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EASI-SMR:
Ensuring Assessment of Safety Innovations for SMR

International Workshop on Thermal-Hydraulic Scaling for SMR Safety Demonstration – December 16-18, 2025 – Bologna

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SMR-SPECIFIC PHENOMENOLOGY TO BE INVESTIGATED

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Co-funded by the European Union

UK Research and Innovation

The Research Council of Norway

Project funded by
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Agenda

- ❑ Introduction
- ❑ Assessment Database
- ❑ Advanced designs using passive systems Phenomena
- ❑ Phenomena and TH aspects for reactor using passive systems
- ❑ Phenomena challenging for modelling passive systems identified in Horizon Euratom EASI-SMR project
- ❑ Passive Systems Needs
- ❑ Conclusions

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Introduction

- Safety is the key pillar for the deployment of nuclear technology.
- Current generation of large water reactors has proven to be a reliable and safe technology.
- People and policymakers are requesting nuclear technologies with increased inherent safety to strengthen the contribution of nuclear energy to the overall energy mix, in line with the 2050 net-zero CO_2 objective.
- Reactors using passive mitigation strategies have become a flagship of the nuclear industry.
- Defence-in-Depth (DID) concept is fundamental to the safety of nuclear installations.
- Deterministic Safety Analyses (DSA) is a fundamental component of DiD.

Introduction

- Passive systems are adopted in NPP since the beginning (e.g. accumulator);
- The Chernobyl and the Fukushima Daiichi events determined an increase of interest in accident mitigation strategy based on the use of passive systems;
- New passive systems concepts have been designed and nowadays are more and more considered among the features desired in future advanced plants in order to increase the inherent safety of the plants.
- Passive safety systems are currently considered in large scale Generation III+ reactors and in advanced Small Modular Reactor (SMR);
- SMR specific features, strengthen the suitability of passive safety systems to reinforce the first three DiD levels: e.g. Lower core power; Integral design of the primary system; Large core surface-to-volume and coolant inventory-to-power ratios; Fuel design.

Introduction

- ❑ DSA play a central role in demonstrating the safety of nuclear technologies:
  - Characterizing the plant response under accident conditions;
  - Describing the time-dependent behavior of the system;
  - Identifying the dominant physical phenomena and processes involved;
  - Verifying that safety limits are met, both in steady-state and transient operational conditions.

- ❑ DSA rely on the integration of multiple elements:
  - Representative experimental data with a rigorous treatment of scaling effects;
  - State-of-the-art computational tools;
  - Application of consolidated methodologies:
    - Best Estimate Plus Uncertainty (BEPU);
    - Structured techniques to assess the reliability of passive safety systems as REPAS.

- ❑ Historically:
  - ❑ Experiments were utilized, even before the advent of computers, to estimate, understand, and prepare models phenomena that may appear in the prototype.
  - ❑ With the advances in NPP technology, the plant's design and operation rely more on the computer code safety analyses.
  - ❑ Currently a mix approach is used: safety determination of reactor design and operation is to evaluate the prototype response through data from experiments, and/or computer code calculations.

- ❑ Research contributes to enhancing the safety of operating reactors and supports the continuous development and robust demonstration of the safety features and approach in advanced technologies.

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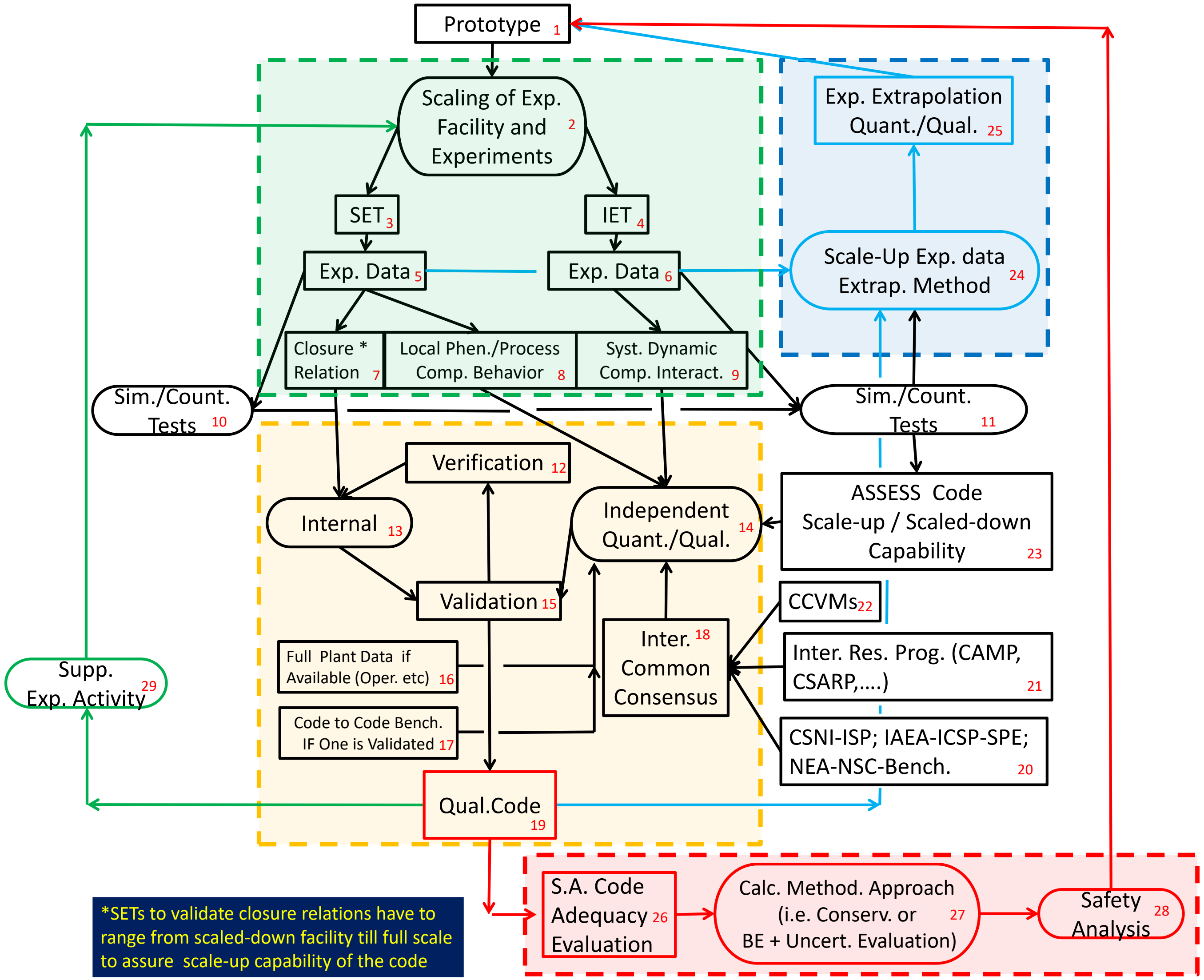
Assessment database

- Experimental activity and application of scaling methodology for the design of facility and experiments

- Code Verification and Validation

- Full plant code prediction:
  - Address scaling issue;
  - Deterministic safety analyses for safety review (plus calculation methodology approach).



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Assessment database

- Scaled-down experiments are utilized in developing an "assessment database".
- The assessment database is useful to:
  - Characterize prototype design;
  - Validate computational tools for safety analysis;
  - Study extrapolation to full scale prototype.
- Scaling analysis is necessary to assure that scaled-down experimental data obtained are representative of the thermal-hydraulic behavior of the full-scale prototype;
- Large number of scaling parameters should be preserved at the same time due to:
  - Reactor complex geometry;
  - Multiple component interactions;
  - Two phase TH phenomena.
- It's then difficult to have a complete and consistent set of scaling criteria.
- Qualified system codes constitute possible tool to scale-up experimental data (developed in scaled down facility) to full scale prototypical condition. Therefore they can be used as an extrapolation tool.

Scaling Methodology

- Scaled-down facility “measured transient” should be characterized by the same dominant and relevant phenomena of the full scale prototype “real transient”;
- Scaling analyses have to determine:
  - Which are the dominant and relevant phenomena that should be investigated [PIRT];
  - The independent dimensionless groups that should be preserved.
- Main distortions should be related only to the not dominant/relevant phenomena.

Identification of Thermal Hydraulic/Safety Issue

↓

Identification of Reactor Prototype

↓

Identification of Transient Scenarios

↓

Phenomena Identification and Ranking Table (PIRT)

↓

Identification of Scaling Approach Strategy

↓

Selection and Application of the Scaling Methods

Advanced designs using passive systems phenomena

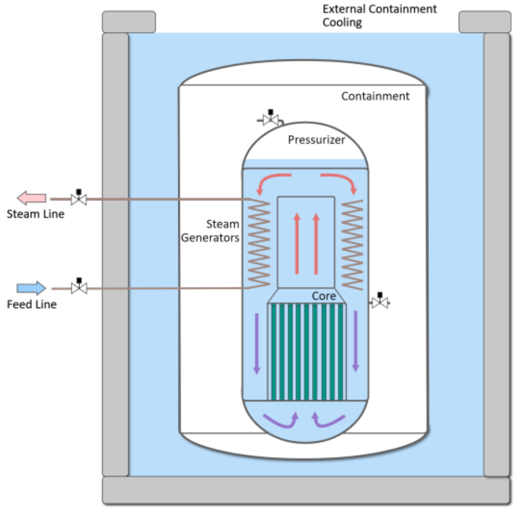
- ❑ Passive and, in general, other advanced reactor designs are characterized by some common features with the current generation of reactors (e.g., large scale PWR and BWR) and by other features typical of their design.

- ❑ In relation to the features common with current reactors, advanced designs may be characterized by a different ranking of some phenomena.

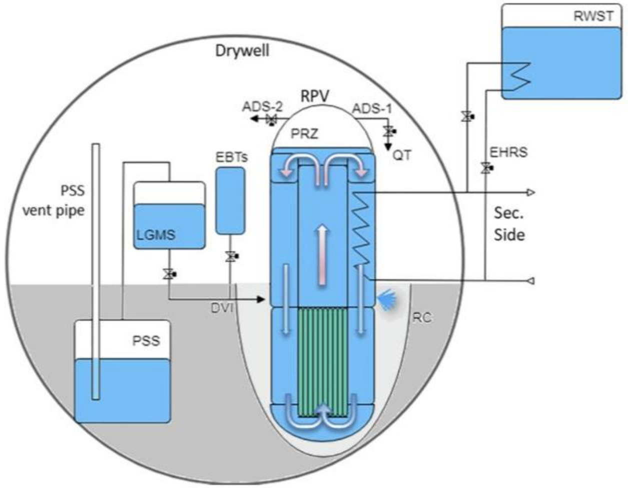
- ❑ In relation to the features typical of advanced designs, this determines the occurrence of new kinds of phenomena and accident scenarios that can be grouped in:
  - Containment process and interactions with the RCS;
  - Low pressure phenomena;
  - Phenomena related specifically to new system components or reactor configurations.

❑Considering that advanced reactors using passive mitigation strategy are characterized by the presence of specific phenomena or by different ranking of phenomena with respect to active mitigation strategy:

❑Computational tool need to be proven able to accurately predict the TH phenomena typical of passive systems.



Example of iPWR design with submerged metal containment



Example of iPWR design using several passive systems

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Phenomena and TH aspects for reactor using passive systems

PHENOMENA	CHARACTERIZING THERMAL-HYDRAULIC ASPECT
Behaviour in large pools of liquid	○ Thermal stratification ○ Natural/forced convection and circulation ○ Steam condensation (e.g. chugging, etc.) ○ Heat and mass transfer at the upper interface (e.g. vaporization) ○ Liquid draining from small openings (steam and gas transport)
Effects of non-condensable gases on condensation heat transfer	○ Effect on mixture to wall heat transfer coefficient ○ Mixing with liquid phase ○ Mixing with steam phase ○ Stratification in large volumes at very low velocities
Condensation on containment structures	○ Coupling with conduction in larger structures
Behaviour of containment emergency systems (PCCS, ectrenal Vooling, etc)	○ Interaction with primary cooling loops
Thermo-fluid dynamics and pressure drops in various geometrical configurations	○ 3-D large flow paths e.g. around open doors and stair wells ○ connection of big pipes with pools, etc. ○ Gas liquid phase separation at low Re and in laminar flow ○ Local pressure drops
Natural circulation	○ Interaction among parallel circulation loops inside and outside the vessel ○ Influence of non-condensable gases ○ Stability ○ Reflux condensation
Steam liquid interaction	○ Direct condensation ○ Pressure waves due to condensation
Gravity driven cooling and accumulator behaviour	○ Core cooling and core flooding
Liquid temperature stratification	○ Lower plenum of vessel ○ Down-comer of vessel ○ Horizontal/vertical piping
Behaviour of emergency heat exchangers and isolation condensers	○ Low pressure phenomena
Stratification and mixing of boron	○ Interaction between chemical and thermo-hydraulic problems ○ Time delay for the boron to become effective in the core
Core make-up tank behaviour	○ Thermal stratification; Natural Circulation

Phenomena and TH aspects for reactor using passive systems

Basic Phenomena	○ Evaporation due to depressurization ○ Evaporation due to heat input ○ Condensation due to pressurization ○ Condensation due to heat removal ○ Interfacial friction in vertical flow ○ Interfacial friction in horizontal flow ○ Wall to fluid friction ○ Pressure drops at geometric discontinuities ○ Pressure wave propagation
Critical Flow	○ Break ○ Valves ○ Pipes
Phase Separation/Vertical Flow with and Without 1 Mixture Level	○ Pipes/Plena ○ Core ○ Downcomer
Stratification in Horizontal Flow	○ Pipes
Phase Separation At Branches	○ Branches
Entrainment/Deentrainment	○ Core ○ Upper Plenum ○ Downcomer ○ Steam Generator Tube ○ Steam generator mixing chamber (PWR); ○ Hot leg with ECCI (PWR)
Liquid-Vapour Mixing With 1 Condensation	○ Core ○ Upper Plenum ○ Downcomer ○ Steam Generator Tube ○ Steam Generator Mixing Chamber (PWR) ○ Hot Leg with ECCI (PWR)
Condensation in Stratified Conditions	○ Pressurizer (PWR) ○ Steam generator primary side (PWR) ○ Steam generator secondary side (PWR) ○ Horizontal pipes

Spray Effects		○ Core (BWR) ○ Pressurizer (PWR) ○ Once-Through Steam Generator Secondary Side (PWR)
Countercurrent Flow / 1 Countercurrent Flow Limitation		○ Upper Tie Plate ○ Channel Inlet Orifices (BWR) ○ Hot and Cold Leg ○ Steam Generator Tube (PWR) ○ Downcomer ○ Surgeline (PWR)
Global Multidimensional 1 Fluid Temperature, Void 2 And Flow Distribution		○ Upper plenum ○ Core ○ Downcomer ○ Steam generator secondary side
Heat Transfer	Natural or Forced Convection Subcooled/Nucleate Boiling DNB/DryoutPost Critical Heat Flux Radiation Condensation	○ Core, steam generator, structures ○ Core, steam generator, structures ○ Core, steam generator, structures ○ Core, steam generator, structures ○ Core ○ Steam generator structure
Quench Front Propagation/Rewet		○ Fuel rods ○ Channel walls and water rods (BWR)
Lower Plenum Flashing Guide Tube Flashing (BWR) One And Two Phase Impeller-Pump Behaviour One And Two Phase Jet-Pump Behaviour (BWR) Separator Behaviour Steam Dryer Behaviour Accumulator Behaviour Loop Seal Filling And Clearance (PWR) Ecc Bypass/Downcomer Penetration Parallel Channel Instabilities (BWR) Boron Mixing And Transport Non-Condensable Gas Effect (PWR) Lower Plenum Entrainment		

Phenomena challenging for modelling passive systems identified in Horizon Euratom EASI-SMR project

- ❑ Steam condensation in a safety condenser tube;
- ❑ Thermal exchange in a plate heat exchanger;
- ❑ Gravity injection from a gravity accumulator passive safety system;
- ❑ Single-phase and two-phase natural circulation in water, covering:
  - Natural circulation in a Safety Condenser loop;
  - Ex-vessel reactor cooling performance;
  - Natural convention around containment immerged in a large water pool;
  - Decay Heat Removal assessment performance through a close metallic containment.

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Passive Systems Needs

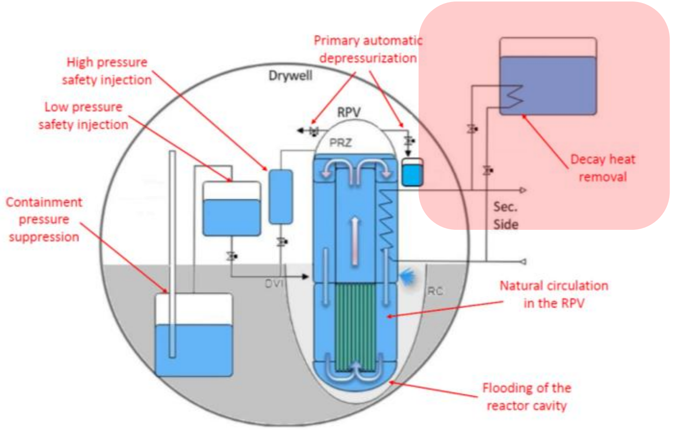
- Two interrelated needs on passive systems in general and for SMRs specifically:
  - Safety assessment:
    - Reliability of passive systems;
    - Deterministic safety analyses.
  - Qualification of computational tools including metamodels.

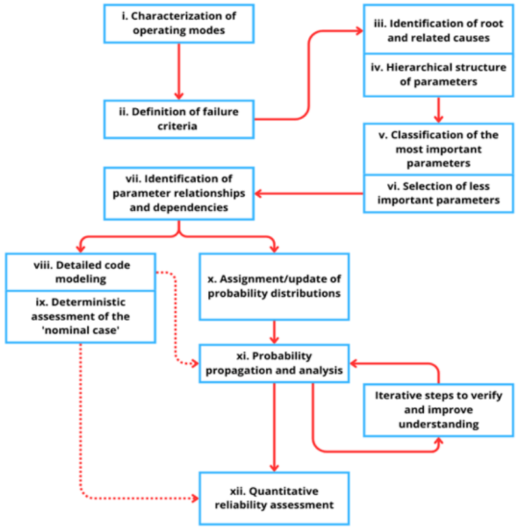
- Deterministic analysis codes: key elements used to develop safety analyses:
  - Results have to be properly qualified;
  - Uncertainty of the results should be quantified;
  - Qualification highly relies on experimental support within the range of application.

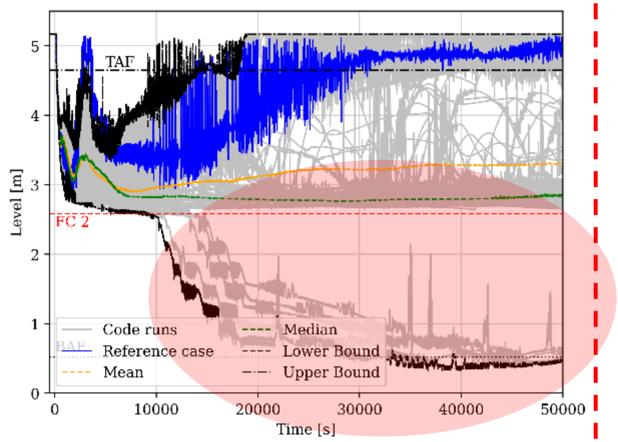
- Four main specific subtopics/needs have been identified considering the current State-of-Art:
  - Experimental assessment database;
  - Code modeling;
  - System reliability;
  - System designs and engineering process.

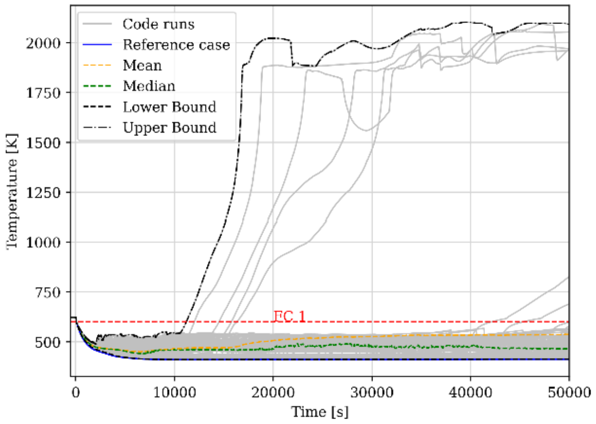
Passive Systems Functional Reliability (Phenomenological failure) – Example through REPAS APPLICATION

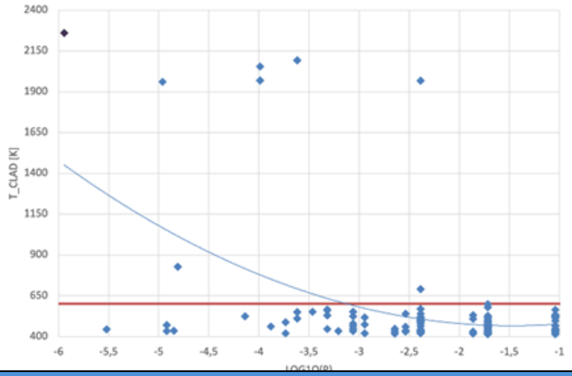
- A key challenge is the uncertainty surrounding the full range of operational scenarios that a passive system may experience.
- Under certain combinations of external and internal conditions, the T-H load may exceed the system's capacity or narrow the available safety margins, ultimately resulting in functional failure.
- Critical parameters that may contribute to functional failure typically include:
  - Presence of non-condensable gases;
  - Undetected leaks;
  - Excessive heat losses;
  - Suboptimal piping layout;
  - Limited valve opening area in discharge lines;
  - Fouling or plugging in heat exchangers.
- These aspects require further clarification from a deterministic perspective, particularly to identify and assess the conditions under which they can occur.

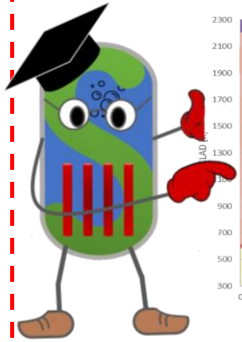


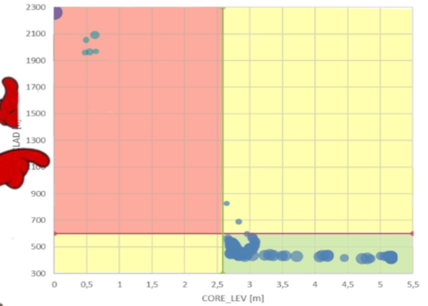












Uncertain Parameters discrepancy by REF					
Run Id	Δ%_k_EHRS	Δ%_RWST_LEV	Δ%_NCG	Δ%_VOR	Δ%_EHRS_roughness
24	53,22258735	47,71045791	35,40759088	-45,6473276	-1,161594274
42	13,86286101	75,69486103	3,57000577	-0,19507538	-2,475193421
63	10,33065212	65,91681664	19,93942957	-90,284977	-2,419081866
69	66,12602042	40,39192162	58,61524383	-51,9485351	1,600747611
108	34,60244541	71,06578684	14,14375189	-72,1914818	-1,821688161

Some first preliminary code results: ASSESS THE FUNCTIONAL FAILURE IN POSTULATED EXTREME CONDITION

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Conclusions

- Safety is the key pillar for the deployment of nuclear technology;
- Reactors using passive mitigation strategies have become a flagship of the nuclear industry;
- New passive system concepts have been designed and nowadays are more and more considered;
- DSA are essental to safety demonstration, combining experimental data, and computational tools.
- Scaled-down experimental facilities are essential to build assessment databases, but scaling must be properly addressed to ensure representativity of full-scale reactor behaviour.
- SMR using passive saftye systems introduce specific challenges, combining features of current large reactors with new configurations that affect thermal-hydraulic phenomena and their ranking.
  - Despite the existence of experimental programmes on passive safety systems, only a limited set of publicly available data is used by the international community, preventing an exhaustive validation of state-of-the-art thermal-hydraulic codes.
  - Validation of the DSA codes for all passive system operation mode is on-going relevant for several challenges;
  - Functional failures are addressed by advanced reactors designers but must be considered also in an independent safety review process.
- Ongoing national and international efforts, such as EASI-SMR, are key to strengthening the scientific basis for safety assessment of passive systems and performance evaluation.

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Passive safety systems

- Passive safety systems are currently considered in large scale Generation III+ reactors and in advanced Small Modular Reactor (SMR);
- Following IAEA definition (*IAEA, TECDOC-626: Safety related terms for advanced nuclear plants, 1991):*
  - A passive system is *either a system which is composed entirely of passive components and structures or a system which uses active components in a very limited way to initiate subsequent passive operation*.
  - And a passive component is *a component which does not need any external input to operate.*
- Considering the different degrees of passivity, 4 categories have been identified (IAEA-TECDOC-626, 1991).

Passive safety systems

CATEGORY A

- No signal inputs of 'intelligence'
- No external power sources or forces
- No moving mechanical parts, and
- No moving working fluid.

CATEGORY B

- No signal inputs of 'intelligence'
- No external power sources or forces
- No moving mechanical parts; but
- Moving working fluids.

CATEGORY C

- No signal inputs of 'intelligence'
- No external power sources or forces; but
- Moving mechanical parts, whether or not
  Moving working fluids are also present.

CATEGORY D

- Signal inputs of 'intelligence' to initiate the passive process
- Energy to initiate the process must be from stored sources such as batteries or elevated fluids
- Active components are limited to controls instrumentation and valves to initiate the passive system
- Manual initiation is excluded.

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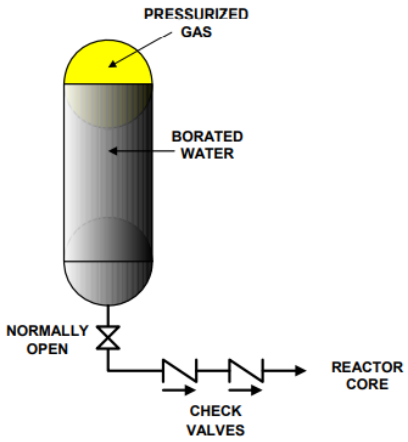
Passive safety systems

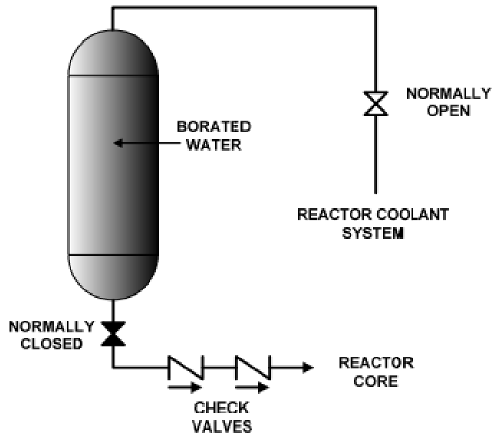
- Passive systems can be adopted in advanced reactors to perform several safety functions: Decay heat removal; Safety injection; Automatic depressurization of primary system; Containment cooling; etc.

  - Passive safety systems for **Core Decay Heat Removal**:
    - Pre-pressurized core flooding tanks (accumulators) → C
    - Elevated tank natural circulation loops (core make-up tanks) → D
    - Gravity drain tanks → D
    - Passively cooled steam generator natural circulation → D
    - Passive residual heat removal heat exchangers → D
    - Passively cooled core isolation condensers → D
    - Sump natural circulation → D

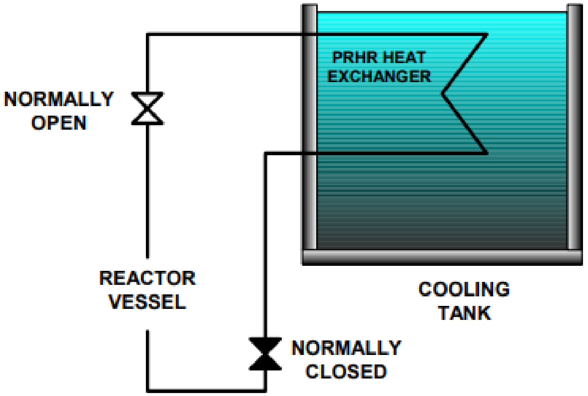
  - Passive safety systems for **Containment Cooling and Pressure Suppression**:
    - Containment pressure suppression pools → B and C
    - Containment passive heat removal/pressure suppression systems → B and D
    - Passive containment spray → B and D



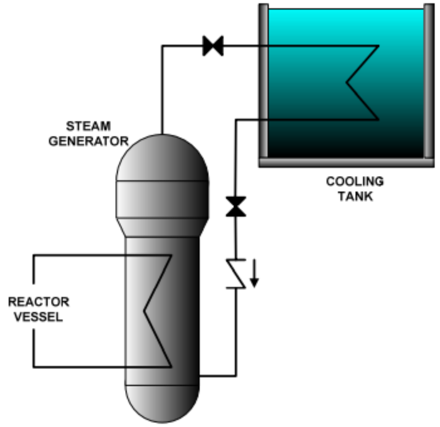
Accumulator
Category C



Elevated tank natural circulation loops (core make-up tanks).
Category D

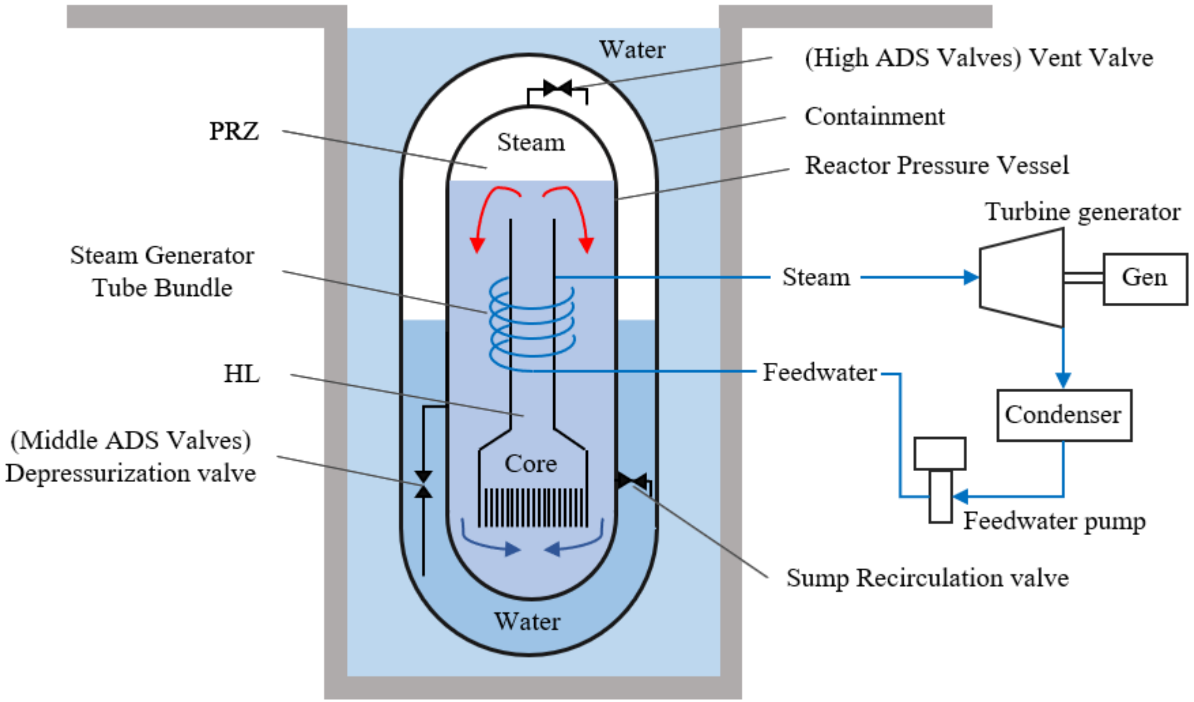


Core decay heat removal using a water-cooled passive residual heat removal heat exchanger loop
Category D



Core decay heat removal using a passively cooled steam generator (air-cooled).
Category D

SPECIFIC EXAMPLE: DESIGN RELY ON NATURAL CIRCULATION FOR THE REMOVING OF THE CORE POWER DURING NORMAL OPERATION



- The designs of some advanced reactors rely on natural circulation for the removing of the core power during normal operation.
- Example of these reactors is the MASLWR (Multi-Application Small Light Water Reactor):
  - An i-PWR relying on natural circulation during both steady-state and transient operation;
  - Basis for the NUSCALE design.

Advantages and challenges of passive safety systems

ADVANTAGES

- Simpler design
- In principle higher reliability
- Operation without external power supply
- Operation without operator intervention → reduced probability of human error
- Reduced cost and the easier maintenance.

CHALLENGES

- Lower driving force
- More complex safety evaluation
- Reduction of operator intervention → lower possibility to control the system
- Need for better manufacturing and installation of the components
- Possible presence of instabilities
- Functional failure without mechanical failure

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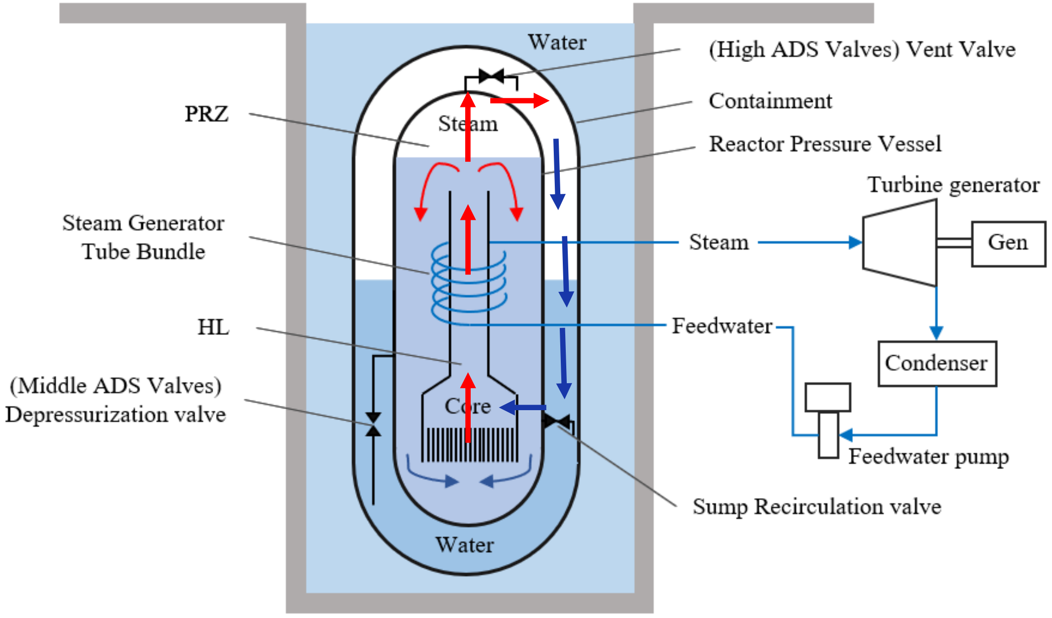
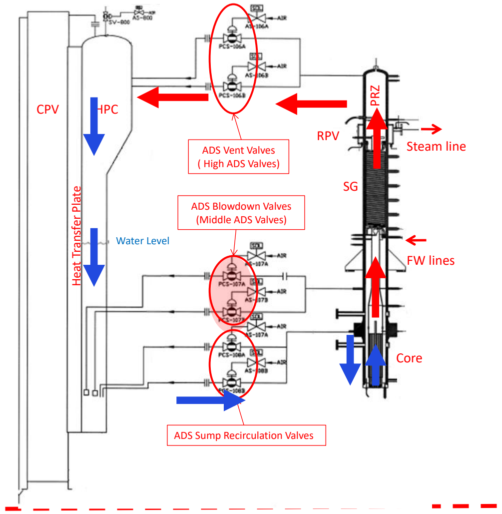
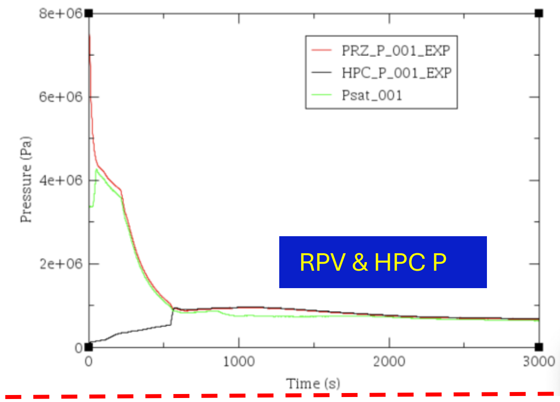
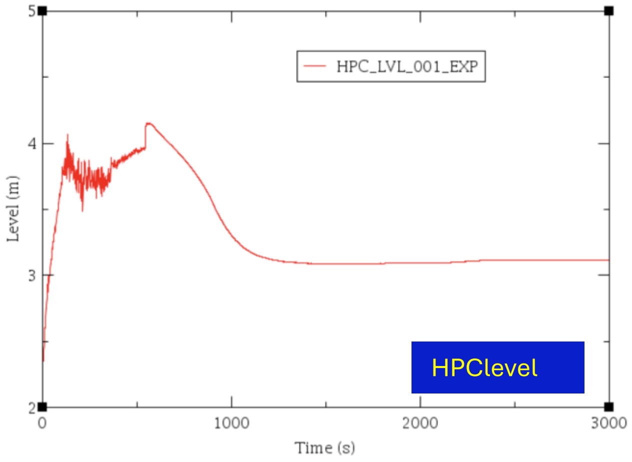
CONTAINMENT PROCESS AND INTERACTIONS WITH THE RCS (POINT A)

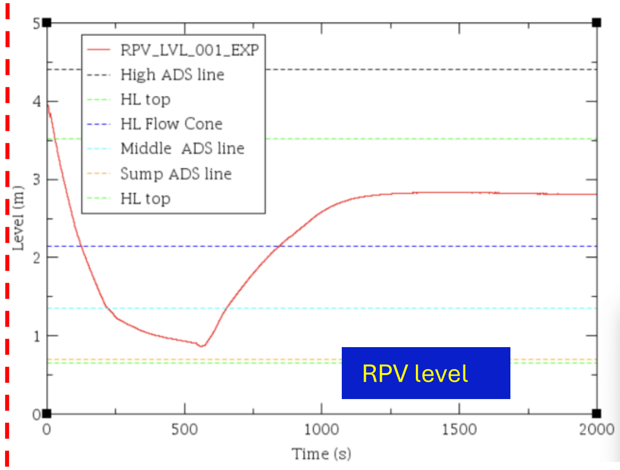
- MASLWR Small Break LOCA (SBLOCA) mitigation strategy can be used as an example of containment process and the interaction with the RCS.











EXAMPLE: Strong coupling between the RCS based on the OSU-MASLWR 001 data

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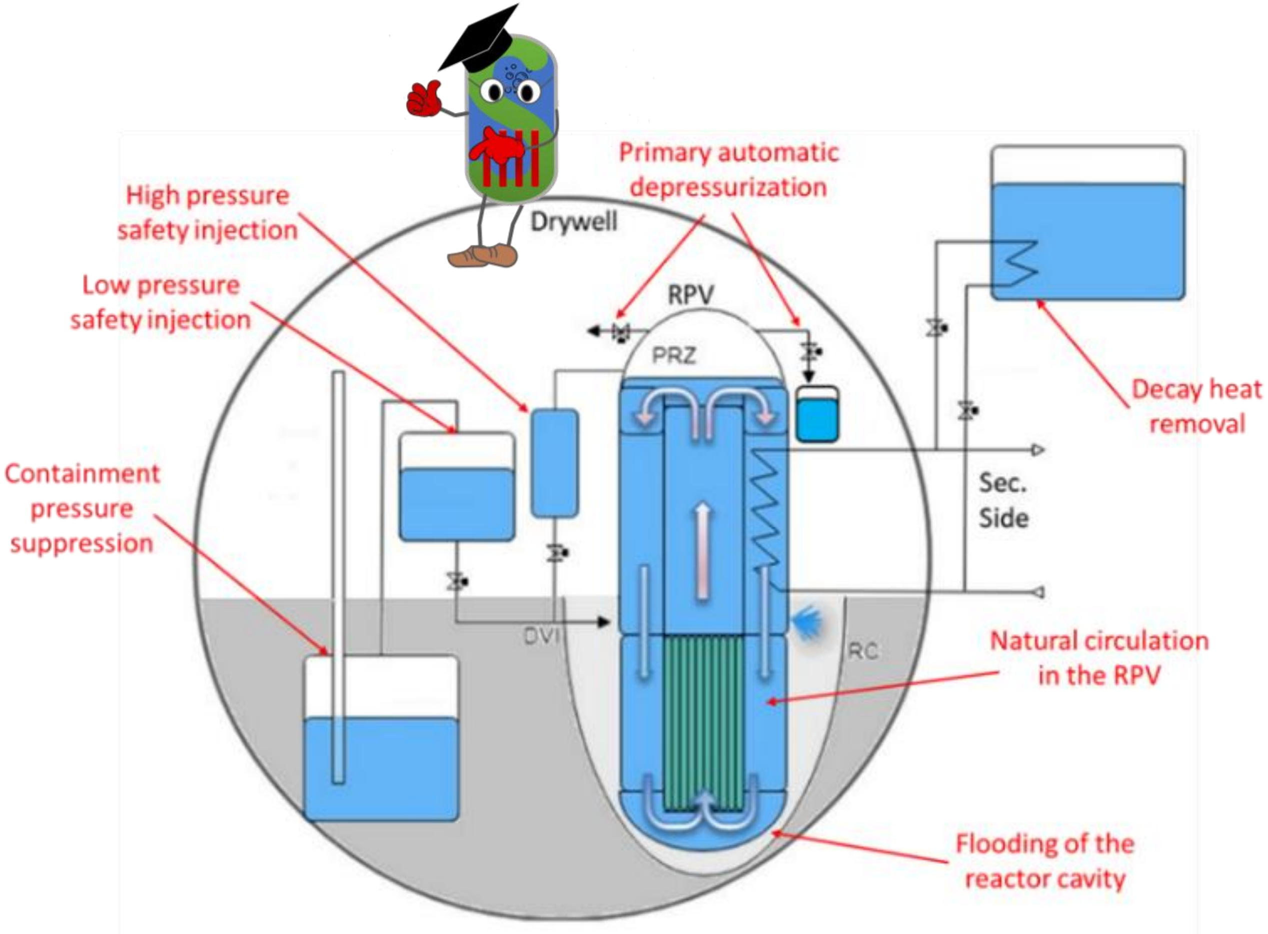
Phenomena taking place at low pressure, as the atmospheric pressure (POINT B)

- It can be mentioned:
  - Natural circulation phenomena:
    - e.g. interaction among parallel circulation loops inside and outside the vessel
    - influence of non-condensable gases,
  - Steam liquid interaction phenomena (e.g. direct condensation),
  - Gravity driven reflood phenomena (e.g. heat transfer coefficient)
  - Liquid temperature stratification phenomena (e.g. vessel lower plenum and downcomer).



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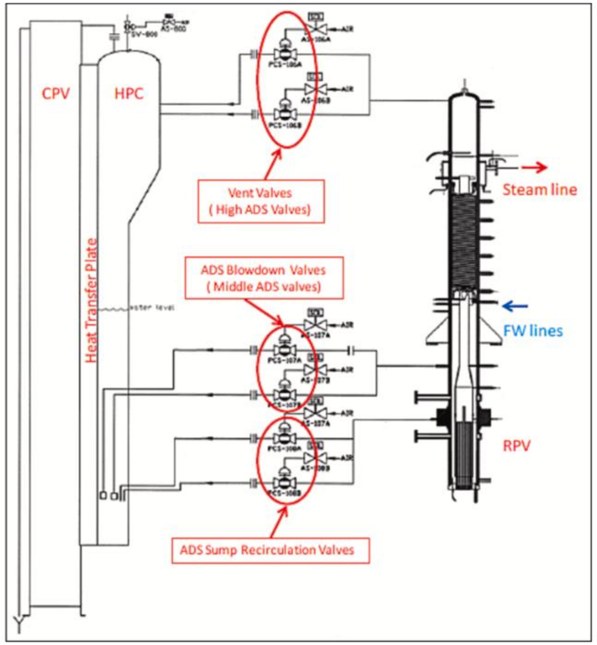
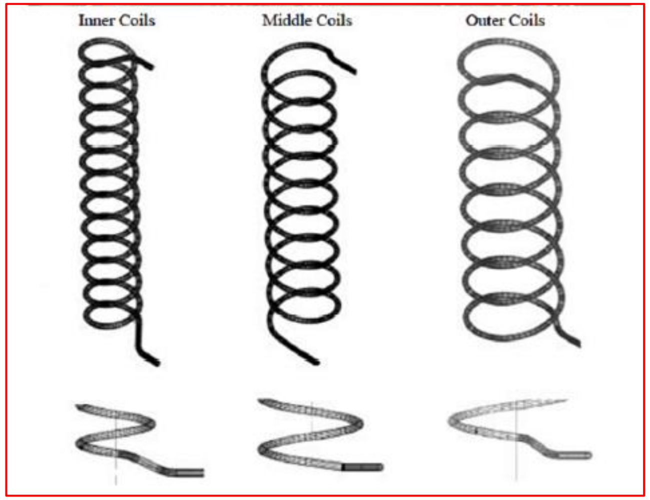
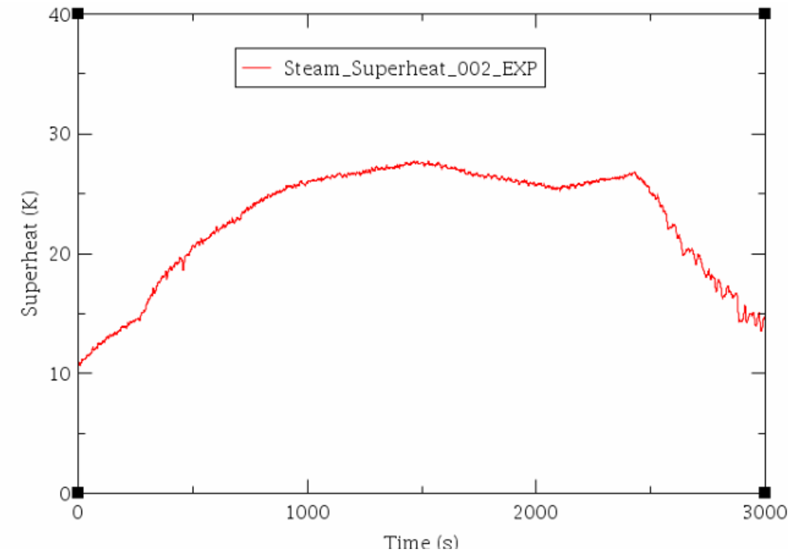
Phenomena related specifically to new system components or reactor configurations (POINT C)

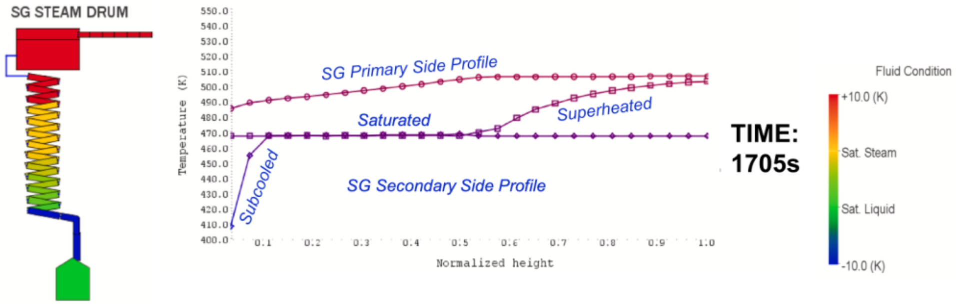
- It can be mentioned:
  - Behavior of compact SG, as helical coiled ones;
  - Passive residual heat removal systems;
  - Natural circulation in integral type configuration (in transient and steady operation).

Phenomena related specifically to new system components or reactor configurations (point a) - HELICAL COILS SG



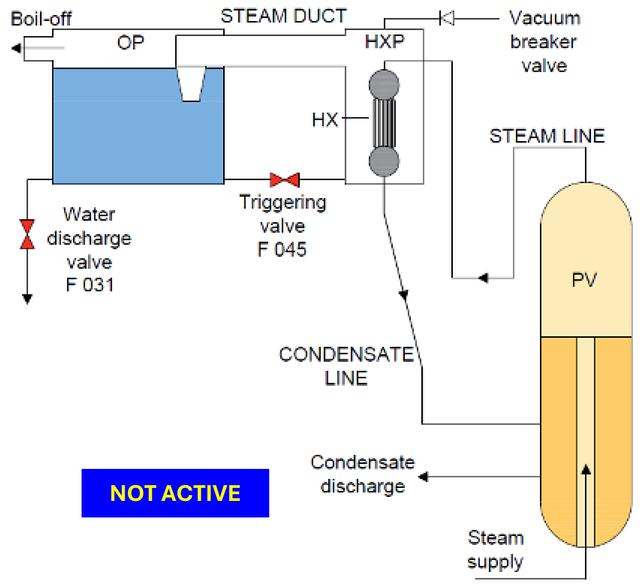


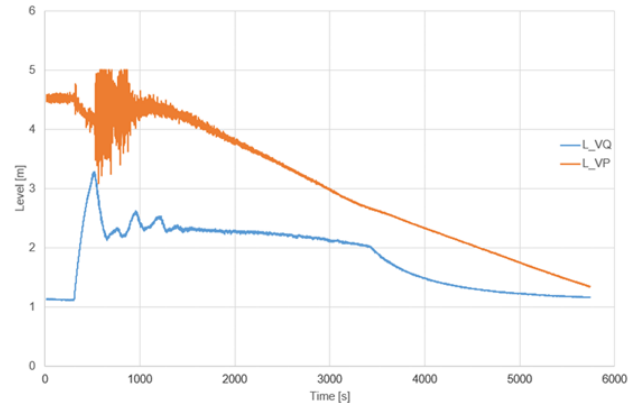


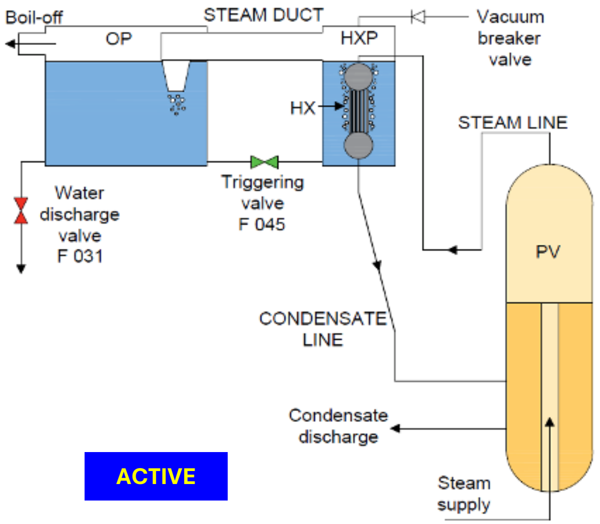


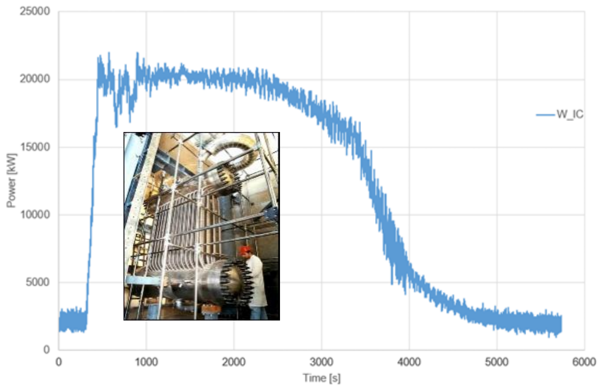
Phenomena related specifically to new system components or reactor configurations (point b) – PASSIVE RESIDUAL HEAT REMOVAL SYSTEM

- The data collected in PERSEO facility are particularly useful for the analysis of the behavior of heat sinks of passive systems:
  - In-tube condensation;
  - Pool-side nucleate boiling;
  - Pool-side thermal stratification;
  - Coupled pools dynamics.
- Two tests have been analyzed and simulated:
  - Test 7 at around 70 bar;
  - Test 9 at around 40 bar.



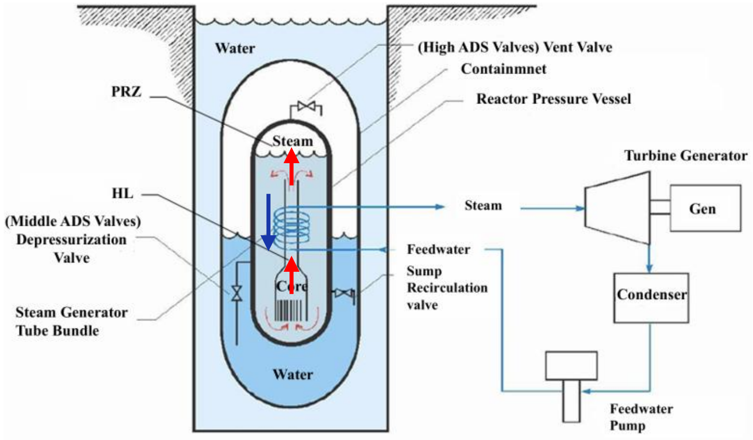




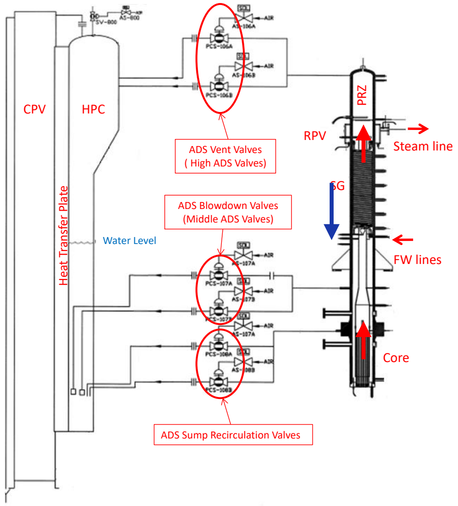


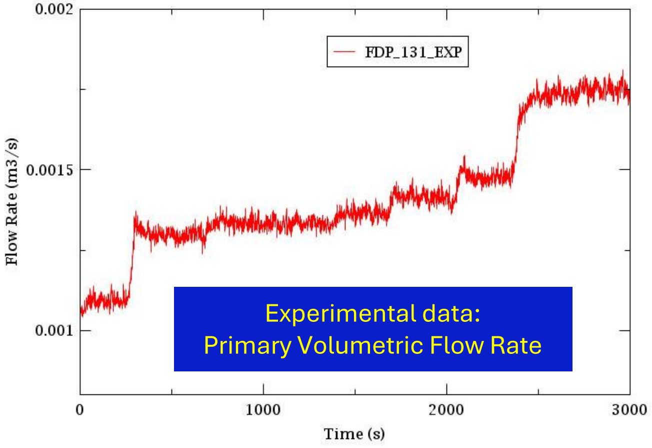
Phenomena related specifically to new system components or reactor configurations (point c) – natural circulation in integral configuration

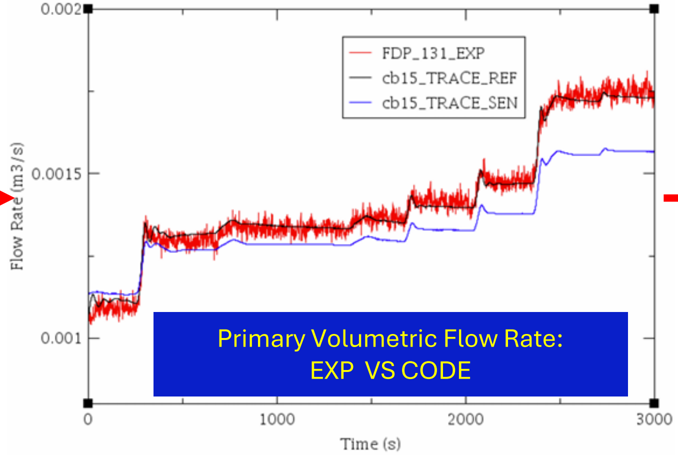
Prototype



Experiments







E.g.: Numeraical scaling