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# Results of the Reassessment of the Protection of French Nuclear Power Plants against External Flooding

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# RESULTS OF THE REASSESSMENT OF THE PROTECTION OF FRENCH NUCLEAR POWER PLANTS AGAINST EXTERNAL FLOODING

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ABSTRACT

The current general principles for the protection of the French Nuclear Power Plants against flooding of external origin are defined in the French Basic Safety Rule I.2.e.

The partial flooding of « Le Blayais » Nuclear Power Plant in 1999 has called into question the design bases used for the protection against external flooding and the existing measures, especially the warning systems, the site protection measures, the protection of safety-related equipments, the procedures and the emergency organization.

Following this event, the protection of the French Nuclear Power Plants against external flooding has been completely reassessed to ensure that the installations would be effectively protected. As a result, numerous additional protection provisions have been implemented on all the French Nuclear Power Plants.

## KEY WORDS

External flooding - Protection measures – French experience feedback

## 1. Introduction:

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The partial flooding of « Le Blayais » Nuclear Power Plant in 1999 has called into question the design bases used for the protection against external flooding and the existing measures, especially the warning systems, the site protection measures, the protection of safety-related equipments, the procedures and the emergency organization.

Following this event, the protection of the French Nuclear Power Plants against external flooding has been completely reassessed to ensure that the installations would be effectively protected. As a result, numerous additional protection provisions have been implemented on all the French Nuclear Power Plants.

## 2. Current French regulation

The general principles for the protection of the Nuclear Power Plants against flooding of external origin are defined in the French Basic Safety Rule (BSR 1.2.e) whose respect is considered as being in conformity with the French technical regulations. According to BSR 1.2.e, protection is mainly provided by:

1. The setting of the platform supporting the buildings which shelter safety-related equipment at a level at least equal to that of the maximum flood level, plus a margin of safety (the corresponding level is referred to as the design basis water level).

2. The closure of the potential pathways for water ingress into the chambers sheltering materials necessary to maintain the installation in a safe condition and located below the level of the platform.

For the sites commissioned prior to the coming into effect of BSR 1.2.e on April 12, 1984, this regulation stipulates as retroactivity clause that those sites not meeting the first criterion must in any event satisfy the second one and that complementary measures must be proposed to ensure a level of protection equal to that required by BSR 1.2.e.

### *2.1 Design basis water level for river sites*

The design basis water level is the highest level calculated for two scenari: natural flood and dam failure.

The water level reached at the site in case of natural flood is calculated for a flow rate defined by statistical extrapolation of the flows observed near the site. The statistical method used is a POT (Peak Over Threshold) method. It implies the study of samples of flow rates higher than a threshold and to integrate historical data (former to the continuous period of recording). The flow rate is calculated for a return period of 1000 years. The BSR then imposes to take the upper bound of the 70 % confidence interval of this flow rate, and moreover requires an increase of 15% of this value to define the design water level. The water level on the site is obtained with a model (generally numerical) representing a reach of the river in which the flood is routed considering a steady flow.

The second phenomenon considered is the collapse of a dam. The rupture of all large dams located upstream of the site are successively examined in order to define the most critical dam break for the site. The failure of dams is postulated without consideration on the causes of the failure. According to the constitutive materials of dam, two types of failure are considered: for concrete dams (arch or gravity dams) total and instantaneous failure, for rock or earth-fill dams progressive failure due to internal erosion or overtopping. Downstream routing of dam break wave to the site is calculated on a numerical model considering a base water flow of the river equal to 100-years flow rate (or, if greater, the flow rate of the maximum observed flood), to obtain the flood level at the site.

### *2.2 Design basis water level for coastal sites*

The design basis water level results from the addition of the maximum level reached by astronomic tide and the set-up calculated for a return period of 1000 years. The maximum water level related to astronomic tide is calculated using semi-empirical formula adjusted on series of data measured at a gauge station near the site. For French NPP coastal sites the tidal range is between 6 and 10 meters. Series of water level measurement are corrected from the level of the astronomic tide to obtain time series of set-up. A statistical extrapolation, using the POT method, provides the extreme set-up, calculated for a return period equal to 1000 years. For French NPP sites, extreme set–up are about 2 meters.

It can be note that no tsunami has been recorded on the French Atlantic coast, if we except observed fluctuations of a few centimetres due to very distant tsunami. Some historical reports of observed tsunami are available for Atlantic coast in the vicinity of France. The most documented event is the tsunami generated by the Lisbon (Portugal) earthquake in 1755. Water levels rising of about 2 meters were observed in several harbours on the southern coast of England and Ireland. However, the methodology used to evaluate extreme storm surges is based on the identification of all abnormal high sea levels which result in most of cases from storm but include also other causes such as tsunami. The BSR considers that the extreme storm surge covers the effects of tsunami for French NPP sites.

### *2.3 Design basis water level for estuary sites*

Due to the possible combinations of maritime and river conditions, the design basis water level is the highest level calculated for three scenari presented in the table 1.

### *2.4. Synthesis*

| | | | |
|---|---|---|---|
| DBWL for river site<br>the highest water level obtains on site from : | | | |
| (a) | 100-years flood flow<br>(or, if greater, historical flood flow) | + | dam failure<br>(the one critical for the site) |
| (b) | 1000-years flood flow | + | 15% in flow rate |
| DBF for coastal site (Atlantic)<br>combination of: | | | |
| (c) | 1000 years set-up (storm surge) | + | maximum astronomic tide |
| DBF for estuary site<br>the highest of combinations of continental and maritime events: | | | |
| (d) | 1000 years set-up (storm surge) | + | maximum astronomic tide |
| (e) | (a) | + | average astronomic tide |
| (f) | 1000-years flood flow | + | maximum astronomic tide |

Table 1 : Design basis water level according to the BSR 1.2.e

During the discussions before BSR 1.2.e came into force in 1984, it was pointed out that it is impossible to determine extreme events with a probability of exceedance of less than 10-3 per year, because of the data available in France. As shown in the previous table, the DBF results in all the cases, except for case (b), from the combination of an extreme event and a rare event. The probabilities of these combinations are less than 10-3 per year, but not quantified.

However, this type of combination can’t be used for river flood due to run-off. Then, a margin of 15% is added to the flow rate in order to decrease the frequency at which the level is exceeded by about one order of magnitude, leading to a frequency less than 10-3 per year. BSR 1.2.e states that “In order to ensure a certain homogeneity between the probabilities of different risks due to external hazards and taken into account in sizing the nuclear facilities, a margin of safety is fixed on an overall basis as being the water level corresponding to an excess flow rate equal to 15% of the flow rate of the estimated 1000-year flood”.

## 3. French experience feedback on external flooding

The most safety significant external flooding event concerns the partial flooding of the Le Blayais NPP at the end of the year 1999.

The site of « Le Blayais » Nuclear Power Plant (4-Unit PWR) is located in the county of Gironde, 50 km north-west of Bordeaux. The installations are located on the banks of the River Gironde in a swampy area. The position of the site on the estuary of the River Gironde is shown in figure 1 (red circle).

Figure 1 – View of the Gironde estuary area and of the Le Blayais site location (red circle)

Assessments made to estimate the high water levels of the Gironde have shown that at the “Le Blayais” site, the effects of the sea are more important than those of the river. Therefore, the approach adopted for quantifying these levels is that used for coastal sites.

The original site design regarding the external flooding hazard was based on a projected high Gironde estuary level from a highly conservative astronomical tide height combined with additional water level elevation from atmospheric and open sea windy conditions. The site platform height, established based on this approach, was then of 4.5 m above the reference sea level (French standard sea level called NGF). Later engineering reviews following the change of the French regulations and the application of the Basic Safety Rule 1.2.e resulted in the construction of a plant protection dyke around the site. The height of the dyke between the plant and the Gironde estuary was 5.2 m NGF and the one of the other sides of the dyke was 4.75 m NGF, as shown in figure 2.

The latest reassessment carried out by Electricité de France in the late 90”s identified that the existing dyke height was not sufficient to protect the plants against the worst-case conditions of the Gironde. Electricité de France had therefore planned to increase the height of the protection dyke to 5.70 m NGF; work scheduled to be performed in 2002.

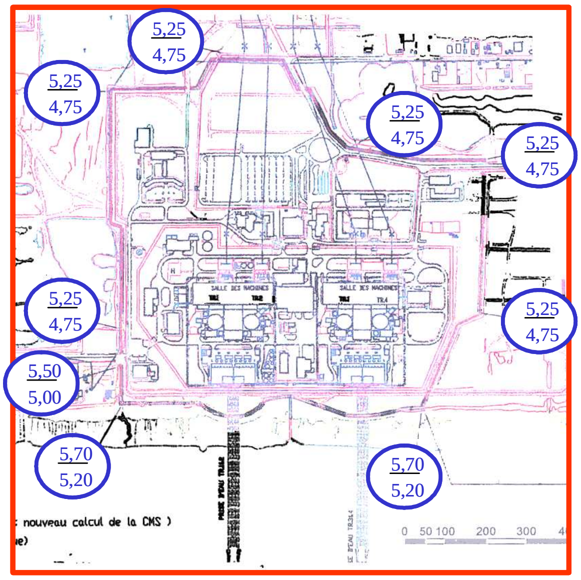


Figure 2 – Dyke height (below numbers: height the 27th of December 1999; above numbers: foreseen height)

### 3.1 Event description

On the 27th of December 1999, a severe storm from the Atlantic Ocean approached the southwestern part of France. In the vicinity of the "Le Blayais" Nuclear Power Plant, this storm induced the following phenomena:

- a quick drop of the atmospheric pressure to a value lower than 985 hPa,
- strong winds, around 180 to 200 kilometers per hour.

At that time, Blayais Units 1, 2, and 4 were at full power, and Unit 3 was being prepared for start-up from a planned refuelling outage, with the vessel head on and water level at the midloop operation level.

The simultaneity of the high storm-driven level in the Gironde estuary and of the waves induced by the wind, with an estimated height of 1,5 to 2 meters, led to important water volumes washing over the plant protection dyke. This washing over began around 9:30 PM and, due to the wind direction, concerned mainly the northern part of the protection dyke, exposing preferentially the Units 1 and 2. Moreover, another water ingress from the surrounding flooded swamp areas was localized through an access road in the North-West part of the site. The water reached a depth of around 30 cm in the North-West corner of the site, value obtained by observing branches which were caught in the access gates (see figure 3).


Figure 3 – View of the Nort-West gate of the site

Access to the site was prevented for several hours by flooded roadways and fallen trees. This access was possible only around 2:00 AM the 28th of December 1999.

Large amounts of water arriving on the site began entering electrical cable and auxiliary steam service trenches on the plant site. As a matter of fact, these trenches are covered either by unleaktight mettalic plates (see figure 4) or concrete panels (see figure 5).

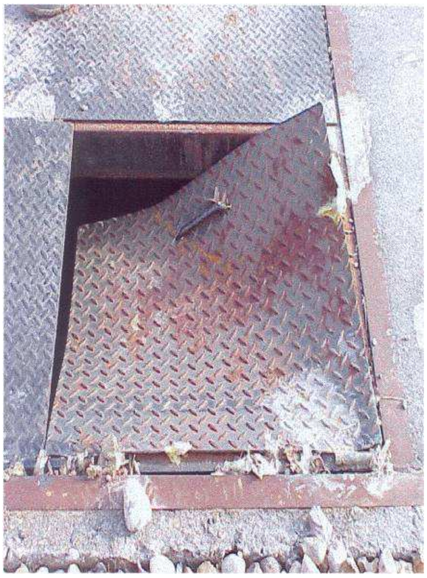

Figure 4

Figure 5

From these trenches, water flew to underground galleries whose connections to the Nuclear Island were not designed as leaktight. Then from these galleries, the water flew into the Nuclear Island compartments as follows.

For the Unit 1, the increase of the water level in a connected general site gallery led to water ingress into the Electrical Building of Unit 1 and eventually the fire door between the gallery and this building was burst open. Water then spred through the Electrical Building, to the containment cables prestressing gallery of Unit 1 and, through the Safety Iinjection System and the Containment Spray System pipes penetrations, to the Fuel Building basements of Unit 1 housing the Low Head Safety Iinjection System and the Containment Spray System pumps.

The Essential Service Water System galleries of Units 1 were also flooded both via the site galleries and via some connections to the Electrical Building. The water then entered through penetrations the Fuel Building and the compartments housing the train A pumps of the Essential Service Water System (see figure 6).

Figure 6 – damaged electrical penetration in the Unit 1 Fuel Building basement

For the Unit 2, the water entering the Electrical Building of Unit 1 also spred to the connected Electrical Building of Unit 2. Additional water pathways to Unit 2 from other site galleries were also identified. From these different entries, the water flooded both ESWS galleries, the Fuel Building basements and the containment cables prestressing gallerie of the Unit 2.

Eventually, an estimated 100,000 cubic meters of water flooded the site area of the Units 1 and 2. Of the facilities which were flooded in Units 1 and 2, the following should be noted:

- • the rooms containing the essential service water pumps. The essential service water system of each unit comprises four pumps on two independent trains (A and B); each pump is capable of providing the entire throughput required. In Unit 1, the essential service water system pumps of Train A were lost as a result of immersion of their motors;
- • some utility galleries, particularly those running in the vicinity of the fuel building linking the pump house to the platform;
- • some rooms containing outgoing electrical feeders. The presence of water in these rooms indirectly led to the unavailability of certain electrical switchboards;
- • the bottom of the fuel building of Units 1 and 2 containing the compartments of the two LHSI pumps and the two CSS pumps and the associated electrical and electronic components. The nuclear operator considered that the pumps were completely unavailable. The systems to which these pumps belong are the engineered safety systems of the installation which are designed mainly to compensate for breaks in the primary system.

For the Units 3 and 4, the genaral layout of the site trenches and galleries has prevented these Units from being too much flooded. Only some water ingress in the Train A gallery of the Essential Service Water System has occurred.

### *3.2 Lessons learned from the flooding of the Blayais site in 1999*

The “Le Blayais” site flooding has pointed out the possible occurrence of modes of degradation of the safety level affecting simultaneously all the units at a site and has revealed some weaknesses in the site protection against external flooding related to:

- the extreme meteorological conditions considered in the design of the site protection. For the “Le Blayais” site, high strom-driven waves coincident with high water level in the Gironde estuary had not been initially considered.
- the warning system and its criteria, allowing the anticipation of severe weather (verification of the protection devices, implementation of movable equipment…) and the shutdown of the plants in a timely schedule.
- the site accessibility (blocked roadways), highlighting both the need for additional staff of operating and emergency response personnel prior to the arrival of the severe flooding conditions and the need for an adequate autarchy of the site (water quality and fuel supply…).
- the flooding-related procedures and the on-site emergency organization, considering all the divese aspects linked to the flooding conditions including:
    - the accessibility of the equipment located outside of the protected buildings.
    - the simultaneous impact on several plants, with a potential risk of loosing both the external power supplies and the ultimate heat sink.
    - the isolation of the site and the difficulties to provide rescue staff and equipment.
- the detection of water in the flooded rooms, allowing a quick response of the operating staff for implementing the necessary action, like the implementation of movable pumping devices,
- the faults in electrical isolation, likely to lead to some electrical busbars loss whereas the external grid may be lost due to the severe weather conditions,
- the management of release of the water collected in the flooded facilities.

More generally, these weaknesses are taken into accounbt in the reassessment of the protection of the French Nuclear Power Plants against external flooding have been undertaken by Electricité de France.

## 4. Reassessment of the protection of all French NPPs against external flooding:

In the light of the observations carried out during the flooding of the Blayais site, a number of lessons have been drawn for all the French sites. The main safety and technological areas that have been investigated or examined to ensure that the installations would be effectively protected from the risk of external flooding are presented hereafter. They had been the topic of discussions between the French Nuclear Safety Authority and its technical support IRSN on the one hand and Electricité de France on the other hand since March 2000.

### *4.1 Hazards characterization*

The first stage of the reassessment process is a wide and systematic review of all the phenomena and events that might generate an extreme flood hazard as well as their potential combinations. The identification of these phenomena and the characterization of the corresponding hazards should allow a better assessment of the vulnerabilities of all the sites and notably of the following predictable "site vulnerabilities" the facilities should be prevented from or be able to cope with:

- flooding of nuclear buildings sheltering safety-related equipments due to the submersion of the site platform as well as due to the rise of ground water;
- flooding of safety-related equipment in pumping station with a risk of accidental situation corresponding to a partial or total loss of the heat sink that might affect all the units of the site. This risk is linked to the water level on the pumping station platform and thus to the immersion of safety related equipments Moreover, the potential risk of loosing the heat sink due to a threat of water intake clogging has also been considered,
- loss of all off site power supplies due to the submersion of electrical stations or switchyards, to electrical towers instability in flooded ground or to storm conditions at the coastal sites (electrical towers collapse…);
- temporary site isolation caused by roads obstruction.

#### 4.1.1 Phenomena identification

A preliminary list of phenomena was then drawn up with an aim of exhaustiveness and without taking into account the importance and the frequency of these events in France. The phenomena were investigated according to their origin, as shown on figure 7.

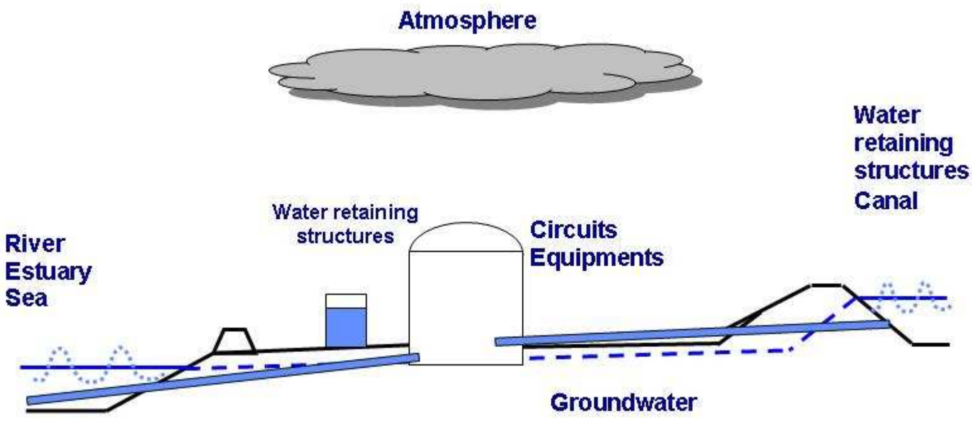


Figure 7: sources of flood phenomena

The preliminary list of phenomena was analyzed to identify the phenomena which are likely to affect one or several of the 19 French nuclear sites. One of the objectives of this selection is to limit as much as possible the number of phenomena to be considered in the detailed studies site by site in order to facilitate the review process. This analysis thus results in drawing aside the phenomena which can be excluded taking into account the geographical environment of the sites. Moreover, the phenomena whose potential impact is covered by that of another phenomenon are not identified as particular phenomenon. For example “river flood” covers flood due to run-off and also due to obstruction of the river channel by ice or debris jams. This work has led to the identification of 13 phenomena which must be taken into account in the re-examination.

5 among these 13 phenomena have been previously identified in a Basic Safety Rule (BSR) that defines requirements for river/estuary/marine water levels to consider in the design of French NPP: (1) River flood, (2) Dam failure, (3) Tide, (4) Storm surge and (5) Tsunami.

In addition to these 5 phenomena, 8 “complementary” phenomena are defined:
(6) Wind-waves on sea,
(7) Wind-waves on river or channel,
(8) Swelling due to operation on valves or pumps,
(9) Water retaining structures (other than dams) deterioration,
(10) Circuits or equipments failure,
(11) Rainfalls on site, brief and intense,
(12) Rainfalls on site, regular and continuous,
(13) Groundwater rising.

The distribution of these 13 phenomena according to the water origin is shown on figure 8. The description of selected phenomena is presented in the following part.

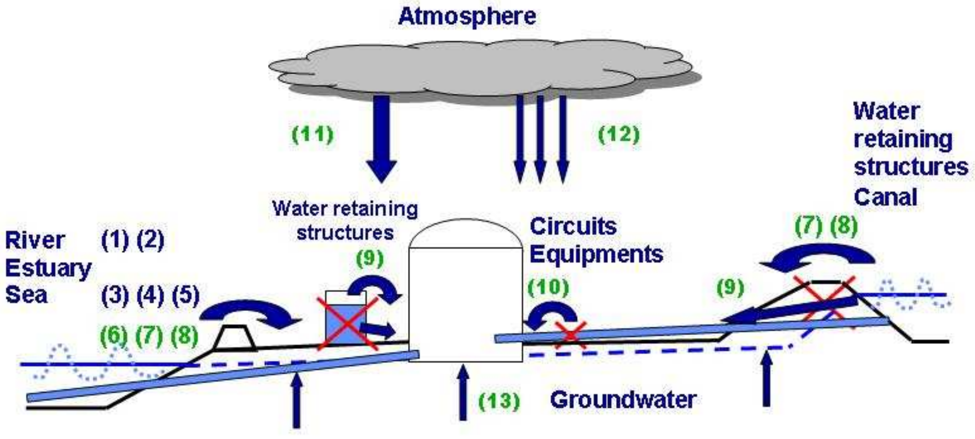


Figure 8: selected phenomena

## 4.1.2 Extreme phenomena/events definition

Extreme events related to the selected phenomena are defined in terms of Intensity, Dynamic and Frequency.

- Intensity is characterized by physical parameters such as water level, water volume, water flow rate, rainfall intensity … depending on phenomena
- Dynamic deals with two durations:
  - the minimal duration of the rise from a value of normal intensity to an extreme value, this parameter is necessary in the choice of the safety devices to use, and for warning system definition,
  - the duration during which an extreme intensity is maintained
- Frequency is derived from a statistical analysis of the phenomenon (for example rainfall) or of the initiating cause of the phenomenon (for example winds for wind-waves). The frequency is the

probability that a given intensity is exceeded. However, it is not always possible to calculate this parameter. Some extreme phenomena such as dam failure are postulated without consideration of their probability.

Methods used to characterise extreme events resulting from the 8 "complementary" phenomena are briefly exposed here after.

(6) Wind-waves on sea
The wind-waves are characterized by the significant height and the associated period according to the following methodological steps:

- definition of extreme offshore waves on the basis of measurement of waves (or reconstitution from data related to wind), with a return period of 100 years, calculated by using the POT method;
- determination, by numerical modelling of the characteristics of these waves propagated to the near shore area of the plant site, by considering a constant water level in time corresponding to the extreme marine level;
- evaluation of the effects of these waves on the site in terms of flow rate and volume of water which can overflow protections.

The duration of the extreme event is determined by the duration of high tide level.

(7) Wind-waves on river or channel

This phenomenon is equivalent to the previous one, but may affect smaller water bodies such as estuary (le Blayais event), flooded plain or channel. The significant height and associated period characterise also this phenomenon. The methodology to evaluate the effects of waves differs only for the first step. Extreme waves height and period on the water body are calculated from extreme wind speed, fetch (the distance which the wind can travel on water when raising waves), constant water depth … using empirical formulas. A statistical analysis of wind speed observed at or near the site provides extreme value to consider, with a return period of 100 years. The duration of the extreme event is also determined by a study of the high wind speed observation.

(8) Swelling due to operation on valves or pumps

A sudden change in flow of water in a channel may cause strong variations in the water level and swell of water. This concerns both canals near the site and canals created for water supply of the NPP. Typical situations are: (a) gates or valves closing on the driving force channel of a hydroelectric plant downstream of the site, (b) gates or valves malfunction generating uncontrolled inflow of water in the channel, (c) sudden stop of Circulating Water pumps that operate on a semi-closed channel. The "swelling" phenomenon is characterised by the maximum overflow rate or the maximum corresponding height on the site, as well as the duration of the fast dynamic phenomenon. Considered scenarios results from postulated situations (stop of n pumps)…and the extreme characteristics are derived from hydraulic calculations using numerical models.

(9) Water retaining structures deterioration

This concerns deterioration of structures such as canal embankments, reservoir ponds, water retainers, tanks of air coolant towers. These structures are located near or on the site and at a level higher than the site platform. The intensity of extreme phenomena is characterised by the released volume of water and/or the maximum flow rate resulting from the deterioration. The occurrence of these phenomena is considered as a result of different load cases such as earthquake, explosion, airplane crash hydraulic deterioration, etc. According to the stability of the structures under the load cases, water flow may result from a complete failure or from a lost of tightness.

(10) Circuits or equipments failure

This concerns cooling circuits. The extreme phenomenon is characterised by the volume of water released by the failure taking into account the specific flow rate through the break until isolation of the flow. The configuration taken into account corresponds to a "Vandellos" type of situation with the partial break of a Circulating Water pump sleeve. In that configuration, it is considered that a manual isolation of the break can be performed in all cases within at most 20 minutes. Taking into account in particular the water flows in play (about $20m^3.s^{-1}$), this situation is identified as the most pessimistic case of break of circuits or equipments.

(11) Rainfalls on site, Brief and Intense

Brief and Intense Rainfalls are the phenomena classically examined for drainage system design. The typical durations of these events are in the range of some minutes to some tens of minutes. They are related to the surface of catchment areas on NPP sites and can be evaluated by time necessary to the water run-off from the point furthest away from the outlet of the catchment area, to reach this outlet. The intensity is characterised by the amount of water that falls during the duration of the event. Intensity (I) and duration (t) are related by the empirical formula:

$$I(t) = a . t^{b}$$

Where a and b are dimensionless coefficients depending on the regional precipitations and the considered frequency. They have been calculated for each site on the basis of statistical studies of observed rainfalls. The greatest return period considered is 100 years.

(12) Rainfalls on site, Regular and Continuous

Regular and continuous rainfalls have been identified as possible causes of flood if the drainage system of the site can't be used. This situation can occur for example as a consequence of a river flood which imposed to close gravity discharge of the drainage system to avoid flooding of the site through this system. As for Brief and Intense Rainfalls, statistical studies of precipitation observed in the region of each site are performed to calculate the extreme intensity, with a return period up to 100 years. Generally, the extreme intensity is calculated for a duration of 24 hours. However, according to the considering scenario for site study, the duration may be adapted to the duration of drainage system unavailability.

(13) Groundwater rising

Extreme rising are characterised by water table level and, if this level reaches the surface of the ground, water flow rate and water volume on the ground. Rising of groundwater level is generally a consequence of another phenomenon which may generate flood. For the majority of the sites, the extreme levels of groundwater are due to river risings or extreme marine levels. However, the rainfalls or Water Retaining Structures Deterioration can also be at the origin of extreme groundwater increase. Several approaches are implemented to characterize the extreme events. In certain cases, very coarse and conservative approaches are sufficient, for example, the level of groundwater can be taken equal to that of the river flood. For the other cases, it is necessary to implement hydrogeological models. Hydrographs of river flood, extreme rainfalls, or water retaining structures deterioration are then used to define the boundary conditions of the models. In the majority of the cases, calculation must be carried out for flows in transient state. Due to this approach, the frequency of occurrence of extreme groundwater rising depends on the frequency of the initiating scenario. No specific duration can be defined, even if this phenomenon has a slower dynamic than all the others.

### 4.1.3 Hazards definition

Considering that flood may result from the simultaneous occurrence of several events, particular attention should be paid to combinations of events which result in the largest flood to be considered for the design of protection. Before the flooding of le Blayais site, flood hazards for NPP were defined in the Basic Safety Rule 1.2.e., which presents requirements for determining river/estuary/marine water level (see § 2). Recent works lead to the definition of complementary hazards, presented here after.

The same deterministic logic as applied in BSR 1.2.e is used. Then a set of hazards resulting from one extreme event or from a combination of events (of adjusted severity) has been identified. The main criterion used to select combinations is the interdependancy of phenomena. Combinations have been selected in a deterministic approach, based on expert judgement. No quantified probabilities are associated with the combinations. However, probabilistic considerations provide in some cases useful guidance for the selection.

| | | | |
|---|---|---|---|
| Complementary hazards for river sites<br>combination of: | | | |
| (g) | Water level for 1000-years flood flow | + | 100-years wind waves |
| (h) | Water level for 100-years flood flow | + | 100-years rainfalls on site, regular and continuous |
| (i) | DBWL (run-off = b) | + | 10-years rainfalls on site, regular and continuous |
| (j) | DBWL (a and b) | + | Swelling due to operation on valves or pumps (on site) |
| Complementary hazards for coastal sites (Atlantic) and estuary sites (under marine influence)<br>combination of: | | | |
| (k) | DBWL | + | 100-years wind waves |
| (l) | 100-years water level (tide + set up) | + | 100-years rainfalls on site, regular and continuous |
| (m) | DBWL | + | 10-years rainfalls on site, regular and continuous |
| (n) | DBWL | + | Swelling due to operation on valves or pumps (on site) |

Table 2 : Complementary hazards

The use of interdependency criteria is illustrated by hazards (g) and (k). For river sites (g), it is considered that there is no direct relationship between a flood due to run-off and extreme wind situation that may cause extreme wind-waves at the site. For coastal sites (k), the extreme water level results from a storm (on maximum tide) this storm is also at the origin of wind-waves. Then, the water level considered for coastal site is more conservative that for river site.

The use of probabilistic criteria is illustrated by hazard (i). The combination of extreme river flood (DBWL) and rainfalls on site is considered only for flood due to run-off. The probability of DBWL resulting from dam break is regarded as sufficiently low so that it is not necessary to take into account simultaneously rare rainfalls.

Three hazards are defined as resulting from only one phenomenon, independently from any other flooding cause.
(o = 9) Water retaining structures deterioration
(p = 10) Circuits or equipments failure
(q = 11) Rainfalls on site, brief and intense.

Hazards related to groundwater rising are defined as a consequence of the following extreme events or combinations of extreme events:
(r) Water retaining structures deterioration (o)
(s) DBWL (dam = a)
(t) DBWL (run-off, coast, estuary) + 10-years rainfalls on site, regular and continuous (i or m)
(u) DBWL (coast, estuary) +100-years wind waves (k).

This list of 21 hazards is used for the reassessment.

### *4.2 Reassessment of the protection of the NPPs*

The reassessment of the protection of the NPPs mainly focused on the topics presented hereunder.

### 4.2.1 Improvement of the equipment and works structures involved in the sites protection:

Given the different flooding hazards, one of the aims of the reassessment was to ensure that the equipment and systems required for bringing and maintaining the units in a safe state were kept dry.

The protection means, either passive (dykes,…) or active (pumps to drain water from rainfalls,…), required to prevent the spreading of the water on the site platforms or to limit its height have been reassessed. Besides, the spreading ways taken by the water in the event of immersion of the platform have been examined, with the aim to suggest additional provisions where required. Moreover, the capacity of the drain systems that could drain the water stored on the platform has been checked. In particular, the emergency power supply of the draining pumps has been investigated for those sites where a risk of loss of their external electric power supply has been identified.

For all the plants, this has led to implement a compact "watertight area". This "watertight area" includes all the substructures and, when required depending on the sites vulnerabilities and specificities, the superstructures (up to the required protection level) of the buildings that shelter safety-related equipments required for bringing and maintaining the units in a safe state, protecting them from the different flooding hazards and especially the groundwater rising one. The provisions aimed to keep this area leak tight have been examined in terms of:

- identification of all the openings and water paths (hoppers, pipe or cable penetrations, exhausts pipes, entrance doors…),
- qualification of the material used to plug them,
- provisions implemented in case of opening (maintenance works…) for closing them in a short delay during the warning phase,
- prevention of the potential ways of bypassing this area (discharge lines of the inner draining systems…).

Considering defense in depth, the provisions allowing to cope with a residual leakage of the "watertight area" have been checked, based on the existing draining means installed in the sumps of the nuclear island and on additional mobile pumps installed during the warning phase. The requirements for these pumping means have been defined, especially the need for an emergency power supply.

### 4.2.2 Improvement of the warning systems, site protection preparedness and emergency organization:

Givent the potential vulnerabilities of the plants and the provisions used for protecting the safety related equipment, the reassessment has also focused on the suitability and effectiveness of the warning process, the operating procedures and the site organisation to cope with a flooding event.

*Warning system:*

For predictable hazards, the following aspects of the warning systems have been checked:

- ability of the warning system to detect the risk of flooding of the plant depending on the nature of the hazards involved (river flood, storm surge, wind-wave on sea, dam rupture, on-site rainfalls),
- principles of implementation and reliability of the parameters monitored and of the devices and equipment used (tide sensors, wind measurements ...), definition of the criteria activating the alarm and integration of the information provided by organizations external to the sites involved (Météo France),

Several successive warning phases have been defined;

- stand-by phase,
- vigilance phase (carrying out of some early actions),
- early warning phase (site protection preparedness, tanks filling up…),
- alert phase (plants to be brought to a safe shutdown state).

The corresponding activation thresholds have been assessed so that the durations of the warning phases are long enough to carry out all the actions required for the site protection and for the plants safe operation, including safe shutdown, before the first predictable "site vulnerability" occurs.

*Operating procedures:*

Specific operating procedures dealing with external flooding have been developed and checked. These procedures, to be applied in the vulnerable sites during the warning phase of the flooding event, aim to:

- prepare the site protection all along the warning phase: closure of the dykes openings, closure of hoppers and doors of the "watertight area", installation of mobile shutters, installation of mobile pumps in the chambers…,
- anticipate a situation for which the plants will have to be maintained in a safe shutdown state for a long duration or might encounter an accidental situation. In particular, the possible occurrence during a flooding of the "loss of the ultimate heat sink" or/and the "loss of external power supplies" is examined. The corresponding specific actions required during the warning phase, in order to prevent, to delay or to be able to cope in the long term with these situations, are then defined, such as the filling of tanks (fuel for the diesel generators, secondary water inventory) in order to increase the autarchy of the plants,
- during the alert phase, bring the plants to a safe state which depends on their initial state.

In practice, each vulnerable site requiring a warning system has been provided with a site-specific procedure dedicated to the coresponding flooding event.

Then, the procedures applied in the two accidental situations considered above have been reviewed. These are the classical symptom-oriented accidental procedures. However, they have been adapted to a flooding event that might lead to an accidental situation at all the site units and not only in one unit as generally stipulated in these procedures. Moreover, the combination of a total loss of the heat sink and a loss of external electric power supplies, which might result from a single external flooding event, has been adressed.

*Emergency organization:*

The on-site emergency organization has been adapted to a flooding event considering that:

- all the plant units might be affected by the flood and by the potential induced accidental situation. Therefore, all the units might require in the same time additional emergency resources and competencies,
- the site might be isolated during the flooding.

In case of a flooding, an on-site emergency organization is defined for the warning phases as well as for the flooding phase and even in case of induced accidental situation. From the beginning of the early warning phase, an on-site team is in charge of the coordination and supervision of all the actions related to the site protection, the personnel security, the additional human resources required in case of site isolation, the site supplying (of fuel…), the site operation (surveillance in the pumping station...). The alert threshold of the warning system activates the national emergency organization involving several emergency teams: on-site emergency teams, national EDF emergency teams and public authorities teams (from the French Nuclear Safety Authority and from its technical support IRSN).

In practice, guidelines of national scope have been written to define how to adapt the on-site emergency organization to a flooding situation and how to address simultaneaous emergency situations at multiple units of one plant. No adaptation of the existing off-site emergency planning has been considered as necessary.

### 4.2.3 Maintenance programs and periodic tests

All the equipement used as the line of defense against the external flooding has been considered as safety related and the corresponding safety requirement have been examined. Among those, the suitability of the maintenance and the periodic tests programs have been checked.

### 4.2.4 Complementary improvements coming from the lessons learned during the flooding event in Le Blayais

In addition to the reassessment of the above mentionned topics, some additional specific topics whose significance has been shown during the flooding incident in Le Blayais have been examined. They deal notably with the following topics:

- potential ingress of water in the chambers during the flooding in case of a leakage of the "watertight area": the requirements on detection means, their location and the availability of the corresponding measures in the control room;

- faults in electrical isolation, as far as they cannot be excluded during a flooding since the materials outside the "watertight area" are not watertight. Morover, several of these materials might be affected by the flooding. It has then been checked that these electrical isolation problems could not cause a loss of the electrical switchboards that supply safety-related equipments.

- the management of the water collected in the flooded facilities, in terms of possibility to discharge or to stock them given their radiological content.

## 5 Main results of the reassessment:

Hereunder are presented the main results of the reassessment of the protection of all the French Nuclear Power Plants against the external flooding.

### *5.1 Protection of the equipment and systems required for bringing and maintaining the plant in a safe state*

As mentionned above, a watertight area has been defined and implemented for the substructures of all the NPPs. The product and the process used for the clogging of the penetrattions of this area have been qualified by specfic qualification tests. Figures 9 and 10 give some examples of penetrations that have been made watertight.

Figure 9

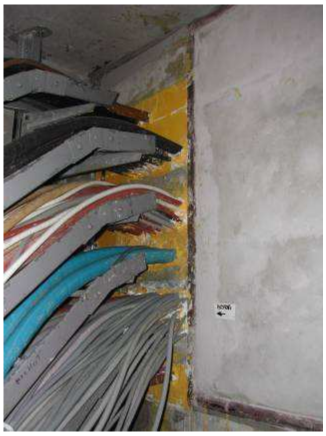

Figure 10

Regarding the risk of flooding of the platform of the nuclear island in case of dam failure, river flood or a combination of tide, strom surge and wind waves, 10 sites over 19 have been identified as sensible to this risk. Therefore, new provisions for protecting the platform and/or protecting the superstructures of the buidlings housing the equipment and systems required for bringing and maintaining the plant in a safe state have been implemented, or the existing ones have been reinforced. Among these provisions are dykes (see figure 11), watertight walls (see figure 12).

Figure 11

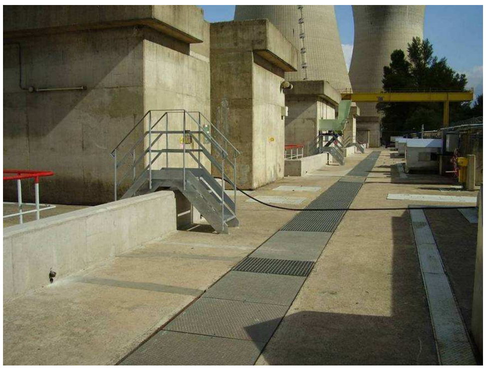

Figure 12

The swelling of the water level due to operation on valves or pumps is significant for one site. Walls of protection have been erected to avoid the flooding of the pumping station platform of this site (see figure 13).

Figure 13

The failure of water retaining structures, such as the cooling tower bassins, have been of concern for 3 particular sites. Concrete walls will be erected to protect the nuclear island from the spreading of the water.

The risk of flooding in case of rainfalls concerns 5 sites for which specific provisions have been taken (concerte walls of protection, increase of the capacity of the drainage system,…).

### *5.2 Other vulnerabilities of the French NPPs*

Additionally to the flooding of nuclear buildings sheltering safety-related equipments due to the submersion of the site platform as well as due to the rise of the ground water table, the other vulnerabilities has been examined in order to check if the French NPPs are prevented from or able to cope with them.

Concerning the risk of loosing the ultimate heat sink, 6 sites have been identified as sensible to the flooding of the equipment necessary fir ensuring the efficiency and the surveillance of the filtration function of the water. Specific provisions have been implemented, mainly surveillance actions at the pumping station and operating procedures to deal with a degradation of this function.

For all the sites, a potential risk of loosing the heat sink of several NPPs simultaneously due to a threat of water intake clogging has been identified. The Rhône river flood in December 2003 confirmed this point, a lot of debris having been carried by the river towards the water intake of the pumping station of the NPPs located along this river (see Figure 14). Current operating procedures have been modified in order to deal with this risk and specific equipement improvements have been realized (like the automatic switch-over of the non safety-related pumping systems following an increase of the headloss across the filtration system).


Figure 14

The risk of loosing the offsite power, following the submersion of electrical stations or switchyards or, for the coastal sites, following a storm, concerns 9 sites. Provisions have been implemented either to avoid such a risk or to limit its duration.

Regarding the temporary site siolation, 8 sites have been identified so far as being sensible to it. The development of the operating procedures for these sites as well as of their warning system used in case of external flooding took this problem into account.

### *5.3 Warning system*

All the French NPPs, apart from two coastal sites not being considered as sensible to the external flooding risk, are now provided with a dedicated warning system consistent with :

- the phenomena that they are concernd with,
- the vulnerabilities of each site,
- the operating procedures to be used in case of an external flooding and the corresponding actions.

## 6. Future French regulation

The studies which followed the flood of le Blayais site highlighted some limit of the Basic Safety Rule (BSR) 1.2.e which defines the principles for the protection of the Nuclear Power Plants against flooding of external origin. The Nuclear Safety Authority (NSA) has required the revision of the rule to integrate the contributions of recent work. The future rule shall deal with all the hazards likely to lead to a flood of external origin of nuclear sites, while attempting to identify the combinations of events being able to be at the origin of the flood.

The NSA specified that the rule must relate to:

- the choice of the hazards (due to extreme events and combinations of events),
- methods for characterizing all these hazards,
- the taking into account of the difficulties which the characterization of hazards can present corresponding to rare and extreme events through the treatment of uncertainties and definition of margins.

Moreover, the future rule will be applicable to all the types of nuclear installation (reactors, laboratories, factories of the fuel cycle, storage of waste), at the stage of design and also at the stage of safety reassessment.