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## **1) The NURES SAFE objectives**

Numerical simulation tools used for the design and safety evaluation of nuclear power plants (NPP) are under continuous development, improvement and validation. In this field, a key challenge is the development and consolidation of integrated simulation platforms to support safety analysis and future fission reactor designs. These simulation platforms must integrate the dynamic 3D coupling of the codes simulating the different physics of reactor problems into a common multi-physic simulation scheme in order to enhance the prediction capability of the computations used for safety demonstration of the current light water reactors (LWR) nuclear power plants and the design of innovative LWR.

In this context, the NURES SAFE European project had two major objectives:

- to deliver to European stakeholders a reliable and predictive up-to-date software platform usable for safety analysis needs for LWR and to further improve the “safety culture” by developing a high level of expertise in the proper use of the most recent and most advanced simulation tools; this software capacity is the NURESIM (Nuclear Reactor SIMulation) European reference simulation platform.
- to create a community that brings together the European key-players, to promote the use of an advanced scientific basis among this community and engage it in advanced and predictive simulation for LWR.

The NURESIM software platform offers:

- higher fidelity methods as for example pin-by-pin resolution rather than nodal methods and innovative computational fluid dynamics methods
- an integrated multi-physic environment enabled by the SALOME open-source software (<http://www.salome-platform.org/>). SALOME provides a generic user-friendly interface and is designed to facilitate the coupling of computing codes in a heterogeneous distributed environment as well as to facilitate interoperation between CAD modeling and codes.
- a toolbox for uncertainty quantification, sensitivity analysis and model calibration: the URANIE open-source software (<http://sourceforge.net/projects/uranie/>).

The NURESIM software platform was developed from 2006 to 2015 by 22 European organizations. It incorporates from now the latest advances in core physics, two-phase thermal-hydraulics and fuel modeling for present and future reactors together with, sensitivity and uncertainty tools as well as multi-scale and multi-physic features. It provides tools parallel of those of industry, with higher fidelity. These tools are usable for simulation of design basis accidents of LWRs as well as normal operation

The different physics of the NURESIM platform were validated and fully integrated into the platform using SALOME, in order to provide a standardized state-of-the-art code system to support safety analysis of current and evolving LWRs.

## **2) A “Situation Target” driven approach**

In order to enhance the computational capacities to predict safety-relevant parameters with more accuracy and more reliability, predictive physical models,

efficient solvers and codes and coupling capacities are needed. To achieve the NURESIM objectives and to demonstrate the predictive capability of the software platform, NURESAFE focused on some challenging reactor situations named “Situation Targets”. As safety analysis is the main issue within the project, all these situation targets consist in some accidental scenarios. The challenging “Situation Targets” have been selected according to the required coupling between two or three different disciplines.

The following Situation Targets have been selected. They have been grouped into five categories:

- 1) Advanced boron dilution modeling
- 2) PWR main steam line break (MSLB)
  - ✓ PWR application
  - ✓ VVER application
- 3) Boiling water reactor anticipated transient without scram (BWR ATWS)
- 4) Lost of coolant accident (LOCA) in PWR
  - ✓ Modeling of LOCA
  - ✓ Pressurized Thermal Shock (PTS)
- 5) BWR thermal-hydraulics scenarios, particularly behavior of the pressure suppression pool in accidental conditions

The NURESIM platform addresses these Situation Targets through predictive simulations including validation and uncertainty quantification. Therefore, NURESIM allows the reduction in uncertainty of design margins and facilitates optimization of fuel management, power uprate and lifetime extension for current reactors and facilitates the introduction of new reactor designs with enhanced performance characteristics.

To summary, let us say the NURESIM implementation strategy comprised four steps:

- 1) Develop physical models and computational tools with enhanced predictive capacity
- 2) Integrate these tools in the SALOME software platform to get a standardized environment with the multi-physics / multi-scale functionalities
- 3) Develop and run tools for simulation of some challenging reactor problems or « Situation Targets »
- 4) Implement a methodology for verification and validation

### **3) Validation of the NURESIM platform**

NURESAFE carried out an extensive validation program in order to ensure its predictive capacity when running reactor accidental transients and to quantify biases and uncertainties. This validation program included four components:

- Critical experiments,
- Numerical validation using Monte-Carlo reference solutions for cell or lattice,
- Thermal-hydraulics experiments at the different time and space scales considered in the platform,
- Operating power plant measurements.

Each Situation Target included a specific sensitivity and uncertainty analysis correlated to the validation task. In order to avoid duplication, the NEA and IAEA databanks were used to contribute to the validation.

The completion of the four components demonstrated the reliability of the NURESIM software platform and the accuracy of the core simulation capability that can be used by the nuclear industry.

#### 4) The NURESIM roadmap

The roadmap of the NURESIM simulation platform in general aimed at improving the safety of light water reactors (LWR) through deterministic analysis of NPP events in the scope of the plant design basis (Design Basis Accidents - DBA). It is part of a global trend to move towards “higher-fidelity” simulation techniques in reactor analysis. Validation of the codes against experimental data was also an important objective for the roadmap.

The work under this roadmap was carried out through three successive projects as shown in figure 1. The first project, NURESIM, established the basic architecture of the platform and resulted in a first prototype of a truly integrated multi-physics simulation environment. The NURISP project was conceived as a consolidation of the platform together with an extension of the simulation capabilities towards higher-resolution both in space and time. The NURES SAFE project showed the extended capabilities of the platform, demonstrated the readiness of the tool for Industrial safety applications and established the platform as a reference European tool.

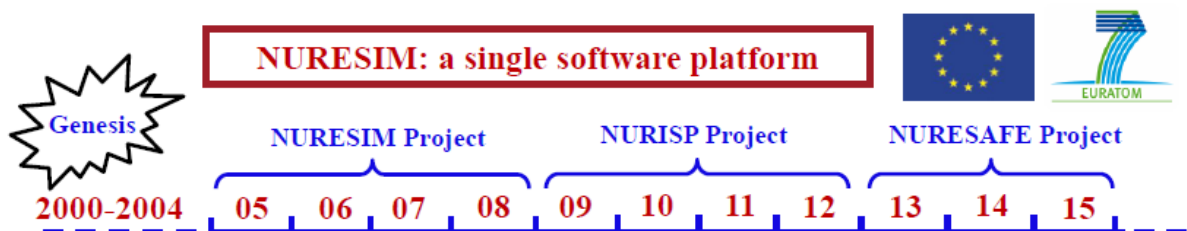


Figure 1 – the NURESIM roadmap

#### 5) The NURES SAFE consortium

The NURES SAFE partnership brought together the majority of European organizations with suitable skills in order to develop novel modeling capabilities and an advanced integrated software platform usable for predictive simulation of light water reactors. This consortium connected nuclear technology and fundamental research through the partnership gathering utilities, industry, technical support organizations (TSO), universities and research institutes. The project management ensured the tight collaboration among the partners. Thus, the consortium has the capability to share complementary expertise in order to implement an interdisciplinary competence and to develop solutions applicable to industry challenges.

The NURES SAFE consortium includes 22 contributors to the development:

- 6 Universities or high-schools (UPM, KTH, U-PISA, UCL, LUT, ICL)
- 2 Large industries (EDF, AREVA)
- 10 Research Institutes (KIT, CEA, HZDR, PSI, JSI, VTT, INRNE, UJV, KFKI, ENEA)

- 3 TSOs (GRS, IRSN ; NCBJ)
- 1 SME (ASCOMP)

## 6) The NURES SAFE Sub-projects

The objective of the NURES SAFE project was achieved through 4 sub-projects devoted to software development and validation. These sub-projects were designed to ensure that the NURESIM platform has all necessary physical models, multi-physics capacities and functional features necessary to accurately simulate reactor transients or normal operation.

- 1) Multiphysics applications involving core physics: This sub-project developed the coupled models involving thermal-hydraulics and neutronics and conducted the analysis of MSLB and BWR ATWS.
- 2) Multiscale analysis of core thermo-hydraulics: The objective was to develop new CFD models for LWR core analysis and to implement models in the NURESIM CFD codes. This work was conducted in a multi-scale approach.
- 3) Multiscale and multi-physics applications of thermal-hydraulics: Within this sub-project, the challenge problems concerning LOCA, PTS and BWR thermal-hydraulics applications were analyzed. New methods were developed and applied to the simulation of these situation targets.
- 4) Software platform: The goal of this sub-project was to integrate the models and software developed by other sub-projects into the SALOME software.

In addition, a comprehensive education and training program was conducted within NURES SAFE in order to enable participants from the different NURES SAFE partners to share models, modules and methods in order to catalyze their engagement including scientist staff of the partners, PHD students and postdoctoral associates.

### 6.1 Sub-project 1 (Multiphysics applications involving core physics)

The objective of this sub-project was to enhance the prediction capability of the computations used for safety demonstration of the current LWR nuclear power plants through the dynamic 3D coupling of the codes simulating the different physics of the problem into a common multi-physics simulation scheme. Within this sub-project, three physics were considered: core physics, thermal-hydraulics and fuel thermo-mechanics. Individual models, solvers, codes and coupled applications, were run and validated through modelling some Situation Targets: MSLB and one selected BWR anticipated transient without scram (ATWS). Industry-like applications were released at the end of the project:

- Square lattice PWR main steam line break (MSLB),
- BWR turbine trip without scram,
- VVER main steam line break (MSLB),

The analysis also included uncertainty quantification using the URANIE open-source software.

The MSLB transient analysis provided more accurate assessment of margins between predicted key parameters and safety criteria. The outcome of the transient simulation was evaluated with respect to the following phenomena:

- Local re-criticality,

- Maximum reactor power level.

The BWR turbine trip analysis framework featuring coupled simulations combined:

- System thermo-hydraulics,
- 3D neutronics,
- Thermo-mechanic evaluation of fuel safety parameters,
- Uncertainty evaluation.

### 6.2 Sub-project 2 (Multiscale analysis of core thermo-hydraulics)

The objective of this sub-project was to advance the fundamental knowledge and develop new models based on detailed Direct Numerical Simulation (DNS) for momentum exchange and boiling heat transfer issues present in thermal hydraulics of Light-Water Reactors (LWRs). New benchmark data bases for fundamental and applied problems were developed. This sub-project included four work-packages.

A first work-package has been tailored to extend the existing computational multiphase flow strategies to cope with a wider range of practical applications.

The second work-package was devoted the development of novel methods for pool and convective boiling in a channel.

Within the third work-package, advanced strategies for modelling turbulent bubbly flow in a channel and in a rod bundle were analyzed. Novel ideas were explored and others further refined as to combining large-scale and small-scale prediction techniques that should in the medium term replace state-of-the-art methods that are limited to one flow regime. These novel techniques are applicable to more complex core-level thermal-hydraulics situations involving boiling.

In the last work-package, the novel models and simulation techniques have been implemented in the CFD platform codes NEPTUNE\_CFD, TransAT and TRIO\_U, validated and delivered to end-users, including most advanced numerical simulation features and the associated modelling approaches for the physics pertinent to both PWR and BWR.

### 6.3 Sub-project 3 (multiscale and multi-physics applications of Thermal-hydraulics)

The objectives of the SP3 were to develop multi-scale and multi-physics simulations of LOCAs, PTS and BWR thermal-hydraulics for more accurate and more reliable safety analysis.

**LOCA** is usually simulated with industrial versions of thermal-hydraulics system codes such as CATHARE-2 and ATHLET. Although system codes are able to answer most safety needs, the status and limits of current methods and tools for plant analysis was reviewed during the NURISP project and areas for improvements have been pointed out.

Concerning LOCA, this sub-project aimed at developing advanced tools and methods for a multi-scale and multi-physics analysis and simulation of LOCAs including situations with deformed or ballooned rods and possible fuel relocation. Such transients are currently treated by system thermal-hydraulic codes. The addition of two-phase CFD tools and of advanced fuel models allowed revisiting these transients for more accurate and reliable predictions. Geometrical effects of ballooned rods were better understood at CFD scale; This required improving and coupling CFD to system codes

or improving system codes and system codes coupled with fuel thermo-mechanics codes.

Furthermore, methods of uncertainty and sensitivity analysis applied to system codes must be improved, and in this framework, a special focus was put on the issue of the quantification of the uncertainties of the closure laws. This work was based on a benchmarking of the possible methods using reflooding experimental data (FEBA and PERICLES).

**PTS:** The objectives were to progress in the simulation of PTS scenarios by improving CFD modelling with analysis of new experimental data (including TOPFLOW steam-water tests and KAERI CCSF test). In this context, 2-phase PTS phenomenology was clearly identified and addressed in the modelling; In addition, sensitivity and uncertainty methods were applied to CFD codes and synthesis on validation and uncertainty of CFD application to reactor issues was done.

**BWR:** The objectives were to progress in the simulation of two-phase thermal-hydraulics issues in BWR. This includes Dry-out prediction, transient core thermal-hydraulics and steam injection in pressure suppression pool. CFD codes, and sub-channel codes were used, improved and validated during the project. Pertinent phenomena leading to dry-out were better identified at CFD scale. Effects controlling condensation regimes in pressure suppression pool were analyzed.

#### 6.4 Sub-project 4 (software platform)

The NURESIM platform is a set of codes at the state of the art, connected to the SALOME software which gives generic capabilities for pre and post processing, supervision and coupling (figure 2). The objective of this sub-project was to provide a support to developers for integration of the codes into the SALOME software and to produce and manage the successive versions of the NURESIM platform on a dedicated repository.

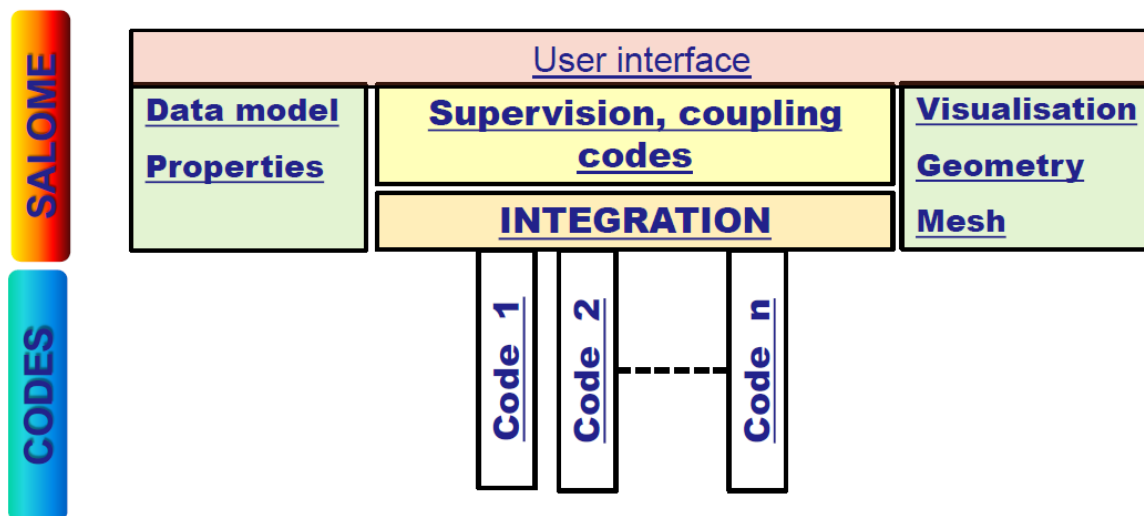


Figure 2 – Architecture of the NURESIM platform

## **7) The NURESIM software platform**

### 7.1 Overview of the platform

The NURESIM software platform comprises predictive computer tools based on state-of-the-art physical models and numerical methods, supplemented by uncertainty quantification and validation against experimental data. This platform currently hosts a new generation of experimentally validated "best estimate" simulation tools. It provides an accurate representation of the physical phenomena by promoting and incorporating the latest advances in reactor and core physics, two-phase thermal-hydraulics. It has also features enabling easy coupling of some different codes through the use of a common data structure and generic functions as well as pre-processing and post-processing functions that make the codes more user-friendly. These features are provided by the SALOME open-source software

The NURESIM platform currently includes (figure 3):

- One neutronics deterministic spectral code for cross-section generation,
- One neutronics and radiation propagation Monte-Carlo code,
- Three complementary core kinetics codes,
- Three complementary thermal-hydraulics sub-channel codes,
- Two complementary thermal-hydraulics system codes,
- Three complementary CFD codes,
- One Sensitivity and uncertainty quantification software (URANIE),
- Two fuel thermo-mechanics codes.

Neutronics simulation can be performed for 2D lattices, 2D and 3D core configurations for light water reactors at nodal scale or pin-by-pin. The NURESIM core simulators are connected to a cross-sections generator that provides specific cross-sections for the core and transient considered.

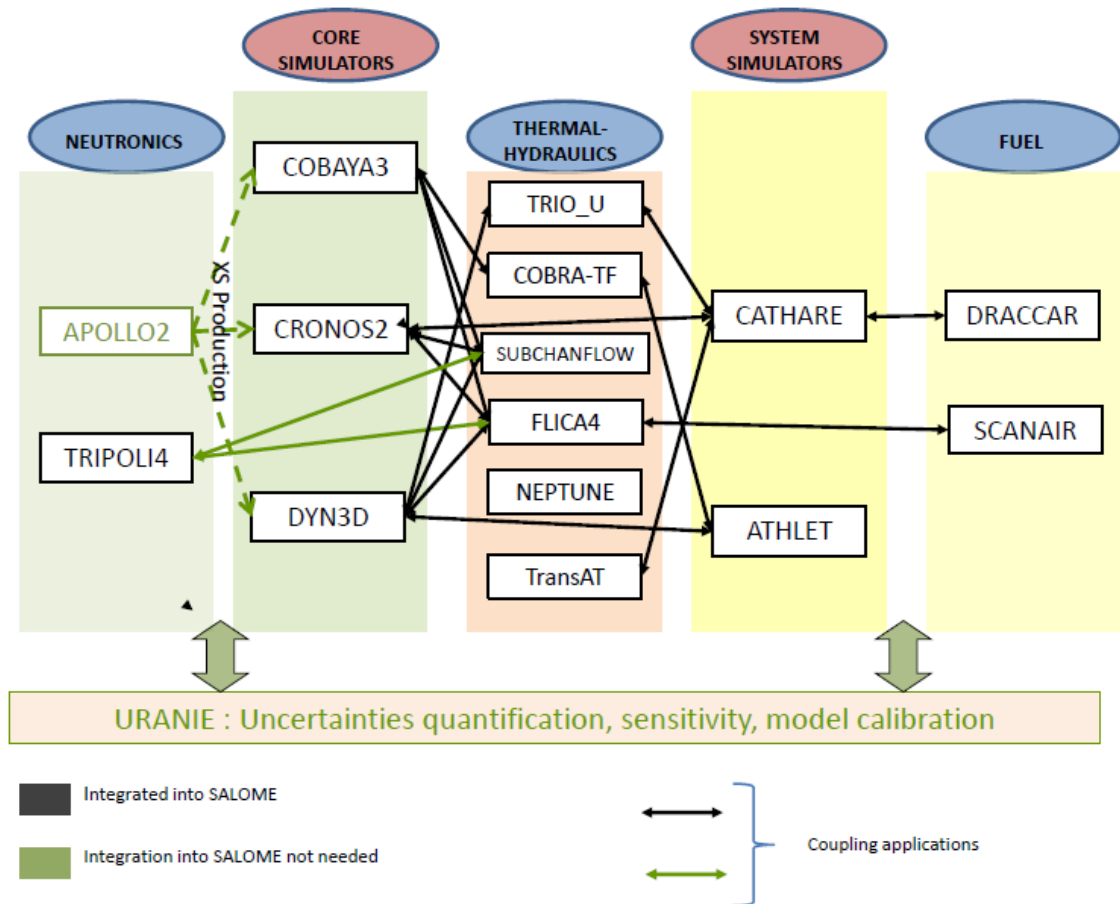


Figure 3- The NURESIM platform, at the end of the NURESAFE project (January 2016)

## 7.2 The SALOME framework

The NURESIM platform is based upon the SALOME. It is an open-source project, (<http://salome-platform.org>), which implements the interoperability between a CAD modeler, meshing algorithms, visualization modules and computing codes and solvers. It mutualizes a pool of generic and user-friendly tools for pre-processing, post-processing and code coupling. SALOME facilitates coupling between codes in a heterogeneous environment and promote the use of software standards. Therefore SALOME Contributes to reduce the costs and facilitates sharing models and software.

The SALOME supervision module (YACS, figure 4) provides functionalities for code integration, dynamic loading and execution of components on remote distributed computing systems, and supervision of the calculation.



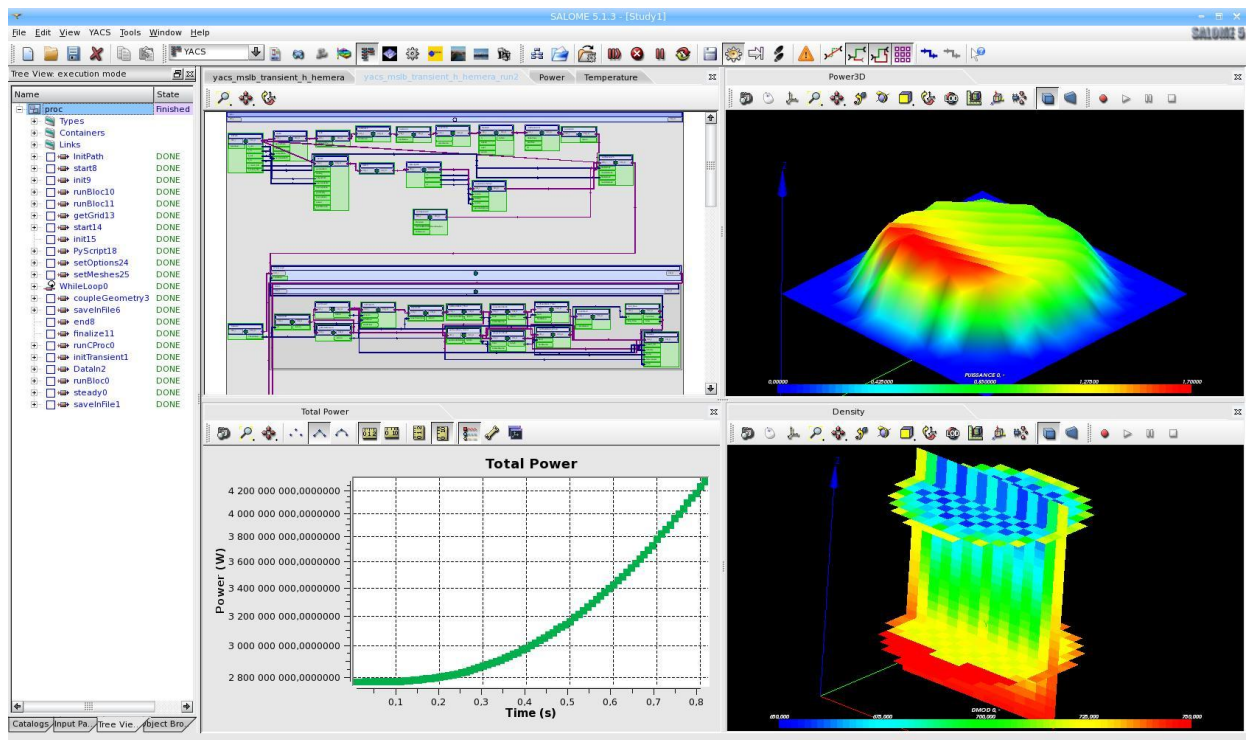


Figure 4 - The YACS user interface

The computing codes are wrapped into a C++ class which provides a coupling interface, and afterward they are integrated in SALOME platform as CORBA components (the CORBA layer being automatically generated by the platform integration module). This integration technique has the advantage of not requiring an access to the source of the coupled codes. Also it provides an explicit interface to the codes, which enables the coupling in an external coupling scheme, in our case a python script or a graph. This scheme is not implicit and embedded inside the source of the codes being coupled, thus it is clearer, and the debugging is much easier.

The data exchange is facilitated by the adoption of a common format for numerical meshes and fields (the MED library, an open standard provided by SALOME platform). This feature is of high importance as it is the basic support for all the coupling schemes that can be implemented between different codes once they are integrated as SALOME components. The MED library also provides a complete set of interpolation algorithms, which has proven to be very useful when codes rely on different meshes.

### 7.3 The URANIE toolbox for uncertainty analysis and code calibration

Of particular importance to all simulation areas is the development of a capacity to:

- quantify the uncertainty in the evaluations,
- perform sensitivity studies
- calibrate parameters of physical models.

These tasks were an important part of NURES SAFE work-program. URANIE is an open-source software based on the CERN ROOT toolbox.

URANIE includes also:

- the capability to a build surrogate models of codes
- a simple mechanism for interfacing codes and perform studies
- a C++/python interface to facilitate the implementation of new algorithms developed by different laboratories
- HPC capabilities

### **8) Prospects**

The NURESIM platform provides a simulation capacity of light water reactor design basis accidents. Compared to methods used by industry, the platform offers higher fidelity physics and coupling functionalities. This results in a better knowledge of conservatisms and margins. The scope of NURESIM is not limited to the Situation Targets analyzed within the project but it covers the range of design basis accidents and it will be able to quantitatively assess several safety relevant features like for instance:

- Boiling crisis,
- Negative or positive void coefficient,
- Maximum power of a fuel rod or pellet,
- Low flow in some reactor channels,
- Absorber rods effectiveness,
- Reactivity injection accident
- ...

In addition, the more accurate tools delivered by NURES SAFE will help optimization of the new reactor designs while supporting compliance with safety related criteria and the platform has now a larger scope covering innovative design features like, for instance, highly heterogeneous cores or passive safety systems.

The NURES SAFE partners (TSOs, industry, research institutes or universities) had the opportunity, within the project, to use directly the NURESIM platform, either directly or through the work made by other partners. Thus, they were able to compare their own codes and methods to those of the NURESIM platform. These actions resulted in a better knowledge of the strengths and weaknesses of the various industrial codes in use in different organizations. The advanced models and methods developed within the NURESIM roadmap are and will be available in the future for all partners which can pick-up and re-use them in their own codes. In this way, progresses made in the framework of the project can spread easily in a larger framework and it will reinforce the reliability of simulation tools used by the European Nuclear Industry.

The NURESIM platform became the tool to realize, share, compare and judge the latest advances in methods, models and codes. It will encourage collaborative work on methods beyond the state-of-the-art. As an important effort of integration of software into the SALOME platform was made during the project, most of the NURESIM software use standardized tools for pre and post-processing, and coupling capacities so that the generic tools can be mutualized and the interoperability and comparison between codes becomes easier. In this way, both regulators and industry will have from now the possibility to benefit from all the generic platform features, even if they use

different software. Thus this standardized environment offered by the platform and the interoperability of codes facilitates the development of this collaborative work.

Further to the NURES SAFE project, the platform will continue to break down the barriers between disciplines and federate a team of top international level experts coming from many European countries and institutions. So, the NURESIM platform will have a catalytic effect to structure teams which, on a national scale, would remain below critical mass. Their collaborative work will increase the leadership of European science for nuclear reactor simulation.

The NURES SAFE consortium will be a vector to share common views, methods and tools for numerical simulation of nuclear reactors within Europe. This will result in strengthening nuclear safety in these countries.

### **9) Acknowledgements**

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