TREATMENT OF THE LOSS OF ULTIMATE HEAT SINK INITIATING EVENTS IN THE IRSN LEVEL 1 PSA

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Abstract:

The total loss of the ultimate heat sink is an initiating event which, even it is mainly of external origin, has been considered in the frame of internal events Level 1 PSA by IRSN. The on-going actions on the development of external hazards PSA and the recent incident of loss of the heat sink induced by the ingress of vegetable matter that occurred in France in 2009 have pointed out the need to improve the modeling of the loss of the heat sink initiating event and sequences to better take into account the fact that this loss may be induced by external hazards and thus affect all the site units.

The paper presents the historical steps of the modeling of the total loss of the heat sink, the safety stakes of this modeling, the main assumptions used by IRSN in the associated PSA for the 900 MWe reactors and the results obtained.

Keywords: level 1 PSA, external hazards, loss of the ultimate heat sink

1. INTRODUCTION

The total loss of the ultimate heat sink is an initiating event which, even it is mainly of external origin, has been considered in the frame of the level 1 Probabilistic Safety Assessment (PSA) performed by IRSN for internal events. According to the French PSA Fundamental Safety Rule, this kind of initiators should be considered by the plant operator in the frame of the "Reference PSA".

Up to now, the analysis and modelling of the sequences induced by a loss of the heat sink were analysed considering the impact of the initiator on a single unit.

The on-going actions on the development of external hazards PSA and the recent incidents of loss of the heat sink induced by the ingress of vegetable matters and debris that occurred in France in 2009 have pointed out the need to improve the modelling of the loss of the heat sink initiating event and sequences to better take into account the fact that this loss may be induced by external hazards and thus affect all the site units.

The following paragraphs refer to 900 MWe PSA. However, some of the presented aspects are also valid for other French operating reactor types (1300 MWe or 1450 MWe reactors).

2. HEAT SINK GENERALITIES (900 MWE NPPs)

Maintaining reactors cooling in all situations is one of the main safety functions. Inside the pumping station, the raw water coming from the river or the sea is firstly filtered by a pre-filtering grid which is cleaned by a trash removal system and then filtered through rotating filters (chain filters or drum screens depending on the NPP sites), each one being equipped with a flushing system. This raw water supplies the cooling circuit of the safety systems of the nuclear island (essential service water system (ESWS)) and the cooling circuit of the conventional island.

The ESWS consists (for almost all the French PWR) in two redundant trains, each one equipped with two pumps designed to deliver 100% of the required flow-rate. The system is an open circuit system: the water pumped in the pumping station is transported up to heat exchangers and then returns to the river or the sea. Through these exchangers, the ESWS ensures the cooling of an intermediate, closed circuit system, called the component cooling water system (CCWS) of the nuclear island. The ESWS and the CCWS are systems important to safety.

CCWS ensures cooling of many systems and components important to safety:

- the heat exchangers of the containment spray system (CSS),
- the heat exchangers and pumps of the residual heat removal system (RHRS),
- the heat exchangers of the fuel pool cooling and purification system (FPCS),
- the reactor coolant pumps (thermal barrier and electrical motor),
- the non-regenerative heat exchanger of the chemical and volume control system (CVCS),
- the condensers of cooling systems DEG and DEL (respectively nuclear island and electrical building chilled water system),
- the emergency ventilation system DVH dedicated to the ventilation of rooms housing the high head safety injection (HHSI) pumps.

As a consequence, a loss of the heat sink, in particular in case of natural hazards threatening the pumping station, leads to the loss of ESWS and may principally cause for reactors at power or in hot shutdown:

- A small break LOCA at the primary pumps seals. Indeed, the non-regenerative heat exchanger of the CVCS is no longer cooled in case of loss of the heat sink. The water is discharged by the CVCS at an increasingly high temperature. If the letdown line is not isolated, by the automatism or by the operator, the hot water will reach the charging line. The filters upstream and downstream of the CVCS pumps are not designed to withstand such temperatures and are thus liable to be damaged and possibly form debris which, when injected into the primary pump seals, are liable to damage the pumps. If the intake temperature reaches or exceeds around 130°C, the CVCS pumps cavitate. In this case, injection at the seals is lost and thermal barriers of the primary pumps are no longer cooled by the CCW system. Damage of the primary pump seals may result in a primary system break.

  Moreover, the primary pumps are automatically shutdown when the radial and thrust bearing lubricating oil temperature upper threshold of the primary pumps is reached (as the pumps are no longer cooled by the CCWS). If the primary pumps are not shut down, a small break LOCA will occur.

- The loss of cooling of the CSS heat exchanger used to maintain the temperature of the water in the reactor building sumps below the design limit of the safety injection pumps.

If the reactor is in shutdown state, the loss of CCWS leads to the loss of the residual heat removal system.

In all the reactor states, the spent fuel pool cooling is also lost as a consequence of the CCWS failure.

3. RISKS ASSOCIATED TO THE LOSS OF THE ULTIMATE HEAT SINK

The total loss of the ultimate heat sink is a real risk which was not fully identified at the initial design of French plants. It was not included in the list of design basis accidents and was introduced after the design stage in the list of the multiple failures situations ("design extension") considered in the safety demonstration.

The identification of the risks associated to a loss of the heat sink mainly comes from the insights of the level 1 PSAs. The main steps regarding the identification and treatment of this risk are presented hereafter.

3.1 Insights of the first Probabilistic Safety Assessments

PSAs provide a risk assessment method based on systematic investigation of accident scenarios, involving multiple failures likely to lead to consequences exceeding those of the design-basis operating conditions. Actually, PSAs have been extensively used in France as a complement to deterministic analysis to identify possible weak points in the conception. In particular, during the second half of the 1980's, PSA for PWR 900 MWe developed at IRSN highlighted some scenarios induced by multiple failures, not identified at the initial design, which may have, however, a significant frequency.

Notably, scenarios induced by a total loss of the ultimate heat sink (due to a common cause failure of the water intake or the loss of all ESWS or CCWS trains), have been identified by PSA as leading to a significant core damage frequency. In the first PSA performed in 1990 by IRSN for the 900 MWe French NPP, the core damage frequency for the initiating event "loss of heat sink in full power" was assessed to 6E-06 /r.y..

The dominant core damage sequences corresponded to human errors to quickly isolate the letdown line before the degradation of the CVCS pump (or to perform actions necessary to maintain an injection to the primary pumps seals), leading to the occurrence of a leak at the seals and to the failure of the HHSI function (ensured also by the CVCS pumps) that is necessary to cope with the primary circuit leak.

On the basis of the level 1 PSA results obtained by IRSN and confirmed by the utility (EDF), several significant design and organizational improvements were implemented on 900 MWe NPPs:

- improvement of accidental procedures and integration of a new strategy to cope with a loss of the ESWS. This strategy consists in using the thermal inertia of the refuelling water storage tank water (RWST) as an emergency heat sink for temporarily cooling the CCWS, throughout a CCWS/CSS heat exchanger. This temporary cooling allows the operation of one reactor cooling pump and one charging pump so that a safe state can be reached. The accident procedure - which was really applied for the first time in France during the incident of loss of the heat sink that occurred at Cruas 4 NPP in December 2009 - proved itself to be effective. This incident is presented in appendix;

- implementation of an automatic isolation of the letdown line in order to protect the CVCS pumps,

- replacement of the CVCS filters to improve their heat resistance.

The total loss of the ultimate heat sink has then been included in the list of the multiple failures accidents of the safety demonstration.

3.2 Impact of external hazards on the heat sink hazards

In the framework of the deterministic studies but also in the level 1 PSA, the loss of the heat sink has been studied for a single unit, considering a recovery time of the cooling of 100 hours with a probability of 95% (33 hours considered as the mean recovery time in the PSA based on an exponential statistical distribution).

However, in the framework of the periodic safety reviews, the list of the natural hazards and combinations of hazards to be considered in the safety demonstration and the characterization of the "design basis hazards" have been reviewed, considering the operating experience (extreme cold winters in 1985-1987, partial flooding of Le Blayais NPP during the 1999 severe storm, extremely high temperatures in 2003 and 2006, frazil in the pumping station in Chooz NPP in 2009…). Consequently, many improvements of the protection measure have been implemented at all French NPPs.

In addition, the initial assumption of the independence between external hazards and some accident situations such as a loss of the heat sink or a loss of the external electrical supplies has been reconsidered.

It has to be noted that, even if, initially, external hazards were considered as been independent from internal events accidents, studies performed in the framework of the periodic safety reviews have revealed that a correlation between the external hazards and internal events may exist. For example, the total loss of the heat sink may be induced by external hazard such as: extreme cold weather with frazil or ice blockage, ingress of vegetable matters, debris (leaves, algaes…) or hydrocarbon, external flooding at some sites (in particular when the flood carries debris and when the function of the filters and its flushing system are degraded in case of extreme flood), drought with very low level of the river…

Studies have been performed to analyze the types of accidents that may affect all the site units at the same time and for a long duration. These studies have brought about:

- stronger requirements on the water inventory in the tanks necessary to refill the secondary water tanks of the auxiliary feed water system in case of a loss of the heat sink of long duration;
- adaptation of the accident procedures in order to deal with multi-units loss of the heat sink and of the external electrical supplies;
- improvement of the on-site emergency planning to deal with multi-units accidents, in particular in case of external hazards (with possible difficulties to reach the site and to circulate).

On the probabilistic point of view, the current situation in France is as follows:

- As already mentioned, the modeling in the PSA of the loss of the heat sink initiator and the corresponding accident sequences didn't explicitly consider that they are, in fact, induced by an external hazard.
- Today, at IRSN, concerning hazards, priority is given to internal fire and internal flooding. However, developments are in progress in particular for earthquake and studies for different external hazards are expected from the utility for the next periodic safety review of operating NPPs.

4. UPDATE OF PSA MODELS AND FIRST RESULTS

During the third periodic safety review of the 900 MWe reactors, the modeling of the total loss of the heat sink in the level 1 PSA was updated by IRSN and EDF. It was the occasion for IRSN to better take into account the fact that a total loss of the heat sink, already modeled as an initiator of the level 1 PSA, may be induced by natural hazards.

The modeling assumptions and data, as the occurrence frequency of the loss of the heat sink induced by a natural hazard, the recovery time and the impact on the human actions necessary to deal with the accident, are not straightforward. The main assumptions (some of them being shared by IRSN and EDF and others not) and the results are presented hereafter.

4.1 Main assumptions

Characterisation of the initiating event

In French PSA, the occurrence frequency and the recovery time have been evaluated by expert judgement based on French and international operating feedback.

Even if the loss of the heat sink is treated in the "internal events" level 1 PSA independently from external hazards, its occurrence frequency (about 10^{-4}/y.r.) and, to a lesser extent, its recovery time (33 hours) are assessed on the basis of some natural events that had challenged the pumping station at some sites, in particular during the very cold winters in 1985-1987. A consensus was found between EDF and IRSN PSA teams on these values already considered in the level 1 PSA. However, the analysis of the recent event of loss of the heat sink that occurred in France (Cruas in 2009; see appendix) is in progress in order to confirm or reassess these values, in particular the frequency, in the update of the loss of the heat sink model. It has to be noted that the duration of the loss of the heat sink in 2009 (10 hours) was covered by the value taken into account in the PSA.

In a second step, it will be relevant to consider longer recovery times of the heat sink in order to take into account the impact on the pumping station of some extreme hazards. The evaluation of longer loss of the heat sink in the PSA will be useful to assess the sufficiently of the complementary design and organizational measures defined in France on the basis of the conclusions of the "stress tests" performed after the Fukushima accident.

Multi-units impact

One of the major changes for the update of IRSN model of the loss of the heat sink is the assumption of the multi-units effects of the initiator. Indeed, if the loss is caused by a natural hazard, IRSN assumes that all the units may be affected (in particular the units with common pumping station or with neighboring water intakes). This rather conservative assumption is not shared by the utility EDF that studies the impact on only one unit. It must be noted that even if the cooling by the ESWS at Cruas was totally lost at only one unit, 2 of the 3 other units were also challenged (with partial loss of the ESWS).

The modeling of the impact on multi-units leads to consider in the PSA the following aspects:

- the limited availability of water reserves for the secondary cooling, due to common reserves for several units and designed to cope with a loss of the ultimate heat sink at only one unit;
- the impossibility to use the common means on site (as the ultimate site diesel generator or other ultimate devices) by more than one unit at the same time;

- the impact on the human factor, as only one “safety engineer” is available for twin units;

- the impossibility to use back-up by twin unit specific systems (as the charging line of the other unit which can be used by the first unit as a substitute for safety injection in some situations).

For the moment in the IRSN PSA, the simultaneously impact on the reactor and on the spent fuel pool has not been considered yet and will be dealt with in a second step.

Integrity of the primary circuit

As already mentioned, in case of loss of the CCWS, the thermal barriers of the main coolant pumps are no longer cooled and the water injection to seals by the CVCS pumps may be also unavailable. Thus, the primary pump seals may be damaged which can lead to a leak. Based on specific tests performed by the pumps manufactory, the leak rate per pump has been assumed (since the first PSA developed in France) for 900 MWe French NPP to be equal to 60 t/h with a probability of 0.2 and to 5 t/h with a probability of 0.8, when the pumps are shut down and when the primary system temperature is above 180°C. If the primary pumps are not shut down, the leak rate is assumed to be equal to 100 t/h with a probability of 1. Regarding these assumptions a consensus exists between EDF and IRSN PSA teams.

It has to be noticed that EDF is performing studies and tests, in particular in the framework of the improvements after the Fukushima accident, to identify the possible solutions to improve the pumps seals in order to ensure their robustness in case of loss of their cooling.

CVCS/HHSI pumps cooling

In the absence of cooling by the CCW system of the normal and safety ventilation systems of the rooms containing the CVCS pumps (systems DVN and DVH), it was assumed, on the basis of a study of the temperature variation in these rooms, that loss of the heat sink:

- would not cause a loss of the CVCS pumps if the ventilation systems DVN and DVH continue to operate without cooling,

- will causes the loss of the CVCS pumps (which are also the high head safety injection (HHSI) pumps for the 900MWe plants) when DVN system is unavailable and only the DVH system operates without cooling (for example in case of simultaneous loss of the heat sink and loss of the off-site electrical power supply which will lead to loss of DVN system, since this system is not supplied by the diesels generators).

Protection of the CVCS/HHSI pumps

The operator is required to perform two manual actions to ensure proper operation of the CVCS pumps in case of a loss of the heat sink (increasing the injection rate at the seals to ensure minimum pump flow and isolating the seals leak-off line which is no longer cooled).

It has been assumed that the failure of any of these actions will result in failure of the CVCS pumps and induce a loss of the injection to the primary pumps seals, as well as the loss of the HHSI function (ensured also by the CVCS pumps).

Cooling of the electrical compartments

It was assumed that in the absence of cooling of the electrical compartments ventilation system, the time available before reaching conditions prejudicial to proper operation of the electrical systems is sufficient to enable recovery of the heat sink or implementation of mobile cooling resources.

Accidental procedures

The PSA update considers the current symptoms-oriented procedures, instead of the previous events-oriented procedures.

Resistance of equipment in case of external hazards

At this stage, the update of the "loss of the heat sink model" focuses on the review of the functional assumptions and data used. The detailed nature of the external event which result in this loss is not taken into account. This first step of the future PSA model improvements will be to identify and characterize the reliability of the lines of defense against the external hazards (prevention and mitigation) and of the main equipment involved (affected by the hazard or needed to mitigate the effect of the hazard).

In a second step, IRSN plans to adapt the modeling to some external events. This difficult step will require deeper analyses on the impact of the hazard on the equipment (evaluation of the equipment robustness) and on the management of the situation (specific procedures used, specific difficult conditions for the operators, impact of the hazard on the site accessibility and the on-site emergency management, possible anticipation of some actions using a warning system…).

4.2 Results

The core damage frequency for the initiating event "loss of heat sink in full power" was assessed in the first PSA to 6E-06 /r.y. The dominant core damage sequence corresponded to the occurrence of a leak at the primary pumps seals with failure of the safety injection function.

In the updated PSA, considering multi-units impact, symptom oriented procedures and design improvements to limit the risks of primary leak in case of loss of the heat sink, the core damage frequency for the initiating event "loss of heat sink in full power" has been estimated to 5.5E-7 /r.y.

The dominant sequence in the updated PSA corresponds to the exhaustion of the secondary water reserves before the heat sink recovery (sequence due to multi-units consideration). In this situation where the cooling of the primary circuit by the secondary circuit is no more available, the feed and bleed procedure can't be used to remove the decay heat due to the absence of the heat sink (indeed the CCWS is necessary to cool the containment spray system used to maintain the temperature of the water in the reactor building sumps below the design limit of the safety injection pumps).

The frequency of the sequence that used to be dominant in the first study (leak to the primary pumps seals) has been reduced due to the design and procedures improvements. The efficiency of the new procedures and design has been shown during the 2009 Cruas incident.

5. CONCLUSION

The total loss of the heat sink was not initially addressed in the safety demonstration of French NPPs. On the basis of the insights of the first probabilistic assessments performed in the 80's, the risks associated to this "multiple failure situation" turned out to be very significant and design and organisational improvements were implemented on the plants.

Reviews of the characterization of external hazards and of their consequences on the installations and French operating feedback have revealed that extreme hazards may induce a total loss of the heat sink. Moreover, the accident that occurred at Fukushima in 2011 has pointed out the risk of such a loss of long duration at all site units in case of extreme hazards.

In this context, it seems relevant to further improve the modelling of the total loss of the heat sink by considering the external hazards that may cause this loss. In a first step, IRSN has improved the assumptions and data used in the loss of the heat sink PSA model, in particular by considering that such a loss may affect all the site units.

The next challenge will be the deeper analysis of the impact of external hazards on the equipment necessary to cope with the loss of the ultimate heat sink.

APPENDIX:
INCIDENT AT CRUAS 4 IN 2009 - TOTAL LOSS OF THE HEAT SINK (IAEA/NEA IRS N. 8068)

The Cruas site has two twin-unit plants, i.e. four 900 MWe PWR reactors. Each pair of plant units has a common pumping station: one station for plant units 1/2 and one for plant units 3/4.

During the night of December the 1st, 2009, a massive amount of vegetable matter (around 50 m^3 compared with a monthly average of 5 m^3) blocked the water intake of the common pumping station of Cruas NPP units 3 and 4, by clogging the pre-filtration trash racks. The fall in the water level between the pre-filtration and the rotating drum screens made unavailable one of the two trains (train A in operation) of the essential service water system (ESWS) of plant unit 4. This led the operator EDF to shut down reactor 4 by dropping control rods, in application of the incident situation procedures. Then, EDF switched the ESWS onto the other train (train B) that was also unavailable because of the lack of water intake. Unit 4 was therefore in a situation of total loss of the heat sink, the first time in France.

Unit 4 was brought into a fallback state in normal shutdown, the reactor being cooled by steam generators, with the primary circuit at the conditions allowing to connect the residual heat removal system (RHRS), but with RHRS unconnected. To temporarily cool the component cooling water system (CCWS), a specific operation strategy (mentioned in the procedures) was implemented, using the thermal inertia of the refuelling water storage tank (RWST) throughout a heat exchanger and a pump of the containment spray system (CSS).

The on-site emergency organization was activated. National emergency organizations were also activated afterwards, involving several emergency teams: national crisis teams from EDF and from public authorities (French Safety Authority (ASN) and IRSN).

During the incident, cleaning operations of the pre-filtration trash racks and of the filtration drum screens were continuously performed. The monitoring and protection means existing in the Cruas pumping stations were unable to ensure the ESWS supply. Furthermore, the means of cleaning of the systems ensuring the pre-filtration and filtration of the raw water from the river Rhone, installed on the site in a fixed and durable manner, were not sufficient to cope with this situation. This necessitated resorting to mobile means, as a trash removal truck for cleaning the pre-filtration trash racks, as well as collection trucks to aspirate and store the waste from the rotating drum screens.

The total loss of heat sink of unit 4 lasted 10 hours.

Other plant units were also impacted by the clogging of the trash racks: plant units 2 and 3 partially lost their heat sink.