A DELINEATION OF ACTIVITIES IN THE CSNI WORKING GROUP ON THE ANALYSIS AND MANAGEMENT OF ACCIDENTS (WGAMA)

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The CSNI Working Group on the Analysis and Management of Accidents (WGAMA) is committed to advancing the understanding of the physico-chemical processes of accident phenomenology in current and advanced reactors. As a result, it addresses a broad spectrum of safety issues related to the reactor coolant system and the containment including safety and auxiliary systems for management of design-basis and severe accidents. The present paper is a succinct introduction of the group and the type of activities it conducts, with a short reference to the most recent ones and a few emblematic examples illustrating the significance of technical and safety orientation ever present in the topics addressed.

DESCRIPCIÓN DE LAS ACTIVIDADES DEL GRUPO DE TRABAJO SOBRE ANÁLISIS Y GESTIÓN DE ACCIDENTES (WGAMA) DEL CSNI

El Grupo de Trabajo en Análisis y Gestión de Accidentes (WGAMA) del CSNI tiene como fin último progresar en la comprensión de los fenómenos físico-químicos dominantes en situaciones accidentales de reactores nucleares actuales y futuros. Como consecuencia, su campo de actuación se extiende a un amplio espectro de fenómenos relacionados con la refrigeración del reactor y la contención de las potenciales consecuencias tanto en accidentes base del diseño como severos, incluyendo sistemas de seguridad y auxiliares implicados en su gestión. El presente artículo presenta de modo sucinto el grupo WGAMA mediante la descripción del tipo de actividades que aborda, con particular alusión a los resultados más recientes obtenidos. Además, se discuten con mayor detalle algunas contribuciones emblemáticas que ilustran el nivel técnico y la importancia para la seguridad de los problemas abordados por el grupo.

INTRODUCTION

The Working Group on the Analysis and Management of Accidents (WGAMA) was created on December 31st 1999. It is one of the nine groups of the Committee for the Safety of Nuclear Installations (CSNI), which is responsible for the promotion of Nuclear Safety among the 33 member states of the Nuclear Energy Agency (OECD/NEA). Figure 1 shows the CSNI working groups structure and OECD/NEA joint projects; the WGAMA group is highlighted.

The overall WGAMA objectives are to assess and strengthen the technical basis needed for the prevention, mitigation and management of potential accidents in nuclear power plants (NPP) and to facilitate international convergence on safety issues and accident management analyses and strategies. In order to fulfil these objectives, the Working Group exchanges technical experience and information relevant for resolving current or emerging safety issues, promotes the development of phenomena-based models and codes used for the safety analysis, assesses the state of knowledge in areas relevant for the accident analysis and, where needed, identifies and fosters research activities aimed at improving such understanding, while supporting the maintenance of expertise and infrastructure required for nuclear safety research. The intention is always to make significant contributions to the regulatory decision-making on prevention and management of accidents, reactor safety capacity building, continuously improving the state of knowledge and knowledge management.

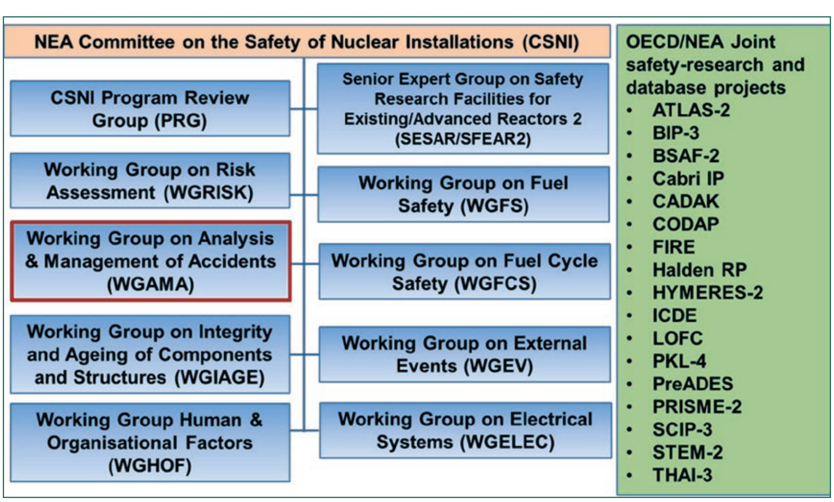

Figure 1. Working Groups and Project under the NEA/CSNI framework.

The specific scope of the group extends over a number of fields associated with both current and advanced reactors: reactor coolant system thermalhydraulics; in-vessel behaviour of degraded cores and in-vessel protection; containment behaviour and containment protection; and fission product release, transport, deposition and retention. Such a vast scope requires involving large resources, which in numbers translates to more than 100 registered working group members (the largest CSNI group), over 200 scientists and engineers involved in the running of activities and more than 25 technical reports published in the last 5 years, most of which have already been heavily referenced.

The present paper gives a brief introduction of WGAMA by describing the type of activities the group carries out and by summarizing the most recently finished activities. Emblematic examples illustrating the significance of technical and safety orientation ever present in the topics addressed, regardless the time at which they were produced, have been also described. Finally, the ongoing activities are enumerated in each of the fields within the WGAMA scope: thermal-hydraulics, computational fluid dynamics (CFD) and severe accidents. Given that the main aim of this paper is to foster reader's interest in WGAMA activities, a good number of references is given at the end of the paper and the full set of reports may be reached at https://www.oecd-nea.org/nsd/docs/indexcsni.html.

WGAMA ACTIVITIES

Regardless the field addressed, the WGAMA activities can be grouped in four major types: State Of the Art Reports (SOARs), technical reports (either technical opinion papers or "status reports"), International Standard Problems (ISPs), workshops and/or seminars.

SOARs are key scientific and technical references for the entire community that compiles the fundamentals, proper links to the supporting dataset and how they are implemented in the analytical tools presently being used; they are usually extensive reports that include a vast list of references so that they become the essential literature resource of those involved in the specific matter addressed for years. From that perspective, they turn into an essential cornerstone for knowledge transfer. Status reports are different from SOARs; their main focus is to report on how the specific issue is dealt with worldwide and as a result they are not usually so extensive and, even though they can contain some introduction of the issue fundamentals, they are not usually targeted towards disciplines, as SOARs do (i.e., nuclear aerosols), but towards any issue coming up at a time (i.e., Spent Fuel Pools following Fukushima). Finally, Technical Opinion Papers (TOPs) are much shorter documents whose main driver is to briefly summarize the main gaps still existing around a specific safety issue, so that decision makers can initiate projects to be launched under the NEA framework.

ISPs are code assessments against experimental data, representative of key phenomena and scenarios for the safety of nuclear reactors. They are a key instrument not just for validation of analytical tools, but also for fostering sharing of code user experience in modelling. Through these ISPs, it is not unusual to identify further need for codes and data that eventually will be embodied in roadmaps of code developers and experimentalists.

Workshops and/or seminars are meeting points of different nature that always foster technical discussions to add clarity to current understanding of a specific subject or issue. Sometimes, the workshops are organized around specific activities ongoing in the WGAMA, although not restricted to it, like the CFD4NRS workshop series; in other circumstances, specific presentations are requested to be prepared by experts so that the key bases for discussions are tabled and resolved during the event. One way or the other, the final session of these workshops is usually oriented towards examining the way forward, the potential avenues for work ahead, what is still missing and how to overcome any obstacle to reach the necessary maturity in the safety analyses within the WGAMA scope. As for seminars, the most outstanding example is the the seminar on transfer of competence, knowledge and experience gained through CSNI activities in the field of thermalhydraulics (THICKET), of which four seminars have already been held and one more is under preparation.

Something common to all the activities described above is that their corresponding reports usually include a section in which issues requiring resolution are identified and, occasionally, provide insights into the best way to address them. This has traditionally been a source of inspiration for WGAMA project intake under OECD/NEA framework in the last two decades. This being said, it is important to emphasize that OECD/NEA projects are not WGAMA activities per se, although all the members in WGAMA are invited to contribute if the project addresses an issue within the WGAMA scope.

RECENT FOOTPRINTS OF WGAMA

Since 2011, WGAMA has produced nearly 40 technical reports that have been approved by CSNI. Soon after the accident at the Fukushima Daiichi site, the group articulated a number of activities and four of those reports were closely linked to the accident: status report on filtered containment venting (NEA, 2014a); status report on hydrogen management and related computer codes (NEA, 2014b); status report on spent fuel pool loss of coolant/cooling accidents (NEA, 2015a); benchmarking on fast-running software tools used during accidents (NEA, 2015b).

In the area of thermal-hydraulics two pieces of work have been the flagships in this period: the evolution of the work on best estimate methods uncertainty and sensitivity evaluation (NEA, 2011a) through the PREMIUM activity (NEA, 2014c; NEA, 2016a) and the SOAR on scaling in system thermalhydraulics applications to nuclear reactor safety and design (NEA, 2016b). A short description of the steps taken on the former activity is given in the next section.

In the area of CFD, several CFD workshops for nuclear reactor safety applications (CFD4NRS-4, -5, -6) have been held and their proceedings have been made available (NEA, 2011b; NEA, 2014d; NEA, 2016c). Periodic benchmarks have been set up on single phase scenarios of relevance in nuclear safety, like the gas mixing in containment post-accident atmospheres and the potential break-up of stratified layers (NEA, 2016d) or the currently ongoing on the turbulent mixing of cold and hot water streams when water injection is activated in the course of an accident. In addition, key reports have been issued: a revision of the best practice guidelines for the use of CFDs in nuclear reactor safety application (NEA, 2014e); the second revision of assessment of CFD codes for nuclear reactor safety problems (NEA, 2014f); the phase 3 extension of CFD codes application to 2-phase flow safety problems (NEA, 2014g); and, very importantly, the review of uncertainty quantification methods for CFD (NEA, 2016e).

The area of severe accident has been particularly prolific in this period, fostered by the accident at Fukushima. More than 15 reports have been produced. Other than those mentioned at the beginning of this section, it is worth highlighting some others to fully perceive the dimension of the work completed: a phenomena identification ranking table on accidents in spent fuel pools (NEA, 2017a); an exercise on informing severe accident management guidance for nuclear power plants through analytical simulation (NEA, 2017b); a containment code validation matrix (NEA, 2014h); a SOAR on molten core-concrete interaction and ex-vessel coolability (NEA, 2016f); and others. Among this backdrop of extensive production, a report is considered a breakthrough for having addressed for the first time an issue of outstanding relevance: the long-term management and actions for a severe accident in a NPP. This status report looked at the three commercial nuclear power plant accidents and compiled the lessons learned concerning management of accidents once the reactors were made stable; in addition, through a classification of actions to be implemented in the long run, a number of activities requiring further research have been identified, which will be part of what has been defined as NI2015 (Nuclear Initiative 2050; https://www.oecd-nea.org/ndd/ni2050/).

EXAMPLES OF WGAMA CONTRIBUTIONS

In the next sections, some examples illustrating the depth and diversity of WGAMA contributions since its inception in each of the fields covered are given. It is worth noting that the studies chosen are not the most recent ones. The rationale behind their selection is, instead, having become a key milestone in each respective discipline and/or a pioneering work never addressed that way before. They all resulted in materials heavily referenced in the accident analysis community.

Thermalhydraulics

A sizable work program was established under the acronym of BEMUSE (Best Estimate Methods Uncertainty and Sensitivity Evaluation) to evaluate the practicability, quality and reliability of BE methods (NEA, 2006). In addition, an evaluation of uncertainties for nuclear reactor safety applications was performed to promote the use of these methods by the regulatory bodies and nuclear industry. The activity was divided into five phases. As test cases, the BEPU analyses of the LOFT L2-5 test and of a Large Break Loss-Of-Coolant Accident (LBLOCA) were proposed. This challenging activity concluded that the practicality and/or validity of these BE codes was not adequately established to support general use and to be accepted by industry and safety authorities. A systematic qualitative and quantitative accuracy evaluation of simulation results was performed, along with sensitivity analyses, and the lessons learned were used as guidance for deriving uncertainty bands in subsequent phases of BEMUSE. This initial BEMUSE activity attracted 14 participants with 6 thermalhydraulic codes.

The next step within BEMUSE was to simulate a cold leg double guillotine Large Break LOCA with the high-pressure injection system unavailable in a 4-loop 1040 MWe Westinghouse PWR (Zion NPP). The scenario was successfully simulated and the main parameters predicted with credible consistency. The predicted peak cladding temperatures (PCT) were quite close to one another (Figure 2), although the temporal variation of PCT and the timing of complete core rewet were inconsistent. The major differences among calculated results came from reflooding behaviour and timing and they were attributed to code effects. The exercise helped to understand the nuances of user effect and the need to differentiate user effect and code effect. In addition, participants (13 organizations; 6 thermalhydraulic codes) were able to identify the parameters that strongly affect PCT and reflood.

The final stage of the BEMUSE activity was to complete an uncertainty analysis of a LBLOCA analysis, us-

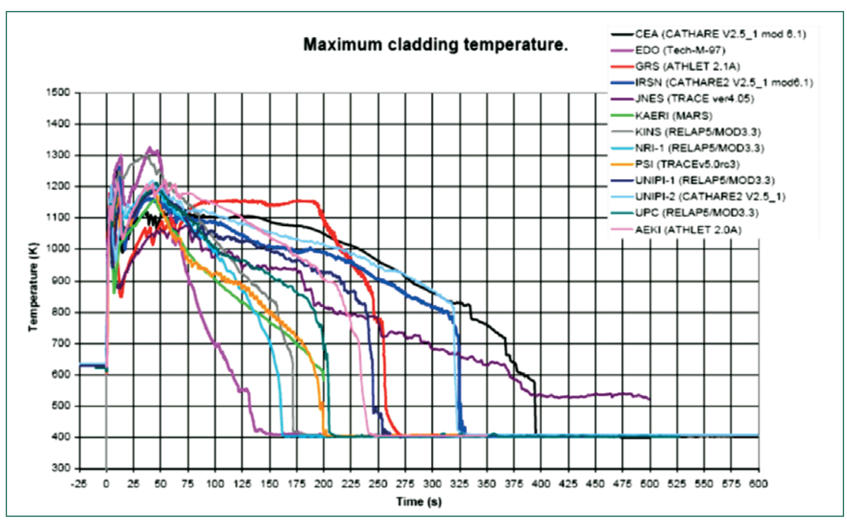

Figure 2. A comparison of calculated peak cladding temperature in BEMUSE (Zion exercise).

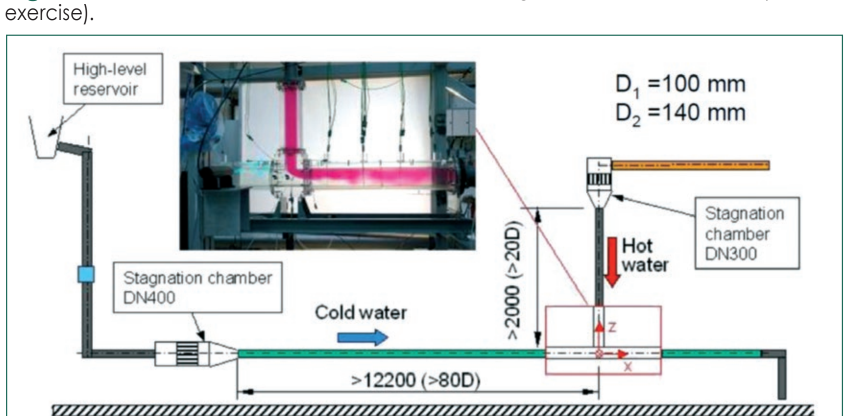

Figure 3. A schematic and a photographic view of Vattenfall T-Junction test apparatus.

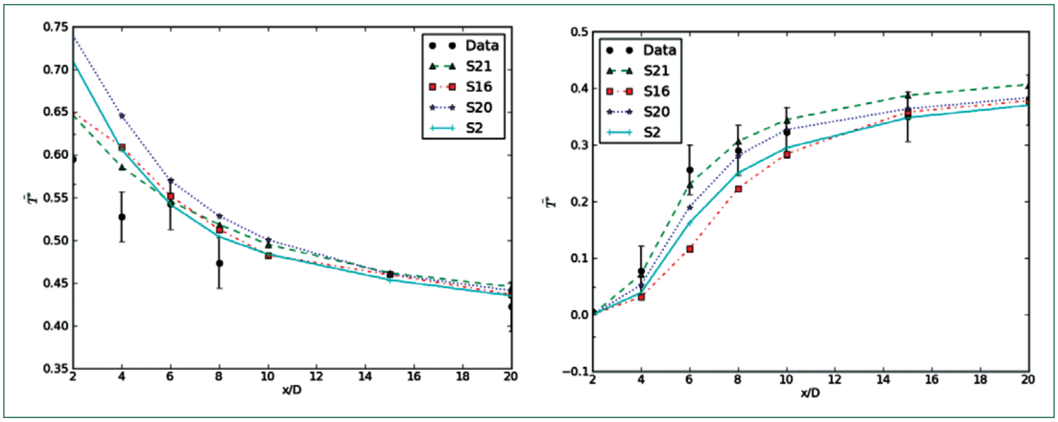

Figure 4. Time-averaged non-dimensional temperature at the downstream pipe.

ing the Zion exercise (NEA, 2008) as a reference calculation to obtain uncertainty bands for a number of variables (i.e., PCT; upper plenum pressure; maximum peak cladding temperature; time of complete core quenching; etc.). Two methods were applied to obtain uncertainty bands: the propagation of input uncertainty, and the propagation of output accuracy. The former method was used by 12 participants whereas just 2 participants used the latter. A main result of the activity was that all participants managed to obtain uncertainty bands with reasonable width (NEA, 2009). The overall results from the study were a step forward to consolidating the different methods, although familiarity with the technique was recommended to participants using the probabilistic approach.

The conclusions and recommendations mentioned in the previous paragraphs plus some others were synthesized in a summary report compiling the main insights stemming out from this long activity (NEA, 2011a).

CFD Applications in Nuclear Safety Analyses

An exercise on thermal fatigue in a T-Junction, where hot and cold streams of liquids merge and mix, was organized based on an *ad-hoc* experiment as described in NEA (2011c) (Figure 3).

Overall, the T-junction benchmark was very successful (Smith et al., 2011). The exercise complemented activities in other areas and helped in understanding the origins of thermal fatigue in this geometry. Different codes, different modelling approaches, and different numbers of control volumes were adopted by the various participants, and useful information was forthcoming from those who used the same code. Figure 4 compares non-dimensional measured and calculated T* values for select submissions denoted as S21, S16, S20 and S2. A simple heat balance calculation showed that T* = 0.38 for perfect mixing of the streams. The asymptotic dissipation in the left hand graph shows this trend very well in the experiment and calculations, where turbulent mixing gradually overcame the initial flow stratification.

Severe accidents

Even though a number of ISPs have been run in the area of severe accidents since WGAMA inception, the most interesting ISP conducted due to data representativeness and comprehensiveness of the scenario was the ISP-46 on the PHEBUS-FPT1 experiment (NEA, 2004). The ISP-46 attracted more than 30 teams, who submitted 47 base case calculations and 21 additional best estimate calcula-

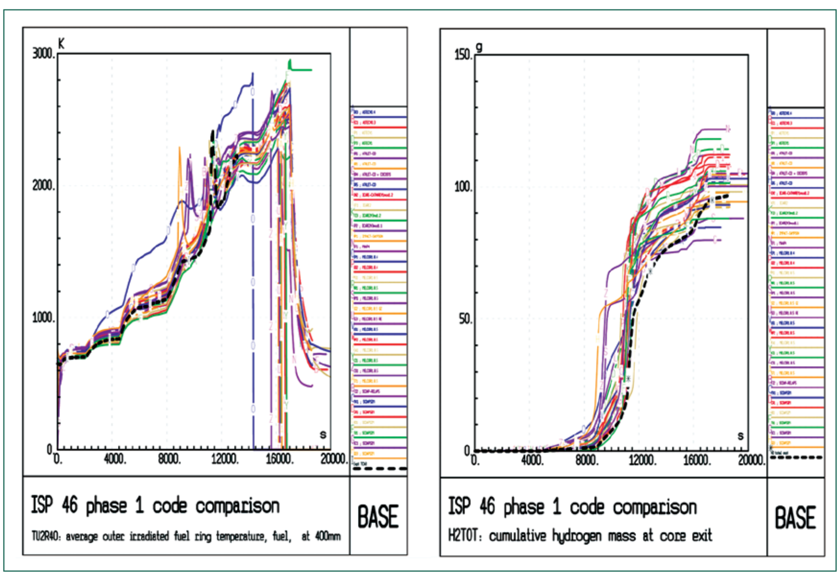

Figure 5. Variables describing core status during the degradation phase.

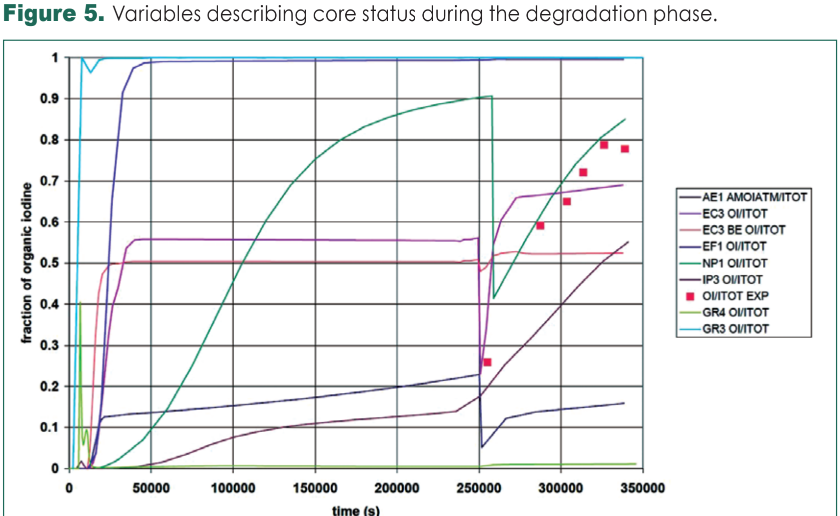

Figure 6. Organic iodine concentration in containment.

tions with 15 different codes. Major insights were gained from the data-estimate comparisons and from the code-to-code comparisons. Whenever key parameters were rightly chosen, the thermalhydraulic evolution and the H_2 production during the core degradation showed a good agreement and the final state of the core was reasonably predicted. Figure 5 shows code predictions along with data (black dash line) for core temperature and cumulative H_2 generation. Even though volatile fission products release were well predicted, large discrepancies existed when coming to semi-volatile and low-volatile fission products, which indicated the need for additional modeling improvements. But the major difficulties in getting good estimates were for iodine behavior in the PHEBUS containment, where there was a large scatter when iodine gas (particularly organic iodide) concentrations were estimated. Figure 6 plots the in-containment organic iodine predicted and measured (red dots) during the FPT1 test.

FINAL REMARKS

In the sections above, a brief introduction to WGAMA of NEA has been outlined by summarizing what has recently been produced. WGAMA is a very active working group of NEA who in the very last years has demonstrated an outstanding capability of response, being capable of shaping their activities to the prompt and demanding needs that stem from the Fukushima analysis without neglecting its own mandate, strategic initiatives and scheduled activities. Beyond how prolific the Group is in terms of Status Reports and State Of the Art Reports (SOAR), the diversity of the Group's activity is significant, encompassing a broad spectrum from education (THICKET) to code benchmarking activities. The continuous renewal of WGAMA commitment to providing technical support for the regulatory decision-making process has resulted in an ambitious current work program: a Source Term workshop (held in Jan. 2019); a specialist workshop on advanced instrumentation for thermalhydraulics and severe accident experiments (SWINTH-2019) to be held in Oct. 2019; an international Conference on Severe Accident Management (ISAMC), held on Oct. 2018; a status report on thermalhydraulic passive systems design and safety assessment; a CFD cold leg mixing benchmark including uncertainty quantification (CLM-BM); the preparation of the proceedings of the CFD4NRS-7; a status report on the capabilities of 3D thermal-hydraulic codes; a status report on the systematic approach for uncertainty quantification in thermalhydraulic codes (SAPIUM); and, finally, an update of the methods and tools for the application of CFD to nuclear safety, the database on two-phase flows and the requirements for CFD-grade experiments.

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REFERENCES

– NEA, 2004. "ISP-46 - PHEBUS FPT-1 Integral Experiment on Reactor Severe Accidents". NEA/CSNI/R(2004)18.
– NEA, 2006 "BEMUSE Phase 2 Report: Re-Analysis of the ISP-13 Exercise, Post Test Analysis of the LOFT L2-5 Test Calculation", NEA/CSNI/R(2006)2.
– NEA, 2008. "BEMUSE PHASE IV Report: Simulation of a LB-LOCA in ZION Nuclear Power Plant - Main Report", NEA/CSNI/R(2008)6/vol 1.
– NEA, 2009. "BEMUSE Phase V Report: Uncertainty and Sensitivity Analysis of a LB-LOCA in ZION Nuclear Power Plant", NEA/CSNI/R(2009)13.
– NEA, 2011a. "BEMUSE Phase 6 Report - Status report on the area, classification of the methods, conclusions and recommendations", NEA/CSNI/R(2011)4.
– NEA, 2011b. "Proceedings of the Workshop on CFD for Nuclear Reactor Safety Applications (CFD4NRS-3)", Bethesda, USA, September 14-16 2010, NEA/CSNI/R(2011)14.
– NEA, 2011c. "Report of the OECD/NEA - Vattenfall T-Junction Benchmark Exercise", NEA/CSNI/R(2011)5.
– NEA, 2014a. "Status Report on Filtered Containment Venting", NEA/CSNI/R(2014)7.
– NEA, 2014b. "Status Report on Hydrogen Management and related Computational Codes", NEA/CSNI/R(2014)8.
– NEA, 2014c. "- Post-BEMUSE Reflood Model Input Uncertainty Methods (PREMIUM) benchmark: phase II, identification of influential parameters", NEA/CSNI/R(2014)14.
– NEA, 2014d. "Proceedings of the Workshop on CFD for Nuclear Reactor Safety Applications (CFD4NRS-4)", Daejeon, South Korea, September 10-12 2012, NEA/CSNI/R(2011)14.
– NEA, 2014e. "Best Practice Guidelines for the Use of CFD in Nuclear Reactor Safety Applications – Revision. NEA/CSNI/R(2014)11.
– NEA, 2014f. "Assessment of CFD codes for nuclear reactor safety – Revision 2", NEA/CSNI/R(2014)12.
– NEA, 2014g. "Extension of CFD application to two-phase flow safety problems – Phase III", NEA/CSNI/R(2014)14.
– NEA, 2014h. "Containment Code Validation Matrix", NEA/CSNI/R(2014)3.
– NEA, 2015a. "Status Report on Spent Fuel Pools under Loss-of-Coolant Accident Conditions Final Report", NEA/CSNI/R(2015)2.
– NEA, 2015b. "Benchmark of Fast-Running Software Tools used to Model Releases during Nuclear Accidents - Final Summary Report", NEA/CSNI/R(2015)19.
– NEA, 2016a. "Post-BEMUSE Reflood Model Input Uncertainty Methods (PREMIUM) benchmark: phase V, final report", NEA/CSNI/R(2016)9.
– NEA, 2016b. "Scaling in System Thermal-Hydraulics Applications to Nuclear Reactor Safety and Design: a State-of-the-Art Report", NEA/CSNI/R(2016)14.
– NEA, 2016c. "Proceedings of the Workshop on CFD for Nuclear Reactor Safety Applications (CFD4NRS-5)", Zurich, Switzerland, September 9-11, 2014, NEA/CSNI/R(2016)14.
– NEA, 2016d. "The Nuclear Energy Agency/Paul Scherrer Institute Computational Fluid Dynamics Benchmark Exercise", NEA/CSNI/R(2016)2.
– NEA, 2016e. "Review of uncertainty methods for CFD", NEA/CSNI/R(2016)4.
– NEA, 2016f. "State-of-the-Art Report on Molten-Corium-Concrete interaction and Ex-Vessel Molten-Core Coolability", NEA/CSNI/R(2016)15.
– NEA, 2017a. "Phenomena Identification and Ranking Table (PIRT) on Spent Fuel Pools under Loss-of-Cooling and Loss-of-Coolant Accident Conditions", NEA/CSNI/R(2017)18.
– NEA, 2107b. "Informing Severe Accident Management Guidance and Actions for Nuclear Power Plants through Analytical Simulation", NEA/CSNI/R(2017)16.
– Smith B.L., Mahaffy J.H., Angele K. and Westin J., 2011. "Report of the OECD/NEA-Vattenfall T-Junction Benchmark Exercise", NEA/CSNI/R(2011)5.