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ETSON views on R&D priorities for implementation of the 2014 Euratom Directive on safety of nuclear installations

Following the Fukushima-Daiichi accident in 2011, the Council Directive 2014/87/Euratom has reinforced the previous 2009 Directive that had established a Community framework for the safety of nuclear installations. In particular, one new article introduces a high-level EU-wide safety objective of preventing accidents through defence-in-depth and avoiding radioactive releases outside a nuclear installation. For achieving this objective, the research necessary outcomes are mainly a better knowledge of the involved physical phenomena and its capitalization in methodologies and tools such as simulation codes. ETSON, the European Technical Safety Organisation Network, had already identified in its Position Paper in 2011 the main R&D priorities. The present paper underlines that most of these priorities, with a few updates due to progress of knowledge, remain consistent with the objectives of this new Directive. And it illustrates the ETSON involvement through examples of on-going or planned R&D national and international projects.

R&B Prioritäten zur Implementierung der 2014 Euratom Direktive Nukleare Sicherheit kerntechnischer Anlagen aus ETSON Sicht. *Nach den Unfällen in Fukushima-Daiichi im Jahr 2011 hat der Rat der europäischen Union in seiner Direktive 2014/87 die Ausführungen der Direktive aus dem Jahr 2009 erweitert. Letztere beinhaltet übergeordnete Anforderungen an die Sicherheit kerntechnischer Anlagen. In die 2014-er Direktive ist ein neuer Artikel eingeführt worden, in dem hochrangig und EU-weit die Vermeidung von Kernschmelzunfällen sowie die Freisetzung von Spaltprodukten in die Umgebung durch ein adäquates Defence-in-Depth-Konzept vorgeschrieben wird. Die Umsetzung der Direktive erfordert zunächst Forschungsaktivitäten zu ausgewählten physikalischen Prozessen und Phänomenen, deren Beschreibung mittels Modellen sowie die Implementierung dieser Modelle in Simulationsprogrammen. Das European Technical Safety Organisation Network (ETSON) hat bereits im Jahr 2011 die hierzu notwendigen Themen identifiziert und priorisiert. Der vorliegende Beitrag unterstreicht, dass zahlreiche der identifizierten Themen, auch heute noch relevant sind. Darüber hinaus gibt es – aufgrund der Fortentwicklung des Kenntnisstandes – zu einigen Themen einen zusätzlichen Forschungs- und Entwicklungsbedarf. Des Weiteren beschreibt der vorliegende Beitrag den Beitrag von ETSON Partner anhand von ausgewählten laufenden und geplanten nationalen sowie internationalen R&D-Aktivitäten.*

1 Introduction

The safety of nuclear energy production in the European Union (EU) is the primary responsibility of nuclear power plant (NPP) operators supervised by independent national regulators. An EU-wide approach to nuclear safety is important because a nuclear accident could have negative consequences for countries across Europe and beyond.

Following the Fukushima-Daiichi accident in 2011, the existing Council Directive 2009/71/Euratom that established a Community Framework for the safety of nuclear installations had to be reinforced: it has been done in July 2014 through the 2014/87/Euratom amending Directive. Its scope covers the following nuclear installations: NPP, nuclear fuel fabrication plant, enrichment plant, reprocessing plant, research reactor facility, spent fuel storage facility (plus storage facilities for radioactive waste on the same site).

Several articles of the Directive address the legislative, regulatory and organisational framework, the role of licence holders, the expertise and skills in nuclear safety and the information to the public. ETSON, the European Technical Safety Organisation Network, is the European association of nuclear assessment bodies (TSOs) that realize the technical evaluation of safety files in support of their national authorities. The network activities are closely linked to this Directive and in particular, regarding its research activities, to the fully new article 8 that addresses issues such as preventing accidents through defence-in-depth and, should an accident occur, mitigating its consequences and avoiding radioactive releases.

The objective of this paper is to underline the R&D priorities considered by ETSON on these aspects, in consistency with the ETSON position paper on R&D priorities that was released in 2011 [1], and to illustrate the ETSON members involvement through examples of on-going or planned new R&D projects (this list is absolutely not exhaustive).

2 The Euratom Directive and its links with R&D

The Directive 2009/71/Euratom provided Europe for the first time with a common safety framework based on the Euratom Treaty, making international nuclear safety principles legally binding in all Member States (MS). The objective of the Directive is to maintain and promote the continuous improvement of nuclear safety. MS shall provide for appropriate national arrangements for a high level of nuclear safety to protect workers and the general public against the dangers arising from ionizing radiation from nuclear installations.

The amending Directive 2014/87/Euratom, released in August 2014, takes account of a review of the EU framework on nuclear safety in the light of the Fukushima-Daiichi accident in 2011 and the findings of the EU stress tests exercise. It is based on various sources, such as the European Nuclear Safety Regulators Group (ENSREG), the Western European Nuclear Regulators' Association (WENRA) or the International Atomic Energy Agency (IAEA). MS will have to transpose the provisions of the directive in national law within three years. It reinforces the provisions of the 2009 directive by:

- strengthening the powers and independence of **national regulatory authorities** that supervise the activities of nuclear operators,
- introducing a **high-level EU-wide safety objective** to prevent accidents and avoid radioactive releases outside a nuclear installation,
- setting up a **European system of peer reviews** on specific safety issues (through ENSREG and WENRA),
- **increasing transparency** on nuclear safety matters (information and cooperation obligations and involvement of the public),
- providing for **regular safety reassessments** of nuclear installations,
- enhancing the consistency of national **on-site emergency preparedness and response** arrangements,
- highlighting the importance of the **human factor** by promoting an effective nuclear safety culture through management systems, **education and training** and arrangements by the operator.

For operating plants, this objective should lead to implement "reasonably practicable" safety improvements. For future plants, significant safety enhancements are foreseen, based on the state of science and technology.

More in details, the new Article 8 addresses the following issues:

- "Objective to prevent accidents and mitigating its consequences, avoiding: early releases requiring off-site emergency measures but with insufficient time to implement them, and large radioactive releases requiring protective measures that could be limited in area or time
- Defence-in-depth to ensure: minimizing the impact of extreme natural and unintended man-made hazards; preventing abnormal operation and failures; controlling abnormal operation and detecting failures; controlling DBA; controlling severe conditions, incl. prevention of accident progression and mitigation of SA consequences".

3 ETSON position paper

The ETSON Position Paper [1], published in October 2011 with the additional contribution of safety authorities SSM (Sweden), CSN (Spain) and KFD (Netherlands), presented the research needs according to their relevance-to-safety. It took into account the preliminary lessons learned from the Fukushima-Daiichi NPP accident. It allowed also ETSON contributing to the NUGENIA R&D roadmap that was published in a condensed version in October 2013 [2] and in a detailed version in April 2015 [3]. The following R&D priority needs that were identified in the ETSON position paper contribute, at a very large majority of them, to the objectives of the Article 8 of the 2014 Directive:

a. Safety assessment methods (safety margins methodology, deterministic and probabilistic approaches)
b. Multi-physics multi-scale safety approach (coupled tools and uncertainties)
c. Ageing of materials for a long-term operational perspective
d. Fuel behaviour (LOCA or loss of coolant accident, RIA or reactivity insertion accident, criticality)
e. Human & organisational factors in safety management
f. Instrumentation & control (I&C) systems
g. Internal and external loads and malicious acts (integrity of equipment and structures, fire propagation…)
h. Severe accidents phenomenology and management
i. Emergency preparedness and management

4 R&D priorities from ETSON point of view to implement this new Directive

The following sections 4.1 to 4.6 address the different issues underlined in the Article 8 of the new Directive.

4.1 Extreme natural and unintended man-made hazards

ETSON members contribute to the activities of the OECD/NEA WGRISK (Working Group on Risk Assessment) and of other groups such as the Working Group on Natural External Events. They also participate in the ASAMPSA_E (Advanced Safety Assessment Methodologies: extended PSA) FP7 project [4]. The project aims to extend the scope of PSA to all natural or man-made external hazards. Guidance is being developed on conducting extended PSAs in an efficient manner, and verifying that all dominant risks are identified and managed. This project allows the partners to share experience and make public their conclusions; at present the lack of publically available information is a significant hindrance to assessing extreme hazards events. Considering the very large scope and wide participation of ASAMPSA_E, it is reasonable to expect that further research work will be needed in this area.

The key requirement is for an integrated approach to hazard assessments, including external natural hazards. Such hazards should not be treated in isolation, as measures that protect against one hazard may be relevant to another; equally, protection against one hazard may exacerbate the effects of another. In addition, the distinction between internal and external hazards can be a hindrance: an external hazard can cause an internal hazard, and protection against both needs to be considered together. For example, a seismic event can cause fire and flooding, possibly at the same time.

The following recommendations for future work have been developed by Amec Foster Wheeler, based on experience and on a review of documents from IAEA, ASME, US DoE, SKI, NEA, ENSI, US NRC, NUREG and WENRA. They are consistent with the 2011 TSO position paper [1].

- **Integration of natural external hazards in the plant safety case and PSA**. This integration starts with the identification of a comprehensive list of hazards, the site specific screening of hazards, and continues to the definition of the design basis hazards and hazard combinations. These must then be integrated into the overall safety case and PSA. This is partially addressed in ASAMPSA_E through a study on screening approaches and existing experience on PSA for earthquake, flooding, extreme weather, lightning, air craft crash, biological infestation and man-made hazards. It is recommended that this is investigated further to develop a methodology applicable to all nuclear facilities.

- **Development of hazards PSA requirements.** If the risk from hazards and external hazards is to be numerically assessed, hazards PSA will need to be carried out. There is currently no consensus as to the requirement for full-scope hazards or external hazards PSA in the international licensing process, although individual hazards are normally assessed (in general fire and earthquake). It is recommended to carry out a survey of stakeholders to determine the present views and post-Fukushima expectations on future developments.
- **Hazard combinations.** Combination of hazards, including coincident and dependent events, needs to be part of hazards assessments in future, but there is little published information on this topic. This has been identified as a major issue by ASAMPSA_E partners, but practical solutions to implement the assessment of hazards combination seem to be beyond the state-of-the-art. It is recommended to gather available information and develop a methodology that can serve as a basis for future hazards assessments.
- **External events modelling.** There are no approved methodologies for assessment of external hazards; it is recommended that methodologies in use are identified, and recommendations made as to their applicability for licensing purposes. There continues to be a need for simulation of impacts from blast, aircraft and missiles.
- **Fire.** It is a major risk to NPP, and risk management relies on defence-in-depth. Several ETSON members participate to the PRISME2 (Fire Propagation in Elementary, Multi-room Scenarios) OECD/NEA project on fire experiments and modelling, led by IRSN. A new project AMENOFIS (Advanced Methods for the Evaluation of Noxious consequences Of Fires on Installations Safety), led by VTT, is proposed for the next H2020 call; it aims to produce new and improved methods, recommendations and guidelines to support fire PSA and performance-based fire safety design.
- **Human reliability.** Existing guidance on human reliability is insufficient for hazards PSA, especially with regard to dependencies and human interactions, confidence of personnel measurements and availability of increasing numbers of personnel (e. g. a crisis team or external support). This applies to PSA Levels 1, 2 and 3. It is recommended that the issue of human reliability following infrequent events and/or in extreme conditions is investigated further.
- **Simulators.** Current simulators simulate design basis events effectively, but the majority do not currently model beyond design basis faults and hazards. This is a major gap in current operator training, as procedures for severe accident conditions cannot be tested or practised. It is proposed that best practice in use of simulators for severe accident conditions should be established.

4.2 Preventing abnormal operation and failures, controlling abnormal operation and detecting failures

The prevention of abnormal operation and failures needs to address instrumentation, I&C and regulation systems, maintenance of equipment and systems, and operators actions. This is consistent with e) and f) above priorities coming from the ETSON Position paper. In this section, only the specific issue of electrical power supply systems is addressed.

The electrical transients in July 2006 at Forsmark-1 in Sweden and in May 2008 at Olkiluoto-1 in Finland revealed weaknesses in the general understanding of electrical power supply hazards to systems and components important to safety. Subsequent investigations showed that other units throughout the world also had weaknesses of a similar or related nature. There is therefore a need to better identify the potential challenges from the behaviour of the grid and in-plant generators to in-plant distribution systems.

The main R&D recent activities took place in the frame of OECD/NEA/CSNI (Committee on the Safety of Nuclear Installations) and addressed the behaviour of electrical systems. The ROBELSYS (ROBustness of ELectrical SYStems) Task Group, coordinated by IRSN, worked in 2013–2014 with participation in particular of BelV, GRS, JSI and NRA. The work was based on previous DIDELSYS (Defence In Depth of ELectrical SYStems) successive projects (2008–09 and 2010–2011) [5], coordinated by SSM (Sweden) where GRS and IRSN had participated. The ROBELSYS objective was to identify and discuss the lessons learned from the Fukushima-Daiichi accident as concerns the electrical systems and the provisions taken by various countries in terms of requirements and design in order to enhance their robustness, especially as regards the protection against extreme external hazards. A final workshop in April 2014 concluded on recommending CSNI to establish a permanent working group on electrical systems, based on the prime importance of electrical systems in ensuring the safety of NPPs and on the technical objectives identified with associated mid-term goals and longer term perspectives. Among the recommended actions that will need further R&D, the following ones concern mainly the TSOs:

- Conduct a hazard review to determine the plant-specific range of possible voltage surge transients (including anticipated lightning surges, symmetric and asymmetric faults, switching faults, generator excitation system malfunctions), and develop a design specification to be used as a basis to qualify existing or replacement equipment. Such a hazard review should consider the impact of such faults in conjunction with a single failed or delayed protective device operation.
- Review the possible impact of voltage surge transients propagating through uninterruptible power supply, rectifiers, and other power supplies, causing detrimental effects on safety system loads and confirm that protective settings are properly co-ordinated to assure incoming supplies to battery chargers are tripped before devices powered from the batteries are lost.

4.3 Defence in depth

The IAEA Report [6] emphasized that the application of the defence in depth concept should be improved at two levels: firstly the prevention of (severe) accidents through decay heat removal from the reactor core and the spent fuel pool (SFP), and secondly the protection of the containment integrity. Passive safety systems have the potential to create options and extra time in accidents characterized e. g. by loss of power and loss of cooling water.

The function of passive safety systems is directly based on physical phenomena such as gravity, natural convection, condensation and/or evaporation. Their effectiveness is independent of operator actions. Lower failure rates are, therefore, attributed to passive safety systems. Currently, the worldwide definitions of passive systems differ: the most widespread classification by IAEA [7], others by EPRI [8] or national regulations such as German Sicherheitsanforderungen an Kernkraftwerke [9]. These different definitions complicate the assessment of passive systems, the development of respective assessment methodologies and the comparison of active and passive safety systems [10].

Already in 1992 issues such as functional requirements, consideration of a single failure, required redundancy and diversity, quantification of reliability and omission of human interaction were discussed in [11]. Some of the above mentioned issues are not yet conclusively solved. Current remaining issues are [10]:

- Which initial and boundary conditions are needed for the operation of a passive system? Can it be assumed that these conditions are present on demand?
- How passive systems behave under deviating, extreme conditions?
- Is the passive system on demand in intact condition? Is it ensured that damages that could lead to a complete failure of a passive system can be reliably detected?
- How to test passive safety systems? How to evaluate the reliability of a passive system when it can be neither tested in representative conditions, nor inspected or maintained?
- How does aging of the materials and components influence the operation mode of the passive safety systems?
- How to evaluate the parallel operation and the mutual interactions of redundant trains of passive safety systems especially from the viewpoint of small driving forces?
- How to evaluate the mutual influence of different passive systems?
- What are the requirements for experimental and analytical evidences? What are the acceptance criteria?

Evidences to be used in nuclear procedures should meet the following minimum requirements:

- Performance of component tests and integral tests preferably with original geometries, materials, reactor typical and beyond design initial and boundary,
- Understanding and description of all relevant physical phenomena,
- Calculation of the experiments with at least one code and performance of sensitivity and uncertainty analyses,
- Comparison of experimental and analytical results (plausibility), comparison with other experiments and/or calculations.

The large number of outstanding issues highlights the need for further research and harmonisation of national regulations. In particular it concerns the a) priority on "Safety assessment methods" in the ETSON position paper.

Two R&D projects should be proposed to the next H2020 call that was published in October 2015:

- APASS (Assessment of Passive Safety Systems) on investigation and development of passive safety systems for residual heat removal from the reactor pressure vessel (RPV) or from SFPs, in particular for retrofitting to existing NPPs. The result of the project shall be a toolbox of component design, validated codes and numerical models, including test results of components as well as generic examples of the integration of such systems.
- NUSMoR (NUGENIA Small Modular Reactor) on definition of a generic European SMR design based on currently best available safety features and fulfilling the demand for higher safety. The project tackles ranking of gaps, experimental and analytical investigations (benchmarks of different codes, sensitivity and uncertainty analysis), development and EU-wide harmonization of requirements for proofs and success criteria in nuclear procedures.

4.4 Controlling DBA

A design basis accident (DBA) is a postulated accident (such as a pipe rupture or component failure) that must be controlled by the safety systems in such a way that effects on the environment are kept below the specified planning values of the Radiological Protection Ordinance, i. e. the effective dose to a worker or members of the public is less than 50 mSv. The IAEA Safety Requirements (NS-R-1) [13] consider all events that have a probability of occurrence more than once every 10,000 years. DBAs are used as boundary conditions to establish the design bases of the safety systems following a conservative approach. DBA conditions are calculated taking into account the less favourable initial conditions and equipment performances, and considering the single failure affecting the most global performance of the safety system. With regard to the design of structures and components, the margins result from both the methodology followed to define the loading conditions and the compliance with the stress limits defined by the design/manufacturing codes. Uncertainties are also determined by applying a conservative approach. The possibility of cliff-edge effects needs to be investigated and necessary margins have to be added to increase the capability of the Structure, System and Components (SSCs). In addition, a design margin could be added by the designer to cope with possible changes during the NPP lifetime (e.g. ageing). Consequently, the margin can be understood as the difference between the calculated and expected capabilities.

In 2012 IAEA has reflected safety developments and experience accumulated in the area of NPP design [12]. The most significant changes, compared with [13], are the extension of plant states (so-called Design Extension Condition (DEC)) to consider in the plant design, which should also include multiple failures potentially leading to severe accidents and the strengthened independence of different levels of defence in depth. New important additions and developments are discussed in details in [14]. In accordance with [12] and [14], the design should also address the necessary provisions for the mitigation of severe accidents. It should be convincingly demonstrated that all conditions potentially leading to early or large releases are practically eliminated. Especially the lessons learned from the Fukushima-Daiichi accidents have led to the identification of important topics for safety enhancement, such as the consideration of site specific external natural hazards exceeding the design basis, the possible loss of ultimate heat sink and the capability for using of mobile sources of electric power and coolant. Margins of equipment for DECs are expected to be smaller than those existing for DBA conditions. According to SSR-2/1 Requirement 20 of [12], the analyses of the design extension conditions may be performed using more realistic assumptions. Furthermore, meeting the single failure criterion is not required.

With regard to the design margins, there is a substantial difference between DECs without core melt and DECs with core melt, which is not considered in SSR-2/1: for the former, the uncertainties are similar to those for DBAs, while for the latter the uncertainties are larger than those for DBAs. In both cases margins can be based on the best-estimate approach.

Because the plant behaviour is the result of complex multi-dimensional physical phenomena that are tightly coupled, the proper assessment of safety and risks needs a continuous effort to reduce the uncertainties and gaps in the existing methodologies and validate them at the appropriate level, but also to develop a harmonized safety culture that takes into account the latest R&D results. These issues were largely addressed by ETSON in [1] (as well as in the NUGENIA roadmap [3]). As illustration two current European projects deal with such issues.

- The NURESAFE project (NUclear REactor SAFEty Simulation Platform, www.nuresafe.eu), led by CEA with contribution of several ETSON members (GRS, INRNE, IRSN, JSI, PSI, VTT). The project aims at delivering to European stakeholders a reliable software capacity (see Fig. 1), based on the NURESIM FP6 and NURISP FP7 former projects, usable for safety deterministic analyses and to develop a high level of expertise in the proper use of the most recent simulation tools. The main outcome of NURESAFE will be the delivery of multi-physics and fully integrated applications on some safety relevant "situation targets".
- The INCEFA-Plus project (INcreasing Safety in NPP by Covering gaps in Environmental Fatigue Assessment), led by AMEC with contribution of ETSON members (IRSN, LEI, PSI, UJV, VTT). It aims to deliver new experimental data and guidelines for assessment of environmental fatigue to ensure safe operation of European NPP. The gaps in available fatigue data lead to uncertainty in current assessments and will be targeted so that fatigue assessment procedures can address behaviour under conditions closer to normal plant operation than currently possible. Increased safety can thus be assured. Additionally the project will bring together national programs through which a strong EU response to the NRC methodology will be obtained with improved safety assurance through increased lifetime assessment reliability.

In addition, ETSON members participate to some OECD projects such as PREMIUM on methodologies, data review and codes benchmark on the quantification of the uncertainty of the physical models in the system thermal-hydraulic codes. They could participate also to a few projects supposed to be submitted to the EURATOM Call 2016–2017: ACUOS (Assessment of COre Uncertainties and Operational Safety Margins), APASS (see § 4.3), AMENOFIS (see § 4.1), NARSIS (New Approach to Reactor Safety ImprovementS).

4.5 *Controlling severe conditions, incl. prevention of accident progression and mitigation of severe accident consequences*

Despite 30 years of research, there are still uncertainties in the phenomena related to severe accidents, partly because large scale experiments with real materials are extremely difficult to execute. In addition, transferring the experimental results to the reactor scale is not straightforward.

Severe accidents include notably core degradation with melting of core materials. In preventing the accident progression, it is of primary importance to try to supply coolant to the core. Phenomena related to cooling of intact core are well-known but the efficiency of cooling of damaged cores with molten corium and debris is uncertain.

If accident proceeds to late-phase, corium can be stabilized either in- or ex-vessel. The feasibility of In-Vessel Melt Retention (IVMR) has been demonstrated in the past for certain reactor types. However, recent research has showed that it is important to review, for example, how the heat flux profile behaves in transient conditions.

If the RPV fails, the containment integrity is at risk. If corium discharges into a water pool, energetic and highly random fuel-coolant-interaction takes place and a steam explosion may be triggered. Based on current research, it cannot be confirmed in which conditions this may happen. Another mechanism that may lead to the early containment failure is the direct containment heating occurring if the RPV fails at high pressure and corium is released into a dry cavity.

Removal of the decay heat from ex-vessel corium by water injection has to be ensured to avoid possible basemat melt-through during Molten-Core-Concrete-Interaction (MCCI). Formation of a flammable gas mixture is also possible in the containment and reliable models for gas deflagration and deflagration-to-detonation are still under development.

Significant uncertainties are also related to the source term, starting from the release of radioactive materials from the fuel, especially in oxidising atmosphere, and continuing to fission product and aerosol chemistry in the primary circuit as well as in the containment.

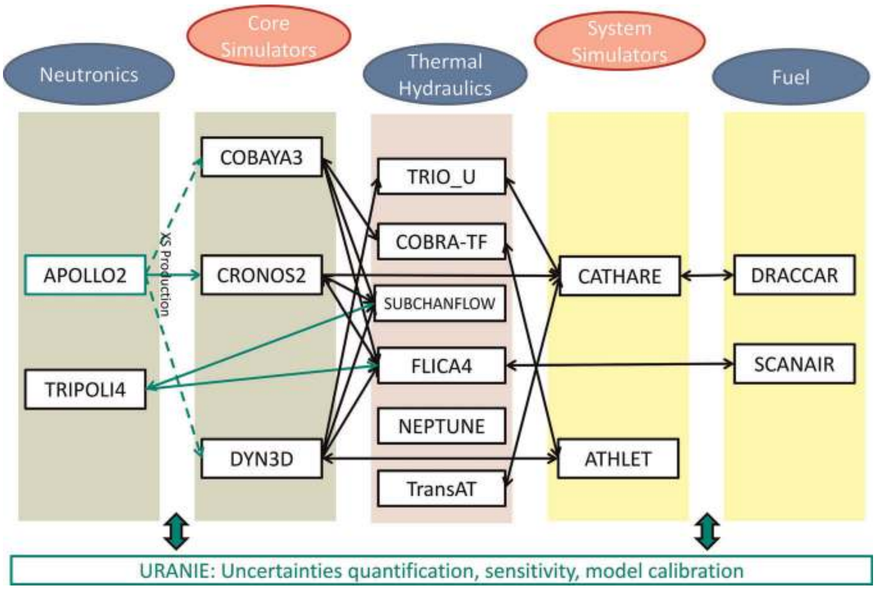

Fig. 1. Codes platform structure in NURESAFE

Large R&D efforts have been devoted in the last 10 years in Europe in the frame of the SARNET network (Severe Accident Research NETwork of excellence) [16] with a strong involvement of the ETSON members. The ranking of priorities has been updated in 2012 in SARNET frame [18], accounting for preliminary lessons from Fukushima-Daiichi accidents. SARNET was then integrated in the NUGENIA Association that is continuously updating its Global Vision Report addressing the main R&D objectives [3].

The highest R&D priorities in the field of severe accidents are related to:

- In-vessel accident progression: efficiency of degraded core cooling, IVMR (corium and debris behaviour in vessel lower head, corium thermo-chemistry, vessel external cooling),
- Early containment failure: steam explosions (especially the premixing phase) and gas combustion (deflagration and detonation, efficiency of recombiners),
- Ex-vessel coolability of corium: water injection during MCCI,
- Source term: ways to decrease iodine and ruthenium release into the environment (Filtered Containment Venting Systems (FCVS), pool scrubbing) including long term situations.

All these issues were already underlined in the ETSON position paper in 2011 [1].

Theoretical simulations form the basis for understanding of complete accident scenarios and then evaluating the adequate mitigation measures. Thus, it is extremely important that the simulation codes and methods are validated for their intended purposes. Large efforts have been devoted especially in SARNET to capitalize knowledge into the integral code ASTEC (Fig. 2) and to validate it [17].

Several international R&D projects, all with a strong involvement of ETSON partners, are ongoing with the objective to improve the prevention of severe accidents and mitigate their

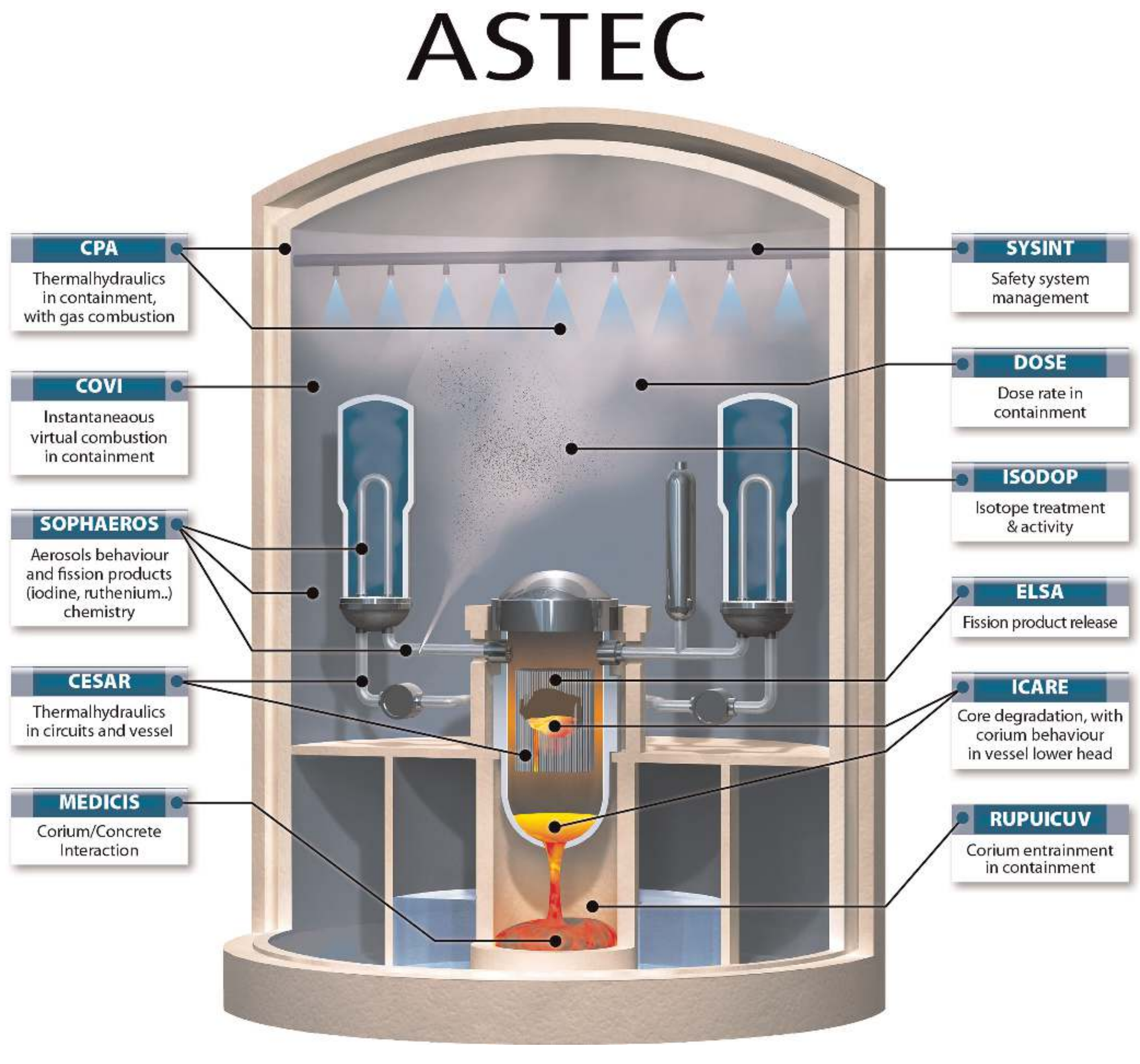

Fig. 2. Scheme of ASTEC integral code

consequences, as well as decrease the remaining uncertainties on the above phenomena:

- Three FP7 or H2020 projects coordinated by an ETSON member:
  - IVMR (In-Vessel Melt Retention severe accident management strategy for existing and future NPPs) on applicability and technical feasibility of the IVMR strategy to high power reactors [21],
  - PASSAM (Passive and Active Systems on Severe Accident source term Mitigation) on improvement of existing FCVS and testing of innovative systems,
  - CESAM (Code for European Severe Accident Management) on ASTEC code improvements for simulation of severe accident management.
- Four OECD/NEA/CSNI projects:
  - BSAF2 (Benchmark Study of the Accident at Fukushima),
  - STEM2 (Source Term Evaluation and Mitigation),
  - THAI3 (Thermal-hydraulics, Hydrogen, Aerosols and Iodine),
  - BIP3 (Behaviour of Iodine).

In addition, several national projects address these issues, such as in Finland the SAFIR programme and in France a large concerted effort following Fukushima-Daiichi events including ICE on steam explosion, MITHYGENE on hydrogen explosion and MIRE on source term.

4.6 SFP accidents

SFPs are large accident-hardened structures that are used to temporarily store irradiated nuclear fuel. Due to the robustness of the structures, SFP severe accidents have long been regarded as highly improbable events, where there would be more than adequate time for corrective operator actions. The Fukushima-Daiichi accident has renewed international interest in the safety of spent nuclear fuel stored in SFPs under prolonged loss of cooling conditions following the accident [19].

The fuel damage in the SFP and the associated accident progression and its consequences, in particular on the source term, were already identified as one important issue by ETSON [1] (Fig. 3).

Separate and integral effect tests have been conducted since the 1980 s to better understand the fuel behaviour and degradation under severe accident conditions. A number of the tests, while not originally developed for SFP accidents, provided valuable data and insights for application to SFP accident phenomenology.

Fuel degradation and fission product release phenomenology are relatively well known from severe accident studies, however expected SFP accident conditions differ and source term estimation is a challenge (more heterogeneous distribution of fuel assemblies, lower decay power, air-containing environment and lower pressure in SFP than in reactor case).

The only integral tests specifically targeted for SFP were performed at Sandia National Laboratories (USA), partly within the CSNI Sandia Fuel Project (2009–2013) where some ETSON members participated (IRSN, GRS and PSI). There was also the accident in 2003 in the Paks unit 2 NPP SFP where fuel was damaged: a codes benchmark was organized in CSNI frame, involving for instance GRS and IRSN. To better understand the evolution of the SFP accidents, IRSN launched in 2014 the DENOPI French project for a period of six years and has been joined by BelV.

Currently available computational tools are intended primarily for analyses of reactor accidents and most of them have been enlarged (or work is ongoing) to model SFPs accidents. The benchmarks carried out for the OECD/NEA Sandia Fuel Project helped identify code limitations. Recently, applicability of severe accident codes to SFP is being studied in the "AIR-SFP" task of the NUGENIA+ FP7 project, with participation of several ETSON members (IRSN, GRS, JSI, LEI, PSI and SSTC-NRS). A R&D roadmap is also planned in this task, focusing mainly on fuel air oxidation phenomena.

An OECD/NEA/CSNI activity has just started, led by IRSN with the participation of BelV, GRS, PSI, NRA, on applying a Phenomena Identification and Ranking Technique (PIRT) for SFPs.

National projects focusing on SFP issues are addressed by several ETSON members, e.g. in cooperation with universities and research institutes in case of BelV, related to analysis of processes in SFP for LEI, sensitivity analysis of various modelling options on SFP accidents in SSTC NRS etc.

5 Conclusion

The R&D priority needs that were identified in the 2011 ETSON position paper already correspond, for a very large majority of them, to the objectives of the new 2014 Euratom Directive on the safety of nuclear installations. Besides, the ETSON members have been strongly involved for many years in R&D projects related to the improvement of safety of the European NPPs, such as SARNET for instance, and this situation was even reinforced after the Fukushima-Daiichi accidents in 2011. Most of the ongoing or planned projects that are underlined in this paper, either in an international frame such as FP7/H2020 Euratom or OECD/NEA/CSNI or in a national frame, aim at preventing accidents through defence in depth and at avoiding radioactive releases outside a nuclear installation.

ETSON members plan to update the 2011 position paper in 2016 in order to account for the progress of knowledge in the last 5 years. They will also continue to actively participate to new R&D international projects that will provide a better

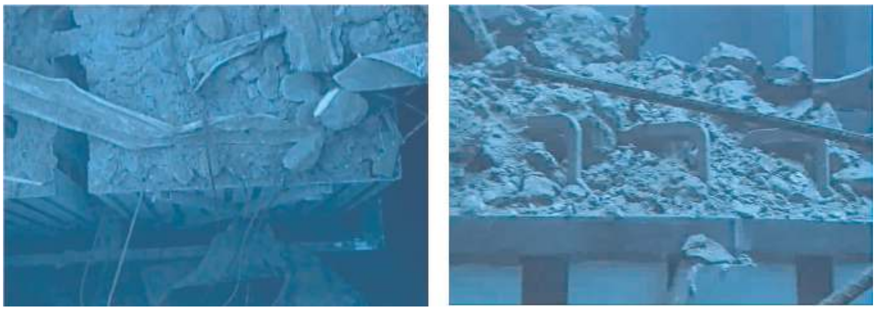

Fig. 3. Possible natural circulation flow under SFP storage conditions [20]

knowledge of the involved physical phenomena and its capitalization in methodologies and tools such as simulation codes, which will help to better answer the main objectives of the 2014 Directive.

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The 36th edition of the annual Reference Data Series No. 1 (RDS-1) contains estimates of energy, electricity and nuclear power trends up to the year 2050, using a variety of sources, such as the IAEA's Power Reactor Information System and data prepared by the United Nations.

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