**Post Fukushima Research in the View of the European TSO Network ETSON**

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**Abstract.** ETSON is the network of ten major European Technical Safety Organizations (TSOs) and of three associated TSOs from Japan, Ukraine, and Russia. ETSON aims at the convergence of nuclear safety practices in Europe by exchanging on nuclear safety assessment guidelines and by collaboration in research.

As regards the Fukushima Daiichi NPP accident, the ETSON members obtained deep insights into the course of the accident including related human factor and emergency management aspects. With its knowledge about gaps in the understanding of safety relevant phenomena and about the needs for safety improvements, ETSON is an important driver for the definition and conduction of common post Fukushima research activities. Still in 2011, ETSON presented a research and development position paper that identifies the main research topics also taking into account the lessons learned from the Fukushima accident. Since then ETSON has been spending continuous efforts to further prioritize the identified topics and to define coordinated research projects. In spring 2014, the ETSON Research Group held a workshop to exchange results of ongoing projects and to share views about common future activities. The workshop focused on the improved simulation of the Fukushima accident, including core degradation, vessel failure, and ex-vessel phenomena as well as Hydrogen distribution and explosion. Among others, it also highlighted the efforts to better understand the phenomena governing potential accident progression in spent fuel pools, and e.g. to improve the capability for fast and reliable source term assessment.

Common work is also directed towards the support to IRSN in the development of the European severe accident reference code ASTEC.

In order to efficiently work on these priorities, the ETSON members participate in research projects of OECD/NEA like BSAF (“Benchmark Study of the Accident at the Fukushima Daiichi NPP”) and they collaborate in the framework of EURATOM projects like CESAM (“Code for European Severe Accident Management”).

The paper will provide an overview on the Fukushima related research pursued by ETSON members in the framework of international research programs.

1. **The European TSO Network ETSON**

The European Technical Safety Organizations Network ETSON consists of ten European Technical Safety Organizations (TSOs) from Belgium, Bulgaria, Czech Republic, Finland,
France, Germany, Lithuania, Slovakia, Slovenia and Switzerland and of three associated TSOs from Japan, Ukraine and Russia.

The ETSON partners defined the following major objectives for their co-operation:

- contribute to fostering the convergence of technical nuclear safety practices within the European Union and beyond,
- form a suitable forum for voluntary exchanges on analyses and research, and
- planning, implementation and conduction of common nuclear safety research projects.

The long-standing collaboration amongst ETSON members on safety research issues is essentially supported by the common participation in international research programs of OECD/NEA, EURATOM, and IAEA.

2. Activities of ETSON members related to the Fukushima Daiichi NPP Accident

In the context of the Fukushima nuclear accident, ETSON member organizations operated or at least supported the national nuclear crisis centers by providing technical and radiological information. Further, they took part in the definition and conduction of the respective national and European NPP stress tests. Through all this involvement, ETSON members obtained deep insights into the technical course of the accident, into related human factors and organizational aspects, and into the potential environmental and health effects.

Already in 2010, ETSON started prioritizing the research needs according to their relevance-to-safety. The results were laid down in the ETSON Position Paper “Research Needs in Nuclear Safety for Gen 2 and Gen 3 NPPs” [1] published in October 2011. The paper also took into account the preliminary lessons learned from the Fukushima Daiichi NPP accident. Through this position paper and their activities in the framework of the European Sustainable Nuclear Energy Technology Platform (SNETP), ETSON also contributed to the SNETP report on the “Identification of Research Areas in Response to the Fukushima Accident” published in January 2013.

Moreover, different ETSON working groups held three workshops in 2011, 2013 and 2014 dealing with several Fukushima related subjects like accident progression, emergency preparedness, national stress test approaches, and severe accident research. The 2014 workshop of the ETSON Research Group focused on the improved simulation of the Fukushima accident, including core degradation, vessel failure, and ex-vessel phenomena as well as hydrogen distribution and explosion. Among others, it also highlighted the efforts to better understand the phenomena governing potential accident progression in spent fuel pools, the importance of measures and systems to mitigate the source term of severe accidents and e.g. to improve the capability for fast and reliable source term assessment.

3. Main conclusions from the Fukushima Daiichi accident and open questions

As a result of the ETSON position paper and the workshops, consistently with the analyses of OECD/NEA and others, the following main conclusions can be drawn from the Fukushima accident.

- Obviously, natural hazards were underestimated in the siting and the design of the Fukushima Daiichi Nuclear Power Plant and the defense in depth concept as it was implemented was not sufficiently robust against beyond design natural impacts.
Multiple failure events involving long lasting Station Blackout and loss of the Ultimate Heat Sink were not sufficiently taken into account when planning the on-site accident management (AM) measures.

Damages of the infrastructure and hostile environments - like debris, radiation, danger of hydrogen explosions - and loss of communication were not appropriately considered in assessing the feasibility and the effectiveness of the accident management actions.

In addition, the countermeasures were complicated by the fact that several units were impacted at the same time, such that beyond the mutually exposed threats, there was a lack of staff and equipment.

Further, the execution and success control of the accident management actions taken was hindered by deficient hardened instrumentation that could have provided appropriate information on the actual plant conditions.

And finally, as the report of the Japanese Diet clearly stated, there were major deficits in the regulatory process as well as in the organizational structure.

Open questions remained regarding the course of the accidents and their consequences. So for instance, it is not fully clear whether and how long the passive core cooling systems still worked after the loss of battery power and how they functioned in an uncontrolled mode. It is also not known through which ways the hydrogen escaped from the Primary Containment Vessels (PCV) and consequently how it distributed in the building structures. And there is still insufficient information on the failure modes and the final states of the reactor pressure and the primary containment vessels. The accident progression in the Spent Fuel Pool is another important issue.

4. Fukushima related research activities of ETSON

The research activities relevant in response to the said conclusions and open questions cover a large number of fields comprising e.g. (1) assessment of extreme natural hazards, (2) consideration of extreme natural hazards in advanced PSAs, (3) in-vessel and ex-vessel corium behavior, (4) in-vessel corium retention, (5) hydrogen generation, distribution and explosion, (6) severe accident phenomena in spent fuel pools, (7) fast running methods for source term assessment, (8) source term mitigation measures, (9) on-site accident management, (10) human factors and organizational aspects under extreme accident conditions, and (11) emergency preparedness and response. Further research needs not addressed in this presentation are related to (12) radiation protection and epidemiology, (13) clean-up of large contaminated areas, and (14) dismantling of damaged NPPs after the occurrence of a severe accident.

In the following, the presentation will be restricted to a selection of important international research activities with major involvement of ETSON, which were at least partly initiated by ETSON partners.

4.1. Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Plant

Though Fukushima has not revealed absolutely new severe accident phenomena, there is no thorough and complete understanding of what has happened in detail.
Therefore, ETSON partners participate in the OECD NEA Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Station (BSAF). BSAF started in 2012. It aims at the analysis of the accident progression and the prediction of the current status within the RPVs and the PCVs of units 1-3 in order to

- promote the understanding of observed phenomena through comparison of code results and with measurements,
- reveal deficits in severe accident models and codes through validation against data available from the Fukushima reactors, and
- assist with the preparation of the dismantling of those units, incl. corium removal.

Institutions from 8 countries participate in the Benchmark, applying 6 different codes (SAMPSON, MAAP, MELCOR, ASTEC, ATHLET-CD and SOCRAT). The Japanese participants facilitate modeling by providing detailed as possible information about the accident and the status of safety relevant systems.

In the first phase, the benchmark comprises modeling until stable cooling is reached. The spectrum of phenomena ranges from heat-up of the core up to corium concrete interaction. As an example, Figure 1 shows the current analyses results of the Fukushima unit 3 accident sequence, which were obtained by best-estimate calculations of GRS using a coupled version of the best-estimate codes ATHLET-CD and COCOSYS. It can be seen, that both the calculated pressure in the RPV and in the PCV qualitatively agrees with the available measuring data during the first 42 hours. Earlier calculations underestimated the measured pressure in the PCV during the first 20 hours of the accident. Now, the improved agreement was achieved by a more detailed modeling of the suppression chamber (S/C) in order to adequately reproduce an inhomogeneous azimuthal temperature distribution in the S/C.

![Figure 1](image)

*FIG. 1 Calculated and measured pressure in RPV (left) and PCV (right) of Fukushima unit 3 until relocation of fuel to lower plenum [2]*

4.2. European Severe Accident Reference Code ASTEC

The Fukushima accident further showed that a continuous improvement in on-site severe accident management (SAM) measures is necessary in order to mitigate effectively the consequences to the environment. Conclusions for the improvement of SAM can be drawn from the application of qualified severe accident codes that are capable of describing the overall plant behavior and the source term into the environment.
Since 1995 IRSN and GRS have been jointly developing the code ASTEC (Accident Source Term Evaluation Code), which meanwhile became the European Severe Accident Reference Code. Currently, in the framework of the EURATOM project CESAM (Code for European Severe Accident Management, [3]), 18 participants from 11 European Countries and India, among them several ETSON partners, apply and enhance ASTEC for severe accident management analysis. CESAM focuses on the

a) assessment of existing ASTEC models, especially those important for phenomena that occurred during the Fukushima accident,

b) the implementation and validation of improved models,

c) elaboration of reference input decks for the main types of European NPPs including a generic spent fuel pool,

d) and ASTEC calculations for the evaluation of the impact of SAM actions on selected scenarios in these NPPs.

ASTEC models will be elaborated for instance for passive autocatalytic particle bed recombiners, which are applied in several European NPPs.

4.3. Passive and Active Systems for Severe Accident Source Term Mitigation

Besides the issue of recombiners, Fukushima in general highlighted the importance of measures and systems to mitigate the source term of severe accidents. This is the reason why the European project PASSAM (Passive and Active Systems on Severe Accident source term Mitigation, [4]) was set up with ETSON members participating. PASSAM, among others, focuses on the enhanced understanding of major retention phenomena of filtered containment venting systems. Current experiments at PSI Switzerland address the hydrodynamics of pool scrubbing systems in the presence of submerged structures at increased jet velocities. The models used today were developed for bare pool conditions and bubbly flow regimes. They are only restrictedly applicable in the presence of structures and highly turbulent two-phase flow.

4.4. Severe accident phenomena in the spent fuel pool

The Fukushima accident has also shed light on the fact that the community spent too little attention to severe accident sequences in the spent fuel pool in the past. For example, still too little is known about cladding oxidation and burning in the presence of a steam – air – atmosphere, and the amount of hydrogen generated under such conditions. In case of leaking pool scenarios there are sequences with lower steam concentrations that could lead to air ingress and Zirconium fire. Such scenarios were investigated in the Sandia OECD/NEA fuel project [5] and the associated benchmark. It is important to note that the experiment showed exothermal nitrification in oxygen poor zones at higher temperatures. Several ETSON partners took part in the accompanying computational benchmark. As shown in FIG.2 the first heat-up phase is well reflected by all the codes that participated in the benchmark. Scatter around the experiment and among the codes increases after accelerated oxidation has started. There is only one code that takes into account nitrination and later re-oxidation. In spite of that it does not significantly better reflect the experiment. This is a clear indication that the phenomena after ignition are not fully understood and that further model development is necessary.
4.5. Hydrogen phenomena

It is a main safety objective to maintain the integrity of the containment as the ultimate barrier to mitigate the release of radioactivity to the environment. Retention capacity needs also to be maintained in the presence of hydrogen and other combustible gases, and during venting of the containment atmosphere. Current research activities with ETSON members’ involvement concentrate on

- simulation of the gas distribution in the building compartments considering the influence of mitigation systems,
- more reliable models for hydrogen deflagration and deflagration-to-detonation transition, and
- scaling from experimental facilities to real containments.

As regards the hydrogen distribution, experiments are conducted at the PANDA (PSI Switzerland) and the MISTRA (CEA France) test facilities within the OECD/NEA project HYMERES (HYdrogen Mitigation Experiments for REactor Safety, [6]). The main objective of HYMERES is to support improved modelling of the hydrogen behaviour in the containment through realistic as possible experiments. For that, realistic flow conditions will be established (e.g. diffuse flow resulting from a jet impinging onto walls) which will provide crucial information on the basic modelling requirements (mesh size, turbulence models, etc.) to be fulfilled for the analysis of a nuclear plant.

4.6. Assessment of the radioactive source term

In all severe accident situations, the central question is that about the radioactive source term. Tools are needed, which can be used during emergencies for fast and reliable source term prediction in order to rapidly establish adequate short-term protective measures. Due to the intended application such tools have to meet specific requirements on computational speed and on the capability to run with a minimum of input information. Currently a benchmark of fast-running software tools is performed within the OECD NEA project FASTRUN [7].
participants, amongst them 4 ETSON members, are using 23 codes. These codes are evaluated against 5 postulated accident scenarios at different locations and reactors (2 PWR, 2 BWR, 1 PHWR). For each scenario, three datasets were defined containing information that becomes available to source term assessment not before 1 hour, 6 hours, and 1 day after the accident. The outcome of the benchmark is expected at the end of this year and will inform about the strengths and weaknesses of the applied tools, and very important about the comparability of the calculated source terms.

4.7. External hazards

The Fukushima Daiichi NPP accident revealed the need for a more comprehensive consideration of external events (natural and man-made) that are beyond the current design basis. As regards natural hazards, an improved assessment of extreme beyond design impacts is necessary for any effective protection. Therefore, on the one hand, research is needed to clarify (1) which natural hazards – ranging from flooding and high winds up to seismic and volcanic activity – have to be taken into account at certain characteristic sites and (2) which intensity of the natural impact is connected with lower return frequencies than those based to the design. In this way, the loads can be specified to be expected at very low frequencies of return.

On the other hand, better understanding of the response is needed of the systems impacted by such extreme loads to identify how and when the systems turn to non-linear and/or catastrophic behavior.

To get a survey of how the specific combination of high winds and floods is considered and of the related design basis in major OECD countries, ETSON members participate in the newly founded Task Group on Natural External Events (TG NEV) of OECD/NEA. The Task Group will come up with its report beginning of 2015. A workshop will be held in June 2015 to discuss the implications of the findings from the survey and further steps to address other natural hazards.

Beyond that, several ETSON members take part in the EURATOM project “Advanced Safety Assessment Methodologies: extended PSA (ASAMPSA_E, [8])”, launched in mid-2013. Among others, the project aims at systematically extending the scope of PSA to all potential natural or man-made external as well as internal hazards. Guidance documents will be developed to help European stakeholders in conducting extended PSAs in an efficiently manner and to verify that all dominant risks are identified and managed.

As regards the systems response to high seismic loads, the participants from 15 countries currently collaborate within the OECD/NEA project MECOS (Metallic Component Margins under High Seismic Load, [9])

- to quantify the existing seismic margins associated with the existing design practices of safety class components,
- to evaluate the consequences of plant ageing, and
- to propose more realistic analysis for high seismic levels, including recommendations for complementary research.

Until now, 114 reports on seismic tests and analyses carried out in Japan, USA, France, UK, Germany and India have been compiled in order to identify the best suited test cases for a benchmark. Further, a survey is ongoing about the practices for seismic analysis input generation, seismic design basis, and beyond design seismic considerations.
5. Summary

In the context of the Fukushima accident, ETSON member organizations operated or at least supported the national nuclear crisis centers. They also took part in the definition and conduction of national and the European NPP stress test. Through all this involvement, ETSON members obtained deep insights into the technical course of the accident, into related human factors and organizational aspects, and into the potential environmental and health effects.

Since 2011, through workshops and other initiatives, ETSON has been drawing conclusions about the prior research needs resulting from the lessons learned from the Fukushima accident. These research priorities cover a large number of fields ranging from the assessment of extreme natural hazards and the in-vessel and ex-vessel corium behavior up to source term assessment and severe accident management. ETSON members made available their Fukushima related expertise to EURATOM, OECD/NEA, and the IAEA to initiate appropriate research projects in response to the Fukushima accident.

Today, ETSON partners are involved in a large number of international research programs and benchmarks dealing for instance with the improved consideration of extreme natural hazards, the completion of the understanding of the course of the accident, and the improvement of severe accident mitigation measures. Major efforts are spent on the further development of the European severe accident reference code ASTEC being developed by IRSN and GRS since 1995. Currently, in the framework of the European project CESAM, new ASTEC models are elaborated for the enhanced simulation of accident management measures.

ETSON is ready to share as far as possible the results of these international projects with and to make available the codes of its members, like ASTEC, to the TSO community in order to make the best use of research to enhancing nuclear safety worldwide.

References