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PROJECT FINAL REPORT

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1 Final publishable summary report

1.1 Executive summary

For some years, there is a worldwide trend to move towards “higher-fidelity” simulation techniques in reactor analysis. One of the main objectives of the research in this area is 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-physic simulation scheme. In this context, the objective of NURESAFE was to deliver to European stakeholders a reliable up to date software capacity usable for safety analysis needs 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 based on the NURESIM (Nuclear Reactor SIMulation) European reference simulation platform (Figure 1).

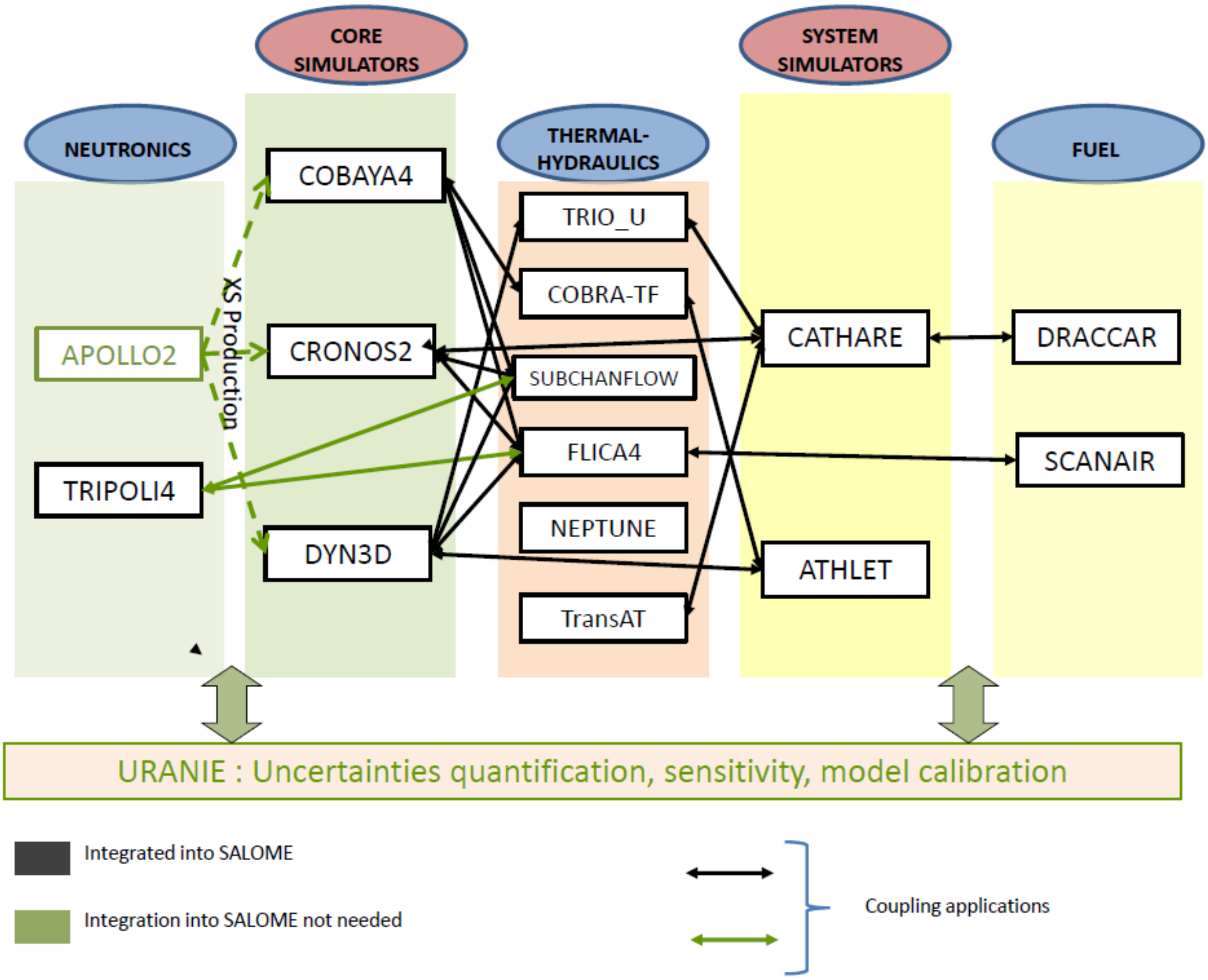

Figure 1- The NURESIM platform, at the end of the NURESAFE project

This platform includes advanced core physics, two-phase thermal-hydraulics, fuel modelling and multi-scale and multi-physics features together with sensitivity and uncertainty tools. These physics are validated and fully integrated into the platform using the open-source software SALOME, in order to provide a standardized state-of-the-art code system to support safety analysis of current and evolving LWRs.

The objective of the NURESAFE project was achieved through 4 scientific sub-projects presented hereafter:

1) Multiphysics applications involving core physics
2) Multiscale analysis of core thermo-hydraulics
3) Multiscale and multi-physics applications
4) Software platform

1.2 Description of project objectives

1.2.1 Objectives of 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, thermohydraulics and fuel thermo-mechanics.
Individual models, solvers, codes and coupled applications, were run and validated through modelling "situation targets" corresponding to nuclear reactor situations and including reference calculations, experiments, and plant data. As safety analysis was the main issue within the project, all these situation targets consisted in some accidental scenarios. The challenging selected "situation targets" have been selected according to the required coupling between two different disciplines. Industry-like applications were released at the end of the project:

- Square lattice PWR main steam line break (MSLB),
- One selected BWR anticipated transient without scram (ATWS),
- 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 ATWS analysis framework featuring coupled simulations combined:

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

1.2.2 Objectives of Sub-project 2 (Multiscale analysis of core thermo-hydraulics)

The objective of this SP 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.

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 analysed.
The novel models and simulation techniques are implemented, validated and applied in the context of the last work-package.

Within this Sub-project 2, new versions of the CFD platform codes NEPTUNE_CFD, TransAT and TRIO_U have been delivered to end-users, including most advanced numerical simulation features and the associated modelling approaches for the physics pertinent to both PWR and BWR.

1.2.3 Objectives of Sub-project 3 (multiscale and multiphysics applications of Thermal-hydraulics)

The objectives of the SP3 were to develop multi-scale and multiphysics simulations of LOCAs, PTS and BWR thermohydraulics 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.

The WP 3.1 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. 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). Then a synthesis on PTS investigations showed the status with respect to the objective of simulating PTS with 2-phase CFD. In addition, sensitivity and uncertainty methods must be applied to CFD codes and a state of the art on validation uncertainty and uncertainty of CFD application to reactor issues was done.

BWR

The objectives were to progress in the simulation of two-phase thermohydraulics issues in BWR. This includes Dry-out prediction, transient core thermohydraulics and steam injection in pressure suppression pool. CFD codes, and sub-channel codes were used, improved and validated during the project.

1.2.4 Objectives of Sub-project 4 (software platform)

The NURESIM platform is based upon the software simulation platform SALOME. SALOME is an open-source project, (http://salome-platform.org), which implements the interoperability between a CAD modeller, meshing algorithms, visualisation modules and computing codes and solvers. It mutualises a pool of generic tools for pre-processing, post-processing and code coupling. Its supervision module (YACS, Figure 2) provides functionalities for code integration, dynamic loading and execution of components on remote distributed computing systems, and supervision of the calculation.

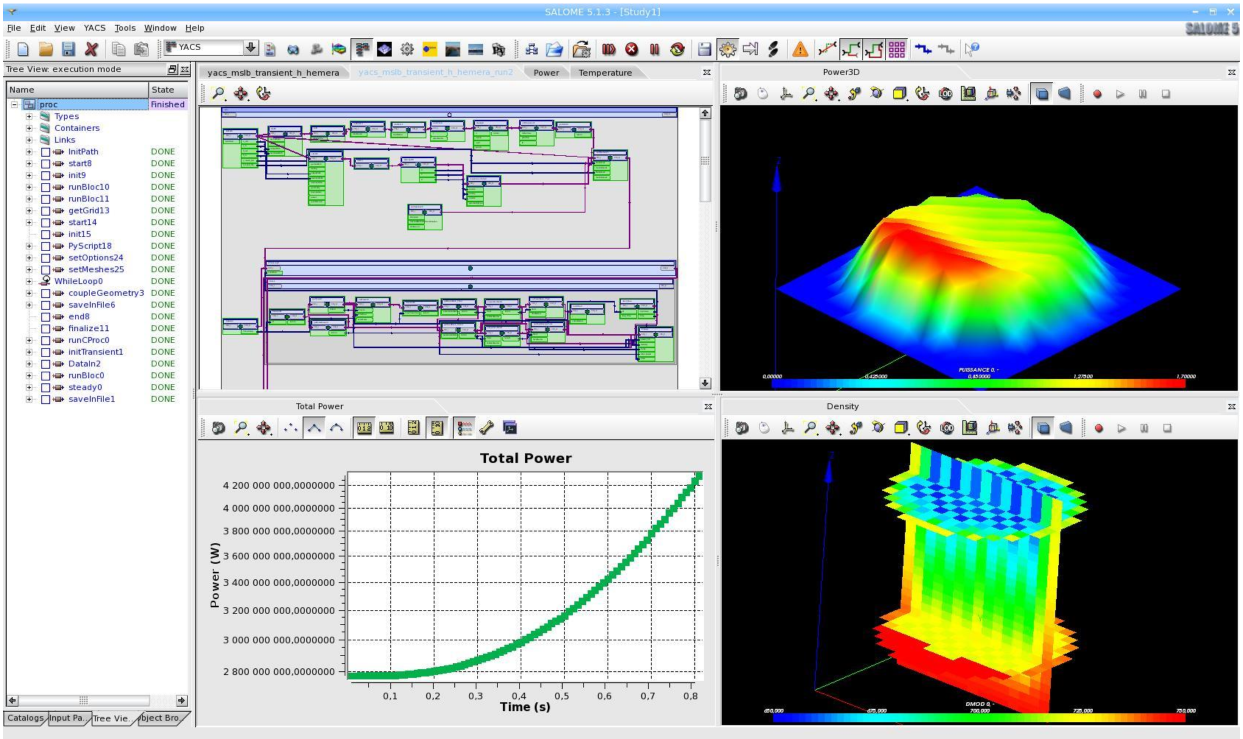

Figure 2 - The YACS user interface

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.

1.3 Main S&T results/foregrounds

1.3.1 Multiphysics applications involving core physics (SP1)

The SP1 aimed at developing transient simulations for light water reactors (PWR including VVER, and BWR) at the cutting edge using the multi-physics coupling capabilities of the NURESIM platform, supplemented by uncertainty evaluation for thermal hydraulics and thermomechanical parameters.
To meet these requirements, the emphasis was put on the development and validation of integrated coupling interfaces between:

- System thermal-hydraulics,
- 3D neutronics, at pin-by-pin level,
- Detailed simulation of mixing phenomena in the reactor pressure vessel, including core region,
- Thermo-mechanic evaluation of fuel safety parameters.
- Uncertainty evaluation.

The work in this subproject was divided into four work packages. The first work package dealt with the integration of new codes and updates of couplings in the NURESIM platform. The other three work packages were dedicated to the three situation targets: main steam line break analysis in a PWR (WP12), ATWS transient in a BWR (WP13) and main steam line break analysis for a VVER reactor (WP14).

1.3.1.1 Testbed for integrated coupling and UQ methods (WP11)

In the context of moving to higher-fidelity simulation of LWR reactors, there is a strong motivation to couple well established and validated (legacy-) codes covering different domains of the reactor analysis: Core-thermal-hydraulics codes coupled with transient core-dynamic codes with the aim of benefiting from advanced thermal-hydraulic modelling. Such R&D effort is frequently labelled multi-physics coupling, e.g. in the case of coupling neutronics and thermal-hydraulics codes, but also multi-scale coupling is of interest, e.g. coupling of different thermal-hydraulic scales in the case of CFD coupled to system transient codes. This allows for detailed TH-analysis where necessary and still considering the response to the whole reactor system.
This general development was taken up in the NURESIM and NURISP projects, where several core dynamics codes have been coupled with a core-thermal-hydraulics code that also offers sub-channel capability, using the SALOME coupling software.
In the NURESAFE project the emphasis has been on the development and validation of integrated coupling interfaces between: System thermal-hydraulics, 3D neutronics at the pin-by-pin level with detailed simulation of mixing phenomena in the reactor pressure vessel, including core region, the thermo-mechanic evaluation of fuel safety parameters, and supplemented by Uncertainty evaluation.
The concrete outcome of the WP1.1 sub-project has been the SCANAIR fuel thermo-mechanics code integrated in the NURESIM platform, and to develop and test the new coupling interfaces between codes COBAYA4, FLICA, CTF, DYN3D, CRONOS, ATHLET, TRIO_U and DRACCAR, that have been integrated in a SALOME-based platform, supplemented with the coupling of the ATHLET thermal-hydraulic code with the module BESTEST within URANIE for Uncertainty estimations.
The new integrated tools has been tested using small scale problems, using the High-Performance-Computation capabilities of the SALOME platform in order to allow for the use of large computation clusters for LWR analysis.
The development effort on SALOME (for version 6 and 7) was focused at the support of parallelism to take advantage of the increasing available computer power: parallel visualisation with the

integration of Paraview, enhanced functionalities to access HPC resources, new parallel mesh and field structures, the improvement of hexahedral mesh generation, new integration tools.
Then the NURESIM platform followed this move: all the components adopted the new parallel mesh and field structures. The code interfaces were extended to support the coupling to a thermal mechanic component. The definition of common data models within applications promoted to facilitate the uncertainties propagation.
This task in particular coordinated the integration of all the codes, and coupling tools made by the different partners and in coordination with the integration subproject SP4.

As a result of this task, **the codes licensed among the partners are:**

	Licensor	**Licensee**
COBAYA4	UPM	KIT
COBAYA4	UPM	INRNE
FLICA4	CEA	UPM
FLICA4	CEA	KIT
CRONOS	CEA	KIT
COBRA-TF	PSU	KIT
COBRA-TF	PSU	UPM
COBRA-TF	PSU	KTH
COBRA-TF	PSU	GRS
APOLLO2.8	CEA	UPM
DYN3D	HZDR	IRSN
DYN3D	HZDR	KTH
DYN3D	HZDR	KIT
DYN3D	HZDR	GRS
DYN3D	HZDR	UJV

And the Coupled codes outside SALOME (OS), and integrated inside SALOME5 (S5), or inside SALOME6 (S6) are:

NURESAFE Coupled Codes

	TH-Core	TH-Core	TH-Core	Plant System	THM-Core	THM-Core	NK-Core	NK-Core	NK-Core	TH-Vessel	Plant System	TH-Plant
	FLICA	COBRA-TF	SCF	CATHARE	SCANAIR	DRACCAR	CRONOS	DYN3D	COBAYA	TRIO_U	ATHLET	TRANSAT
TRANSAT				S6								
ATHLET		S6						OS, S6				
TRIO_U		S6		S5, S6			OS, S6					
COBAYA	S5	OS,S6	OS, S5									
DYN3D	S5, S6	S6	OS, S5, S6									
CRONOS	OS, S5, S6		S6		S6							
DRACCAR												
SCANAIR	S6											
CATHARE	OS											

SCF			
COBRA-TF			

1.3.1.2 Higher order PWR MSLB simulation (WP12)

The main objective of NURESAFE work package 1.2 was to perform best-estimate analyses for the selected situation target of WP12. For this situation target a PWR main steam line break (MSLB) event has been chosen. Simulation schemes have been developed and executed towards higher-fidelity simulations of this MSLB transient for improved predictions of the key safety parameters. A two-step approach was applied. In the first step, reference results for the situation target were produced using the platform codes with higher resolutions of coupling between core nodal and sub-channel scale. In the second step, CFD evaluations have been included into the solution. In that way, an improvement in the prediction of the target safety parameters could be achieved. In order to increase the confidence into the CFD results, a validation was performed by comparing the calculation results with experimental data from HZDR test facility on coolant mixing ROCOM.

In the first step, the MSLB scenario specification was created. For the benchmark a 4-loop PWR at the end of the fuel cycle had to be simulated. Based on the specification, input data sets for the NURESIM platform codes were created. As far as two system codes are part of the platform (ATHLET and CATHARE), input data sets for both codes had to be developed. This was done using available input sets for the ZION PWR reactor. Input data sets for the thermal hydraulics of the core (for the FLICA4 code) and the corresponding neutron kinetic codes (DYN3D, COBAYA4, CRONOS2) have been developed completely from scratch.

The nodal cross section libraries have been created in close co-operation between IRSN and UPM on basis of the specification. For the creation of the cross section libraries new methods of grid point selection have been developed. Nevertheless the huge amount of about 16.000 h of CPU time was spent for the creation of the nodal libraries. For the verification of the libraries, extensive comparison calculations have been carried out by all three neutron kinetic platform codes CRONOS2, DYN3D and COBAYA4. They confirmed a very good agreement between all three codes for the hot zero power state before the transient.

System codes are a-priori not able to treat 3D coolant mixing effects inside the reactor pressure vessel in a right manner. In order to obtain adequate input data to conduct a realistic main steam line break analysis, measurement data from the 1:5 scaled coolant mixing test facility ROCOM were used for the creation of mixing matrices for inclusion into the interface between system code and core model. In addition the data were used to validate the CFD code TRIO_U for coolant mixing scenarios.

The following table gives an overview on the different calculations schemes applied for the reference case calculations on the MSLB scenario.

	HZDR	**GRS**	**IRSN**	**UJV**	**UPM**	**PSI**
System	ATHLET	ATHLET	CATHARE	ATHLET	Time dep. b.c.	TRACE
Core-TH	FLOCAL/ FLICA/ TRIO_U[1]	ATHLET/CTF	FLICA	FLOCAL	CTF	CTF
Core-NK	DYN3D	DYN3D	CRONOS2	DYN3D	COBAYA3	SIMULATE

All participants in the benchmark used the NURESAFE MSLB cross-section (XS) library created by IRSN/UPM. Six different solutions using different combinations of NURESIM platform codes and external codes were provided for the benchmark. The quantitative comparison of the results is dominated by the differences created on the secondary side during the depressurisation. The source of these differences comes mainly from the application of different models for the two-phase leak flow available in the different system codes. The use of two different thermal hydraulic system codes influences the results much more than expected when the benchmark was created.
In a second phase so called advanced calculations had to be performed. Here the possibilities of the platform new developed during the project time have been used. One of these new achievements was the coupling of the reactor dynamics code DYN3D and the CFD code TRIO_U. Especially by help of this coupling and the application to the main steam line break scenario the advanced capabilities of the platform and the integrated codes could be demonstrated.
The obtained results confirmed that the NURESIM platform is applicable for challenging coupled transient in PWR. Furthermore, by accomplishing the above mentioned coupling of a reactor dynamics code and a CFD code the superiority of the NURESIM platform was demonstrated. The conducted advanced calculations demonstrated the excellent status and the readiness for industrial applications of the NURESIM platform and the integrated codes.

1.3.1.3 BWR ATWS with uncertainty quantification (WP13)

The objective of WP 1.3 was to develop and execute simulation schemes using the NURESAFE codes to analyse a BWR ATWS transient coupled with Uncertainty Quantification (UQ).
The available simulation tools for WP1.3 include:

- Plant-system and RPV scale: ATHLET
- Core thermal-hydraulics: ATHLET, COBRA-TF
- Core physics: DYN3D
- UQ tools: BESTEST/URANIE

In addition the TRACE-PARCS coupled code system is available at KTH and provides an independent solution to benchmark the other two performed on the NURESIM platform.
In order to develop the input model for each code, an accurate description of the BWR system and core characteristics was needed. The requirements for the selection of the BWR system are:

- Data available to all WP participants
- Data quality compatible with ATWS simulations

The WP participants selected the OECD NEA Boiling Water Reactor (BWR) Turbine Trip (TT) Benchmark for the simulation and evaluation of the BWR ATWS. The term 'ATWS' covers a broad range of transients. The selection of the transient has a strong influence on the sequence of event and thus on the systems involved, the range of variations of the feedback parameters, etc… Therefore, the transient chosen by the four participants is the Turbine Trip (TT) without SCRAM. The ATWS case was also part of the OECD NEA Benchmark (Extreme Scenario #2).

During the first phase of the project the different inputs for all codes were developed and tested:

- The ATHLET model described the whole system which is composed of a 33-channel core with bypass, an upper and a lower plenum, a recirculation loop with pumps, a downcomer, an ideal separator and the steam domes as well as a steam line.
- The CTF model of the Peach Bottom 2 reactor core contains 764 fuel bundles. The fuel bundles are of three different TH types. The core is divided into three radial zones with different inlet

orifices. The model is coupled to the ATHLET power plant model and receives the inlet mass-flows, inlet temperature as well as core outlet pressure, from the 33 channel model of ATHLET described above.

- In the DYN3D model, 19 assembly types are defined where assembly type #19 is the radial reflector The cross-section libraries are the one delivered in the scope of the OECD/NEA Benchmark. In these libraries, the burnup and the historical parameters are implicitly included in the macroscopic cross-section.

These inputs were used in two coupled models. In the first, the ATHLET model covered the whole BWR system with boundary conditions for the steam line pressure and the feed-water mass-flow/temperature. ATHLET was coupled to DYN3D inside the core using the so-called internal coupling approach. In the second, the ATHLET model was the same, including the core model. The CTF model covers only the core and is coupled (one-way coupling) with ATHLET at core inlet/outlet. This approach is known as parallel coupling. The DYN3D model was coupled to both ATHLET and CTF models but receives the TH feedbacks only from CTF.
The Turbine Trip transient without SCRAM was simulated with 3 different coupled code systems: ATHLET-DYN3D, ATHLET-CTF-DYN3D and TRACE-PARCS. The results obtained with these code systems agree well qualitatively. However, a large dispersion is observed when comparing the maximum power, which is the limiting parameter. These deviations were expected and the uncertainty analysis performed in this Work Package Task shown that the uncertainty bands covered the best-estimate results of all three coupled code systems. The measured power peak value also lies within the standard deviation range.
In addition, a sensitivity analysis was performed and identified the most important uncertain parameters for each output parameter. The results of the sensitivity analysis confirmed the expected behaviour. Nevertheless, the TRACE-PARCS uncertainty analysis uncovered some internal TRACE issues during the study of some sensitivity parameters (especially concerning the gas gap conductance). This shows how Uncertainty/Sensitivity analysis can help identify weaknesses in the simulation codes and improve them.
These results confirmed that the NURESIM platform is applicable for challenging coupled transient in BWR. Furthermore, it showed the compatibility of the NURESIM simulation tools with the URANIE platform for uncertainty and sensitivity analysis.

1.3.1.4 Higher resolution VVER MSLB (WP14)

The situation target of this work package was a VVER MSLB accident from hot full power. The MSLB benchmark consisted of a RPV TH boundary condition (BC) problem, a full-core N/TH BC problem and BC problems for core sub-sets, and was derived from the OECD VVER Coolant Transient benchmark (V1000CT-2).

The main objective was to develop and execute improved calculation schemes iterating towards higher-resolution simulation of VVER MSLB transients. A specific objective was to evaluate the benefits of new developments in the platform codes.

The main developments included:

- CFD and dynamically coupled CFD/system code calculation of the coolant mixing in the RPV
- Loosely coupled TRIO_U/FLICA calculation of the lower vessel and core thermal hydraulics
- New code versions (COBAYA4-MG, DYN3G-MG) and new couplings in the nodal core simulators

- (DYN3D-2G/COBRA-TF (CTF), COBAYA4-MG/COBRA-TF)
- Advanced multi-parameter cross-section libraries at the nodal and pin level
- DYN3D nodal/pin-power reconstruction simulation of a mini-core
- Coupled pin-by-pin COBAYA4/CTF calculation of a fuel assembly

Higher-resolution RPV flow mixing simulation
For validation of the RPV TH models, plant data from the Kozloduy-6 VVER-1000 vessel mixing experiment were used.
The initial set of core BCs for core N/TH modelling was obtained from a CATHARE2 24-sector RPV calculation. For higher-resolution, computationally efficient TRIO_U and FLUENT models using k-epsilon turbulence model and relatively coarse mesh were validated vs. Kozloduy-6 plant data and FLUENT was used to produce transient CFD computed core inlet BCs which replaced the CATHARE computed ones in the latest core N/TH calculation.
TRIO_U was dynamically coupled to CATHARE2 and the coupling was validated.
In all cases, the flow mixing results showed an improvement of the resolution.

Refined nodal core simulation
For testing of the core N/TH at the nodal level, results from validated standalone and coupled N/TH models were compared code-to-code.
An advanced MSLB nodal XS library was generated by INRNE/UPM using an innovative calculation scheme in APOLLO2 with the higher-order Linear Surface MOC and optimised parameter grid such that the error in k-eff is below 120 pcm over the whole parameter range. Two options were released - compact and extended. The compact XS library with up-scattering correction and implicitly included interface discontinuity factors (IDF) was used for 2G solvers, and the extended one with full scattering XS matrix, explicit IDF and TH feedback dependent kinetic parameters was used with MG solvers.
The library was verified in coupled N/TH calculations at 92% hot power vs. plant data from Kozloduy-6. The biases are well within the uncertainty band of the Core Monitoring System.

New code versions (COBAYA4) and new N/TH couplings (DYN3D-2G/CTF and COBAYA4-MG/CTF) with the CTF 9-equation code were developed and executed in MSLB transient simulations. COBAYA4 and CTF are capable of node subdivision and have the potential for parallelisation of the solvers. The results were compared to each other and to COBAYA/FLICA and COBAYA/COBRA3 simulations. The impact of node subdivision in neutronics and TH was evaluated. The code-to-code comparison in steady state and transient showed a good overall agreement, with some variations in the peaking factors depending on the node sub-division and the flow mixing models.

PPR and pin-by-pin simulation of core subsets
For evaluations at the pin level, two approaches were considered: nodal/PPR calculation and direct pin-cell calculations.
A pin-by-pin multi-parameter MSLB library of transport-corrected diffusion cross-sections and kinetic parameters for a mini-core was generated with APOLLO2 and verified in calculations vs. transport reference solutions. A compatible nodal multi-parameter XS library was produced for nodal/PPR mini-core calculations, supplemented by a multi-parameter library of APOLLO2 computed pin-by-pin power shapes for PPR.

A suite of MSLB-related BC problems for core subsets was defined and solved in a step-by-step testing procedure as listed below:

- DYN3D/FLOCAL nodal/PPR solutions for a 7-assembly mini-core vs. TRIPOLI4 and COBAYA4 pin-by-pin and node-average (nodal) solutions. The results at HZP showed an absolute mean value of pin-power deviations in locations of all pins of about 4% for the central UOX-CR assembly, and a max error of 14% at the assembly corners.

- COBAYA4 pin-by-pin solutions for a fuel assembly and 7-assemly color set vs. transport ref solutions at HZP. The colour set results show a very good agreement when using side-dependent IDF, with max pin power deviations of 1% for UOX-GT and 1.7% for UOX-CR assemblies.
- CTF sub-channel transient solutions of the VVER MSLB Hot assembly TH BC problem, as well as steady-state solutions for a 7-assembly mini-core and a full-core. Comparisons vs. FLICA4 and SUBCHANFLOW for the hot assembly TH BC problem showed a good agreement; with some differences in the predicted vapour volume fraction depending on the sub-cooled boiling and flow mixing models.
- Coupled COBAYA4/CTF pin-by-pin/sub-channel solution for a fuel assembly with reflection BC at the lateral boundary (a step towards two-level nodal/pbp simulation). Initial comparisons of assembly averaged results vs. COBAYA4/CTF and COBAYA3/Simula nodal results showed a good agreement. A comparison vs. MCNP/CTF ref pin-by-pin solution is still ongoing.

Provisions for a full-core nodal/PPR simulation of the VVER MSLB benchmark have been made by producing a full-core multi-parameter PPR pin-by-pin power shape library.

Conclusions and recommendations

- New developments towards higher-resolution simulation of RIA in VVER have been implemented and evaluated
- The CFD and CFD/plant system code calculations for VVER RPV thermal hydraulics are now closer to the industrial applications
- The hexagonal geometry versions of the NURESIM 3D core codes COBAYA4 and DYN3D at the nodal level and their new couplings to the CTF 9-equation TH code reach maturity for industrial applications
- In the near future, the DYN3D nodal/PPR technique tested for mini-cores could be readily applied for full-core nodal MSLB simulation with PPR for the hot assembly, using the provided full-core nodal XS library and full-core PPR pin-by-pin form-function library
- The tested coupled pin-by-pin COBAYA4/ CTF calculations needed to be extended either to
  - two-level nodal calculation of the core and pin-by-pin of the hot assembly, with appropriately computed lateral BCs, or
  - full-core pin-by-pin calculation which requires an extension of the COBAYA IDF allocation algorithm to the full-core domain, and parallelisation of the solvers

1.3.2 Multiscale analysis of core thermal-hydraulics from DNS to sub-channel modeling (SP2)

The objectives of this SP is to advance the fundamental knowledge and develop new models based on detailed DNS simulation for momentum exchange and boiling heat transfer issues present in thermal hydraulics of Light-Water Reactors (LWRs). A first WP has been tailored to extend the existing computational multiphase flow strategies to cope with a wider range of practical application. The novel models and simulation techniques are implemented, validated and applied in the context of the last WP.

1.3.2.1 ITM coupling with phase-average models (WP2.1)

Multiphase flows involves a hierarchy of length scales intricately combined into interfaces and dispersed entities interacting with turbulence. The issue here is that there is no unified approach capable to treat the various topologies at once on the same grid: the mainstream uses one single strategy everywhere, which necessarily reduces the predictive performance of the model.

We aimed here at developing a unified approach while treating each sub-portion of the flow individually using massively resolved grids (DNS) to feed the model with the pertinent physics (phase transition/inversion criteria) that cannot be quantified using today's experimental technology. A new All Flow regime Model (ARM) was developed and implemented in the TransAT computer code by ASCOMP and JSI, and a model was implemented and used within the NEPTUNE_CDF code by CEA/EDF. Both models use Interface Tracking Models within the mixture phase-averaged models. In other words, they combine the two computational approaches most suitable for topologies of flows which exhibit large interfaces as well as dispersed flow features (small bubbles or droplets). The Interface Tracking (ITM) is suitable for simulating flows with interfaces and mixture phase-averaged strategies are more suitable for simulating dispersed flows.

The ARM model was developed from an ITM called level set, which tracks a signed distance from the nearest surface. Onto this a mixture model was implemented, which treats all bubbles or droplets that are too small to reliably capture with ITM, as a mixture of two phases or fluids. Because the ARM model is new and somewhat different from similar models it was tested on some numerical and physical test cases: 1D advancing front, breaking droplet, impinging water jet, and rising bubble.

The results obtained in these test cases were assessed as adequate to continue development and to apply the model to three experimental set-ups:

- Impinging jet experiment, where water is injected down along the vertical axis into stagnant pool from various heights and with various jet velocities;
- Szalinski experiment represents a case where large air bubbles are injected into a tall vertical pipe filled with liquid water from the bottom;
- Castillejos experiment: air is injected into the liquid at the bottom of a large pool.

ARM model was applied in 2D geometry in all three cases. A known limitation of the current version of the ARM model is a lack of a model, which would allow formation of the large interface that could be tracked with level-set, from a finely dispersed mixture with no recognisable large interface. Thus, the initial conditions and boundary in each of these cases were modified in order to introduce the large interfaces for the level-set model at the boundary of the computational domain. ARM model was recognised as a tool that is capable to simulate flows where mixtures of dispersed and separated flows exist in the same computational domain. It gave a relatively successful prediction of the impinging jet experiments, except for the highest jet velocities. This might be because of missing implementation of coalescence which causes a change in the properties of the liquid that was being penetrated. The model was also reasonably successful in simulations of the Castillejos experiment; however, it gave rather poor predictions of the slug flow in the long thin pipe of Szalinski.

Although the ARM model together with the implementation turned out to be harder to develop than was expected when initially proposed, it holds great potential and a powerful way to describe the configuration of phases. The overall experience with the use of the coupled model in the TransAT code was that the model has not yet reached the full maturity and cannot be blindly used to simulate complicated two-phase flows. Nevertheless, for certain types of flows it can deliver improved results compared to the pure level set or pure phase averaged models. Note that ARM was extended lately by the introduction of a subgrid scale mass transfer model for the ITM part in flow situations exhibiting strong fragmentation into bubbles due to shear.

More mature coupling model was developed and used by CEA/EDF. They proposed the Hybrid Multi-field Approach for flow regime transitions. The dispersed field is modelled through the Euler-Euler two-fluid model and the interface of the continuous gas field is located with a tracking method, extending a level-set method to the two-fluid Eulerian formalism. The two-phase flow was modelled by Eulerian approach and the gas phase was split into two fields. The small bubbles, assumed to be spherical, were modelled with a dispersed approach whereas the larger bubbles, considered as too distorted to be accurately described by correlations, were simulated through an interface locating method. As a first step towards this new approach, the general concept was simplified by considering the liquid phase as continuous. This approach was generalised to simulate free surfaces (large bubbles considered as continuous gas phase degenerate into large interfaces) and heat and mass transfer. Successful simulations with this model are discussed in the deliverables.

1.3.2.2 DNS and LES of pool and convective boiling (WP2.2)

As the first stage of this WP, CFD simulation methods based on Interface Tracking Method (ITM) were developed for three boiling conditions: pool boiling, convective boiling in channel flow (PWR condition) and convective boiling in annular regime (BWR condition). The second stage was development of upscale model based on the computed results using the method developed in the first stage. As we expected from the beginning of this project, the development of boiling simulation method based on ITM (i.e. the first stage) was definitively challenging task, because the numerical method for phase change had not been well established yet, especially boiling on the heat transfer surface (i.e. at triple line, where the liquid, vapour and solid phases come into contact). In addition, the simulations using interface tracking method required tremendous computational resources, for which supercomputer at Swiss National Supercomputing Centre (CSCS) was used. In the second stage, we faced furthermore difficulties since the database computed with ITM was not fully sufficient. However, we finally achieved these tasks owing to the effort of each research group and the collaboration between the groups. The summary of each task is described below.
A simulation method for pool boiling was developed by ASCOMP and ICL and it was implemented in TransAT. The mass transfer was computed with the Schrage phase change model, and the conjugate heat transfer between solid and fluid phases could been taken into account. In addition, a sub-grid microlayer model was developed. The simulation method was validated against the experiment of nucleate pool boiling carried out at MIT. The computed bubble departure time shows better agreement with the experiment, in case that the sub-grid model for microlayer was employed.
For the simulation of pool boiling simulation, PSI has developed a simulation method employing depletable micro-layer model and a nucleation site model. In this method, the transient phenomena of micro-layer could have beentaken into account, e.g. it depletes when the micro-layer vaporised completely. The conjugate heat transfer was computed accurately. Several validation cases were computed: nucleate boiling from single nucleation site and nucleate boiling from multiple nucleation sites. The boiling regime simulated for multiple nucleation sites was from isolated bubble to vapour mushroom region. In both cases, the bubble growth rate was predicted accurately, and the computed heat-transfer coefficient agreed well with that of the experiment. In addition, a variety of statistical data, such as the heat flux partitioning, the ratio of vapour-to-liquid area over the heat transfer surface, etc. which cannot be measured in the experiments, but can be derived from the results of the simulations.
In the simulation of convective boiling simulation in channel, the main challenge was to properly incorporate the physical models required to correctly capture the phase-change and turbulence mechanisms in an intrinsically coupled manner. ASCOMP developed a Sub-Grid Scale (SGS) model to capture nucleation in flows over heated surfaces implemented in TransAT. The 3D DNS simulation using the SGS was able to automatically nucleate small scale bubbles on the heat transfer surface. The

DNS results showed indeed the nucleation of various bubbles, changing the nature of the flow quite substantially. LES was then performed, and the simulations were capable of nucleating a lot of bubbles interaction with the core flow. The important finding was that bubbles nucleation was observed only in selected hot, low-speed, thermal streaks only.
Since the simulation method of PSI showed good agreement with the experiments, and statistics of the results were obtained for pool boiling from multiple nucleation sites, an upscale model for pool boiling flow was developed as an improvement of wall boiling model (RPI model) by UJV. The improved RPI model shows better agreement with experiment than the original RPI model, which may imply the possibility of RPI model to predict more accurate boiling heat transfer.
The development of Large Leddy Simulation (LES) for boiling flow in annular regime faced difficulty in the reproduce of disturbance waves which take place co-current flow in vertical upward liquid-vapour flow. ICL took strategic approach to understand the mechanisms of disturbance wave by simulating fixed-wave shape flow, and observed the turbulence in the wave carefully. PSI took brute-force approach, simply conducting two-phase boiling flow simulation using LES, and revealed that the vapour velocity field behind the disturbance wave amplify the wave height. Finally, both ICL and PSI concluded that the temperature field underneath the disturbance waves are higher than the other region.
The upscale model for upward boiling flow for BWR condition was developed by ICL and ASCOMP, in which RANS k-ε turbulence model was employed together a phase-averaged multiphase model. The simulation demonstrated that the vapour generated due to the wall boiling and then dispersed along the flow and towards the centre of the pipe.
As summarised above, the tasks defined at the initial stage of this project were achieved, however the boiling simulation using ITM still admited of improvement. Thus it would be appreciated if the development for boiling heat transfer could continue in order to make more accurate and robust numerical model supported by ERC in the future.

1.3.2.3 DNS and LES of bubbly flow (WP2.3)

ASCOMP and CEA performed DNS of the turbulent bubbly flow in a channel, where both turbulence and the bubbles were fully resolved. In contrast to the problem treated by CEA where the bubbles were homogeneously distributed in the channel, in ASCOMP's problem, the bubbles were concentrated near the wall to focus on the impact of the bubbles on the wall layer. The case was chosen by reference to the MIT experiment. A rich data basis was generated for RANS model development and upscaling, both for single and multiphase flow scenarios. An extensive data analysis was conducted in particular by filtering the DNS data to infer mixture variables and balances; a campaign that has never been conducted hitherto. The interactions between the bubbles and the liquid were studied through an in-depth analysis of the turbulence statistics. The near-wall flow was affected by the bubbles, in particular as to the anisotropy of turbulence, energy exchange between the normal stresses. Shear stress was enhanced by about 30% in the wall layer compared to single-phase turbulence. The coherent structures were different in shape than in single-phase flow, featuring less elongated, broken structures. The decay in the energy spectra near the wall was found to be significantly slower (slope of -3) for the bubbly flow than for a single-phase flow (slope of -6). The database generated was of sufficient quality to extract phase-averaged quantities, paving the way for model upscaling for near-wall bubbly flow simulations using the mixture formulation. First upscaling routes and ideas were proposed, in particular as to the impact of the bubble field on the eddy viscosity distribution near the wall.
DNS of bubbly flow in conditions close to reactor core was achieved. A high void fraction of 10% characterises this DNS, beside a strong relative velocity between the liquid and the bubbles resulting from problem setup. As in the former case, here, too, the DNS was validated for single-phase flow data; the same was true for the ITM technique employed. A rich data basis has been generated, separately for gas and liquid phases. The momentum interfacial transfer has been computed by the

evaluation of each term of the momentum equation. The analysis reveals that the momentum transfers between phases are strong and most of the energy was transferred from the liquid momentum to the vapor momentum. In the stream wise direction, the momentum transfer was weaker; the energy received from the liquid was accumulated in the deformation of the interfaces under the form of surface tension, which seemed to play a major role in the redistribution of energy. Full up-scaling process to two-phase RANS CFD model of NEPTUNE_CFD was covered. Some very common hypotheses such as the negligible effects of surface tension on the mean flow properties or the wall lubrication formulation were challenged and our work suggests they should be revised. Conversely, some other models were assessed and give satisfactory results. The drag force model has been shown to slightly under-estimate DNS results but remains mostly valid. Tchen's theory has been found very satisfactory to evaluate the level of turbulence in the dispersed phase. A low-Reynolds turbulence model (EBRSM) has been implemented in NEPTUNE_CFD and validated against the results of single-phase flow DNS. All the results (either at the local scale with the DNS or at the averaged-scale with the standard closure hypotheses of NEPTUNE_CFD) showed that the interfacial forces and the models for momentum transfers play a dominant role on the flow prediction over the turbulent closure hypothesis. This work has demonstrated that the modelling efforts should be first focused on the interfacial transfer closure. Then, the second-order turbulence model should be improved by considering an algebraic relation to build a tensorial description of the turbulence dissipation rate from its scalar value.
The last part has dealt with the LES of turbulent convective flow along a PWR sub-channel with and without phase change. The problem was inspired by the PSBT OECD single sub-channel benchmark. The objective was to understand the turbulent flow behaviour in the presence of boiling. Turbulent effects are modeled using LES resolving the viscous-affected layer, with and without the RPI wall-boiling model. This was the first attempt to resolving such flows using les combine with a wall boiling model.
In summary, the LES of boiling flow in downscaled conditions were achieved using TransAT. The very important finding here is that boiling changes completely the nature of the flow, be it mean or turbulent part. More critically, it was found that the frictional velocity in the boiling case increases by a factor of 2 compared to the single-phase flow case, which means that boiling acts indeed as a roughness structure over the rod surface. The heat transfer coefficient in the boiling section should also increase by about the same order of magnitude. What does that imply in terms of upscaling was that (i) the wall functions that apply in the boiling section have to consider the increase of frictional velocity or friction coefficient, (ii) the usual correlations for convective heat transfer coefficient in this section should be augmented according the finding, and (iii) a unified global heat transfer coefficient could be developed beyond the triple flux decomposition, in favor of a simpler decomposition a la Chen, involving nucleate boiling and convective boiling only.

1.3.2.4 Validation, verification and application (WP24)

EDF proposed Hybrid Multifield Approach for flow regime transitions. Two-phase flow was modelled by Eulerian approach and the gas phase was split in two fields. The small bubbles were modelled with a dispersed approach whereas the larger bubbles are simulated through an interface locating method. The model was implemented in NEPTUNE_CFD code and tested on Castillejos experiment with bubble plume. It was demonstrated that 3-field and 2-phase model can capture small bubbles that cannot be resolved on given mesh by the 2-field and 2-phase approach.
ASCOMP & JSI proposed a new hybrid model called the ARM (All-Regime Multiphase) Approach for flow regime transitions. The ARM consisted of a new computational prediction strategy for gas-liquid flows featuring a mixture of dispersed phases (bubbles and/or droplets) and large-interfacial flows characterised by a distinct, sheared front amenable to ITM prediction (short for Interface Tracking Methods; fully genuine Level Set -without interface sharpening- or VOF with true interface

reconstruction). The model has been used for the following problems: Impinging water jet and Taylor bubble in a vertical pipe.
UJV developed a wall heat flux splitting model for pool boiling. The model was based on the data from DNS simulations of Gaertner experiment. DNS simulations were performed by PSI. UJV implemented the boiling model in NEPTUNE_CFD code and tested it on three pool boiling cases. ASCOMP implemented the same boiling model in TransAT V5.3 code and tested it on the same cases. The wall boiling model was able to reproduce very well all the parameters on the wall in both codes for all three cases.
A new criterion for detection of critical heat flux from local parameters was proposed by UJV. The criterion was based on the ratio of evaporation heat flux to total wall heat flux. The method was tested in NEPTUNE_CFD V2 code on data from the tables of CHF in tubes and in rod bundles. The critical heat flux could be predicted with ±10% accuracy in many cases. The method did not work for low mass flux cases.
ENEA performed simulations of PTV experiments with boiling bubbly flow in vertical channel using CFD codes NEPTUNE_CFD and TransAT. In both codes, a good agreement with experimental results was obtained for cases with low heat fluxes. With increasing wall heat flux, both codes over predicted flow acceleration near heated wall due to boiling and the results were getting worse.
Based on DNS simulations, ASCOMP developed three different upscaled models of momentum exchange in bubbly flow: modified k-ε, with a bubble-attenuated eddy viscosity model (BA-EVM), modified k-ε, with a bubble-induced eddy viscosity à-la-Sato (EVM-Sato), and modified k-ε, two-layer bubble-induced turbulence model (TLV-BI). ASCOMP applied Algebraic Slip Model (ASM) with EVM-Sato model to the simulation of TOPFLOW experiment with bubbly flow in a vertical pipe. The newly developed model predicted void fraction and phases velocities profiles better than the ASM model alone. The same ASM with a DNS-based EVM-Sato model was used to simulate the Chaptal experiment.
CEA and EDF implemented Elliptic Blending Reynolds Stress Model of turbulence (EBRSM) into NEPTUNE_CFD code. This model can overcome some deficiencies of the SSG turbulence model which is implemented in NEPTUNE_CFD code for simulation of boiling flow. NEPTUNE_CFD code with the EBRSM model was applied to the reference case of Kim (DNS simulation of single phase flow). Very good agreement with the reference results was obtained. The EBRSM model was extended to two-phase flow.
EDF performed simulations of CHAPTAL experiment with NEPTUNE_CFD code using two-fluid approach. The CHAPTAL experiment simulates adiabatic high pressure bubbly flow in a vertical tube. A reasonable agreement was obtained between calculated and experimental data.
ASCOMP applied Algebraic Slip Model (ASM) with a DNS-based EVM-Sato model to the simulation of bubbly flow (water-air) in a large vertical pipe. Data from TOPFLOW experimental facility were used for the model validation. The results compared to experimental data showed that the developed model predicts void fraction and phases velocities profiles better than the ASM model alone.

1.3.3 Multiscale and multiphysics applications of Thermo-hydraulics (SP3)

This subprojects applied a multi-scale analysis to LOCA, PTS and BWR, which corresponded to three Work Packages. Detailed programs of work for LOCA, PTS and BWR thermalhydraulics were established and documented at the beginning of the project.
The thermohydraulics and fuel thermos-mechanics softwares of the NURESIM platform used for this sub-project are NEPTUNE-CFD, TransAT, CATHARE-2 & CATHARE-3, ATHLET, DRACCAR, FLICA and CTF. They were delivered during the first period of the project, implemented, and training sessions were organised.

The main objective was to improve the accuracy and reliability of simulations of safety issues such as LOCA, PTS and some BWR issues by developing and applying advanced multi-scale and multi-physics tools and methods. This overall objective was fully met with various degree of satisfaction depending on the application. In summary the progress towards the objectives is:

1.3.3.1 LOCA (WP 31)

- **3-Field model**: A three-field for system code has been further developed and validated on droplet deposition in the SEROPS (PWR Upper Plenum) tests. Moreover the Okawa models for entrainment and deposition was found to perform better than the Hewitt and Govan model for dry-out prediction
- **Reflooding with ballooned rods**: An extensive modelling effort was devoted to reflooding (FEBA, ACHILLES, THETIS, PERICLES and SEFLEX tests) with both non deformed and deformed rods using advanced fuel thermos-mechanics and either sub-channel codes or CFD codes. It was demonstrated that CFD can be used to improve sub-channel analysis codes. An Eulerian-Lagrangian model for steam-droplet flow as encountered in core reflooding was developed and implemented in the NEPTUNE-CFD code. First simulations of a sub-channel flow were obtained. Some validation was still required before using this tool as a support of sub-channel and system codes. It was demonstrated that that the effects of turbulent diffusion and dispersion in a core during both reflooding in a LBLOCA and core dewatering in a SBLOCA are very local and do not affect the average values in an assembly and the peak clad temperatures and justify that diffusion models are not necessary in a coarse core 3D modelling.
- **Core boiling flow**: Simulations of PSBT tests with NEPTUNE-CFD conclude on the ability of the NEPTUNE-CFD code to predict the void fraction.
- **Break flow-critical flow**: The DEM flashing model devoted to critical flow prediction was further evaluated and validated. It was implemented in a 1-D 6-equation model (Waha code). It was applied to choked flow and double critical flow experiments and could well predict the mass flowrate. It was implemented in the NEPTUNE-CFD code and predicted correctly both Super-Moby Dick choked flow tests and double-choked flow tests. The model has also been improved using the CIRCE methodology developed at CEA.
- **CCFL prediction with CFD**: Pioneering CFD simulation of CCFL experiments were performed with interface sharpening method and show reasonable predictions of wave frequency but some disagreement on liquid entrainment. This opens the way to a numerical prediction of flooding limit but still requires improvements.
- **Coupled System and CFD codes**: A coupling of system and CFD simulation of PERSEO tests representing a passive heat removal system in a pool has been developed and successfully tested on PERSEO experimental results.
- **Advanced 3-field CFD modelling** (continuous gas, dispersed gas and liquid) with phase averaging of dispersed gas combined with an interface tracking of the large interfaces was developed and tested on some experimental data. This approach could extend the two-phase-CFD technology to the most complex flow regimes.
- **System code model uncertainties**: The activity on model uncertainties of system codes revealed unexpected difficulties during the PREMIUM benchmark. In view of overcoming the difficulties, benchmarking of several methods to determine input uncertainties of system codes was continued. Some reasons of the difficulties were clarified and better methodologies are in progress but the issue is not closed and requires further investigations.

1.3.3.2 PTS (WP32)

- **The CFD modelling of two-phase PTS scenarios** is a full success after long efforts spent during NURESIM, NURISP and NURESAFE projects. TOPFLOW tests were simulated with various test conditions and using either a RANS 2-fluid +LIM model (CEA, EDF, IRSN with NEPTUNE-CFD) a RANS 2-fluid model (HZDR, with CFX) or a 1-Fluid RANS method (PSI with TransAT). A benchmark was performed on a specific steam-water TOPFLOW-PTS test. Very good predictions of TOPFLOW PTS tests were obtained with NEPTUNE-CFD and by CFX showing that the long modelling effort spent during NURESIM, NURISP and NURESAFE finally reaches the objective.
- **The KAERI CCSF test** related to PTS was simulated with TransAT using both RANS & VLES modelling/simulation strategies. It has been observed that the obtained phasic velocity profiles do not match the KAERI ones: the calculated interfacial shear stress seems to be too high. In order to fix this issue, a modified damping function for near interface turbulence (low-Re) has been developed. This approach has yielded good results. The second main problem is that most existing condensation models fail for high sub-cooling rates of the order of 70 Deg.
- **Experimental and numerical investigation** of stratified shear flows were performed by UCL. An experimental facility reproducing the experiments by Thorpe was refurbished and the procedures were adapted to limit the shortcomings of previously obtained results. New tests were performed using water and kerosene, as well as with water and n-hexane. The instability was quantified using image processing techniques. Two solvers, an in-house level set code and NEPTUNE_CFD, were benchmarked against this new test case. The results revealed that such benchmark is still challenging for the codes and there is still room for improvement.
- **A synthesis of PTS activities** was made which summarises the main results obtained on multi-scale and multi-physics simulation of Pressurised Thermal Shock (PTS). Simulations were done for TOPFLOW-PTS steam-water experiments considering the influence of different model options and the meshing. A benchmark showed acceptable agreement with experimental results for NEPTUNE_CFD and ANSYS-CFX. In additions simulations on the KAERI CCSF test case were done. New experimental data were obtained by a CFD-grade experiment on Kelvin-Helmholtz instability. Sensitivity and uncertainty methods were tested for CFD-simulations on PTS-related cases.
- In a pioneering effort, methods for **uncertainty of CFD** were developed and tested on simple cases. There are 4 contributors for this task: CEA, EDF, JSI and PSI. EDF wrote a State of the Art report more focused on the validation issue. Other participants applied methods to cases with experimental data. JSI and PSI consider the GEMIX experiment whereas CEA considers an experiment with both buoyancy and convection effects: the so-called “heating floor” experiment. JSI and PSI use a method based on meta-models, with few input parameters whereas CEA uses direct Monte-Carlo method with numerous and miscellaneous input parameters. A state of the art report devoted to the uncertainty quantification was also written during the second period of this project and was coordinated by the CEA. Note that University of Pisa has contributed to this document.

1.3.3.3 BWR thermohydraulics issues (WP33)

- **System and sub-channel code application to BWR**. The German system code ATHLET simulated the NUPEC BFBT tests data. In overall, very good agreement of the solutions with the experimental data was found, laying almost all of the results within the ±10% error band. The coupled ATHLET/COBRA-TF model for the Oskarshamn-2 NPP are presented and the main results of the ATWS transient analysed are discussed. This coupling was implemented inside the SALOME platform using the MED Coupling interface and the details are provided in this report.

- **Modelling annular-mist flow up to dry-out prediction at CFD scale** is an objective followed since NURESIM beginning. During the second phase of NURESAFE, a unified two-phase computational fluid dynamics (CFD) modeling framework has been developed for prediction of dryout occurrence, as well as the corresponding post-dryout heat transfer. The dryout occurrence is indicated according to the local liquid film thickness criterion, which is determined simultaneously based on a local dryout model. For the post-dryout region, the various heat and mass transfer mechanisms between the wall, the gas phase, and the droplets are identified to calculate the wall temperature. The models were implemented and all the calculations were conducted using the open source CFD code OpenFOAM. The source code for the developed models was provided for implementation in the NEPTUNE_CFD code.

- Attempts to **extend NEPTUNE_CFD boiling flow models to annular and annular mist-flow** were made. NEPTUNE_CFD was used to simulate BWR-related boiling tube experiments. Sensitivity studies were performed with respect to meshing and modeling choices. From the detailed results one can easily identify the most influential models, the CPU time effect of meshing & modeling choices and effects of single modeling choices & combinations. For future, the basic possibilities to extend the NEPTUNE_CFD simulation of boiling bubbly flow to higher void fractions are discussed.

- **Modelling steam injection in a pressure suppression pool** with all possible stable and unstable condensation regimes is a difficult challenge for codes. This objective was followed by LUT during NURESIM, NURISP and NURESAFE projects using two-phase CFD. Significant progress was obtained for slow condensation and some chugging regime. Attempts were made to develop a more generally applicable and carefully validated condensation model for pressure suppression pool modelling by using CFD including cases with stronger deformation of the interface. Although the final objective is not fully met, progresses made so far are considerable.

1.3.4 Software platform (SP4)

1.3.4.1 Objectives and realisation

Salome is a generic development platform for numerical simulation, developed by EDF and CEA. It is an open-source project, code and binaries are available for free download on the internet web site of the project (http://www.salome-platform.org). The platform is provided with native modules, which handle pre-processing, post processing, and code coupling. An important feature of the platform is that it is possible to integrate solvers, in order to couple them together and with the native modules.

Salome provides native modules with a graphical user interface (GUI), a python and a C++ interface (TUI). The use of python has proven to be very useful and enables the parametrisation of the calculations. The platform can be used alone for pre and post processing needs, or in conjunction with integrated modules in multi-physics applications.

Salome is connected to Uranie, an open-source platform developed by the CEA, which is based on the data analysis framework ROOT, (http://root.cern.ch) an object-oriented and petaflopic computing system developed by CERN. Uranie aims at providing methods and algorithms about Uncertainty and Sensitivity (US) and Verification and Validation (VV) analyses in the same framework. Uranie and Salomé platforms work nicely together. Any calculation scheme developed in Salome can be used within Uranie.

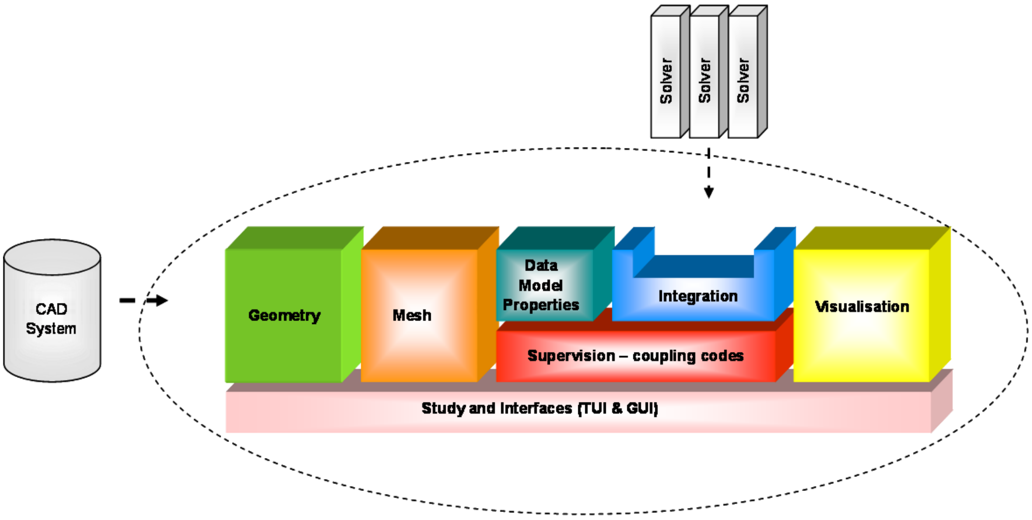

Figure 3 - SALOME global view

The objectives of the sub-project 4 were to integrate in SALOME a set of state of the art codes devoted to the simulation of normal operation and design basis accidents of light water reactors. All the thermal-hydraulic, neutronics and fuel thermo-mechanics codes and solvers benefit from mutualized services provided by the platform (pre and post processing) and can be coupled together. Integrated codes and SALOME simulation tools will work concurrently within the applications specified above and developed by the other sub-projects.
SP4 team assisted and advised the partners in integrating their modules and codes, ensured the production and the maintenance of the NURESIM platform, its quality and non-regression, and maintained the URANIE platform, assisted the partners in using it for their sensitivity analysis, model calibration and optimisation studies.
SP4 objectives have been implemented into three work packages:

- Integration of codes in the NURESIM platform, support and assistance,
- Maintenance and production of the NURESIM platform,
- Maintenance of the URANIE platform, assistance and support.

During the first half of the project, SP4 focused on code integration, as it was essential to realise the integration work on time, before the start of the coupling actions scheduled in SP1.
During the second period, the focus moved to support and assistance, and to the production and maintenance. The objectives are met: code integration was finalised on time to allow the coupling work to be done in the subproject 1. The final project version of NURESIM platform has been released in December 2015. It is available on the SVN repositories of the project. Binaries can also be delivered on demand on various Linux distributions. This version will be maintained for five years.

1.3.4.2 Coupling interfaces

SALOME platform provides two coupling mechanisms. The first one use interfaces to couple codes. Each code provides an interface, and the coupling is done by calling the methods/services of the interface. The second one is a message passing mechanism (MPI-like send/receive protocol). The data are sent from the inside of the codes, and are received later in another code, without synchronisation.

For NURESAFE, we have chosen the first mechanism, for the following reasons:

- It is less intrusive, and doesn't require adding "send and receive" orders inside the code sources. The data exchange is performed by a thin C++ layer developed above the code,
- It is safer and less error prone, as the coupling scheme is explicitly written, contrary to the implicit schemes of the message passing approach.
- It allows normalisation, which is an important point, considering the large number of codes we are dealing with.

Components are integrated in the Salomé platform as CORBA components, with a "three layers" architecture:

1. The lowest layer contains the legacy codes, and their libraries.
2. The intermediate layer is a thin C++ layer, composed by a class that provides the component interface. The services are implemented by calling the libraries of the underlying layer.
3. The upper layer is the CORBA layer, and is used by Salomé to distribute the components on remote machines.

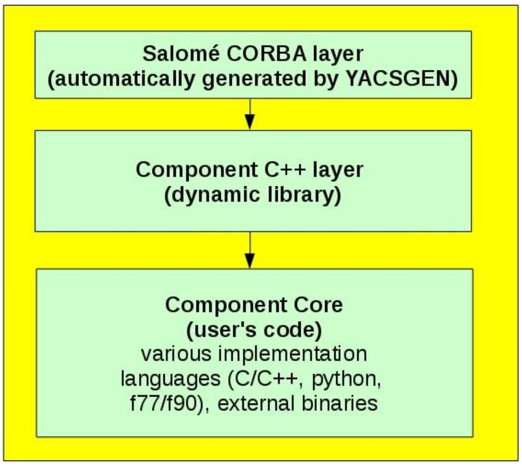

Figure 4 - three layers component architecture

To facilitate this integration, Salomé provides an integration tool (called YACSGEN), which generates the CORBA layer out of the C++ component interface. Therefore the integrator only has to focus on the services he wants to provide and should only implement the intermediate layer.

With this architecture, the coupling can be done either directly in C++, or when extra memory or extra CPU is required in CORBA from Salomé platform.

1.3.4.3 Standardisation

MEDCoupling is the library in Salomé which holds the numerical meshes and fields. It was developed in the framework of the adaptation of SALOME platform to HPC. The new library is fully written in C++ and wrapped in Python. These structures integrate the HPC constraints (compact structures, limitation of object copies, lazy evaluation) and are optimised (they require less memory and are faster). Last but not least, MEDCoupling implements a complete set of algorithms linked to the data structure. These algorithms manage notably area, volumes, barycenters, arithmetic operations, localisations, intersections and interpolations.

An important task of the project was to integrate the new codes with MEDCoupling library, and to update the already integrated codes. This task is completely achieved; all codes exchange now their numerical data at MEDCoupling format.

The standardisation effort didn't stop here. A standard coupling interface, called ICOCO and based upon MEDCoupling, was adopted by the project. This standard interface, originally used by TRIOU and CATHARE codes, was extended by NURESAFE, and is now used by other codes: DYN3D, FLICA, COBAYA.

The interest of using a standard interface is to facilitate the writing and understanding of computational coupling schemes. The extension of coupled schemes to the new codes is also eased and therefore the amount of work is reduced. The adoption of ICOCO can be seen as a step toward interoperability. The platform developers have now the capacity to implement generic coupling procedures.

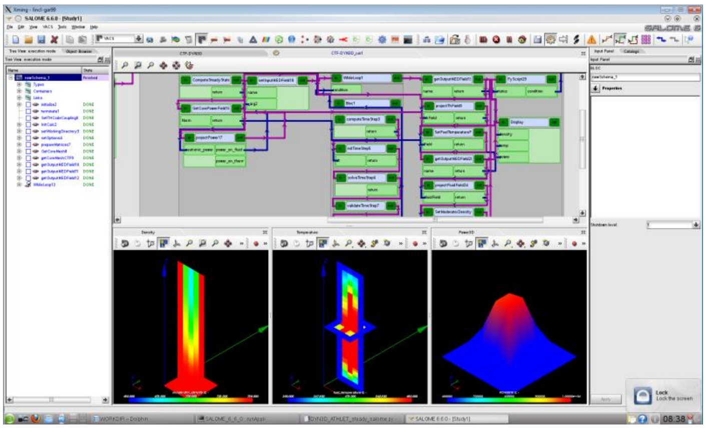

Figure 5 – coupling integrated components with Salomé

1.3.4.4 Graphical User Interfaces

Salomé architecture also allows integrating graphical user interfaces (GUIs) in the platform. The mechanism is based on the notion of plugin. To be integrated a graphical user interfaces should be developed with the Qt framework and should implement an abstract interface provided by Salomé platform. Doing this, the integrated interface will be part of Salome main desktop, and will benefit from the platform services.

GUI's are integrated in Salomé platform to provide new services, like for example handling the pre-processing of a computational code. NURESIM platform provides GUI's for TRIPOLI, DYN3D, CATHARE, NEPTUNE, MELANGE, PWRDATA.

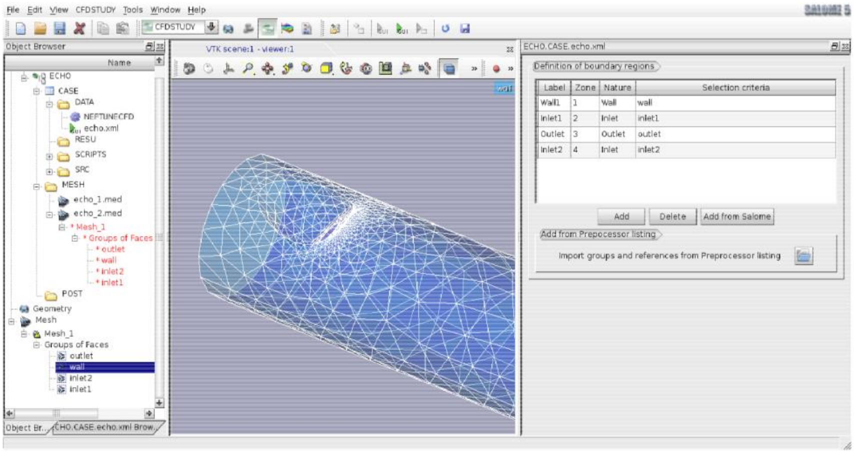

Figure 6 - Example of integrated GUI (Neptune-CFD pre-processing tool)

1.3.4.5 Global view of NURESIM platform

The NURESIM platform provides a set of state of the art software devoted to the simulation of normal operation and design basis accidents of light water reactors: BWR, PWR, VVER. The platform currently includes 14 codes covering different physics: neutronics, thermal-hydraulics, fuel thermo-mechanics at different scales: local, fuel assembly, core and reactor system. All these code have been extensively benchmarked and validated against experiments during the course of the three collaborative projects (NURESIM, NURISP, NURESAFE).

Above the standalone codes is the layer of Salome integrated modules. All NURESIM platform codes have either an integrated GUI, or an integrated component interface. All the codes with a coupling interface can be coupled together. A lot of combinations have been implemented and validated during the project. The figure 7 below summarises the coupling that have been tested and validated by the project.

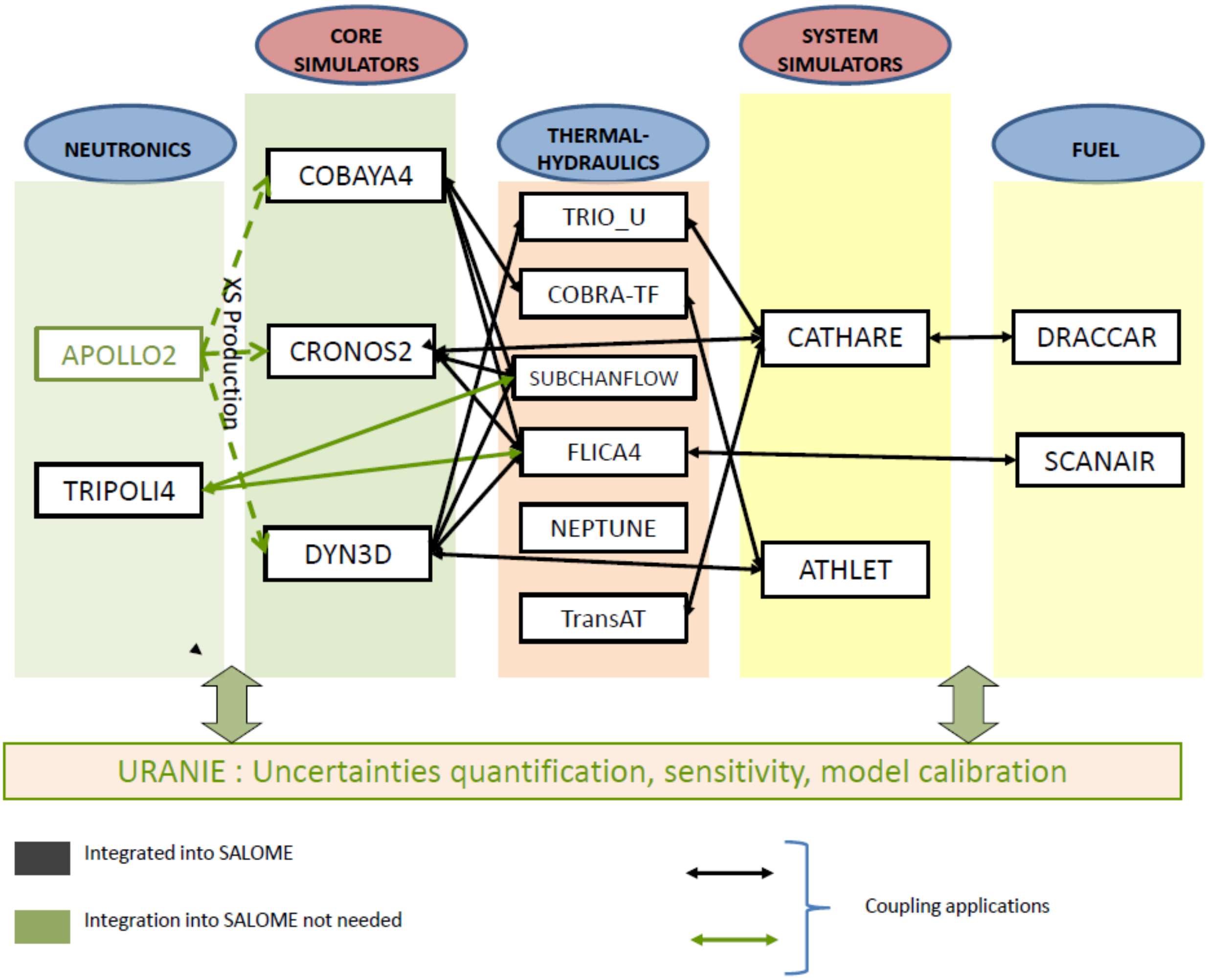

Figure 7 – the NURESIM platform at the end of the project

Above the integrated NURESAFE modules are the Salomé native modules. They are used for pre-processing, post-processing, and code coupling. The NURESIM platform also provides coupling computational procedures (as YACS graphs or python scripts).

Finally it was possible to evaluate the computational schemes developed with Salomé and the integrated component thanks to the link with Uranie. Users can perform Sensitivity Analysis, Model Calibration and Optimisation studies. This possibility has been used successfully in Sub-project 1.

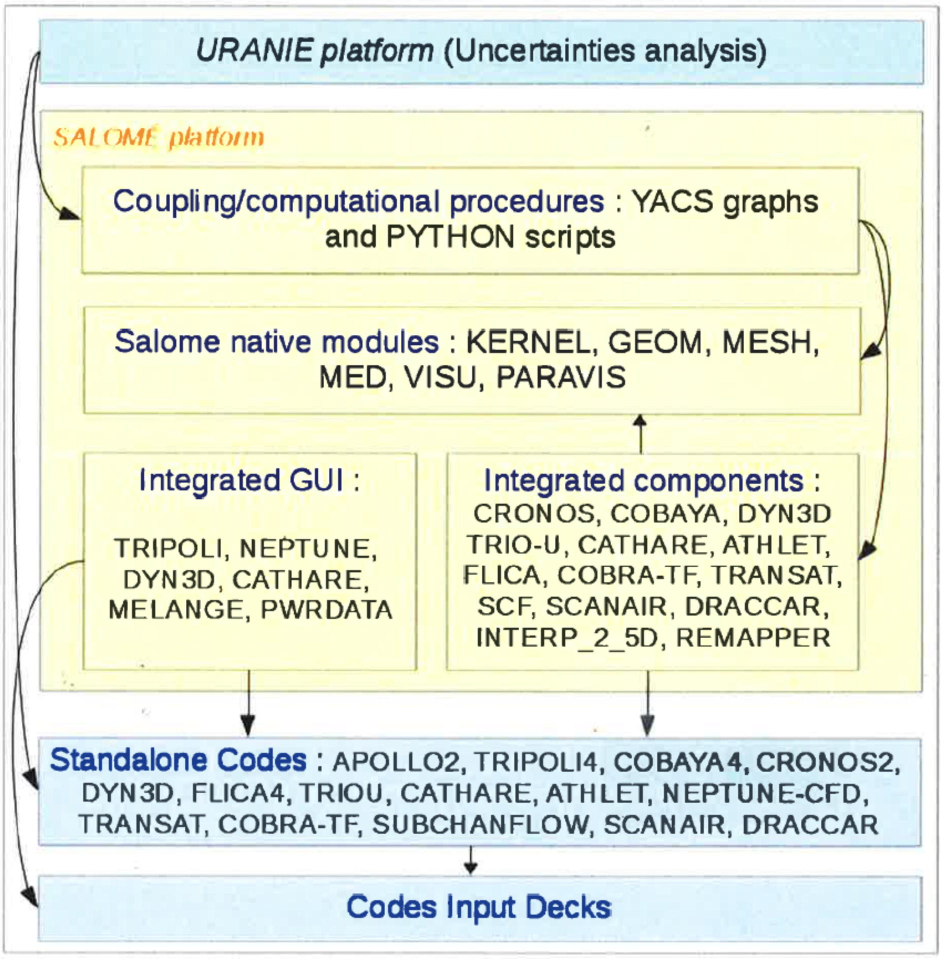

Figure 8 - NURESIM platform : view of the software structure

1.3.5 Training activities (sub-project 5)

The main objective of the education and training sub-project was to provide all the training sessions devoted to the numerical tools e.g. neutronics, thermal hydraulics, uncertainty and sensitivity which are used within the NURESAFE project by the different partners. Training courses focused on the platform itself and regarding the main features and functionalities of the platform are also included.

By this way, the training courses foster the dissemination and facilitate the use of the platform codes within project partners for an efficient use of the codes to accomplish the technical goals of the project. Therefore training activities have a close connection to the other NURESAFE subprojects.

During the first months of the NURESAFE projects two first training sessions were organized in to prepare for the start of the work program that uses tools on which the platform is based upon.

1. February 2013, in GRS (Garching). A workshop devoted to the code integration into SALOME was organized. Participants from 10 NURESAFE organizations were present at this workshop.

2. April 2013, in CEA (Saclay). A training session on the UQ platform URANIE was organized and about 10 NURESAFE partners participated.

Then many training sessions (table below) were given during the course of the project so that all the training needs were satisfied. More than 100 people from NURESAFE partners participated to one or more training sessions. Training sessions devoted to some codes were also organized during the NURISP project which was the "predecessor" project of NURESAFE.

Code or method	When ?	Partner in charge
Neptune_CFD	July 2013	EDF
Neptune_CFD	May 2014	EDF
CATHARE-2	October 2013	CEA
CATHARE-2	October 2014	CEA
SALOME	April 2013	CEA
FLICA4	April 2014	CEA
DYN3D	July 2013	HZDR
DYND3D	March 2014	HZDR
TRIO_U	September 2013	CEA
Coupling within SALOME using the ICOCO standard	September 2013	CEA
TransAT	October 2013	ASCOMP
CATHARE-2	September 2014	CEA
TRANSAT	November 2014	ASCOMP

Also employees of some partner organizations travelled for individual training stays to other partners

Stays for training

Name	*Origin*	Host partner	Dates	Code
M.Tajchman	CEA	UPM	21/09/2013- 25/09/2013	SALOME
S.Sanchez-Cervera	UPM	IRSN	10/02/2014- 13/02/2014	APOLLO
O.Kamenscic	INRNE	UPM	16/07/2014- 22/08/2014	COBAYA
O.Kamenscic	INRNE	GRS	26/01/2015- 29/01/2015	COBRA
I.Spasov	INRNE	UPM	18/05/2015- 04/06/2015	COBAYA
O.Kamenscic	INRNE	UPM	25/05/2015- 29/05/2015	COBAYA

1.4 Potential impact

1.4.1 Outcome of the project

The NURESAFE project aimed at providing to all European nuclear stakeholders an advanced and well proven capacity in modelling nuclear reactors based on the NURESIM European reference simulation platform. This capacity is now available and hinges on a more accurate representation of core physics, thermohydraulics and fuel thermo-mechanics in a standard environment for easy multi-physics and multi-scale simulations and uncertainty analysis.
LWR will constitute the main part of the fleets during the first half of the century (at least) and improvement of safety of Gen III reactors is a major stake. Therefore, NURESAFE project concentrated its technical tasks on the development and validation of more reliable and accurate software for the safety assessment of LWR.
Higher-resolution multi-physics and multi-scale developments were implemented, tested and delivered for safety analysis involving core physics, or for optimisation of the fuel management of PWR, VVER and BWR cores.
Integrated industry-like applications were developed, validated and delivered for PWR core thermohydraulics under LOCA conditions, for Critical Heat Flux prediction, for analysis of PTS two-phase scenarios, and for BWR core thermohydraulics. They include more reliable physical models and flexibility.

The current users of the NURESIM software platform benefit after the end of the project from the improvements made within the NURESAFE project when they perform their industrial studies (for safety analysis, optimisation of reactor operation, reactor design). These improvements are presented below.

Of particular importance to all simulation areas is the development of the capability to quantify the uncertainty in the evaluations (on the URANIE platform), which was an important part of NURESAFE work-program.

The NURESIM platform is of course not limited to situation targets modelled in the project but 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,
- Condensation in a BWR pressure suppression pool

As a first outcome, innovative deterministic and statistical methods and tools for quantification of the uncertainties developed within NURESAFE give a better knowledge of conservatisms and margins. The determination of closure laws uncertainty of system codes and the uncertainty methods for CFD application progressed within NURESAFE project.
In addition, the more accurate tools delivered by NURESAFE will help optimisation the reactor design 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.
As an important effort of integration of software into the SALOME platform was made during the project, most of the NURESIM software use standardised tools for pre and post-processing, and

coupling capacities so that the generic tools can be mutualised 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.

TSOs, utilities or vendors, as partners or members of the NURESAFE users' group, 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 reference platform. These actions resulted in a better knowledge of the strengths and weaknesses of the various industrial codes in use in different organisations. The advanced models and methods developed within NURISP and NURESAFE projects 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.

1.4.2 Evaluation of the impact

As the NURESAFE project purpose was to develop, to run and to deliver to end-users more reliable numerical tools applicable to the analysis of some situation targets of LWR, its impact is closely connected to the achievement of the technical objectives as described above. Furthermore, it is possible to measure the impact of the project through the following indicators:

1. Improved understanding of physical phenomena: 2-phase PTS phenomenology was clearly identified and addressed in the modelling; phenomena leading to dry-out are better identified at CFD scale; geometrical effects of ballooned rods are better understood at CFD scale; effects controlling condensation regimes in pressure suppression pool
2. Improved ability to model nuclear reactors:
    i. A multi-scale approach was developed which provides some local zoom when necessary.
    ii. Advanced fuel models are coupled to advanced thermal-hydraulics.
    iii. Challenging DNS & LES simulations were performed within SP2 to analyse bubbly flow with and without phase change in order to understand intricate phenomena that are beyond measurements capabilities. New modelling routes were proposed based on these results, and have been documented and implemented in the platform codes available to all stakeholders.
    iv. Novel ideas were explored and others further refined within SP2 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.
3. Number of codes connected to the platform: 2 system codes, 2 single-phase CFD codes, 2 two-phase CFD codes, 3 sub-channel analysis codes, 2 advanced fuel thermo-mechanics codes, 2 DNS codes, 3 neutron-kinetics codes
4. Number of international publications with simulations made using the NURESIM-platform: almost 40 papers are published based on NURESIM platform application
5. Reference to the NURESIM-platform in international publications: more than 30 papers refer to the NURESIM-platform
6. Attendance to the NURESAFE open seminars: 40 people at the first NURESAFE open seminar and 50 at the second seminar

7. Extension of the team built during the NURISP project: new members. AREVA and ENEA became members of the consortium. Penn-State University became member of the users group.
8. Influence of the NURESAFE developments on the methods previously used by the NURESAFE partners: CFD simulations can be used to improve system codes in LOCA situations (core with deformed rods, break flow,.) and MSLB situations (RPV and core flow mixing); CFD can be used for fuel design and for improving CHF prediction

Measurable progress made for safety issues related to the situation targets:

i. PTS (Pressurized Thermal Shock): a big milestone was reached with very satisfactory predictions of TOPFLOW combined effect tests
ii. LOCA (Loss of Coolant Accident): better understanding of complex flow in ballooned rods, enhanced capabilities to simulate geometrical effects; improved break flow prediction; coupled system-CFD simulation of reactor with pool passive heat exchanger
iii. BWR: full modelling of annular
iv. -mist flow and dry-out prediction by 3D 3-field CFD tool: small scale geometrical effects can be predicted
v. MSLB (Main Steam Line Break): good prediction of the Kozloduy-6 vessel mixing experiments by computationally efficient CFD and system models, and coupled CFD-system codes; improved prediction of local effects in the core

1.4.3 The end-users of the NURESIM platform

The end-users of the NURESIM platform are from now the members of the NURESAFE consortium (22 organisations) and the members of the NURESAFE users-group (5 organisations). Thus, The NURESAFE partners were themselves the most important users of the codes. All these user organisations could be divided into:

1. Utilities:

- EDF: 58 PWR
- FORTUM: 10 NPPs (BWR, PWR, VVER)
- GDF-SUEZ: 7 PWR

These three utilities operate the majority of the European fleet of nuclear reactors

2. Reactor or fuel vendors:

AREVA, which is a very large industry company currently uses several codes of the platform.

3. Technical Support Organisations

These are IRSN, NCBJ and GRS

4. R&D Institutes or universities

- CEA, KIT, PSI, KTH, UPM, VTT, UJV, KFKI, JSI

These organisations are also end-users of codes through performing expertise for industry and safety institutes.

5. Universities and Institutes doing research on Nuclear Safety

- UCL, ICL, UPISA, LUT, ENEA, CEA, PSI

In conclusion, the end-users of the NURESIM platform cover a very large part of the European Nuclear Community.

The address of the project public website is the following: www.nuresafe.eu and below an image will illustrate the home page of the website:

The official logo of the project can be visible also on the official website and it is illustrated below:

Furthermore, an internal workspace was used during the project - **NURESAFE internal workspace (NIWS).**
Partners continued to exchange documents related to NURESAFE by using the secured collaborative platform. The project information was uploaded onto this shared workspace ensuring a uniform level of information for all. The tool chosen by the Project Coordinator for NURESAFE was Sharepoint, maintained and administrated by CEA and updated by LGI.

Furthermore, project logo, diagrams or photographs illustrating and promoting the work of the project (including videos, etc…), as well as the list of all beneficiaries with the corresponding contact names can be submitted without any restriction.

2 Use and dissemination of foreground

The NURESIM platform became the tool to realise, 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. The standardised environment offered by the platform and the interoperability of codes facilitates the development of this collaborative work.
Further to the NURESAFE 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 NURESAFE project 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 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.

After the end of the NURESAFE project, further use and development of the software platform will be ensured thanks to:

- ✓ Further maintenance by CEA (at least during 5 years) of the software repository,
- ✓ Further development and maintenance of the general purpose software SALOME and URANIE (two open-source software supporting the entire platform)
- ✓ Further development and maintenance of each individual by code owners that started in durable frameworks many years ago.

A new activity for dissemination of NURESAFE scientific results is planned in 2016. It was agreed with the editor of Nuclear Engineering and Design (NED) to publish a special issue of NED devoted to NURESAFE. The detailed list of papers in this issue (about 20 papers) is currently under discussion.

The manner in which organizations can access NURESAFE codes is presented for each code in Table B below.

In addition the internal NURESAFE workspace (the NURESAFE sharepoint) will be maintained and updated after the project by CEA and LGI.

Section A (public)

TABLE A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES

NO.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers[2] (if available)	Is/Will open access[3] provided to this publication?
1	Effects of cross sections tables generation and optimization on rod ejection transient analyses	S. Sanchez-Cervera	Annals of Nuclear Energy	Vol. 73	Elsevier		2014	387-391		yes
2	Optimization of multidimensional cross-section tables for few-group core calculations	S. Sanchez-Cervera	Annals of Nuclear Energy	Vol. 69	Elsevier		2014	226-237		yes
3	Boron dilution transient simulation analyses in a PWR with neutronics/thermal-hydraulics coupled codes in the NURISP project	G.Jimenez	Annals of Nuclear Energy	Vol. 84	Elsevier		2015	86-97		yes
4	Coupling CFD code with system code and neutron kinetic code.	Vyskocil L.	Nuclear Engineering and Design	279 (2014)	Elsevier B.V.		2014	210-218	DOI: 10.1016/j.nucengdes.2014.02.011	no

[2] A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).
[3] Open Access is defined as free of charge access for anyone via Internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

5	Simulation of SDA Opening Test at VVER-1000 NPP by Coupled System of Athlet, DYN3D and Fluent Codes.	Macek J.	Proceedings of the NURETH-15 Conference	May 12-17, 2013	American Nuclear Society	Pisa, Italy	2013	NURETH 15-011		no
6	Numerical Modelling of Low-Reynolds Number Direct Contact Condensation in a Suppression Pool Test facility	G. Patel	Annals of Nuclear Energy	Volume 71	Elsevier Limited			376-387		Yes
7	Computational fluid dynamics simulation of single bubble dynamics in convective boiling flows	Yohei Sato , Sreeyuth Lal , Bojan Niceno	Multiphase Science and Technology	Vol. 25/Issue 2-4	Begell House Inc.	United States	2014	287-309		
8	Direct Numerical Simulation of Bubble Dynamics in Subcooled and Near-saturated Convective Nucleate Boiling	Yohei Sato , Sreeyuth Lal , Bojan Niceno	International Journal of Heat and fluid flow		ELSEVIER	United states	2014		DOI : 10.1016/j.ijheatfluidflow.2014.10.018	
9	Development and validation of the multi-physics DRACCAR code	S. Bascou	Annals of Nuclear Energy		ELSEVIER	United states	2014		DOI: 10.1016/j.anucene.2014.09.040	yes
10	Validation of the Thermal-hydraulics System Code ATHLET based on selected pressure drop and void fraction BFBT tests	V. Di Marcello, J. Jimenez V. Sanchez	Nuclear engineering and Design		ELSEVIER	United states	2015	Vol 288 (183-194)		
11	Advanced multi-physics simulation for reactor safety in the framework of the NURESAFE project	B. Chanaron, C. Ahnert, N.Crouzet, V. Sanchez, N.Kolev, O Marchand, S. Kliem, A. Papukchiev	Annals of Nuclear Energy		ELSEVIER	United states	2015		DOI : 10.1016/j.anucene.2014.12.013	yes

12	CFD Model of Adiabatic Annular Two-Phase Flow using the Eulerian-Lagrangian Approach	Li, H. and Anglart, H.	Annals of Nuclear Energy	Volume 77	ELSEVIE R	United States	2015	pages 415-424		yes

TABLE A2: LIST OF DISSEMINATION ACTIVITIES

NO.	Type of activities[4]	Main leader	Title	Date/Period	Place	Type of audience[5]	Size of audience	Countries addressed
1	Conference	Macek J.	Simulation of SDA Opening Test at VVER-1000 NPP by Coupled System of Athlet, DYN3D and Fluent Codes.	May 12-17, 2013	NURETH-15 conference Pisa, Italy	Scientific Community, Industry		
2	Conference	Institute for Nuclear Research and Nuclear Energy (INRNE)	Benchmarking of calculation schemes in APOLLO2 and COBAYA3 for VVER lattices	09/05/2013	Mathematics and Computation in Nuclear Science & Engineering (M&C 2013)	Scientific Community, (Higher education, research, industry)		Countries developing nuclear energy

[4] A drop down list allows choosing the dissemination activity: publications, conferences, workshops, web, press releases, flyers, articles published in the popular press, 6videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters, Other.

[5] 7A drop down list allows choosing the type of public: Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias, Other ('multiple choices' is possible).

					Sun Valley, USA			
3	PhD Thesis	S.Sanchez-Cervera	Methodologies for assessing neutronics-related uncertainties in best estimate transient analysis	Defence in 2016	UPM, Madrid	Scientific Community, (Higher education, research, industry)		Countries developing nuclear energy
4	PhD Thesis	G.Rucabado (UPM)	Numerical Methods acceleration in special computer architecture	Defence in 2017	UPM, Madrid	Scientific Community, (Higher education, research, industry)		Countries developing nuclear energy
5	PhD Thesis	A.Sabater (UPM)	Development of neutronic/thermohydraulic coupling for best-estimate analysis in transients for safety margins optimization in nuclear reactors	Defence in 2017	UPM, Madrid	Scientific Community, (Higher education, research, industry)		Countries developing nuclear energy

6	Presentation	G.Jimenez (UPM)	NURISP multiphyiscs achievements (FLICA/COBAYA and FLICA/DYN3D)	18/06/2014	NURESAFE General Seminar, Budapest	Scientific Community, (Higher education, research, industry)		Countries developing nuclear energy
7	Presentation	C.Ahnert (UPM)	Capacities and achievements of the COBAYA4 code after the NURESAFE project	04/11/2015	NURESAFE General Seminar, Brussels	Scientific Community, (Higher education, research, industry)		Countries developing nuclear energy
8	Oral presentation to a scientific event	Karlsruher Institut fuer Technologie	Advanced Numerical Simulation for Reactor Safety	15/10/2013	FISA 2013, Vilnius	Scientific community (higher education, Research) - Industry		
9	Oral presentation to a scientific event	Commissariat A L'energie Atomique Et Aux Energies Alternatives	The European NURESAFE simulation project for reactor safety	10/07/2014	ICONE22 conference, Prague	Scientific community (higher education, Research) - Industry		
10	Oral presentation to a scientific event	Karlsruher Institut fuer Technologie	Sensitivity Analysis of the Oskarshamn-2 Stability Event Using the Uranie software	15/12/2014	NUTHOS10 conference, Okinawa (Japan)	Scientific community (higher education,		Countries developing nuclear energy

						Research) - Industry		
11	Oral presentation to a scientific event	Universita Di Pisa	Validation of the FFTBM-based methodology for evaluation of uncertainty of system code input parameters	10/07/2014	ICONE22 conference, Prague	Scientific community (higher education, Research) - Industry		
12	Oral presentation to a scientific event	Institut Jozef Stefan	Simulation of flooding waves in vertical churn flow	10/09/2014	CFD4NRS-5 conference, Zûrich	Scientific community (higher education, Research) - Industry		
13	Oral presentation to a scientific event	Commissariat A L'energie Atomique Et Aux Energies Alternatives	Two-phase cfd validation: TOPFLOW-PTS steady-state steam-water tests 3-16, 3-17, 3-18, 3-19	10/09/2014	CFD4NRS-5 conference, Zûrich	Scientific community (higher education, Research) - Industry		Countries developing nuclear energy
14	Oral presentation to a scientific event	Helmholtz-Zentrum Dresden-Rossendorf Ev	CFD based approach for modeling direct contact condensation heat transfer in two-phase turbulent stratified flows	22/11/2013	International Colloquium 150th Birthday of Richard Mollier, Dresden	Scientific community (higher education, Research) - Industry		
15	Oral presentation to a scientific event	Institute Of Nuclear Research And Nuclear Energy - Bulgarian Academy Of Sciences	Generation and Testing of XS Libraries for VVER Using APOLLO2 and TRIPOLI4	28/10/2013	SNA + MC 2013 conference , Paris	Scientific community (higher education, Research) - Industry		Countries developing nuclear energy

16	Oral presentation to a scientific event	ASCOMP GmbH	Large Eddy & Interface Simulation (LEIS) of turbulent flow and convective boiling in a PWR rod bundle	27/05/2013	8th International Conference on Multiphase Flow, Jeju (Korea)	Scientific community (higher education, Research) - Industry			
17	Oral presentation to a scientific event	Universite Catholique De Louvain	Choked Flows Relevant to LOCA DEM model and implementation in system codes	17/11/2013	IMECE 2013 conference - Novak Zuber symposium, San Diego (USA)	Scientific community (higher education, Research) - Industry			
18	Oral presentation to a scientific event	Commissariat A L'energie Atomique Et Aux Energies Alternatives	Multiscale thermalhydraulic analyses performed in the NURESAFE project	10/07/2014	ICONE22 conference, Prague	Scientific community (higher education, Research) - Industry			
19	Oral presentation to a scientific event	Universite Catholique De Louvain	Delayed equilibrium model (DEM) of flashing choked flow relevant to LOCA and implementation in system codes	09/07/2014	ICONE22 conference, Prague	Scientific community (higher education, Research) - Industry			
20	Oral presentation to a scientific event	Institut Jozef Stefan	Analysis of Gas-Liquid Churn Flow in a Vertical Pipe	10/09/2013	Conference: Nuclear Energy for New Europe, Ljubljana	Scientific community (higher education, Research) – Industry			

21	Oral presentation to a scientific event	Universite Catholique De Louvain	Uncertainty analysis of delayed equilibrium model (DEM) using the CIRCE methodology	02/09/1015	NURETH 16 Conference, Chicago	Scientific community (higher education, Research) – Industry		
22	Oral presentation to a scientific event	Universita Di Pisa	Validation of CATHARE TH-SYS code against experimental REFLOOD tests	02/09/2015	NURETH 16 Conference, Chicago	Scientific community (higher education, Research) – Industry		
23	Oral presentation to a scientific event	Universita Di Pisa	Development and assessment of a method for evaluating uncertainty of input parameters	02/09/2015	NURETH 16 Conference, Chicago	Scientific community (higher education, Research) – Industry		
24	Oral presentation to a scientific event	Universite Catholique De Louvain	Implementation and assessment of the delayed equilibrium model for computing flashing choked flows in a multi-field CFD code	02/09/2015	NURETH 16 Conference, Chicago	Scientific community (higher education, Research) – Industry		
25	Oral presentation to a scientific event	ENEA (Italy)	Boiling flow in a vertical rectangular channel simulation using NURESAFE platform CFD codes	02/09/2015		Scientific community (higher education, Research) – Industry		
26	Oral presentation to a scientific event	Lappeenranta University of Technology (LUT)	Numerical study of direct contact condensation of steam on stable interface in a BWR suppression pool test facility	02/09/2015		Scientific community (higher education, Research) – Industry		

27	Oral presentation to a scientific event	Lappeenranta University of Technology (LUT)	CFD modelling of chugging condensation regime of bwr suppression pool experiments	02/09/2015		Scientific community (higher education, Research) – Industry		
28	Oral presentation to a scientific event	UNIVERSITA DI PISA	Assessment of NEPTUNE_CFD Code Capabilities to Simulate Two- Phase Flow in the OECD/NRC PSBT Subchannel Experiments	15/09/2015		Scientific community (higher education, Research) – Industry		

Section B (public)
Part B1

The applications for patents, trademarks, registered designs, etc. shall be listed according to the template B1 provided hereafter.

The list should, specify at least one unique identifier e.g. European Patent application reference. For patent applications, only if applicable, contributions to standards should be specified. This table is cumulative, which means that it should always show all applications from the beginning until after the end of the project.

TEMPLATE B1: LIST OF APPLICATIONS FOR PATENTS, TRADEMARKS, REGISTERED DESIGNS, ETC.					
Type of IP Rights[6]:	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Application reference(s) (e.g. EP123456)	Subject or title of application	Applicant (s) (as on the application)

[6] A drop down list allows choosing the type of IP rights: Patents, Trademarks, Registered designs, Utility models, Others.

Part B2 (public)

The concrete output of the project consists of the codes included into the NURESIM platform. Codes can be used standalone or coupled with some other platform codes. To use most of the codes, just ask the owner of the code for a user license agreement. In principle, licenses are free for use limited to research and development purposes.

Code	Scope	Highlights	How to get the code	Contact person
	Common generic tools			
SALOME	Software that provides a generic platform for pre and post-processing and coupling for numerical simulation	Open source Includes CAD (Computer Aided Design) interface Website: http://www.salome-platform.org/	Open-source software, can be downloaded from the website	
URANIE	Software that provides a generic platform for uncertainties analysis for numerical simulation	Based on ROOT software developed by CERN for large database numerical processing. Website: **http://sourceforge.net/projects/uranie/**	Open-source software, can be downloaded from the website	
	Reactor system simulators			
CATHARE	Analysis of the whole spectrum of leaks and transients in PWRs and BWRs	CATHARE2 with 2-fluid model: Extensive validation for PWR CATHARE-3: R&D version with multi-field, Transport of Interfacial area and turbulence modeling capabilities in 0D, 1D and 3D Website: http://www-cathare.cea.fr/scripts/home/publigen/content/templates/show.asp?L=EN&P=134	Ask CEA for a User License agreement Contact person:	patrick.blanc-tranchant@cea.fr
ATHLET	Analysis of the whole spectrum of leaks and transients in PWRs and BWRs	Validation for PWR & BWR Website: http://www.grs.de/en/computer-code-athlet	Ask GRS for a User License agreement ww.grs.de	kiril.Velkov@grs.de
	Core simulators			
COBAYA4	PWR and BWR Core simulation inc. neutronics and a simplified thermal-hydraulics model, for normal operation and transients	2D, 3D, cartesian, hexagonal geometries. Multigroup diffusion with IDF (Interface Discontinuity Factors). Pin-by-pin & nodal solvers. Domain decomposition, Parallelization. Steady state and transient problems. Specific simplified thermal-hydraulics capacity	Ask UPM for a User License agreement	carolina.ahnert@upm.es
DYN3D	PWR and BWR Core simulation inc. neutronics and a simplified thermal-hydraulics model, for normal operation and transients	3D cartesian, hexagonal, triagonal geometries. Multigroup solvers: Diffusion and SP3 Pin power reconstruction Steady state and transient problems. Specific simplified thermal-hydraulics capacity	Ask HZDR for a User License agreement	Soeren Kliem (s.kliem@hzdr.de)
Code	**Scope**	**Highlights**	**How to get the code**	**Contact person**
CRONOS	PWR and BWR Core simulation inc. neutronics and a simplified thermal-	1D, 2D, 3D, cartesian, cylindrical, hexagonal geometries. Multigroup Solvers: Finite differences, Pn and Sn Transport. Static and kinetic calculations.	Ask CEA for a User License agreement	patrick.blanc-tranchant@cea.fr

	hydraulics model, for normal operation and transients	Burnup simulation nuclide by nuclide Specific simplified thermal-hydraulics capacity		
Neutronics				
APOLLO2	Lattice code for PWR and BWR: cross-section generation for core-simulators Reference deterministic simulations.	2D spectral and core code. Multigroup and Multiparameter XS's generation. MOC solvers, collision probability solvers	Ask CEA for a User License agreement	patrick.blanc-tranchant@cea.fr
TRIPOLI4	Monte-Carlo code applicable for core physics, criticality and shielding studies	Monte Carlo method to simulate neutron and photon behaviour in three-dimensional geometries Static and kinetic calculations	This code can be downloaded for free from the OECD NEA website, under a standard license agreement	patrick.blanc-tranchant@cea.fr
Thermal-hydraulics				
NEPTUNE_CFD	CFD 2-phase thermal-hydraulics code	2-fluid & multi-fluid 2-phase CFD (Computational Fluid Dynamics) Models for boiling bubbly flow and for free surface flow Developments on-going for all flow regimes	Ask EDF for a User License agreement	patrick.blanc-tranchant@cea.fr
TRIO_U	Single-phase CFD Two-phase pseudo-DNS	Single phase CFD (RANS & LES) 2-phase pseudo DNS with Interface Tracking Method http://www-trio-u.cea.fr/	Open-source software, can be downloaded from the website	
TransAT	Single-phase CFD Multiphase CFD & CMFD	Phase average N-phase model Interface Tracking Phase change heat transfer Lagrangian droplet tracking (2 way) Compressible multiphase flow	Ask ASCOMP for a User License agreement	Djamel Lakehal (lakehal@ascomp.ch)
FLICA	Sub-channel core thermal-hydraulics	Two phase TH simulation for BWR and PWR	Ask CEA for a User License agreement	patrick.blanc-tranchant@cea.fr
SUBCHANFLOW	Sub-channel core thermal-hydraulics	Single and two phase (mixture) subchannel code for water, sodium, lead and gas cooled reactors. Fast running implicit fix-point iteration solver with axial plane wise matrix solution. Applicable to LWR & Innovative reactors (SFR) Website : http://www.inr.kit.edu/632.php	Ask KIT for a User License agreement	victor.sanchez@kit.edu
COBRA-TF (CTF)	Multipurpose subchannel thermal-hydraulics	Two-phase, three field equations models, flexible geometry definition for PWR and BWR applications, improved numerical solvers, parallelization, vertical and horizontal flow regimes, RPV and core thermal hydraulics, up-flow and reverse flow, boron tracking models, etc.	Ask North Carolina State University for a User License agreement	Kostadin Ivanov (knivanov@ncsu.edu)
Fuel-Thermomechanics				
Code	**Scope**	**Highlights**	**How to get the code**	**Contact person**
DRACCAR	Fuel behaviour during LOCA, Spent fuel pool LOCA,	3D thermos-mechanics modeling from a single rod to a full core. Modeling of fuel rods ballooning, contact between rods, fuel relocations, cladding oxidation under steam and air conditions, hydriring, impact on flow and fuel cooling and integrity.	Ask IRSN for a User license agreement	francois.barre@irsn.fr

SCANAIR	Single Fuel Rod behavior during RIA	2D thermomechanical modeling of a single rod Specific model for clad behavior during RIA ‘included rupture modelling) Specific Thermalhydraulics and fission gas behavior models for RIA	Ask IRSN for a User license agreement	francois.barre@irsn.fr

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