



EDF, Framatome, ASNR and CEA present the

**30th Edition of the
CATHARE User Club (CUC)**

Collection of Abstracts

1-2 June 2026

Paris, Île-de-France

NUPTUNE

Welcome Address

30th Edition of the CATHARE User Club (CUC)

Paris, Île-de-France
1–2 June 2026

Dear Colleagues, Partners, and Distinguished Guests,

It is with great pleasure and a deep sense of pride that we welcome you to the **30th Edition of the CATHARE User Club (CUC)**, hosted in the vibrant city of Paris. This milestone edition marks five decades of innovation, collaboration, and excellence in the field of thermal-hydraulics and nuclear safety.

The CATHARE code has been a cornerstone of research and industrial applications, enabling groundbreaking advancements in energy systems worldwide. As we gather here today, we celebrate not only the achievements of the past but also the promise of the future, one that is shaped by your expertise, dedication, and shared vision.

Over the next two days, we will explore the latest developments in CATHARE applications, engage in thought-provoking discussions, and foster new partnerships. This event is a unique opportunity to exchange ideas, address challenges, and inspire the next generation of innovations in thermal-hydraulics.

We extend our heartfelt gratitude to the **NEPTUNE project launched by Framatome, EDF, ASNR and CEA** for their unwavering support in ensuring the success of this event. Special thanks also go to our speakers, organizers, and participants, without whom this gathering would not be possible.

As we embark on this journey together, let us embrace the spirit of collaboration and curiosity. May this edition of the CUC be a catalyst for transformative ideas and enduring connections.

Wishing you an inspiring and productive conference!

The CATHARE Team

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CATHARE News & Future Prospects

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ABSTRACT

This presentation begins with a brief overview of CATHARE-3's core capabilities, highlighting its role as a leading thermal-hydraulic simulation tool for nuclear safety analysis [1]. We will then outline the collaborative development framework, which involves CEA, EDF, Framatome, and ASNR.

Building on this foundation, we will introduce the major advancements implemented since the last CATHARE Users Club (CUC) [2], providing a comprehensive update that sets the stage for the detailed technical sessions scheduled over the next two days.

Additionally, this presentation will address the key challenges facing the CATHARE team in the coming years, including validation needs.

Among the future challenges, we will place a special focus on exploring the potential of AI-driven tools, including Large Language Models (LLMs) and intelligent agents, discussing their applications and presenting their advantages for enhancing CATHARE's capabilities and for the CATHARE team.

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**4th-Generation Nuclear Reactors and Innovative Nuclear: Innovations in Reactor
Technology, Safety, and Applications**

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ABSTRACT

The R4GNI program drives 4th-generation nuclear reactor development, focusing on sodium-cooled fast reactors (RNR-Na) and molten salt reactors (MSR) to overcome key scientific and technological barriers. R4GNI collaborates with global leaders to integrate multi-vector applications, such as hydrogen production and high-temperature heat, while supporting the development of LW and Gen4 small modular reactors (SMR/AMR) designs.

The CATHARE code is a cornerstone of the R4GNI program, playing a pivotal role in advancing 4th-generation reactor safety and performance. As a best-estimate thermal-hydraulic (TH) simulation tool, CATHARE enables high-fidelity modelling of transient and accident scenarios, such as Loss of Flow Accidents (LOFA) in Sodium-cooled Fast Reactors (SFR) or Loss of Coolant Accidents (LOCA) in Gas-cooled Fast Reactors (GFR). Its integration with complementary codes such as TrioCFD and TrioMC (for core behaviour) enhances its ability to assess complex multi-scale simulation cases, which is critical for validating designs and narrowing uncertainty ranges.

Within R4GNI, CATHARE supports key objectives such as optimising sodium loop dynamics, evaluating flow conditions on structural material in molten salts reactors, and ensuring reactor operability under extreme conditions. By providing realistic safety margins and regulatory-compliant analyses, it bridges the gap between R&D and industrial deployment, aligning with the Gen IV International Forum's goals for sustainability, efficiency, and proliferation resistance. Its proven track record, from PHENIX and SUPERPHENIX to VHTR hydrogen-coupled systems, reinforces its indispensability in shaping next-gen nuclear innovation.

CATHARE code at EDF/DT

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ABSTRACT

The EDF/DT's presentation begins by detailing the Technical Branch, its missions, the major events for EDF group since the last CUC in 2024, the on-going industrial projects, etc ...

Next part of the presentation is dedicated to the use of the CATHARE code at DT, with its industrial usage constraints (portable computing machines or servers, the OS, etc...). Knowledge management and the sharing of experience appear to be key points for improving the efficiency of our teams (newcomers and experienced people).

The third part presents some activities related to code validation versus experimental facilities data (through international collaboration projects or internal projects). The last part highlights the needs and wishes of the users at short, middle and long term, for on-going fields of application and potential new fields of use. Artificial Intelligence (AI) could be a way to accelerate skill development and preserve technical competence in long term. Another EDF/DT's presentation will discuss about the items for real-time simulator applications.

The conclusion highlights the strategic role that CATHARE code plays for EDF in safety studies as reference thermal-hydraulics system scale code for the Operating Fleet and New Projects, with increasing scopes of application.

ASNR Activities Using the CATHARE System Code: Overview and Focus on Passive Safety Systems and METERO-V Applications

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ABSTRACT

The French Nuclear Safety and Radiation Protection Authority (ASNR), one of the partner of the development of the code, extensively uses the CATHARE system thermal-hydraulic code to support safety assessment, for research activities, and for technical expertise related to nuclear reactor systems. This presentation will provide a comprehensive overview of the current ASNR activities involving the CATHARE code, highlighting its role in the analysis of operational and accidental transients for existing and future nuclear installations.

The presentation will first introduce the general framework of CATHARE activities within ASNR and provide an overview of the studies currently performed using the code in various fields of system thermal-hydraulic analysis.

A particular focus will then be placed on activities related to passive systems. In this context, CATHARE is used to investigate different thermal-hydraulic phenomena associated with the operation of such systems, especially natural circulation phenomena occurring in passive systems of the safety condenser type, as well as the associated heat transfer mechanisms.

Finally, the presentation will highlight ASNR activities associated with the METERO-V project using the CATHARE code. These activities contribute to the investigation and modeling of specific thermal-hydraulic phenomena of interest for system analyses and code model development.

This presentation aims to provide a concise overview of current ASNR activities using the CATHARE code and to promote discussions and exchanges within the CATHARE User Club community.

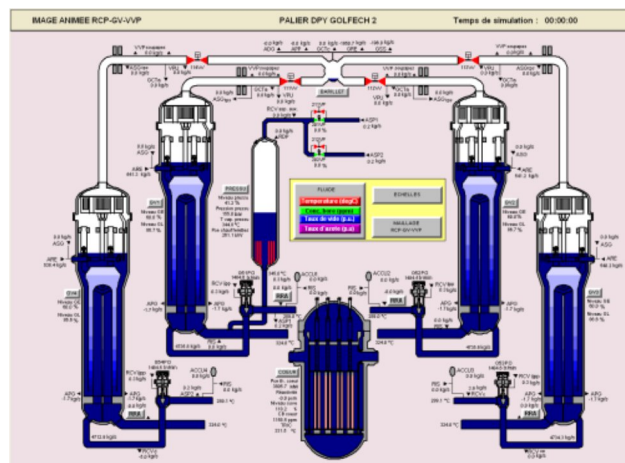


Figure: SOFIA - CATHARE simulation of the Golfech reactor system

Development works on CATHARE-COCAGNE coupling for IB-LOCA studies

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ABSTRACT

This work presents a 3D multi-physics simulation of an intermediate break loss-of-coolant accident (IB LOCA) for the KAIST-1A benchmark core based on the coupling of the CATHARE 3 and COCAGNE codes. The objective is to better assess the impact of strong axial and radial heterogeneities on neutron kinetics during rapid changes of the thermal-hydraulic environment in a PWR core under accident conditions. This aspect is especially important for IB LOCA, where core blowdown is significantly slower than in large-break LOCA scenarios.

In previous work, CATHARE 3 standalone 3D Cartesian core was investigated for IB LOCA applications using point neutron kinetics, thereby challenging the assumption of a stationary power shape [1]. More recently, a dedicated coupling between the 3D Cartesian core model of CATHARE 3 and the 3D neutron kinetics model of COCAGNE was developed [2]. In this approach, moderator density, moderator temperature, effective fuel temperature, and fission power fields are exchanged between the two codes, allowing the fission power distribution to evolve both axially and radially during the IB LOCA transient.

This work focuses on two recent developments. First, control rod drop is now taken into account, providing a more realistic representation of reactor shutdown following break opening. Second, a simple model for residual power has been implemented in the coupling to account for the non-negligible heat source that remains after the sharp decrease in fission power. First results indicated a noticeable impact of these models on the core thermal response, particularly on peak cladding temperature evolution. The study represents a further step toward more realistic LOCA simulations and future comparisons with full-system calculations and benchmark data.

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Containment thermal-hydraulics using CATHARE

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ABSTRACT

The Pmin methodology is a conservative 0D approach designed to minimize the pressure inside the containment following the release of a high-energy fluid caused by an accidental transient (LOCA or MSLB). This minimized total pressure is subsequently used as the containment back- pressure at the break maximizing the mass flow rate at the break and slowing down the reflooding.

CATHARE has been selected for this purpose, to replace the historical CONPATE code. The adopted approach adopted to qualify CATHARE for containment thermal-hydraulics is based on non-regression with respect to the CONPATE code. In this framework the development of a CATHARE dataset and benchmarking between CONPATE and CATHARE based on physical validation tests are performed.

A first coupling between the primary circuit and the containment has been implemented using CATHARE, allowing the transfer of containment pressure as well as released mass and energy between the different circuits. The historical methodology is retained while offering new perspectives for improvement paths.

The availability of containment datasets generated with CATHARE opens the way for simplified parametric studies using the USUL tool. An exploratory study has also been carried out to investigate uncertainty propagation in support of statistical methodologies (ESM3D). This work paves the way toward enhanced containment analyses based on CATHARE.

Overview of CATHARE use at TechnicAtome

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ABSTRACT

TechnicAtome is specialized in design, construction, commissioning and operational maintenance of compact nuclear reactors in the field of naval propulsion, research and energy.

In this context, TechnicAtome uses CATHARE2 for reactor design and safety analysis. In a near future CATHARE 3 will also be used. The use of CATHARE is divided in three main activities: Pre-shutdown analysis, Post-Shutdown analysis, and general reactor operations.

The main objectives of the pre-shutdown analysis, is to demonstrate the integrity of the first barrier during accident transients. Thus, a CATHARE2 simulation chained with a core calculation code is employed to determine the margin to the Critical Heat Flux (CHF). In this chained simulation, CATHARE2 is used to determine the physical quantity characterizing the water flow in the reactor core. These quantities are used in a quasi-static core calculation code in order to determine the margin to the CHF.

The main objectives of the post-shutdown analysis, are to design the safety systems. The post-shutdown analysis also allows to assess the pressure and temperature to qualify equipment placed in the containment vessel. Moreover, the post-shutdown analysis, allows to assess the consequences of the accident transient on the three containment barriers. To achieve all these objectives, CATHARE2 simulations are currently performed. Ongoing works aim to performed CATHARE3 simulations for post-shutdown analysis.

Last, TechnicAtome uses CATHARE2 through the SARIE full-scope simulator. SARIE allows to use the same tools from the preliminary design to the operation training. Therefore, SARIE is able to provide an accurate representation of the real system – in particular of the instrumentation and control system – while allowing a real time simulation.

In conclusion, CATHARE is an important scientific computing tool, used in a wide range of application in TechnicAtome. Efforts are being made in collaboration with the CEA to ensure its continued use, to deploy CATHARE3, and to adapt internally developed tools.

Use of the CATHARE Code at the University of Pisa for Research and Teaching

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ABSTRACT

The University of Pisa has been the first non-French user of CATHARE back in 1986, starting with the doctoral thesis of Walter Ambrosini, working at the time in the group of Prof. Francesco D'Auria. The tradition of using CATHARE at the University of Pisa continued in the past decades and recently it was made even more lively by activities performed by the present Authors in the frame of the EU ELSMOR [1] and TANDEM [2] Projects, through the doctoral study of Dr. De Angelis. Additional work is being performed in the frame of the EU EASI-SMR Project [3] and, after receiving a specific code license in 2025, for teaching purposes in the frame of the 12 ECTS course of Nuclear Safety delivered by Prof. Ambrosini at the second year of the MSc in Nuclear Engineering [4], fully taught in English at the University of Pisa. Further work in the coupling of CATHARE with an in-house neutronic code has started, waiting for possibly receiving a Python Application Programming Interface (API) to run CATHARE models through Python scripts.

While the use of CATHARE in the frame of ELSMOR has been already presented at the CUC in June 2022, the work performed in more recent years will be presented here, highlighting the interest of the University of Pisa to tighten the present cooperation with CEA and with code developers, also to establish useful exchanges in the frame of MSc and PhD student thesis works.

The work being presented concerns: a) the coupling of CATHARE with Modelica, made in the frame of the TANDEM Project in cooperation with CEA Cadarache, Politecnico di Milano and ENEA, for the study of light water SMRs with a cogenerating Balance of Plant; b) the application of CATHARE in the frame of the EASI-SMR project to analyse an experiment being conducted at PSI on the PANDA facility, related to condensation and large pool behaviour; c) the didactic use of CATHARE for describing to students a representative nodalisation of a NPP from one of the test cases of CATHARE and making them exercise in sensitivity analyses with it and with a containment pressurisation case set up for the purpose, to be compared with hand calculations.

The following figure reports examples of the material to be presented.

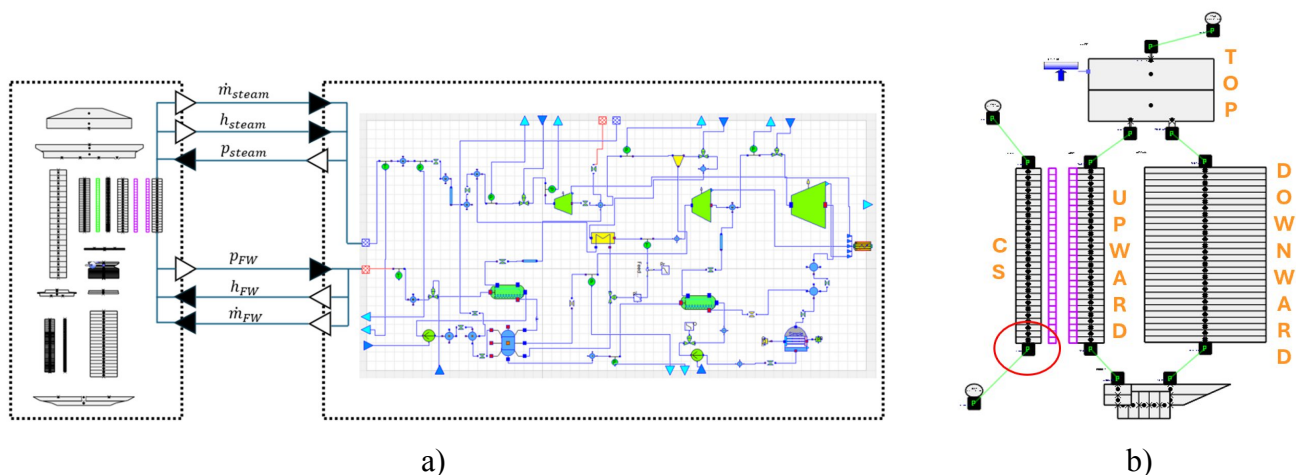


Figure 1: Screenshots from the CATHARE applications in a) TANDEM and b) EASI-SMR

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- [4] Website of the MSc in Nuclear Engineering at the University of Pisa, <https://nucleare.ing.unipi.it/it/>

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Thermal-Hydraulic Simulation of the S-Allegro Integral Test Facility with CATHARE2 code

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ABSTRACT

The S-Allegro Integral Test Facility (ITF) [1] is an electrically heated, helium-cooled, scaled-down experiment supporting research and development activities of the first-of-a-kind gas-cooled fast reactor demonstrator ALLEGRO. It is built and operated in Pilsen, Czechia, by CVR Rez. The S-Allegro is a key research infrastructure utilized to test safety systems and components of ALLEGRO under real operational and accident conditions. The presented results summarize extensive work [2] carried out within the Euratom TREASURE and national SIMONA projects [3]. The work is also part of benchmarking activities on the S-Allegro loop under the IAEA Coordinated Research Project [1]. First steady-state and transient simulations are presented using the thermo-hydraulic (TH) model of S-Allegro (Figure.1) developed at VUJE, a.s. for the CATHARE2 code. The work is part of broader activities aimed at building and qualifying relevant simulation tools to be used for the design and deployment of the ALLEGRO GFR demonstrator.

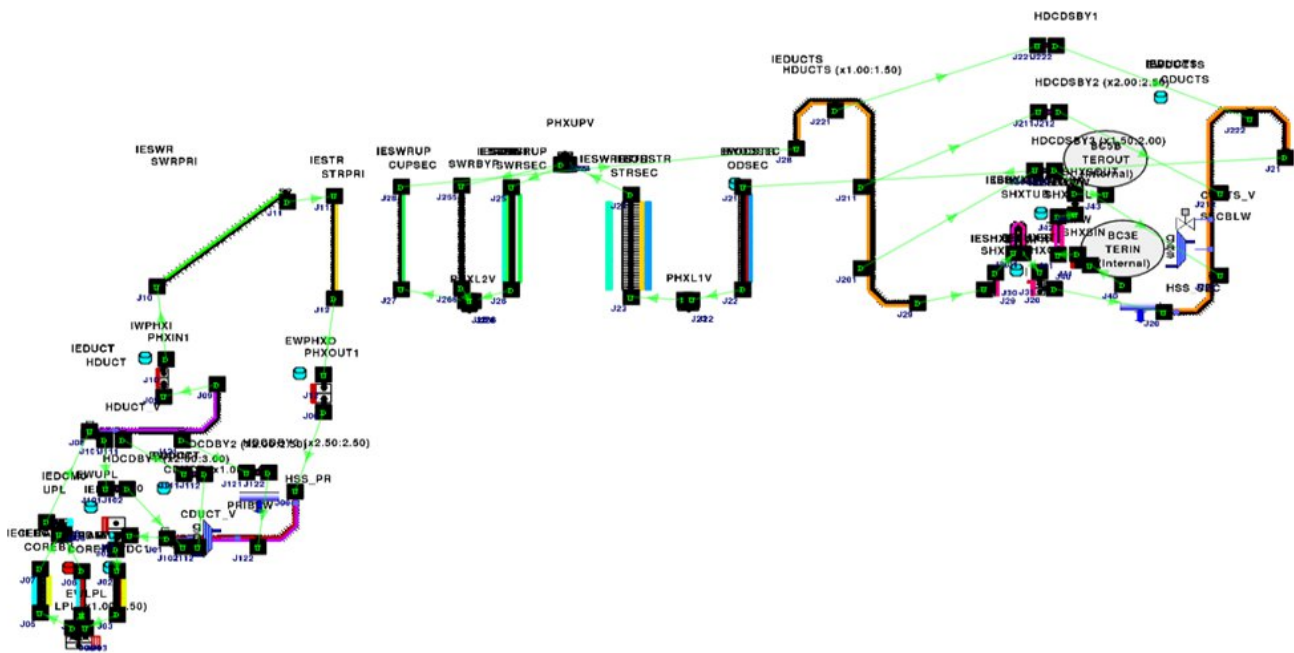


Figure. 1: S-Allegro integral test facility, CATHARE2 TH model

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CATHARE Activities at ENEA

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ABSTRACT

For several decades, ENEA has employed the CATHARE code as one of the primary tools for the thermal-hydraulic simulation and safety assessment of nuclear systems. Actually, this expertise is being leveraged to address the evolving requirements of next-generation reactors and innovative safety features. This work provides an overview of the recent activities carried out by ENEA focusing on the development and assessment of advanced system models within the framework of major EU-funded projects, TANDEM (Small Modular Reactor for a European safe and Decarbonized Energy Mix), and the ongoing EASI SMR (Ensuring Assessment of Safety Innovations for SMR).

In the TANDEM project ENEA was involved in the update of the E-SMR CATHARE model and in simulation of LOOP (Loss Of Offsite Power).

Within the EASI SMR project framework, a comprehensive experimental program is underway to support the safety assessment of passive systems. In this context, ENEA is responsible for the development of the CATHARE 3 input deck for the ELSMOR II facility (located at SIET, Piacenza), which is specifically designed to investigate passive heat removal systems based on natural circulation. This activity is conducted in collaboration with the EDF R&D group to deepen understanding of complex physical behaviour within the ELSMOR project test matrix. The study focuses on validating CATHARE's capability to simulate key thermal-hydraulic transients and exploring alternative nodalization strategies to optimize the accuracy of the results.

Another activity related to the EASI-SMR project is the development of CATHARE model of the E-LOOP_SMR plant and the simulation of a LBLOCA in cold leg 2 (without PRZ).

Use of CATHARE Code in Simulators at EDF: Overview and Prospects

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ABSTRACT

EDF has been relying on nuclear power plant simulators for several decades to support both operator training and engineering activities. In this framework, the thermal-hydraulics system code CATHARE plays a central role in the modelling of the Nuclear Island for Full Scope Simulators (FSS) and Simulator Assisted Engineering (SAE). This presentation highlights an overview of the current use of CATHARE-based models in EDF simulators, recent industrial achievements for the Operating Fleet and New Build projects, and the ongoing transition from CATHARE_2 to CATHARE_3.

For the French Operating Fleet, CATHARE_2 is the reference code, with proven numerical robustness and reliability under challenging real-time constraints. Multiple industrial configurations are used or under development, covering a wide range of reactor designs, normal operation states (from nominal power operation to cold shutdown states), and incidental or accidental transients. EDF is confident in the results of the code thanks to its experience in model integration, validation practices, and the knowledge of the limitations associated with interfaces and real-time use.

For New build projects (EPR FA3, EPR HPC and EPR2), EDF Technical Branch has developed detailed Nuclear Island models in close collaboration with Edvance and Framatome. The paper mentions the validation methodology prior to simulator delivery, including extensive benchmarking in batch mode, calibration against onsite functional tests, and full-scope simulator validation. Recent developments such as the extension of the CATHARE model (i.e. Safety Injection System) and updated engineering data sets are also discussed.

Finally, the presentation reviews recent work dedicated to the transition from CATHARE_2 to CATHARE_3 for simulator applications. Key results from non-regression testing, performance comparisons and remaining technical issues are summarized, together with an ambitious and challenging roadmap toward first industrial use of CATHARE_3 in real-time simulators.

First achievements for the future CATHARE-3 based Sodium Fast Reactor simulator SIRENA

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ABSTRACT

Since 2012, a Sodium Fast Reactor simulator called SIRENA [1] and representing the Superphénix facility is used for training (Réacteurs à neutrons rapides refroidis au sodium : fonctionnement et sûreté (simulateur SIRENa) - INSTN) and reactor operation studies purposes at the Reactor Studies Department of CEA Cadarache. At this time, it had been developed to replace the in-site Phénix simulator SIMFONIX [2] that was about to be stopped. For the moment, SIRENA is still operational and used, but several constraints associated to this current configuration of the simulator have been identified in the past five years. One subject concerning the stability of the graphical interface has been solved in 2023 by switching from the platform Aggregate (no more maintained) to Ignition. The other subjects concern mostly the current core of the simulator which is the thermal-hydraulic computational code DYN4G, that is in a fixed physical and numerical state since 2016. As it is based on a particular language ESOPE-Fortran that was developed decades ago at CEA, we started having troubles to compile it on computer systems more recent than Debian 8. To by-pass this difficulty, we started in 2024 to use of a virtual machine able to support DYN4G. But this is only a temporary solution that is not sufficient for the coming years, especially with the upcoming increasing activities on SFRs, and we have in mind to completely replace the thermal-hydraulic core of the simulator by CATHARE-3. All the necessary activities to reach this goal have been identified in a development roadmap published last year [3] and the work is ongoing to upgrade the Superphénix CATHARE data deck to a simulator level and validate it by benchmarking with DYN4G. The first achievements will be presented at the CUC 2026.

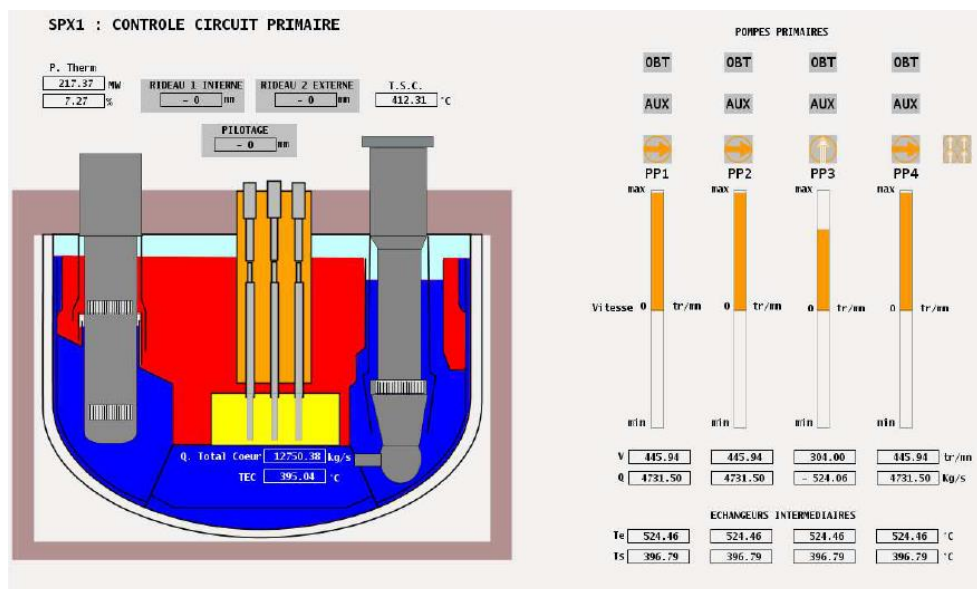


Figure: Superphénix primary circuit representation in the current SIRENA simulator

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GUITHARE V3: The New Graphical User Interface for CATHARE 3

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ABSTRACT

Since 2004, GUITHARE (Graphical User Interface for CATHARE) has been the standard Human-Machine Interface (HMI) for the CATHARE 2 and CATHARE 3 codes. Based on the SALOME platform, it has been used for over 20 years as a tool for importing, visualizing, constructing, running, and post-processing CATHARE data decks. Its versatility and continuous development have made it a widely used tool among all users of the code, whether they are researchers, industry professionals, or academics. In fact, it is often through this interface that users discover the code: GUITHARE is indeed indispensable for all teaching activities and serves as a first practical introduction to CATHARE. In service for many years, the version 2 of the GUI is no longer maintained or developed since the end of 2025.

Developed since 2023 within the CEA Software Engineering for Simulation department (DM2S/SGLS), the new version of the GUI for CATHARE 3 is called GUITHARE V3. Based on recent versions of SALOME, the interface no longer requires a data deck interpreter, allowing it to naturally follow the evolution of the code. Faster and more robust, the interface already includes the main features of the previous version GUITHARE V2, as well as many new features: loading of results while calculations are in progress, the ability to detach submodules in the mesh view, simplified access to documentation, implementation of automated tests... In April 2026, the first practical application in a teaching environment was successfully carried out. Moreover, extensive work is underway to make the first version of GUITHARE V3 ready for industrial use.

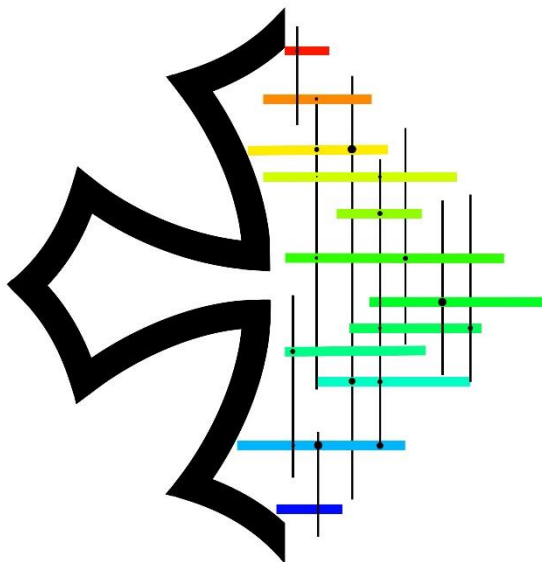


Figure 1: New GUITHARE V3 logo

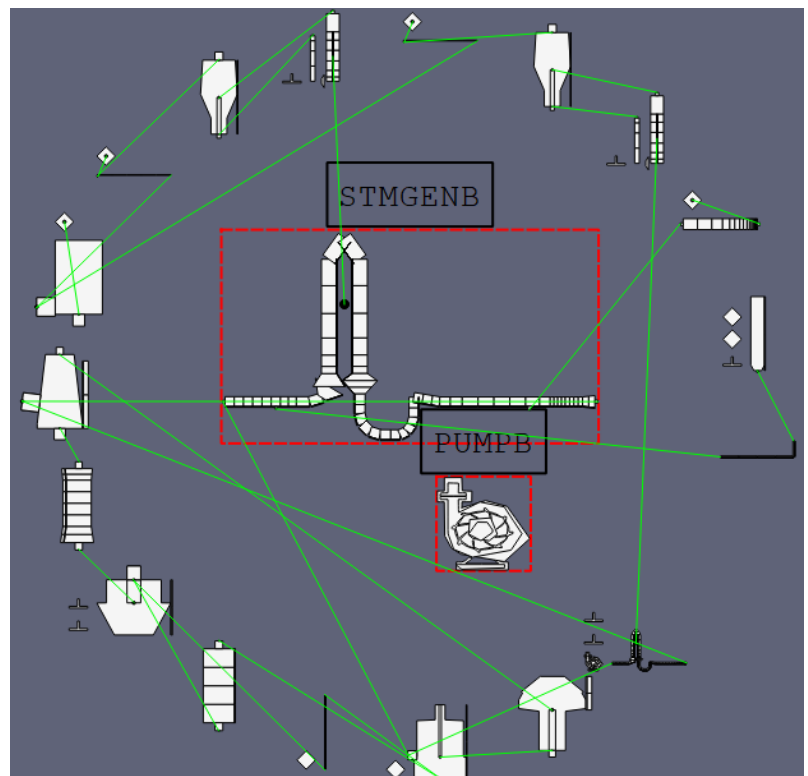


Figure 2: Example of a GUITHARE V3 view of a CATHARE input data deck

R&D activities using CATHARE code at Bel V

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ABSTRACT

In Bel V, the CATHARE_2 code is used for R&D activities since many years (~20 years) with the objective to investigate LWR safety issues occurring mainly under DBA and DEC-A cases [1]. This includes integral tests, performances of passive safety systems [2] and specific natural circulation phenomena in Steam Generators and spent fuel pools. For these purposes, Bel V is actively participating in several experimental international activities like the NEA experimental ATLAS and POLCA projects as well as in the frame of EURATOM EASI_SMR project. In addition, participation within analytical activities like the WGAMA International Standard Problems ISP52 and ISP53 were also considered.

In this presentation, example of different CATHARE code assessments results obtained through the aforementioned activities are shown and discussed.

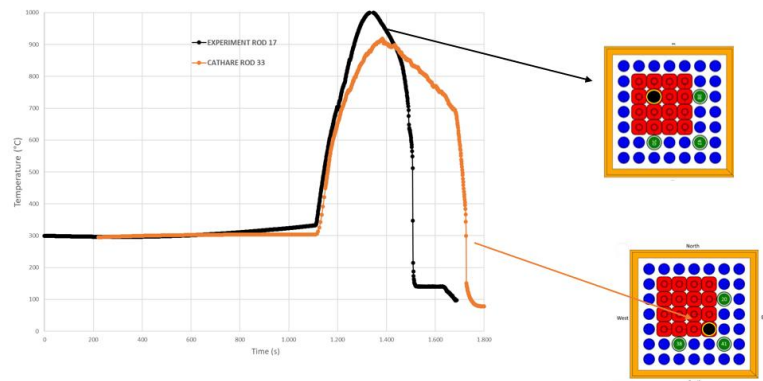


Figure 1: CATHARE2 Calculation results of the ISP53 benchmark.

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Gas-cooled thermal-hydraulic analyses with the CATHARE code at HUN-REN EK

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ABSTRACT

The EURATOM TREASURE project ensures long-term financial support for the gas-cooled fast reactor development in Europe, which has several work packages (WPs), aiming at enhancing the safety of the ALLEGRO reactor. In most of the WPs, HUN-REN EK participates with the CATHARE code.

The first main task is to justify the helium-cooled ALLEGRO fast reactor's cooling capability using CATHARE transient calculations. Previously, four initiating events were identified [1], which were aimed to cover most of the scenarios. The current CATHARE analyses for these transients showed that the maximum peak cladding temperature values stay below the given criteria for the newly defined REFRACTORY V5 core configuration (see Figure 1).

The second task is to understand the mixing phenomena between the subchannels of an assembly. In a gas-cooled reactor, the coolant density change is relevant along the fuel, which results in a significant velocity change in the axial direction in the assembly. This implies that if one fuel pin has higher power than the others, there is a significant mass flow towards the neighboring subchannels. Some preliminary CATHARE calculations will be presented using TEE elements.

Thirdly, another work in the TREASURE project is dedicated to CATHARE-KIKO3DMG coupling, where KIKO3DMG is an in-house nodal neutronics code of HUN-REN EK. The preliminary results showed that using the ICOCO built-in library, communication between the two codes is possible.

Fourthly, in parallel with the above tasks, a code-to-measurement benchmark activity is on the way for the S-ALLEGRO test facility built in Pilsen, Czech Republic. The preliminary results suggest that there may be huge bypasses at the flanges of the hot ducts.

Fifthly, we recently published a paper [2] about the investigation of different gases in the ALLEGRO's decay Heat removal system (DHR). The results showed that replacing water with gas in the DHR secondary circuit is feasible.

Out of the TREASURE project, we participate in the OECD HTGR TH code-to-code and code-to-measurement benchmark activity with the CATHARE code. The helium-cooled experimental mockup of HTTF is built at Oregon State University. Using a sophisticated CATHARE model, the radial heat propagation can be described well compared to the measured values [3].

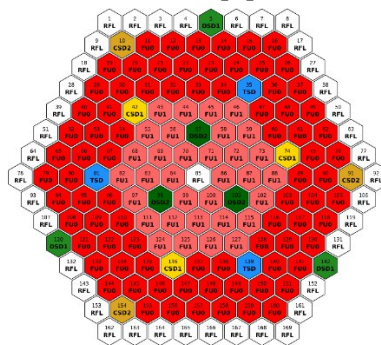


Figure 1: ALLEGRO REFRACTORY V5 core layout

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Numerical study of the EVEREST passive cooling system facility

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ABSTRACT

The EVEREST facility located at the Cadarache site was designed to study the passive, natural convection decay heat removal system, used in the old design of the small modular pressurized water reactors NUWARD. It consists of 3 water circuits. The first one brings hot to a plate steam generator where heat is transferred to the secondary circuit. The latter exchanges heat with a tertiary circuit through a condenser. Hot water from the tertiary circuit is then evacuated in a tank, which constitutes the cold source of the system.

Two testing campaigns, conducted in 2024 and 2025, made it possible to:

- Evaluate the circuits performances under different scenarios (standby state, different accidental transients);
- Characterize the initiation of natural convection, either spontaneously when the primary temperature is high enough or by manually opening a dedicated valve when the system is in stand-by;
- Study the system's sensitivity to various parameters such as the quantity of water in the secondary circuit;
- Observe unexpected phenomena such as flow instabilities, the loss of convection in the tertiary circuit or a sudden pressure drop in the secondary circuit. [1]

The present study is part of the validation process of the CATHARE 3 scientific calculation tool in such configuration, on the basis of experimental data. It focuses on the test done to characterize the impact of the liquid mass in the secondary circuit on the performance of the loop at high-temperature. The results obtained with CATHARE 3 show good agreement with the experiments.

The influence of the quantity of non-condensable gases present in the secondary circuit was studied, due to its strong impact on the loop performances. Additional sensitivity studies are currently underway, and concern the influence of the heat exchangers and the physical models implemented in CATHARE 3.

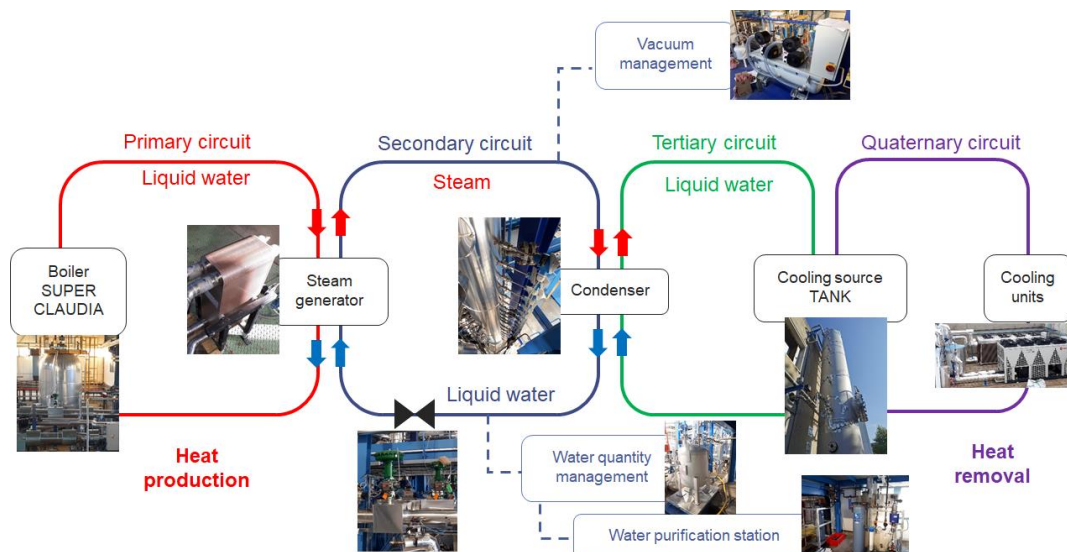


Figure: EVEREST loop diagram [1]

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Overview of CATHARE-3 validation work on the Molten Salt Reactor Experiment

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ABSTRACT

The molten salt reactor (MSR) is one of the six advanced reactor concepts declared by the Generation IV International Forum (GIF). The technology is characterised by the inherent safety, small high-activity level waste footprint, low pressure and high-temperature process heat generation for industrial applications. Due to the interest in MSRs, system thermal-hydraulic codes like CATHARE-3 are being adapted for the safety assessment of these reactor designs. The validation of these tools mainly relies on the experimental data obtained during the 1960s at the 8MWth graphite-moderated MSRE integral test facility at ORNL (Rosenthal, M. W. et al., 1969). This presentation provides an overview of the MSR capabilities implemented in CATHARE-3 (Rosselli et al., 2024) and the latest validation work on MSRE during steady and transient conditions.

The CATHARE-3 geometrical model represents the whole fuel circuit, while the coolant circuit has been modelled in an open circuit configuration. The comparison between code and experimental results at a nominal power of 7.42 MW shows a good agreement on the power level, flow rate and temperature distribution within the fuel circuit. In addition to that, different types of transients providing insights into neutron dynamics and core power responses have been simulated. Step reactivity insertion transients of 13.9 pcm, 19 pcm and 24 pcm at power levels of respectively 8 MW, 5 MW and 1 MW show CATHARE3 capabilities to capture the experimental tendency of power variation, although there are quantitative discrepancies. The simulation of a natural convection transient has shown the code capabilities to follow the core power and temperature evolution in the fuel circuit, although important assumptions had to be made to model the early stage of the transient.

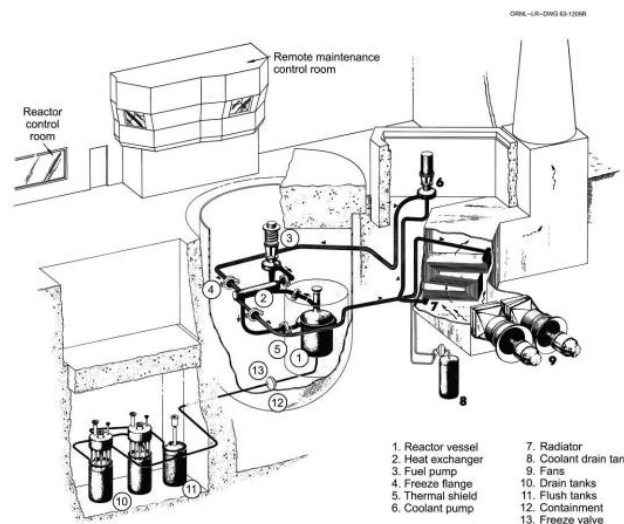


Figure 1: sketch of the Molten Salt Reactor experiment at ORNL.

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New physical models in CATHARE and perspectives

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ABSTRACT

The presentation outlines some of the research areas being carried out within CEA. It features a list of models to be introduced in the upcoming code revision 6.3, alongside some of the ongoing research topics being developed by the CATHARE Team. The stratification, film boiling, and ballooning models are detailed, as well as the improvements made to CATHARE 0D module, flashing, and the update of Groeneveld tables. Several R&D topics are presented, focusing on the objectives of these ongoing projects, such as the entrainment model in horizontal legs, modelling of spray systems, condensation models in vertical tubes, scaling of passive systems, 3D friction in reactor cores, spacer-grid impact on two-fluid regimes in reactor cores.

CATHARE code in international projects: CEA activities

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ABSTRACT

CEA participates in several international projects and benchmark exercises, such as those organised by the OECD (PANDA, SYSTHER, ATLAS, RBHT, COAL, ATRIUM, PRIME), European projects (EASI-SMR), or networks like FONESYS (Forum & Network of SYS-TH Codes in Nuclear Reactor Thermal-Hydraulics). This involvement enables integral (IET), separate (SET) and combined (CET) validation and supports the development and the improvement of specific models. Ultimately, this contributes to a more accurate and reliable code with reduced uncertainties. The different projects are briefly presented, highlighting the objectives of each exercise, the experimental facilities used, the models involved, and the corresponding code results. The perspectives of this participation and the lessons learned are also discussed. For projects still in their early stages, their objectives and current progress are presented. This document highlights the importance of the international participation in benchmark and collaborative activities for code development and validation, as well as the benefits derived from it.

Using system code for scaling analysis: A new integrated tool in the CATHARE code applied to a SB-LOCA transient

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ABSTRACT

The CEA is currently developing new tools in CATHARE to facilitate its use for scaling analysis, which contribute significantly in the identification of dominant phenomena occurring during reactor accidental transients and in the design of experiments able to simulate major phenomena with minimal distortions. Previous published work on scaling analysis with the CATHARE code [1] focused on the primary mass and primary pressure equations to identify the dominant terms controlling the mass inventory and the system pressure. These terms were calculated “by hand” during the post-processing phase. A recently published article describes a new tool [2] that enables this analysis to be carried out automatically during a calculation, by fetching the thermal-hydraulics quantities at code execution. The integrated momentum equation along cooling loops [3] is also added to the analysis. As a result, the three main equation of the CATHARE code (mass, momentum and energy) are now available for analysis. This work describes the methodology of the CATHARE scaling analysis, and the way this tool is implemented in the code. The different equation terms, the normalization strategy and the aggregation rules are fixed at code level. It is then applied to a SB-LOCA transient using the scaling equations of mass, momentum and pressure. Figures of merit and available post-processing are presented, which enables the dominant phenomena to be quantified. By reducing the impact of the user in the scaling methodology, the proposed framework significantly improves the consistency and comparability of scaling analyses. Leads for future developments are given.

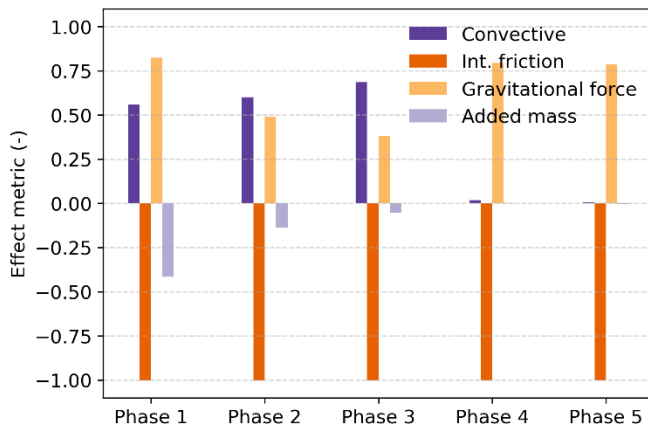


Figure 1: Main effect metrics of the primary system, crossed equation, for all transient phases

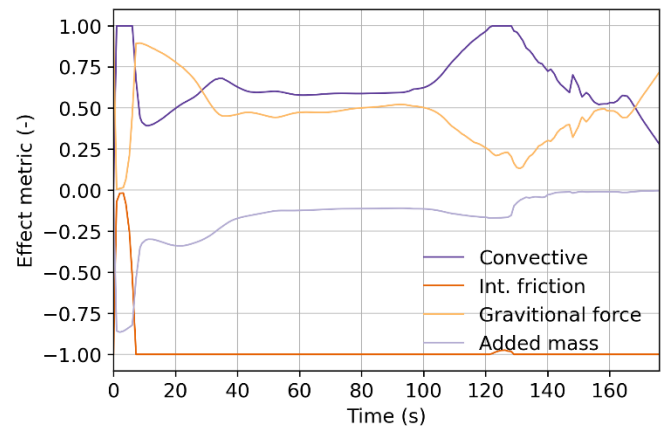


Figure 2: Time evolution of effect metrics of the primary system, crossed equation, first 3 phases

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BORA4-PTS and HYBISCUS-II: how to model salt water mixture with CATHARE3

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ABSTRACT

When a break occurs in a nuclear reactor, a fast cooldown has to be down to prevent the melting of the core. This is done by the injection of cold water at 7 °C, in a pressurized vessel at 295 °C. This is a Pressurized Thermal Shock. To improve the safety of the nuclear reactor, experimental facilities were built to analyse the mix of hot and cold water in the downcomer of the vessel. There is the BORA4-PTS and the HYBISCUS-II experiments. Salt water at 45 °C is injected into stagnant pure water at around 20 °C, to represent the injection of cold water in hot water. Through this experiment, a scaling was establish to compare it with the reactor case. We then made a numerical simulation of those experimental facility with the CATHARE code. With this simulation come another scaling, in order to properly compare the numerical and the experimental results. The numerical simulations give results that are very similar to the experimental ones. With those experiment, we show the excellent capacity of CATHARE to simulate and model the complex thermohydraulic inside a downcomer.



Figure 1 Left: photography of the BORA4-PTS experiment. Right: photography of the HYBISCUS-II experiment.

Thermal energy storage using an ultra-high-temperature reverse Brayton cycle heat pump

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ABSTRACT

Carnot batteries are thermal storages used to store electricity. A simple electrical heater or the compressor of a heat pump converts electricity into heat. This heat is stored in the thermal storage. When electricity is needed, the thermal energy stored is converted back to electricity with the turbine of a power cycle. This technology has the advantage of having no geographical constraint compared to pumped hydro-electric storage (PHS) while being able to store large amount of energy compared to Li-ion batteries.

The thermal energy can be stored as latent heat with a phase-change material (PCM) or as sensible heat with temperature rise. Several demonstrators with sensible storages are currently operating in Europe [1,2,3]. High temperatures are preferred for sensible heat to increase the energy density of the storage. For this purpose, a new 30 kW ultra-high temperature heat pump called BATCAR will be installed in CEA Grenoble in June. It will be coupled to an already installed 100 kWh thermal storage.

In BATCAR, air is compressed using 4 radial turbocompressors from 1 to 10 bar, increasing its temperature to 430 °C. It passes through the thermal storage and heats up the material. At the outlet, the air flow through an internal recuperator and part of the power used by the compressor is recovered with an axial turbine. It is then heated up again by the cold heat exchanger and the recuperator, completing the cycle.

As the charging process is inherently transient, CATHARE was chosen to model numerically the experimental setup. Numerical results will be compared to experiment for the thermal storage, and the implementation of the compressor and turbine will be detailed.

Other on-going works on Carnot Batteries using CATHARE at CEA Grenoble will be briefly presented.

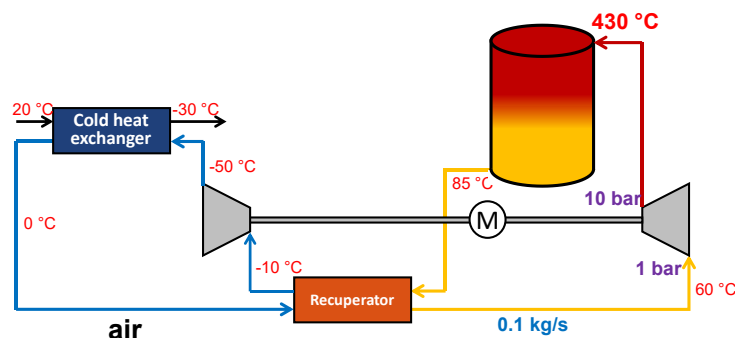


Figure: Charging of the thermal energy storage using BATCAR heat pump

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VINCI rocket engine chill-down: from forecasts to flight exploitation and beyond

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ABSTRACT

For the engine of a cryogenic rocket, the chill-down process consists in cooling the main parts of the engine that will see cryogenic propellants: feeding lines, turbo-pumps and their bearings, etc. This process has to be completed before the start-up to ensure the engine functioning and avoid any cavitation issue, massive evaporation... that could be detrimental.

In ArianeGroup, chill-down simulations for the VINCI engine (Ariane 6 upper stage) have been performed since 2014 using the CATHARE code coupled with SAMCEF THERMAL to model 3D and 2D axisymmetric elements such as the engine turbo-pumps. This co-simulation process is called COMETE [1]. Specific CATHARE features were introduced to deal with cryogenic propellants – liquid hydrogen (LH2) and liquid oxygen (LOX) – and to master heat transfers in microgravity conditions [2], as chill-down is also performed during ballistic (orbital) phases, when there is no more acceleration of the rocket, to prepare the re-ignition of the engine.

The previous CUC in 2024 took place one month before the first Ariane 6 flight, thus only chill-down forecasts were presented, as well as comparisons with ground tests. Since then, seven flights have been successfully performed. The data gathered about chill-down and thermal evolutions of the engine during orbital phases were compared with the forecasts and proved to be in good agreement. Besides, the exploitation of the flights and their reproduction with COMETE helped to improve the model representativeness and paves the way for further optimization of the chill-down process to improve the rocket performance.

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Modelling of cryogenic exchangers: Ariane 6 APU and green mobility applications

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ABSTRACT

In multiple contexts at ArianeGroup, the modelling of cryogenic exchangers (methane, oxygen, hydrogen), and especially tores and tube exchangers, is mandatory. On Ariane 6, the APU system consists of a gas generator chamber connected to an oxygen and hydrogen tores and tubes exchangers, which generates autogenous pressurant gas for the tanks throughout the flight (and especially orbital phases, where engine tap-off is not possible). This allows to massively reduce the amount of helium, and dry mass associated with a number of helium tanks, to be installed on the upper stage, and thus reduces costs and increases payload mass to orbit. This design can also be used for green-mobility in the context of hydrogen/air combustion (where only hydrogen needs to be vaporized for gas/gas combustion).

In ArianeGroup, exchanger modelling has been performed for a few years using the CATHARE 2 code. Specific pre-processing and post-processing tools have been developed for this task, and together they are able to simulate virtually any geometry of tubes and tores exchangers, from simple single row exchangers to regenerative circuit geometries and complex multi-row mixed fluid exchangers. Specific UDFs have also been developed to model fuel injection in the combustion chamber, combustion, and nozzle modelling, including automatic heat flux imposition on the tubes external surfaces.

This model has been compared to ground APU tests performed in Vernon and Lampoldshausen (in two benches, BCLH2 for horizontal tests and HFT for flight orientation), to flight (especially the first flight) and to BCLH2 tests of the LH2/air version for green mobility applications.

Improvement and validation of CATHARE-3 streamline rotodynamic pump model for gas-liquid two-phase flows

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ABSTRACT

Two approaches can be used to model nuclear reactor cooling pumps with the CATHARE-3 code. The most common one is based on a point (0D) model [1]. This approach models the pump as a source of momentum and energy. However, it relies on experimental data. This restricts its use in situations where pump performance is unknown, such as new systems design.

In addition to this nodal approach, a one-dimensional pump model was developed and validated between 2015 and 2019 [2]. This model is based on CATHARE-3's one-dimensional (1D) system of equations, making it both generic and predictive. However, validation was only carried out for single-phase and low void fraction flow regimes, in the context of accidental behaviour modelling of Sodium Fast Reactors primary pumps.

In the present work, two-phase pump simulations reproducing experiments from the EVA campaign are carried out using this 1D model. Analysis of the results and feedback from previous work highlights the need for model evolutions in order to simulate Pressurized Water Reactors primary pumps accidental behaviour. Frame change, flow regime map and shock losses repartitions are modified in order to better represent the pump physics [3].

Following these model evolutions, a better agreement with experimental data is obtained, and perspectives for further work are drawn up.

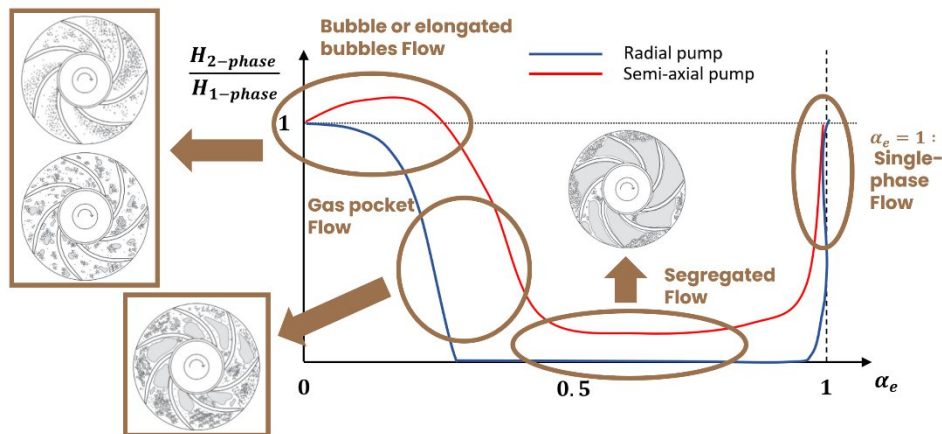


Figure: Two-phase head of rotodynamic pumps as a function of inlet void fraction and pump geometry (radial, semi-axial), and corresponding flow regime – based on an illustration from W. Monte Verde et al.

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Applying Very Small and Random Perturbations to CATHARE Test Cases for Development Assessment

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ABSTRACT

In the frame of CATHARE continuous improvement, rigorous validation and verification processes are required to ensure reliability and accuracy in the simulations. To achieve high-quality results, the tests used for validating code changes must meet specific criteria, ensuring that the solution is sufficiently converged for meaningful analysis. For instance, with a non-sufficient time discretization constrain, misleading results may be obtained, obscuring potential issues and undermining the integrity of the verification process. Therefore, achieving optimal test conditions is key to ensure acceptable code improvements. One thing that a CATHARE user may have experienced once, is to work on a hypersensitive test case. In the CATHARE validation process, hypersensitivity denotes a significant influence of small perturbations on the simulations results. These small perturbations may be introduced by round-off errors when computing operations on real numbers (due to the representation of real numbers in computing science). For instance, the same calculation may give different results when using two compilers, because of: bad time discretization constrain, too-coarse meshing or non-relevant recording frequency of CATHARE results are defined in the test case. Furthermore, if at some point in the calculation an event depends on a threshold, the solution may also be significantly influenced. Several questions arise from these observations: what are the hypersensitive test cases of CATHARE validation matrix? How important is this hypersensitivity? Does this hypersensitivity can be explained? Can it be resolved if necessary? Aiming at addressing these issues, a methodology has been developed, which consists in randomly and very slightly perturbing (to simulate rounding errors) all real numbers in the test case definition a certain number of times. Each perturbed test is ran and the envelope of results is plotted to perform analysis. This methodology can detect hypersensitive test cases and facilitate the decision making of developers assessing a code improvement.

Assembly-scale core simulation with the New Module 3D of CATHARE during a 6-inch cold break scenario, with evaluation of CPU-time performance and parallelization gains

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ABSTRACT

This study presents an advanced thermal-hydraulic simulation of a 900 MWe pressurized water reactor core during a 6-inch cold-leg break scenario, performed using the New Module 3D (NM3D) of the CATHARE code. The objective is to assess the ability of the NM3D to address an industrial-scale application, in terms of modelling capabilities, robustness, and numerical performance. The reactor core is modelled at the assembly scale using a Cartesian mesh. The calculations are performed with the autonomous NM3D, i.e. without integration into a reactor system. Only the core region is represented, while appropriate boundary conditions are imposed to reproduce the circuit depressurization and the control rod drop within the core. Particular attention is given to numerical optimization, including the performance of the TRUST library on large-scale meshes and the evaluation of MPI parallelization gains. The simulation provides a detailed description of the transient evolution within the core, including flow redistribution and core uncovering. The results, illustrated in Figure 1, are analyzed against reference calculations obtained with the standard CATHARE code. The comparison focuses on the main transient trends, including pressure evolution, void fraction distribution, and timing of core uncovering. This work highlights the ability of the NM3D to handle industrial datasets and paves the way for future subchannel-scale core simulations. In particular, the results show that the NM3D, combined with efficient parallel numerical methods, is a promising approach for large-mesh thermal-hydraulic applications.

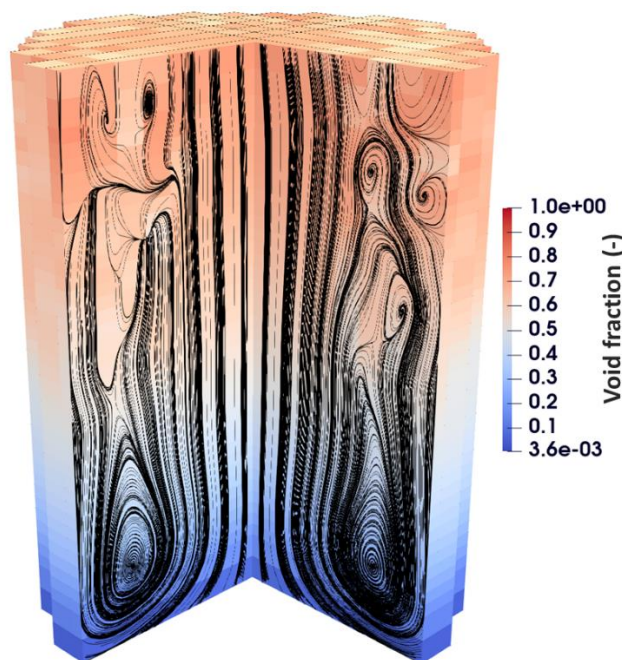


Figure 1 - Core cross-section showing void fraction and liquid streamlines

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