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

Deliverable 8.4
End-user workshop

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

Type of action: Innovation action

Grant Agreement number:	847606
Start date of project: 1 September 2019	Duration: 36 months
Lead beneficiary of this deliverable:	ARTTIC
Due date of deliverable: 31/08/2021	Actual submission date: 28/02/2022
	Version #: R1.0

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

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

Revision History

Release	Date	Reason for Change	Author	Distribution
R0.1	23/02/2022	Draft for internal review	S. Barreault	Consortium
R1.0	28/02/2022	Final version	S. Barreault	Public

Deliverable Contributors

Authors

Partner	Name
ARTTIC	Susan Barreault

Contributors

Partner	Name
EDF	Albannie Cagnac
USTUTT	Michael Buck
GfS	Frieder Hecker
UDE	Haikun Ren
FIVES	Guillaume Taiclet
JSI	Andrej Prošek
KSG	Peter Lasch

Internal Reviewers

Partner	Name
EDF	Albannie Cagnac
USTUTT	Jörg Starflinger

Table of contents

1 Executive Summary 5
2 Introduction 6
3 Purpose of Workshop 7
3.1 Target Audience 7
3.1.1 Advisory Boards 7
3.1.2 General Public 7
3.2 Communication campaign 8
4 Organisation of Workshop 10
4.1 Workshop format 10
4.2 Agenda 10
5 Discussion 12
5.1 Project progress 12
5.2 sCO2 loop/Glass model 12
5.3 Simulation: sCO2 loop with scaled-up components 12
5.4 Licensing requirements & regulatory framework 12
5.5 Components development: Turbomachine and heat exchanger 13
5.6 Simulation: Architecture of sCO2 loops integrated in NPP 13
5.7 Validation of sCO2-4-NPP loop in a virtual "KONVOI" PWR 13
5.8 Roadmap toward exploitation: Regulatory policy, requirements & way forward 13
5.9 Q&A roundup & Conclusion 13
6 Conclusion 14
Appendix A Workshop Presentations 15

List of Tables

Table 1: Workshop registration 8
Table 2: Agenda Day 1: 25 January: End-user workshop - Focus on sCO2 loop in nuclear application 10
Table 3: Day 2: 26 January - Public Workshop - Focus on sCO2 loop generally 11

List of Figures

Figure 1: Workshop Announcement..9

List of Acronyms

Abbreviation / Acronym	Description / meaning
ATHLET	Analysis of THermal-hydraulics of LEaks and Transients. Simulation code use for the analysis of the whole spectrum of leaks and transients in PWRs and BWRs. The code is applicable for western reactor designs as well as for Russian VVER and RBMK reactors.
CATHARE	Code for Analysis of Thermal-hydraulics during an Accident of Reactor and safety Evaluation is a two-phase thermal-hydraulic simulator used, in particular, in PWR safety analyses, the verification post-accidental operating procedures, and in research and development.
CFD	Computational Fluid Dynamics
CHX	Compact Heat Exchanger
DUHS	Diverse Ultimate Heat Sink
KONVOI	KONVOI is a standardized KWU construction line of PWR with about 1300 MW electrical power
Modelica	Real time running code to simulate parametric studies of the sCO2-HeRo and sCO2-4-NPP loop
NPP	Nuclear Power Plant
PWR	Pressurised Water Reactor
SBO	Station Black Out, an accident scenario where the plant is left without alternating current electrical power
sCO2	Supercritical Carbon Dioxide
TRL	Technology Readiness Level

1 Executive Summary

This deliverable D8.4 documents the End-user Workshop held online over two afternoons on 25th and 26th January 2022. The purpose of the workshop was to share intermediate project results with the public, particularly with potential end-users of the supercritical CO2 (sCO2) heat removal system. The workshop was originally foreseen as an in-person event at Month 24 of the project with demonstration of the sCO2 loop in the Glass Model at the premises of partner KSG in Essen, Germany. Due to the pandemic situation, the event was postponed to Month 29 and then modified into a fully remote event.

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

The discussion with the advisory board members is summarised and the presentations from the public session are provided in the appendix.

Project partners shared their intermediate results on all main aspects of development.

- Valuable experience was gained with sCO2 loop experiments in the Glass Model. These experiments also provided the benchmark comparison with thermohydraulic codes.
- Numerical simulations with ATHLET show that the modular structure will work with PWR KONVOI. Depending on reactor type, three or four sCO2 systems are required to adequately remove decay heat in an accident scenario.
- In principle there are no regulatory showstoppers and not many obstacles to integrate the sCO2 heat removal system in existing nuclear power plants or in new designs.
- Based on the performance maps, the turbo-compressor design has a higher reliability than its predecessor. Testing with magnetic and gas bearings show the feasibility of the use of the bearings with sCO2.
- The innovative compact heat exchanger design has been patented.
- For the system architecture, the DUHS (ambient air) footprint is larger than expected, but opportunities for optimisation exist (alternative cooling system, reduction of CO2 storage, connection with existing pipes).
- Preparations for real-time simulation of the sCO2 system in the KONVOI NPP simulator are in progress.
- Technical, regulatory and financial roadmaps are being defined to bring the sCO2 system to commercial exploitation in an NPP.

A final public dissemination event will be organised on 8-9 June 2022 in Essen, Germany.

2 Introduction

This document summarizes the sCO2-4-NPP End-user Workshop held 25th and 26th January 2022. Firstly, the purpose of the workshop is detailed, including the audience for the two sessions. In the following sections, the organisation of the workshop is described, with the communication campaign, the workshop format and the agenda. A summary of the discussion is then provided. Finally, the presentations from the second, public session are provided in the appendix.

3 Purpose of Workshop

An End-user Workshop was foreseen in the Grant Agreement at M24 (August 2021) with the goal of collecting feedback from the End-user Group of external advisors and making adjustments to the sCO2 system if necessary. Plans were made to organise the workshop in M26 (October 2021) at KSG in Essen, Germany, to include demonstrations of the transient loop behaviour of the system at the PWR Glass Model. However, due to the ongoing pandemic situation and to project technical delays, the End-user Workshop was rescheduled to M29 (January 2022) and ultimately held in a fully remote format.

3.1 Target Audience

The End-user Group of external advisors were the main target audience for this event, but as it was conceived as a public event, a broader audience was also targeted, with the intention to include end-users from other sectors, component manufacturers, and the scientific community from related research projects. The interest in attending the workshop for this broad target audience largely falls into two categories:

- Nuclear energy experts: To learn what sCO2 technology can provide for the nuclear industry
- sCO2 experts: To learn about sCO2 developments for the nuclear power application (magnetic bearings, heat exchanger design, etc.)

The workshop was split into two sessions, the first session with the advisory board allowing a narrower focus on the specific application of the sCO2 system in the nuclear power plant, and the second session for the general public with a broader focus on the utilisation of the sCO2 system in other applications.

3.1.1 Advisory Boards

The sCO2-4-NPP project has two boards of external advisors, the End-user Group and the sC02-4-NPP Advisors.

To ensure industrial relevance and future adoption of the sCO2-4-NPP system in the nuclear and other power generation industries, the End-User Group assesses project developments and provides feedback from the end-user perspective, representing operators of different NPP types from different regions and industrial manufacturers of the sCO2 system components.

The SCO2-4-NPP Advisors provide advice to the project on compliance with nuclear safety regulations as well as specific scientific and technical issues (e.g. sCO2-cycles, ATHLET calculations).

The advisory boards include representatives of RWE, Framatome Germany, the Swiss Federal Nuclear Safety Inspectorate (ENSI), TÜV-SÜD, and Naval Group. All external advisors were invited and attended the 25th January session.

3.1.2 General Public

Among the general public who expressed interest in attending the event were engineers and managers in the energy industry and in related academic fields. Twenty-one persons registered for the workshop public session and eleven persons attended, in addition to the project partners. The persons who finally attended the event tended to be more from academia. Included in the list below are two organisations which are project partners, simply because the persons registered are not directly involved in the project.

Table 1: Workshop registration

Organisation	Registered	Attended
Baker Hughes	1	0
Cranfield University	3	3
Engie	1	0
ETN Global	1	1
KSG	1	1
Politecnico di Milano	1	1
Preussen Elektra	1	1
Siemens Energy	1	0
TLK-Thermo GbmH	1	0
Total Energies	4	0
TÜV SÜD	1	0
Università degli Studi Roma Tre	1	1
University of Genoa	1	1
Unknown	4	2
TOTAL	**22**	**11**

3.2 Communication campaign

A communication campaign was necessary to enlarge the audience for the public session. The campaign was undertaken with an announcement (see Figure 1) in electronic version and diffused using the following channels:

- ETN Global, which groups several organisations involved in gas turbine technology and has a Working Group on sCO2. The sCO2-4-NPP workshop announcement was shared within their professional network.
- sCO2-4-NPP public website and social media accounts on Twitter and LinkedIn.
- Diffusion of workshop announcement by project partners to their professional networks

Figure 1: Workshop Announcement

The communication campaign was launched nine days before the public session. The project social media accounts registered over 750 views and 11 shares for LinkedIn and over 100 impressions for Twitter.

4 Organisation of Workshop

4.1 Workshop format

Although the workshop was originally conceived as an in-person event with demonstration of the sCO2 loop, due to the pandemic travel advisories and sanitary protocols, a fully remote format was finally necessary. The agenda was revised and shortened to correspond to the remote format.

4.2 Agenda

The agenda was slightly different between the first session for the advisory board members, who have signed an agreement with the sCO2-4-NPP consortium to protect project confidential information, and the second session for the general public.

Table 2: Agenda Day 1: 25 January: End-user workshop - Focus on sCO2 loop in nuclear application

Start	End	Duration	Topic	Presenter
14:00	14:15	0:15	Welcome & Project Overview	Albannie Cagnac (EDF)
14:15	14:35	0:20	sCO2 loop/Glass model: Test data, lessons learnt & validation of thermal-hydraulic codes	Frieder Hecker (GfS)
14:35	14:50	0:15	Simulation: sCO2 loop with scaled-up components	Michael Buck (USTUTT)
14:50	15:05	0:15	Licensing requirements & regulatory framework	Andrej Prošek (JSI)
15:05	15:25	0:20	Components development: Turbomachine and heat exchanger design	Haikun Ren (UDE) + Guillaume Taiclet (FIVES CRYO)
15:25	*15:40*	*0:15*	*Coffee Break*	
15:40	16:00	0:20	Simulation: Architecture of sCO2 loops integrated in NPP	Albannie Cagnac (EDF)
16:00	16:20	0:20	Validation of sCO2-4-NPP loop in a virtual “KONVOI” PWR	Peter Lasch (KSG)
16:20	16:40	0:20	Roadmap toward exploitation: Regulatory policy, requirements & way forward	Albannie Cagnac (EDF)
16:40	17:00	0:20	Q&A roundup & Conclusion	Albannie Cagnac (EDF)
17:00			*End of meeting*	

Table 3: Agenda Day 2: 26 January - Public Workshop - Focus on sCO2 loop generally

Start	End	Duration	Topic	Presenter
14:00	14:15	0:15	Welcome & Project Overview	Albannie Cagnac (EDF)
14:15	14:35	0:20	Introduction to sCO2 loop/Glass model: Test data, lessons learnt & validation of thermal-hydraulic codes	Frieder Hecker (GfS)
14:35	14:55	0:20	Components development: Turbomachine and heat exchanger	Haikun Ren (UDE) + Guillaume Taiclet (FIVES CRYO)
14:55	*15:05*	*0:10*	*Coffee Break*	
15:05	15:25	0:20	Simulation: sCO2 loop with scaled-up components & Architecture of sCO2 loops integrated in NPP	Albannie Cagnac (EDF)
15:25	15:45	0:20	Roadmap toward exploitation: Regulatory policy, requirements & way forward	Albannie Cagnac (EDF)
15:45	16:00	0:15	Q&A roundup & Conclusion	Albannie Cagnac (EDF)
16:00			*End of meeting*	

5 Discussion

A summary of the main discussion points from the first session is provided below.

5.1 Project progress

The project partners are currently working to finalise the design of the sCO2 system integrated in a nuclear power plant (NPP) and to prepare the real-time simulation model of the sCO2 heat removal system to be integrated into the NPP simulator.

5.2 sCO2 loop/Glass model

The bearings of the previous sCO2-HeRo turbomachine were lubricated with oil-based lubricant which is problematic for sCO2. The system behaviour with sCO2 was studied, including observation of leakages, dissolved substances and foreign particles. The concept with the sCO2-4-NPP turbomachine was to keep sCO2 in a gaseous state near the bearings.

The results of the benchmark test show a good correspondence between the codes ATHLET and Modelica and the measurements taken (see Appendix slide 24 “Some results of benchmark test”). Comparison with the code CATHARE was not possible at that time as a library was missing.

5.3 Simulation: sCO2 loop with scaled-up components

The simulation of the sCO2 loop with scaled-up components showed the heat removal capacity using zero to four sCO2 systems. Depending on the NPP type, three to four systems are necessary with sequential shutdown to adapt to the declining decay heat and extend the grace period beyond 72 hours (see Appendix slide 8 “Integration in thermohydraudic codes”).

A question was raised about the risks of scaling up, especially taking into account non-linear risks and difficulties with 2-phase CO2. For the scaling-up of the turbomachine, performance maps and CFD methods were used. For the compact heat exchanger (CHX), the scaling-up was done via calculating the channels then by extension to more channels.

The scenario studied for the simulation is a Station Black Out (SBO), meaning no power is available to start the back-up safety systems. The idea is to compare the function of the sCO2 heat removal system with a safety condenser (SACO) system, not with a probability study of having a diesel generator.

5.4 Licensing requirements & regulatory framework

There is no international standard for the use of sCO2 equipment in the nuclear power industry. In the project, the approach was to take known standards (manuals, sub-components, testing, etc.) and give requirements to the partners upscaling components, i.e., to use class 3 or 2 materials.

Now, an independent assessment is underway comparing WENRA RL 2020, Issue Q: Plant Modifications and IAEA GSR Part 4 standard for safety aspects with the French and Czech requirements compiled for the sCO2 system in an NPP.

5.5 Components development: Turbomachine and heat exchanger

Magnetic bearings and gas bearings were tested for the improved turbomachine. Both showed promising results for use with sCO2. The turbomachine maximum rotational speed is 40,000 rpm.

The design of the compact heat exchanger has been patented.

For the Diverse Ultimate Heat Sink (DUHS) using ambient air, a 13.5m*6.2m*10m high footprint is needed for 10 Mw with this design. The partners see means for further optimising the DUHS design.

5.6 Simulation: Architecture of sCO2 loops integrated in NPP

For boundary conditions, the same parameters were used as for existing plants (for heat, earthquake, etc.). For the simulation, extreme temperatures of -45°C to +45°C were used on the thermonuclear model. Temperature extremes were also considered with regard to designing the structure to house the sCO2 system.

For the DUHS, air cooling was chosen because in an accident situation with no access to water, air cooling will always work. If, in future, the sCO2 system is considered for other operational scenarios, a water or water and air system could be chosen.

5.7 Validation of sCO2-4-NPP loop in a virtual "KONVOI" PWR

The interface with the sCO2 loop has been defined with a direct connection with the Main-Steam line and Steam-Generator sampling line. Challenges remain, including interfacing the system with a control option.

5.8 Roadmap toward exploitation: Regulatory policy, requirements & way forward

Aging effects must be considered for the equipment qualification. sCO2 has a corrosive effect on materials.

Project experience has shown that the ways of working with safety authorities on qualification of new technologies differs somewhat depending on the country and can be taken into account for the regulatory roadmap.

An intermediate R&D step is needed to better understand 2-phase conditions and to make the system more reliable. Other non-nuclear sCO2 projects are also addressing these issues. Project partners are working to build an international community around the sCO2 technology, with partners of other projects focused on sCO2 in concentrated solar power and in waste heat recovery. All parties have similar issues and can benefit from sharing problems encountered and solutions tested. Scale-up to a full-size pilot system is necessary to test solutions.

A hot standby system application could also be considered. Modularity and flexibility are the goal of the sCO2-4-NPP sCO2 system, which also makes the system more applicable to other uses.

5.9 Q&A roundup & Conclusion

Positive feedback was received from members of the advisory board on the considerations taken into account for the next steps of equipment qualification, on the multidisciplinary consortium, on the results achieved regarding safety aspects and on the development of components. Project partners were advised to resolve the problems as soon as they are identified to minimize risks associated with scale-up and to make the steps between TRL 5 and TRL 7 easier to manage.

6 Conclusion

Despite the challenges of having to postpone and then modify the workshop for a fully remote format, the project achieved its main goal of sharing the progress and intermediate results with potential end users and the public at large. For future events, the communication campaign will start earlier to attract a larger number of participants.

The questions received and feedback obtained were smaller than expected and were perhaps limited by the remote format. However, the feedback received was encouraging and the project partners expect to build on this exchange with the advisory board members in the coming months. Persons who registered for the event will also be contacted strictly with regard to workshop follow-up (provision of a link to presentations).

A final public dissemination event is scheduled for 8^{th} and 9^{th} June 2022 in Essen, Germany. This in-person event will be publicized through the same channels. The event will include presentation of final project results and a demonstration of the interaction of the sCO2-4-NPP system with the virtual NPP in the KONVOI PWR simulator.

Appendix A Workshop Presentations

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

End-user Workshop

25th – 26th January 2022

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

PROJECT OVERVIEW

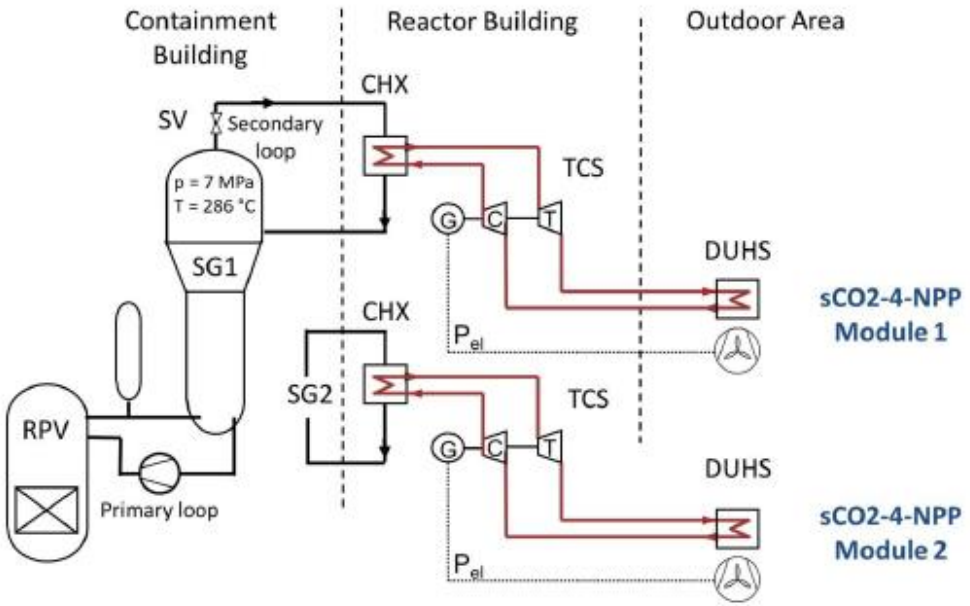
Albannie CAGNAC,
EDF

Joerg STARFLINGER,
USTUTT

SCO2-HEAT REMOVAL SYSTEM

The vision: sCO2-System

- Electricity made out of decay heat
- Modular
- Self-starting
- Self-sustaining
- Retrofittable for existing PWR, BWR, …
- Innovative power conversion system for SMR, GEN IV…

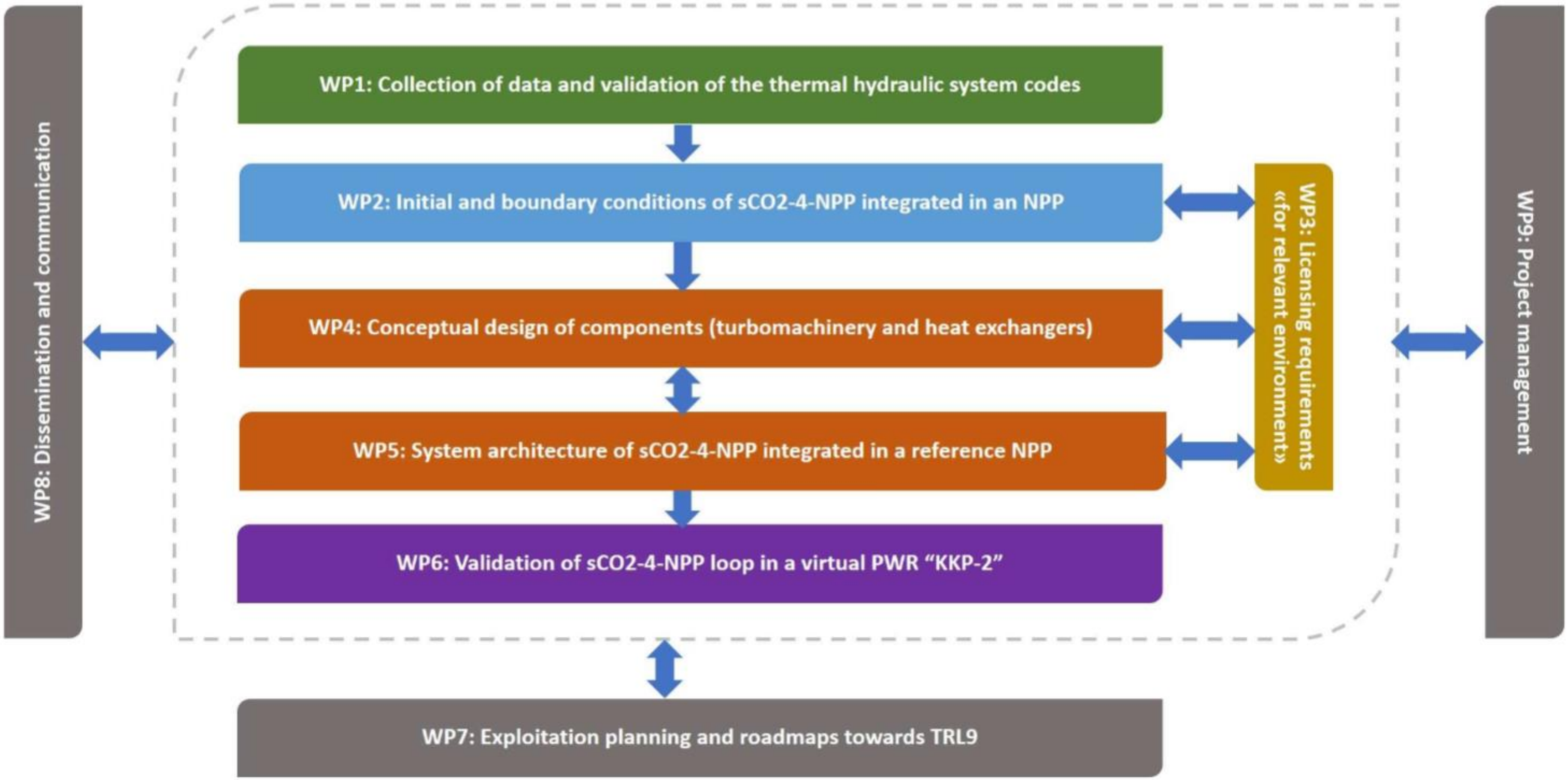


Project Objective: Development of an Innovative sCO2-Based Heat Removal Technology for an Increased Level of Safety of Nuclear Power Plants

GENERAL OBJECTIVES

- Enhanced sCO2 Heat Removal system validation
  - Validation of the sCO2 models with 2 codes : ATHLET and CATHARE (french code)
  - Validation on PWR reactors like western reactors with the 2 codes
  - Operation of the system integrated into PWR simulator
- Preparation of the industrial scaling up
  - Specification of upscaled components for implementation in a full-scale NPP
  - Final design of the system architecture integrated to a real design of PWR reactor
  - Licensing roadmaps and licensing requirements for the upscaled components and the overall system

SCO2-4-NPP WORK PLAN STRUCTURE



SPECIFIC OBJECTIVES AND ASSOCIATED TASKS

- Objective 1: Validation of sCO2 models in thermal-hydraulic system codes on lab scale
  - Test and data generation on performance of sCO2-HeRo system
  - Validation/improvement of ATHLET, ATHLET/Modelica and CATHARE codes
- Objective 2: Specification of an upscaled system, boundary conditions and simulations for implementation of sCO2-4-NPP loop in a full-scale NPP (PWR)
  - Definition of initial- and boundary conditions for an SBO accident
  - Simulation of sCO2-4-NPP loop in a real NPP using scaled-up component models in codes
- Objective 3: Preparation of a licensing roadmap of the sCO2-4-NPP system to ensure compliance with application regulation
  - Identification of the regulatory elements to be considered in the design of components and system
  - Identification of requirements and criteria for reference plant modification on heat recovery system installation
  - Design bases and safety analyses for system and component and Requirements for testing and operation
  - Independent review of requirements

SPECIFIC OBJECTIVES AND ASSOCIATED TASKS

- Objective 4: Design of components for the sCO2-4-NPP loop in the context of licensing requirements (turbomachinery, heat exchanger, auxiliary systems)
  - Improvement and Design of the sCO2-4-NPP turbomachine
  - Conceptual design of the heat exchangers
  - Optimisation of the heat sink HX and heat recovery exchanger
  - Qualification according to Nuclear requirements for Turbomachinery and HX
- Objective 5: Final design of the system architecture of sCO2-4-NPP integrated in a full-scale NPP
  - System architecture design parameters
  - Thermodynamic cycle design
  - Simulation of sCO2-4-NPP loop in a real NPP using real design parameters
  - Dynamic simulations and control system modifications
  - Real-time simulations for implementation in PWR simulator

SPECIFIC OBJECTIVES AND ASSOCIATED TASKS

- Objective 6: Validation of sCO2-4-NPP loop in a virtual “relevant nuclear environment” PWR
  - Defining Interface for sCO2 system code to be implemented to simulator
  - Implementation of sCO2-system code into PWR simulator environment
  - Running Transients
- Objective 7: Prepare technical, regulatory, financial and organisational roadmaps to bring sCO2-4-NPP to market
  - Technological roadmap to reach TRL9
  - Regulatory roadmap to reach TRL9
  - Financial and organisational roadmap to reach TRL9

THE HERO-LOOP IN ESSEN IN WP1

WP 1

Frieder Hecker, GfS

CONTENT

THE HERO LOOP

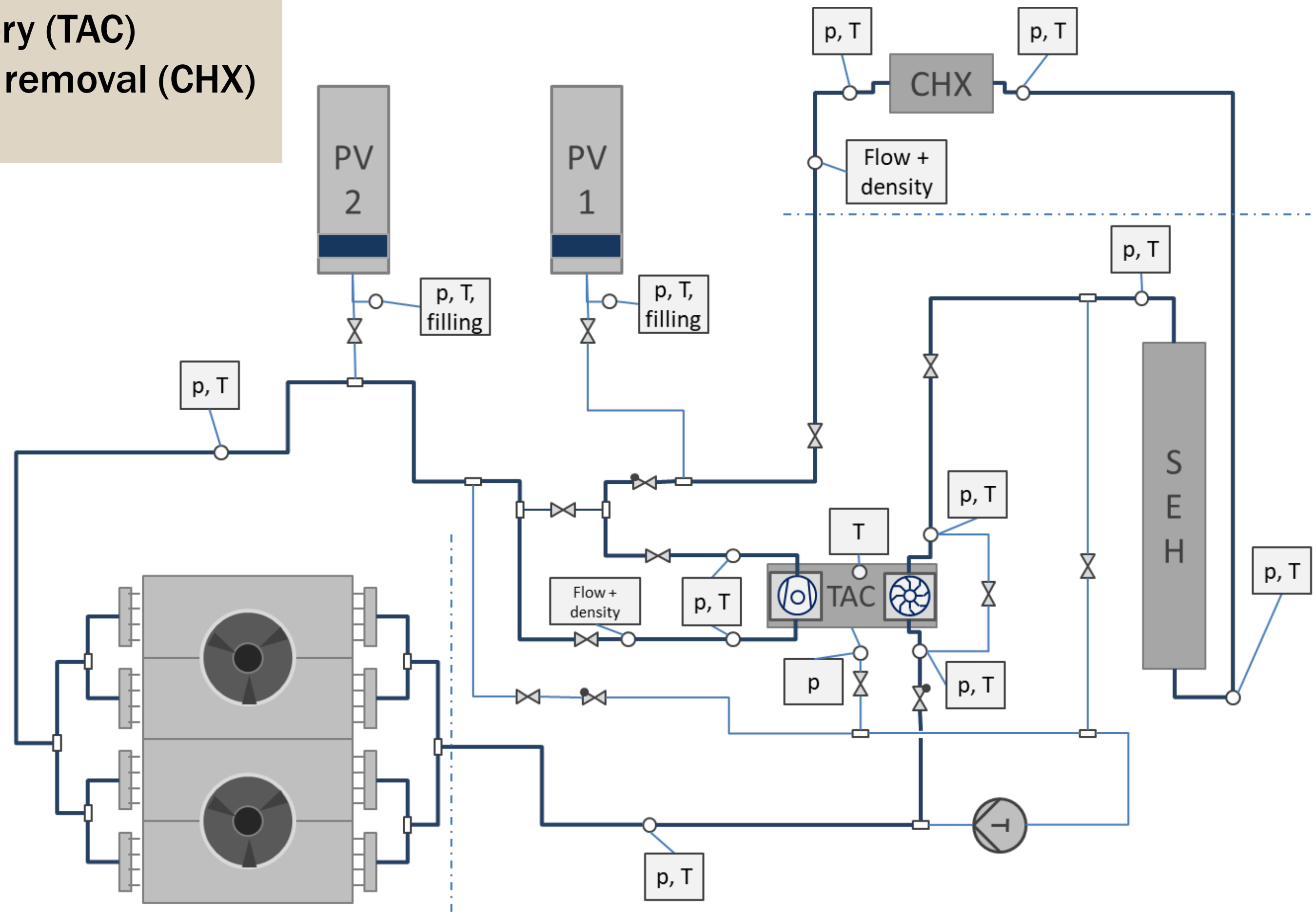
CO2-PROBLEMS

DATA FOR BENCHMARK CALCULATION

WP1

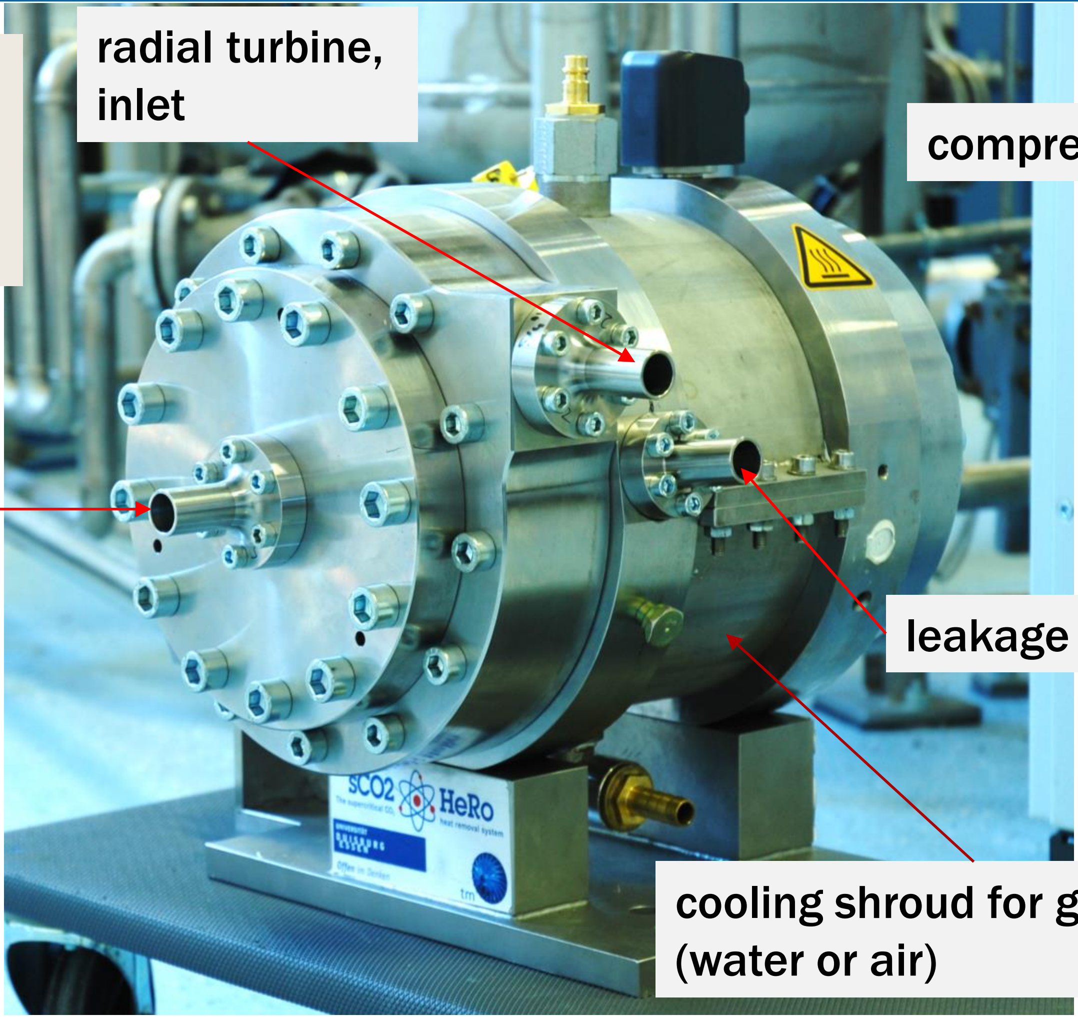
HERO-LOOP (SIMPLIFIED)

- **Test turbomachinery (TAC)**
- **Demonstrate heat removal (CHX)**
- **Study CO_2**



TURBOMACHINERY

- ~5 kW_{el}
- up to 50 000 rpm
- cooled internally by leakage flow

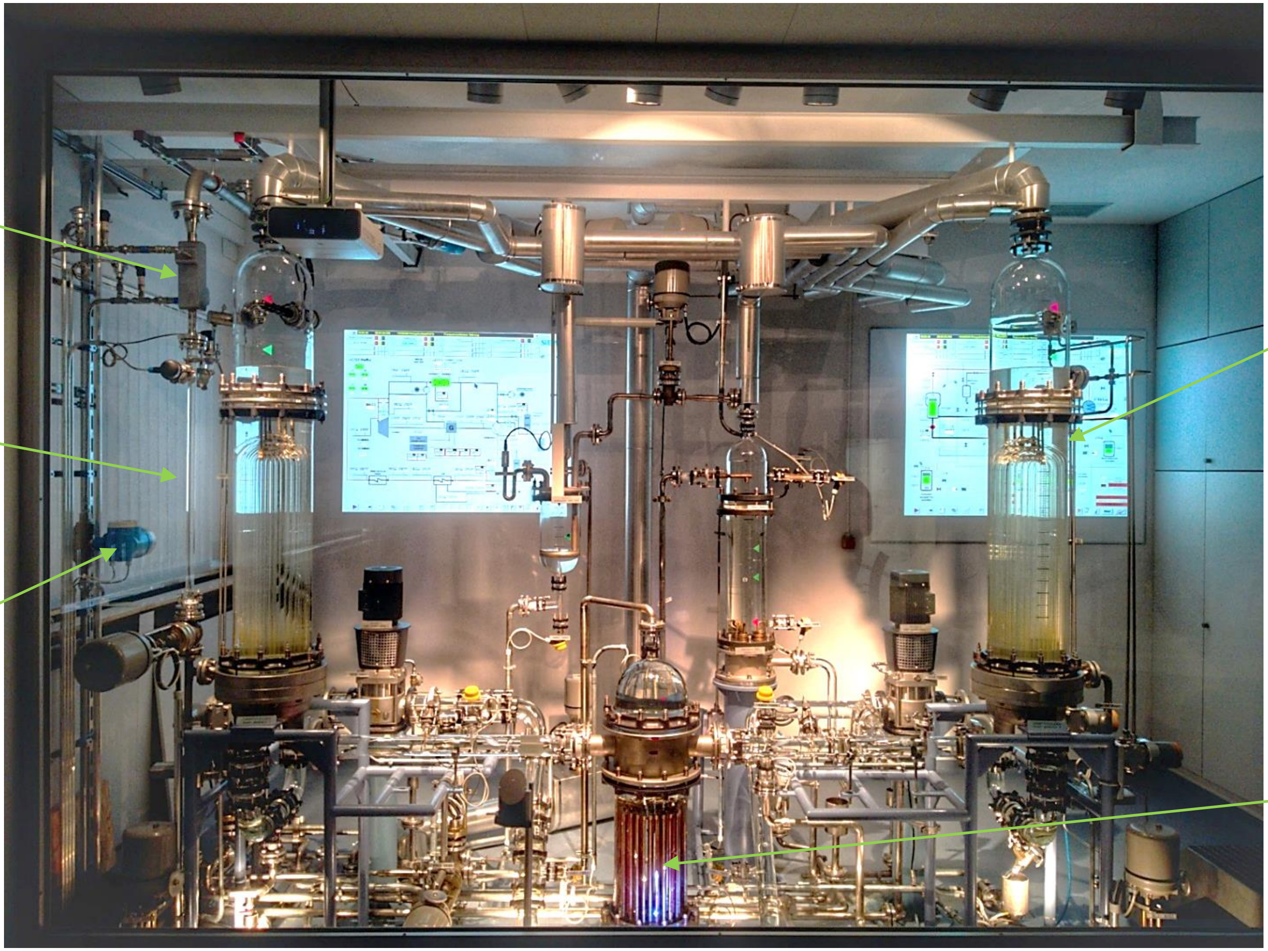


GLASS MODEL AND CHX

CHX,
> 15 kW

condensate
backflow

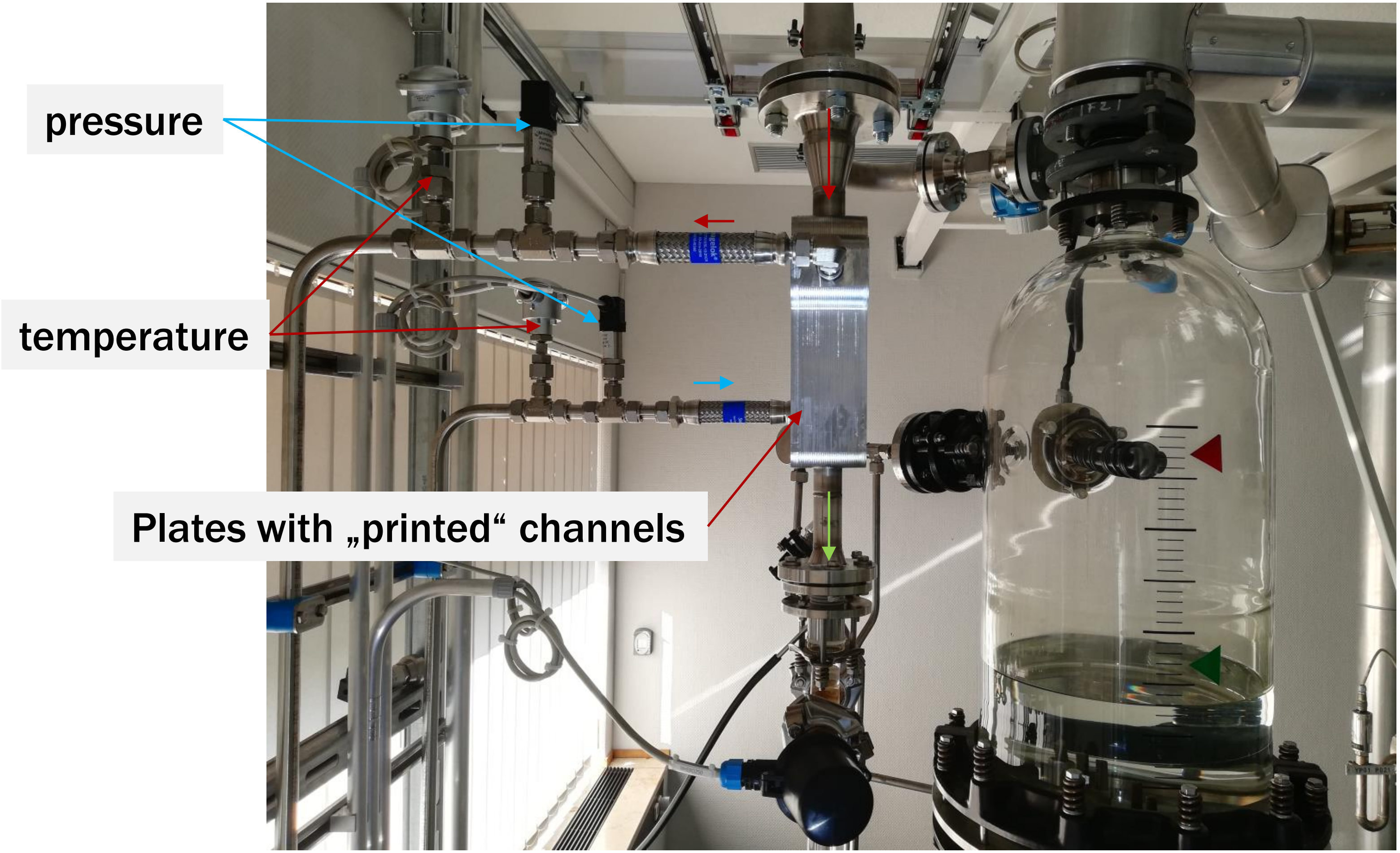
Coriolis:
flow and
density



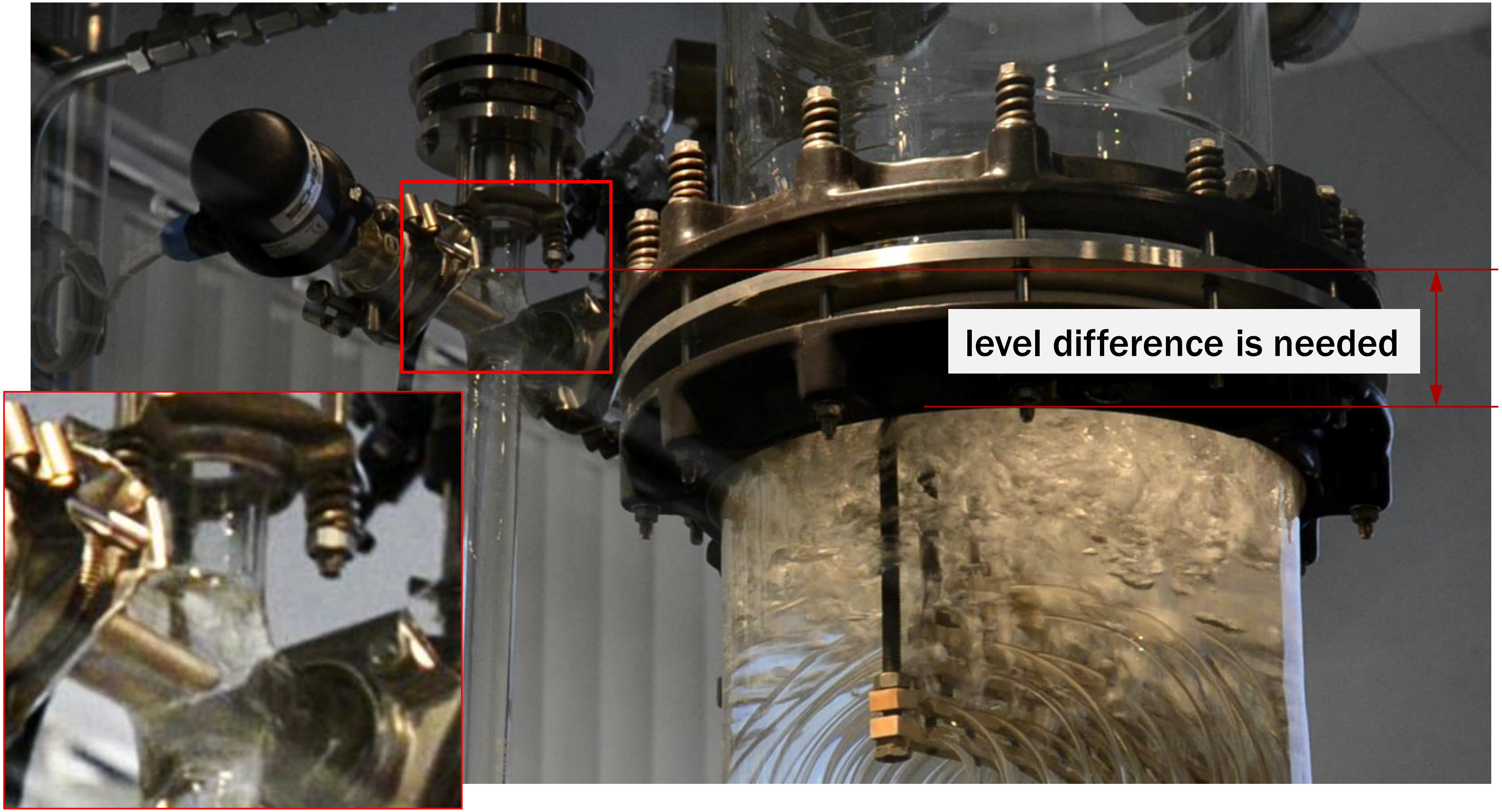
steam
generator

reactor,
up to
60 kW

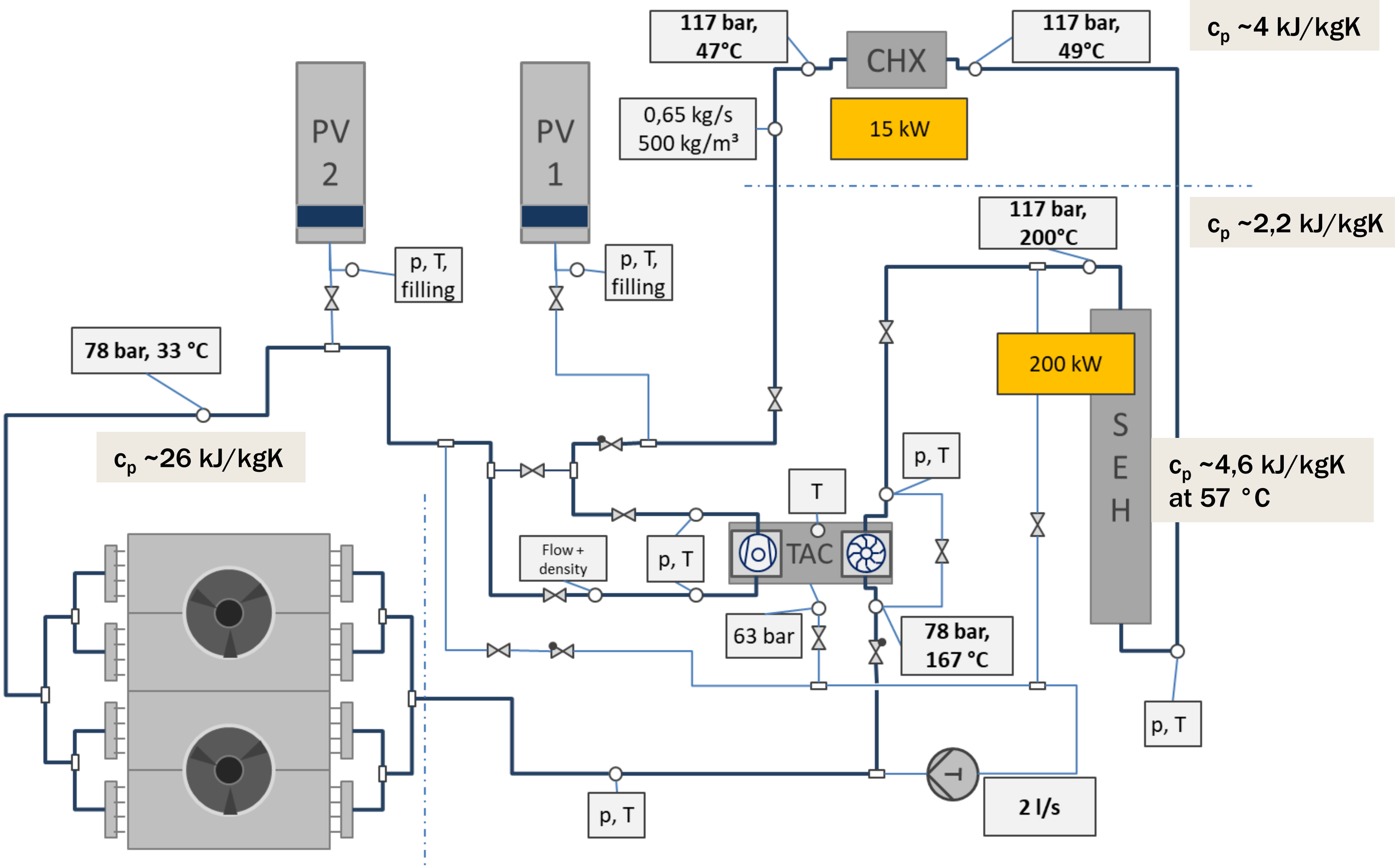
CHX WITH SENSORS



CONDENSATE BACKFLOW



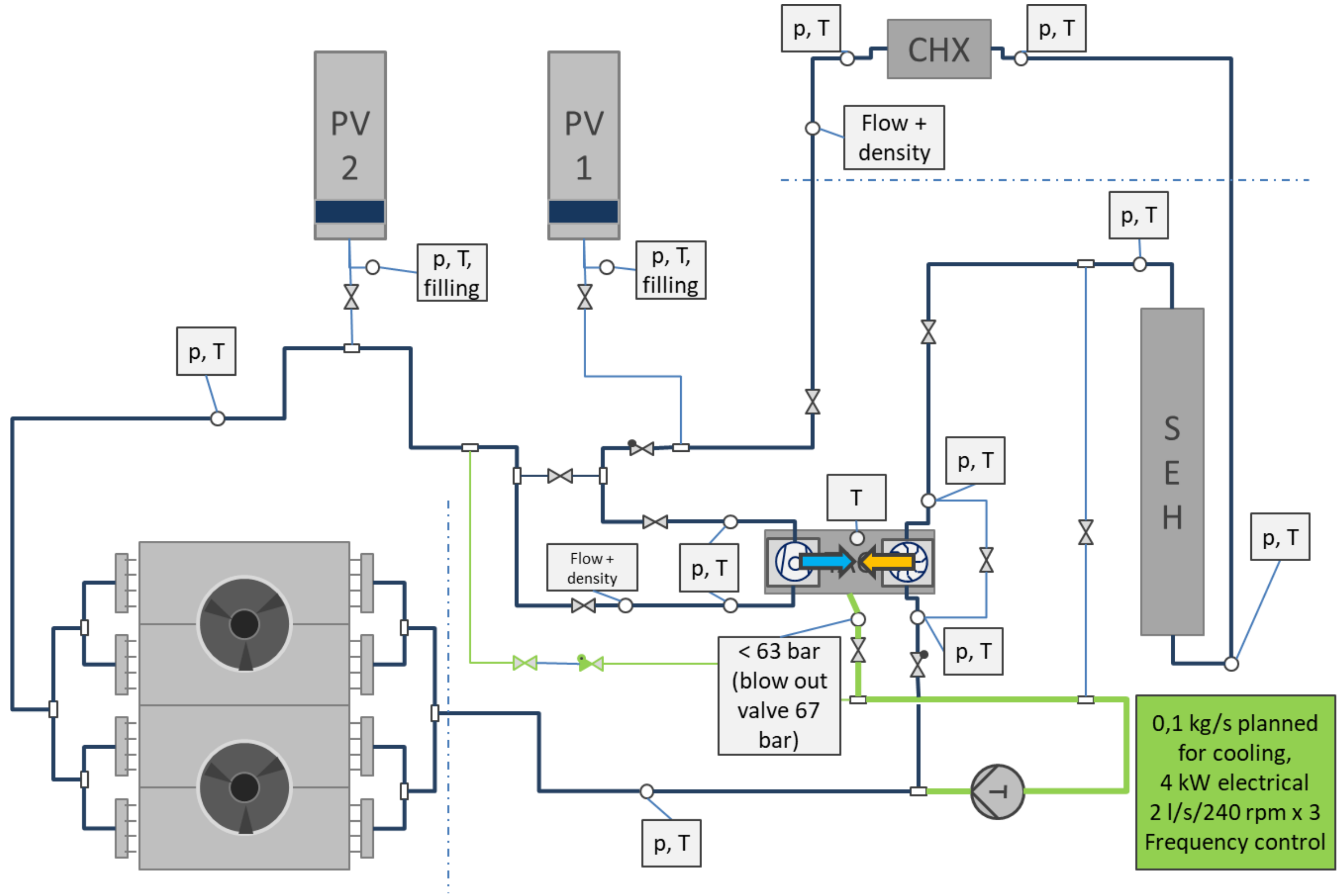
DATA PLANNED



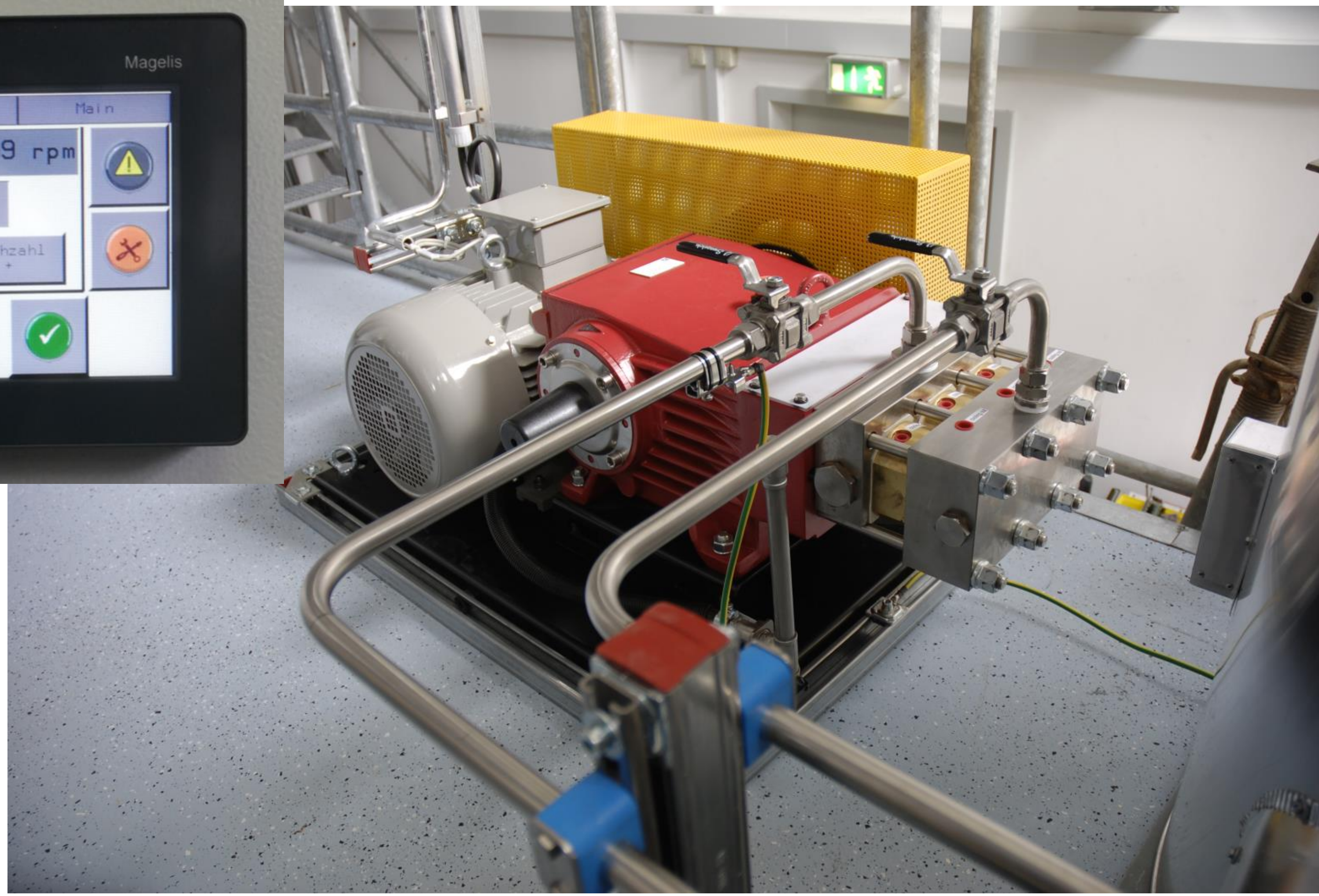
SLAVE ELECTRICAL HEATER

HEAT SINK

LEAKAGE (INNER COOLING OF TAC)



TRIPLEX PUMP (FREQUENCY CONTROLLED)



PISTON PRESSURE VESSELS

WP1(UDE)

Collection of data

and

validation of the

thermal hydraulic

system codes

Deliverable 1.1

Data on behaviour of the sCO2-HeRo-loop and the glass model (UDE, confidental)

Deliverable 1.2

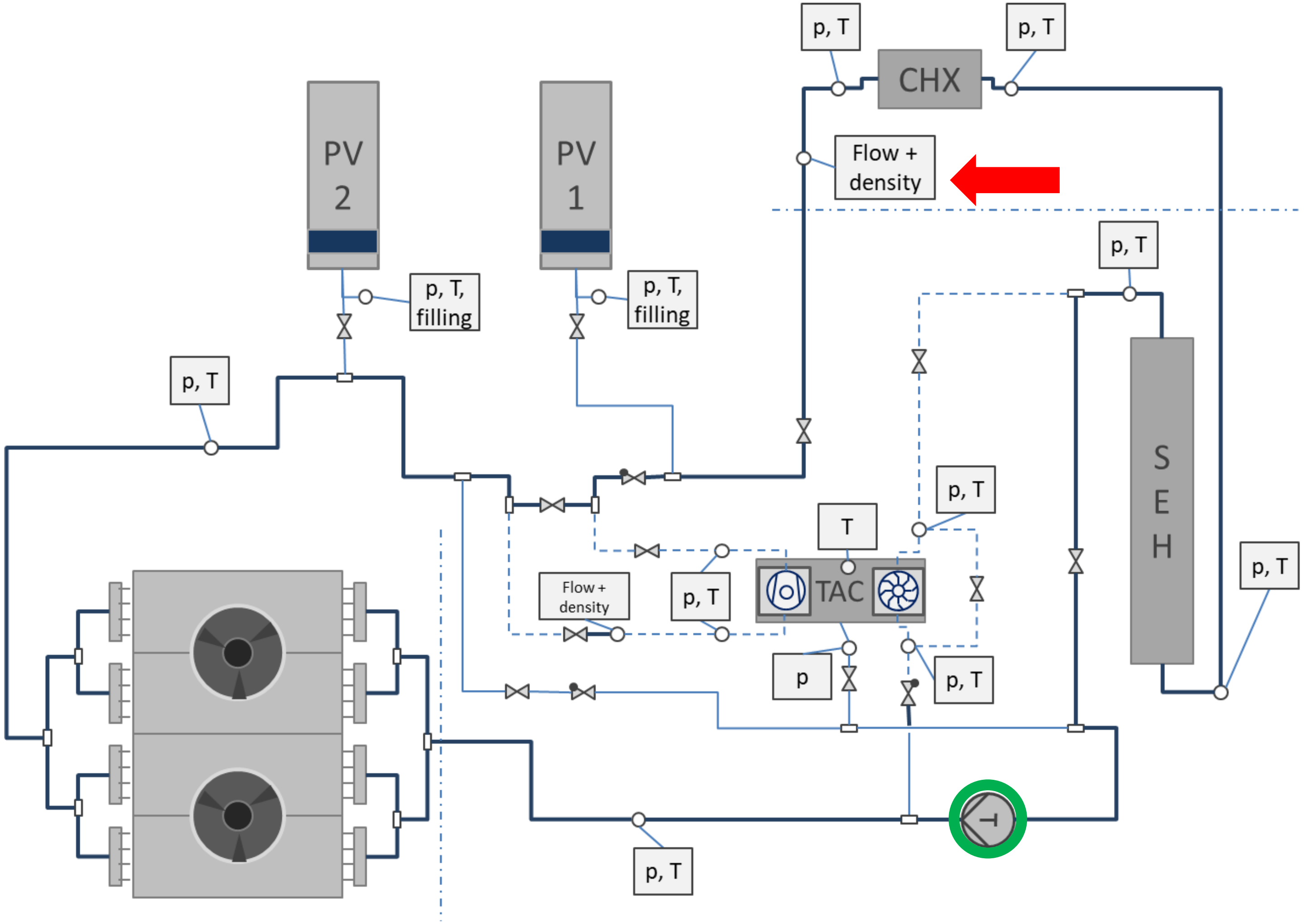
Report on the validation status of codes and models for simulation of sCO2-HeRo loop (USTUTT, Public)

LEARN TO HANDLE THE CO2-SYSTEM (DATA ON BEHAVIOUR)

Some Problems:

- Filling and Mass content
- Dual phase vs. supercritical state
- Loss of CO2 from small leaks
- Impurities and foreign bodies
- Valve characteristics
- Measuring errors
- Vibrations and oscillations

CIRCULATING: MASS CONTENT BY DENSITY



sCO2-4-NPP

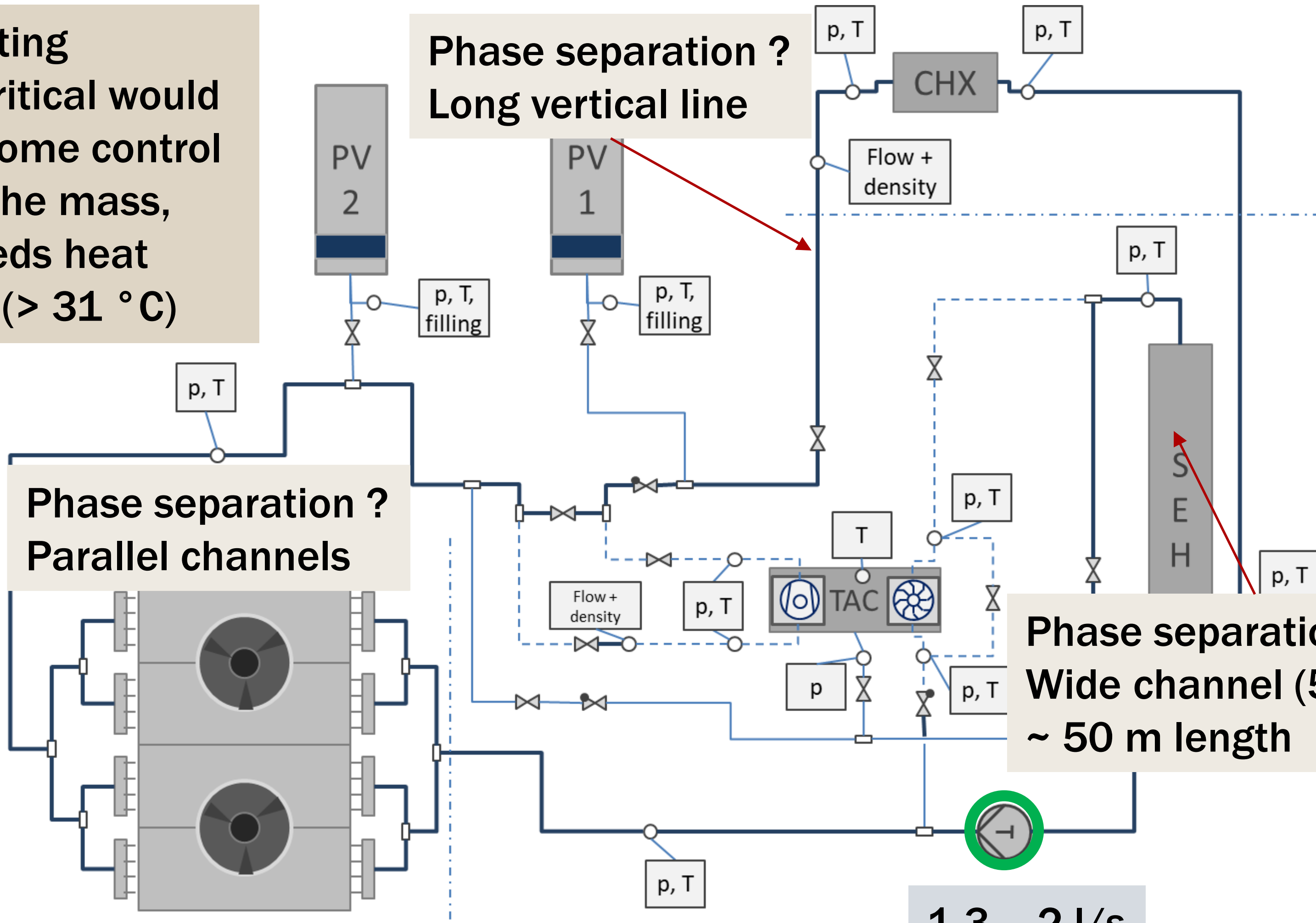
CIRCULATING A MIXTURE – PHASE SEPARATION

Circulating supercritical would allow some control about the mass, but needs heat source (> 31 °C)

Phase separation ? Long vertical line

Phase separation ? Parallel channels

Phase separation ? Wide channel (50 mm), ~ 50 m length

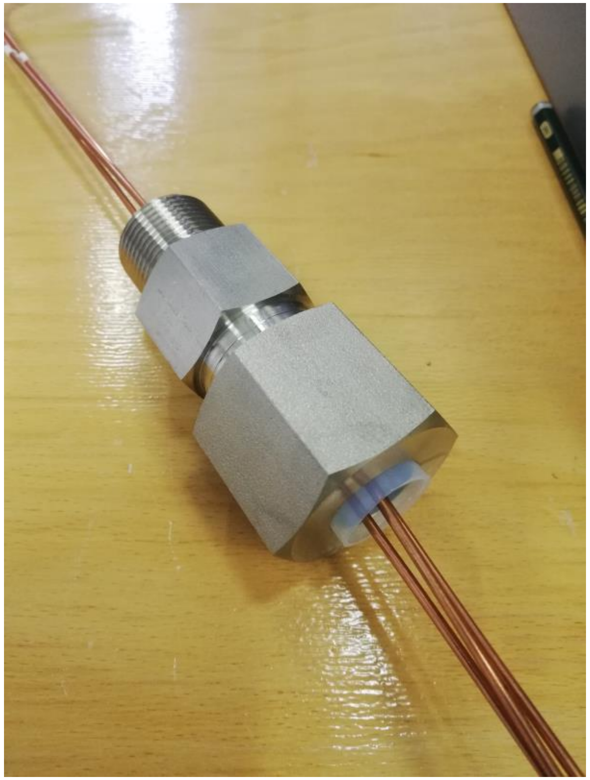


1.3 – 2 l/s

CABLE LEAKAGE

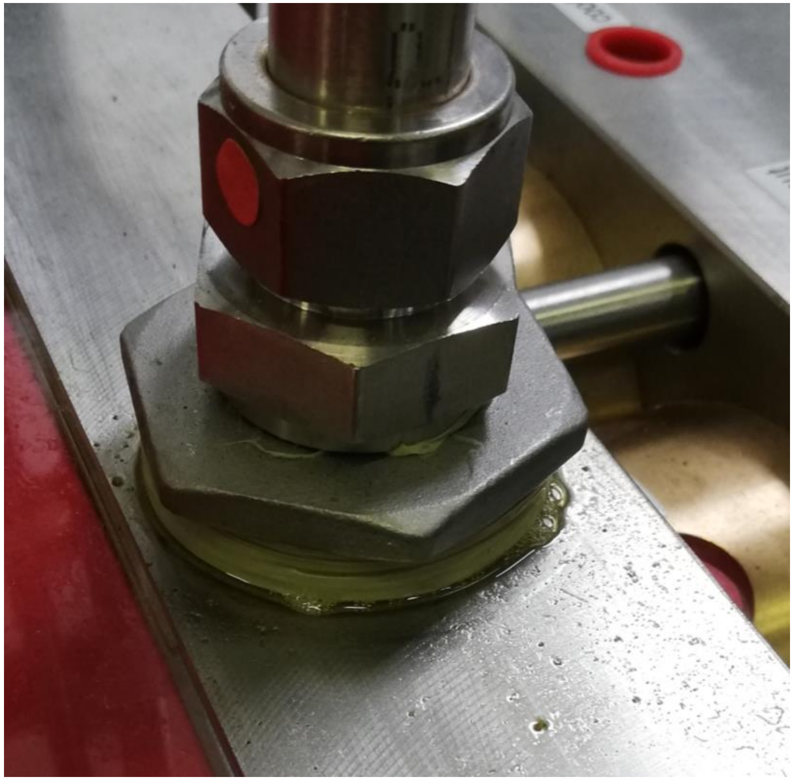
Burst isolation of a flex

contact gland seal, massive wire



LEAKAGES

Oil & water (from CO2)

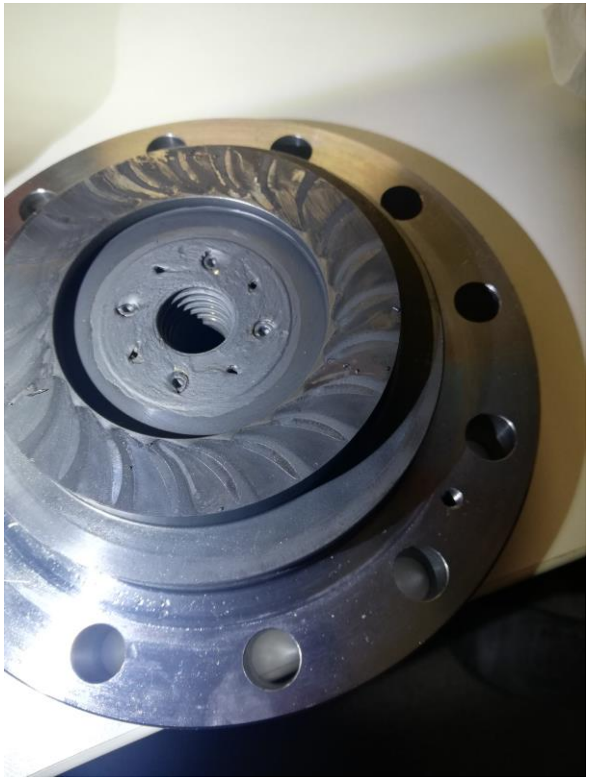


Leakage detection at generator

DISSOLVED SUBSTANCES

PP outlet valves

Graphite? (Turbine)

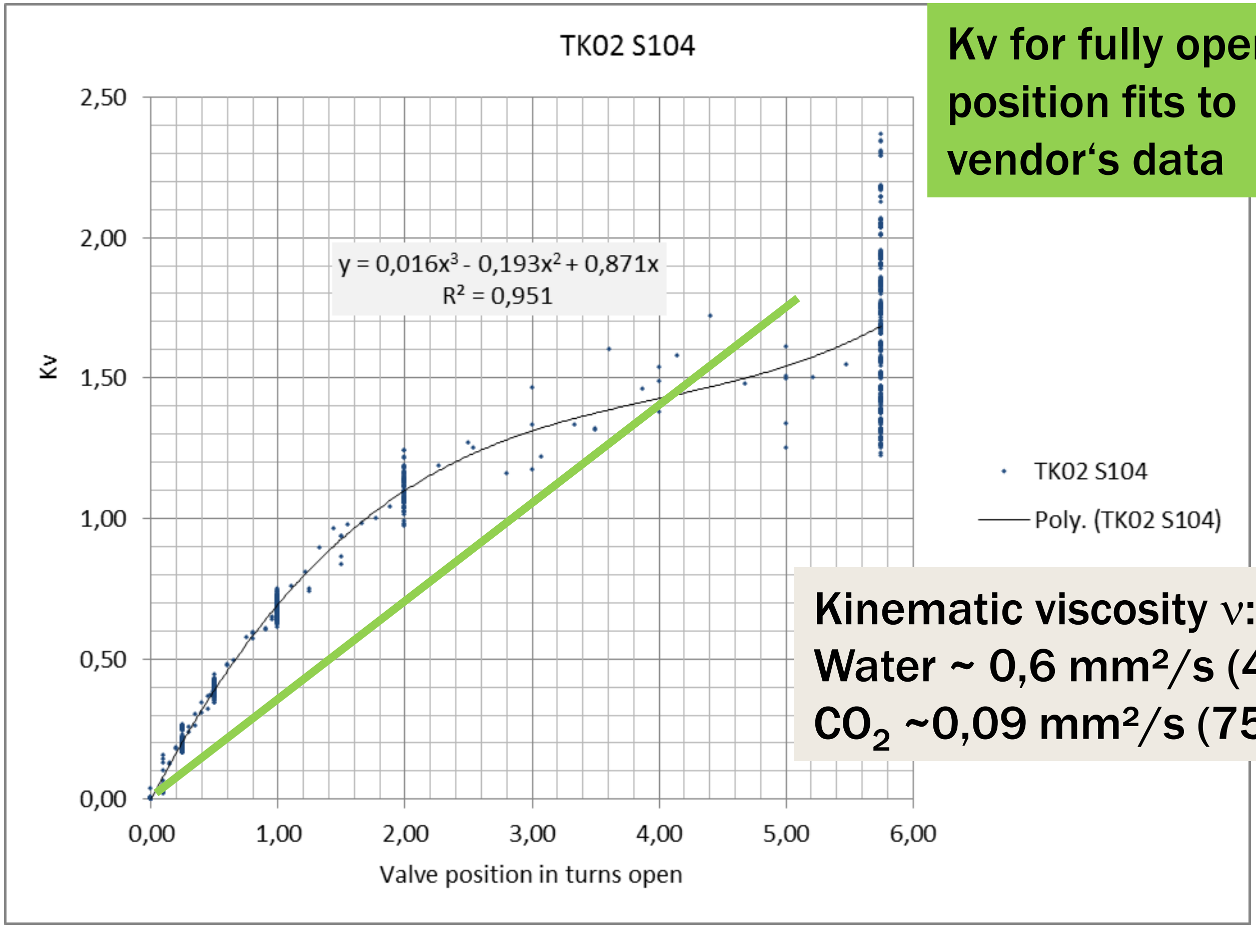


FOREIGN PARTICLES

From inlet of CP

Filter (since WP4)

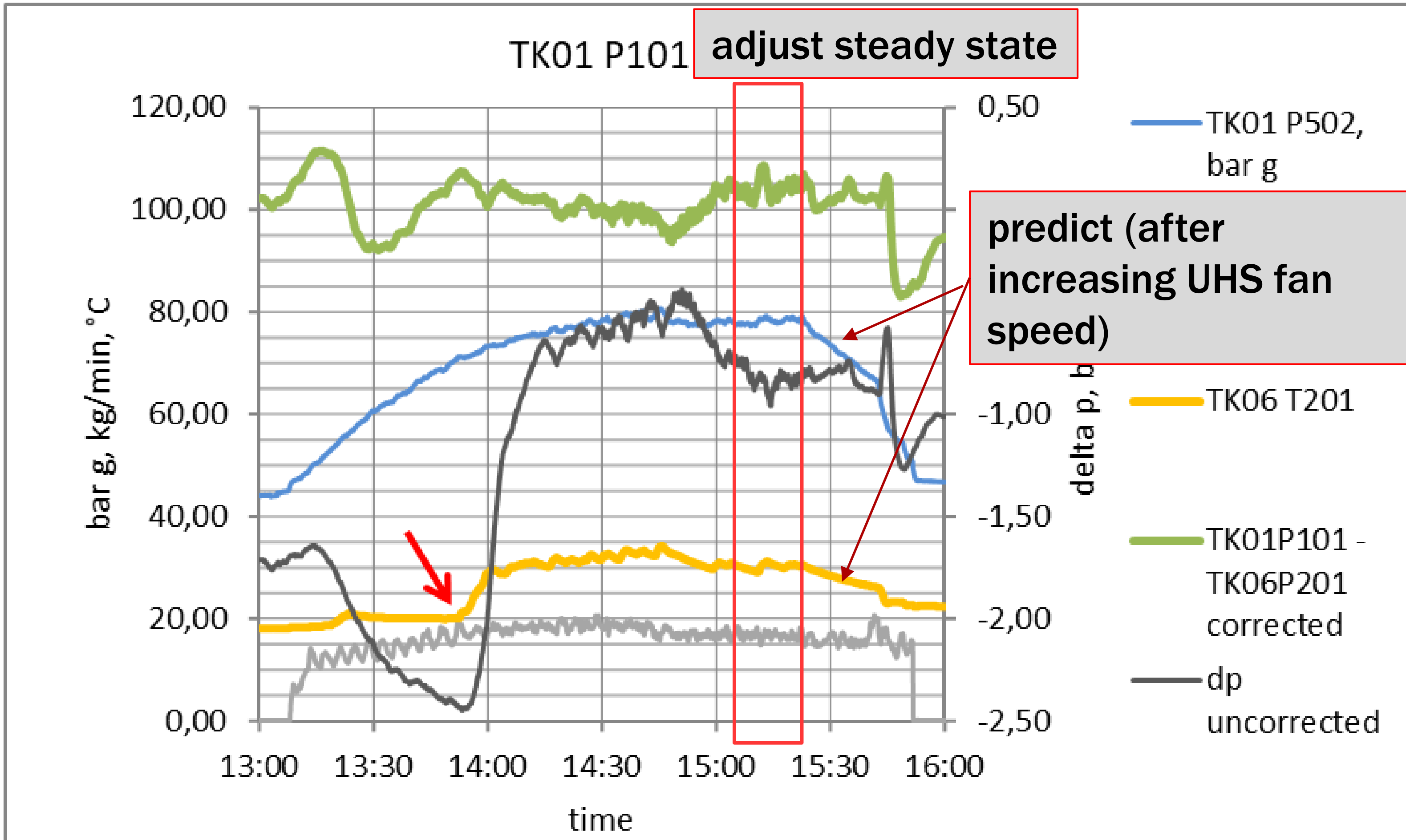
„LINEAR CHARACTERISTIC“ (MAYBE, FOR WATER)



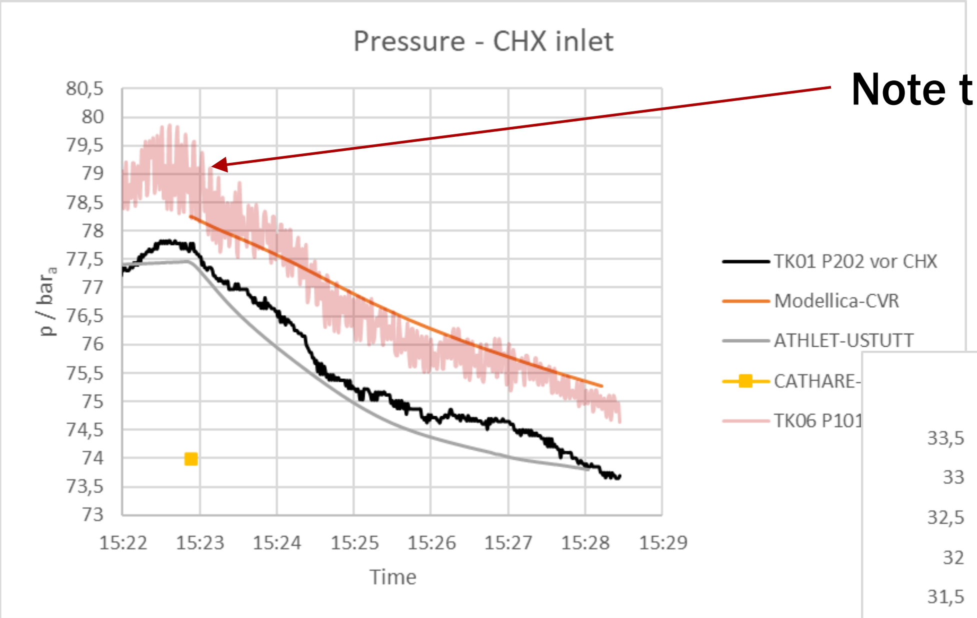
Kv for fully open position fits to vendor‘s data

Kinematic viscosity ν:
Water ~ 0,6 mm²/s (45 °C)
CO_2 ~0,09 mm²/s (75 bar, 45 °C)

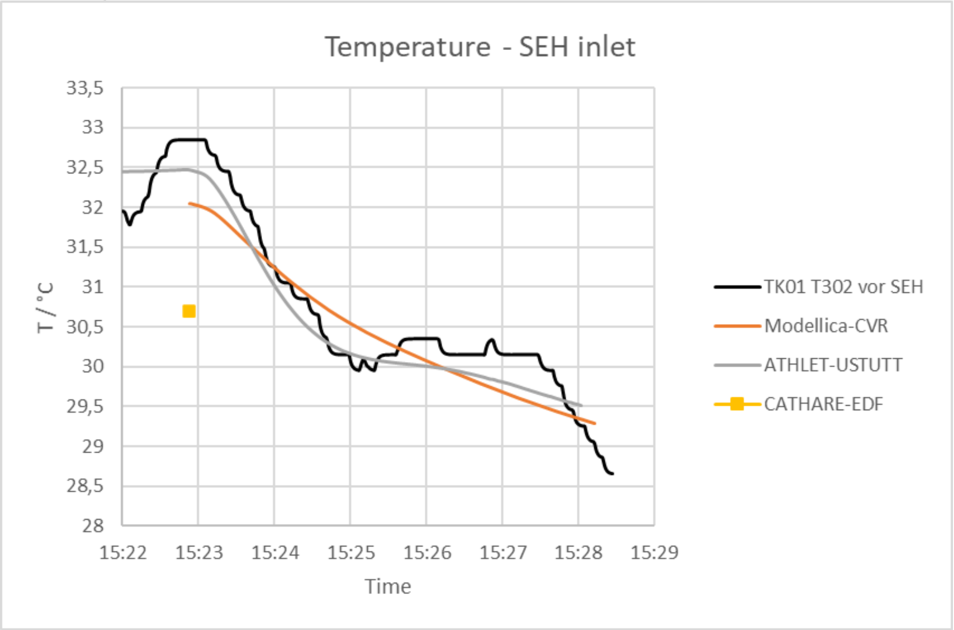
THEN: BLIND TEST FOR BENCHMARK



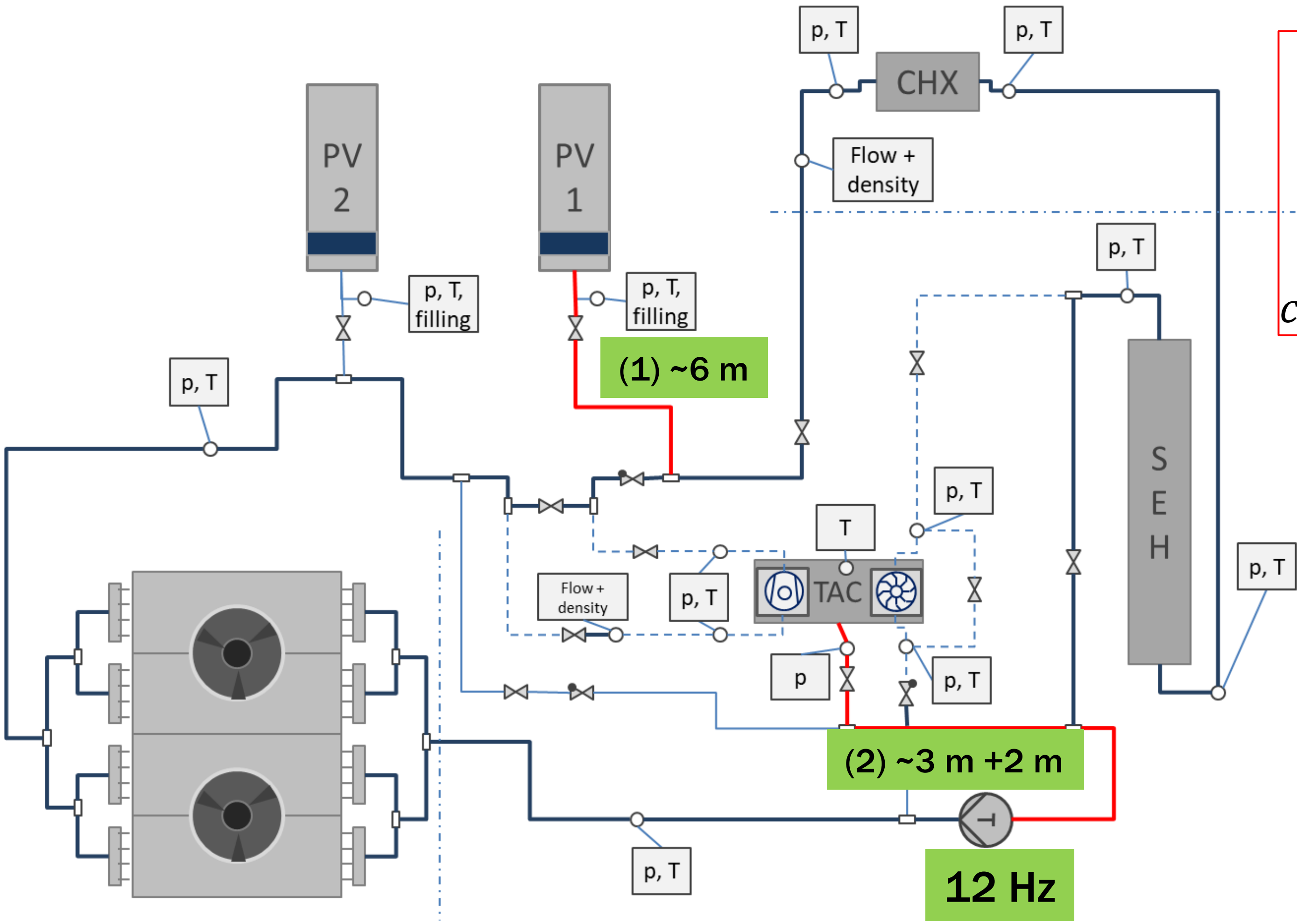
SOME RESULTS OF BENCHMARK TEST (D1.2)



Note the oscillations to PV1



OSCILLATIONS



$$a = \lambda f$$
$$l_{res} = \frac{\lambda}{2}$$
$$c_1 \sim 144\ \frac{m}{s}$$
$$c_2 \sim 72 - 120\ m/s$$

Pressure propagation in 2-phase mix?

DEVELOPMENT AND DESIGN OF THE TURBOMACHINE

WP 4

Haikun Ren

University of Duisburg-Essen

CONTENT

OBJECTIVES ON TURBOMACHINERY IN SCO2-4-NPP

DESIGN OF THE SCO2-4-NPP TURBOMACHINE

TEST RESULTS OF IMPROVED SCO2-HERO TURBOMACHINE

CONCLUSIONS AND OUTLOOK

OBJECTIVES ON THE TURBOMACHINERY

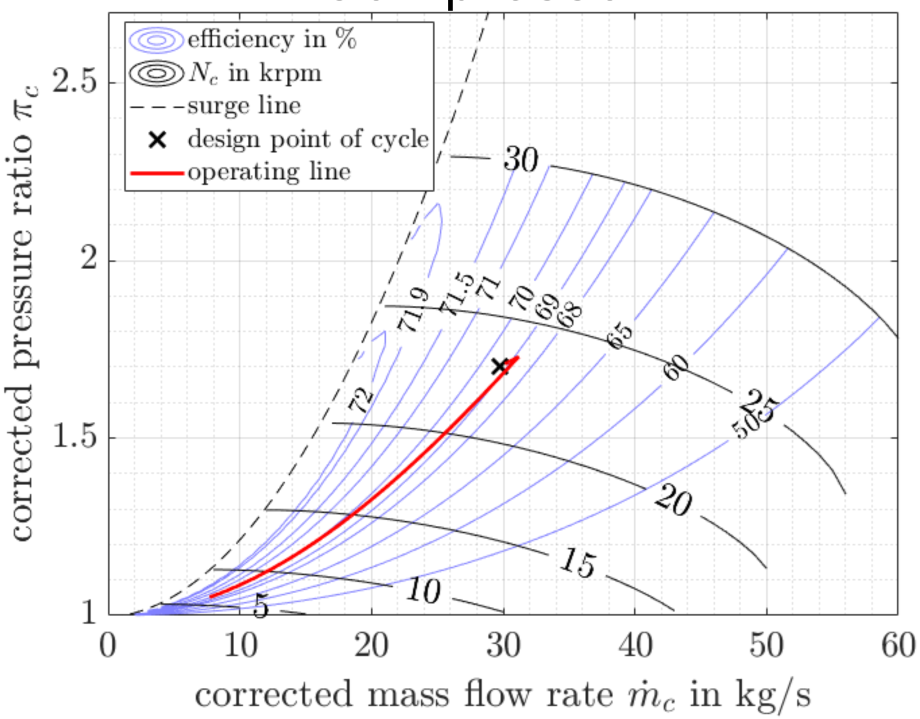
- Objectives in sCO2-4-NPP:
  - Conceptual design of sCO2-4-NPP turbomachine
    - Performance maps incorporated in simulation codes as turbomachine models
    - Heat removal > 72 hours
  - Improvement and further tests of sCO2-HeRo turbomachine
    - Validation of newly applied technology and new design
    - Experience (also from NP TEC) → design of the sCO2-4-NPP turbomachine

- Characteristics of the turbomachine
  - Wide operation range
  - Exploitation of excess power
  - Turbine-Alternator-Compressor (TAC)

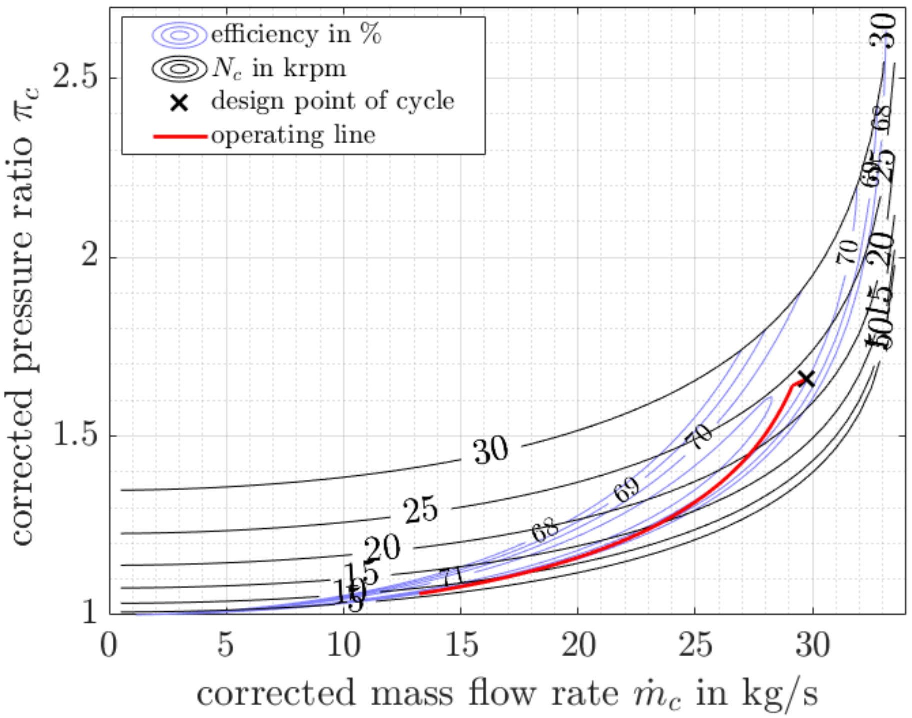
AERODYNAMIC DESIGN OF SCO2-4-NPP TURBOMACHINE

- Design (radial) based on the cycle design parameters
- Off-design using mean-line tools considering internal losses

Compressor



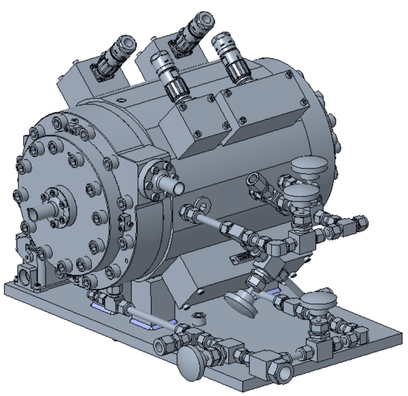
Turbine

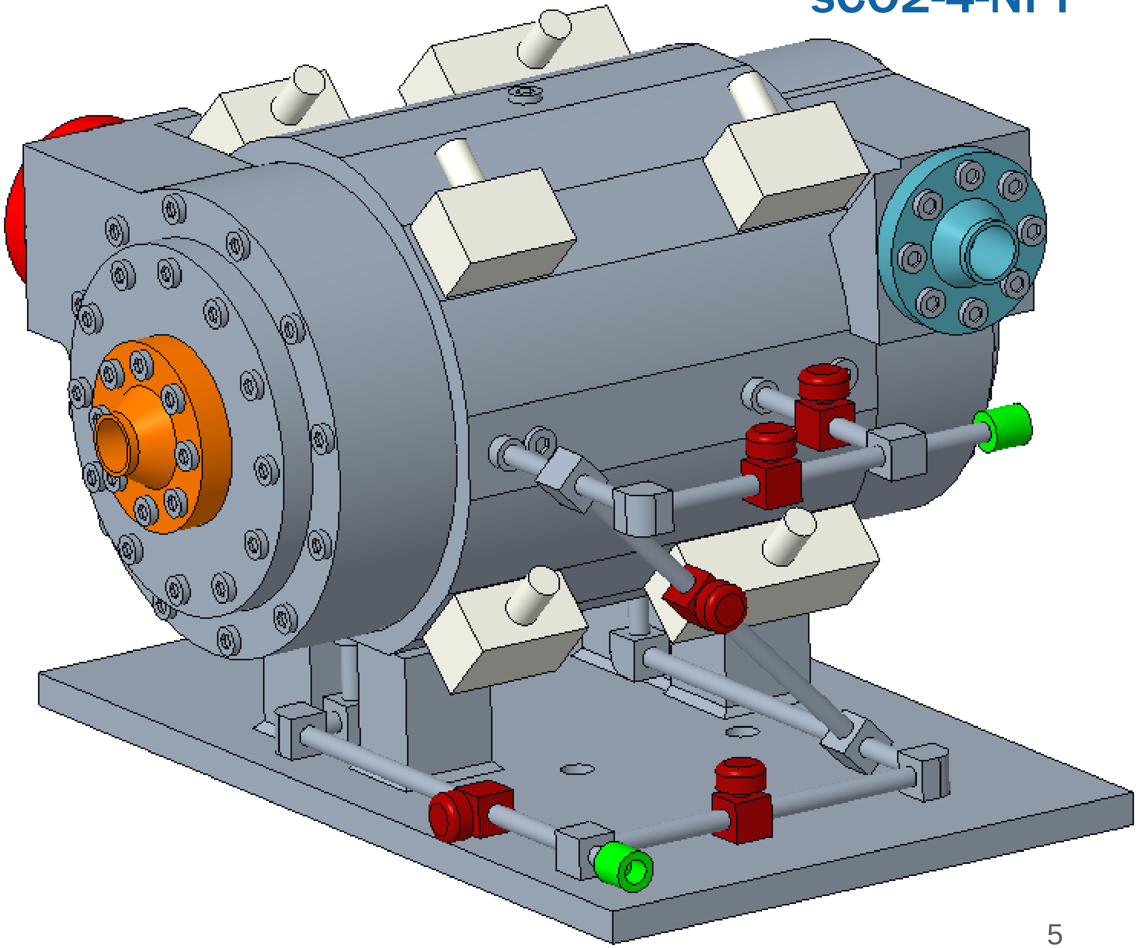


- Operating line from simulation results

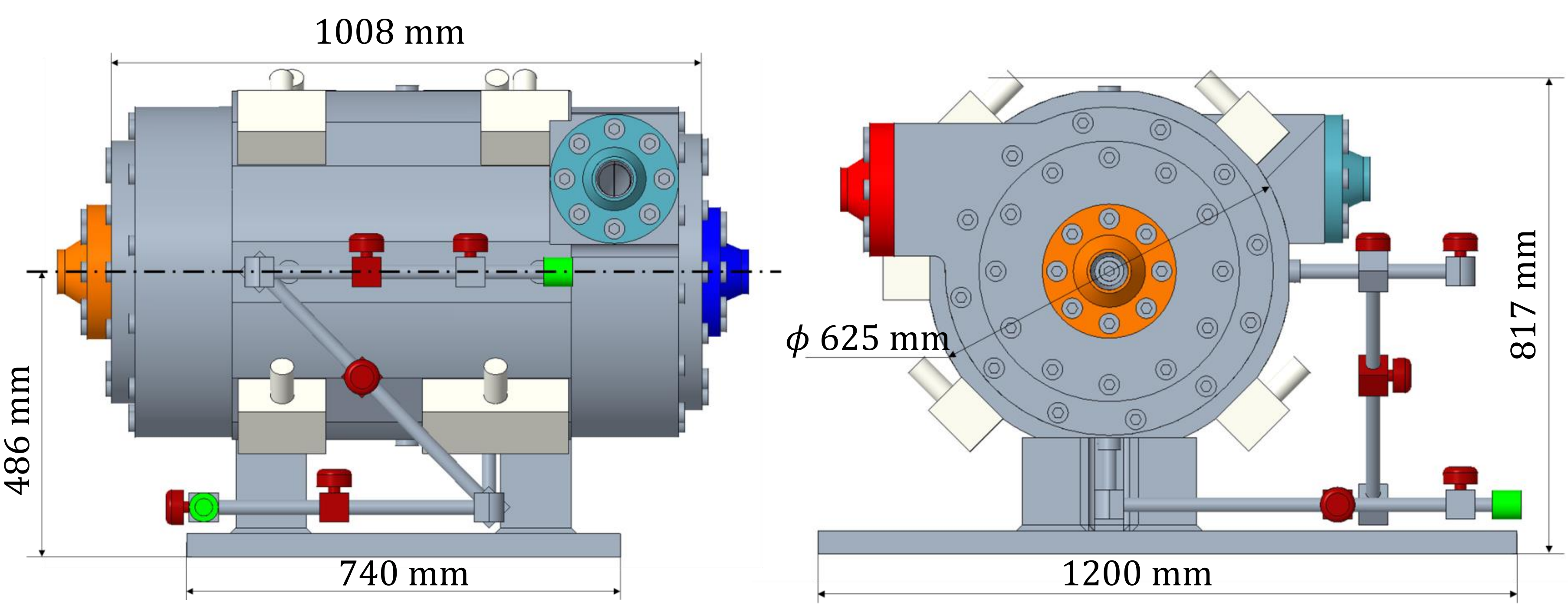
MECHANICAL DESIGN OF SCO2-4-NPP TURBOMACHINE

- Scale up from the sCO2-HeRo^{M} machine



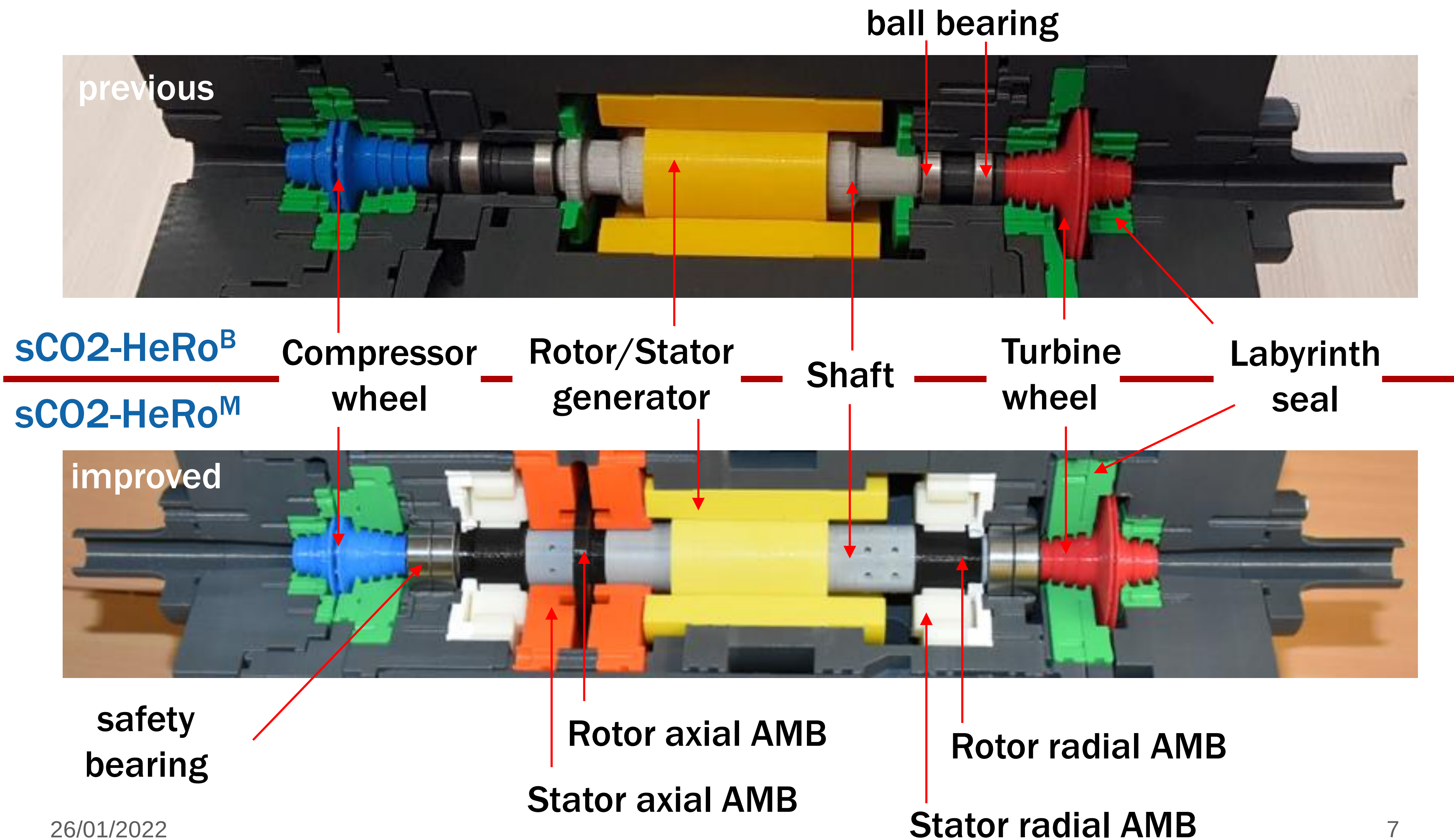


OUTER VIEWS OF SCO2-4-NPP TURBOMACHINE



Red	Turbine inlet	Blue	Compressor inlet	Dark red	Control valve
Orange	Turbine outlet	Light blue	Compressor outlet	Green	Interfaces to the loop

IMPROVEMENT OF THE SCO2-HERO TURBOMACHINE

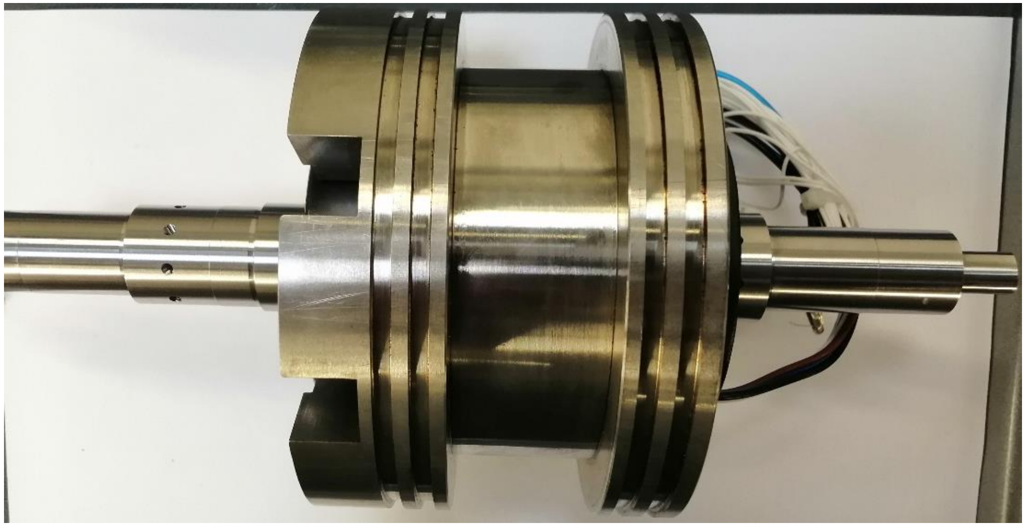


PICTURES OF TURBOMACHINE ELEMENTS

Labyrinth seals

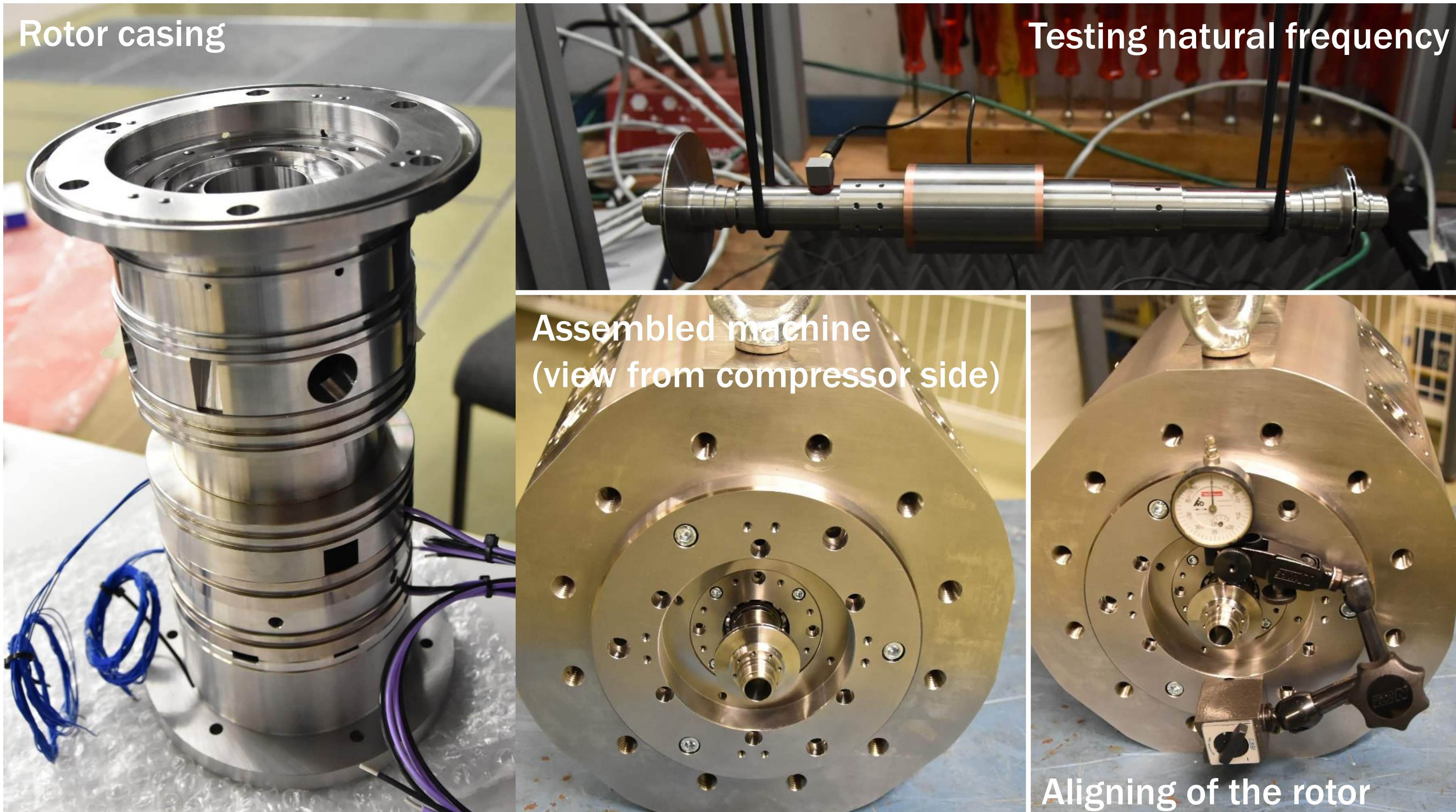
Rotor

Generator



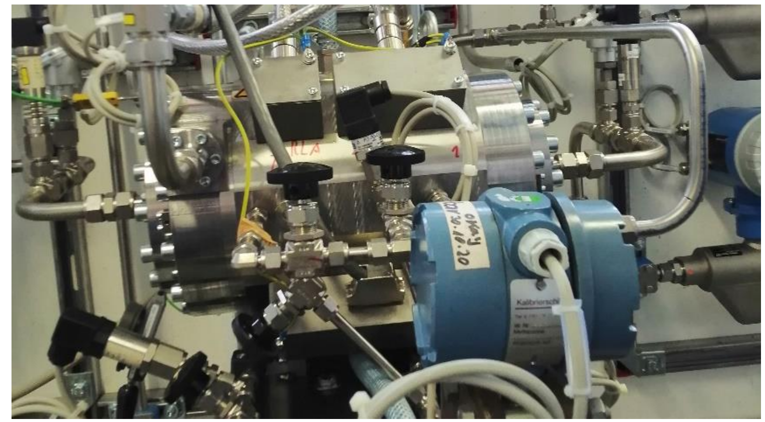
AMB

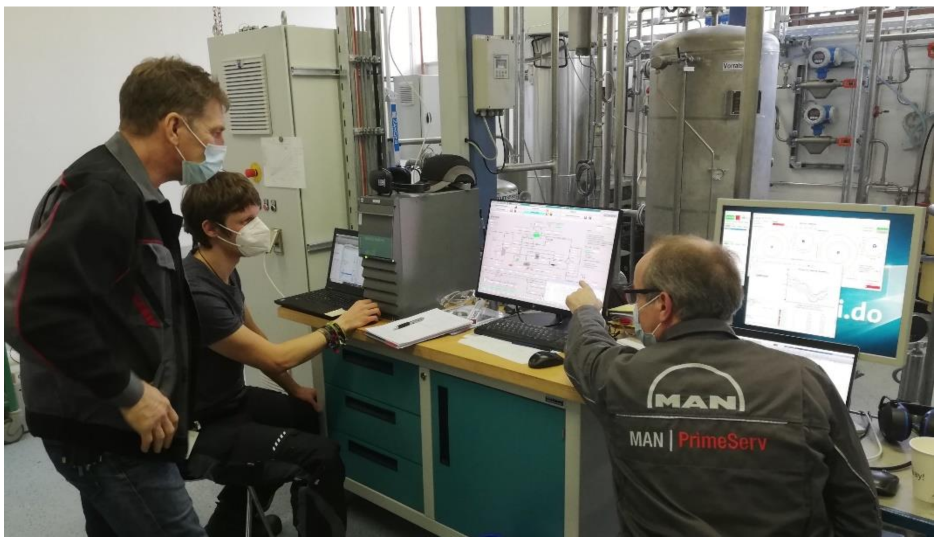
PICTURES OF (TEST) ASSEMBLY



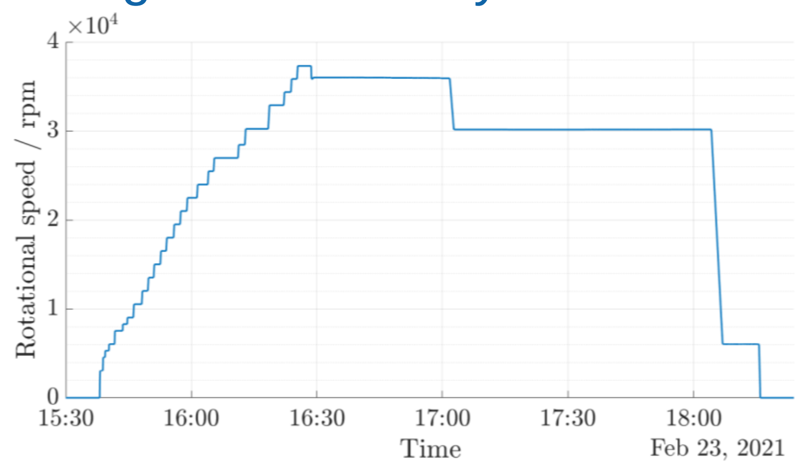
TEST WITH MAGNETIC BEARINGS IN ESSEN

Design, manufacturing and assembly finished





Commissioning of turbomachine with magnetic bearings in HeRo cycle



Test results available to validate robust design and performance maps

➢ Magnetic bearings can be applied

26/01/2022

GAS BEARING MITIGATION

- Mitigation: Ensure availability of suitable, validated bearing technology for operation in sCO_2

- Design and manufacturing of test rig by TU Kaiserslautern
- Preliminary tests on compatibility and operation at USTUTT

- Results:
  - The resistance of the material under supercritical CO_2 conditions is confirmed
  - The measurement data were used to carry out an initial validation of the tool
  - The numerical model enables the estimation of the mass flow rate
  - All results show possibility to apply this technology

CONCLUSIONS AND OUTLOOK

- In this project:
  - Heat removal system with excess power exploitation
  - large operation range (no certain operating point)
  - Low requirement on human intervention (self-launching/-propelling)
  - Flexible for retrofitting in different systems (modular design)
  - Small footprint on environment
  - New robust technology applied and verified (magnetic bearing)

- Potential applications in other areas:
  - Waste heat recovery
  - Concentrated solar power (sCO2-Flex)
  - Other power generations (for certain operating point with higher efficiency)

COMPONENT DEVELOPMENT : TURBOMACHINE AND HEAT EXCHANGER

WP 4

Ren Haikun & Taiclet Guillaume

CONTENT

AIM OF THE TECHNOLOGY

PLATE-FIN HEAT EXCHANGER OVERVIEW

DIVERSE ULTIMATE HEAT SINK (DUHS) DESIGN

COMPACT HEAT EXCHANGER (CHX) DESIGN

NEXT STEPS AND PERSPECTIVES

Heat Exchanger

AIM OF THE TECHNOLOGY

- Aim : create an innovative technology to remove excess heat in case of nuclear accidents, based on supercritical CO_2 (sCO_2)
- Fives role was to develop 2 brazed Plate-Fin Heat Exchangers design to evacuate excess heat via advanced Brayton cycles using sCO_2 and ambient air
- Cooling system modules are highly compact, self-propellent, self-sustaining and self-launching

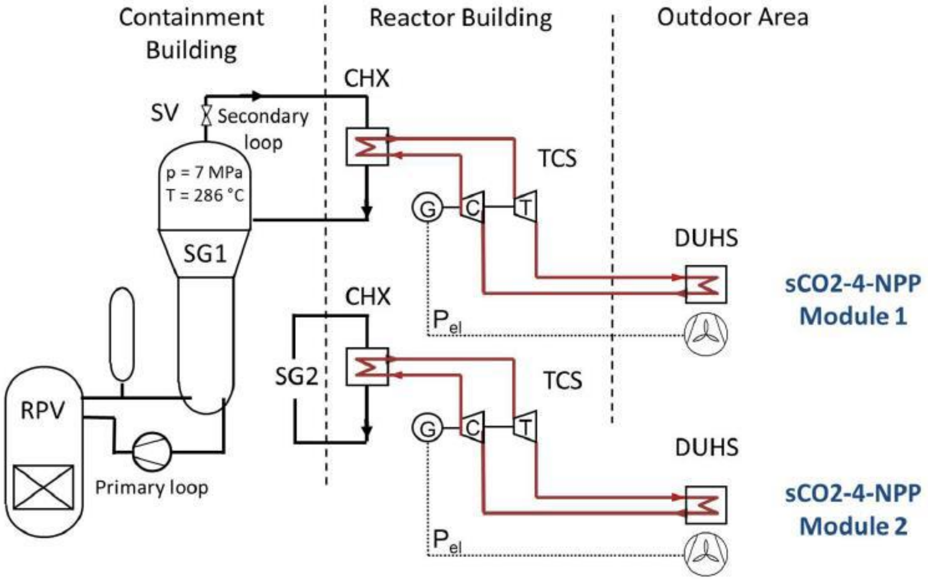
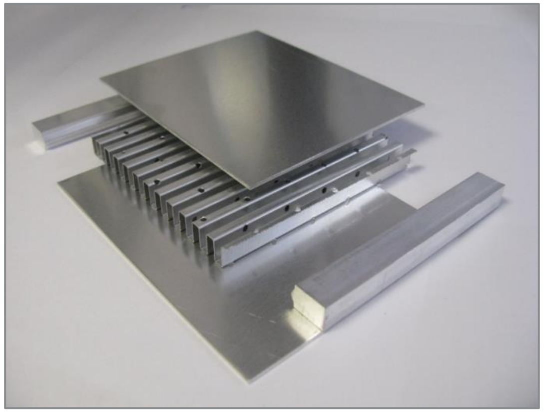


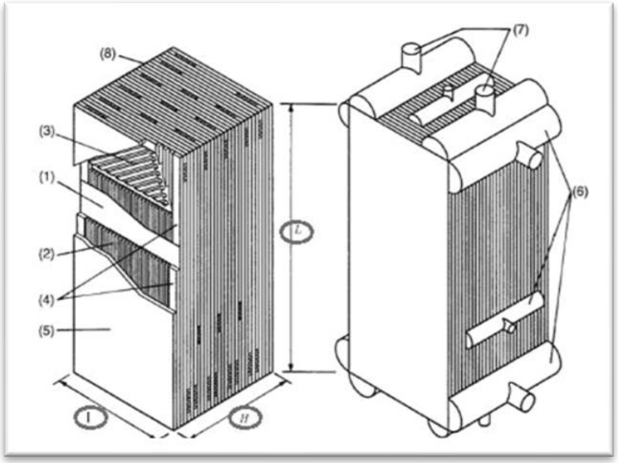
PLATE-FIN HEAT EXCHANGER OVERVIEW

- Plate-Fin Heat Exchanger (PFHE) consists of a block (core) of alternating layers closed by bars, containing corrugated fins, separated by parting sheets.

From layer ...



... to core



- After stacking, all layers are brazed to form one homogeneous core. Brazed joints are created during heating to ensure cohesion.

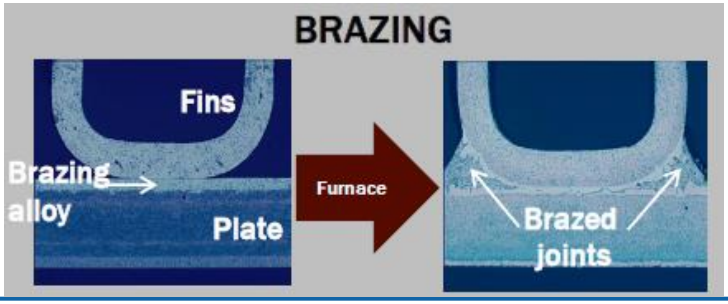
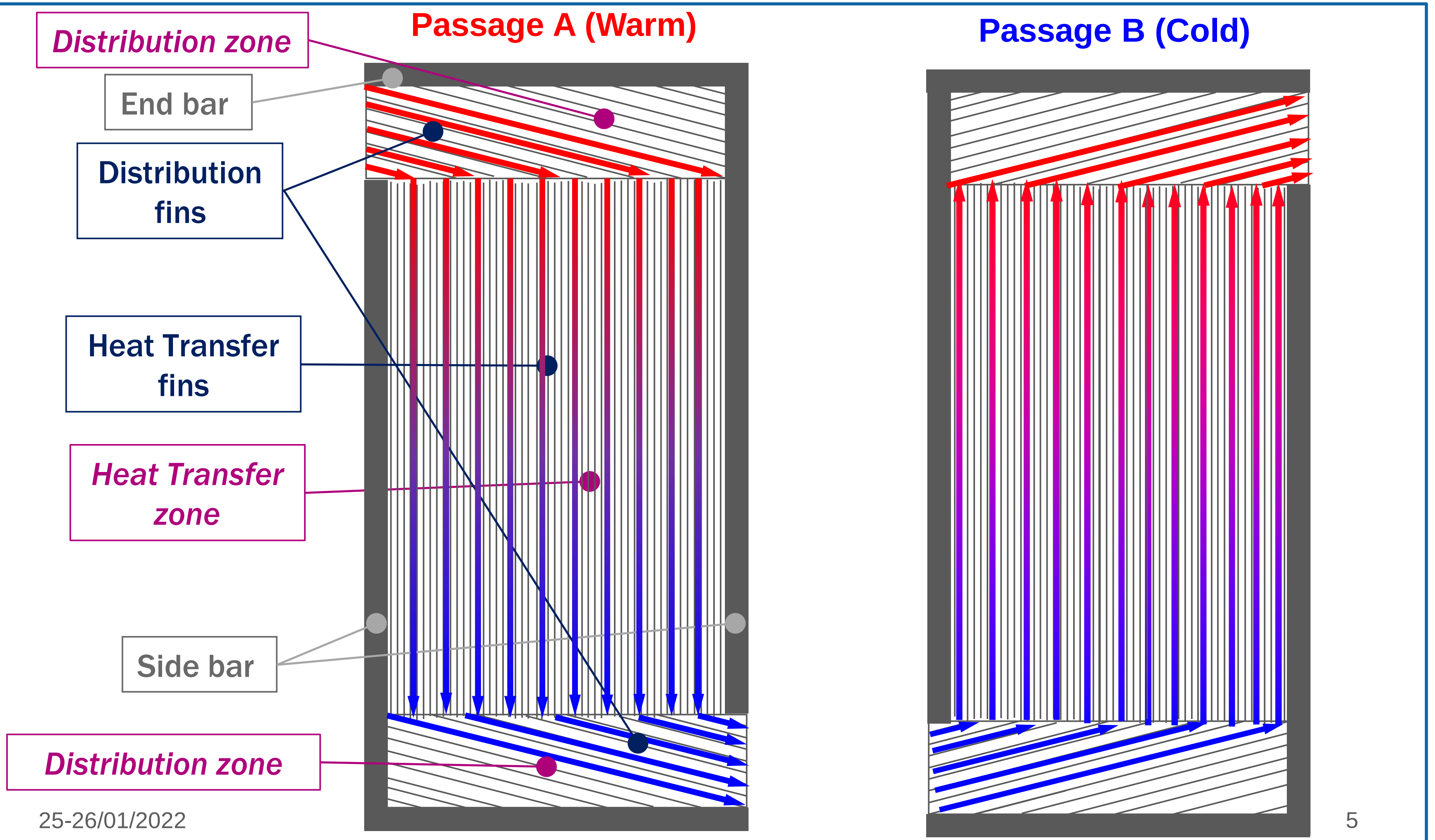
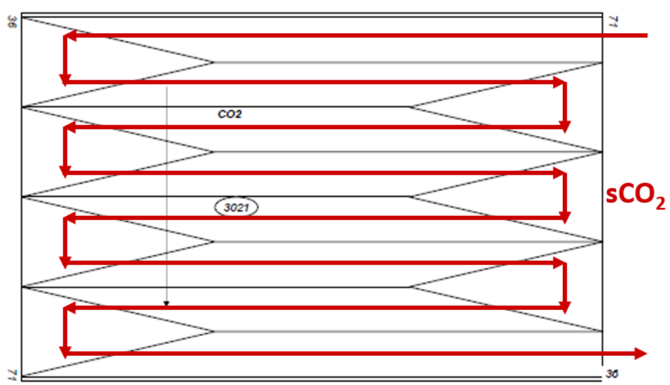


PLATE-FIN HEAT EXCHANGER OVERVIEW

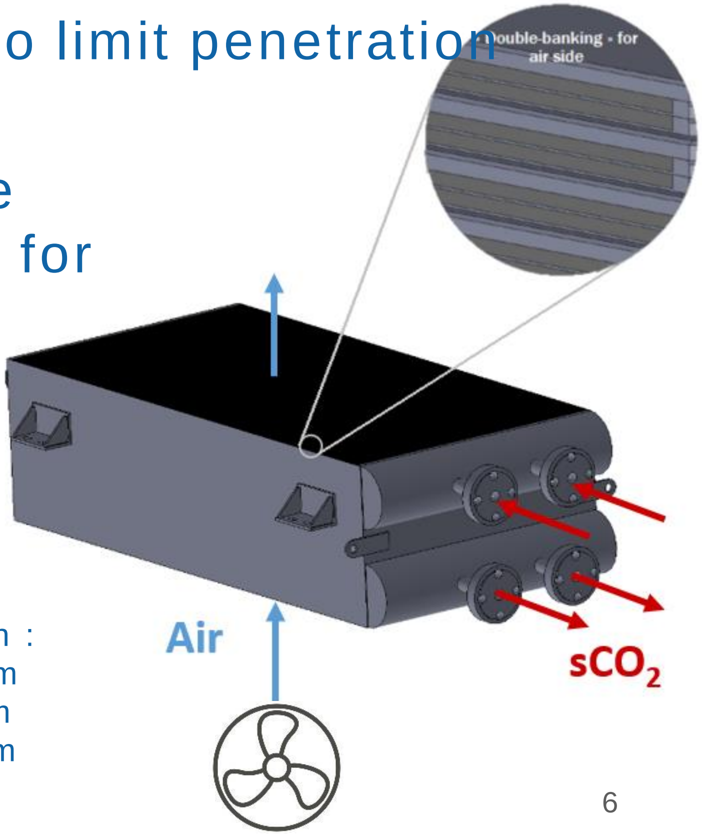


DIVERSE ULTIMATE HEAT SINK (DUHS) DESIGN

- DUHS will remove sCO_2 heat thanks to ambient air flow drive by fans
- 1 unit of 20 cores has a specified heat transferred of 10 MW
- Units can be installed outside building to limit penetration of reactor safety vessel
- sCO_2 in tighter passage, which increase fluid velocity, and multipass are chosen for thermal performance

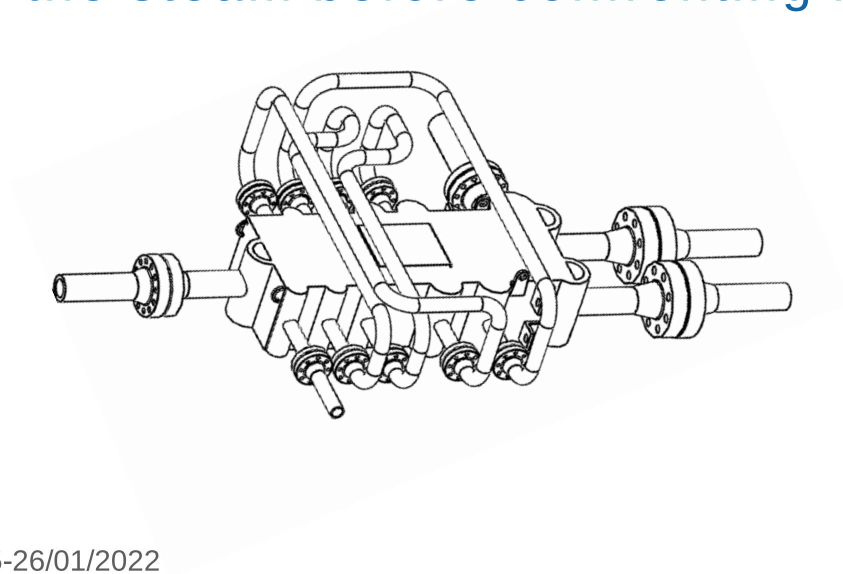


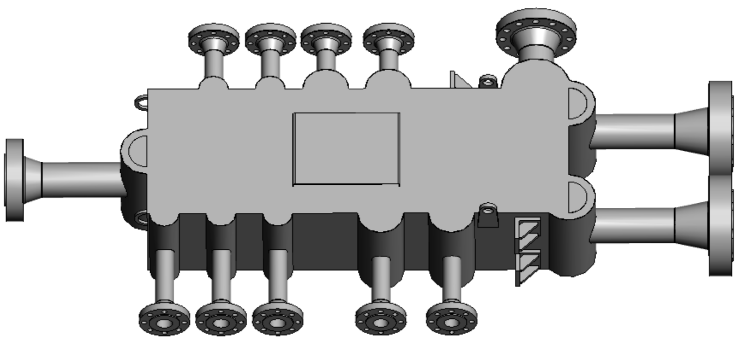
Core dimension :
Width: 2000 mm
Height: 987 mm
Length: 570 mm



COMPACT HEAT EXCHANGER CHX DESIGN

- In the CHX steam produced inside steam generator will condense due to sCO_2 flow
- Specified heat transferred of 10MW
- This is a patented technology that allow heat exchange in a highly compact volume
- This patented configuration allow to blind the latent heat of the steam before confronting it to the cold sCO_2





Core dimension :
Width: 700 mm
Height: 512 mm
Length: 2000 mm

NEXT STEPS AND PERSPECTIVES

- Manufacturing mock-ups at reduced size to test under operational conditions

- Reduce as much as possible high thermomechanical stress (static or dynamic)

SIMULATIONS / SYSTEM ARCHITECTURE INTEGRATED IN NPP

WP 5

Michael BUCK, USTUTT

Albannie CAGNAC, EDF

CONTENT

OBJECTIVES AND CHALLENGES

ARCHITECTURE

THERMO-HYDRAULIC MODELING

PREPARATION FOR SIMULATOR INTEGRATION

OBJECTIVES

Main objectives and sub-objectives
Define final architecture of a module
Establish a preliminary design of the integrated system with the primary and secondary loops of the NPP
Define the control-command of the system and the thermodynamic performance of the cycle
Provide model for the final validation in the KONVOI simulator
Thermodynamic cycle design

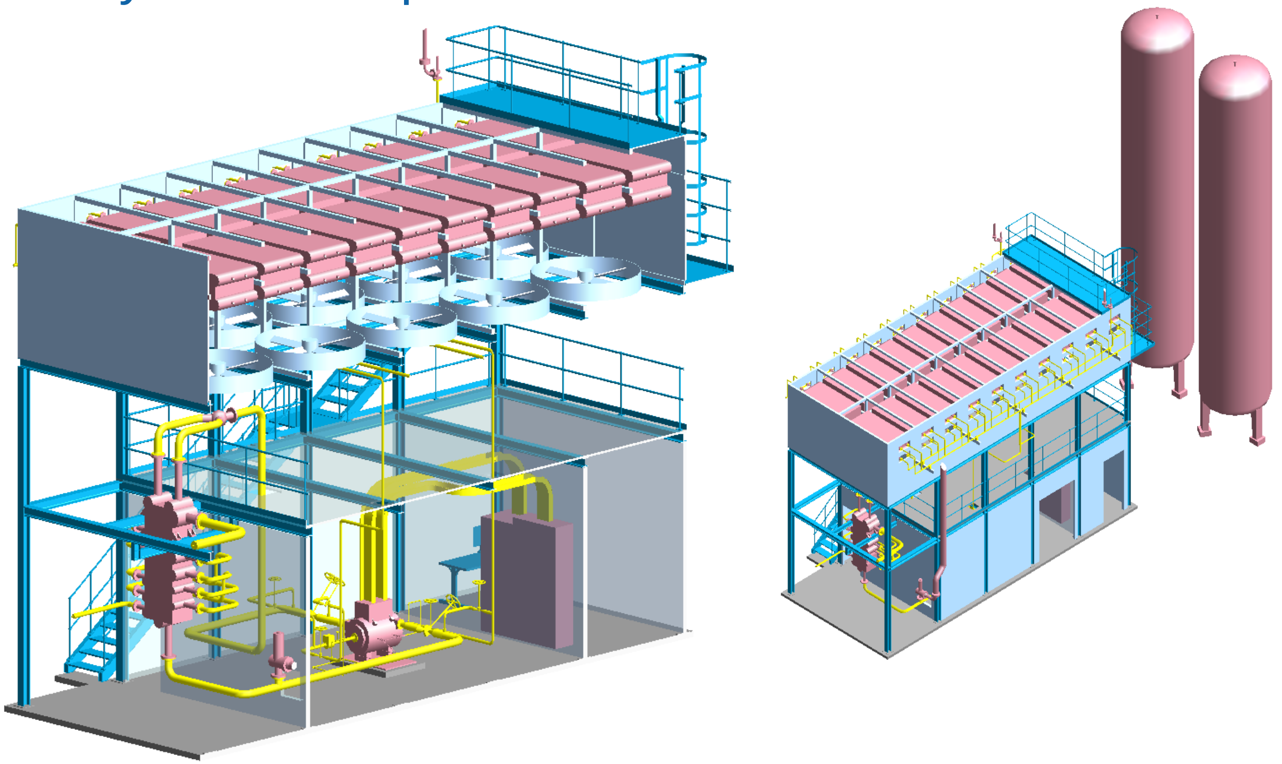
CHALLENGES

- Adaptation of thermal-hydraulic codes to an sCO2 cycle
- Convergence of accidental transients with the sCO2 cycle
- Coupling of the ATHLET and MODELICA models to be integrated in the KONVOI simulator
- Architecture and integration on an existing plant design

SCO2 SYSTEM ARCHITECTURE

- Search for modularity and compactness

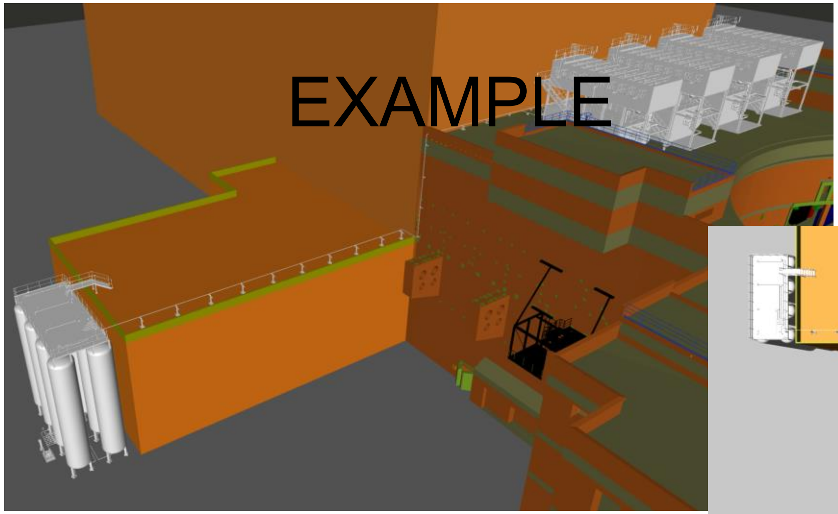
- System
  - 13,5m * 6,2 m
  - Height : 9,8m

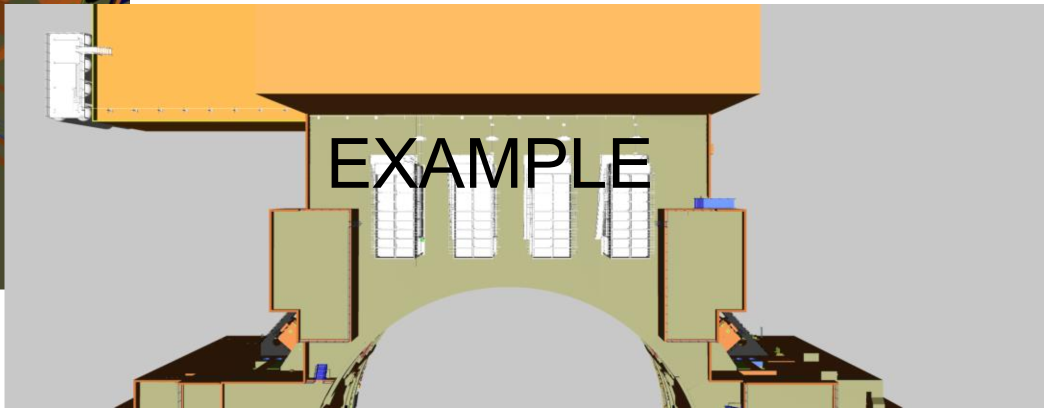


- Potential for improvement: Optimisation of DUHS, Use of an alternative cooling system, Reduction of CO2 storage

SCO2 SYSTEM ARCHITECTURE

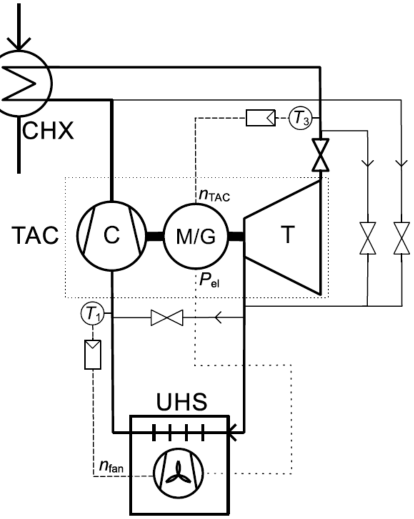
- Challenges :
  - Limited space available on site
  - Minimum of 4 modules required
  - Need to optimise the connection with the NPP existing pipes

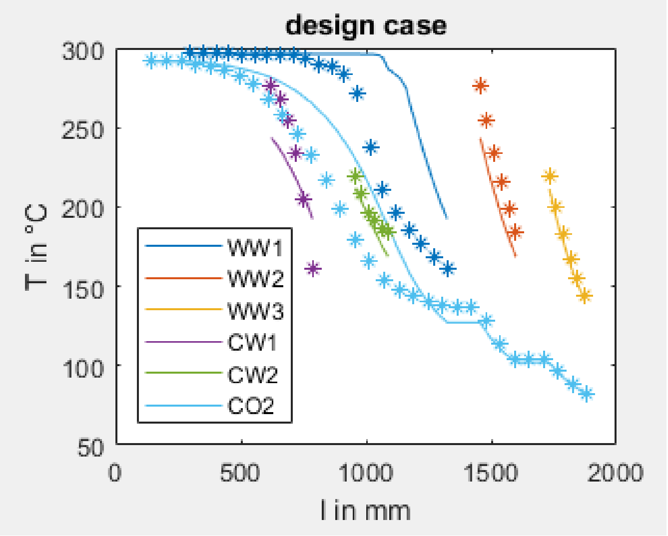




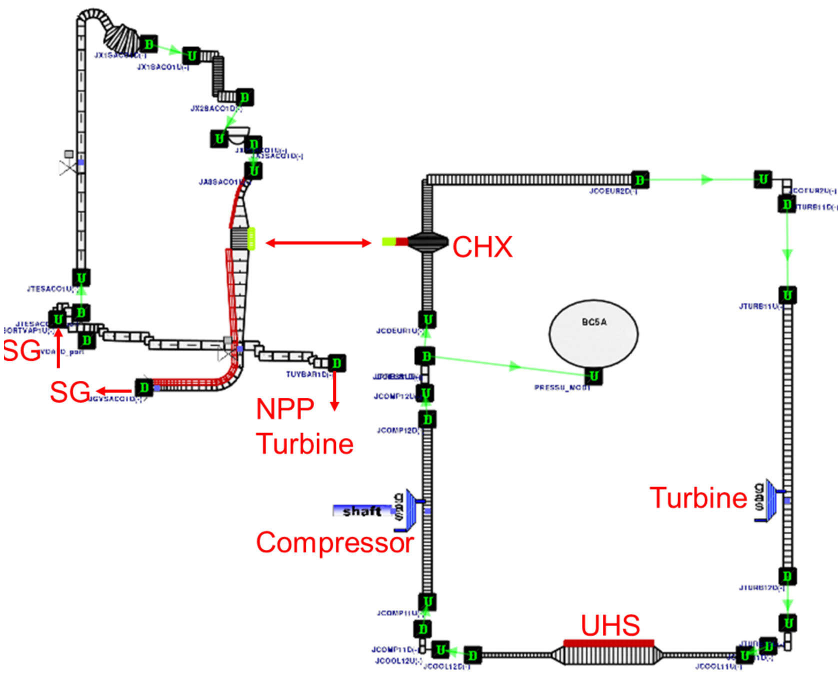
INTEGRATION IN THERMOHYDRAULIC CODES

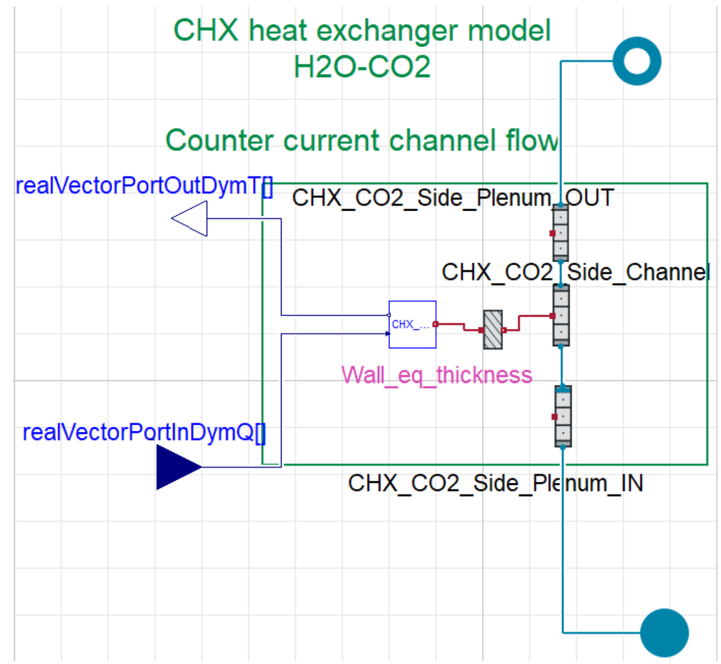
- Challenges :
  - Use of different codes, with SBO type accident scenario, 3 different reactors
  - Testing of different hypotheses (start-up, regulations,...)
  - Modelling of sCO2 cycles in the CATHARE code (new version, new fluid, no components already modelled)





INTEGRATION IN THERMOHYDRAULIC CODES



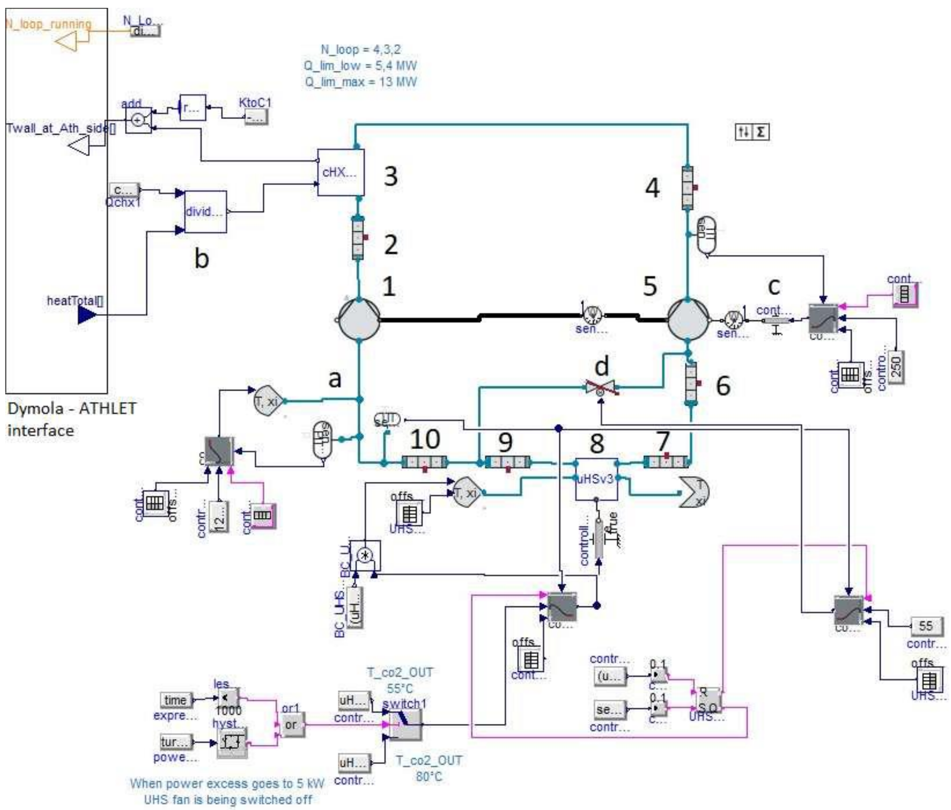


EPR : sCO2 loop allows to cool down the primary circuit but the power dissipated is too low and several sCO2 loops are needed (at least 4)

VVER : 3 starting sCO2 loops can remove the decay heat after the SBO while the fuel-cladding temperature is kept within the safety limits

THERMODYNAMIC MODELING

- Highlights :
  - Evaluation in ATHLET/Dymola for VVER NPP



- Control strategy in Dymola model based on changing the loop filling and UHS bypassing
- Alternative approach without changing the loop filling and without UHS bypassing studied

Start procedures :

- Push start procedure (current choice)
- operational readiness state starting procedure

REAL-TIME SIMULATIONS FOR IMPLEMENTATION IN PWR SIMULATOR

- Challenges
  - Use of MODELICA to build the real-time simulator of the sCO2 heat removal system to prepared for coupling to the existing FORTRAN based simulator of the NPP (KONVOI).
  - General model will be validated by data obtained at the sCO2-HeRo loop (WP1).

- First results
  - FMU version of the Dymola model runs in version FMU Co-simulation ver 1.0. Need to be running in ver 2.0
  - Zero iteration sCO2 loop Dymola model for evaluation of the Dymola model real time capabilities.
  - First iteration Dymola model prepared with input and output connectors – Needs for behavior assessment (controls…)

LESSONS LEARNED

- As the sCO2 system is not yet fully finalised (behaviour of components based on experiments, start-up mode, etc.), the models are based on plausible operating hypotheses but with uncertainties
- Regulation procedures for the sCO2 system, coupled to the reactors, need to be further improved
- The coupling with the power plant will be easier and more compact if it is done at the design stage
- First design proposal available which is feasible. Design improvements necessary for integration into existing NPP

ROADMAP TOWARDS EXPLOITATION: REGULATORY POLICY, REQUIREMENTS AND WAY FORWARD

WP 7

Albannie Cagnac (EDF),

Andrej Prošek (JSI)

CONTENT

REGULATORY ROADMAP

TECHNICAL ROADMAP

FINANCIAL ROADMAP

NEXT STEPS

REGULATORY ROADMAP

- The purpose of the regulatory roadmap is to provide recommendations for future qualification and the necessary steps to achieve licensing of the sCO2-4-NPP system in future user countries to be able to integrate the real operating environment system in existing and future NPPs :
  - Equipment qualification (EQ)
  - Testing considerations
  - Equipment aging
  - Operating environment
  - Seismic qualification
  - Licensing requirements
  - Approval of safety authorities

EQUIPMENT QUALIFICATION (EQ) (1/2)

- Equipment qualification includes environmental and seismic qualification.
- The safety function of a piece of equipment (electrical or mechanical or I&C equipment) is generally established in terms of its required behaviour (active or passive) and its duration.
- The EQ is a process adopted to confirm that the system is capable of meeting, throughout its operational design life, the demands for performing its functions while being subject to the environmental conditions:
  - vibration, temperature, pressure, jet impingement, electromagnetic interference, irradiation, humidity or any likely combination thereof.

EQUIPMENT QUALIFICATION (EQ) (2/2)

- Environmental conditions to be considered include the variations expected in:
  - normal operation,
  - anticipated operational occurrences,
  - design basis accidents and
  - design extension conditions.
- Moreover, consideration shall be given to ageing effects caused by various environmental factors (such as vibration, irradiation and extreme temperature) over the expected lifetime of the equipment.
- The qualification programme shall replicate as far as practicable the conditions imposed on the equipment by the natural phenomenon, either by test or by analysis or by a combination of both.

TESTING CONSIDERATIONS (1/2)

- Service conditions include many considerations for equipment qualification:
  - environmental,
  - loading,
  - power, and
  - signal conditions

  expected during normal operation; expected abnormal extremes in operating requirements; and postulated conditions for design-basis events.

TESTING CONSIDERATIONS (2/2)

- Design-basis events can also be caused by natural phenomena such as an earthquake.
- Service conditions also include operating conditions such as self-heating, cycling, process fluid conditions, and electromagnetic interference.
- Qualification of equipment shall be accomplished by test, analysis, documented operating experience, or some combination of these methods. Type testing is the preferred method for qualification of equipment.

EQUIPMENT AGING (1/1)

- The aging of systems and components is a potential common cause failure mechanism.
- Equipment qualification testing for the effects of aging typically applies techniques that use accelerated aging methods on test specimens to simulate years of service under the expected operating conditions.

OPERATING ENVIRONMENT (1/1)

- The environment in which equipment operates (harsh or mild) and the consideration of seismic events plays a large role in determining the qualification process.
- Whether the equipment is classified as electrical or electromechanical or mechanical also influences the qualification process.
- For example, in a mild environment, the only design-basis event of consequence is a seismic event.
- Also mild environments are not considered to have significant aging mechanisms.

SEISMIC QUALIFICATION (1/1)

- Seismic qualification of safety-related equipment includes meeting both structural integrity and operability requirements under such conditions.
- For simple safety-related equipment, seismic qualification can often be done through analysis.
- For complex safety-related equipment, testing must be performed to show that the equipment meets these requirements under seismic conditions
- Mechanical aging is also a consideration in seismic qualification.
- The dynamic qualification of the equipment shall be achieved by testing, analysis or a combination of testing and analysis.

LICENSING REQUIREMENTS (1/2)

- WENRA reference level (RL) G4.1: The design of SSCs important to safety and the materials used shall take into account the effects of operational conditions over the lifetime of the plant and, when required, the effects of accident conditions on their characteristics and performance.
- WENRA RL G4.2: Qualification procedures shall be adopted to confirm that SSCs important to safety meet throughout their design operational lives the demands for performing their function, taking into account environmental conditions over the lifetime of the plant and when required in anticipated operational occurrences and accident conditions.

LICENSING REQUIREMENTS (2/2)

- Requirements for implementing EQ in nuclear power plants are prescribed by various national and international standards, codes and guides.
- For example, ASN Guide No. 22 tells us that equipment important to safety must be qualified to ensure its ability to meet its defined requirements for the conditions under which it is needed.
- The most commonly used industry standards that provide qualification requirements are developed by the Institute of Electrical and Electronics Engineers (IEEE) and the International Electrotechnical Commission (IEC).

APPROVAL OF SAFETY AUTHORITIES (1/1)

- Once the technology has been qualified, the operator who wishes to install the technology must have the approval of the national safety authority on which he depends.
- This approval is based on probabilistic safety studies, and deterministic studies confirming the improvement or non-degradation of reactor safety.

TECHNICAL ROADMAP

- Objectives of this roadmap
  - Define the next steps in technology development to reach a TRL 7-8 level
  - Identify the potential barriers to be overcome
  - Establish milestones for the components
  - Establish the test program that will enable the qualification process to be carried out and uncertainties to be reduced

TECHNICAL ROADMAP - EQUIPMENTS

- Heat Exchangers :
  - New design (patent) - Improvement of the design to improve certain parameters (maximum temperatures, heat transfers…)
  - Experiments for reliability studies and reduction of calculation uncertainties in modeling
  - Development of non-destructive testing and monitoring methods
- Turbocompressor
  - Construction of a prototype at scale 1
  - Experiments to study behavior at limit conditions, a detailed analysis of reliability and potential failures,
  - Optimization of materials and some sub-components (bearings…) to increase reliability
  - Regulation, monitoring and non-destructive testing procedures.

TECHNICAL ROADMAP – SCO2 SYSTEM

- Testing of possible start-up procedures
  - Currently: push-up start-up solution with storage tanks,
  - Other potential solutions: readiness state of operation, start-up with pressurizer
  - Establishment of advantages and disadvantages and integration in a NPP simulator
- Operating rules
  - Establishment of monitoring procedures, performance monitoring for an operator
  - Establishment of maintenance procedures (periodic tests, periodicity of visits…)
- Safety studies
  - Functional analysis
  - Reliability analysis of the entire sCO2 system, , Integration in PSAs
- Qualification
  - Establishment of qualification file documents
  - Contact with the relevant organisations

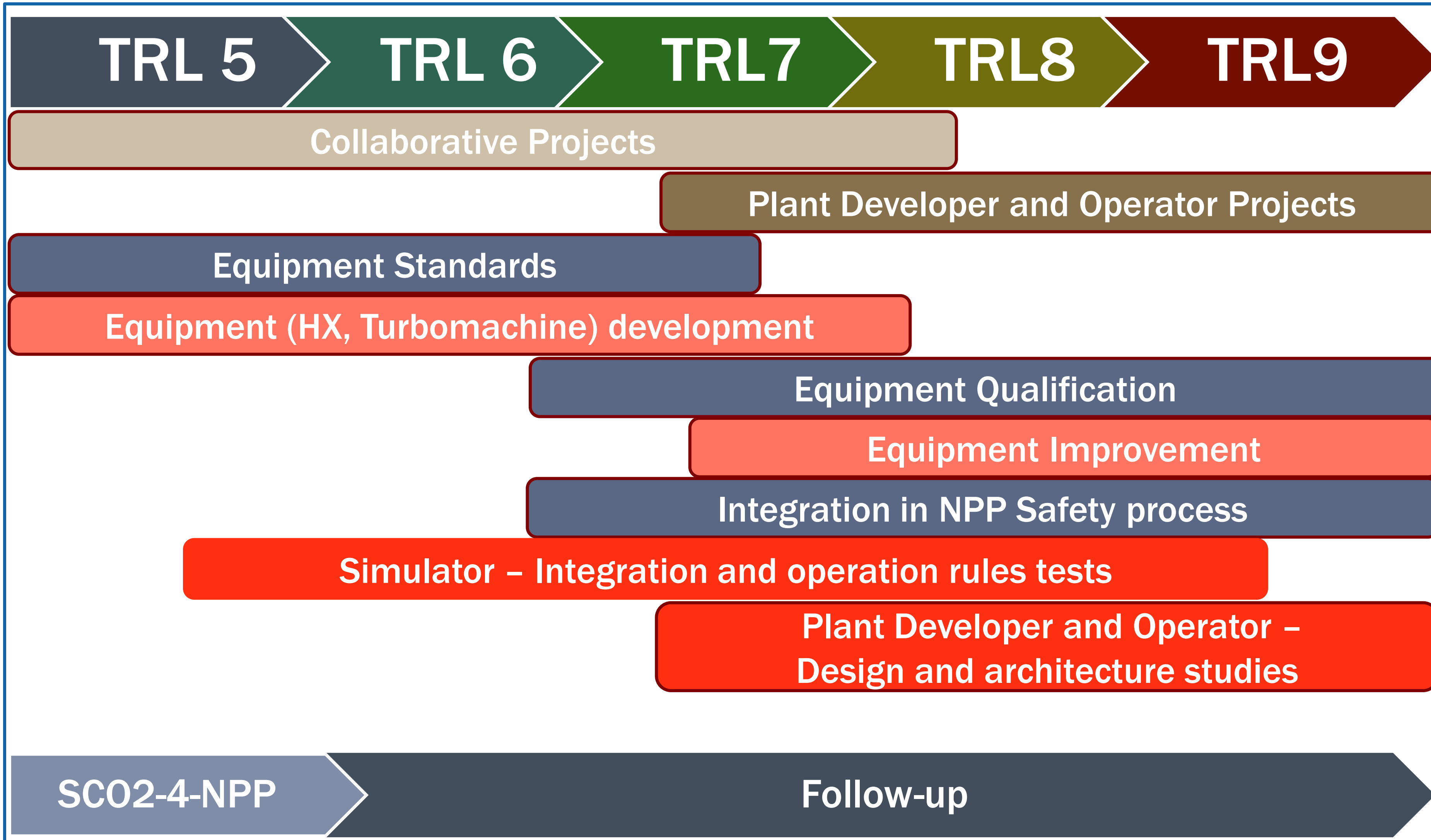
FINANCIAL ROADMAP

- Establishing a financial roadmap seems to us to be important for 2 aspects:
  - To guarantee an sCO2 system at a controlled price
  - Seek to finance the remaining necessary developments
- Objective 1: Controlling the final cost of the sCO2 system
  - Need to demonstrate a concrete contribution of the system to the safety of the NPP
  - Selection of the most suitable materials compatible with the qualification requirements
  - Design as modular as possible.
    - Optimise the cost of installation and possible modifications related to the types of reactors on which the system will be installed.
    - Better control to integrate modifications/customisations required for the type of reactor.
    - Establishment of maintenance and operating procedures for an estimate of OPEX costs

FINANCIAL ROADMAP

- Objective 2: To finance further work on the sCO2 system
  - In the absence of a full-scale pilot, the sCO2 system will not be able to reach TRL 8 level
  - Collaborative Research Projects (with public funds)
    - Further simulation studies could be carried out within the framework of a collaborative research project,
    - Involvement of industrial partners and mastering the processes related to the engineering phases of the design of nuclear solutions, qualification and installation files for nuclear power plants.
  - Create a real community around this solution and integrating non-nuclear stakeholders, but interested in another application

SUMMARY


TRL 5
TRL 6
TRL7
TRL8
TRL9
Collaborative Projects
Plant Developer and Operator Projects
Equipment Standards
Equipment (HX, Turbomachine) development
Equipment Qualification
Equipment Improvement
Integration in NPP Safety process
Simulator – Integration and operation rules tests
Plant Developer and Operator – Design and architecture studies
SCO2-4-NPP
Follow-up

THANK YOU

This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 847606. This text reflects only the author's views and the Commission is not liable for any use that may be made of the information contained therein.