1 Publishable summary

1.1 Objectives

The target of the NURISP Collaborative Project is to make new and significant steps towards a European Reference Simulation Platform for applications relevant to present PWR and BWR and to future reactors. The roadmap of this Simulation Platform will be proposed to be part of the future Strategic Research Agenda of the Sustainable Nuclear Energy Technology Platform (SNE-TP).

The first step towards this ambitious target has been made during the FP6 NURESIM Integrated Project. The NURISP project will start from this basis and develop further the already common and well-proven NURESIM informatics platform. It will also strengthen and enlarge the united team of top level international experts already federated during the NURESIM project and it will transform it into a European pole of excellence in reactor safety computation.

The platform will provide a more accurate representation of the physical phenomena by developing and incorporating into “best estimate” codes the latest advances in core physics, two-phase thermal-hydraulics and fuel modelling. The project will also develop significant capacities for multiscale and multiphysics calculations, and for deterministic and statistical sensitivity and uncertainty analysis, facilitating their use in a generic environment.

New codes will be connected to the platform and new steps will be made for integration, model development (including fuel), coupling, sensitivity and uncertainty analysis, and validation, with broader applications. During the course of NURISP, the focus will be on present (GEN-II) and future (GEN-III) PWR, VVER and BWR, but care will be taken to use generic methods so that future extension to GEN-IV reactors will be possible.

The objectives of NURISP will be realised through six Sub-Projects:

- SP0 (networking);
- RTD Sub-Project 1 (SP1): Core Physics (Coordinator: UPM);
- RTD Sub-Project 2 (SP2): Thermal-Hydraulics (Coordinator: CEA);
- RTD Sub-Project 3 (SP3): Multi-Physics (Coordinator: PSI);
- RTD Sub-Project 4 (SP4): Model Validation & Calibration, Sensitivity and Uncertainty Quantification (Coordinator: KIT-U);
- RTD Sub-Project 5 (SP5): Integration (Coordinator: CEA).

22 organizations participate in NURISP: ASCOMP, CEA, CHALMERS, EDF, FZD, KIT/FZK, GRS, IMPERIAL COLLEGE, INRNE, IRSN, JSI, KFKI, KTH, LUT, NRI, PSI, TUDELFT, UCL, KIT/UNIKA, UPISA, UPM, VTT. They come from 14 European countries: Belgium, Bulgaria, Czech Republic, Finland, France, Germany, Hungary, Italy, Netherlands, Slovenia, Spain, Sweden; Switzerland, United Kingdom.

The overall objective of the Core Physics Sub-Project (SP1) is the development, verification and demonstration of advanced Core Physics safety-relevant numerical simulation codes and tools for the present generation of reactors, including power and research reactors, and also the future generations of reactors. To achieve this goal, it is necessary to build and validate the NURESIM-platform with capacity to simulate neutron kinetics at the needed resolution in the neutron energy, spatial and time scales and to provide consistent coupling with thermal-hydraulics and fuel thermo-mechanics.

The specific objectives of the Core Physics subproject are:

- To achieve the final stages of development of a mature system of neutron kinetics codes for safety-relevant numerical simulation with well-established calculational routes that are consistent in terms of data (nuclear cross-sections and other data,…), modelling options (mesh, solution order, …) and code integration. One of the relevant beyond the state-of-the-art objectives is to develop pin-by-pin neutronics analysis needed for improved understanding of safety margins. Moreover a demonstration of very large Monte Carlo simulation will be investigated in order to open a field in the capabilities of code simulation for reactor safety and design.
- To achieve the verification/demonstration process of the platform by furnishing the tools in order to compute realistic power plant configurations and/or experimental facilities, in coordination with the other subprojects.
The overall objective of the thermalhydraulic Sub-Project (SP2) is the development and qualification of advanced thermalhydraulic numerical simulation tools for reactor safety in order to contribute to a European pole of excellence in reactor safety computations.

To achieve this goal, it is necessary to build and validate a common standardized European software platform able to simulate flow phenomena at four spatial scales and to provide easy coupling with neutronics and fuel thermo-mechanics. The NURESIM project of 6th FP addressed mainly the meso-scale (CFD in open medium) with some applications of the micro-scale (Direct Numerical Simulation). The platform will now also include a new generation of standardized modules for component scale and system scale to build the next generation of experimentally validated "best estimate" tools for modelling present and future PWRs, VVERs, BWRs, and research reactors. Coupling between the four spatial scales will be further developed in order to perform more precise computations, with a local zoom when and where necessary.

Multi-scale analysis and multi-scale coupling of thermalhydraulic tools and coupling of thermalhydraulics with other disciplines will be used to investigate safety issues such as PTS (Pressurized Thermal Shock), CHF (Critical Heat Flux), LOCA (Loss of Coolant Accidents) and steam condensation. PTS will be investigated through coupling of system and CFD codes and validated with the new data of the TOPFLOW and ROSA (OECD-NEA test program) test facilities. Based on the results of FP6 actions, two-phase CFD tools are further developed, improved, and validated on new available experimental data including data from NEA database, in a new step towards their industrial application. Thanks to the involvement of several partners in OECD-NEA Committees and Working Groups, strong interactions with these international activities will be effective.

A first objective of the Multi Physics Sub-Project (SP3) is to develop and demonstrate beyond the state-of-the-art simulation capabilities for improved understanding of safety margins, which requires that multi-physics simulations be extended to the pin-by-pin scale of the fuel pins and subchannels.

The second objective of SP3 is to fully integrate a range of thermal-hydraulic, core physics (neutronics) and fuel thermo-mechanics codes and solvers within the SALOME platform to form an integrated European platform with the aim of providing a state-of-the-art code system to support safety analysis of current and evolving LWRs. The integration will include common post-processing and common data structure.

The third objective (to drive the future platform development) is a high-fidelity tool consisting of the coupling of a system thermal-hydraulic code with a pin-by-pin 3D-neutron transport tool and the corresponding core thermal-hydraulic code, a thermo-mechanic fuel behaviour code and also including a CFD tool will allow for reference-type solutions, initially for asymmetric PWR transients with strong 3D-effects on mixing in parts of the system. In the current project, first steps towards this objective will be made.

The Sub-Project Validation & Calibration & Sensitivity and Uncertainty (SP4) aims at providing essential tools for developing predictive experimentally validated "best-estimate" tools, within the NURESIM simulation platform, modelling thermal-hydraulics and core physics phenomena for LWRs (PWRs, VVERs and BWRs) of current and future generations. The simulation tools developed within this Sub-Project are generic, and could also be used for Gen-IV reactors. This would be particularly important for designing new technologies and facilities based on novel processes, while striving to avoid, as much as possible, the costly and lengthy procedures of building representative mock-up experiments which might confirm—but would not necessarily explain— the predictions of simulation tools.

The tools developed within SP4 will help to identify uncertainties and shortcomings (within allocated manpower and computational resources) for the major neutronics and thermal-hydraulics codes which are part of the NURISP platform. Such uncertainties arise from imprecisely known parameters, modeling errors, boundary and/or initial conditions.

The overall objective of the integration Sub-Project (SP5) is to build with the other sub-projects a qualitatively improved European platform (NURESIM), which will integrate in a simulation framework (SALOME) thermal-hydraulic, neutronics and fuel thermo-mechanics codes and solvers. Integrated codes and SALOME simulation tools will work concurrently within the applications specified and developed by the other sub-projects.

The integration team will assist and advise the partners in integrating their modules and codes. It will provide specific training to enhance autonomy, efficiency and advanced usage of SALOME platform features. It will also participate to specification and development of integrated applications, and adapt the SALOME platform to meet the requirements of these applications.
1.2 Work since beginning of project

1.2.1 Core physics

To deliver the next generation of the best estimate tools for reactor safety and next generation reactor design, all the neutronics platform software (APOLLO2, TRIPOLI4, COBAYA, CRONOS2, DYN3D) to be used for this sub-project were delivered, implemented, and training sessions were organized.

The “Status and limits of current methods for plant analysis” was released. This document covers the state of the arts of the core physics codes, data and implementation as well as limits of the present core physics codes for GEN IV reactors.

Regarding Monte-Carlo codes, the work during the first period of the project aims at adding a smart static thermal-hydraulic feedback capability to TRIPOLI4, the NURESIM reference Monte Carlo code. An efficient method to obtain cross section data at different temperatures that occur during the iterations to obtain the thermal-hydraulic equilibrium state has been developed. Implementation of the interface between the Monte Carlo code and a 1-D thermal-hydraulics code to transfer the local power to the thermal-hydraulics model and to feedback is underway.

For deterministic codes, the new generation of NURESIM codes offers a finer spatial resolution down to pin-wise and is applicable to heterogeneous core problems. For this purpose, advanced heterogeneous cell and assembly discontinuity factors or jumps for pin-cell and nodal meshes finite-difference corrected diffusion have been developed.

1.2.2 Thermalhydraulics

All the thermalhydraulic platform software (NEPTUNE-CFD, TransAT, CATHARE & Pilot code, ATHLET) to be used for this sub-project were delivered, implemented, and training sessions were organized.

The status and limits of current methods in thermalhydraulics for plant analysis was defined by considering capabilities and limitations of the thermalhydraulic simulation codes, including macroscopic codes (system codes and component codes) and the CFD codes. This document focuses on the physical modelling aspects of the codes and, in the second part, on CFD code application to DNB, to PTS, to BWR core thermalhydraulics and to steam discharge in a pool.

Concerning PTS, first air-water TOPFLOW PTS tests were analyzed and simulated either with a RANS approach (FZD, IRSN) or a LES method (PSI) and attention was focused on the possible stratification of the flow in the injection line which affects the behaviour in the cold leg. Further benchmarking will be done with steam-water tests. RANS and VLES simulations of a COSI test and on SWST test (Lim et al data) were done and the comparison will be reported in the second half of the project. A ROSA test relative to the PTS issue was simulated by the ATHLET system code and by a CFD code prior to coupled simulation. The first steps of this work are satisfactory and predictions are close to the measurements. Condensation induced water-hammer tests were simulated with a 1D 2-fluid model with some success at least for high initial water level.

A literature review was made on possible DNB mechanisms looking for a local criterion to be used in CFD simulations. Unfortunately there is no consensus on the DNB mechanism itself and no local DNB criterion was found in the literature for convective boiling which could be implemented in a CFD code. In a short term, CFD may use semi-empirical criterion but a long term activity is required in view of identifying the actual mechanism of DNB in forced convective boiling with possible new experiments and DNS simulations. The current standard wall model of nucleate boiling is not able to detect accurately the CHF value in DEBORA CHF tests. Simulations of boiling flow in tube and rod bundle geometry with Departure from Nucleate Boiling (DNB) show that a criterion based on a limiting local void fraction is not so bad and attempts to develop other criteria still did not succeed.

Concerning BWR Thermalhydraulics, new models are developed for annular-mist flow in particular for predicting droplet deposition. A comparison is made with previous predictions obtained with a Lagrangian particle tracking method. For simulations of steam discharge in a pool, RANS, VLES and DNS methods are considered and some results are obtained. A RANS approach of a simple test are satisfactory whereas a DNS is found too CPU consuming. First simulations of a more unstable test are done which encounter more
difficulties. Attempts to develop a VLES approach are in progress. A comparison of predictions with the 3-field model of CATHARE-3 with experimental data shows some disagreements to be further analyzed.

In the work-package about LOCA, 3D analysis of BFBT and PSBT benchmark experiments with CATHARE-3 provide a unique way of validating void fraction prediction in convective boiling in a real rod bundle geometry. Some improved results are obtained with addition of a turbulent dispersion force. A Lagrangian-Eulerian description of steam-droplet mixture in conditions relevant for LOCA is being developed which could help to improve Reflood modelling at system scale. Precise data were produced about heat transfer of an impinging drop on a hot surface. A radiation modelling for reflooding of a ballooned rod bundle is in progress. Some steps were done towards an improved choked flow prediction using a Delayed Equilibrium Model (DEM) which has to be adapted to the existing system code equations.

### 1.2.3 Multiphysics

The integration of the 3D-fuel-behavior code DRACCAR into the SALOME platform has been done. DRACCAR is coupled to the system code CATHARE in order to better simulate LOCA transients with ballooned fuel and pellet relocation. As DRACCAR has the capability to model a whole fuel-assembly, many new interesting multi-physics applications are foreseeable.

Also, TRIO-U (CFD) as well as CATHARE (system) have been coupled to the SALOME-platform via the ICOCO advanced programming interface. Furthermore, data for several benchmarks (BWR turbine trip, PWR boron dilution benchmark, VVER main steam line break) have been prepared for testing new coupling features of the coupled codes.

### 1.2.4 Validation and uncertainties

New methodologies to be implemented into the validation-sensitivity-uncertainties quantification platform URANIE have been analyzed and described:
- a formalism of polynomial chaos suitable to deal with global sensitivity analysis
- a method based on a more flexible framework than the probabilistic one in order to handle both aleatory and epistemic uncertainties (Rafu method)
- assessment of a method combining statistical and deterministic methods for sensitivity and uncertainty analysis; the objective is URANIE benefits from the strengths of both classes of methods while alleviating their respective weaknesses
- a rigorous methodology for computing best-estimate predictive results using experimental and computational information, using Bayes’ theorem in conjunction with information theory to assimilate consistently all available data

### 1.3 Potential impact and use

In view of its expected performance, the NURESIM-Platform will become a reference tool for Universities, Research Labs, Technical Safety Organisations and the Nuclear Industry.

A Users’ Group including vendors, utilities, technical support organizations (TSO), regulators and some more research organisations is established. It will expand the user-base of the platform, contribute to its qualification through a number of benchmark exercises and provide important feedback from its use for industrial scale applications. This group may also connect other codes to the platform in order to ease their comparison with the reference codes contained within the platform.

**Contact details**

Bruno chanaron - Commissariat à l’Energie Atomique (CEA), France, bruno.chanaron@cea.fr
Carol Ahnert - Universidad Politecnica de Madrid, Spain, carol@din.upm.es
Dominique Bestion – CEA, dominique.bestion@cea.fr
Martin Zimmermann - Paul Scherrer Institute, Switzerland, martin.zimmermann@psi.ch
Dan Cacuci - Karlsruhe Institute of Technology, Germany, dan.cacuci@kit.edu
Nicolas Crouzet (CEA), nicolas.crouzet@cea.fr
Franck-Peter Weiss – Forschung Zentrum Dresden, f.p.weiss@fzd.de

The website of the project is [http://www.nurisp.eu](http://www.nurisp.eu)