure 9. The latter shows two 3D-printed models of turbomachines at 1-to-1 scale, which are also used for dissemination. The left-hand side of Figure 9 presents the turbomachine employed for tests in WP1 and the right hand side shows the improved turbomachine with magnetic bearings. While the alternator (yellow) and the aerodynamic design of compressor (blue), turbine (red) and related stator parts such as the seals (green) remained unchanged, the bearings were exchanged for magnetic ones with the axial bearing (orange) and the radial bearings consisting of the bearing itself (beige) and the sensors (white) together with the safety bearings (metallic). Other features, such as several in- and outlets to the central housing, are not visible in Figure 8**Error! Reference source not found.** or Figure 9. They allow the balancing of axial thrust and conditioning of $sCO_2$ in the cavities by adding $sCO_2$ from the compressor outlet or extracting it from central housing. This allows varying the operational parameters of the magnetic bearings. Hence, it helps to gain a fundamental understanding of the operation of magnetic bearings in $sCO_2$. The rotordynamics can be assessed experimentally by the possibility to control the $sCO_2$ flow in the casing together with measurements of pressures and temperatures. This knowledge will help to validate the rotordynamic models and to develop the $sCO_2$ technology further. Still, the current lack of knowledge poses a risk for operation of the turbomachine with magnetic bearings. Therefore, the mitigation of testing a second bearing option with $sCO_2$ (gas bearings) is employed.

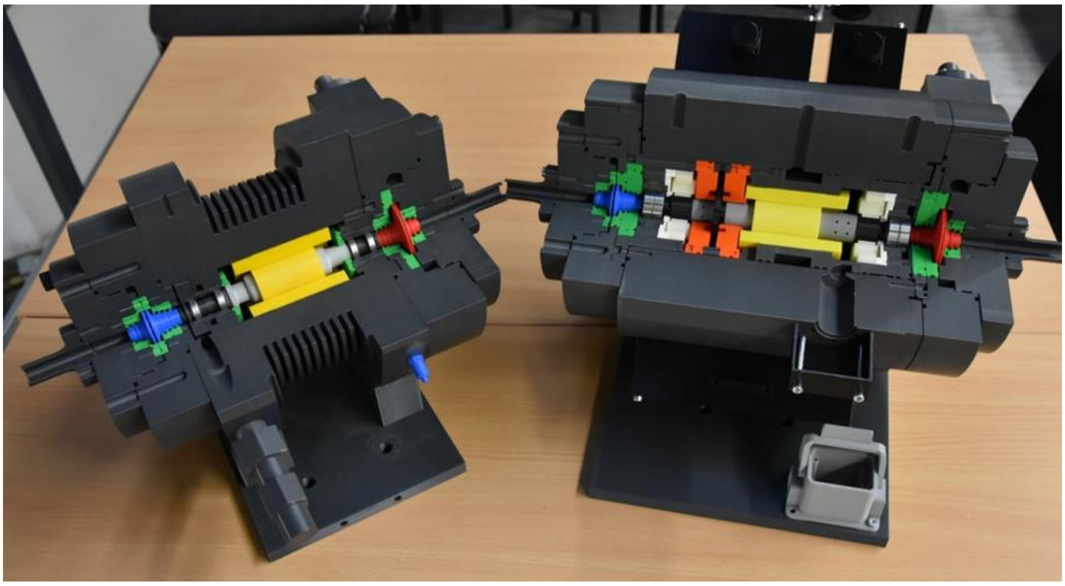


**Figure 9: 3D-printed 1-to-1 scale models of turbomachines developed in the sCO2-HeRo project (left) and its improved version from the sCO2-4-NPP project (right) for laboratory scale experiments**

The following figures give an impression of the work done in manufacturing, assembly and pre-test. Figure 10 presents the completely assembled machine before commissioning. The foreground presents the piping with its valves and sensors to control $sCO_2$ flow in the central housing. The machine itself is connected to the magnetic bearing controller with five cables for power supply and sensor signals. Figure 11 gives an insight showing a selection of parts. Most of these were manufactured in the workshop at University Duisburg-Essen, which was totally closed from March to May 2020 and half open since November 2020 causing a considerable delay in manufacturing, which requires rescheduling D4.1 by 3 months to M21. Figure 12 presents some of the pre-tests to validate the design and guarantee safety of the turbomachine. The pre-tests on design are crucial to validate calculation of eigenfrequencies (top left) which is very important input to rotordynamic calculations and to ensure tolerances of narrow radial clearances of less than 0.1 mm at emergency bearings are met. The commissioning is separated in several steps with the bottom right picture in Figure 12 presenting the first in air environment. In the first week of February, the turbomachine reached design speed of 50,000 rpm with size of the orbit of rotation being less than 10 µm. This proved superior balancing of the rotor and, in general, operability of the turbomachine in a known environment. The turbomachine will now be integrated in the sCO2-HeRo cycle at GfS, Essen and commissioning will continue in the $sCO_2$ environment, which is planned for end of February 2021.

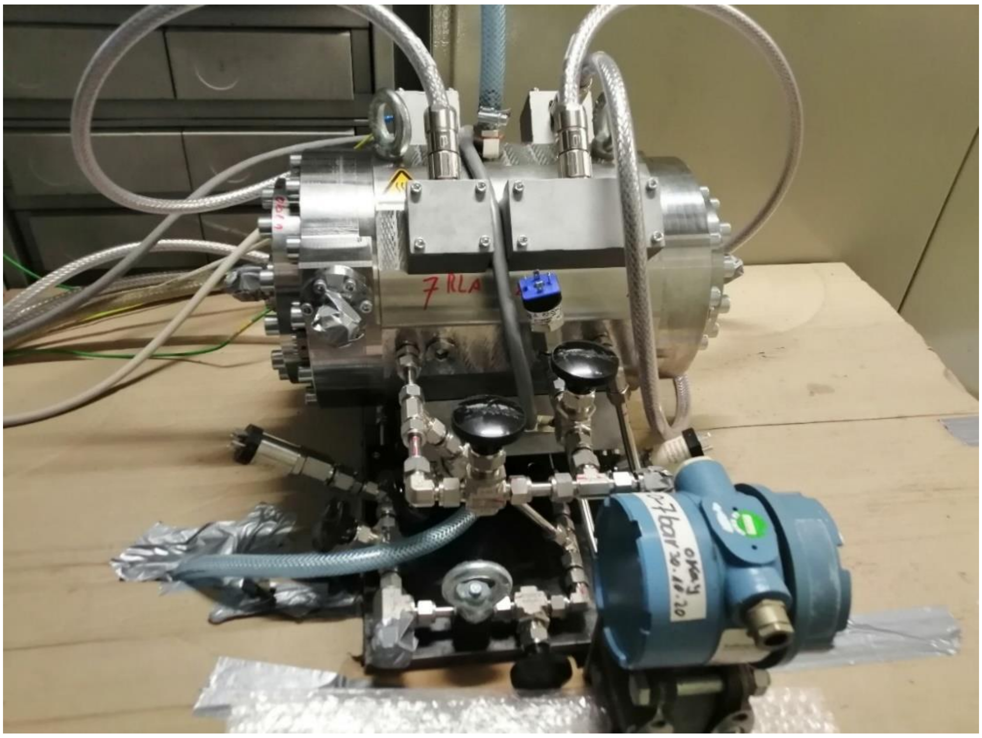


**Figure 10: Assembled turbomachine**

**Figure 11: Parts of the turbomachine – rotor with assembled impellers and generator without bearing parts (top), Labyrinth seals (middle), test assembly of internal stator parts (bottom left), assembled radial bearing (bottom right)**

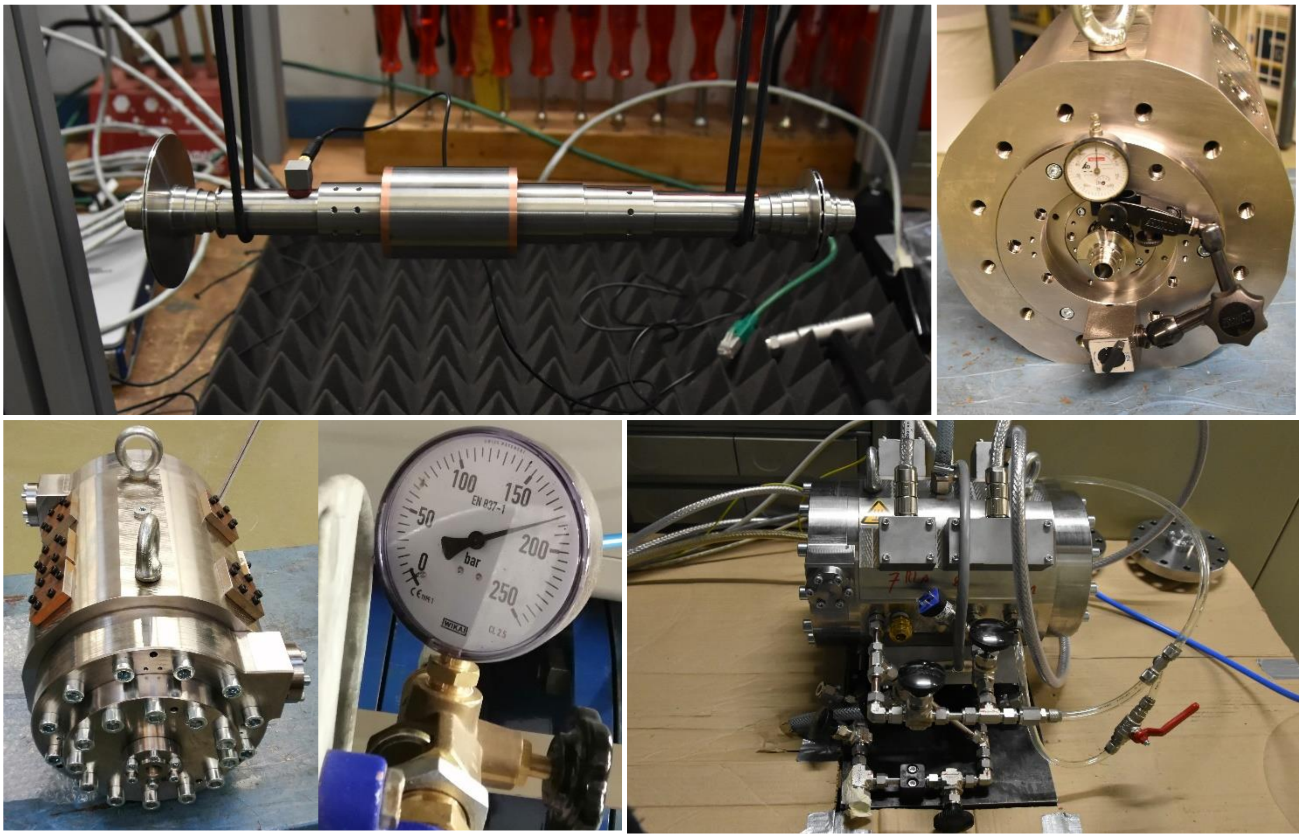



**Figure 12: Test on turbomachine design and safety with validation of eigenfrequencies (top left), concentricity test (top right), pressure test at 180 bar (bottom left) and commissioning in air environment (bottom right)**

**Gas bearings (mitigation):** No turbomachine has ever been operated with bearings in a $sCO_2$ environment. Therefore, as a mitigation, design and testing of hydrostatic gas bearings was subcontracted to TU Kaiserslautern. The bearings are designed by an in-house code providing, amongst others, information on the pressure distribution in the gap between rotor and stator of the bearing shown in Figure 13 on the right. The design of the bearing and its test stand are finished. Test on the bearings with other fluids (air, nitrogen) have already been carried out as preparation for the test with $sCO_2$, showing promising results. Further material tests on gas bearing materials have been carried out proving the material to be compatible to $sCO_2$ under relevant thermodynamic conditions. Since the flow rate of $CO_2$ for the test is too large, the $CO_2$ for the test of the bearings cannot be supplied by a tank of $CO_2$ directly but has to be circulated in a test loop. Partner USTUTT provides its $sCO_2$ cycle (SCARLETT) to connect the gas bearing test rig and run the test. The test is scheduled for April 2021 due to delay in procurement of the dry gas seal of the test rig. Figure 13 shows samples of the bearing material on the left and an exemplary graph with pressure distribution in the gap between stator and rotor of the gas bearing on the right.

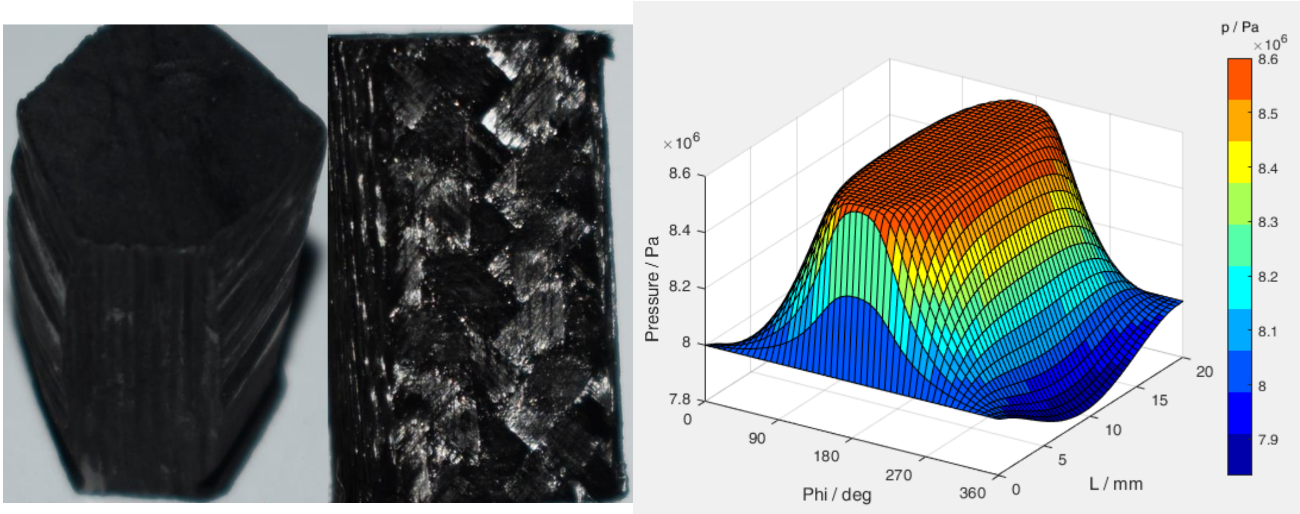



**Figure 13: Gas bearing material test samples of graphite and fibre material (left) and an exemplary calculation of pressure distribution in gas bearing gap between rotor and stator (right)**

The next steps in task 4.1 are:

- Integration and commissioning of turbomachine in the sCO2-HeRo cycle
- Testing of the turbomachine in the sCO2-HeRo cycle
- Gas bearing tests in SCARLETT facility at USTUTT

Partner contributions:

UDE:

- Design of improved turbomachine with magnetic bearings
  - Design calculation
  - CAD design
  - Subcontracting of magnetic bearing to MECOS AG
  - Subcontracting of hydrostatic gas bearings to TU Kaiserslautern
- Procurement of parts
- Manufacturing of parts
- Assembly of turbomachine
- Commissioning of turbomachine
- Planning for gas bearing tests
- Design & manufacturing of gas bearing test rig (TU-Kaiserslautern - Subcontractor)
- Manufacturing of magnetic bearings and commissioning of turbomachine with magnetic bearings (MECOS AG -Subcontractor)

NP TEC:

- Design review of turbomachine in personal meeting
- Calculation of rotordynamic coefficients for seals and generator
- Regular discussions on important design topics

GfS:

- Preparation for tests in sCO2-HeRo cycle

- Modification of sCO2-HeRo cycle to accommodate turbomachine with magnetic bearings
- Commissioning of turbomachine in the sCO2-HeRo cycle

KSG:

- Preparation for tests in sCO2-HeRo cycle
- Modification of sCO2-HeRo cycle to accommodate turbomachine with magnetic bearings
- Commissioning of turbomachine in the sCO2-HeRo cycle

USTUTT:

- Material test on gas bearing material
- Preparation for gas bearing tests in SCARLETT facility

**Task 4.2 Design of the sCO2-4-NPP turbomachine (M1-M36) [UDE, NP TEC]**

The objective of task 4.2 is to develop a conceptual design of turbomachine for the sCO2-4-NPP cycle.

The status of task 4.2 is shown as follows:

- Off-design tool for predicting performance maps of compressor and turbine is established, and is validated with the CFD results of sCO2-HeRo
- Aerodynamic design of the sCO2-4-NPP turbomachine is finished through interaction with sCO2-4-NPP cycle design (USTUTT)
- Performance maps of the sCO2-4-NPP turbomachine are generated and sent to partners (CVR, EDF and USTUTT) working in task 2.2
- Possible deviation of transformed performance maps is recognized in simulation codes (CATHARE and Modelica)
- CAD modelling of sCO2-4-NPP turbomachine has started
- Mechanical design of the sCO2-4-NPP turbomachine is now ongoing and will be reported in D4.2

<u>Highlighted results of task 4.2:</u>

1. *Design-strategy of the sCO2-4-NPP turbomachine*

   The aerodynamic design of the sCO2-4-NPP turbomachine is based on the thermodynamic conditions of the cycle provided by USTUTT. The thermodynamic conditions change over time while the decay heat decreases. There will be an initial operation point right after the start-up of the heat removal system (design point of the sCO2-4-NPP cycle), followed by a continuous decrease of heat input, and a point at which one unit is shutdown. When one unit is shutdown the overall decay heat will be distributed to the remaining units, hence increasing the heat input per unit. This means that the mass flow rate or the rotational speed of the turbomachine will be reduced until a certain operation point is reached and one turbomachine unit will be shutdown subsequently.

   This is in contrast to most energy conversion cycles, where a single design point can be specified. Therefore, a new design procedure is invented. Instead of finding an optimum compressor for a single cycle operating point, the compressor is designed for a wide operation range. This is an iterative process and is conducted in close cooperation with USTUTT. Different design strategies are evaluated.

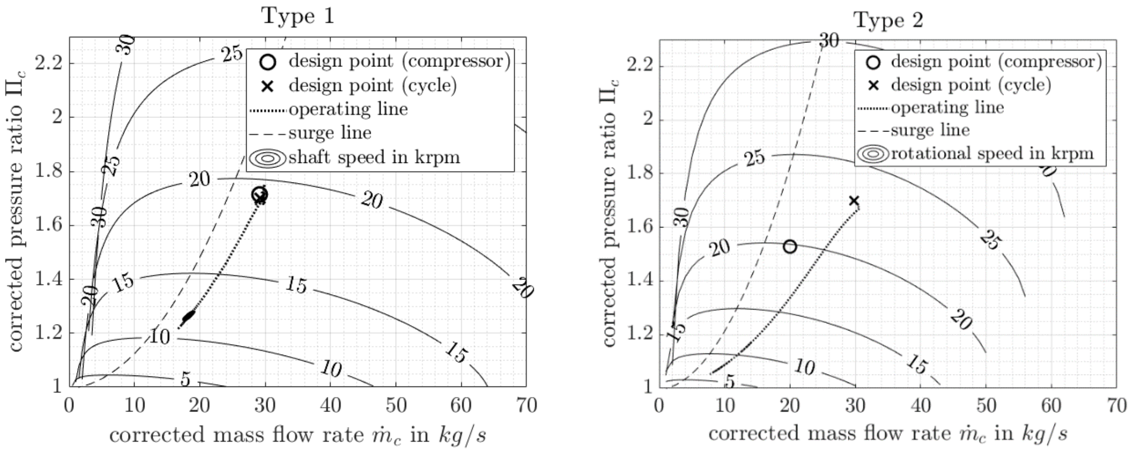



**Figure 14: Comparison of the cycle operations with different design strategies**

These can be better illustrated by Figure 14 which shows a comparison of performance maps of two types of compressor resulting from different design strategies including their operating lines (dotted lines). Type 1 is designed by keeping the design point of the compressor (o) equal to that of the cycle (x). Type 2 is designed by keeping the design point of the compressor (o) between that of the cycle (x) and the surge line. Since the thermodynamic inlet conditions of the compressor are varying during the operation of the sCO2-4-NPP cycle, the performance maps are normalized by corrected pressure ratio and corrected mass flow rate, which correspond to the reference conditions (design point of the cycle). The corrected parameters are calculated according to (Pham, et al., 2016) by:

$$\dot{m}_c = \left(\dot{m}\frac{\sqrt{n_s ZRT}}{n_s p}\right)_a \left(\frac{n_s p}{\sqrt{n_s ZRT}}\right)_{ref} = \left(\dot{m}\frac{1}{\rho c}\right)_a (\rho c)_{ref}, \quad (1)$$

$$\Pi_c = \left[\frac{n_{s,ref}-1}{n_{s,a}-1}\left(\Pi_a^{\frac{n_{s,a}-1}{n_{s,a}}} - 1\right) + 1\right]^{\frac{n_{s,ref}}{n_{s,ref}-1}}, \quad (2)$$

where $n_s$, $p$, $Z$, $R$, $T$, $\rho$ and $c$ are isentropic exponent, pressure, compressibility, specific gas constant, temperature, density and speed of sound respectively, while the subscripts $a$ and $ref$ represent the actual conditions and the reference conditions respectively.

Figure 14 points out that type 2 has a larger surge margin compared to type 1 and, hence, a safer operation against compressor failure. Additionally, type 2 is more robust against the changes regarding the cycle, e.g. higher pressure losses, which might require a higher pressure ratio of the compressor. Therefore, it is reasonable to apply type 2 for the sCO2-4-NPP compressor. In contrast to the design of the compressor, the design point of the turbine is considered as the same as the design point of the cycle, since the turbine does not have problems such as surging.

2. *Aerodynamic design of the sCO2-4-NPP turbomachine*

By considering the design conditions and the design strategy, the compressor is designed by a compressor design tool (Abd El Hussein, Hacks, Schuster, & Brillert, 2020), which is developed by UDE in the Horizon 2020 project "sCO2-Flex", while the turbine design concept is firstly similar to that of sCO2-HeRo. Finally, the aerodynamic design of the compressor and the turbine of the sCO2-4-NPP turbomachine are specified as follows:

**Table 1: Aerodynamic design parameters of sCO2-4-NPP compressor**

| Parameter | Symbol | Value | Unit |
|---|---|---|---|
| Diameter at impeller outlet | $d_2$ | 124 | mm |
| Blade height at impeller outlet | $b_2$ | 2.5 | mm |
| Blade angle at impeller outlet | $\beta_2$ | 95 | ° |
| Diameter at impeller inlet shroud | $d_{1,s}$ | 50.5 | mm |
| Diameter at impeller inlet hub | $d_{1,h}$ | 31 | mm |
| Blade angle at impeller inlet shroud | $\beta_{1,s}$ | 140.7 | ° |
| Blade angle at impeller inlet hub | $\beta_{1,h}$ | 140.3 | ° |
| Blade angle at impeller inlet RMS | $\beta_{1,rms}$ | 141.3 | ° |
| Impeller blade number | $z_{imp}$ | 16 | – |
| Diameter at diffuser outlet | $d_3$ | 258.2 | mm |
| Diffuser height | $b_3$ | 2.5 | mm |
| Diffuser blade number | $z_{diff}$ | 0 | – |

**Table 2: Aerodynamic design parameters of sCO2-4-NPP turbine**

| Parameter | Symbol | Value | Unit |
|---|---|---|---|
| Diameter at impeller inlet | $d_3$ | 161.5 | mm |
| Blade height at impeller inlet | $b_3$ | 4.8 | mm |
| Blade angle at impeller inlet | $\beta_3$ | 90 | ° |
| Diameter at impeller outlet | $d_4$ | 56.5 | mm |
| Blade height at impeller outlet | $b_4$ | 16.6 | mm |
| Blade angle at impeller outlet | $\beta_4$ | 133.9 | ° |
| Impeller blade number | $z_{imp}$ | 11 | – |
| Diameter at nozzle inlet | $d_1$ | 220 | mm |
| Blade height at nozzle inlet | $b_1$ | 4.8 | mm |
| Blade angle at nozzle inlet | $\alpha_1$ | 90 | ° |
| Blade angle at nozzle outlet | $\alpha_2$ | 20 | ° |
| Nozzle blade number | $z_{nozz}$ | 22 | – |

3. *Performance maps of the sCO2-4-NPP turbomachine*

In order to predict and plot the performance maps of the compressor and the turbine, UDE has developed an off-design tool based on mean-line analysis (Ren, Hacks, Schuster, & Brillert, 2021)[1]. This tool is validated with the CFD and experimental results of sCO2-HeRo. Given the thermodynamic conditions and the geometric parameters mentioned above, the off-design tool generates the performance maps of the compressor and the turbine. The efficiencies are conservatively calculated by multiplying a factor of 7/8, since some loss mechanisms are not included in the calculations.

[1] This publication has been approved by the General Assembly for public dissemination through vote # 13 and is named as "sCO2-4-NPP_vote13_UDE". This paper is accepted by the 4th European sCO2 Conference but is not published yet.

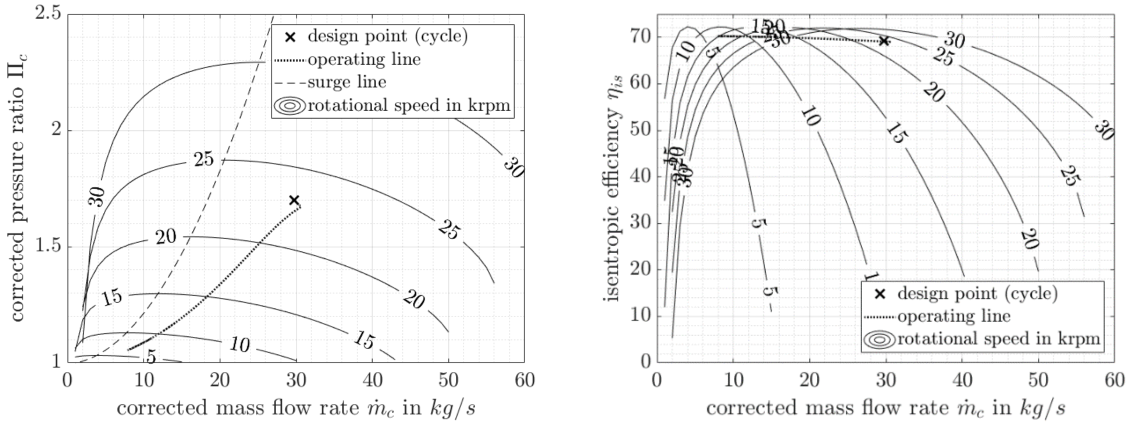



**Figure 15: Performance maps of the compressor with simulated operation in ATHLET**

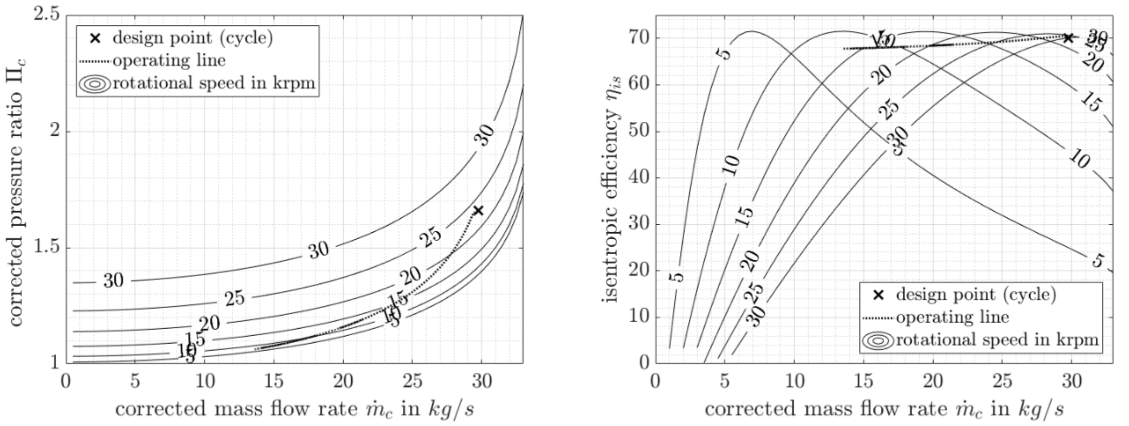



**Figure 16: Performance maps of the turbine with simulated operation in ATHLET**

Figure 15 and Figure 16 show the performance maps of the compressor and the turbine respectively. These performance maps are used by the partners in task 2.2 to conduct the simulations. In ATHLET, a simulation with 4 modules of the sCO2-4-NPP cycle is implemented. A performance of the compressor and the turbine of one of the modules is shown in Figure 15 and Figure 16 as well. The start point of the operation is assumed at the design point of the cycle (x), where an accident happens in the NPP. Subsequently, the rotational speed and the mass flow rate are reduced to match the declining decay heat. The end of the operation lines show the performance of this module at the 24$^{th}$ hour after the NPP accident.

The operation of the compressor and the turbine shows different ranges of corrected mass flow rate. The reason is that the pressure and temperature at compressor inlet and the temperature at turbine inlet are set as constant, while the pressure at turbine inlet decreases due to the declining pressure ratio of the compressor. This causes a deceasing density at the turbine inlet. When the actual mass flow rate of the compressor and the turbine is the same, the corrected mass flow rate of the turbine inlet will be larger than that of the compressor (according to eq.(1)), as the pressure ratio of the compressor becomes smaller.

The right diagrams in Figure 15 and Figure 16 exhibit that the efficiency of the turbomachine remains at a relatively high level during the simulation. The simulation results indicate that the design of the compressor and current operation strategy fulfil the requests in terms of the work package.

More details of the performance maps and the operation characteristics of the turbomachine will be reported in D4.2. If more realistic details are considered, the performance maps will be changed.

4. *Main geometry of the compressor and the turbine*

The main geometry of the compressor and the turbine are as follows. Figure 17 and Figure 18 illustrate the cross-sections of the compressor and the turbine respectively. Since the volute outlet of the compressor and the volute inlet of the turbine could vary, the performance maps of the turbomachine could be changed. They need to be updated later, once the volute design is fixed.

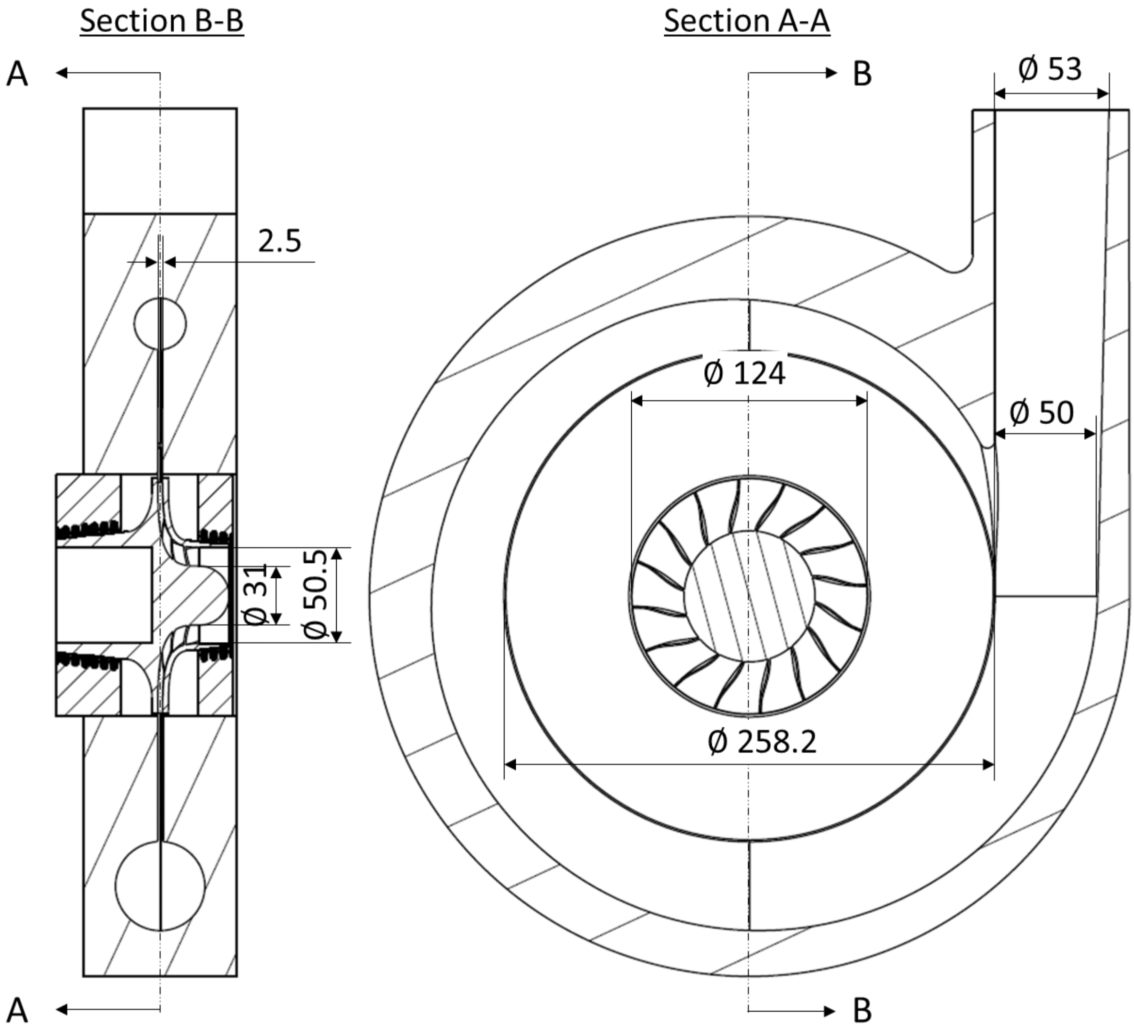



**Figure 17: Cross-section of the compressor (unit in mm)**

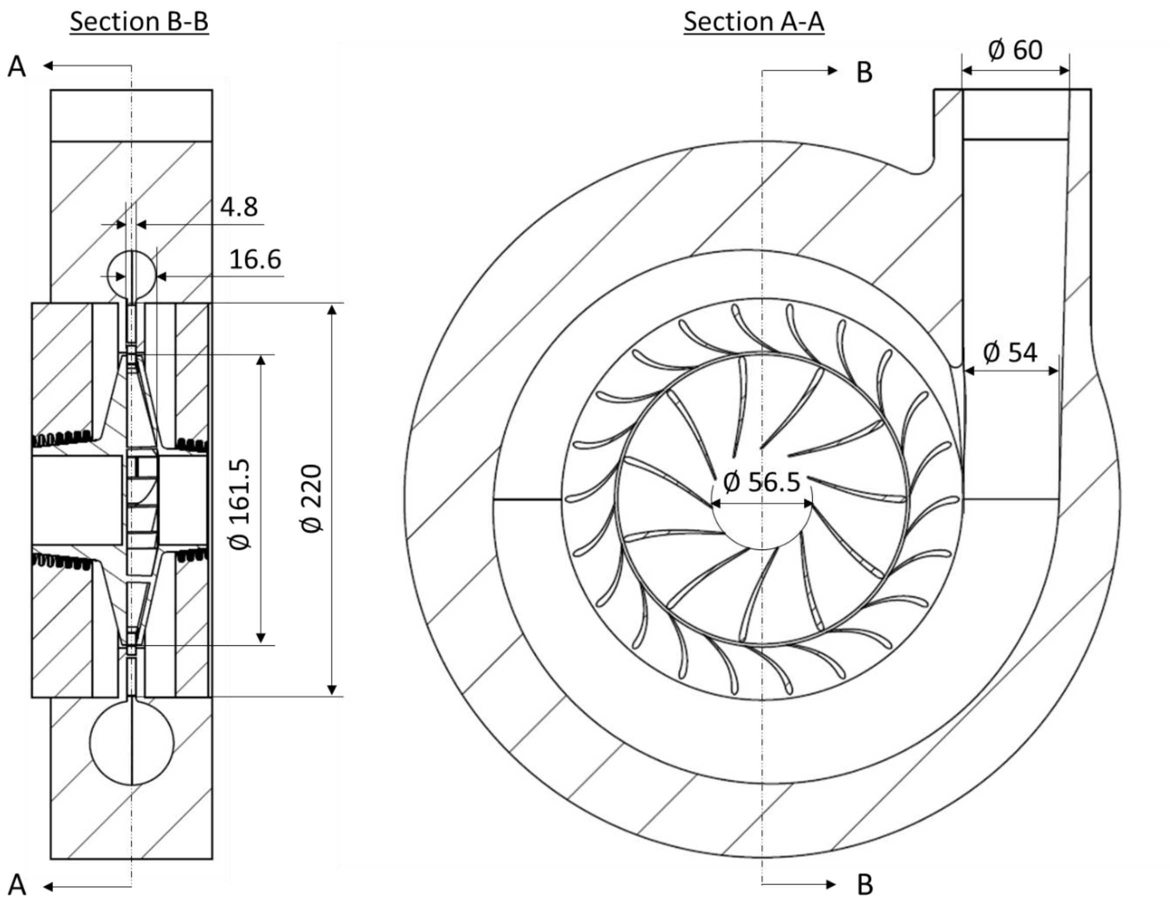



**Figure 18: Cross-section of the turbine (unit in mm)**

5. *Initial design of the shaft*

   Since for the Turbo-Alternator-Compressor (TAC) the compressor, the alternator and the turbine are located on one shaft (same concept as sCO2-HeRo), the shaft is firstly defined by considering the dimension of the alternator and the torque transferred by the turbine. Secondly, the shaft is also designed by considering the axial length of rotor components (rotor of the alternator, rotor of the axial bearing, rotor of the radial bearing, etc.), to reach good rotor dynamics. The initial design of the shaft is shown below:

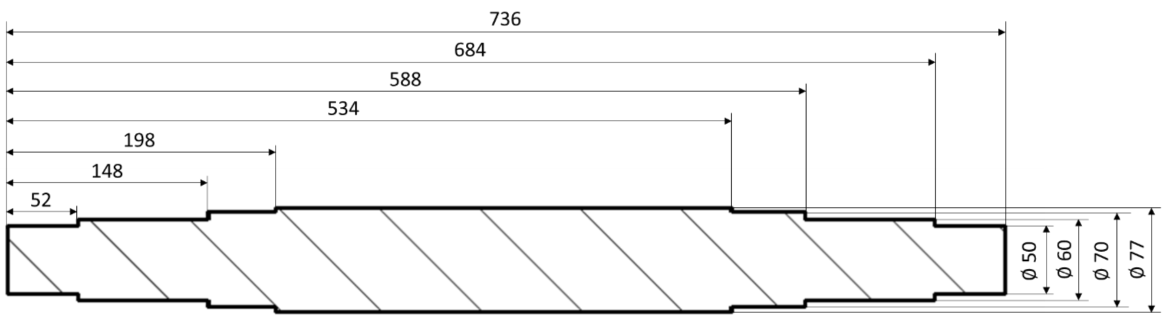



**Figure 19: Initial design of the shaft of the sCO2-4-NPP turbomachine**

Considering the impellers (designed), the bearings (roughly scaled-up), and the alternator rotor (from supplier), the rotor of the sCO2-4-NPP is shown in Figure 19. The design concept of the rotor follows the sCO2-HeRo rotor, in which an axial magnet bearing, two radial magnetic bearings and two sets of emergency bearings are incorporated.

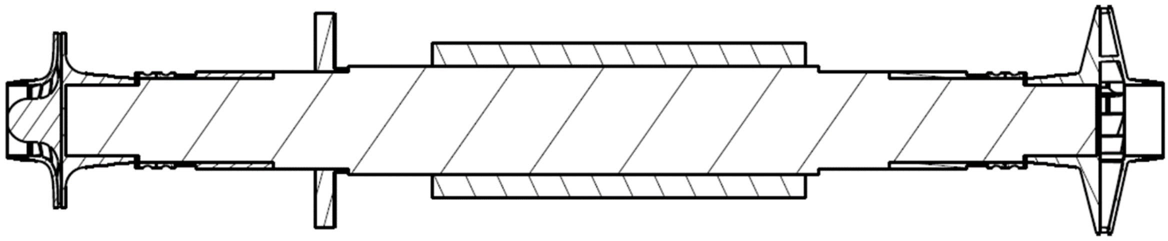


**Figure 20: Rotor of the sCO2-4-NPP turbomachine**

To implement an initial modal analysis of the rotor, the geometry in Figure 22 will be simplified to obtain a model as shown in Figure 21, which is better for a quick analysis to check the first critical speed of the rotor. The analysis will be reported in D4.2.

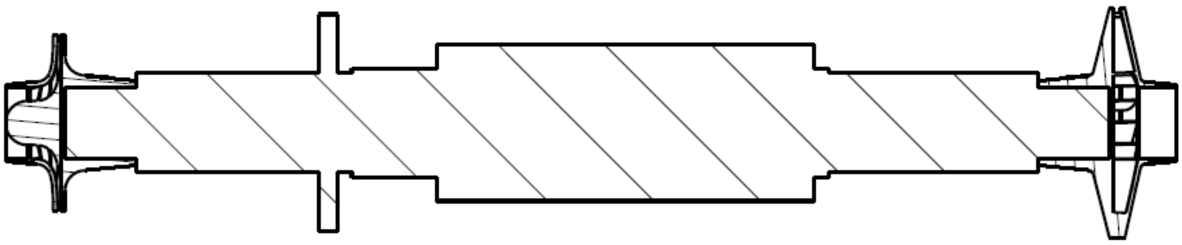


**Figure 21: Simple model of the sCO2-4-NPP rotor**

Overview of task 4.2 next steps:

- Final mechanical design of the rotor components (bearings, shaft)
- Mechanical design of the stators and casing of the sCO2-4-NPP turbomachine
- More realistic performance prediction for final dimensions of the sCO2-4-NPP turbomachine (CFD / 1D)
- Modal analysis, rotor dynamics, FEA

Overview of task 4.2 time plan:

Task 4.2 started in September 2019 and will end in M36. A review on turbomachine design, namely deliverable D4.2, was expected in M20 (April 2021). Since it needs some important inputs from D4.1 (particularly the results of the bearing tests), which is delayed and now rescheduled to M21 (May 2021), it is recommended to extend D4.2 for 2 months, and deliver in M22 (June 2021), to ensure the completeness of the review. The concept design of the turbomachine (D4.3) will be reported in M36.

Overview of partner contributions in task 4.2:

UDE:

- Aerodynamic design of the sCO2-4-NPP turbomachine
- Mechanical design of the components of the sCO2-4-NPP turbomachine
- Participation in iterative cycle design process
- Development of the off-design tool for performance prediction of the sCO2-4-NPP
- Recommendation of design concept from Task 4.1
- Generation and delivery of performance maps

NP TEC:

- Design review of turbomachine in personal meeting
- Regular discussions on important design topics

USTUTT:

- Supplying initial conditions as inputs for turbomachine design
- Supplying and checking simulation results of turbomachine performance within the sCO2-4-NPP cycle from ATHLET
- Supporting recognition of deviation in transforming performance maps in ATHLET

CVR:

- Supporting recognition of deviation in transforming performance maps in Modelica

EDF:

- Supporting recognition of deviation in transforming performance maps in CATHARE

Reference: Abd El Hussein, I., Hacks, A. J., Schuster, S., & Brillert, D. (2020). A Design Tool for Supercritical CO2 Radial Compressors Based on the Two-Zone Model. *Proceedings of ASME Turbo Expo 2020, Turbomachinery Technical Conference and Exposition.* London, England.

Pham, H.-S., Alpy, N., Ferrasse, J.-H., Boutin, O., Tothill, M., Quenaut, J., . . . Saez, M. (2016). An approach for establishing the performance maps of the sc-CO2 compressor: Development and qualification by means of CFD sumulations. *International Journal of Heat and Fluid Flow, Elsevier*, S. 61 (Part B), pp.379-394.

Ren, H., Hacks, A., Schuster, S., & Brillert, D. (2021). Mean-line Analysis for Supercritical CO2 Centrifugal Compressors by Using Enthalpy Loss Coefficients. *4th European supercritical CO2 Conference.* Prague, Czech.

**Task 4.3 Preliminary conceptual design of the heat exchangers (M1-M18) [FIVES, CVR, USTUTT]**

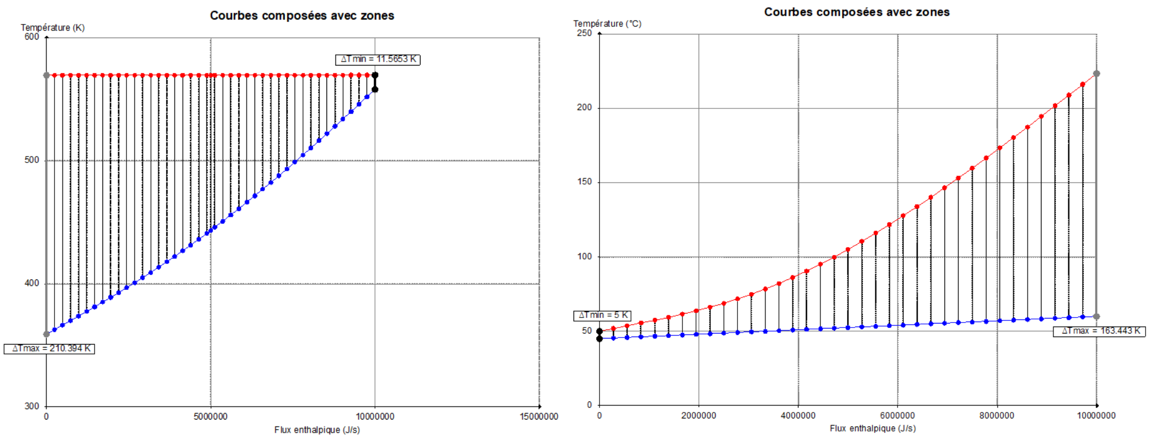
Fives Cryo received first design data from USTUTT. These data are summarized in the table below:

**Table 3: Design data for heat exchangers**

| | CHX | | DUHS | |
|---|---|---|---|---|
| | Steam | sCO2 | sCO2 | Air |
| P_in (MPa) | 8.18 | 25.61 | 12.90 | 0.10 |
| P_out (MPa) | 8.16 | 25.41 | 12.87 | 0.10 |
| **ΔP (mbar)** | **200** | **2000** | **250** | **0** |
| T_in (°C) | 296.56 | 89.42 | 228.44 | 45.00 |
| T_out (°C) | 296.39 | 286.56 | 55.00 | 130.00 |
| H_in (kJ/kg) | | 379.19 | 656.74 | 318.59 |
| H_out (kJ/kg) | | 700.24 | 347.80 | 404.49 |
| m (kg/s) | 6.99 | 6.99 | | 116.42 |
| Q (MW) | 10.00 | | 9.62 | |

Some of these data still need to be optimized, such as the pressure drop values: for example, it is unlikely to design a DUHS heat exchanger considering no pressure drop at all on air side.

Fives Cryo used these preliminary input data to calculate enthalpy curves for both DUHS and CHX as shown in Figure 22 below.




CHX : ΔT max = 210 °C DUHS : ΔT max = 163 °C (reduced to 100 °C)

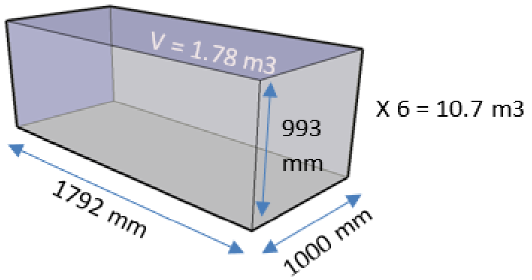
**Figure 22: Enthalpy curves for CHX and DUHS**

Since the actual appropriate material to manufacture brazed stainless steel plates and fins heat exchangers is 316 grade stainless steel, the maximum temperature difference should be reduced to 100 °C in order to meet with the material characteristics. This was possible for DUHS; USTUTT managed to modify and provide us with new input data meeting these requirements, but it is not the case for CHX.

A possible solution to this issue would be to rely on the results obtained in the sCO2-Flex project, where different potential materials for manufacturing heat exchangers were studied. We are still waiting for these results to evaluate the new designs.

A first design of DUHS was achieved. It is constituted of six heat exchanger cores of 1.78 $m^3$ each.

**Table 4: Summary of pressure losses in the heat exchangers**




Preliminary design of DUHS

GENERAL SUMMARY OF PRESSURE LOSSES
Number of heat exchangers : 6.0
Number of layers : 182.0
TOTAL volume (m3) : 10.7
For each heat exchanger :
Width (mm) : 1000.0
Brazed height (mm) : 992.9
Length (mm) : 1792.0
Individual volume (m3) : 1.780
VALUES UNIT : g/cm2

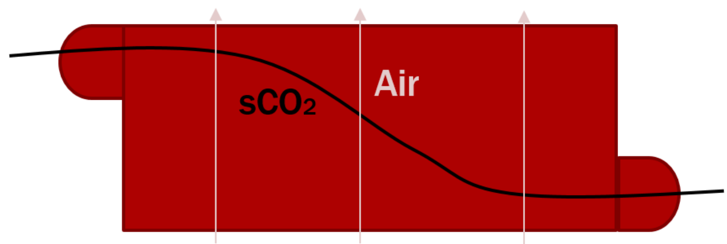
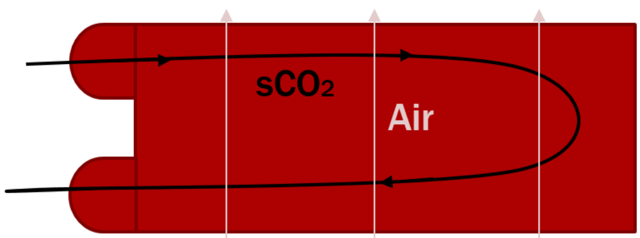
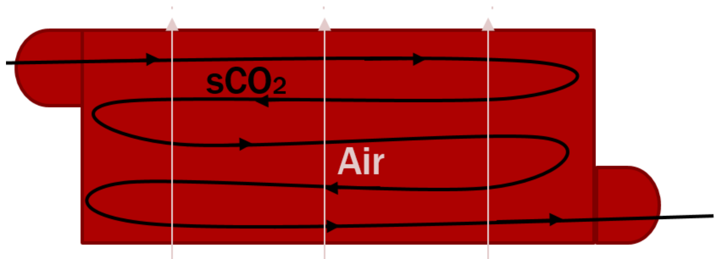
| CIRCUITS | HOT | COLD | DUMMY |
|---|---|---|---|
| DP Collectors/Nozzles | 3.95 | 34.29 | 0.00 |
| DP Nozzles/Headers | 3.53 | 22.33 | 0.00 |
| DP Headers/Distributors | 7.97 | 66.66 | 0.00 |
| DP Transfer zone | 2.06 | 235.18 | 0.00 |
| TOTAL DP | 17.5 | 358.5 | 0.0 |
| DP ALLOCATED | 255. | 0. | 0. |
| DP ALLOCATED / DP CALCULATED | 14.565 | 0.000 | 0.000 |

The table above summarizes simulated pressure losses in the heat exchangers. The full design outputs are available on the project intranet.

It appears that 10% of the total pressure losses are concentrated on the collectors/nozzles.

In order to improve this aspect, Fives Cryo suggests to resort to a "kettle" configuration. Three options are suggested in the table below.

**Table 5: Potential configurations for $sCO_2$ flow in heat exchanger**

| Configurations | Outline | |
|---|---|---|
| $sCO_2$ goes from one side of HX to the other |  | Airside: Total opening on the long sides of HX in « Kettle mode » |
| « Dual circulation » mode for sCO2 |  | |
| « Serpentine » mode for sCO2: High performance Vs high P |  | |

It might also be interesting to combine the kettle configuration with a "cooling tower system" to optimize air evacuation to the atmosphere upwards (see figure below).

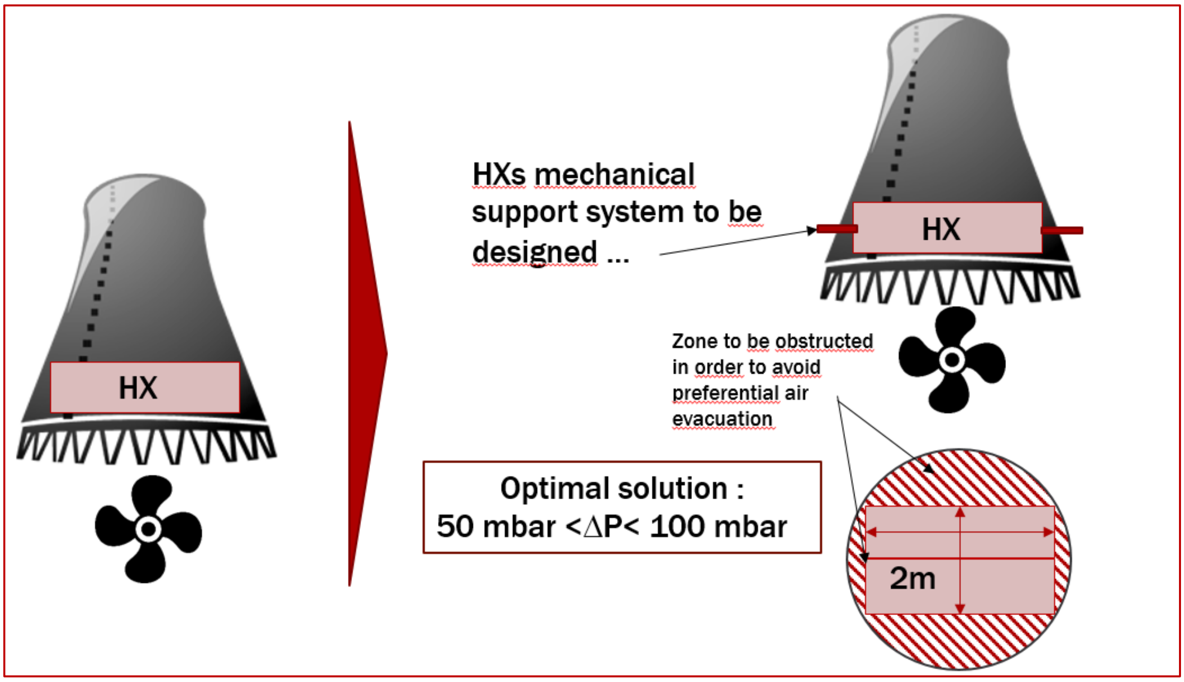



**Figure 23: HX cooling tower system**

Several mandatory clarifications are still needed to achieve the final design:

- Fans power, aspiration pressure and limits of the compressor need to be specified.
- It is interesting to see if we might consider a higher temperature for $sCO_2$ outlet of the DUHS. If this temperature could be set to a higher value, the outlet temperature from the compressor would be higher, which would reduce the DUHS heat exchangers number by approximately a third of the initial volume, and even possibly impact the CHX with a volume reduction.

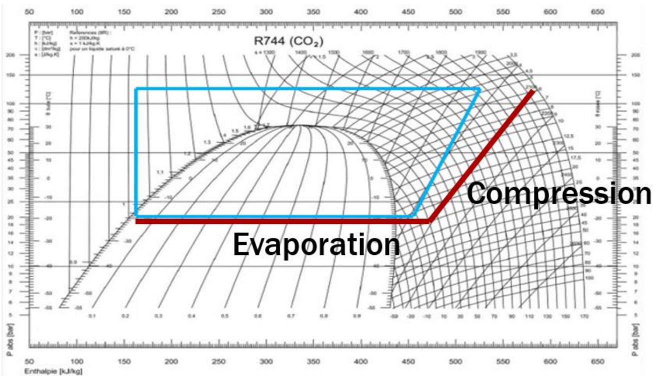



**Figure 24: CO² enthalpy diagram showing sCO2-4-NPP cycle (in blue) and the requirements to achieve heat exchangers design (in red)**

- The maximum temperature difference between fluids needs to be reduced for CHX in order to allow the design of this component.
- Fives Cryo needs to have more specifications about how CHX and DUHS will be solicited (intermittent or continuous operation, and the concerned circuit).

Partner contributions:

USTUTT:

- Input data for design of heat exchangers (partial)
- Regular discussions on important HX design topics

Fives:

- Design of the heat exchangers according to the provided input data (ongoing)
- Regular discussions on important HX design topics

After several discussions during WP4 meetings, the thermodynamic input data for heat exchangers design were adjusted according to heat exchangers manufacturing feasibility and the overall requirements for the other components of the cycle.

The table below summarizes the final data used for DUHS and CHX design:

For CHX, $CO_2$ inlet and outlet pressures were reduced respectively down to 21.42 MPa and 21.22 MPa, keeping the same pressure drops. $CO_2$ inlet temperature was also reduced to 80.84 °C, along with inlet enthalpy which was also slightly reduced to 372.14 kJ/kg. Outlet enthalpy was slightly increased to 708.30 kJ/kg. For steam side, inlet temperature was increased to 308 °C and outlet temperature was decreased to 150 °C, which helped to reduce efficiently the thermal gradient between inlet $CO_2$ and outlet steam (fluids circulate in counter-flow). The steam flow rate was reduced to 4.59 kg/s.

For DUHS, $CO_2$ inlet and outlet pressures were slightly modified to 12.70 MPa and 12.68 MPa respectively, reducing the pressure drop down to 200 mbar. Inlet temperature was increased to 243.19 °C along with an increase of the inlet enthalpy to 674.88 kJ/kg. The outlet enthalpy was slightly modified to 350.97 kJ/kg. For air side, inlet pressure was slightly increased to allow a consideration of minor pressure drops of 3 mbar instead of 0 mbar initially. The outlet temperature was decreased to 115.21 °C and outlet enthalpy slightly lowered to 389.50 kJ/kg. Air mass flow rate was increased to 135.87 kg/s. $CO_2$ mass flow rate in the cycle was increased to 29.74 kg/s.

**Table 6: Thermodynamic input data used for DUHS and CHX design**

| | CHX | | DUHS | |
|---|---|---|---|---|
| | Steam | sCO2 | sCO2 | Air |
| P_in (MPa) | 8.18 | 21.42 | 12.70 | 0.1003 |
| P_out (MPa) | 8.16 | 21.22 | 12.68 | 0.10 |
| **ΔP (mbar)** | **200** | **2000** | **200** | **3** |
| T_in (°C) | 308.00 | 80.84 | 243.19 | 45.00 |
| T_out (°C) | 150.00 | 286.57 | 55.00 | 115.21 |
| H_in (kJ/kg) | | 372.14 | 674.88 | 318.59 |
| H_out (kJ/kg) | | 708.30 | 350.97 | 389.50 |
| m (kg/s) | 4.59 | 29.74 | | 135.87 |
| Q (MW) | 10.00 | | 9.63 | |

***DUHS design:***

Thanks to the efforts made on the thermodynamic design input data, we were able to design the DUHS in 316 grade stainless steel, which is a more economical solution in comparison to nickel based alloys (well known for withstanding high thermal gradients).

The design data (table below) were considered as close as possible to the thermodynamic data for the overall cycle in the previous table.

**Table 7: DUHS design data**

| FLUID | | CO2 | AIR |
|---|---|---|---|
| TOTAL FLOWRATE | kg/s | 30.49 | 132.49 |
| OPERATING PRESSURE | MPa a | 11.92 | 0.1 |
| ALLOWABLE PRESSURE DROP | kPa | 25 | 0 |
| TEMPERATURE IN | °C | 238.66 | 45 |
| TEMPERATURE OUT | °C | 55 | 115.22 |
| SPECIFIED HEAT TRANSFERRED | MW | 9.419 | 9.419 |
| CORRECTED MTD (GLOBAL) | °C | 23.693 | |

The calculated output is shown in the table below. Calculated pressure drops are considered at nominal flow rate x1.

**Table 8: Calculated output**

| FLUID | | CO2 | AIR |
|---|---|---|---|
| CALCULATED PRESSURE DROP | kPa | 8 | 0 |
| DESIGN TEMPERATURE | °C | -30 °C / 300 °C | |
| DESIGN PRESSURE | MPa g | 23 | 1 |
| HYDRAULIC TEST PRESSURE | MPa g | 29.9 | 1.3 |

The design leads to 20 heat exchanger cores for each unit, each core has the following dimensions:

- Width: 2000 mm
- Height: 987 mm
- Length: 570 mm

For a total number of 120 cores for all six units. Each core is a counter-flow heat exchanger with a total number of layers of 196 per core.

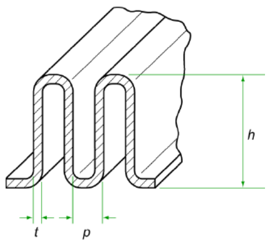
The layers are distributed as follows:

- 64 layers for CO2
- 128 layers for air

- 4 “dummy” layers, which are inactive layers, 2 on bottom stacking and 2 on top, to guarantee the mechanical integrity of the heat exchanger cores.

The material for DUHS core construction is 316 Ti stainless steel (UNS number S31635 / W. number 1.4571). This alloy is suitable for brazing-diffusion bonding and it can withstand high temperature and high temperature differences between fluids. It also benefits from a high mechanical strength and corrosion/erosion resistance. Each layer has a height of 4 mm. Both $CO_2$ and air layers contain “plain” fins but with different geometries, as shown in the table below.

**Table 9: DUHS geometry of fins**

| | CO2 side fins | Air side fins |
|---|---|---|
| **Thickness t (mm)** | 0.3 | 0.15 |
| **Height h (mm)** | 4 | 4 |
| **FPM p (Fin Per meter)** | 787.4 | 393.7 |
| **Geometry of “plain fins”** |   | |

The parting sheets between DUHS core layers are 1 mm thick, external sheets are 4 mm thick.

The thermal performance of the DUHS design is achieved thanks to a smart design: in fact, the stacking pattern used is called “double-banking”, leading to an arrangement of two air layers against 1 $CO_2$ layer alternatively. In addition, for the $CO_2$ side, each layer is constituted of six passes as shown in Figure 25, which allows connecting the headers and nipples on only one side of each heat exchanger core (see the overall DUHS sketch in Figure 26), which is quite practical in order to gain space on the unit.

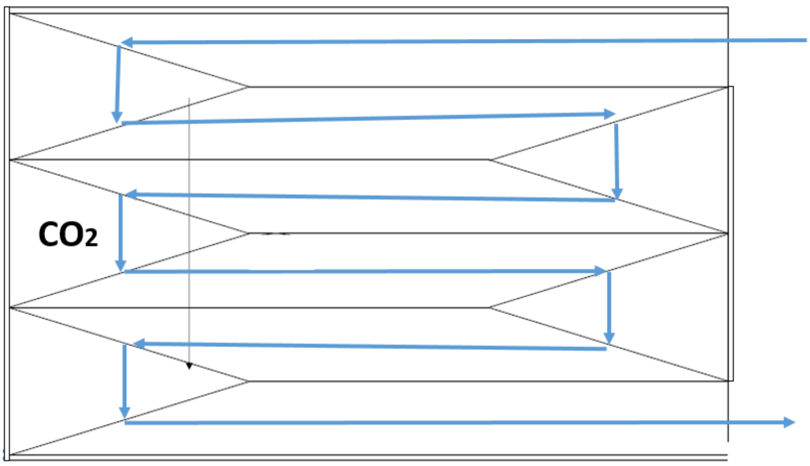



**Figure 25: DUHS layers**

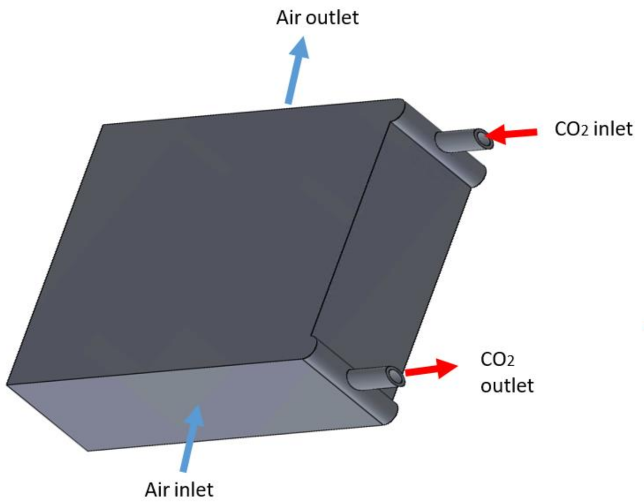



**Figure 26: DUHS sketch with inlets and outlets**

Therefore, there are no headers intended for air side, since we consider a circulation through the whole width perpendicularly, with subtracting obviously the lateral bars width, as shown in Figure 27; which corresponds to an effective passage width of 1928 mm.

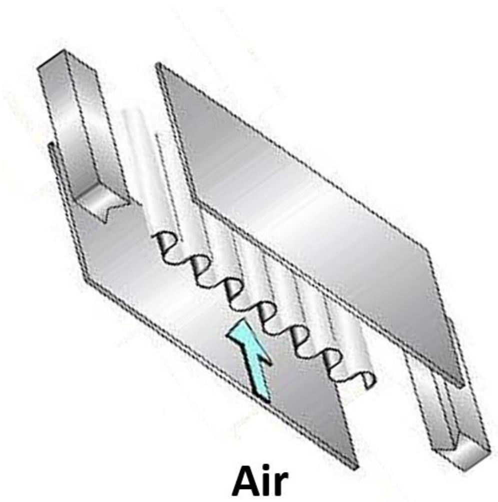



**Figure 27: DUHS circulation**

The output design data are summarized in the table below. This DUHS design allows to develop a total heat transfer area of 9376 m² for $CO_2$ and of 13581 m² for air for one unit of 10 MW.

**Table 10: DUHS output design data**

| FLUID | | CO2 | | AIR | |
|---|---|---|---|---|---|
| EFFECTIVE PASSAGE WIDTH | mm | 83 | | 1928 | |
| EFFECTIVE PASSAGE LENGTH | mm | 12000 | | 560 | |
| TOTAL HEAT TRANSFER AREA | m2 | 9376 | | 13581 | |
| TOTAL FREE FLOW AREA | cm2 | 3002 | | 178802 | |
| NOZZLE SIZE (NOMINAL) IN/OUT | mm | 2x40 | 2x40 | | |
| CONNECTIONS (NOM.) IN/OUT | inch | 40 x 1.5 | 40 x 1.5 | | |

***<u>CHX design:</u>***

The input thermodynamic data for CHX design on Table 6 were used to generate secondary input data in order to match a new design idea, allowing to reduce optimally thermal gradients between fluids.

This design idea is currently under assessment for patent submission, jointly between Fives, USTUTT and KSG/GFS.

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

The CHX design was achieved to lead specifically to only one very compact heat exchanger. In fact, the discussions with the project partners on CHX specifications led NRI and CVR to specify the position and shape on this heat exchanger: it should be in flat design, to allow to place it on the available wall of the room number A820.

The depth should be less than 30 or 40 cm and height should be around 1.5 m.

The exchanger height is limited at the top by the wall penetration, and the bottom of the heat exchanger should be higher than minimal level for maintaining the minimal slope of the pipeline of condensed water.

Length of exchanger is limited only by length of the wall (2.99 m).

The design achieved by Fives, taking account of the specifications listed before, led to a single core with the following dimensions:

- Width: 700 mm
- Height: 512 mm
- Length: 2000 mm

It is a counter-flow heat exchanger with a total number of layers of 101. The layers are distributed as follows:

- 38 layers for CO2
- 59 layers for steam
- 4 "dummy" layers, which are inactive layers, 2 on bottom stacking and 2 on top, to guarantee the mechanical integrity of the heat exchanger cores.

Each layer has a height of 4 mm. Both $CO_2$ and air layers contain "plain" fins but with different geometries, as shown in deliverable D4.4.

The parting sheets between CHX core layers are 1 mm thick, external sheets are 4 mm thick.

This CHX design allows developing a total heat transfer area of 305 m² for $CO_2$ and of 278 m².

**Task 4.4 Optimisation of the heat sink HX (M12-M36) [USTUTT, CVR, FIVES]**

The mechanical design of the DUHS is proposed as a plate & fin type heat exchanger with rectangular channels on the airside, where the main channel optimization parameters (shown in Figure 28) are:

- Height – H
- Pitch – P
- Fin thickness – t

The limitations of the optimization parameters will depend on the manufacturability, availability of the materials on the market, and structural integrity. These parameters have been discussed with Fives Cryo, who will fabricate and deliver the mock-up sample of DUHS for further testing using the experimental $sCO_2$ loop of CVR. Based on the initial thermal and structural analyses, and discussions between the involved partners, the operational parameters (shown in Table 11**Error! Reference source not found.**) and the dimensions (shown in Figure 29) of such a mock-up, which will ensure the structural integrity, were proposed by Fives Cryo. Following efforts in CVR will be in preparation of a CFD model according to the provided geometry with variable parameters listed above. In parallel, efforts will continue in preparing the ground for the testing of the mock-up in CVR's lab according to the proposed scheme shown in Figure 30. The preparation of the experiment implies design and assembly of the testing section, specification and purchase of components and instrumentation, and implementation of the testing section in the $sCO_2$ loop.

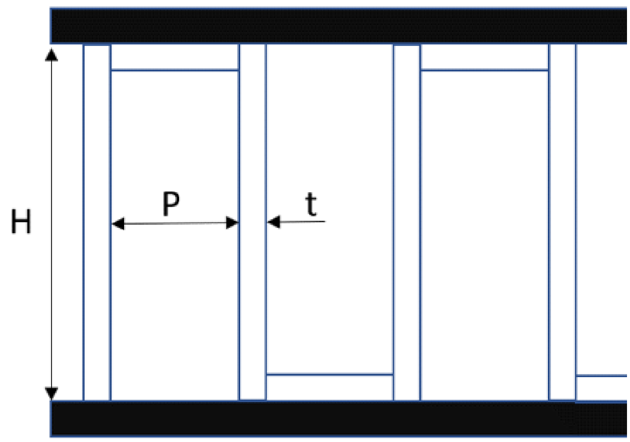



**Figure 28: Optimization parameters for the air side of fin & plate HX**

**Table 11: DUHS mock-up operating parameters**

| DUHS – 10 kW | p ($bar_g$) | t (°C) |
|---|---|---|
| CO2_in | 80 | 166 |
| CO2_out | 80 | 105 |
| Air_in | 0 | 25 |
| Air_out | 0 | 86 |

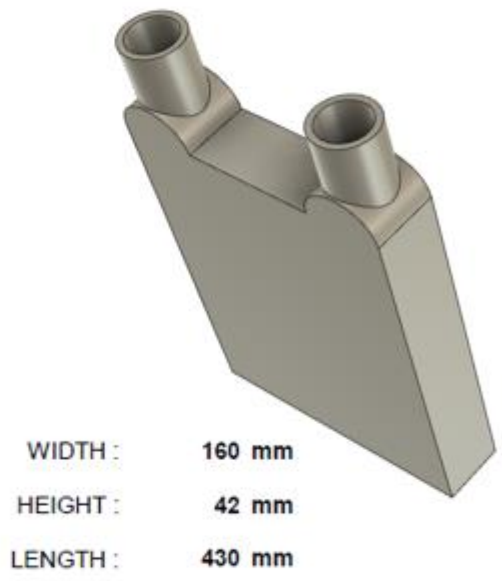



**Figure 29: DUHS mock-up geometry**

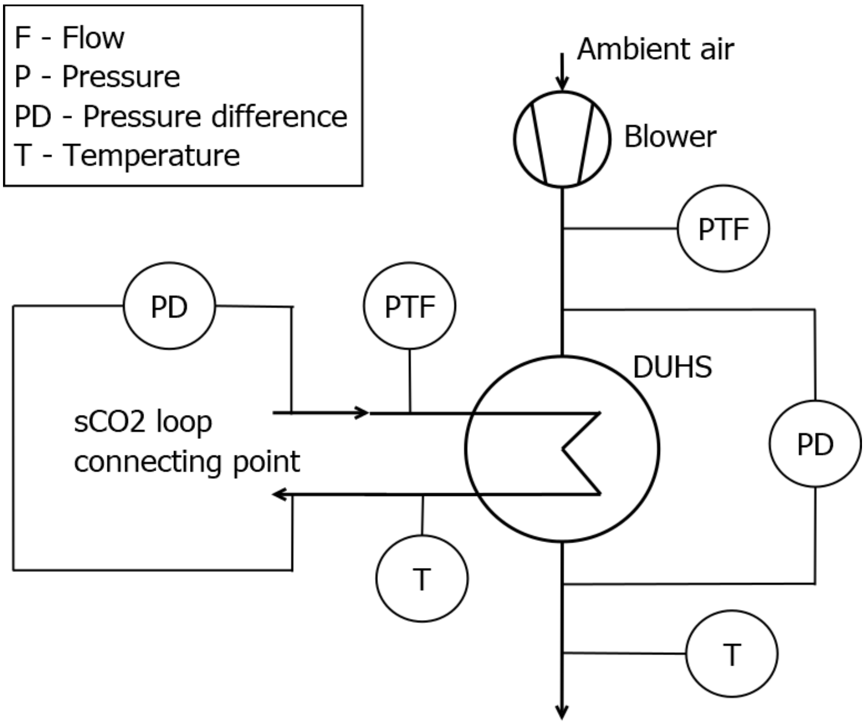



**Figure 30: PID of measuring track for DUHS**

### Task 4.5 Optimisation of heat recovery exchanger (M12-M36) [CVR, USTUTT, FIVES]

For this task, CVR is preparing a construction of a closed loop steam cycle, which will be added to the current $sCO_2$ loop in CVR's lab and should be able to deliver 17 g/s of saturated steam at 8 MPa. The proposed scheme of the experimental loop (shown in Figure 31) should ensure the natural circulation of the steam with the help of the CHX. The proposed experimental loop is composed of an electrically heated boiler with a heating power of 25 kW, an upstream heated leg ensuring superheating of the steam, the CHX mock-up and a downstream leg directing water back to the boiler. Several auxiliary systems such as a filling vessel, a vacuum system for removal of air and gases from the loop, a draining system or data acquisition system were proposed. The mock-up of the CHX will be manufactured by Fives Cryo, who recently provided the final geometry (shown in Figure 32). The heat from the stream loop will be removed by the $sCO_2$ loop of CVR. The operating parameters of the CHX (shown in Table 12**Error! Reference source not found.**) were chosen with respect to the manufacturing capabilities and mechanical integrity. The experiment is intended to evaluate characteristics of the CHX as well as of the whole circuit and its passive heat removal ability. In the next phase, detailed design of the experimental section will be finished and fabrication will be started. In parallel, specifications and purchases of the loop components are ongoing.

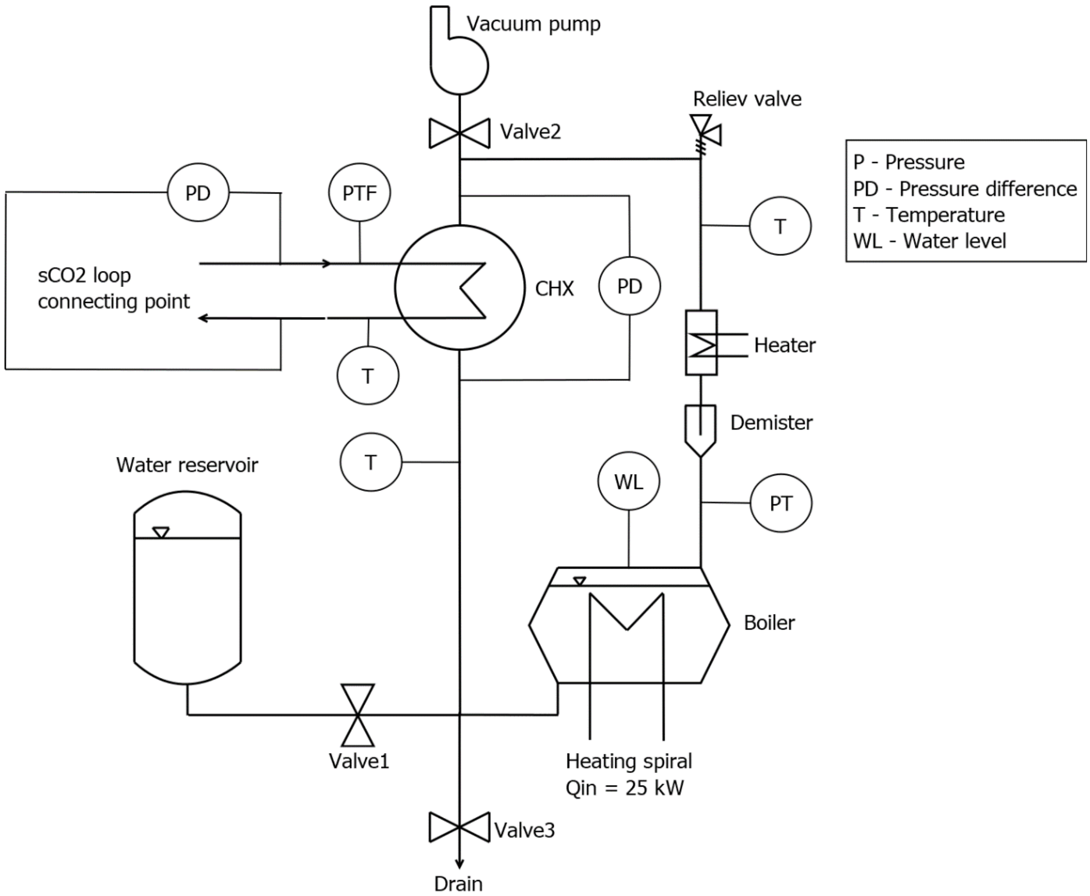



**Figure 31: PID of closed loop steam cycle**

**Table 12: CHX mock-up operating parameters**

| CHX – 25 kW | p ($bar_g$) | t (°C) |
|---|---|---|
| CO2_in | 160 | 200 |
| CO2_out | 160 | 260 |
| Water/steam_in | 80 | 295 |

| | | |
|---|---|---|
| Water/steam_out | 80 | 295 |

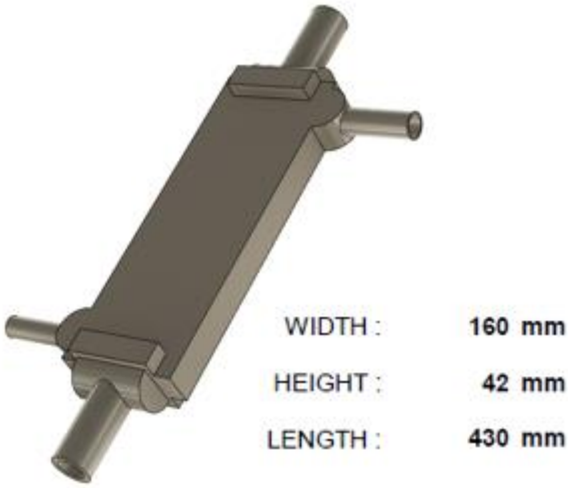



**Figure 32: Mock-up of CHX**

**Task 4.6 Turbomachinery qualification according to Nuclear requirements (M10-M34) [NP TEC, UDE]**

In order to define the needs for turbomachinery qualification according to nuclear requirements, a preliminary analysis of nuclear and industrial standards has been performed.

Preliminary results show that the industrial standard API 617 - Axial and Centrifugal Compressors and Expander-compressors – Part 4: Expander-compressors has to be adopted and that there are no special requirements regarding turbomachinery except for the pressure vessel code to be considered. Since the industrial standard ASME VIII div.2 is less severe for pressure vessels than the nuclear standard KTA 3211 Part 2, the latter has to be used.

During the upcoming months, further analyses will be performed and the qualification methodology for the turbomachinery will be defined. Results will be collected in a guideline to be included in D4.7.

**Task 4.7 Heat Exchanger qualification according to Pressure Vessel Code and Regulations, according to Nuclear requirements (M10-M34) [FIVES, USTUTT, CVR]**

In addition to $sCO_2$ cycle heat exchanger design, the project aims also to clearly define the qualification strategy for this equipment, including the validation of some key points to assess that the heat exchanger technology is suited for nuclear power plants.

In compliance with the construction code RCC-M and the European Regulation of Nuclear Pressure Vessel, Fives Cryo is constituting a note whose aim is to present the approach to be followed and the main important and specific documents to be carried out so that the equipment manufactured meets the criteria of the nuclear PED regulation and the selected nuclear construction code. At this stage of the project, not all technical design choices have been yet fixed for the equipment. Thus, the qualification methodology needs to be finalized afterwards, and will be presented in full in a future report.

The documents identified and listed below are considered important for an appropriate design and manufacturing review in accordance with the nuclear PED regulation:

- Risk and hazards analysis (for pressure and radiation aspects) according to the nuclear PED regulation,
- Instruction for use according to the nuclear PED regulation,
- The list of Important Activities for the Protection of Interests (IAPI) according to modified decree BNI 07/02/2012,
- Definition of the Necessary Dimensions to meet the Essential Safety Requirements (NDESR) and control methods,
- The nuclear particular material appraisals according to the nuclear PED regulation,
- The list of material,
- Supply specifications for base metal and filler metal,
- Capacity of inspection in service according to the nuclear PED regulation,
- The program of fabrication,
- The procedures of controls,
- The visual inspection procedure at the end of fabrication,
- The marking procedure,
- The procedure of materials tracing.

Considering a level 3 defined by the nuclear power plant owner (or nuclear power plant operator) according to ESPN classification, a radiological classification of the system of RP C class and a class 3 according to RCC-M is expected.

### 3.2.5 WP5 System architecture of sCO2-4-NPP integrated in a reference NPP [Months: 18-30]

Leader: EDF

#### 3.2.5.1 Progress towards objectives

| WP Objectives | Achieved (Yes/No and comment) |
|---|---|
| To define which auxiliary components are required for the system and what the final architecture of a module will be. | In progress |
| To establish a preliminary design of the integrated system with the primary and secondary loops of the nuclear power plant. | No |
| To define the control-command of the system as well as the thermodynamic performance of the cycle in order to carry out the simulation of accidents using real NPP parameters and feed into WP6 for the final validation in the KONVOI simulator. | No |

#### 3.2.5.2 Exploitable results

Not applicable as WP just started.

#### 3.2.5.3 Problems met and actions taken (if any)

No problems to report.

#### 3.2.5.4 Details for each task

**Task 5.1: System architecture design parameters (M18-M26) [EDF, CVR, NRI]**

Initial discussions have taken place between different EDF teams. The teams in charge of the realization of the plans, as well as the teams in charge of the development of new reactor designs, have been informed of the first results obtained in WP2 for a scaled-up $sCO_2$ loop. The objective was for EDF to validate the possible choices for the location of the $sCO_2$ modules at plant level.

Partner contributions: EDF

**Task 5.2: Thermodynamic cycle design (M18-M24) [CVR]**

The work on the design of the thermodynamic cycle was initially foreseen to start in month 18. However, it was recognized that the main parameters of the layout of the $sCO_2$ system had to be defined earlier, in order to be able to proceed with the work in other tasks. This concerned WP4, where the development of components required cornerstones for the design of heat exchangers (inlet and outlet temperatures, etc.) and the turbo-compressor system (mass flow rates, pressure ratio, etc.). In addition, the development and implementation of scaled-up models in the computer codes in WP2 would not have been possible without defining the thermodynamic design parameters. Therefore, an initial version of the design of the thermodynamic cycle was prepared within the frame of Task 2.2 (see description of Task 2.2) and documented in an internal technical report (available via the project SharePoint). The specifications of the basic thermodynamic layout are considered as a living document and should be updated according to emerging results from the progress in WPs 2, 4, and 5.

Partner contributions:

USTUTT and partners in WP2

- Determination and definition of thermodynamic design parameters

UDE and Fives Cryo

- Feedback and confirmation of feasibility from component designers' point of view

KSG and GfS

- Consultation and advice from background of plant operation expertise

**Task 5.3 Simulation of sCO2-4-NPP loop in a real NPP using real design parameters (M18-30) [EDF, USTUTT, CVR]**

Activity just started; nothing to report.

**Task 5.4: Dynamic simulations and control system modifications (M18-M26) [CVR]**

Activity just started; nothing to report.

**Task 5.5: Real-time simulations for implementation in PWR simulator (M18-M26) [CVR, KSG]**

Activity just started; nothing to report.

### 3.2.6 WP6 Validation of sCO2-4-NPP loop in a virtual "KONVOI" PWR [Months: 18-36]

Leader: KSG

#### 3.2.6.1 Progress towards objectives

| WP Objectives | Achieved (Yes/No and comment) |
|---|---|
| Validate the performance, control strategy and applicability of sCO2-loops in a virtual PWR-environment of a full scope simulator of the KONVOI/ Pre-KONVOI-type | No, not yet started |
| Identify possible operational and design problems to be assessed in further development | No, not yet started |
| Compare it to the ATHLET/ CATHARE models for confirmation | No, not yet started |

#### 3.2.6.2 Exploitable results

No exploitable results have been achieved so far, as the WP just started in February 2021. Several meetings have been held between KSG, CVR and its sub-contractor XRG. CVR delivered a test case FMU (Functional Mock-Up Unit) of the Dymola model of the sCO2-cycle to KSG. KSG has implemented to FMI (Functional Mock-Up Interface) Standard in its Simulation environment and could successfully connect the model delivered by CVR. Discussion of interface variables has started between KSG and CVR and a general understanding of model boundaries was achieved. KSG will continue testing the delivered model and make sure that all simulator functionalities will be functional.

#### 3.2.6.3 Problems met and actions taken (if any)

The first 2 months of WP6 are intended for specification of the interface between the CVR and KSG models. Currently no problems have arisen. CVR has reported the possible risk of not being able to run its model in real-time.

#### 3.2.6.4 Details for each task

**Task 6.1: Defining Interface for $sCO_2$ system code to be implemented to simulator (M18-M19) [KSG, CVR, GfS]**

CVR and KSG held several meetings to discuss the interface between their simulation models. General agreement was achieved about the model boundaries and the variables that need to be exchanged between the two models.

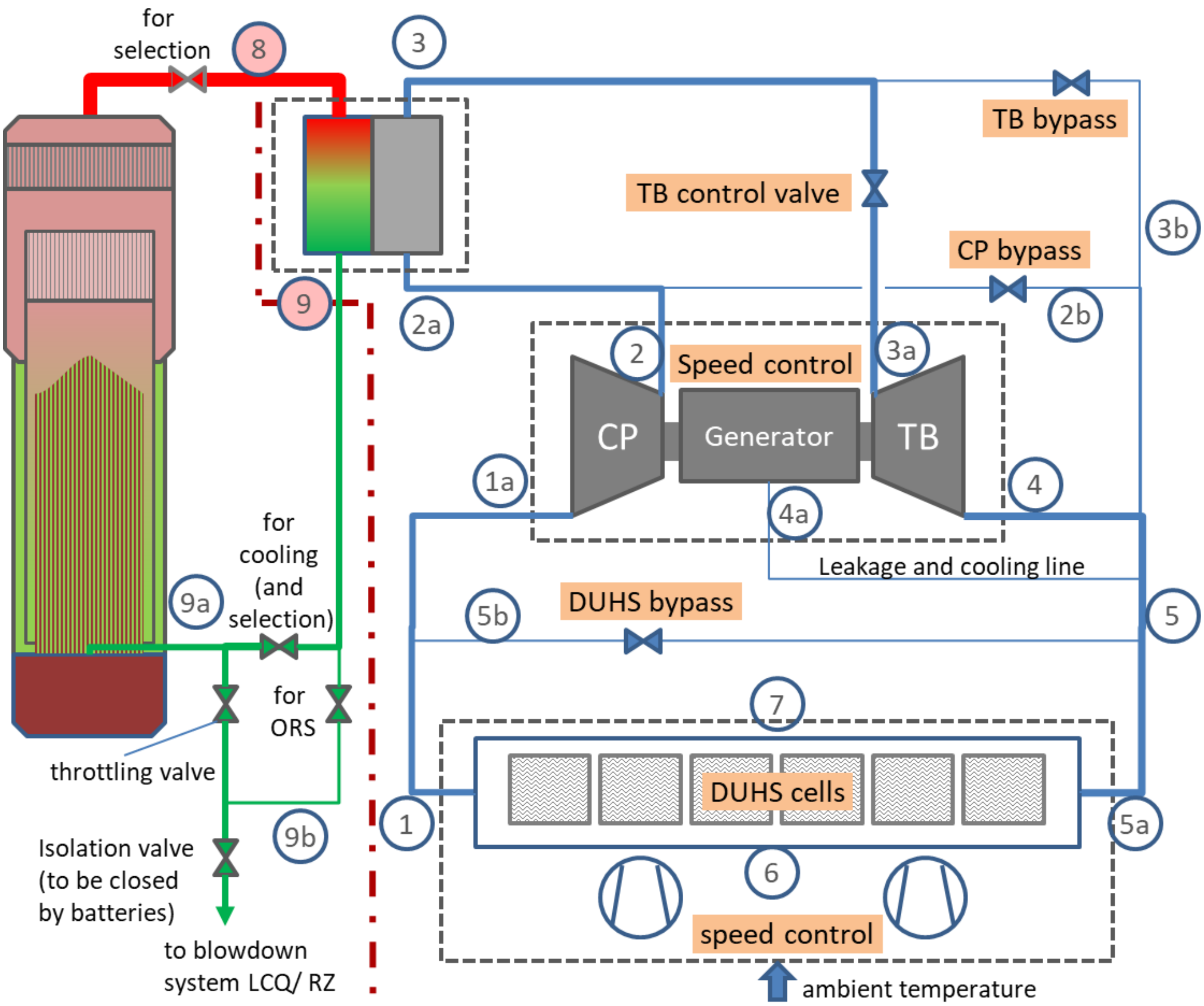



**Figure 33: Model boundary**

The above figure shows the model boundary between CVR and KSG. The model will be spilt at the main steam line and the condensate return line. The steam side of the heat exchanger will be included in the Dymola model of CVR as it was understood that the heat exchanger is a crucial part of the model. For sake of simplicity of the interface, the boundary was drawn as shown above. On all marked points (1-7) the following parameters will be transferred to the KSG model for display purposes:

- pressure
- temperature
- mass flow
- density
- enthalpy
- entropy
- speed of sound

Additional variables needed to be exchanged are:

- speed of fans

- speed of turbine
- position of valves
- $CO_2$ mass in vessel (CHX, DUHS)
- number of DUHS cells active
- heat removed via CHX
- water mass in CHX
- electrical power from/ to generator
- electrical power for fans
- surplus electrical power
- work of turbine
- work of compressor
- efficiency of TB
- efficiency of CP
- distance to surge line (Mach numbers)
- status of battery power supply
- battery capacity remaining

On the interfaces between the CVR and KSG model the following parameters need to be exchanged:

- mass gas/liq
- density gas/liq
- enthalpy gas/liq
- void fraction
- concentration non-condensable gases
- temperature gas/liq
- mass flow gas/liq

Therefore, general agreement between the necessary interface variables has been reached already. With the transferred test case, KSG will evaluate whether a connection can be achieved successfully.

Performance evaluation with regards of real time behavior of the Dymola model of CVR cannot yet been done, as the real time model is still under development. This will be part of Task 6.2.

It was agreed that KSG will develop a visualization of the sCO2-cycle as this can be achieved easily by exchanging the above-mentioned display variables. The FMI-Standard would not allow for an easy way to supply an online graphic of the cycle behaviour.

Furthermore, it was discussed that CVR has to implement several operational readiness states, according to Hofer et al “SIMULATION AND ANALYSIS OF A SELF-PROPELLING HEAT REMOVAL SYSTEM USING SUPERCRITICAL CO2 AT DIFFERENT AMBIENT TEMPERATURES” (see Table 14: Dissemination activities carried out by partners). The start-up of the system from an empty state is not part of the simulation, therefore these operational readiness states need to be available for the transient runs in Task 6.3.

**Task 6.2: Implementation of sCO2-system code into PWR simulator environment (M27-M29) [KSG, GfS, CVR]**

This task is scheduled to start at M27.

**Task 6.3: Running Transients (M29 – M36) [GfS, KSG]**

This task is scheduled to start at M29.

### 3.2.7 WP7 Exploitation planning and roadmaps towards TRL9 [Months: 1-36]

Leader: EDF

#### 3.2.7.1 Progress towards objectives

| WP Objectives | Achieved (Yes/No and comment) |
|---|---|
| Develop a detailed exploitation plan for the sCO2-4-NPP system and components, including technological, regulatory, financial and organisational roadmaps for reaching TRL9 | No (Objective due for M36) |
| Prepare the exploitation of results by industrial partners | No (Objective due for M36) |
| Manage innovation generated in the project | No (Objective due for M36) |

#### 3.2.7.2 Exploitable results

During the first period of the project, several actions were carried out by the consortium in order to start preparing the roadmaps:

- The project was the subject of several requests for public presentations ($sCO_2$ 2020 conference in Paris, $sCO_2$ Symposium in the USA, NUGENIA-SNETP Workshop, etc.). The COVID-19 epidemic has postponed the majority of these presentations until late 2020 and early 2021. These presentations have been prioritized because they are an excellent way to get feedback from industrialists concerned by the subject and to bring out standardization issues. See Table 14 for list of publications.
- The work of WP3 has highlighted the documents needed to establish the next steps related to the qualification of the heat recovery system.
- The D7.1 ‘First version of sCO2-4-NPP exploitation plan’ was issued M18 as scheduled.

#### 3.2.7.3 Problems met and actions taken (if any)

No major deviations.

#### 3.2.7.4 Details for each task

**Task 7.1: Exploitation planning and management of intellectual property (M1-M36) [EDF, ART, ALL partners]**

The list of Background in the Consortium Agreement was updated following General Assembly approval:

- Additional Background (relevant sCO2-HeRo Results/Deliverables) agreed by Owners
- Modification of Background (FIVES, NP TEC)

The Exploitation and Innovation Team (EIMT) was composed of WP7 partners.

A form and process for constituting the project IP Portfolio was agreed.

Partner contributions:

- EDF: Contributions to D7.1
- ART: Coordination of CA Background update with concerned parties, organization of General Assembly approvals, contributions to D7.1
- All partners: Update of partner exploitation plans

**Task 7.2: Technological roadmap to reach TRL9 (M12-M35), [USTUTT, EDF, UDE, FIVES, NP TEC]**

Preliminary plans are reported in D7.1.

**Task 7.3: Regulatory roadmap to reach TRL9 (M12-M35), [JSI, EDF, NRI]**

Preliminary plans are reported in D7.1.

**Task 7.4: Financial and organisational roadmap to reach TRL9 (M12-M35), [EDF, NP TEC, FIVES, ART]**

Preliminary plans are reported in D7.1.

### 3.2.8 WP8 Dissemination and communication [Months: 1-36]

Leader: ARTTIC

#### 3.2.8.1 Progress towards objectives

| WP Objectives | Achieved (Yes/No and comment) |
|---|---|
| Effectively disseminate information about the sCO2-4-NPP system to end-users and other target audiences defined | Ongoing. Public website and social media accounts are active. Some scientific publications at conferences have been delayed due to coronavirus travel restrictions. |
| Preparing the sCO2-4-NPP dissemination and communication strategy and tools for all target audiences | Ongoing. D8.1 Dissemination Plan issued. Communication channels in place. |
| Manage collaboration between the project and the end-user group | Ongoing. Additional members of End-user group agreed by General Assembly. NDA and ToR drafted. |

#### 3.2.8.2 Exploitable results

WP8 has defined ‘success criteria’ to monitor achievement of the WP objectives. The table below shows the criteria defined and the status at M18.

**Table 13: Success criteria for dissemination and communication activities**

| Communication channel | Lead WP | Success criteria | Target numbers | Status @M18 |
|---|---|---|---|---|
| Project website | WP8 | Number of visitors including, when available, dwell time, origin, contacts, etc. Interrelation with NUGENIA | 100 visitors | About 100 visitors/month to project website. Project page on SNETP-NUGENIA website. |
| Social media | WP8 | Number of followers, shares, impressions, showing a positive evolution over the course of the project | 50 followers | 19 Twitter and 32 LinkedIn followers |
| Presentations at relevant events | WP1-6 | Number of presentations and representations (e.g. poster session) at scientific and industry events and qualitative feedback from visitors | 10 | 6 scientific papers presented |
| Video | WP8 | Number of occasions where video is presented or watched online as well as qualitative feedback from viewers | 100 views | |
| Popular publications | WP8 | Number of articles in the popular and industry press linked to targeted messaging (event, press release, news, publication, etc.) | 4 | |
| sCO2-4-NPP Symposium | WP8 | Number of participants from each target audience, including geographical coverage, and their feedback | 50 people | |
| Scientific publications | WP1-6 | Number of peer-reviewed publications in reputable journals | At least 5 | 2 publications in conference proceedings |
| | | Number of joint public-private publications | At least 2 | |
| Meetings with stakeholders involved in bringing the system to TRL9 | WP7 | Meetings with WENRA | At least 1 | |
| | | Meetings with potential industrial integrator | At least 1 | |
| | | Meetings with end-users | At least 1 | |
| | | Meetings with standards bodies | At least 1 | |
| Patents | WP4 | Number of patent applications | At least 1 | 1 in progress |

#### 3.2.8.3 Problems met and actions taken (if any)

| Deviation / Explanation | Impact on other WPs | Impact on resources | Impact on schedule |
|---|---|---|---|
| D8.4 'End user workshop' is scheduled for M24 (31/08/2021). To better attract targeted participants and based on glass model availability, the workshop is rescheduled to September or October. | None | None | Delay of workshop and D8.4 by 2 months |

#### 3.2.8.4 Details for each task

**Task 8.1 Dissemination and communication plan (M1-M3) [ART, EDF, All partners]**

This task closed M3 with delivery of the D8.1 Dissemination Plan. The D8.1 elaborates on the preliminary plan in the Description of Action and serves as a reference for project partners when planning their dissemination and communication activities. It also provides monitoring tools for the Executive Board. The dissemination and communication objectives are listed, along with the strategies for achieving them. The means of communication and dissemination are detailed, both materials provided by WP8 and activities to be carried out by the partners. Key messages to communicate are suggested, along with the target audiences best addressed by the messages and the means. A preliminary schedule is proposed, showing the timing of communication and dissemination activities against project milestones and external related events. Finally, success criteria are proposed to measure effectiveness of the actions undertaken along the project. The Dissemination and Communication Plan will continue to evolve during the project, depending on emergent opportunities and technical progress made.

A number of communication and dissemination activities will be initiated during the project, with the overall objective to target all levels of relevant public and private stakeholder communities, particularly potential end-users. All partners will be involved in preparing the content of communication and dissemination materials and in participating in dissemination events.

Partner contributions:

ART: Drafted D8.1 and organized partner approval. Established and monitored schedule and 'success criteria'.

**Task 8.2 Project communication (M1-M36) [ART, EDF, All partners]**

The **project logo** was created by ART in consultation with EDF and USTUTT and shared with partners for project publicity purposes.

The **D8.3 Public Website** (https://www.sco2-4-npp.eu) was delivered as scheduled (M6). This deliverable describes the website design and the initial site content, which has been approved by the partners of the consortium.

The website objectives, target audience, and key messages are aligned with the Dissemination and Communication Plan described in D8.1. The main target audience for the public website is the general public. As such, non-technical language is used and the focus, particularly for the homepage, is on the project results which are of interest for the European citizen, and specifically how the sCO2-4-NPP system further increases the safety of NPPs.

The website follows a standard format for European research projects, with subpages for describing the project, the consortium, project documentation (press releases, public deliverables, links to scientific publications, etc.), announcing news and events, and a form for contacting the project.

Google Analytics is used to assess the website effectiveness in reaching its target audience.

The website will be updated throughout the project duration, namely with project news and events.

**Social media** accounts for the project were created on Twitter and LinkedIn to share project news and events and attract the targeted audience:

- https://twitter.com/sCO2_4_NPP
- https://www.linkedin.com/in/sco2-for-npp-project-7b56081a2/

A **project video** storyboard and specifications have been drafted. Shooting is postponed due to covid-related travel restrictions.

Partner contributions:

ART: Created project logo, drafted D8.3, designed and implemented public website, created, monitored and contributed content to social media accounts, project video preparations.

**Task 8.3: Dissemination of project results (M1-M36), [ART, EDF, USTUTT, All partners]**

Several partners have prepared scientific publications to be presented at conferences, however, due to the coronavirus-related travel restrictions in 2020, certain conferences were postponed or cancelled.

The table below show the list of dissemination activities approved for public dissemination and carried out by partners. Three additional papers were prepared, but not presented due to conference cancellation or significant postponement.

**Table 14: Dissemination activities carried out by partners**

| Ref. | Type of activities | Main leader | Title | Event | Date | Place | Relation to WBS |
|---|---|---|---|---|---|---|---|
| 2 | Participation to a Conference | USTUTT | Operational analysis of a self-propelling heat removal system using supercritical $CO_2$ with ATHLET | 4th European sCO2 Conference | 22-26/03/2021 | Online | WP2 |
| 5 | Participation to a Conference | UDE | Impact of volumetric system design on compressor inlet conditions in supercritical $CO_2$ cycles | GPPS Chania20 | 07-09/09/2020 | Online | WP1 |
| 9 | Participation to a Conference | FIVES | Industrial Technical Development and Qualification of Highly Efficient Stainless Steel Plates and Fins Heat Exchanger for Heat Removal Supercritical $CO_2$ Brayton Cycle Applied to Nuclear Power Plants | Fluids Engineering Division Summer Meeting (ASME FEDSM 2020) | 12-16/07/2020 | Orlando, FL, USA | WP4 |
| 13 | Participation to a conference | UDE | Mean-line Analysis for Supercritical $CO_2$ Centrifugal Compressors by Using Enthalpy Loss Coefficients | 4th European sCO2 Conference | 22-26/03/2021 | Online | WP4 |

| Ref. | Type of activities | Main leader | Title | Event | Date | Place | Relation to WBS |
|---|---|---|---|---|---|---|---|
| 14 | Participation to a conference | USTUTT | Simulation and Analysis of a Self-propelling Heat Removal System Using Supercritical $CO_2$ at Different Ambient Temperatures | 4th European sCO2 Conference | 22-26/03/2021 | Online | WP2 |
| 15 | Participation to a conference | FIVES | Conceptual design, optimisation and qualification of highly efficient brazed plates and fins heat exchangers for heat removal $sCO_2$ Brayton Cycle to increase the safety of nuclear power plants | 4th European sCO2 Conference | 22-26/03/2021 | Online | WP4 |
| 17 | Social Media | UDE | 3D-printed 1-to-1 scale model of turbomachine | Social media & public website | 17/02/2021 | Online | WP4 |
| N/A | Participation to a conference | EDF | sCO2-4-NPP Project Overview | NUGENIA Technical Area 1 online meeting, SNETP Forum 2021 | 05/02/2021 | Online | Project overview |

Several project deliverables have a dissemination level of "public" and have been disseminated through the public website and announced via the project social media accounts.

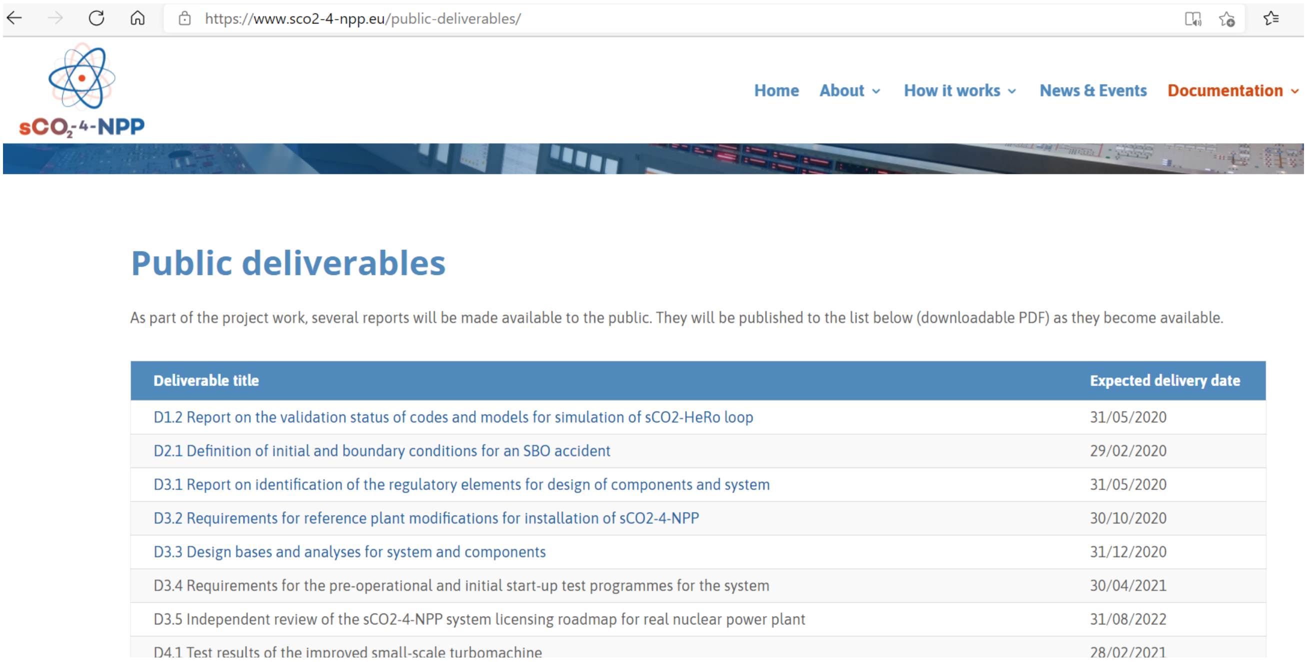



**Figure 34: Public deliverables available through project website**

Preparations have started for the organization of an End-User Workshop in September/October 2021 tentatively at KSG in Essen, Germany. The workshop will include demonstrations of the transient loop behaviour of the system at the PWR Glass Model. The End-user Group will be invited to inform them about the developments and to validate the technology. The related deliverable, D8.4, is expected in October 2021, with a two-month delay due to scheduling of the workshop in the autumn rather than in August.

Partner contributions:

ART: Organisation of dissemination General Assembly approval, monitoring of funding acknowledgements, open access, and publication status.

All partners: Dissemination activities as listed in Table 14.

**Task 8.4: Collaboration with end-user group (M1-M36), [EDF, ART, USTUTT, ALL]**

The composition of the End-user group was discussed among the consortium and representatives of the following entities were approved to participate in the End-user group:

- RWE
- ČEZ a.s.
- Naval Group
- Framatome Germany

A Non-Disclosure Agreement and Terms of Reference were drafted in anticipation of engagement with the End-user Group later in the project.

Partner contributions:

ART: Drafted Terms of Reference, reviewed NDA prepared by EDF, circulated documents for approval

**Task 8.5 Data management (M1-M36) [EDF, ALL]**

The D8.2 Data Management Plan was delivered as scheduled (M4).

The project includes a significant number of simulations under different codes as well as experiments of the heat recovery system coupled to the glass model and a NPP simulator. In order to be able to optimise the impact of the results of the project, the consortium of sCO2-4-NPP has set up a Data Management Plan that meets the requirements of an H2020 research project and the requirements of the project partners and stakeholders.

The data resulting from the project work will be mainly derived from the results of modelling, simulations and the results of the WP1 and 6 test campaigns. It is therefore mainly data stored in IT format.

Some data from the sCO2-HeRo project will be reused as part of sCO2-4-NPP. These data were identified and capitalized on as Results in the sCO2-HeRo project and declared in the Consortium Agreement of the sCO2-4-NPP project as Background.

Partner contributions:

EDF: Drafted the D8.2

### 3.2.9 WP9 Project management [Months: 1-36]

Leader: EDF

#### 3.2.9.1 Progress towards objectives

| WP Objectives | Achieved (Yes/No and comment) |
|---|---|
| Set up the management infrastructure: committees, boards, management procedures, quality plan, risk registers, project management and communication tools, internal web site, etc. | Yes, achieved M4 with D9.1, D9.2 and templates. |
| Ensure the strategic and operational management of the project. | Ongoing. See Tasks 9.1 and 9.3 below. |
| Provide financial and contractual management of the consortium, including the maintenance of the Grant Agreement and Consortium Agreement. | Ongoing. CA Background modified, pre-financing instalments 1 and 2 distributed. |
| Manage relations with the sCO2-4-NPP advisors. | Ongoing. NDA and ToR drafted. Advisors participated to M7 meeting of WP3. |
| Manage collaboration with the sCO2-Flex project. | Ongoing. See Task 9.4 below. |

#### 3.2.9.2 Exploitable results

Not applicable.

#### 3.2.9.3 Problems met and actions taken (if any)

None to report.

#### 3.2.9.4 Details for each task

**Task 9.1: Strategic decision making and project governance (M1-M36) [EDF, USTUTT]**

Pre-financing instalment 1 was issued in November 2019 and pre-financing instalment 2 was issued to partners in October 2020 according to the procedures of the Consortium Agreement.

During the situation related to the COVID-19 outbreak, management closely followed WP risk and mitigation plans through Executive Board meetings and communicated with the EC Project Officer on the status of the project. Through close coordination and implementing mitigation plans, the management has minimized delays.

**Task 9.2: Technical coordination (M1-M36) [EDF, USTUTT]**

Several coordination and technical sharing meetings took place during the first period.

The project coordination ensured that each WP leader made regular contacts with the partners concerned within a WP.

The two coordinators (A. Cagnac and J. Starflinger) regularly exchanged on the progress and difficulties encountered in the project.

The time required for the proofreading of each deliverable was well anticipated by the partners and the project coordination was thus able to carry out this review on time.

**Task 9.3: Project management and administration (Project Office) (M1-M36) [ART, EDF]**

The **D9.1 Management Plan** was delivered as scheduled (M3). The D9.1 summarizes the working procedures and rules for the Consortium partners, defining document templates, the deliverable review process, means of communication and control throughout the project, periodic reporting and reviews, and dissemination and exploitation.

The **D9.2 Collaborative Web Space** was delivered as scheduled (M4). The collaborative web space uses Microsoft SharePoint and provides a platform for the project to efficiently exchange information internally, including tracking the progress of actions, milestones, risks, and deliverables, organizing the project meetings, and archiving project documents. The collaborative web space was made available to the project just after M1 of the project and since then it has been used with success by the sCO2-4-NPP partners.

The following **project-level meetings** were organized during the Period:

**Table 15: List of project meetings**

| Project month | Date | Meeting | Location |
|---|---|---|---|
| M01 | 17-18/09/2019 | Kick off meeting (General Assembly) | EDF, Palaiseau, FR |
| M04 | 17/12/2019 | Executive Board | Teleconference |
| M07 | 18/03/2020 | General Assembly + WP meetings, including WP3 with sCO2-4-NPP Advisors | Teleconference (originally planned for Essen, DE, but modified due to coronavirus) |
| M10 | 22/06/2020 | Executive Board | Teleconference |
| M13 | 28/09/2020 | Executive Board | Teleconference |
| M16 | 04/12/2020 | General Assembly | Teleconference |
| M19 (scheduled) | 11/03/2021 | EC Review (GA) | Teleconference |

Collaboration tools such as mailing lists and project templates were set-up.

Task 9.3 supported the coordinator by collecting partner banking information for distribution of the **pre-financing payment,** organizing internal review and submission of deliverables, and organizing General Assembly votes.

An **internal reporting** exercise was organized for the Period M1-M9. The report, based on the EC contractual reporting templates, covers both technical progress per WP and an estimate of partner spending. The report helped the Executive Board to closely monitor progress and provide information for the distribution of the pre-financing instalment 2.

The composition of the **sCO2-4-NPP Advisors** group was discussed among the consortium and the following persons were approved to participate in the group:

| Name | Organisation | Country | Area of Expertise |
|---|---|---|---|
| Dr. Thomas Wintterle | ENSII | Switzerland | Nuclear safety regulations |

| | | | |
|---|---|---|---|
| Dr. Jeanne Bargsten | TUEV-SUED | Germany | sCO2-cycles, ATHLET calculations (performed the first calculations for the sCO2-HeRo system) |
| Dr. Thomas Fuchs | Framatome | Germany | Representative of vendor of NPPs |

A Non-Disclosure Agreement and Terms of Reference were drafted.

Drs. Wintterle and Bargsten participated to the WP3 meeting in M7 to provide their feedback on the nuclear regulatory approach.

Discussion with the ATHLET developer, GRS, about participation in the Advisory Board is ongoing. Their feedback on modifications in the code would be greatly appreciated.

Partner contributions:

ART: Produced the D9.1 and D9.2, organised the project level meetings, provided operational support to the coordinator and the partners, organised the internal reporting, and communicated with the sCO2-4-NPP Advisors.

**Task 9.4: Set-up and management of collaboration with sCO2-Flex project (M1-M36) [EDF, USTUTT, ART]**

Coordination between the projects is managed via a common Coordinator (Albannie Cagnac).

A joint event in June 2021 is under discussion.

Partner contributions:

ART: Publicity of relevant sCO2-Flex publications via sCO2-4-NPP social media accounts.

# 4 Conclusion

As described in section 3.1 Objectives, the project is largely on track, but delays in WP2 and WP4 due to coronavirus-related laboratory closures, impacting testing and manufacture of parts, have led to achievement of project milestones MS3 and MS4 being approximately three months behind schedule.