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Evaluation of applicability and limitations of existing scaling techniques: Experimental facilities at SIET

EASI-SMR International Workshop on Thermal-Hydraulic Scaling for SMR Safety Demonstration

December 16-18, 2025 – Bologna (Italy)

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FUNDED BY

Co-funded by the European Union

UK Research and Innovation

The Research Council of Norway

Project funded by

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Co-funded by the European Union
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Overview of activities at SIET

The SIET company operates in the field of thermal-hydraulic testing since 1983 for the experimental qualification of components and systems for the safety of nuclear power plants.

System Testing on Integral Test Facilities

Component Testing on Separate Effect Test Facilities

SIET experimental areas

SPES

7 MW, 20 MPa, 365 °C

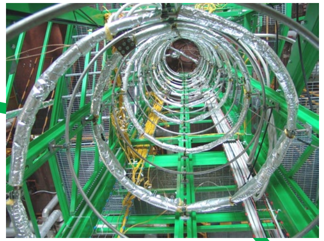
PWR Integral Systems

GEST

10 MW, 10 MPa, 311 °C

Large Scale Components

Heat Removal Systems



IETI

7 MW, 20 MPa, 365 °C

Basic Heat Transfer

Passive Devices

Special Instrumentation

Main testing activities at SIET

Synthesis of the main testing campaigns at SIET

Test section	Test facility	Experimental campaigns	Time period	Customers/ Partners
INTEGRAL SYSTEM	SPES SPES-2 SPES-99 SPES-3	- Experiments on a 3-loops PWR system. - N.15 Experiments for AP-600 Certification Program. - 10" IB LOCA for test facility verification. - Design & Construction of a SMR Simulator (IRIS).	1988-1991 1992-1994 1999 2026-2013	ENEA ENEA, WEC, ENEL ENEA IRIS consortium/ENEA
In-POOL heat removal systems	GEST	- Tests on the 10 MW PCCS HX for SBWR (PANTHESRS) - Tests on the 22 MW ICS HX for SBWR (PANTHERS) - Tests on an enhanced ICS (PERSEO) - Tests on DHRS (ELSMOR, ELSMOR II, SIRIO, LESTO)	1994 1995 2002-2003 2018-2027	ENEA, ENEL, ANSALDO, GE ENEA, ENEL, ANSALDO, GE ENEA EU Projects
STEAM GENERATORS	GEST IETI IETI/GEST/SGFIV HERO	- Performance Tests on the 20 MW ISIS Helical Coil SG. - Tests on full scale single and coupled helical coils of the IRIS reactor SG. - Tests on SMR Helical Coil Steam Generators (TH & FIV). - Test on bayonet tube for Steam Generators	1997 2004-2011 2012-2025 2015-2017	ANSALDO Politecnico di Milano NuScale Power ENEA
STEAM-WATER SEPARATORS	GEST	- Experimental Campaigns on both PWR-SG and BWR Separators and Dryers	1995-2006	WEC, Mitsubishi, Doosan, Toshiba
STEAM INJECTORS or STEAM JET PUMPS	IETI	R&D Test on a SI for LWR safety systems Transient Tests on a SI for ALWR *(EU Synthesis Project)* R&D tests on a CEA (F) design SI for PWR-SG *(EU DEEPSSI Project)* R&D test on a Multi-Stage SI for ABWR	1993-1994 1997 2001-2003 2005-2007	CISE ENEL-CISE-Siemens CEA–Framatome-NRI-CESI-IMP/PAN-SIET Toshiba

Examples of scaling of three test facilities at SIET

The SIET facilities selected as examples of scaling are:

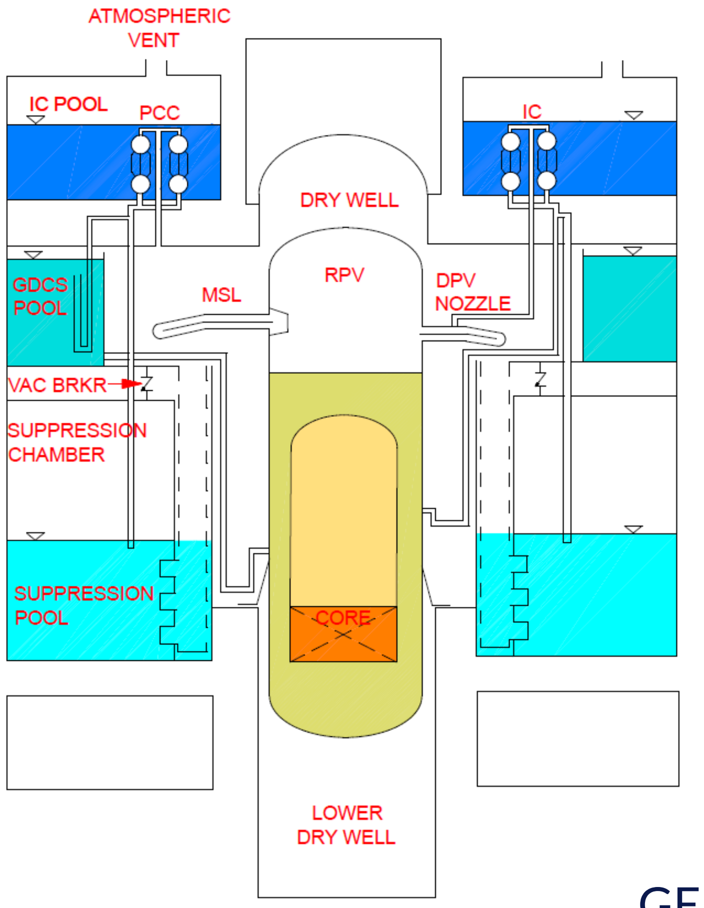
The **PANTHERS** facility used for the structural and steady state thermal hydraulic performance qualification of the GE-SBWR Isolation Condenser (IC) and Passive Containment Condenser (PCC) designs at prototypical flow, pressure, temperature and non-condensable gas fraction.

The **SPES3** facility designed and partially built to simulate the IRIS reactor (IRIS consortium led by WEC) including the primary system, the secondary system, the safety systems and the containment compartments for their active roles in the management of accidents.

The **ELSMOR** facility used to verify the effectiveness of the E-SMR DHRS, based on the former EDF Nuward project that used a compact plate heat exchanger.

The PANTHERS facility

The PANTHERS facility was part of a series of other facilities (GIST, GIRAFFE and PANDA, run by different research centers) aimed at performing tests with the main goal of system verification and TRACG code qualification for the licensing of the SBWR.



GE-SBWR scheme

In the practice, it is not possible to provide the exact simulation of the prototype, however tests on different facilities provide data covering the essential phenomena and system behavior under a variety of conditions.

The PIRT for the reactor identifies phenomena and processes important during the various phases of a postulated accident or class of accidents and the facilities must be adequate to investigate such phenomena.

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The PANTHERS facility scaling approach

The scaling of the facilities was based on the **H2TS** (Hierarchical Two-Tiered Scaling) approach, focused on the post-LOCA containment performance in the latter blowdown phase extending into the long-term cooling phase.

The H2TS approach, developed by the US-NRC, is based on two approaches:

- The **top-down** system approach which defines a hierarchical architecture of the considered reactor system with its decomposition in sub-systems and components, based o their interaction. For Panthers they included: the RPV, the MSL and depressurization valves, the Dry Well and its zones, the Suppression Chamber, the main vents between DW and Suppression Pool, the GDCS, the IC, the PCC and the related pool.

- The **bottom-up** process and phenomena approach which verifies that the controlling processes in the considered sub- systems are properly scaled to be correctly represented in the test facility.

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The PANTHERS facility to simulate PCC and IC

The goal of PANTHERS tests was to qualify the condenser design for structural integrity and steady state thermal hydraulic performance with prototypical flows, pressures, temperatures and non-condensable gas fractions.

The scale was full for the PCC and related pool, while half unit of the IC and a half volume pool were built.

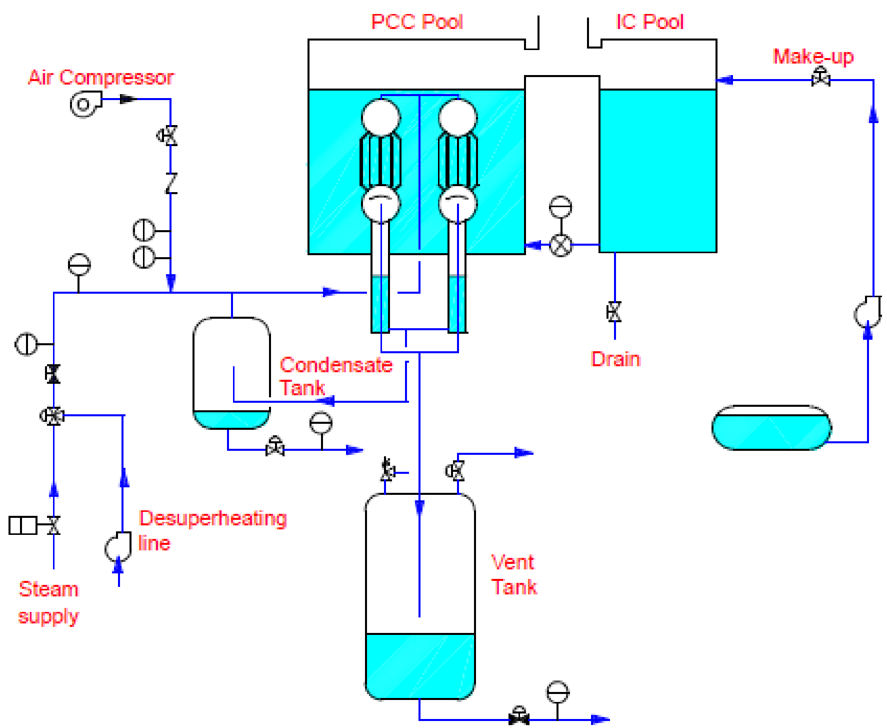
The phenomena to be investigated was mainly the heat transfer on the inside and outside of the condenser tubes with the

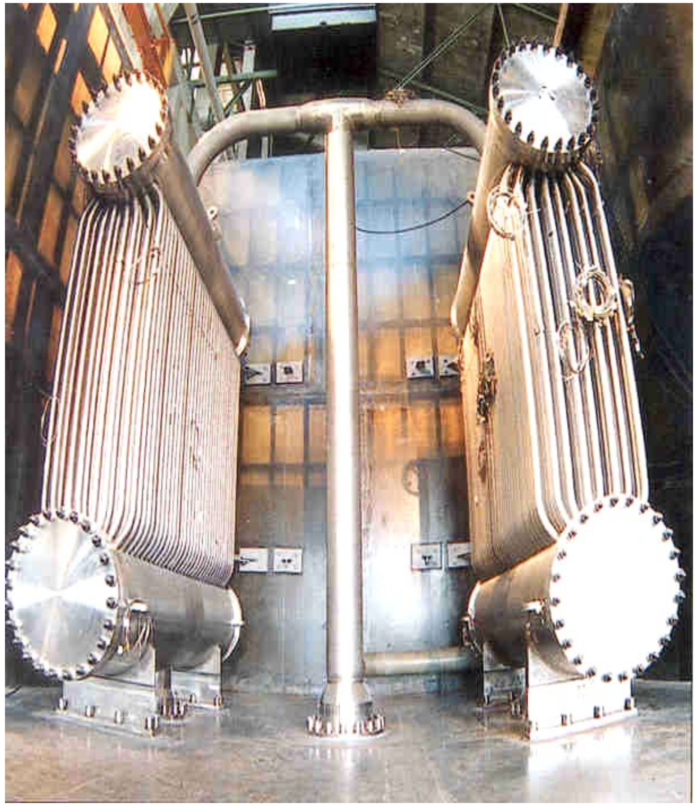
- effect of condensation inside the condenser tubes in the presence of non-condensable gas
- effect of boiling on the secondary side (pool side);
- effect of natural circulation in the pool;
- effect of entrainment of fluid from the pool into the tube bundle;
- flow pattern and void fraction within the tube bundle.

The PANTHERS facility - PCC

No scaling distortions were addressed in the PANTHERS PCC because the containment time constant is much greater than the PCC tube time constant ($\tau_0 >> \tau_{tubes}$). In fact, the characteristic response time for the condenser is of a few seconds both for the transit time of fluid in the tubes and the tube wall response time (small thickness).

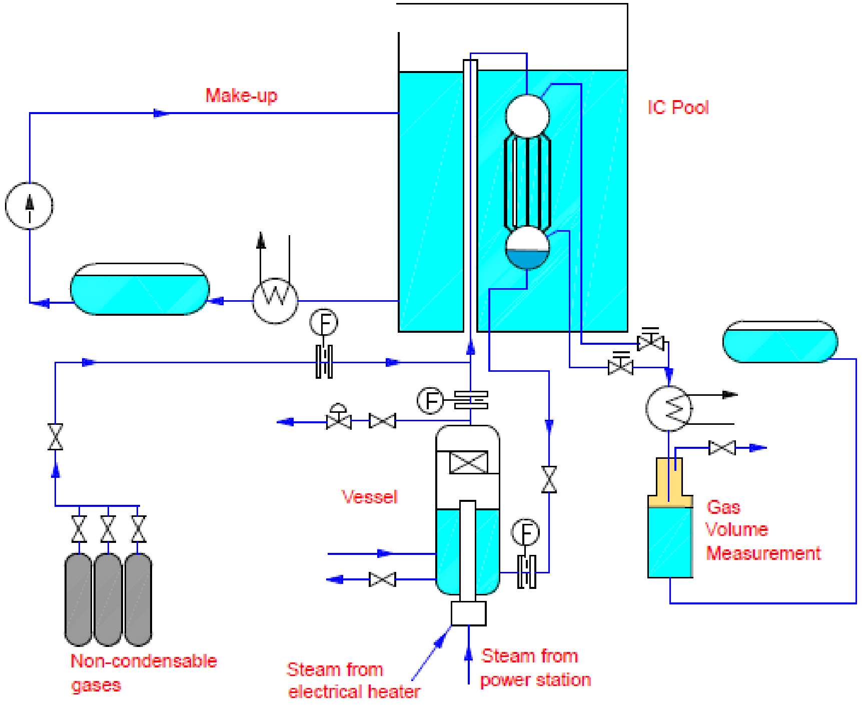
The full scale fully represented the real PCCS.

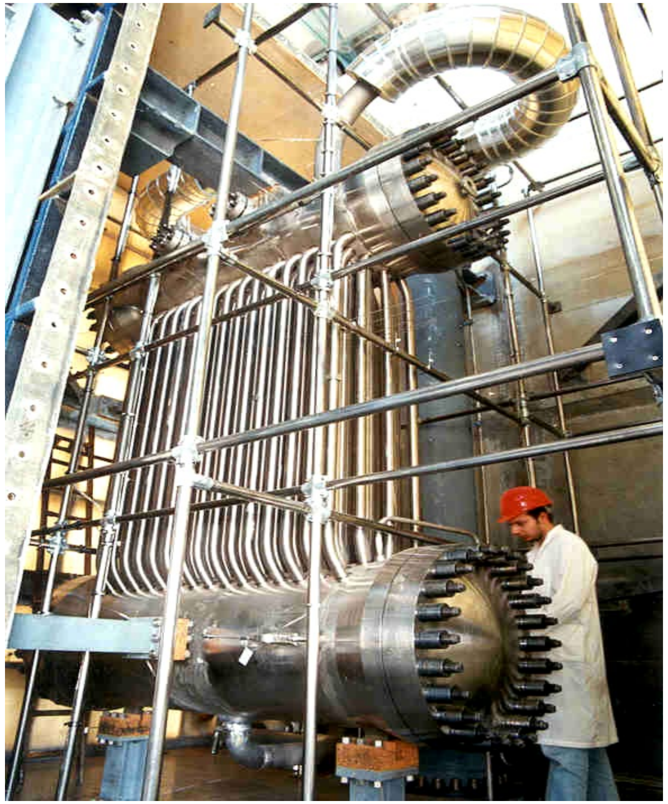




The PANTHERS facility - IC

The scaling distortion for the PANTHERS IC was due to the Pool reduced to one-half of the real one, so impacting the natural circulation for the non-symmetric conditions around the HX. Anyway, the impact on the overall heat transfer coefficient was minimum because the natural circulation affects the HTC when in subcooled conditions and the Pool was mostly boiling.





The PANTHERS facility – impact of spatial scaling

It mainly concerns:

1) Scaling of phenomena and processes
2) Multidimensionality and non-uniform distribution effects
3) Multi-unit and multi-element approach

1) Based on the SBWR PIRT, the influence of the spatial scale is approached with the bottom-up criterion (e.g. stratification in the pool, development of thermal plumes, etc.)

2) Need of good understanding of eventual non-homogeneities in the distribution of the phases due to spatial scale (counterpart tests help to solve the issue of facilities with a reduced scale)

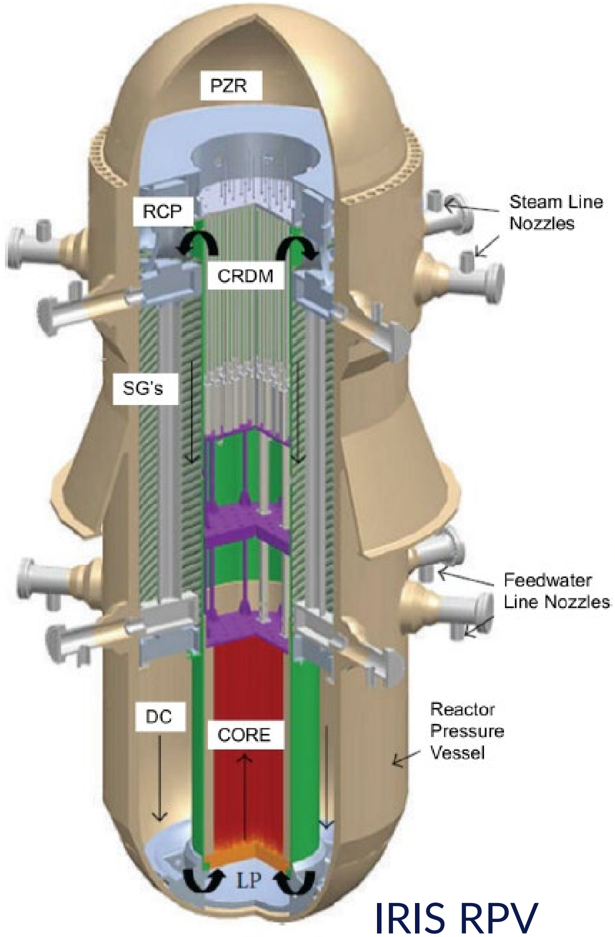
3) Both PCC and IC have a large number of tubes and more units are present in a system that are not reproduced in the experiments and their possible interaction may change the time response (counterpart tests help to solve this issue)

1) + 2) The pressure change rate and the phase change at the interface can be reproduced with a significant scale (power, volume, horizontal area in volumes, flowrate)

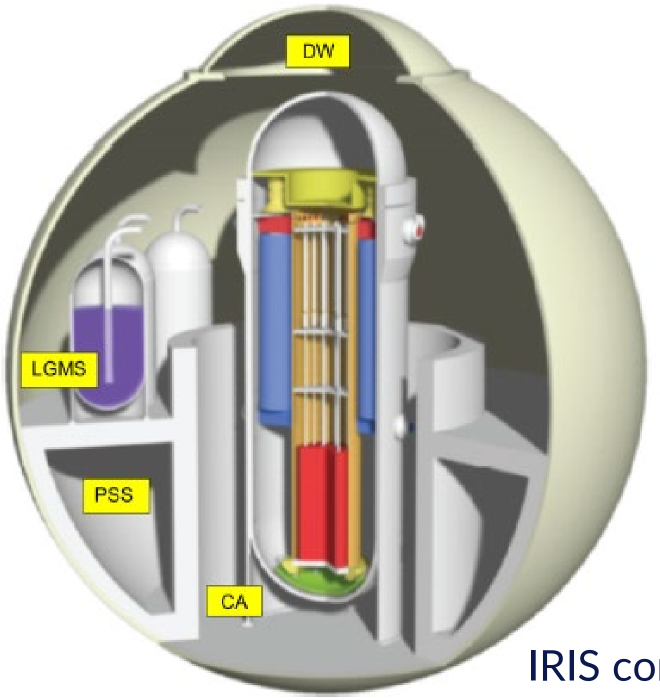
Goal: time scale =1, but if different by 1, the phenomena can be accelerated or slowed down.

The SPES3 facility

SPES3 is an IET facility designed at SIET to simulate the International Reactor Innovative and Secure (IRIS) in the frame of an international consortium led by Westinghouse. The project was later stopped for the exit of WEC by the consortium and for the Fukushima accident after which Italy, encharged of testing, stopped all founds for the research on nuclear fission.



IRIS RPV



IRIS containment

The integral RV design of IRIS included the core, steam generators, pumps, control rods, CRDM, and pressurizer in a safety-by-design approach to eliminate or decrease the consequences of an accident. The RV size was larger than in a traditional PWR, but the steel spherical containment was compact with a higher design pressure.

During the initial phases of a LOCA, pressure in the IRIS containment is allowed to increase providing a back pressure to limit the inventory loss from the RCS. Moreover, the containment could be cooled from the outside in case of EHRS unavailability.

The SPES3 facility - scaling

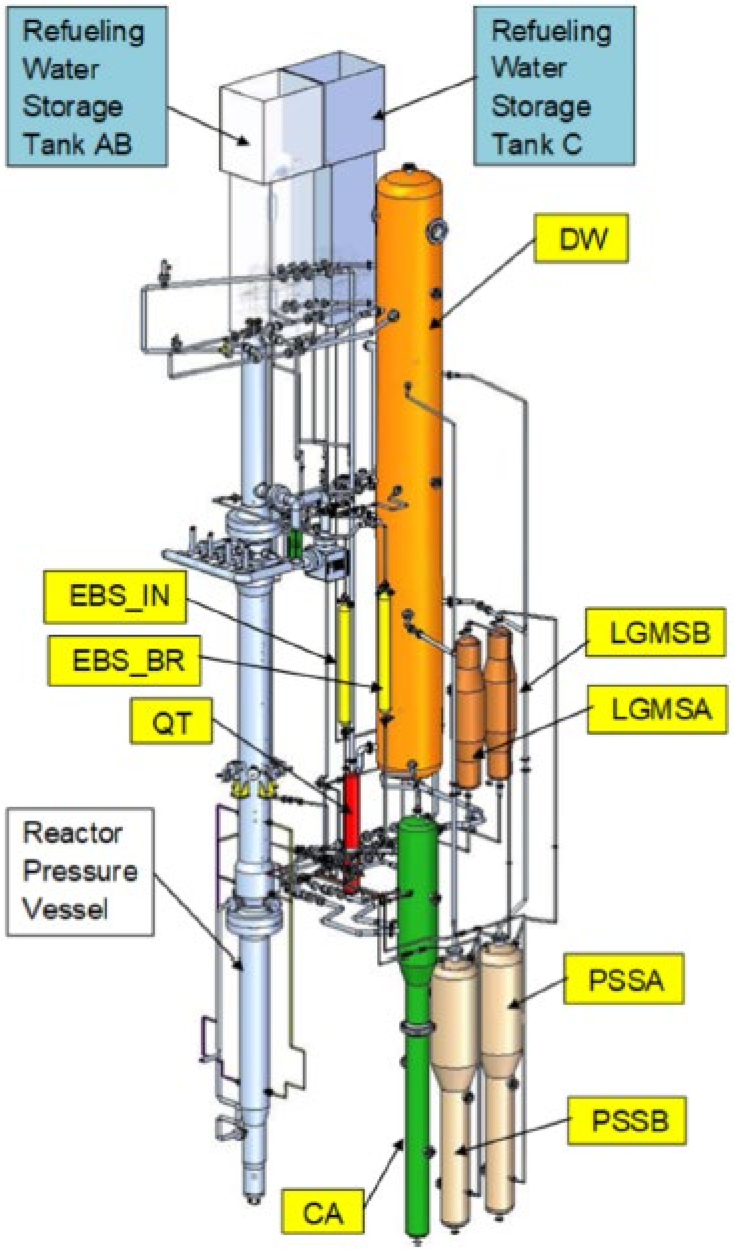
The SPES3 facility simulated the primary side, the secondary side and also the containment compartments of IRIS.

The scaling of SPES3 was done by applying the Fractional Scaling Analysis (FSA) to a system with interacting components where multiple figures of merit had to be respected during complex transient accident scenarios with several consecutive time sequences.

The most challenging transient in IRIS was identified as a SBLOCA in the DVI line and the FSA was applied for two figures of merit:

- Reactor and containment pressure response;
- Reactor vessel water collapsed level response.

The space decomposition was performed first: the RV and containment were divided into components so that important phenomena and their consequences could be evaluated in each of them.



The SPES3 facility - scaling

Then, the time decomposition was performed of the considered transient in consecutive time sequences based on the starts or ends of the defining events.
As the configuration of the system may be different in each time sequence depending on the control system actions (e.g. opening/closure of valves connecting various components), this allows to evaluate important phenomena and their consequences for each component and time sequence.
Also distortions between prototype and model were evaluated by means of non-dimensional groups.

The input data for scaling were based on the results of analyses with:
-RELAP5/GOTHIC codes for IRIS;
-RELAP5 code for SPES3.
The scaling analysis was applied iteratively several times for different IRIS and SPES3 configurations and, along the process, some components of IRIS and SPES3 were redesigned to reduce the distortions.

The SPES3 facility – scaling criteria

The basic criteria for designing SPES3 as a model for IRIS were:

- preserve volume ratio $V_{model}/V_{prototype}$=1/100 for all components as much as possible;
- preserve the power to volume ratio;
- provide vessel wall thickness for the same fluid properties (prototypical pressure and temperature);
- preserve height of the vessels and internals;
- provide horizontal cross-sectional areas for fluid flow ratio =1/100, to maintain the same fluid velocities and residence times;
- preserve pressure drops;
- design vessels and internals shapes to preserve the ratio of water level and water volume.

The SPES3 facility – scaling criteria

These criteria had advantages and disadvantages for designing SPES3 as a model for IRIS

Advantages

- The 1/100 volume ratio and the same power-to-volume ratio is a large scale that reduces distortions due to excessive accumuated heat in the walls;
- prototypical fluid excludes fluid property distortions;
- the full height allows proper simulations of natural convection both in single-phase and two-phase;
- fluid velocities and residence times are the same;
- horizontal transfer area concentrations are the same;
- change of liquid level in the vessel agrees with the change of liquid volume maintaining the same hydrostatic heads.

Disadvantages

- Preservation of the same height leads to have elongated vessels and the side area decreases by 10 times instead of 100 as the volumes;
- Accumulated heat in side walls delays transient thermal responses;
- Some three-dimensional effects cannot be simuated for the elongated shape of components;
- Some components, e.g. heat exchangers and steam generators, are represented with a limited number of tubes with a poor reproduction of bundle effects.

The SPES3 facility – FSA vs. H2TS

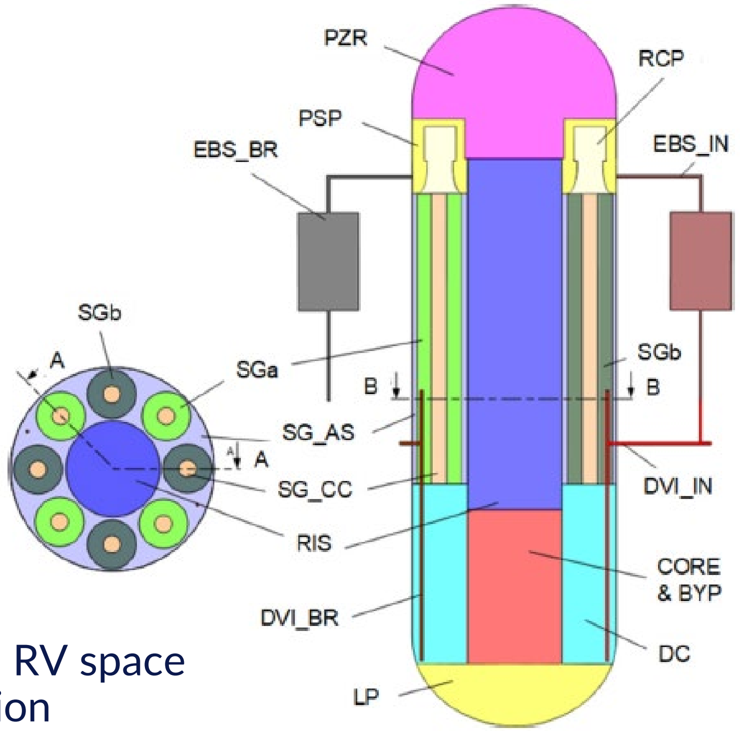
The Evaluation Model Development and Assessment Process (EMADP) by US NRC was followed to verify the RELAP5 and GOTHIC code adequacy to support the IRIS design in a feedback process with the SPES3 analyses up to provide input data for scaling and finalize the design of the facility.

EMDAP recommended the use of a hierarchical two-tiered scaling (H2TS) approach. Anyway the fractional scaling analysis (FSA) was used, derived from H2TS, but less complex in the definitions of hierarchies: three hierarchical levels (system, components, processes) compared to the eight levels of H2TS (systems, subsystems, modules, constituents, phases, geometrical configuration, fields, processes).

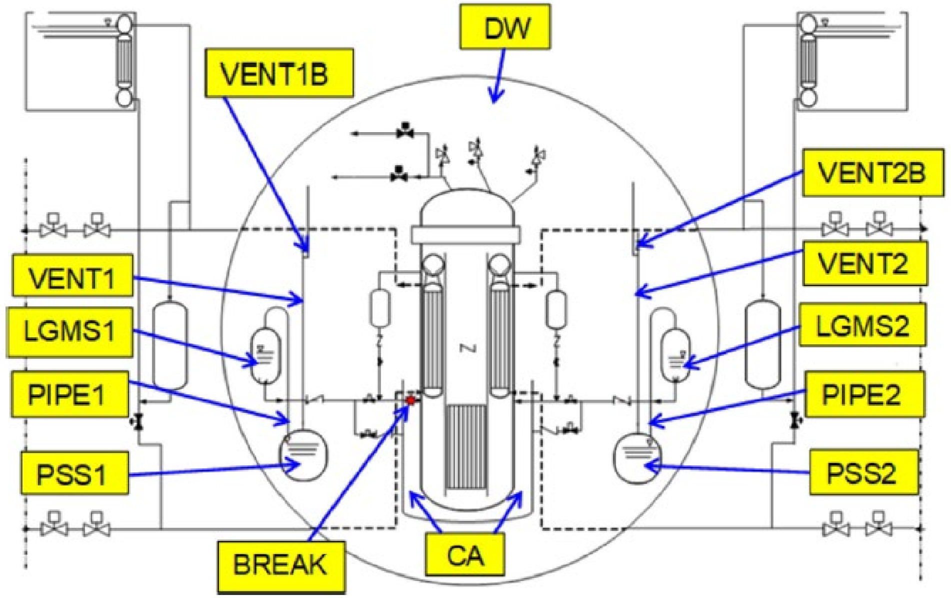
The integral approach of FSA also allowed to simplify the conservation equations in which each term represented the effects of only one phenomenon for an easier quantitative evaluation.

IRIS and SPES3 space decomposition

The space decomposition of IRIS RV and containment was based on PIRT and the expected phenomena in each component, postulated break position and the distribution of control valves connecting and disconnecting components.



IRIS integral RV space decomposition



IRIS containment space decomposition

The space decomposition of SPES3 included a number of components slightly different from IRIS because in SPES3 some parts were not represented and also other parts were compacted (e.g. eight SGs represented by three SGs). Two reasons mainly drove the choice: test facility design and different codes used for the analyses.

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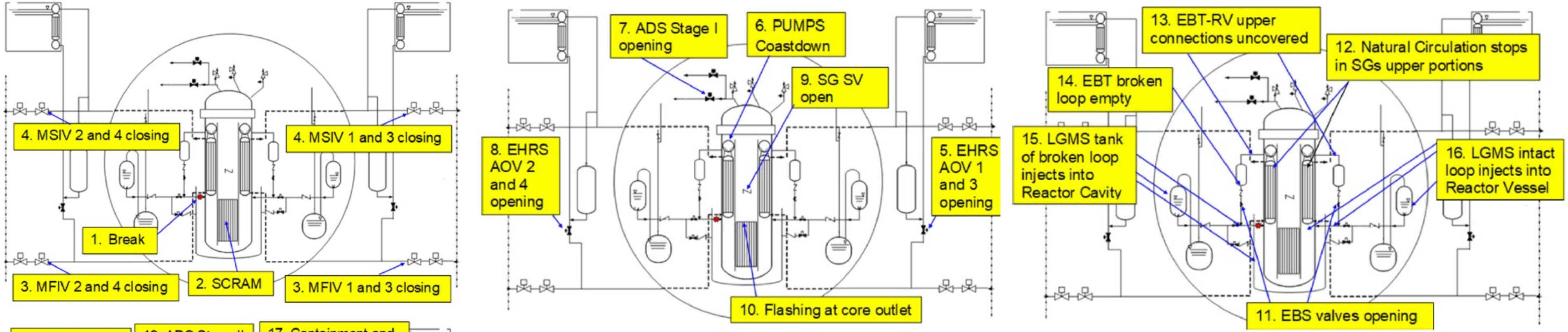
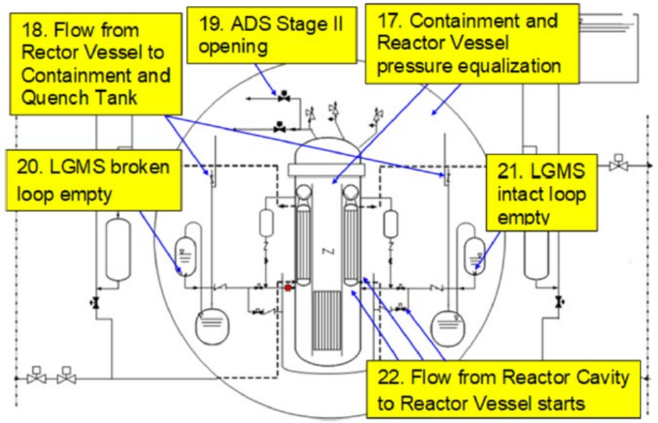
IRIS and SPES3 time decomposition

The postulated accident was the DVI SBLOCA and the transient was partitioned in time sequences characterized by the status of a system based on the start of new events as: the connection between components (e.g. valve opening); the activity of some components (e.g. pumps, heat exchanger, etc.); the presence of physical phenomena in components.

A ranking of processes taking place in the whole transient was established by analyzing the dominant processes in each time sequence that affected the figures of merit.





IRIS time decomposition

SPES3 time decomposition is very similar even if in some cases slight differences in actuation time and in the consecutive order are present.

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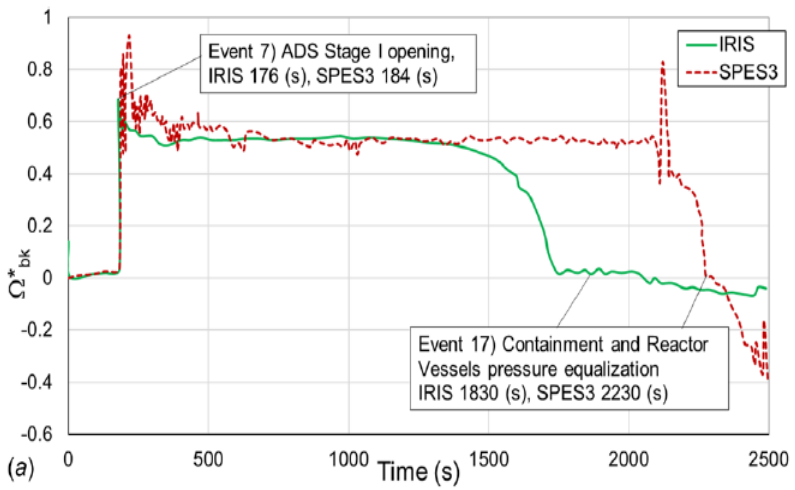
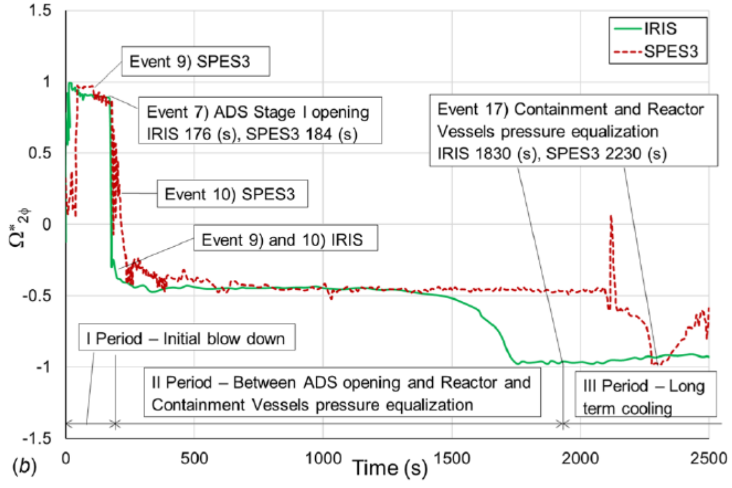
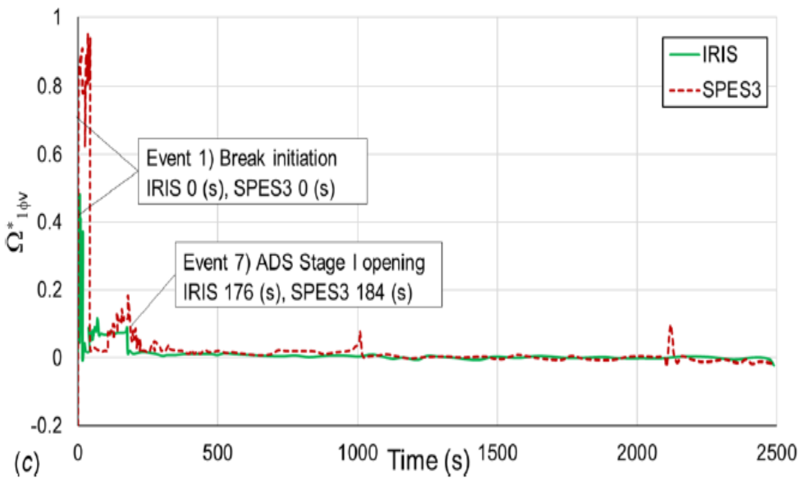
Top-Down System Scaling Analysis

The quantifications of distortions (D) between prototype and model was possible by defining normalized non-dimensional groups to estimate the fractional rate of change of a state variable depending on an agent of the change (e.g. pressure vs. break flow, etc.).

An example of normalized fractional changes for pressure response versus time for the break flow (a), two-phase heat transfer (b) and single-phase heat transfer (c) to vapor are shown below:







The ratio between prototype and model groups allowed to evaluate the goodness or not of scaling, based on a certain scale, but other than the numbers, it is important to keep into account the trend, because distortion could appear large due to time delays in phenomena.

Bottom-Up System Scaling Analysis

Once the important processes and hierarchies are established in the Top-Down approach, detailed scaling analyses of such processes need to be done in the Bottom-up scaling analysis. For IRIS and SPES3, an iterative process was applied to redesign both prototype and model to reduce distortions.

In particular, optimization concerned:

- the containment tank volume;
- the containment tank wall metal masses and temperatures;
- the containment piping pressure drops;
- the EHRS and RWST modelling and heat transfer coefficients.

The final design was completed and the facility partially built.

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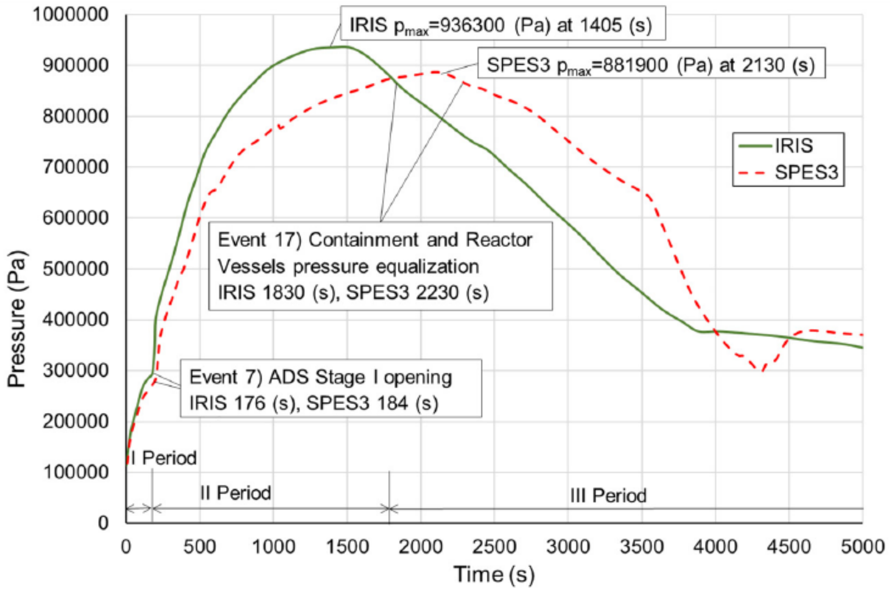
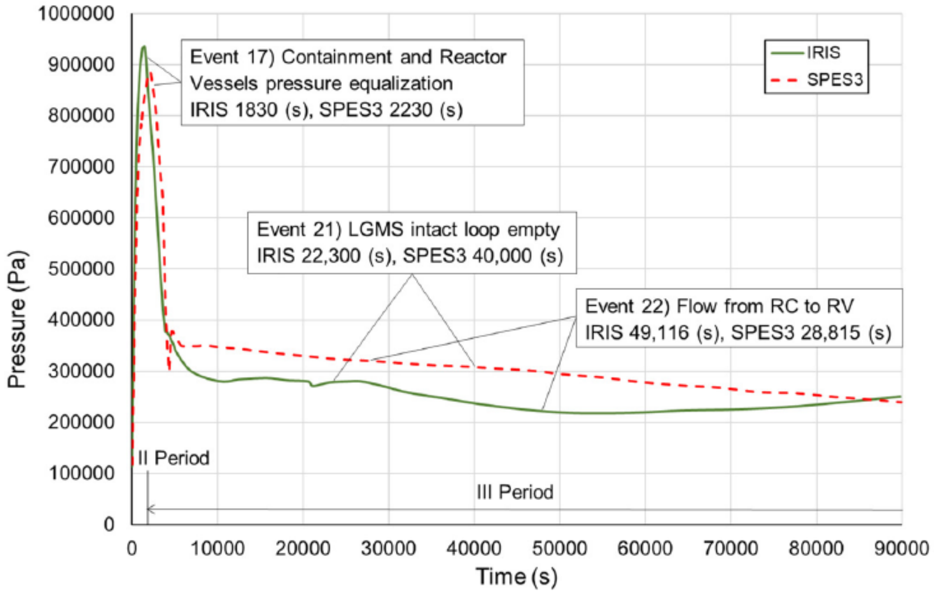
SPES3- Results of the optimized scaling process

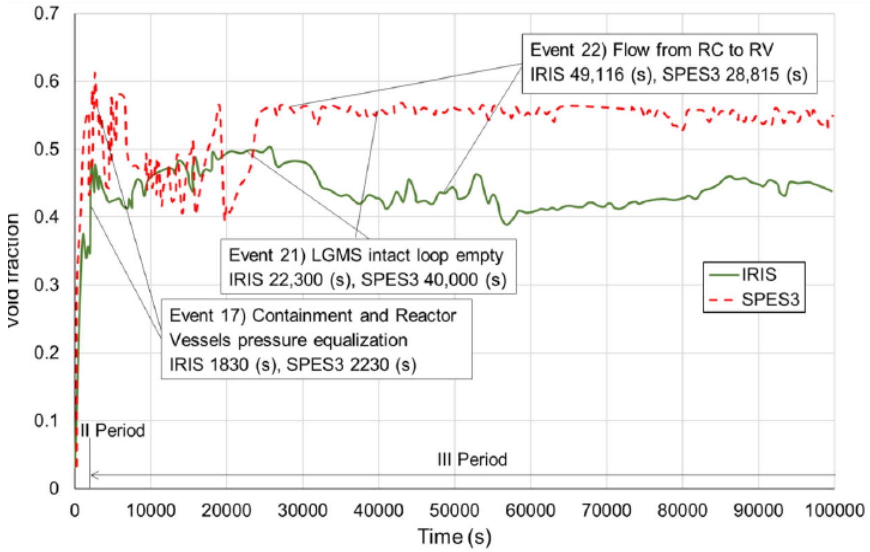
Good agreement for the two figures of merit identified by PIRT for IRIS and SPES3

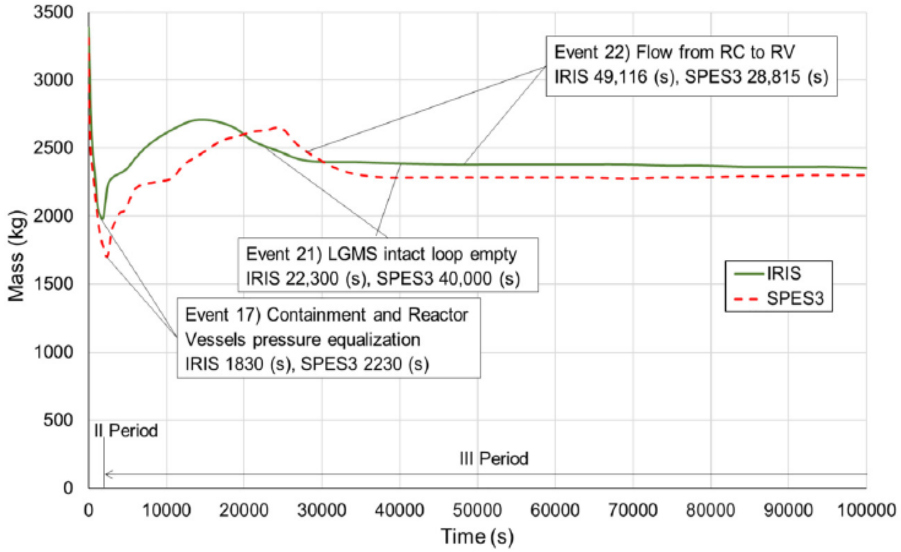
Pressure vs. time





RV void fraction and mass vs. time

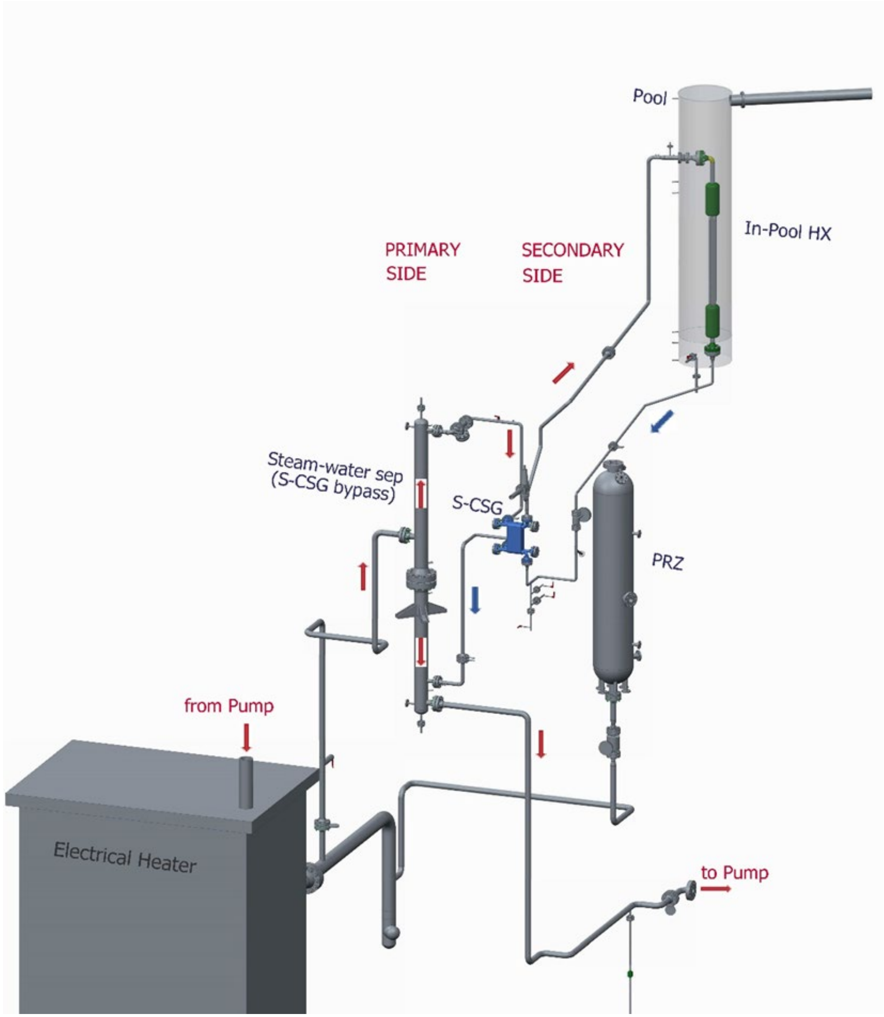




The ELSMOR facility

The ELSMOR facility was built in the frame of the European project ELSMOR (2018-2023) to test a passive decay heat removal system for the E-SMR, based on a compact plate-type heat exchanger included in a natural circulation loop that rejects heat into a water pool.

The potential use of a plate-type heat exchanger in an integral type SMR (former EDF Nuward reactor) had the advantage of high power transfer in an extremely compact configuration, but being the first time this kind of heat exchanger was proposed to be part of a nuclear power plant for civil use, it required wide experimentation before the application for licensing. This is one of the reasons why EDF decided to move to a different design for Nuward based on proven technologies.



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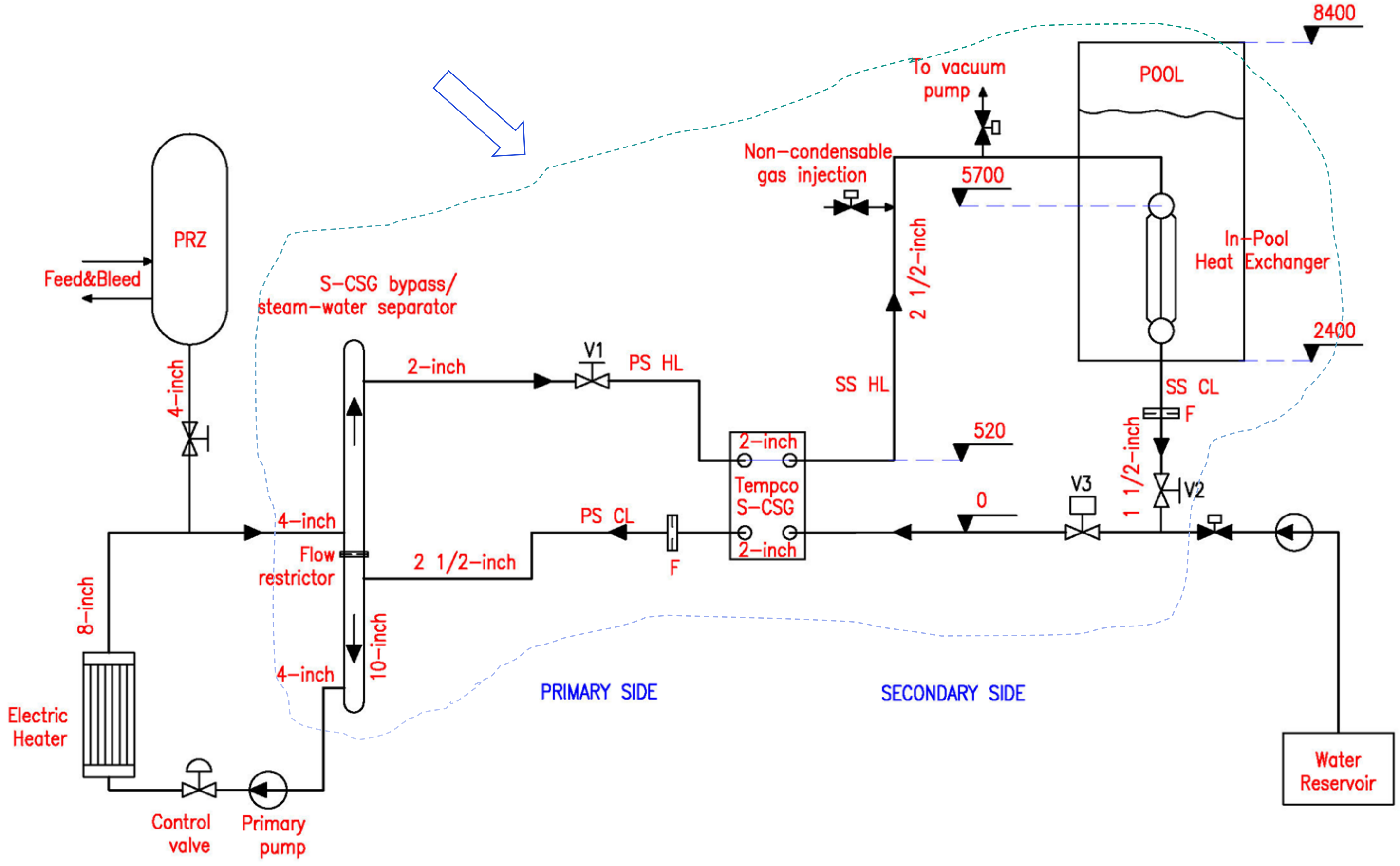
The ELSMOR facility characteristics



Simplified scheme

Total height: ~ 15 m
Power ~ 1 MW
(Plate HX power ~600 kW)

Primary side design conditions:
P 13 MPa; T 330 °C

Secondary side design conditions:
P 10 MPa; T 310 °C

In-pool HX: 5 tubes, 2-inch diameter,
~2 m lenght

Cylindrical water pool:
~ 5 m^3 volume,
~ 6 m height,
atmospheric pressure

The ELSMOR facility scaling

Reference reactor E-SMR
Electric power ~170 MW
Thermal Power ~515 MW
2 Loops EHRS
Decay power per loop ~30 MW (decay power ~10% reactor power/2 ~26 MW)

The scaling for the ELSMOR facility mainly focused on two aspects:

- heat exchanger power and pressure drops;
- loop pressure drops.

Plate-Type heat exchanger specification
HX power ~500 kW
HX primary side pressure drops ~12 kPa (at 2.8 kg/s nominal flowrate)
HX secondary side pressure drops ~30 kPa (at 0.4 kg/s nominal flowrate)

Natural circulation loop specified height ~6 m.

ELSMOR facility scaling factors:
Elevation 1:1
Power ~1:50

The ELSMOR facility design choices

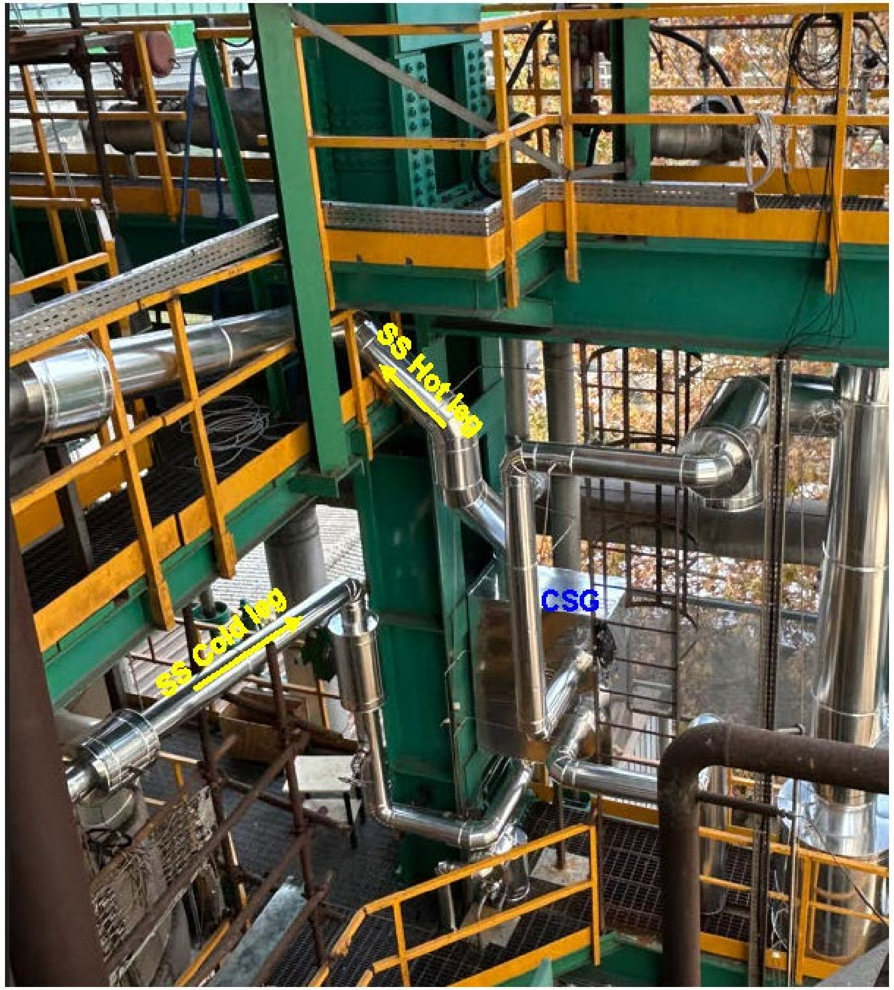
The facility reproduced one of the two DHRS loops of which a few data were known.
The difference of elevation among components was maintained, but the geometry and pressure drops of piping were not available. Thus, manual valves were installed both on the primary and secondary side to experimentally investigate the system performance by varying the pressure drops.

The Heat exchanger immersed in the pool had been designed and built for SPES3 EHRS and it was considered adequate for ELSMOR because operating at similar conditions with similar power.

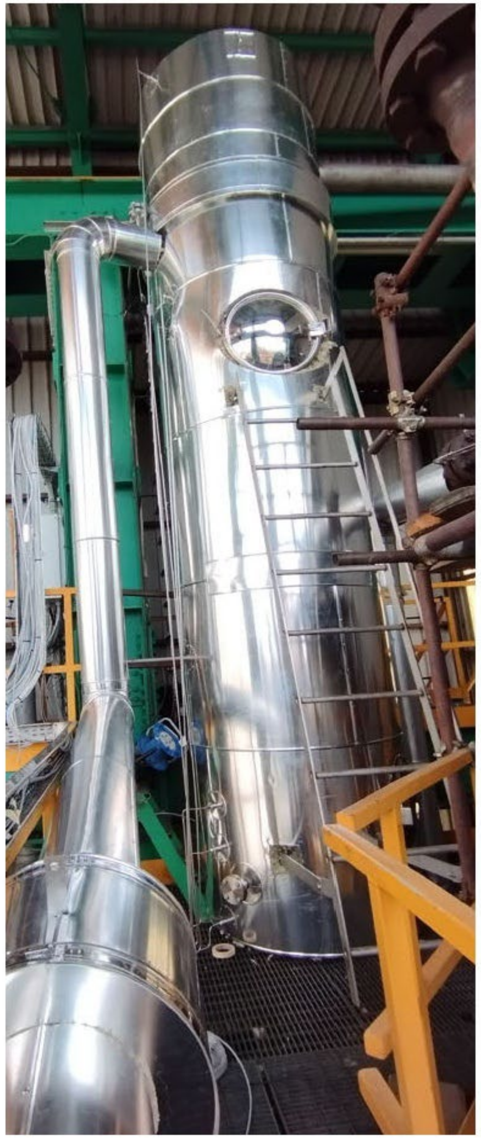
The size of the water pool is no representative of the real pool, but the amount of water is adequate to study the heat transfer in boiling conditions with level decreasing or constant (water make-up system added in the frame of EASI-SMR project)

The ELSMOR facility loops

Primary side



Secondary side



HX Pool

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Conclusions

The scaling approaches of three facilities built at SIET have been presented.

In all cases, it is put in evidence how it is a hard task to reproduce a prototype in a scaled format due to the border effects of the facility on the investigated phenomena.
For this, a single facility is never sufficient for the whole qualification of a design and more rigs are necessary to characterize different phenomena.

Computational codes represent the trait d'union between facilities and reactor design, once validated on experimental data.

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SIET sperimentiamo le tue idee

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Project funded by
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Funding acknowledgment

Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Atomic Energy Community ('EC-Euratom'). Neither the European Union nor the granting authority can be held responsible for them.

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Co-funded by the European Union

UK Research and Innovation

The Research Council of Norway

Project funded by

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
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Swiss Confederation

Federal Department of Economic Affairs, Education and Research EAER
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