PSA MODELING OF LONG-TERM ACCIDENT SEQUENCES

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Abstract:

In the context of the extension of PSA scope to include external hazards, in France, both operator (EDF) and IRSN work for the improvement of methods to better take into account in the PSA the accident sequences induced by initiators which affect a whole site containing several nuclear units (reactors, fuel pools,…). These methodological improvements represent an essential prerequisite for the development of external hazards PSA. However, it has to be noted that in French PSA, even before Fukushima, long term accident sequences were taken into account: many insight were therefore used, as complementary information, to enhance the safety level of the plants. IRSN proposed an external events PSA development program. One of the first steps of the program is the development of methods to model in the PSA the long term accident sequences, based on the experience gained.

Keywords: External Events, Long Term, PSA

1. INTRODUCTION

The worldwide operating experience shows that external hazards are a threat for the safety of nuclear installations. Notably, they have the potential to cause initiating events and simultaneously to impair the safety systems necessary to limit the consequences of the initiating events.

In France several external events occurred, with the potential to threaten nuclear safety. The most significant one was the partial flooding of the Blayais NPP in December 1999 when, during a severe storm, high waves overtopped a protective dyke surrounding the site and partly submerged some areas. This event raised the questions of the design bases used for the protection of nuclear power plants against external flooding and the efficiency of the existing measures, especially the warning systems, the site protection measures, the protection of safety-related equipment, the procedures and the emergency organization.

Also, some other significant external events affected French NPPs:

- December 2005 - Paluel site: ice formation on the grid transformers leading to shutdown of all four reactors and isolation from the external power supply,
- December 2009 - Cruas units 3 and 4: total loss of the heat sink occurred due to the clogging of the pumping station filters due to a massive arrival of vegetable matters,
- December 2009 - Fessenheim unit 2: partial loss of heat sink occurred due to the clogging of the pumping station filtering drum screens due to vegetable matters.

It has to be noted that the identification of the risk of core damage related to the total loss of the ultimate heat sink, during the 80's, as highlighted in the probabilistic safety assessments, led to define some operating and design modifications to cope with such a situation. Finally, these plant improvements enabled to handle the 2009 Cruas site incident (mainly due to the use of the thermal inertia of the refueling water storage tank water reserve as an emergency heat sink for temporarily cooling the component cooling water system, throughout a containment spray system heat exchanger).

These recent incidents related to the external events remind us that environmental conditions, changing over time, may challenge the safety of nuclear reactors and highlight the need for better assessment of the risk related to external hazards. In particular the scope of the PSA should be extended, including all relevant external events and their combinations. In this context, both operator (EDF) and IRSN work, in addition to the review of deterministic bases and studies on external events, on probabilistic aspects related to external events PSA: hazards screening analysis, SSC fragility assessment, Human Reliability Assessment (HRA)… and on the improvement of methods to better take into account in the PSA the long term of accident sequences induced by initiators which may affect the whole site containing several nuclear installations (reactors, fuel pools,…).

Fukushima accident has confirmed the importance and the imperativeness of these external hazards analyses, including external events PSA developments.

At short term, IRSN intends to enhance the modeling of the "long term" accident sequences induced by the loss of the heat sink and/or the loss of external power supply. The objective of this action is to get a tool to verify similar studies which will be developed by EDF.

The IRSN "long term" studies will be also useful for the assessment of the safety impact of the French plant improvements decided in the frame of post-Fukushima assessments. The basis of the methodology for these studies consists on the methodological aspects defined by EDF for its Flamanville 3 EPR "extreme wind" PSA Level 1 study, enhanced by IRSN experience.

2. AVAILABLE PSA GUIDANCE TO MODEL LONG TERM ACCIDENT SEQUENCES

Although the safety demonstration of the French Nuclear Power Plants has been and remains deterministic, the probabilistic approach takes an increasing place in safety decisions. Despite a limited regulatory framework, in fact the risk insights are more and more taken into consideration as a supplement to the traditional deterministic demonstration.

At the beginning of the French nuclear program, PSA was not a regulatory requirement. Probabilistic studies were first developed on a voluntary basis by both the regulator technical support (IRSN) and by the operator (EDF). Partial probabilistic studies were carried out by EDF and IRSN since the 1970s and two global level 1 internal events PSAs were completed in 1990 (for the 900 MWe plants by IRSN and 1300 MWe plants by EDF).

In order to clarify the acceptable approaches, the French nuclear safety authority (Autorité de sûreté nucléaire - ASN) requested the issuing of a Basic Safety Rule on "Development and Use of Probabilistic Safety Assessments" [1] which was published in 2002. The purpose of this rule was to define acceptable methods for the development of PSAs and proven applications of PSAs for operating or future pressurized water reactors (PWR) of the French nuclear power program, incorporating available French and international experience in this area. An important point is that the Basic Safety Rule introduces the notion of "Reference PSA", which has to be developed by the operator for each plant series and reviewed by the regulators and their technical support (IRSN). The reference PSA "minimum scope" is a level 1 PSA, covering all internal initiating events, as well as the loss of ultimate heat sink and the loss of offsite power. All plant operating states should be analyzed in the reference PSA. It has to be noted that the loss of ultimate heat sink and the loss of offsite power are initiating events that may be induced, typically, by external hazards. Thus, they may affect simultaneously all site units.

Regarding the duration of the accident sequences, the Basic Safety Rule (BSR) indicates that the PSA should consider the time necessary to reach the success state. However, a common duration time is generally adopted for the majority of the accident sequences (i.e. 24 hours), except in case of initiating events of external origin. Nevertheless, the BSR states that, in certain cases, it is necessary to take into account events that would occur inevitably later or failure modes specific to equipment's that are not used in the short term and therefore to study the accident sequences on the long term. In order to establish realistic scenarios, for sequences were core damage occurs in the medium or long term, the various restoration options may be taken into account. These restorations may involve repair of components of a system, failure of which contributes to the initiating event or aggravates its consequences, or a manual intervention to implement the appropriate strategy. The time between system failure and core damage can be used in the PSA to process the repair of one of the systems whose failure is involved in the accident sequence studied.

In fact, as stated in the Basic Safety Rule, the reference PSA can be supplemented by complementary specific studies. For example the following situations may be studied: sequences over a longer period of time after the initiating event occurrence and accident sequences taking into account the consequences of the initiating event on all site units. The possible incorporation of the special studies into the baseline PSA and the associated modeling approach (simplification of the special studies, for example) are decided on a case-by-case basis, when the reference PSA is updated. Finally, the term “the PSAs” represents the package constituted by the baseline PSA and the special studies.

Moreover, for new reactors the role of PSA is more important. The Technical Guidelines for the design and construction of the next generation of NPPs with Pressurized Water Reactors adopted by ASN [2] requests for new reactors the performance of a PSA since the design stage, considering a list of initiating events. This list should be as complete as possible and representative of all sequences already analyzed in French PSAs and should include all plant operating states. In this document it is stated that, at the design stage, the use of simplified models and generic data as well as the limitation of calculations to a duration of 24 hours can be sufficient to provide valuable insights as a first step, however, even at the conceptual stage, it is appropriate to investigate specific events which could occur after 24 hours (e.g. refilling of a tank) in order to demonstrate the absence of cliff-edge effects. Moreover, the Technical Guidelines state that, at a later stage, the designer would have to identify clearly the initiating events which could lead to a loss of offsite power or a loss of the ultimate heat sink with long duration. In particular, due attention has to be paid to external hazards which would require long mission times for some systems (long duration of the hazard or long duration of the accident sequences induced by a “short” hazard). Also, the Technical Guidelines state that, in the context of probabilistic studies, the possibilities of a long loss of offsite power or a long loss of ultimate heat sink durations have to be investigated precisely for a given site.

3. EXISTING LONG TERM FRENCH PSAs

Traditionally, in level 1 PSAs, the accident sequences are treated for a mission time of 24 hours, the long term of the accident sequences being taken into account in a simplified manner. For example, some of the mitigation measures which are needed at long term (refilling of water tanks, systems recovery, operator actions decided by the emergency teams, external support…) are credited in the PSA, but the analysis and the associated failures probabilities quantification are estimated based on generic and simplified assessments.

However, it is important to note that, in the French PSA, even before Fukushima accidents the long term accident sequences were already modeled, many insight being used, as complementary information, to enhance the safety level of the plants. These studies are summarized in the following paragraphs.

For example, beginning with the very first PSA study (in 1990) IRSN tried to avoid too many simplifying assumptions on the sequence development time. The sequences were developed completely, either to the point of core meltdown or to a state in which the risk can be considered as negligible. In order to decide that the risk can be considered as negligible, the post-accident situations of long durations were taken into account. Particularly, for Loss of Coolant Accidents (LOCAs), the long-term phase lasting as long as one year was considered for large LOCA. The study of long term scenarios highlighted problems concerning the reliability and the strategies to use specific equipment and features provided for this type of situation, such as the use of mobile devices or interchanging components between systems (like for example, exchanging pumps between low pressure injection system and containment spray system). To make sure that the scenarios were realistic for the long-term sequences it was necessary to allow the possibility of recovery. Recovery may consist of system repair (particularly when the initiating event is the failure of the system) or human intervention to apply a procedure or implement a recovery strategy.

Later, in the updated PSA studies, IRSN considered also that a common duration of 24 hours for all accident sequences can be too reductive and, consequently, IRSN studied some of the accident sequences by defining decoupling criteria based on a “good” availability and redundancy of the remaining mitigation means. For example, for the situations that needs a primary safety injection, a 48 hours duration was considered, corresponding to the necessary time to put in place the mobile means in order to have redundant mitigation means in case of a failure of the safety injection or the containment cooling systems during the long term operation. In the same way, for other type of accident sequences where the Residual heat removal system is used as mitigation mean, a 96 hour duration has been considered for the accident sequences modeling, corresponding to the capacity of the alternative means (spent fuel pool cooling system) to cope with the failure of the Residual cooling system.

In the above mentioned studies, the durations higher than 24 hours considered for the quantification of the reliability of the systems, was not the only way to take into account the long term effects. IRSN PSAs also study other aspects related to the long duration of the accident sequences, notably:

- the availability of the water resources needed at long term, like the demineralized water reserves for the secondary auxiliary feed water system,
- the time available before failure of the electrical and control systems due to the loosing of cooling systems (for example, in case of loss of the ultimate heat sink),
- the role of the emergency organization.

However, the mentioned IRSN PSA studies only considered the reactor and did not take into account the fact that, in some situations, both reactor and spent fuel pool may be simultaneously affected by the initiator. Moreover, the impact on multiple reactors on the site is considered only in a limited manner (availability of water resources).

EDF also developed several long term studies, mainly in the frame of the Flamanville 3 EPR project. In 2006, for the construction license application (preliminary safety report [3]), EDF developed Level 1 PSA long term studies for:

- loss of cooling chain and loss of heat sink (with a maximum of 100 hours considered for recovery time, corresponding to a conventional value),

- loss of offsite power (with a maximum 192 hours considered for recovery time, corresponding to a loss of offsite power induced by an external event except earthquake[8]).

The objective of these studies was to verify that, considering accident sequence durations longer than 24 hours, no cliff edge effects on the core damage frequency were induced. The studies were developed in a similar manner as a traditional PSA, but specifics functions for a long term probabilistic study were also integrated, like: initiators recovery, diesel generators repair, water tanks refilling, etc.. These studies showed the importance of the refilling function of auxiliary feed water tanks from the demineralized water system. As a consequence the safety classification of this function was upgraded. The studies also highlighted the importance of the reliability of the diesel generators and of the possibilities to repair them during the accident. It has to be noted that the studies were developed only for the reactor, the interaction with the spent fuel pool was not considered. Moreover, in the study the loss of offsite power and the loss of heat sink are considered as independent, the possible combinations was not analyzed.

As a complement of these two studies, EDF developed in 2010, as part of the integration of the external events in the Level 1 PSA, a study for the “extreme winds” hazard. This study was developed in the frame of the operating license application of Flamanville 3 NPP. The study considers the simultaneous loss of the heat sink and loss of offsite power induced by an extreme wind. The duration of the accident sequences considered is 100 hours. The possibility to recover the heat sink or the offsite power is considered in the study, as well as the repair of the diesels. The study also considers the impact on the reactor and on the spent fuel pool, taking into account, for example, the fact that some of the systems or water reserves are shared between these two installations. The results showed the importance of the strategy followed by the operators in case of simultaneous loss of the heat sink and loss of the offsite power affecting the reactor and the spent fuel pool at the same time. Even if this study is specific of an “extreme wind” hazard, in fact the developed methodology can represent a more general framework for treating long term accident sequences induced by external hazards and affecting more than one nuclear installation.

4. METHODOLOGICAL INSIGHTS FOR LONG TERM PSA MODELING

Today, both, EDF and IRSN work to improve the PSA methods to include the external events. These methods concern mainly:

- hazards screening analysis,
- hazards frequency assessment,
- SSC fragility analysis for different type of hazards,
- HRA taking into account the crisis organization and the organizational factors, etc..

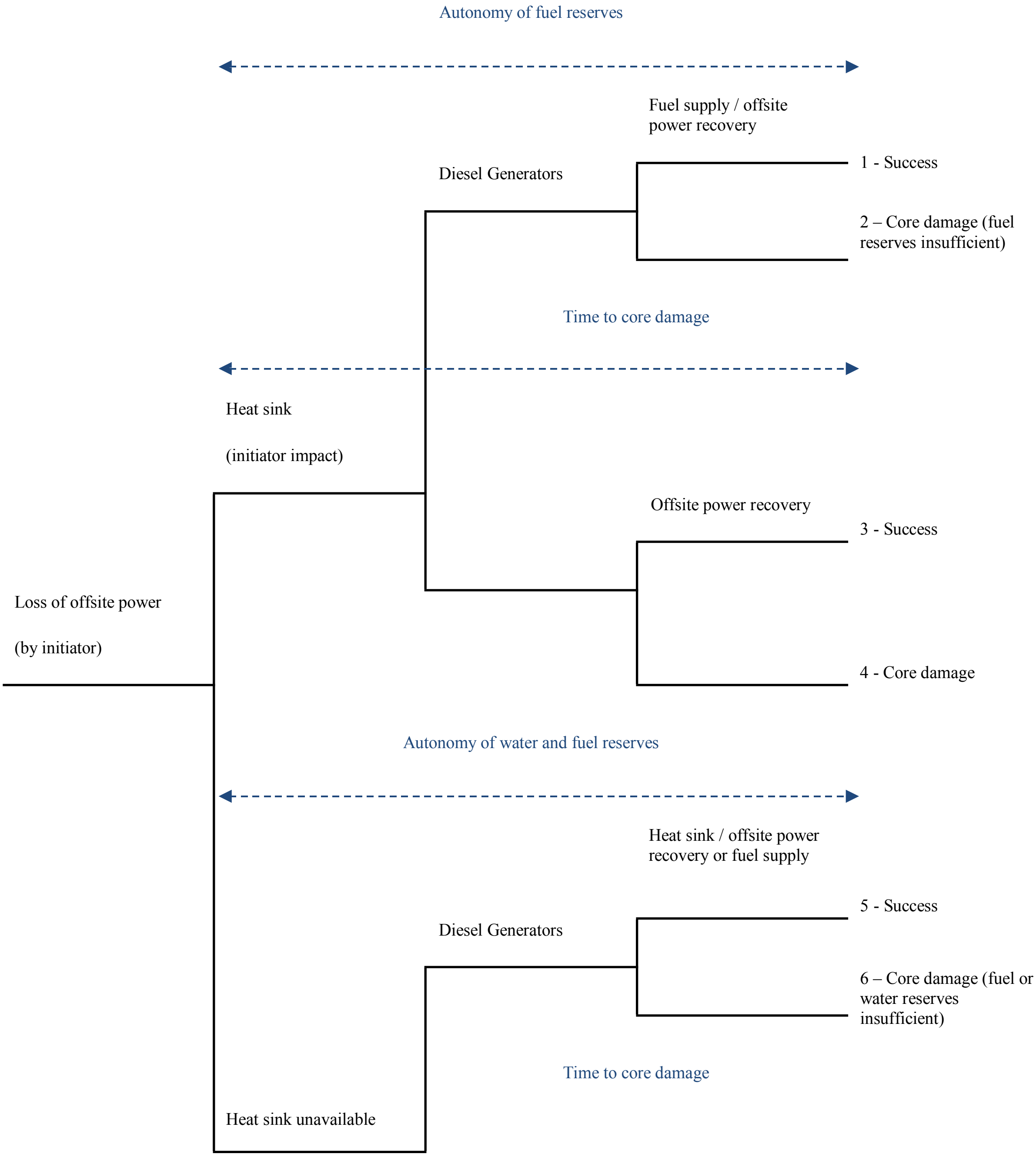
One important identified prerequisite is represented by the development of the methods to analyze the long term of the accident sequences induced by initiators which mays affect more than one installation on the site.

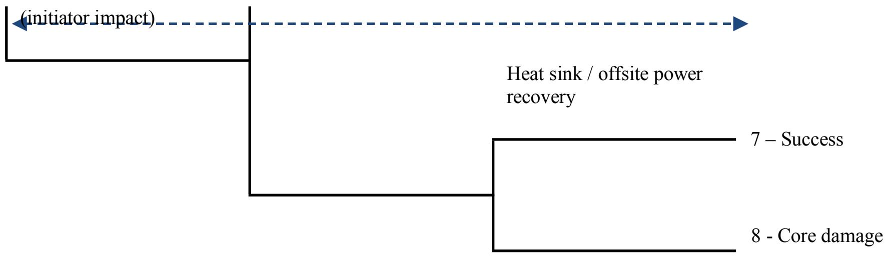
The experience gained by IRSN and EDF after the development of several studies treating long term accident sequences shows that the simple extension of the mission time of the mitigation systems from 24 hours to longer times is not sufficient to realistically quantify the risk and to obtain a correct ranking of the risk contributions; treatment of some recoveries turns out to be also necessary.

[8] Earthquake is treated in a specific probabilistic study.

At short term, IRSN intends to develop a generic study, for a given design, which can be used as a general methodology for the assessment of the long term accident sequences mainly generated by an external event or a combination of external events. This generic study may be then particularized for almost all external hazards and combination of external hazards for which a PSA development will be judged necessary on the basis of the screening analysis results (site specific). For example, the following figure schematizes an example of the possible combinations of events which can be generated by an external hazard. **This example is only illustrative and do not represent a real plant.**

Figure 1. "Long term" generic study





In this example it is assumed that the external hazard will directly lead to the loss of offsite power. In addition, the external hazard may also induce, with a given conditional probability, the loss of heat sink. In fact, most of the climatic hazards may lead, beside other consequences on the installation (projectiles, icing…), to the loss of offsite power and heat sink.

Due to the loss of offsite power, it is considered that the internal power sources (here diesel generators) should be available at long term, depending on the duration of the loss of offsite power and on the fuel reserves (including the assessment of the fuel external supplying possibilities).

In case of the loss of the heat sink the, lowest duration between the duration of the loss of offsite power (upper bound) and the duration of fuel tank capacity (including the assessment of the fuel external supplying possibilities) will be used to quantify the reliability of the internal power sources. The quantification of the reliability of the internal power should be preferably performed by using a method which allows realistically assessing the probability of failure of internal power sources over a long period of time, including the possible repair (for example Markovian or semi-Markovian models). One difficulty here is to correctly assess the success criteria of the internal power sources, especially if they are shared between the reactor and spent fuel pool or shared with other NPPs on the site (if the event affects more than one installation). Another important aspect is related to the assessment of the reliability data for long mission times of the internal power sources, since the available data are in general applicable only for short mission times since the operating experience is mainly based on the performed periodical tests, when the diesels functioning duration is generally short.

In case of failure of the internal power sources, the only possibility to avoid the undesired consequences (on the reactor or the spent fuel pool) is to recover the offsite power before this situation. In general the available time is short. Its probability can be assessed by taking into account the mean time to repair of the offsite power and the sequence duration limitations (for example if the duration is short because of limited fuel tank capacity the probability to not recover the offsite power is higher).

It has to be noted that in this example it is assumed that, by design, no other "non-electrical" means are provided, like steam driven pumps or passive means. If the design is different, the methodology "pattern" may be different.

In case of the loss of the heat sink, besides the internal power supply, the secondary water inventory (for reactor decay heat removal or for spent fuel pool make-up) should also be assessed. The duration which is considered to quantify the accident sequences is, in this case, the lowest duration (as upper bound) between the water and fuel inventories. The reliability of the internal power sources should also take into account in this case the impact of the loss of the heat sink on the availability and capacity of the ventilation and conditioning systems. The study should also take into account, if the water inventory is shared between several installations on the site, the operator strategy for using these resources.

This first attempt to develop the generic study allowed identifying some aspects which may be hazard (or combinations of hazards) dependent and which should be deeply assessed, as for example:

- the number of affected installations (only the reactor, reactor and spent fuel pool, whole site units,…),
- the expected duration of the loss of offsite power,
- the conditional probability of loss of the heat sink,
- the probability of failure of external fuel supply,
- the times to repair and recovery probabilities of the situation (offsite power / heat sink),
- other impacts on the installation in addition to the loss of off-site power and heat sink (for example, the probability of failure of internal power sources by projectile impact)…

The assessment of initial boundaries conditions is another important issue:

- plant(s) operating state (power, shutdown, whole fuel inside the spent fuel pool, etc.),
- unavailability or specific configurations for maintenance,
- outside temperature (summer, winter): the temperature can affect the speed of exhaustion of water and fuel inventories as well as the time before losing the electrical / control systems due to the failure of ventilation or conditioning systems,…

The intention is to use such kind of generic study in connection with the existing internal events level 1 PSA, in order to facilitate the quantification of a large number of scenarios corresponding to several hazards and combination of hazards occurring in different initial boundary conditions.

As the performance of sensitivities studies on the most important or uncertain assumptions is also foreseen, the proposed generic study should be simple and flexible to allow easy modifications of the input parameters and data. For example, the repair times of the different functions and equipment (heat sink, offsite power, diesels…) are, in the same time, important but also uncertain input data. The example presented here was especially defined with the aim to easily perform parametric studies on these key data.

The methodological developments have been started and the first results are expected to be available in the near future.

5. CONCLUSION

In the context of the extension of level 1 PSA scope to address external hazards, both EDF and IRSN work, in addition to the review of deterministic bases and studies on external events, on probabilistic aspects related to external events PSA (hazards screening analysis, SSC fragility assessment, HRA, etc.) for and on the improvement of methods to better take into account in the PSA, the long term of accident sequences induced by initiators which may affect the whole site containing several nuclear installations (reactors, fuel pools,…).

At short term IRSN intends to enhance the modeling of the “long term” accident sequences induced by the loss of the heat sink or/and the loss of external power supply. The experience gained by IRSN and EDF from the development of several probabilistic studies treating long term accident sequences shows that the simple extension of the mission time of the mitigation systems from 24 hours to longer times is not sufficient to realistically quantify the risk and to obtain a correct ranking of the risk contributions and that treatment of recoveries is also necessary. IRSN intends to develop a generic study which can be used as a general methodology for the assessment of the long term accident sequences, mainly generated by external hazards and their combinations. This first attempt to develop this generic study allowed identifying some aspects, which may be hazard (or combinations of hazards) or related to initial boundary conditions, which should be taken into account for further developments.

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