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Review Article

PASTELS project - overall progress of the project on experimental and numerical activities on passive safety systems

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ABSTRACT

Nuclear accidents such as Fukushima Daiichi have highlighted the potential of passive safety systems to replace or complement active safety systems as part of the overall prevention and/or mitigation strategies. In addition, passive systems are key features of Small Modular Reactors (SMRs), for which they are becoming almost unavoidable and are part of the basic design of many reactors available in today's nuclear market. Nevertheless, their potential to significantly increase the safety of nuclear power plants still needs to be strengthened, in particular the ability of computer codes to determine their performance and reliability in industrial applications and support the safety demonstration.

The PASTELS project (September 2020–February 2024), funded by the European Commission “Euratom H2020” programme, is devoted to the study of passive systems relying on natural circulation. The project focuses on two types, namely the SAFETY COndenser (SACO) for the evacuation of the core residual power and the Containment Wall Condenser (CWC) for the reduction of heat and pressure in the containment vessel in case of accident.

A specific design for each of these systems is being investigated in the project. Firstly, a straight vertical pool type of SACO has been implemented on the Framatome's PKL loop at Erlangen. It represents a tube bundle type heat exchanger that transfers heat from the secondary circuit to the water pool in which it is immersed by condensing the vapour generated in the steam generator. Secondly, the project relies on the CWC installed on the PASI test loop at LUT University in Finland. This facility reproduces the thermal-hydraulic behaviour of a Passive Containment Cooling System (PCCS) mainly composed of a CWC, a heat exchanger in the containment vessel connected to a water tank at atmospheric pressure outside the vessel which represents the ultimate heat sink. Several activities are carried out within the framework of the project. Different tests are conducted on these integral test facilities to produce new and relevant experimental data allowing to better characterize the physical behaviours and the performances of these systems for various thermo-hydraulic conditions. These test programmes are simulated by different codes acting at different scales, mainly system and CFD codes. New “system/CFD” coupling approaches are also considered to evaluate their potential to benefit both from the accuracy of CFD in regions where local 3D effects are dominant and system codes whose computational speed, robustness and general level of physical validation are particularly appreciated in industrial studies. In parallel, the project includes the study of single and two-phase natural circulation loops through a bibliographical study and the simulations of the PERSEO and HERO-2 experimental facilities. After a synthetic presentation of the project and its objectives, this article provides the reader with findings related to the physical analysis of the test results obtained on the PKL and PASI installations as well an overall evaluation of the capability of the different numerical tools to simulate passive systems.

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1. Introduction

In the nuclear industry field, safety issues are at the forefront in the design of nuclear power plants. This is the first concern, and mitigation capability in the event of severe accidents is permanently questioned and leads to continuous improvements.

The Fukushima Daiichi nuclear accident showed the vulnerability of nuclear power plants following the losses of electrical power and ultimate heat sink that occurred. During the accident, the insufficient performance of the heat removal system resulted in core melt and in the release of radioactive material to the surroundings with several hundred billion dollars damages. Prevention and mitigation strategies for these events were analysed and have led to the need for safer and more reliable residual heat removal solutions.

Among the possible solutions, passive safety systems have been identified as credible options given to nuclear power plant designers irrespective of the generation of the reactor (GEN II, GEN III, GEN IV ...). They have been integrated in recent designs such as the Russian VVER-AES2006 ([1]), the American AP1000 ([2]) and the Chinese HPR-1000 ([3]). Passive systems form the basis of many Small Modular Reactors (SMR) designs, one of the “most promising emerging technologies in nuclear power” according to IAEA ([4]).

The implementation of passive systems is a choice which depends on safety and economic considerations, as it has a significant impact on the architecture of the whole nuclear power plant. In any case, a passive system must verify that it is able to function properly in all the situations it was designed for, at each stage of the transient accidental scenario and with the adequate performance and reliability levels.

Unfortunately, European actors in nuclear industry (manufacturers, operators, utilities etc.) have little first-hand experience with these systems, even if the implementation of efficient passive systems can be seen as an important improvement of the safety.

In-depth analyses and studies are still needed to properly evaluate the benefit of such systems and identify their drawbacks.

Lastly, the safety demonstration with passive systems must be justified in the safety analysis with the same level of confidence as it has to be done for active systems to be able to estimate the relevance of the implementation of such system in a new plant design.

In order to reach that goal, the study of innovative passive systems encompasses several important aspects:

1. The identification and understanding of the physical phenomena governing the behaviour of these systems.
2. The reliable modelling of these physical phenomena, and their implementation in dedicated computational codes, to validate the use of these numerical tools for the system design and safety demonstration.
3. The consideration in the safety demonstration methodology of the specificity of passive systems (scaling, reliability, performance level, etc.).

The PASTELS project stands for “PAssive Systems: Simulating the Thermal-hydraulics with Experimental Studies”, aims at contributing to the fulfilment of such a roadmap.

The objective of the present paper is to provide an overview of the project’s overall progress. Experimental and numerical activities and results are discussed from an overall perspective. More details can be found in the public deliverables of the project indicated throughout the text and listed in the paragraph “References” at the end of this paper.

2. Context and overall objective of the project

2.1. Motivation of the project

The PASTELS project aims to significantly increase the knowledge of passive systems for European nuclear actors. One of the main objectives

of the project is to evaluate and improve the ability of several thermohydraulic system and CFD codes, used in the nuclear community for design and safety demonstration, to accurately model key physical phenomena for passive systems such as natural circulation loops ([5]).

Given the increasing use of passive systems in non-European nuclear power plants, it is essential, especially with the rise of SMRs, such as NUWARD™, that largely integrate these systems into their design, that the European nuclear community adapts its numerical reference tools to study these promising technologies. This must be undertaken based on relevant and representative experimental data of the passive systems of interest. The SAFETY CONDENSER (SACO) and the Containment Wall Condenser (CWC) are the two innovative passive systems selected for the project.

The project builds on existing combined effects test campaigns obtained in the PERSEO and HERO-2 test facilities (SIET, Piacenza, Italy), but also on new data obtained in integral test facilities operating under conditions close to industrial applications that fill the gap in representative experimental data at European level: PKL test facility (Framatome GmbH, Erlangen, Germany) for SACO ([6]) and PASI test facility (LUT University, Lappeenranta, Finland) for CWC.

Numerical and experimental activities are carried out in a step-by-step approach. Through different benchmarks, PASTELS studies model improvements and proposes new coupling methodologies to obtain the benefits of system and CFD scales in the same calculation.

In addition, important knowledge on the behaviour of SACO and CWC is gained by observing their performance during the test campaigns.

All the results of the project will contribute to the development of detailed methodological guidelines and a roadmap for the licensing and implementation of these innovative passive system technologies in future European nuclear power plants.












3. General presentation of the PASTELS project

3.1. Framework of the PASTELS project

The PASTELS project is part of the European H2020 programme. The project started in September 2020 for a duration of 42 months.

PASTELS gathers eleven European organizations, with complementary skills and expertise which, when combined altogether, are expected to achieve significant progress in the study of passive systems. The PASTELS consortium comprises operators, designers, academics, and regulatory bodies which members are listed in the Table 1 below.

Table 1
PASTELS consortium members.

Consortium		
	Participant short name	Participant organisation name
	EDF (coordinator)	ELECTRICITE DE FRANCE
	ENEA	AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE
	CEA	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES
	FRA-G	FRAMATOME GMBH
	GRS	GESELLSCHAFT FUR ANLAGEN UND REAKTORSICHERHEIT (GRS) gGmbH
	USTUTT	UNIVERSITAET STUTTGART
	IRSN	INSTITUT DE RADIOPROTECTION ET DE SURETE NUCLEAIRE
	LUT	LAPPEENRANNAN-LAHDEN TEKNILLINEN YLIOPISTO LUT
	PSI	PAUL SCHERRER INSTITUT
	UJV	UJV REZ, a. s.
	ART	ARTTIC

3.2. PASTELS overall structure

The PASTELS project is structured in five different work packages (WP, see Fig. 1):

- WP1: Project management
- WP2: Status of code validation on SET & CET
- WP3: SACO construction and PKL experiments
- WP4: Adaptation of the PASI facility and CWC experiments
- WP5: General synthesis, dissemination, and communication

WP1 is responsible for the effective coordination and management of the project.

Separate and combined effects tests are studied in WP2 while integral effects tests are the subject of WP3 and WP4.

WP2 consists of several activities such as research and analysis of the state of the art in the literature or comparisons between new calculations and past available experiments. The first activity is related to the establishment of the current status of code validation for natural circulation safety systems. This includes discussion on models, experimental support, difficulties, and successes encountered in the simulations. The second part presents the results of the simulations and comparisons with simple experiments performed prior to the PASTELS project. Two different tests campaigns provided by ENEA's experimental facilities: HERO-2 ([7]) and PERSEO ([8]), located at SIET – Piacenza (Italy) were considered.

The aim of WP3 is to generate experimental data on the performance of a specific SACO design adapted to PWR under operational and plant accident conditions.

WP4 aims to perform a series of tests on natural circulation and heat transfer in a type of low-pressure open loop CWC.

In WP2, WP3 and WP4, the experimental data available in the project will be carried out in conjunction with deterministic studies using thermal and hydraulic numerical tools at different scales, including system codes such as CATHARE-3 ([9]), ATHLET ([10], [11]), APROS ([12]), RELAP-5 ([13]) and TRACE ([14]), CFD codes such as neptune_cfd ([15]) or FLUENT ([16]), and severe accident codes, such as ASTEC ([17]) and MELCOR ([18]).

Finally, WP5 manages the dissemination of PASTELS results within the European nuclear community.

4. Overview of the progress of the PASTELS project

The PASTELS project is currently in its third year. Many activities have been undertaken in the three technical workpackages WP2, WP3 and WP4. The project is also involved in various communication activities through WP5.

The following paragraphs summarizes the progress made in the different workpackages. The aim is to give the reader an overview of the activities that can be found in the project documentation. A more detailed description of the work and results of the projects can be found in the deliverables and communication media indicated all along these paragraphs.

4.1. Focus on WP2: Status of code validation on SET & CET

The first activity of the project was dedicated to bibliographic research (Deliverable D2.1, [19]) and provided the consortium with a starting point to investigate the existing knowledge in the literature dealing with the relevant phenomena of natural circulation in closed loop (pressure losses, instabilities, effect of non-condensable gases ...). More than one hundred articles are thus classified in this document according to a particular methodology, allowing the reader to efficiently identify the document adapted to his research.

The project then initiate its first numerical analysis on existing test results. The choice was made to start with test facilities capable of isolating “simple” relevant phenomena.

Separated Effect Tests (SET) HERO-2 and Combined Effect Tests (CET) PERSEO have been provided by ENEA. The HERO-2 facility, originally designed to study bayonet tube steam generator, is a test section devoted to basic studies on natural circulation both in steady-state and transient conditions (Fig. 2). The PERSEO facility reproduces the main physical mechanisms of the SACO components: heat exchange with condensation in vertical pipe on the primary side, natural circulation boiling on secondary side, and condensation of steam in a pool by direct injection below the free level. Both test facilities have been simulated with the different numerical tools of the PASTELS members.

The work on HERO-2 has been completed and the main results are available in Deliverable D2.2 ([20]). Various numerical tools at the system scale (ATHLET, CATHARE 3, RELAP5) and at the CFD scale (ANSYS CFX, Fluent, neptune_cfd) has been used to simulate more than 20 steady state configurations. Preliminary work in an open-extended

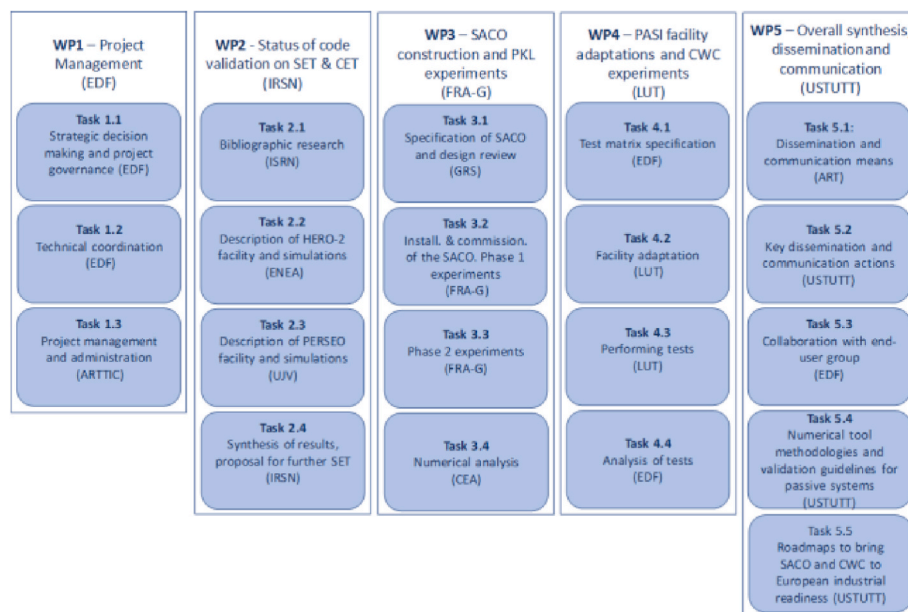


Fig. 1. PASTELS works breakdown structure.

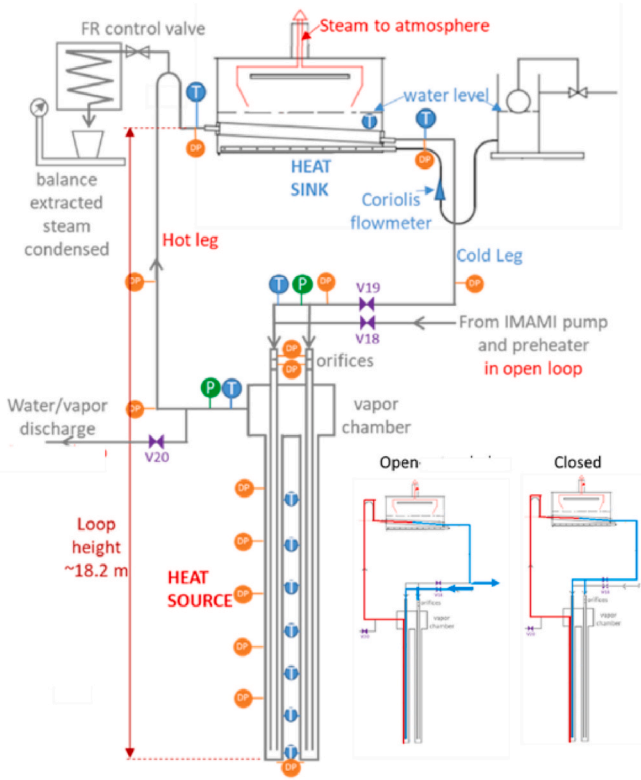


Fig. 2. WP2 - Scheme of HERO-2 facility layout for forced and natural circulation experiments.

configuration of the test facility was carried out for model calibration; in this configuration used to characterise the heat losses and pressure drops in most of the loop sections, water in subcooled condition circulates in forced flow through almost the entire circuit (cf. Fig. 2, enters by Valve V18 and exits at V19). Acceptable results were obtained with thermal-hydraulic system codes but further studies, especially the modelling of heat transfer, are needed to provide directions to improve the reliability of these tools. The CFD codes have encountered difficulties in performing the closed configurations. Detailed results were obtained but the required computing resources did not allow to achieve stabilized solutions. Specific procedure was developed to establish natural circulation ([21]).

The calibration performed on the open-extended configuration permit to start simulation of a more complex case: the closed loop configuration for the study of natural circulation flow regime. The simulations were carried out but the time to reach steady-state conditions was too long. Further analysis of this case at CFD scale are still in progress (Fig. 3).

The numerical analysis of PERSEO is still in progress and final results should be available by mid-2023 at the latest.

4.2. Focus on WP3: SACO construction and PKL experiments

The studies of the decay heat removal from the core with passive system is being investigated by new experimental campaigns at PKL facility at Framatome GmbH, Erlangen ([22]).

The SACO is a passive system connected to the steam generator (secondary circuit) of a pressurized water reactor. The construction of the SACO, its pool (Figs. 4 and 5), related piping systems and measurement devices were built and integrated to the PKL test facility at the first stage of the project and the commissioning was completed by the end of 2021.

The specifications for the design and construction of this new passive system on the PKL test loop were discussed with the PASTELS

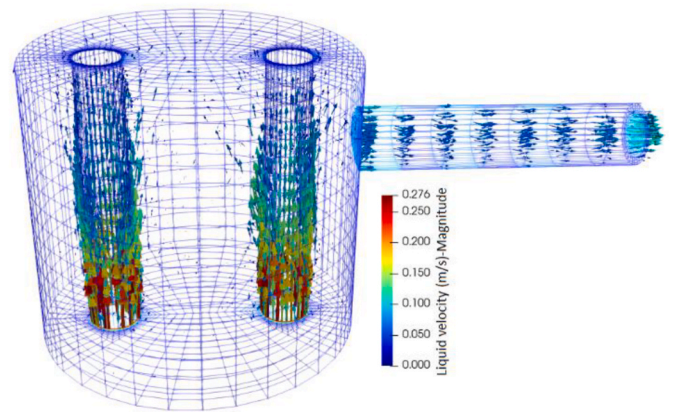


Fig. 3. WP2 - Velocity vectors in the vapor chamber in the stationary condition calculated by neptune_cfd



Fig. 4. WP3 - PKL SG No.1, SACO and pool – components and mock-up in principle (primary side not shown).

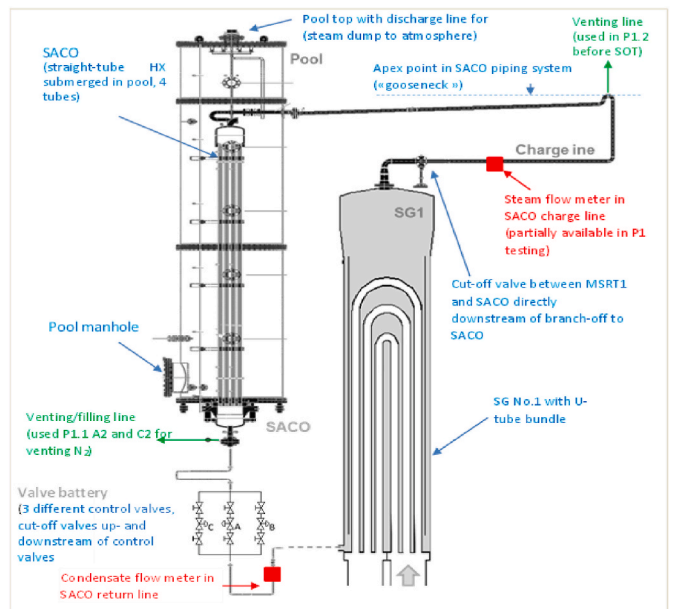


Fig. 5. WP3 - PKL SG No.1, SACO, and pool – components and mock-up in principle (primary side not shown), picture not to scale.

consortium and are detailed in the Deliverable D3.1 ([23]). The final design of the SACO heat exchanger (HX) comprises four straight vertical tubes between two manifolds. The SACO-HX is fully submerged in a pool, a stainless-steel cylindrical vessel of about 7,6 m height and 1,4 m internal diameter. A Passive Pressure-Pulse Transmitter (PPPT, [24]) can be used to activate the SACO in the event of a pressure drop in the secondary side of the Steam Generator. This system was designed as a fully passive switching element as part of the Framatome’s BWR-type KERENA reactor (formerly known as SWR 1000). The SACO currently installed on the PKL site is designed to evacuate 450 kW, which corresponds to a power of 65 MW on the scale of the PWR.

During the initial period of the project, the first part P1 of the SACO tests matrix was prepared to evaluate the performance of the SACO as a function of varying parameters of interest, with steady-state (P1.1) or transient (P1.2) operating conditions.

Five steady-state cases (A to E) were defined for P1.1 (Fig. 6); the pool fill level is modified for each case and core power is adjusted by the operator in response to the decrease in heat removal capacity in the SACO to achieve a new steady state. During this series of experiments, an uncontrolled amount of non-condensable gases (NCG) had a significant impact on the SACO heat transfer capacity and it was decided to repeat phases A and C (labelled A2 and C2) ... In A2 and C2, a “hot venting procedures” (venting of NGC under high temperature and pressure through the gooseneck in the charge line and the bottom of the SACO calotte in the return line, see Fig. 5) was applied to minimise at least as possible the amount of NCG in the system.

For 1.2 test, the pool temperature, amount of NCG, SACO tube fill level and pressure and temperature of secondary were the initial condition variations considered before Start Of Test (SOT; see Fig. 7)). For this series of tests, the primary and secondary sides have been decoupled in terms of heat transfer (by nitrogen charges to the Steam Generator U-tubes) and the primary side condition did not affect the secondary side and vice versa. After conditioning of the secondary side, the SACO is opened, and objective of the runs is to study secondary side heat removal over time from the SACO (e.g. depressurisation of the secondary side from 60 to 2 bar; see Fig. 8).

The P1 matrix was simulated with AC²-ATHLET, CATHARE-3, RELAP5, TRACE for the system codes. Some simulations were also performed with CATHARE-neptune_cfd coupling methodologies (the T/H of the pool is simulated with the CFD code to benefit from the local 3D approach in this tank instead of having a volume/axial refinement).

Fig. 9 show an example of the numerical analysis performed on the P1.2 tests by GRS with the ATHLET system code on run 0. In these figures, we can clearly identify that the mass flow rate of the condensate

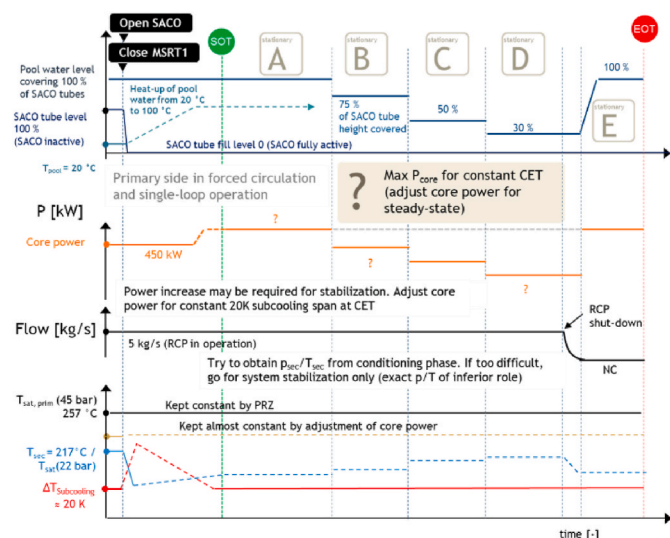


Fig. 6. WP3 - Planned procedure (sequence of parameter changes).

inside the SACO is underestimated compared to the experiment. Therefore, heat exchange of the tubes immersed in the water pool has to be corrected to improve the reliability of the simulation tool.

Fig. 10 illustrates the value of thermal coupling in taking into account phenomena such as thermal stratification and natural convection in the pool, which cannot be well modelled with the 0D/1D system codes. Nevertheless, the coupling simulations carried out at this stage of the project were inconclusive compared with the code system simulations.

A direct comparison was made between the CATHARE and CATHARE-neptune_cfd simulations. Fig. 11 illustrates the heat transfer with the pool. The power exchanged at SACO is close to the experimental value for the CATHARE and coupling simulations, but the power obtained by the CATHARE simulation fluctuates more. This can be explained by the fact that the coupling model does not take into account the presence of NCG.

The complete analysis of P1 experiments and numerical simulations will be available in the forthcoming Deliverables D3.2 ([25]) and D3.3 ([26]).

The second part P2 of the matrix is not yet fully finalised. So far, one transient test P2.1 has been completed: a cool-down transient under extended loss-of-AC-power condition. This test examines the SACO behaviour in operational environment and studies the typical phenomena of cool-down procedure in Station Black Out condition with SACO employed as decay heat removal. This test should be used by the project as a blind-test and will give the possibility to evaluate the capabilities of the different numerical tools to reproduce this scenario on the basis of the results obtained on the P1 tests. The numerical simulations of this test should be completed by the end of summer 2023.

The main PASTEL overall objective remains to understand the physics of the passive systems and to be able to assess the current capability of the numerical tools. Therefore, P2.2 tests will probably be devoted to repetition of some tests of the P1 matrix in order to consolidate our knowledge on SACO performances.

4.3. Focus on WP4: PASI facility adaptation and CWC experiments

The PASI facility ([27], [28]) at LUT University (LUT), Lappeenranta, Finland, is a one-loop model of an open passive containment cooling system (Fig. 12). The applicable reference system for the PASI test facility is the passive containment heat removal system of the AES-2006 type pressurized water reactor. The design height scale of the PASI facility versus the reference system is 1:2. PASI consists of a steam vessel including a bundle of heat exchanger tubes, a natural circulating water loop connected to a water pool at atmospheric pressure, and measurement and data acquisition systems (Fig. 13). A valve was also installed in the downcomer in order to control the overall mass flowrate in the loop.

The PASI test program within PASTELS aims to address the different objectives of the project:

- Understanding in more detail the physical behaviour of a thermosiphon cooling system in an interaction between the containment as a heat source and the external water tank as a heat sink.
- Characterization of the system performance for a geometry that has been designed in similarity with the actual system design present in an AES-2006 reactor maintaining relative gravitational and frictional pressure losses in the scaling
- Development of an extending database with sufficient measurements in order to help the community of researchers and designers to simulate the phenomena with their own codes and standards.

A total of ten tests have been programmed along the project (eight quasi-steady-tests and two transient tests). Six out of ten tests have been performed in 2022 (tests 1, 2, 3,4,5 and 10). The objectives of the tests are the following:

	P1 R0 (reference)	P1.2 R1	P1.2 R2	P1.2 R3	P1.2 R4	P1.2 R5
T_{sec} p_{sec} at SOT	233 °C (T_{sat}) 22 bar	275 °C (T_{sat}) 60 bar	275 °C 60 bar	275 °C 60 bar	275 °C 60 bar	247 °C (T_{sat}) 38 bar
Pool water temperature at SOT	≈ 20 °C (ambient)	≈ 20 °C (ambient)	≈ 100 °C	100 °C	100 °C	100 °C
Pool water level at SOT	100 %	100 %	100 %	100 %	100 %	100 %
SACO tube target fill level during test	0	0 (SACO tubes empty of water)	0	0	50 % (SACO tubes filled to half height, kept constant)	0
Nitrogen on Secondary side	none	none	none	100% = volume of SACO, charge and return lines	none	none

Fig. 7. WP3 - Characteristics of P1.2 tests matrix.

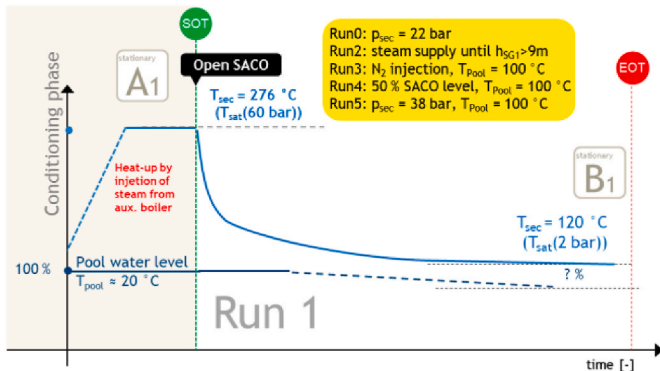


Fig. 8. WP3 - Example of P1.2 R0 scenario.

- Test 7-8 to explore the impact of modified geometry of the sparger (closing of the pressure distribution hole in the top part of the riser pipeline) on the system behavior.
- Test 9 to characterize the system startup from the nominal initial pre-accident conditions with cold water in the pool and no flow in the loop
- Test 10 to characterize the system response to the refilling of the depleted water pool with cold water, after having operated at accident conditions and spent the water inventory.

The complete description of the PASI tests matrix and its objectives are reported in Deliverable D4.1 ([29]).

Experiments 1-4 showed that the system efficiently removed heat over the wide range of added loop flow resistances tested. The loop mass flow rate was stable until saturation was approached. With low sub-cooling condition in the loop, geysering-like flow oscillations occurred (Fig. 14) Heat removal capability from containment to loop side remained consistently good despite the flow oscillations. Decreasing heating power reduced the oscillation frequency of the loop flow, but the amplitude stayed constant. After each increase in the flow resistance using the valve, the void fraction in the riser increased and the system found at once a new quasi-steady state and the heat was adequately

- Test 1-4 to characterize the cooling system behaviour and natural circulation in the thermosiphon loop under different heating powers and the effect of the added loop flow resistance
- Test 5-6 to explore the influence of the gravity head on the performance of the loop and on initiation of the loop flow oscillations

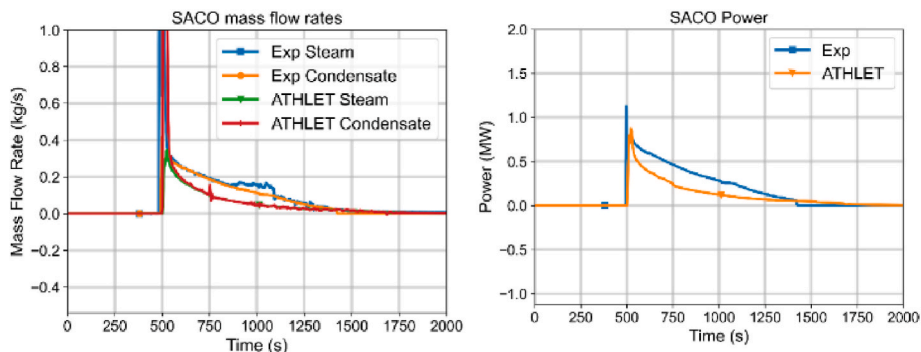


Fig. 9. WP3 - Example of P 1.2 run0 simulation with ATHLET code.

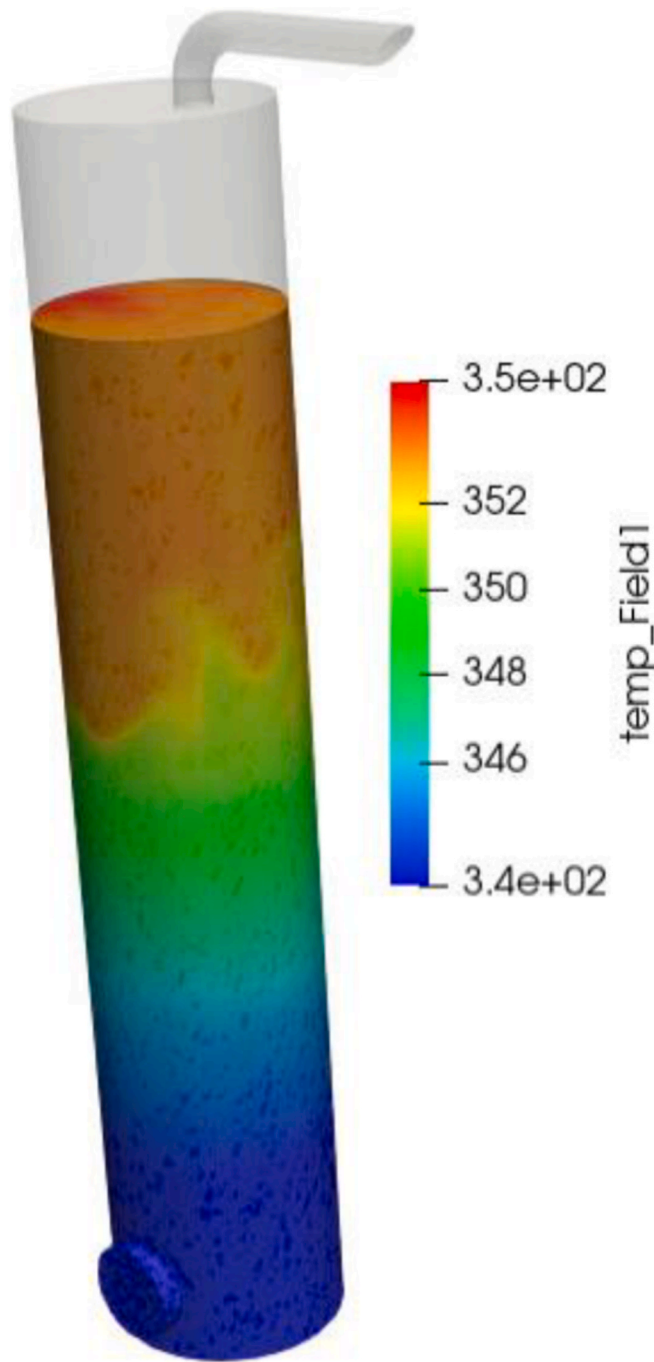


Fig. 10. WP3 – Example of temperature field illustrating the thermal stratification in the SACO pool (coupling simulation).

transferred.

Pre-test analysis has been carried out in the project with the different system codes AC²-ATHLET, CATHARE-3, RELAP5, TRACE (see Deliverable D4.3 ([30])) and also with the “lumped parameter code MELCOR” used for severe accident analysis. A general agreement has been found by all the codes on the qualitative results with development of the oscillations in the thermosiphon loop despite some differences on quantitative parameters such as power extraction, ranges of mass flow rate during oscillations.

A numerical analysis of the PASI test measurements is still in progress and the results should be available during 2023.

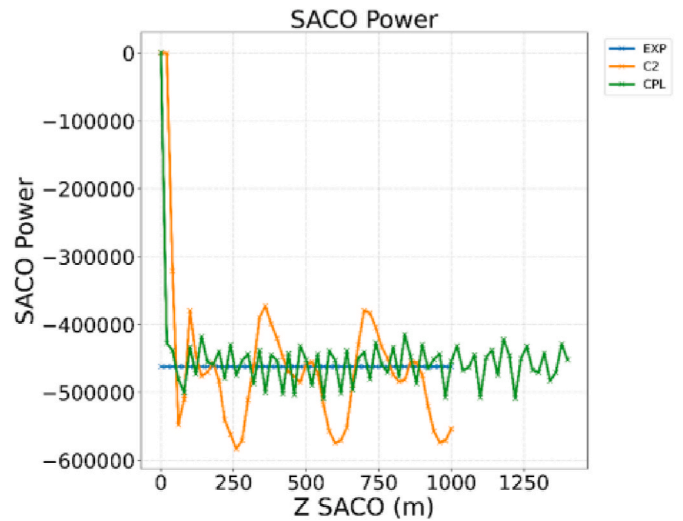


Fig. 11. WP3 – SACO power – comparison between experiment (exp), CATHARE (C2) et coupling simulations (CPL).

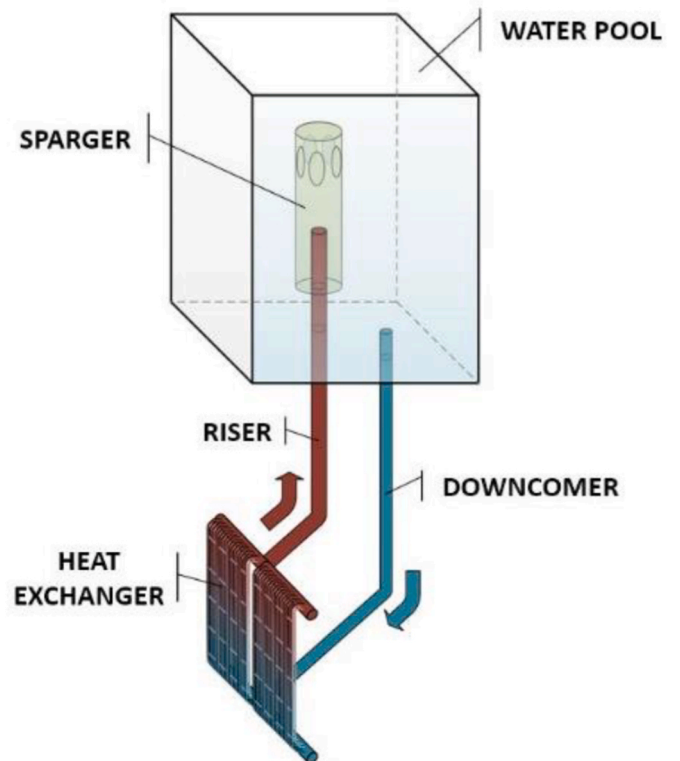


Fig. 12. WP4 - Schematic presentation of the Passive Containment Cooling System (PCCS).

4.4. Focus on WP5: Dissemination and communication

As part of the technical work performed all along the project, all the partners of the consortium are concerned with communication of the work performed during the project. The PASTELS project has been involved in many international Conferences such as IAEA conference ([21]), NURETH ([31], [32]), NUTHOS ([33]), and European forums/conferences like FISA ([34], [35]), SNETP ([36]).

PhD and Master Thesis Students are involved in the project to accelerate the dissemination of PASTELS research in the young scientific community ([37]).

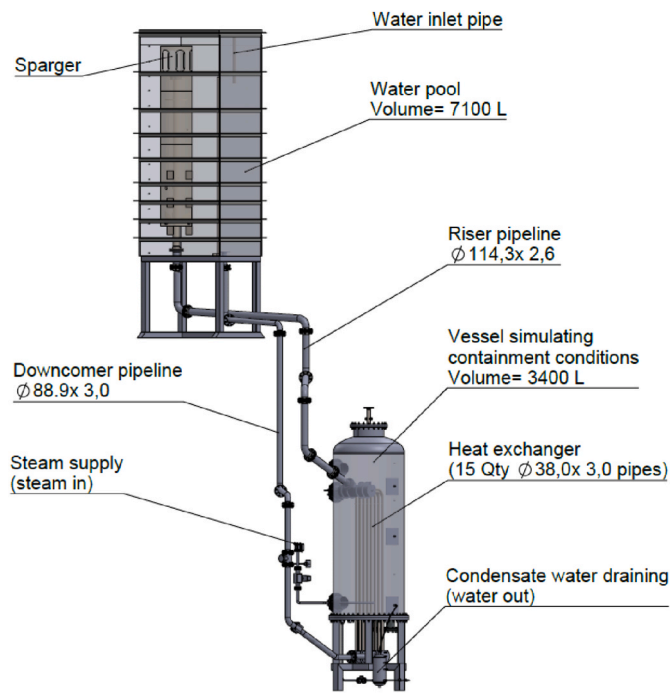


Fig. 13. WP4 - PASI test facility.

The project also proposed a short pedagogical video to explain with simple concept the objectives of the project. This video is available on YouTube: <https://www.youtube.com/channel/UCwP950KufavMA-czKUrWYXg>.

5. Conclusions

The PASTELS project is entering its final year of activity. Numerous experimental tests have been carried out highlighting the capabilities of the tested passive system (SACO, CWC) to remove residual heat from the system at a relevant power level for different T/H conditions (e.g.: energy to be extracted, influence of head losses, non-condensable gases, inventory of ultimate sink sources). Regarding the PASI/CWC system, an oscillatory behaviour was measured which, although not having a really significant impact on the system performance, was only roughly

simulated by the computing tools. Regarding the SACO on the PKL facility, due to design reasons, it was not possible to completely eliminate the non-condensable gases inside the SACO circuit at the beginning of the phase 1 tests; even though the heat exchange rate was affected by these gases, the system continued to show a good cooling capacity. Nevertheless, presence of non-condensable in the test loop should be assessed in the second step of the analysis as it complexifies the understanding of the physics and remains a challenge to be precisely considered by the codes.

In the aforementioned tests, the local effects were found to be quite weak (no significant thermal stratification, reasonable amount of non-condensable gases, limited 3D cross flow ...). No major drawbacks or deficiency was identified in the calculations carried out so far showing a reasonable agreement between the system codes and the experiments. Nevertheless, code to code comparisons showed some discrepancies related to user effect, especially the choice of nodalisation (“volume” and/or “axial” components) to model the water tanks with exchangers.

At full-CFD scale, the situation is more delicate. The modelling of two-phase thermosiphon loop at low pressure with strong interaction between the different circuits of passive systems remains a challenge.

- The whole system is difficult to simulate because it leads to very large calculation domains with large number of cells, most of the time incompatible with the V&V process in time of the project.
- Some physics requires very accurate modelling which are not systematically implemented in the codes or need refined meshes that increase calculation time.

Methodologies for coupling CFD code (neptune_cfd) and system code (CATHARE) have been performed for some PKL/SACO tests. Currently, these calculations gave few additional improvements in results compared to the stand-alone calculation of the system, probably due to the lack of 3D effects.

In 2023, the last tests will be carried out on PKL and PASI, followed by numerical analysis. By early 2024, the PASTELS project should be completed and will propose some “methodologies and guidelines for validation and use of numerical tools” and a “roadmap for European versions of SACO and CWC”.

No direct follow-up is planned after the end of the PASTELS project in 2024. Nevertheless, the lessons learn on the physical behaviour and simulation of innovative passive safety systems would be used as input data for the next *Euratom Research and Training Programme 2023-2025*. In this programme, one innovative action is proposed on *Safety of light*

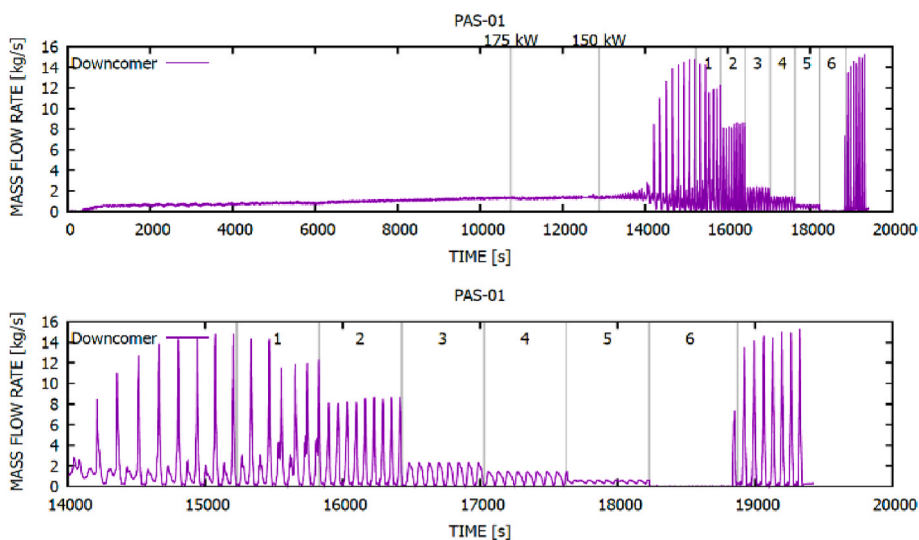


Fig. 14. WP4 - Downcomer mass flow rate in the PASI test 1 Downcomer valve position: 1 - fully open, 2-50 % closed, 3-81 % closed, 4-86 % closed, 5-91 % closed, 6-95 % closed.

water small modular reactors (LW-SMRs). Most of the partners of the PASTELS project are already involved in defining the programme for this new project, which will also be supported by relevant new test facilities designed to address SMR issues. The simulation capabilities of the T/H codes will continue to be put to the test as part of this new project.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Michael Montout reports financial support was provided by European Commission. Michael Montout reports a relationship with EDF Reserach and Development Chatou Site that includes: employment.

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Nomenclature

CET	Combined Effect Test
CFD	Computational Fluid Dynamics
CWC	Containment Wall Condenser
GEN II+, GEN III, GEN IV	Generation II + or III or IV of reactor
NGC	Non Condensable Gas
NPP(s)	Nuclear Power Plant(s)
PCCS	Passive Containment Cooling System
PWR	Pressurised Water Reactor
SACO	SAfety COndenser
SOT	Start Of Test
SET	Separated Effect Test
SMR	Small Modular Reactor
T/H	Thermalhydraulic
V&V	Verification and Validation
WP	Workpackage

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