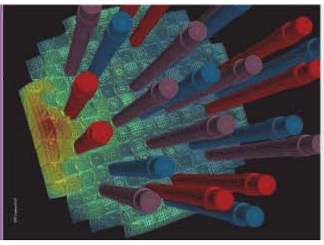


FISA 2022

30 May - 3 June 2022
Lyon, France

CODES AND METHODS IMPROVEMENTS FOR SAFETY ASSESSMENT AND LTO: VARIED APPROACHES

APAL PROJECT

APAL - Advanced PTS Analysis for LTO

Objectives of APAL project

- **Development of advanced probabilistic pressurised thermal shock (PTS) assessment methods**
- **Quantification of safety margins for LTO improvements**
- **Development of best-practice guidance.**

APAL – basic information

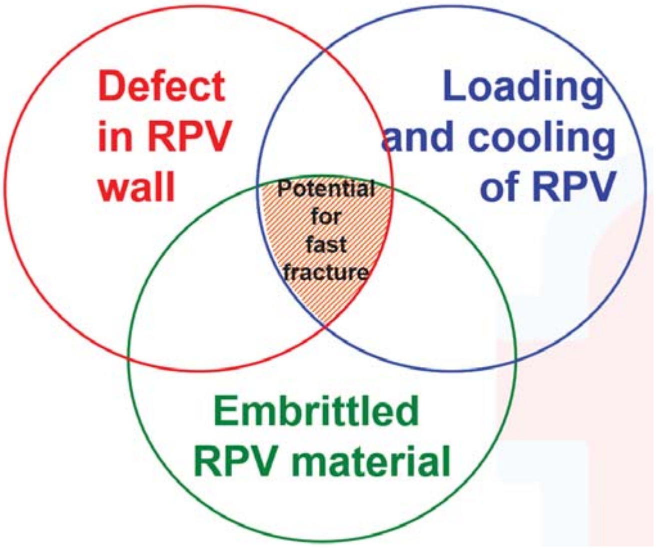
- **EU funded project – Horizon 2020 research and innovation programme**
- **Duration 10/2020 – 9/2024**
- **Budget 4 mil. Euro**
- **14 EU partners + 2 international partners**

APAL – partners

Participant No		Participant organisation name	Country
1	UJV	ÚJV Řež, a. s.	**CZ**
2	FRA-G	Framatome GmbH	**DE**
3	PSI	Paul Scherrer Institut	**CH**
4	IPP	IPP Centre LLC	**UA**
5	KIWA	Kiwa Inspecta Technology AB	**SE**
6	TECNATOM	Tecnatom S.A.	**ES**
7	GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (GRS)	**DE**
8	BZN	Bay Zoltán Nonprofit Ltd. for Applied Research	**HU**
9	EURICE	European Research and Project Office GmbH	**DE**
10	JSI	Jožef Stefan Institute	**SL**
11	IRSN	Institut de radioprotection et de sûreté nucléaire	**FA**
12	LUT	Lappeenranta University of Technology	**FN**
13	WUT	Warsaw University of Technology	**PL**
14	SSTC	State Scientific and Technical Center for Nuclear and Radiation Safety	**UA**
I1	OCI	Oakridge Consulting International	**US**
I2	JAEA	Japan Atomic Energy Agency	**JA**

Characterisation of pressurised thermal shock (PTS)

- Rapid cooldown of the primary circuit
- (Usually) non-uniform cooldown
  - due to ECCS injection
  - due to asymmetric cooling down by steam generators
- (Usually) high inner pressure

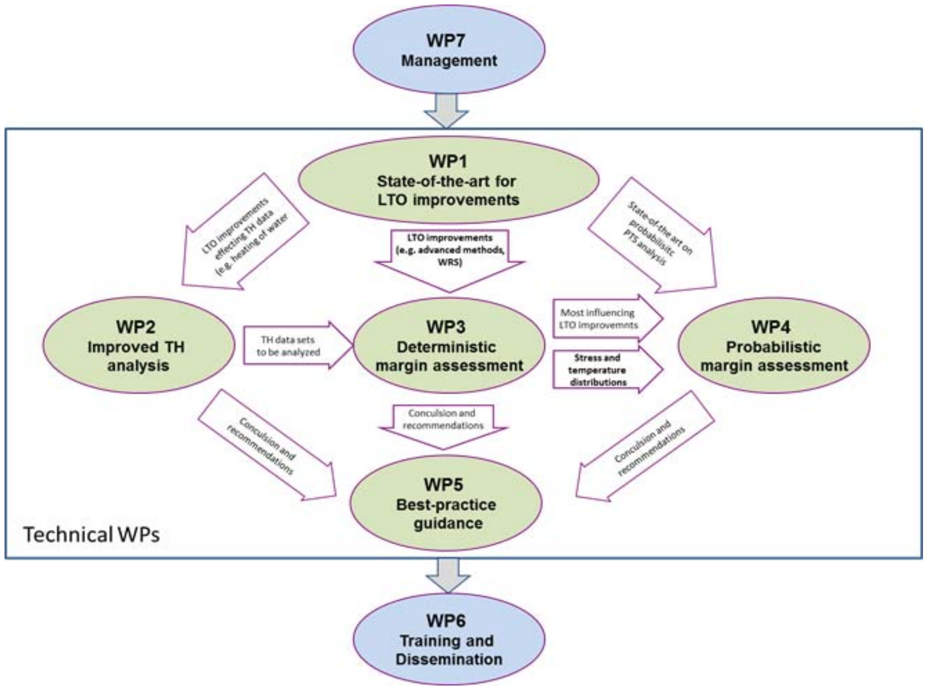


Under which circumstances fast fracture in RPV could occur?

Main parts of PTS analyses

- Thermal-hydraulic analyses
  - system
  - mixing
- Structural analyses
  - temperature fields
  - stress fields
  - fracture mechanics

APAL - Project Structure



APAL – overview of the technical work packages (WP1 – WP5)

- **WP1 State-of-the-art of Long-Term Operation Improvements.** Extensive literature review and collection of experience (based of questionnaires filled by the partners) to identify the state-of-the-art of LTO improvements that may have an impact on the results of PTS analysis. WP1 finished 2/2022. Public summary report of WP1 can be downloaded from APAL public web page **https://apal-project.eu/**
- **WP2 Improved TH analysis.** System and mixing thermal-hydraulic (TH) calculations are performed, including uncertainty quantification relevant to the PTS assessment. The impact of both LTO improvements and human factor on the results of TH analysis are quantified.
- **WP3 Deterministic margin assessment.** Deterministic structural and fracture-mechanics analyses will be performer to quantify the safety margins related to both LTO improvements and uncertainties in TH analyses. At first they will be tested on a common deterministic benchmark.
- **WP4 Probabilistic margin assessment.** Probabilistic fracture-mechanics analyses will be performed. They will enable the quantification of safety margins in terms of risk of RPV failure. An appropriate benchmark for the probabilistic fracture-mechanics analysis will be performer first.
- **WP5 Best-practice guidance.** Recommendations and conclusions will be gathered from the work to define the best practices for advanced PTS analysis for LTO.

Numerical Codes used in APAL

- Several codes and software are used in APAL project, in order to reach the objectives of the project. These tools can be categorized following the different approaches studied in the PTS analyses.
- **System thermal-hydraulic analysis.** It's the analysis of behaviour of the whole NPP system (primary and secondary circuits, emergency core-cooling systems, auxiliary systems, etc…) from the thermal-hydraulic point of view. The resulting parameters include, among others, temperatures, pressures, flow rates, velocities, and heat transfer coefficients.
- **Mixing thermal-hydraulic analysis.** It's the detailed analysis of coolant mixing inside the reactor, namely in the reactor downcomer.

Numerical Codes used in APAL

- **Structural and fracture-mechanics analyses.** The structural and fracture-mechanics analyses can be performed using either a **deterministic or a probabilistic approach**. The software tools for both approaches significantly differ.

– **Deterministic approach:**

- **For structural analysis, commercial "general" finite-element method (FEM) software** tools are used. Among many capabilities of general FEM codes, the solutions of heat-transfer problem and mechanical problem (either linear-elastic or elastic-plastic) are used for PTS analysis. The **fracture-mechanics analysis** is generally performed in two different methods. The first method is based on the formulae from standards. The second method is based on the FEM model of the RPV with the assessed crack included in the FEM mesh. Fracture-mechanics parameters are calculated directly in the post processor of the commercial FEM software.
- **Probabilistic approach:**
- Because the commercial software is not suitable for this type of analyses, a **specific software** especially for the fracture-mechanics assessment, frequently created in-house, is used. The main task of the probabilistic software for fracture-mechanics analysis is sampling some of the input data, which are treated as statistically distributed, and to **calculate the conditional probability of crack initiation** or RPV failure. Usually, a Monte Carlo method or FORM/SORM method is used.

CAMIVVER PROJECT

- **CAMIVVER Project Context**
  - VVER type constitutes a dynamic and growing part of the European fleet. Several VVER reactor units are planned for construction – or are currently under construction – inside the EU (Slovakia, Hungary and Finland) and in the neighboring countries (Ukraine, Turkey, Belarus, Russia)
  - VVER fleet is highly dependent on Russia for fuel supply. The Euratom Supply Agency (ESA) underlined as a matter of concern the reliance on a single Russian supplier, which constitutes a significant risk. Consequently the EU is strongly supporting the development of alternative supply chains, preferably within Europe
  - **Considering the growing influence of international export controls the same statement can be drawn regarding scientific softwares used by the nuclear industry for designing reactors. The availability of european state-of-the-art computer codes became a priority for preserving EU sovereignty and nuclear operators independence**

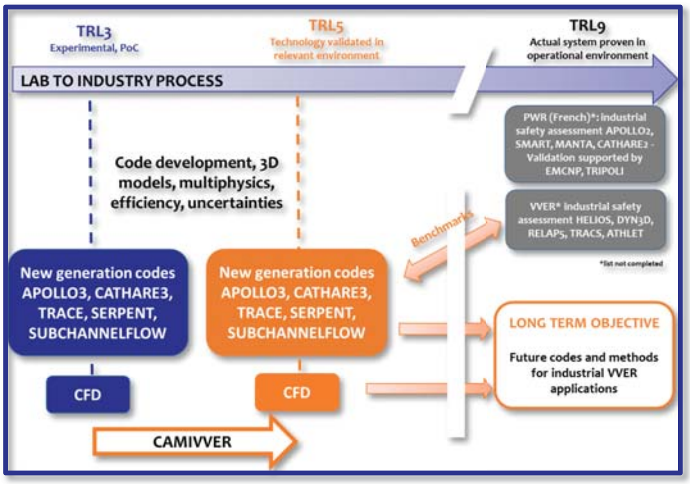
www.camivver-h2020.eu

camivver-h2020-european-project

CAMIVVER Project Ambitions

- Pushing new generation codes and methods towards an industrial use for VVER and PWR safety assssments
- Performing code development of a neutrons library generator prototype based on APOLLO3® code and of a proof of concept of an innovative coupling based on APOLLO3®/CATHARE3 codes.
- Benchmarking those new generation codes against codes currently used for VVER and PWR safety assessment and high-fidelity calculations based on Monte Carlo codes (TRIPOLI-4 and SERPENT, coupled with subchannel codes (SUBCHANNELFLOW)) for steady state and transient calculations.
- Performing methods development based on 3D-modelling to improve system thermal-hydraulics modelling of VVER plant, especially by challenging the robustness and validation of CATHARE3 against reference RELAP5 and TRACE models.
- Performing methods development based on 3D-modelling and uncertainty propagation in CFD analyses, using partners codes (STARCCM+, CFX, FLUENT, TRIO-CFD).

CAMIVVER Roadmap

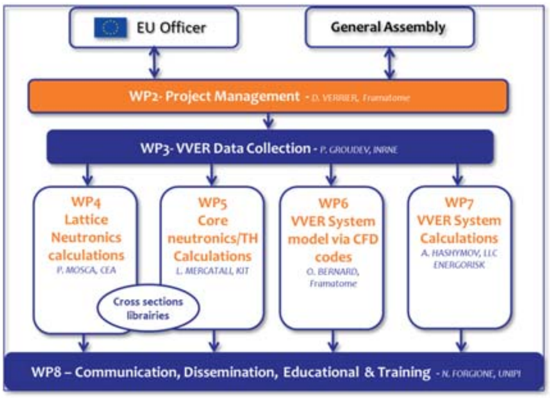


CAMIVVER Project Overview

- *Consortium is 7 partners from 5 countries*:
  - Framatome, EDF and CEA from France,
  - LLC Energorisk from Ukraine,
  - INRNE from Bulgaria,
  - KIT from Germany, and
  - UNIPI from Italy
- *The Project*
  - Budget of **4 M€** funded by the European Commission, in the framework of the Horizon 2020 research program
  - Started on September 1st 2020, for a duration of 3 years
  - Framatome is the project coordinator

CAMIVVER Project Organization

- CAMIVVER relies on lead Industries in the nuclear sector, Research Centers and Universities
- CAMIVVER relies on a strong safety culture established on Gen. II and Gen. III reactors, a consolidated experience of VVER and PWR safety analyses, and on a strong expertise of codes and methods development and validation



Focus on some CAMIVVER works (not exhaustive)

WP4 Lattice Code

- **Task 4.1** dedicated to the status and characterization of the APOLLO3® lattice code and to the set up of first steps toward its industrialization (common work done with EDF and CEA) – ***1st prototype expected in 2022***

  D4.1 - Representative use cases and specification requirements for the prototype multi-parameter library generator

- **Task 4.2** dedicated to APOLLO3® calculations V&V for PWR and VVER-1000 assemblies

  D4.3 – Definitions of tests cases for the verification phases of the multi-parametric library generator
  http://camivver-h2020.eu/src/assets/doc/D4-3.pdf

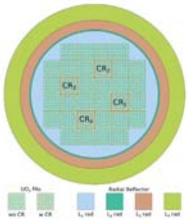
- **Task 4.3** dedicated to VVER lattice calculation scheme optimization **–** ***1st calculation scheme expected in 2022 - Development and validation of the double-level scheme in 2023***

- **Task 4.4** dedicated to APOLLO3® advanced application (e.g. 3D MOC modeling)

WP5 Core physics

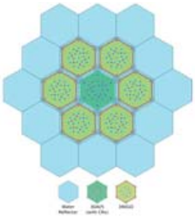
- **Task 5.1** dedicated to the definition of the **mini core reference test cases** and boundary conditions

  D5.1 - Description of the core reference test cases – Part 1
  http://camivver-h2020.eu/src/assets/doc/D5-1.pdf



- **Task 5.2** dedicated to APOLLO3®/THEDI core calculations of the VVER mini core case and benchmark against SERPENT/SCF

- **Task 5.3** dedicated to the :
  - development of a proof of concept of APOLLO3®/CATHARE3 advanced coupling dedicated to rod ejection and loss of flow transients on the PWR mini core case
  - extension to an hexagonal VVER geometry
  - Tests of multiparametric data libraries provided by WP4
  - Benchmarking with SERPENT/SCF



Focus on some CAMIVVER works (not exhaustive)

WP6 CFD of primary vessel

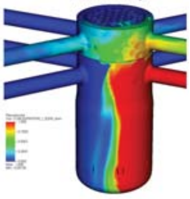
- **First Task in 2021** consisted in the development of CFD models
  - CAD construction
  - 100% NP steady state calculations
  - Code-to-code comparison on core outlet distribution

  D6.1 – Description of CFD models from partners Results of outlet flow distribution benchmark
  http://camivver-h2020.eu/src/assets/doc/D6-1.pdf

- **Coming activities**:
  - Mixing experiment (Kozloduy-6 Start-Up test) : CFD validation regarding the evaluation of mixing matrices for VVER primary vessel
  - Uncertainties propagation:
    - Demonstration of inlet-parameters uncertainty propagation through CFD models
    - Application of Deterministic Sampling method

Figure 4.1 : CAD model of the VVER internals (a), zoom to the upper plenum (b), zoom to the lower plenum (c)

a) Visualization by a passive scalar of the flow that comes from loop 1



WP7 System Analysis

- **First Task in 2021** consisted in the development of the CATHARE3 model

  D7.1 –Description of thermal-hydraulics models. Results of steady-state benchmark
  http://camivver-h2020.eu/src/assets/doc/D7-1.pdf

- **Beginning of 2022** results of Kozloduy-6 Main Coolant Pump start-up test have been established

  D7.2 - Results of Kozloduy-6 MCP start-up transient benchmark
  http://camivver-h2020.eu/src/assets/doc/D7-2.pdf

- **Coming activities**:
  - Code-to-code comparisons on Small-Break LOCA due to SG failure
  - Code-to-code comparison on Main Steam Line Break

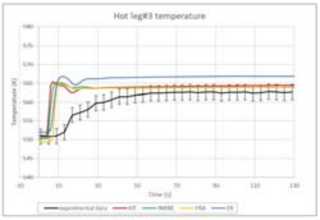


Figure 3.2.4.3 Hot leg #3 temperature

SCO2-4-NPP PROJECT

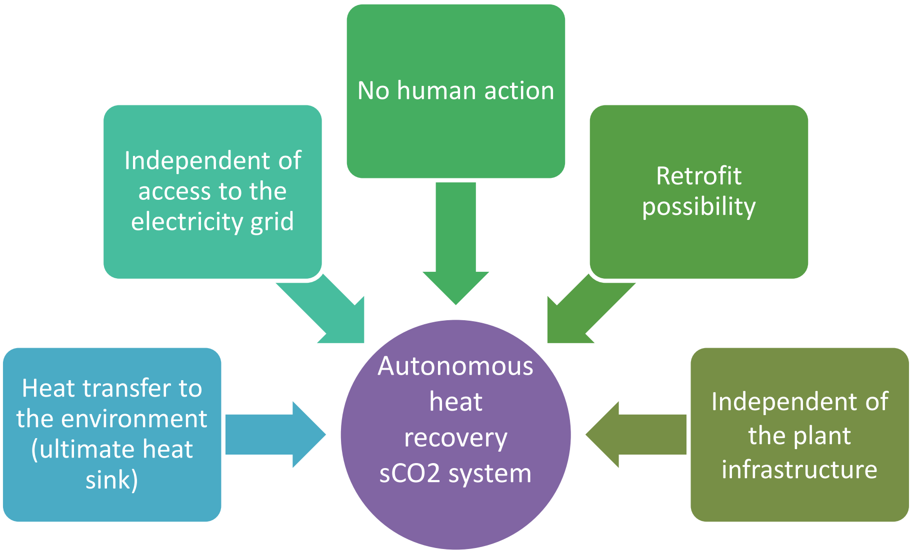
Motivation - Fukushima Follow-Up

- Loss of ultimate heat sink
- Loss of main, auxiliary, and emergency power supply
- Loss of infrastructure
- Difficulties of rapid access and rehabilitation of the plant

Source: Tepco

Scientific Trend: **Passive safety systems**, but small driving forces, requirement of large space, difficult for retrofitting, performance under off-design conditions unknown, …

Motivation - New approach



No human action

Independent of access to the electricity grid

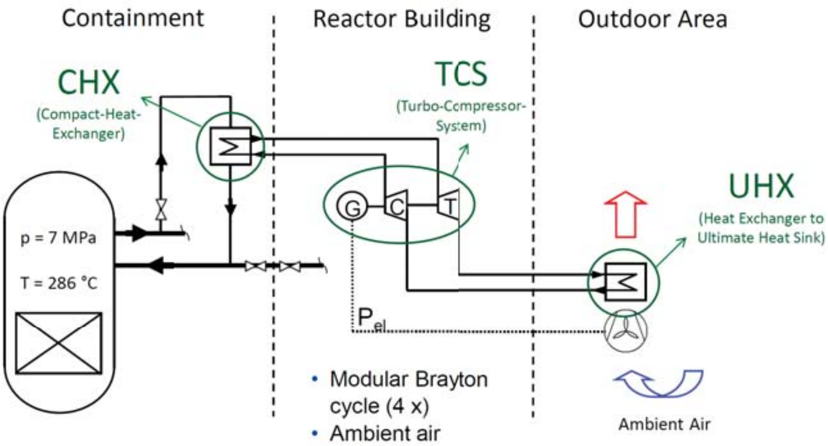
Retrofit possibility

Heat transfer to the environment (ultimate heat sink)

Autonomous heat recovery sCO2 system

Independent of the plant infrastructure

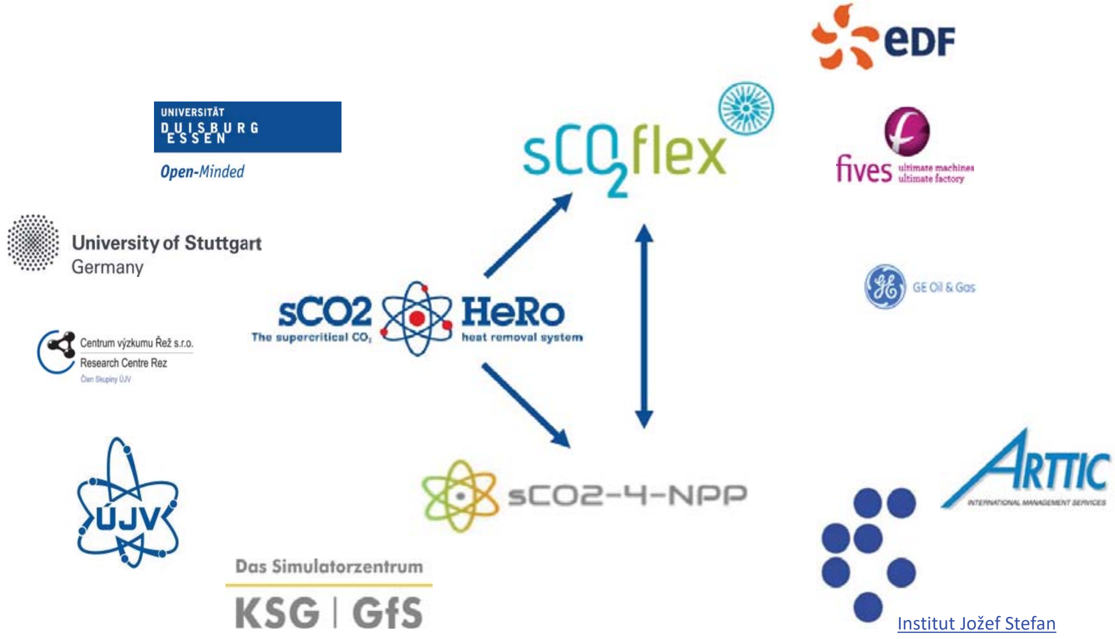
Background : A look back at the work of the sCO2-Hero team



- Modular Brayton cycle (4 x)
- Ambient air
- Excess power
- Supercritical CO_2

© sCO2-HeRo project

Consortium

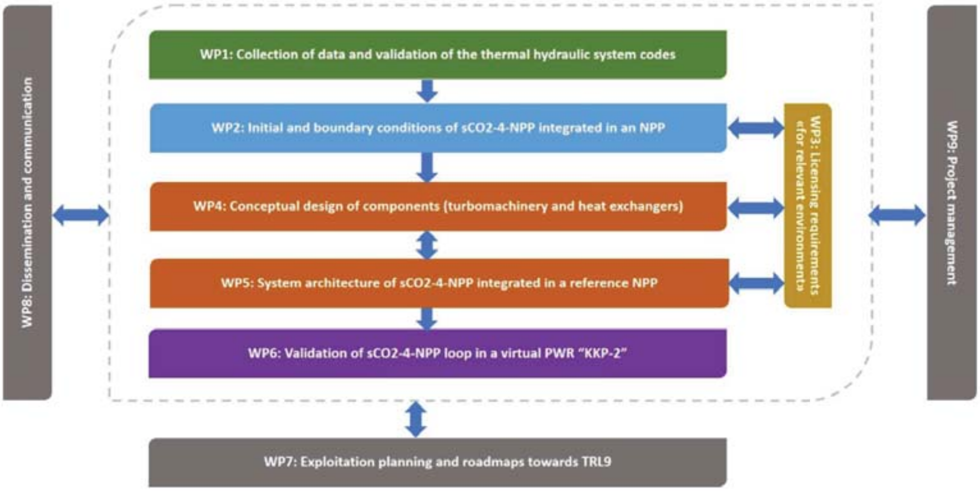


General objectives

- 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

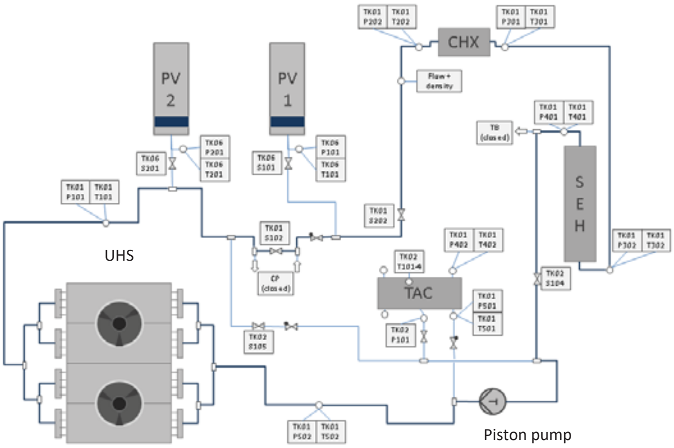
- Preparation of the industrial scaling up
  - Specification of upscaled components for implementation in a full-scale NPP
  - Final design of the system architecture integrated to a real design of PWR reactor
  - Licensing roadmaps and licensing requirements for the upscaled components and the overall system

SCO2-4-NPP Work Plan structure



sCO_2 loop modelling

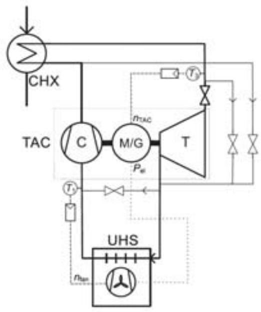
- Loop modelling in 3 thermohydraulic codes

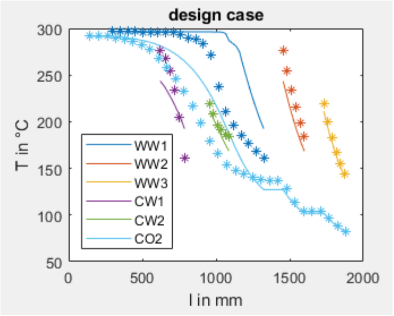


- Results: Comparison between tests data and models in ATHLET, CATHARE, MODELICA

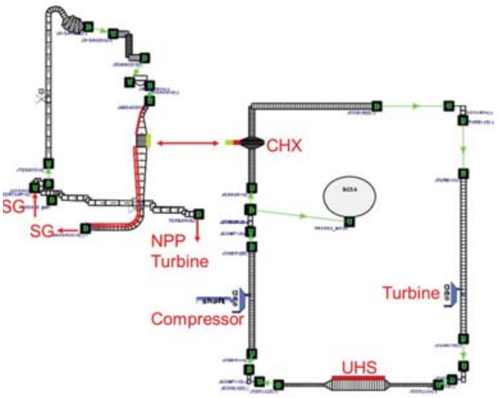
Integration in Thermohydraulic codes

- 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)

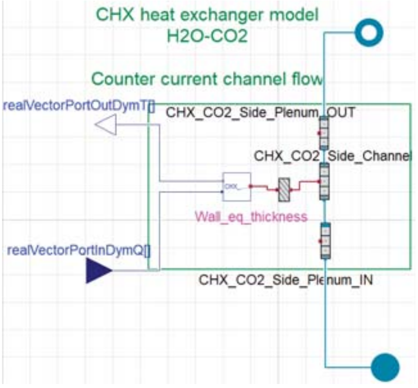




Integration in Thermohydraulic codes



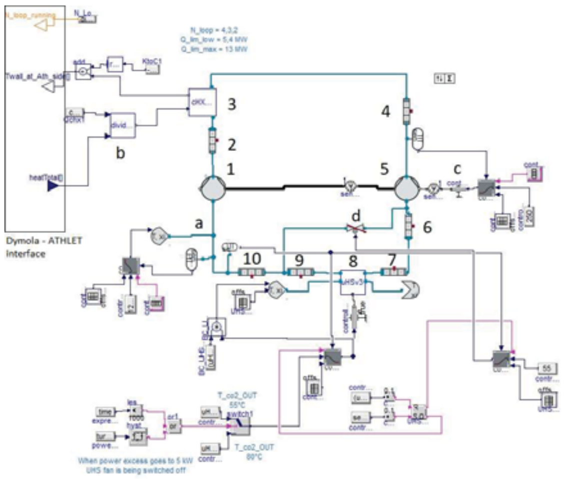
EPR : sCO2 loop allows to cool down the primary circuit but the power dissipated is too low and several sCO2 loops are needed (at least 4)



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 modelisation

- 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-up starting 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 capabilites.
  - First iteration Dymola model prepared with input and output connectors – Needs for behavior assessment (controls…)

Lessons learned

- Continue the necessary comparisons and harmonizations of the different codes
  - Ensure that the results obtained for these different codes will be of acceptable quality for the different nuclear studies in cases where keeping different codes is necessary.
- Share new developments related to innovations.
  - New developments of libraries or models in a code.
  - Improve the dissemination of these innovations
- Moving towards common digital tools.
  - Sharing and common developments can also lead the different actors towards the choice of a common tool, and not the multiplication of codes.

Thank You

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