Current and Future EDF R&D activities on External Event Assessment

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Abstract

In this paper, we present an overview of external hazard related research activities at EDF R&D in the department of *Industrial Risk Management*. We give some key points on the way EDF is considering theses issues on its nuclear fleet, and describe some of its R&D projects including the screening of hazards, the use of graded approach for probabilistic safety assessment, the use of extreme statistics and correlated events to go deep through the evaluation of such rare events and the event combinations they may imply, multi-unit issues, and dam spill-water reliability. We also give some perspectives on research efforts to enhance dynamic approaches and their integration with deterministic approaches/codes to better understand the safety margins. Other experimentations are also ongoing to reduce computational complexity and use parallel processing or to experiment network metrics to shed another light using graph theory on the structure of our defense in depth lines against potential accident of cumulative effects of such external hazards.

1 Introduction

Despite the low frequency of their occurrence, external hazards are becoming one of the most important preoccupations of safety decision makers in the nuclear industry. Indeed, their consequences may be of great impact on the safety of the systems and thus on the efficiency of defense in dept principles as it has been unfortunately the case in Japan in 2011.

In this paper, we present an overview of EDF R&D activities regarding external hazard issues.

French Nuclear Power Plant design considers some external hazards (*External flooding*, *High wind* and associated missiles, *Extreme cold temperatures*, *Extreme hot temperatures*, *LHUS* due to clogging, *frazil ice*, *Snow load*, and *Earthquake*). These events and others are considered and studied in different variety of ways using different approaches.

In addition to the international state of the art and the different national and international standards, many R&D projects at EDF are ongoing to develop or adapt (existing) methodologies to deal with such events. This includes screening methodologies to order priorities and detail level of the different studies and eventually screen out when appropriate some non relevant events. For this reason, EDF R&D is adopting a graded approach which is based on 3 phases: 1. simplified analysis using today's tools, 2. more detailed analysis using more sophisticated tools and 3. a more PSA refined model requiring substantial methodological development. In addition to these methodological developments, there are efforts to overcome the lack of data and refine of the evaluation of extreme events frequencies using extreme statistics and the state of the art of new methods for the assessment of correlated events. These works are completed by a multi unit approach to deal with the full reality of such external events.

This paper is organized as follows. Section 1 presents the actions EDF is considering in a general framework with respect to the main standards and with respect to the new regulatory requirements. In section 2, we present different approaches developed at EDF to deal with external hazards (screening 2.1, graded approach 2.2, multi-unit 2.4, extreme statistics 2.3, long term studies 2.5 and spill water 2.6). Finally, in 3, we give some perspectives and an idea of the near feature development.

a* EDF general related external hazards actions on the nuclear fleet

EDF in conjunction with the French Safety Authority have taken actions to mitigate the effects of natural hazards on its NPPs. These actions are evolving according to the operational experience and the feedback on different significant events in France and abroad. EDF engaged proactive safety revues that resulted in new external hazard requirements in response to Blayais event, a *Heat Waves Plan in response to the*

events of 2003 and 2006, and a *Hardened safety core* following the stress tests that have been performed after the Fukushima Event.

1.1 How French NPP Design Involves External Hazards ?

In most cases, the maximum intensity level of hazards is defined conventionally by EDF and French Safety Authority. For instance, the design of power plants with respect to the river flood is assuming a majored millennial flood. The majored millennial flood is the level which is reached by a river flood whose flood called reference flood is obtained by a majoration of 15% of the millennial food which is retained with a confidence interval of 75% (cf. Projet de Guide de l'ASN n°13 [ASN, mai 2012]).

This document gives the maximum wind values for the different areas in France. For external flooding, among the events that must be studied in the frame of external flooding, we have:

- Flood due to waves effect defined by the bounds of the 75% confidence interval for the centennial event.
- Flood due to heavy rain defined by the bounds of the 95% confidence interval for the centennial event.

The bounds of confidence interval are determined by statistics but data are sparse. Given their maximum intensity level, hazards are studied by deterministic approaches.

1.2 Safety goals

The initial approach for the design of nuclear power plants in France is clearly deterministic, and consists of listing all the events that may lead to radioactive releases and then design the plant in such manner the risk remains acceptable (cf. [1, 13]): For frequent events, the consequences should remain minor (radioactive releases during operation should be far less than the natural radioactivity). For rare events the consequence may be more important, which justify particular protections. Rarer events may not need particular protections and are considered as a residual risk (cf. diagram of figure 1).

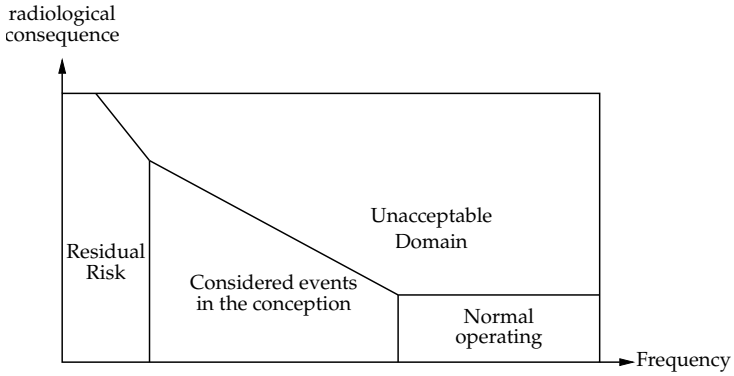

Figure 1: Radiological consequences/Frequency diagram

In the Safety Report (Rapport de Sûreté), 4 event categories are defined by an interval of annual frequency and regulatory limits in terms of radioactive release.

- Condition 1: Normal operation and normal operating transients > 1
- Condition 2: Incidents of moderate annual frequency $10^{-2} < f < 1$
- Condition 3: Accident with very low annual frequency $10^{-4} < f < 10^{-2}$
- Condition 4: Hypothetical accidents $10^{-6} < f < 10^{-4}$

From these probabilistic safety goals the systems design is done in a deterministic way taking into account:

- Envelop scenarios

- A conventional list of situations in the primary circuit
- The application of Single Failure Criteria
- Rules, norms and codes

1.3 New requirements and new regulations

1.3.1 Events

Events experienced by EDF plants showed that the likelihood of natural external hazards may be higher than foreseen : Flooding at Le Blayais[1] in 1999, more recently in 2003 and 2006 (and this year again) heat waves and a Loss of Ultimate Heat Sink due to clogging in Cruas in 2009. The Climate change and its short-term and long-term consequences should be considered and monitored for the design and the periodic evaluation of nuclear sites[2].

The design and implementation of defense in depth mitigation against undesired events were done in the past mostly on the basis of a unique event and mostly on a unique plant. The Fukushima Da'Ichi experience showed that a conjunction of hazards is possible and can, in addition, have impacts on many plants on the same time challenging the technical, human and organizational capabilities of the nuclear power site.

1.3.2 Regulation

French Safety Authority asked for a systematic study of external hazards in the frame of NPP lifetime extension project (INB Law) and WENRA reference levels asked for External hazards PSA development.

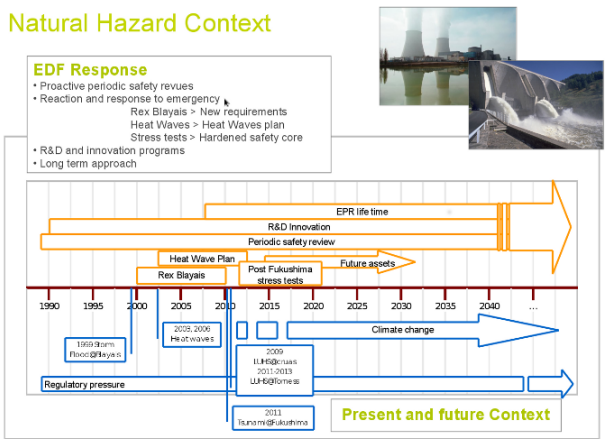

Figure 2: Natural Hazard Context

2 R&D activities regarding external events

In this section, we present an overview of the R&D activities regarding external events which are part of 3 EDF R&D projects.

[1] Le Blayais Nuclear Power Plant (4 900 MWe PWR) is located in Gironde in south west of France. *In the night of 27 to 28 December 1999, high waves, caused by a combination of tide and exceptionally high winds, moved up the River Gironde and partly submerged the « Le Blayais » site* (cf.).

[2] In AIEA- Safety Standards Series No. SSG-18 *The major effects with regard to the hazards to nuclear power plants are related to the following causes*: (a) Changes in temperatures of the air and the sea; (b) Changes in the patterns, frequency and storminess of winds; (c) Changes in the characteristics of precipitation such as higher peak levels; (d) Changes in rises and anomalies in sea levels; (e) Changes in the flow rates of rivers.

2.1 Screening

EDF R&D has developped a methodology for screening of natural external hazards [16] in response to the requirements of the French Safety. Authority. It is mainly based on the international standard with declinaison to EDF context. The aim of this approach is to evaluate for all individual or combined hazards the available margins, brought by the design, the operational procedures and the organization on site. A defense in depth scheme was used to assess these margins covering the following topics:

- Prevention from hazard effects due to design dispositions
- Surveillance of both the natural hazard and the protection devices
- Mitigation of hazard effects

This methodology must be approved by the EDF Engineering and Nuclear Generation divisions before any industrial implementation. The development of this methodology required three steps:

1. The definition of the list of potential hazards to be analysed
2. The definition of the criteria to be applied to exclude hazards when considered independently of one another
3. The definition of criteria to be applied to exclude combinations of hazards

2.2 Graded Probabilistic Assessment : External Flooding Example

The graded approach prposed by EDF (cf. [16]) is structured in three phases, from the most simplified analysis to more detailed analysis, and ultimately the development of a model that is close to a Standard PSA one (Probabilistic Safety Analysis) ([4]). Each phase includes an identification of the different relevant scenarios, the modelisation of their corresponding sequences and the estimation of their frequencies. The first phase of the Graded Approach has been applied to a pilot study for External River flooding. Currently the methodology is only focused on the reactor building, with the classical 24 hours PSA duration and only for core damage risk.

2.3 Extreme statistics and correlated events

EDF engaged R&D projects with various expert profiles to deal with extreme statistic values representing the frequency of different risks for different phenomena. These experts in collaboration with other EDF divisions have developped a methodological guide to deal with many problems related to the evaluation of extreme values and the potential combination of some of these events (cf. [2]).

2.4 Multi unit issues

Dealing with external natural hazards means dealing with global events that may affect the whole site of a nuclear power plant and then all of its units and sometimes the other units of neighbors power stations. Therefore, multi units issues should be considered in the external hazard assessment. All operators have almost already their PSA models on per/unit basis. EDF R&D has proposed a methodology to extend the PSA model to cover twin units on a given site. The study focused on a twin PWR 900Me units. The main idea is to consider the different environment constraints which in principle may have the same impact on the units of the same site. In addition, the availability of shared systems and resources (Systems with cross ties, systems shared at the site level, common or inter-connecting rooms that exist between the two units and human resources that are common in terms of operating and maintenance teams...) and the way they must be credited are studied.

The approach proposed a way to deal with a more realistic site risk by developing upgraded PSA models for both units:

- Suggest a selection criterion for the systems that definitely need to be modelled, retaining the multi-unit aspects (operating mode of the twin unit, inter-unit common cause failures).

- Suggest a less conservative modeling of shared resources
- Suggest a precise method for establishing the inter-unit common cause failure parameters, based on the feedback available or existing parameters.
- Suggest a method for dealing with potential situations in which, following a type II initiating event, one unit is already experiencing a severe accident while the other is not.
- Improve the HRA to handle some habitability issues such as humidity, radiation, or high temperature that may result from an accident.

2.5 Long term scenarios

Some accident scenarios may take some time after the conventional 24 hours period assumed in the current PSA models. Moreover, this assumes there is a need and a possibility to recover some systems and maybe to connect others. These long term scenarios are mainly studied with the help of dynamic and/or hybrid approaches: Dynamic in the sense that the boolean framework in no more relevant and the time during the different transitions of the plant play a key role in the way the accident sequences are considered, modeled and evaluated. At EDF the BDMP (Boolean logic Driven Makrov Processes) framework (cf. [6])) with the `KB3` [21] platform is mainly used. Instead of minimal cutsets, all the undesired events are governed by sequences of events (failures or reparations, or any other transitions . . . .) whose identification and quantification is obtained through a sequence explorer tool `FIGSEQ` [7] or a monte carlo simulation tool `Yams` [9] developed at EDF.

For instance, in the context of post fukushima studies, the LOOP is studied for the 900 MWe to satisfy a regulatory request (cf. [19] and [5]) to consider the loss of offsite power and the loss of ultimate heat sink for a duration of 192 hours (cf. [22]). In this study, the BDMP approach is still used in addition to petri nets to include deterministic delays (for instance, tank autonomy and grace time to core meltdown). The model is modified to consider re-feeding consumables such as fuel, oil and water tanks, mobile pumps and small additional diesel generator which are introduced according to the ultimate procedures.

2.6 Reliability of dam spillwater

In addition to the assessment of external hazards such as external flooding, the reliability of the different dams EDF is concerned about is an important concern. Therefore EDF developped a dedicated method for the reliability assessments of gated spillways, which discharge flood-water and prevent overtopping and possible failure of the dam (cf. [10]). Called GASPART, this method is based on a hybrid modeling approach taking into account the time factor in discharge processes. Therefore two phenomena of different nature are in competition : one representing water level evolution in the upstream basin of the dam which is a deterministic and continuous phenomenon governed by ordinary differential equations, and the second consists of a set of discrete stochastic events which, for instance, stand for failure occurrences. The theoretical framework of Piecewise Deterministic Markov Processes (PDMP cf. [11]) allows for the simultaneous consideration of these two phenomena which is out of reach for the classical dependability assessment approaches mainly based on fault and event trees or even classical markov processes.

2.7 Tools for automated massive modifications

The implementation of external hazard events may need a number of massive modification of the PSA model to deal with new elements such as (creation of ne failure scenarios, new hazard failures, new failures modes and the integration of these failures at the relevant places in the PSA model, creation of new conditions and activation of these conditions ...). These operations may be very cumbersome and error prone and thus have to be somehow introduced using automated tools. EDF R&D was actively part of the *Open PSA Initiative* [14] and has developed tools that help using scripting interfaces to create automatically such pieces (cf. Andromeda Scripting interface [15]). An example, is illustrated in § 2.4, where a program were developped to create automatically the CCFs events and groups of the integrated model, and extending the CCF groups by multi-site CCF events.

2.8 Visual Analysis for computational questions

Different complexity questions are resulting from the implementation of external hazard events. Some are related to the size of the models which are incresing over the time. Others are inherent to the full scope PSA models that are by nature very big and therefore may challenge the computation time for an industrial operational use. For all these complexity questions there is a need to understand the structure of the model and the way it can be computed using parallel processes.

This compunational complexity question is intimately related to the structure of the so called master fault trees, and the way they are obtained and assembled. EDF is experimenting ways to evaluate the complexity of different "independant" parts of the model for parallel processing using different means (complexity measures, statistical measures and visual analysis using complex network analysis (cf. [20]).

3 Perspectives

Many research aspects are explored in EDF R&D includig long term scenarios and dynamic PSA or the integration of probabilistic approach and physical deterministic codes to better understand the motion of the potetial accidents and the way undesired events may happend. We give a short description of these subjects in the following subsections.

3.1 Long term scenarios and hybrid situations

For the simulation and assessment of some accident scenarions for long term durations, we have to consider recovering systems and sometimes reconnecting components/pipes which assumes a cinetic consideration of many events. In addition to these dynamic behavior, we have also to consider the evolution of physical parameters according to their laws which are mainy governed by differential equations. Therefore, ware are facing hybrid situations where physical variables implies continuous behavior and the need of differential equations modeling. EDF R&D has developped a new tool combining a declarative style (i.e. the possibility to use generic knowledge bases) and the power of modern object programming tools (cf. Pycatshoo [8]).

`Pycatshoo` can handle knowledge bases in python and is thus easily compatible with many other tools. In particular, it can be run under `Adromeda` allowing the different dynamic pieces to remain close to the main model an then be up-to-date with the current data and assumptions.

3.2 Dynamic PSA and integration of deterministic and probabilistic codes

Currently probabilistic models rely on the different success criteria obtained through the deterministic codes using a number of approximations and envelop assumptions. These assumptions should at least be confirmed. An integrated approach combining the two methods may help to ensure consistency of the dynamic behavior and to understand the ways that to preserve safety margins regarding dynamic phenomena. EDF R&D is part of this effort and participate to international initiatives to enhance this reflexion and assemble multi-disciplinary teams of analysts involving experts in deterministic and probabilistic analyses, material sciences, human factors, computer scientists (cf. [12]).

3.3 Network experimentations over power plant systems

In addition to the traditional Probablistic and Deterministic approaches, EDF R&D is experimenting network algorithms and network metrics to model and understand accident scenarios (cf. [17, 3] and [18]). The main idea is to explore the relations between Probabilistic Safety Assessment models and graph theory (complex networks). From an event sequence diagram, representing the scenarios following the occurrence of an initiator, a network is built representing the different relations between the network nodes and the different consequences of the event sequence diagram. We are expecting different qualitative observations regarding critical/important components using low complexity algorithms and potentially understand hidden dependencies and more structure based connections. The approach may be of interest in modeling external hazards as a attribute layer using multiplex networks (ongoing PhD thesis).

4 Aknowlegement

The authors would like to thank Inn Seock, Alain Sibler, Marie Gallois and Valentin Rychkov for their helpful suggestions and discussions.

References

[1] Règle fondamentale de sûreté n° 2002-01 relative aux études probabilistes de sûreté.

[2] A.Dutfoy, S. Parey and N. Roche. Multivariate extreme value theory - a tutorial with applications to hydrology and meteorology. *Depend. Model.*, 2:30–48, 2014.

[3] Ait-Ferhat D., Friedlhuber T. & Hibti M. An andromeda extension for network based safety assessment. In *American Nuclear Society Winter meeting on Risk Management for Complex Socio-technical Systems*, 2013.

[4] ASME. Addenda to asme/ans ra-s-2008 standard for level 1/large early release frequency probabilistic risk assessment for nuclear power plant application. Technical report, ASME, 2008.

[5] D. BERNARD-JULLIEN B. PAYAN. Ensn120001 – « gp d'orientations de la ddf "démarche générale de sûreté" – propositions de positions/actions en réponse aux projets de recommandations de l'irsn ». Courrier (rapport 2011-005-Tome1), Jan 2012.

[6] Bouissou M. & Bon J-L. . A new formalism that combines advantages of fault-trees and Markov models: Boolean logic driven Markov processes. *Reliability Engineering and System Safety page 149-163*, 82(Issue 02):149–163, November 03.

[7] Bouissou M., Mercier S. Calcul robuste de la convolution de densités de probabilité et application au logiciel figseq. Technical Report HT-52/03/044/A, EDF R&D, 2003.

[8] H. Chraibi. Dynamic reliability modelling and assessment with pycatshoo : Application to a test case. In PSAM, editor, *International topical conference on Probabilistic Safety Assessment and Management PSAM Topical Conference*, 2013.

[9] Chraibi H. Manuel d'utilisation du simulateur Monte Carlo YAMS. Technical Report H-T52-2006-01668-FR, EDF - R&D, Département Management des Risques Industriels, septembre 2008.

[10] Chraibi H et al. Gaspart, a new method and tool for reliability assessments of gated spillway systems. *MMR2015 9th international Conference On Mathematical Methods in Reliabaility*, Tokyo (Japan), 1-4 June 2015.

[11] Davis, M. H. A. Piecewise-deterministic markov processes: A general class of non-diffusion stochastic models. *Journal of the Royal Statistical Society*, 46(3):353–388, 1984.

[12] Francesco Di Maio, Enrico Zio, Curtis Smith, and Valentin Rychkov. Integrated deterministic and probabilistic safety analysis for safety assessment of nuclear power plants. *Science and Technology of Nuclear Installations*, 2015.

[13] EDF. *Mémento de la sûreté nucléaire*. DPN, 2004.

[14] Epstein S. & Rauzy A. Standard model representation format for probabilistic safety assessment. Technical report, The Open PSA Initiative, 2007-2008.

[15] Friedlhuber T., Hibti M. and Rauzy A. Overview of the open PSA platform. *PSAM/ESREL 2011*, 2012.

[16] Gallois M. et al. Development of a method for the screening of natural hazards at edf. *ANS PSA 2013 International Topical Meeting on Probabilistic Safety Assessment and Analysis Columbia, SC, September 22-26, 2013, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2013)*, 2013.

[17] M. Hibti. What if we revisit evaluation of PSA models with network algorithms? *Proceedings of the International Topical Meeting on Probabilistic Safety Assessment and Analysis*, 2013.

[18] Hibti M., Oudjit A. & Marechal A. Exploring LOCA with complex network based analysis: A mean-centrality based criteria,. Technical report, EDF R&D, 2014.

[19] IRSN. Projets de recommandation irsn rapport 2011-005. Technical report.

[20] M.Hibti. Andromeda : Specification for model cartography generation. Technical report, EDF R&D, 2016.

[21] Pillière M., Mouttapa P., Villatte N. & Renault I. *KB3: Computer Program For Automatic Generation of Fault Trees*. RAMS'99, Washington (U.S.), January 99.

[22] A. Sibler. Modèle de risque dynamique pour la perte de long terme des sources électriques externes 900 cpy. Technical report, EDF R&D, 2016.