# 1. Assessing flooding hazards: new guidelines

(V. Rebour\*, F. Ménage\*)

\*IRSN, BP 17 – 92262 Fontenay-aux-Roses, France

#### Abstract:

The Blayais event and the following studies showed the limits of the I.2.e Basic Safety Rule (BSR) and has led the French Nuclear Safety Authority (ASN) to launch its revision. The new Guide, which supersedes and replaces the I.2.e BSR, will be applicable to all type of nuclear installations except waste repository in deep geological formations. After several years of preparation, a draft guide was approved by the advisory committees for nuclear reactors (GPR) and for nuclear installations (GPU) in May 2012. The Guide should be edited by ASN at the end of the year.

The Guide defines 11 Reference Flooding Situations (RFSs) to be taken into account for assessing the risk of flooding. The RFSs have been defined on the basis of engineering judgment and using a probabilistic target (probability of exceedance of 10<sup>-4</sup> per year, in order of magnitude, and covering associated uncertainties). The Guide presents acceptable methods for quantifying the RFSs, accounting uncertainties. Finally, the Guide provides recommendations for defining protective equipment adapted to the specific nature of the flooding risk and implemented by the operator in accordance with the installation's life cycle.

# **1 INTRODUCTION**

The basic safety rule (BSR) "I.2.e" established in 1984, deals with the risk of flooding of external origin for pressurized water reactors. Despite being consistent with the protection provisions required by this BSR, Blayais nuclear power plant (NPP) was partially flooded in 1999, causing a failure of several safety systems. As a result of this occurrence, EDF conducted a review of the risk of flooding of external origin for all of its NPP. The methodology used for this review, called "REX Blayais", has been examined by the advisory committee for nuclear reactors (GPR) in 2001 on the basis of an assessment of the Institute for Radioprotection and Nuclear Safety (IRSN).

The Blayais event and the following studies showed the limits of the I.2.e BSR and the opinion of the GPR has led the French Nuclear Safety Authority (ASN) to launch its revision. The new Guide, which supersedes and replaces the I.2.e BSR, will be applicable to all type of nuclear installations except waste repository in deep geological formations. After several years of preparation, a draft guide was approved by the advisory committees for nuclear reactors (GPR) and for nuclear installations (GPU) in May 2012. The Guide should be edited by ASN at the end of the year.

The paper presents general information on the Guide, before focusing on guidelines for flood hazard definition and for flood protection measures.

Towards Convergence of Technical Nuclear Safety Practices in Europe

# 2 GENERAL INFORMATION

#### 2.1 Guide preparation

In order to prepare the Guide, ASN and IRSN have conducted a working group in order to prepare a draft guide. It has been decided to create two subgroups. The first, entitled "phenomena" and led by IRSN, has focused on identification of and characterization methods for the phenomena that can potentially generate flooding. This technical subgroup has gathered experts from universities (Montpellier university) or research organisms (CETMEF, Maritime and Waterway Technical Research Centre; CEMAGREF, Research institute for water and territories sustainable management; SHOM, French Naval Oceanographic and Hydrographic Service; Meteo-France, French national meteorological organisation; BRGM, public institution in the Earth Science field for the sustainable management of natural resources and surface and subsurface risks), hydro operator (CNR, designer and operator of hydropower plants, dams and locks), government offices or agencies (BETCGB, Dam Engineering and Control Office, ASN, IRSN) and nuclear operators (Andra, Areva, CEA, EDF). The second subgroup, entitled "objectives" and led by ASN, has focused on the safety objectives to be assigned to nuclear installations regarding their protection against flooding hazard.

The draft guide has been submited to a public consultation by ASN during summer 2010. After examination of the proposed modification, IRSN has prepared a new version of the draft guide, for examination by the advisory committees for nuclear reactors (GPR) and for nuclear installations (GPU) in May 2012. The Guide should finally be edited by ASN at the end of 2012.

#### 2.2 Purpose of the Guide

External flooding in the Guide refers to flooding from sources outside structures, areas and buildings containing systems or components that require protection. These sources include rain, cresting rivers, storms, broken pipes, etc.). In the following text, flooding shall refer to external flooding.

The Guide aims to

- define situations to be taken into account for assessing the risk of flooding for the site being considered;
- offer an acceptable method for quantifying them;
- list recommendations for defining protective equipment adapted to the specific nature of the flooding risk and implemented by the operator in accordance with the installation's life cycle.

The Guide takes into account climate change when current knowledge is available. Installation design shall take into account predictable changes in climate according to current knowledge for a period that represents the foreseeable lifetime of the installation and shall take these changes into account for each safety review until the subsequent review.

Use of the Guide requires, for each installation considered, identification in advance of the functions necessary for the nuclear safety demonstration that need to be ensured in the eventuality of a flooding. They are termed "safety functions" in the Guide.

The Guide applies to basic nuclear installations, including reactors, laboratories, factories, storage facilities and those being dismantled. For radioactive waste storage facilities, it applies only to aboveground facilities.

# 3 REFERENCE SITUATIONS TO BE TAKEN INTO ACCOUNT FOR FLOODING RISK

Flooding can be caused either by a single event of high intensity, or by the conjunction of several events of any magnitude (natural events occurring at the same time or in succession, failure of a protective structure or equipment, etc.). A 'Reference Flood Situation' (RFS) is defined on the basis of an event or a conjunction of events, the characteristics of which may be amplified (conjunction conservatively quantified or amplified to compensate for the limits of current knowledge).

A list of RFSs shall be drawn up to reflect the characteristics of the installation site and to account of the different water sources relevant to the site. The design of the installations as regards the flood risk shall be justified in view of these RFSs, taking account of any dynamic effects.

The RFSs determined shall as a minimum encompass all situations likely to be encountered on the basis of relevant past experience of the site.

The recommendations given for defining and determining the RFSs are the outcome of a generic analysis of flood risk for different types of site, in the light of current knowledge of the subject (accessible data and methods of characterising events) and expertise based on a knowledge of existing basic nuclear installation sites.

The RFSs are expressed either on the basis of a statistical analysis of the available data or deterministically.

Conjunctions of events have been chosen particularly where there is a proven or presumed dependency between events likely to cause flooding. In addition, when the risk of concomitance has been identified in the light of the duration and frequency of one or other of the events, the conjunction of these events has been included. This approach is illustrated in particular by RFSs involving wind-waves (detaled below).

Even if it's not explicitly mentioned in the guide, the set of RFSs have been defined on the basis of engineering judgment and using a probabilistic target. RFSs should have a probability of exceedance of 10<sup>-4</sup> per year, in order of magnitude, and should cover associated uncertainties. To achieve such a goal, different approaches have been implemented for the different RFSs: direct calculations, additional margins, conventional conjunctions of events, and definition of complementary scenarios.

The list of RFSs is illustrated by figure [1].



Figure 1: All RFSs

In the above figure, the following abbreviations have been used:

|     | -              |
|-----|----------------|
| PLU | Local rainfall |

| CPB | Flood on a small | watershed |
|-----|------------------|-----------|
|     | i loou on a smai | watersneu |

- **CGB** Flood on a large watershed
- **DDOCE** Deterioration or malfunction of structures, circuits or equipment
- **INT** Intumescence Malfunction of hydraulic structures
- **RNP** Rise in groundwater levels
- **ROR** Failure of a water-retaining structure
- CLA Chop
- NMA Sea level
- VAG Waves SEI Seiche
- Sei Seiche

# 3.1 RFSs to be taken into account for all sites

There are at least five RFSs to be taken into account: local rainfall, flood on a small watershed, deterioration or failure of structures or equipment, intumescence and rise in groundwater level.

#### 3.1.1 Local rainfall

All rainfall is characterised by the cumulative height of the precipitations in a given period. The reference rainfall is defined by the upper limit of the 95% confidence interval of the hundred year rainfall calculated using the data from a weather station that is representative of the conditions on the site.

To take account on the one hand of the risk of the stormwater drainage system becoming obstructed during extreme events, and on the other hand of events rarer than those defined by the reference rainfall, the installation must be able to cope with a scenario of surface water runoff when access to the installation's local stormwater drainage system is unavailable. This scenario of reference surface water runoff is defined by the hundred year rainfall (value of the upper limit of the 95% confidence interval) lasting one hour.

Additional analyses shall be undertaken for downstream level of stormwater drainage systems and for the watersheds situated upstream of the installation.

#### 3.1.2 Flood on a small watershed

The reference flood on a small watershed is defined by an instantaneous peak flow, for a ten-thousand-year return period.

The reference flood on a small watershed with a surface area of between 10 and 5,000 km<sup>2</sup> is evaluated preferably using a method that models the asymptotic behaviour of the mean rainfall-runoff transformation for a time step appropriate to the watershed's time of concentration. One method of obtaining the instantaneous peak flow consists of working with a sample of average flows and multiplying the flow resulting from the extrapolation by a shape factor.

For watersheds with a surface area of between 10 and 100 km<sup>2</sup>, the flow associated with this RFS can be calculated from the hundred year rainfall (upper limit of the 95% confidence interval) by multiplying the flow obtained by a factor of 2.

The operator shall examine individual points where debris jams likely to aggravate the effects of the reference flood on the site could occur.

#### 3.1.3 Deterioration or malfunction of structures, circuits and equipment

The consequences of potential malfunctions or deterioration of structures, circuits or equipment should be determined where these could lead to a significant amount of water being discharged on the site.

An exhaustive analysis of these structures, circuits and equipment is performed. Those close to or on the site, outside buildings housing safety-related systems or components, are taken into consideration.

The types of structures, circuits and equipment to be taken into consideration are:

- basins, reservoirs, drums, tanks,
- circuits, pipes, filling or discharging structures, water-retaining structures,
- dykes along water courses and canals, and the associated hydraulic structures,

except for the structures considered in the 'failure of a water-retaining structure' RFS and dry dykes.

The failure or overspill of structures, circuits or equipment can, for example, be the result of:

- the malfunction of these structures, circuits or equipment,
- intrinsic defects such as hydraulic deterioration for backfill structures or failure due to ageing,
- external damage likely to affect the site (earthquake, explosion, fire, aircraft crash, etc.),
- specific damage associated with the particular geographical location of the structure, circuit or equipment.

The types of failure to be taken into consideration are simple failures or multiple failures with a common cause.

# 3.1.4 Intumescence

The reference intumescence is a wave resulting from a rapid change in flow in an open-air hydraulic structure that is on the site or upstream or downstream of the site. It is characterised by its intensity (peak discharge flow, corresponding maximum water height on the site, volume discharged) and its duration (taking account of the different dynamics associated with the main wave and the effects accompanying this main wave).

An analysis of the possible causes of an intumescence should identify the intumescence scenario(s) likely to affect the site. The reference situation is chosen taking into consideration the initial level and flow conditions leading to the worst possible intumescence. When working out the initial level, no consideration is given to any situations rarer than the flood or sea level RFSs defined for river sites and coastal sites.

Malfunctions of hydraulic structures can also lead to a difference between the flows entering a reach and the flows leaving it and can cause the water level at the site to increase. When analysing this type of situation, methods of rebalancing the flows in order to correct this difference shall be justified.

#### 3.1.5 Rise in groundwater level

The reference groundwater level is determined on the basis of a hydrogeological study of the site, depending on the data available, using one of the following two methods.

1. The combination of an 'initial value' and the effect of a rise due to an 'initiating event'.

The 'initiating event' is the one event, among all those examined to determine the RFSs (flood, sea level, rainfall, deterioration of a structure, etc.), which causes the biggest rise in the groundwater level.

The 'initial level' of the groundwater applies a fixed magnitude to the contributions from all the phenomena considered to be secondary. The initial level is defined as the ten year return period level.

#### 2. A statistical analysis of the groundwater level

The reference level may be defined as the level associated with a hundred year return period, taking the upper limit of the 95% confidence interval. The statistical analysis relates to the highest levels reached in a long series of piezometric levels, constituted from a set of levels measured in situ over time. This set may be extended by means of a simulation. Taking account of the relatively short return period available to this statistical analysis, the reference level is calculated using particularly conservative hydrogeological hypotheses.

This approach is applied as required, to calculate the consequences associated with reaching a particular groundwater height measurement: induced pressure, peak flow or total volume of water to be drained away.

#### 3.2 RFSs to be taken into account for river sites

There are three further RFSs to consider: flood on a large watershed, failure of a waterretaining structure and chop.

#### 3.2.1 Flood on a large watershed

A large watershed generally has a drained surface of more than 5,000 km<sup>2</sup>. However, this value depends on the nature of the watershed, its average altitude, its slope, its geology, etc. A flood on a large watershed is characterised by a reference flow, a reference water level and the associated flood zone.

The reference flow is the instantaneous peak flow associated with the thousand year flood taking into consideration the upper limit of the 70% confidence interval, plus 15%.

The reference level is the maximum level on the site resulting from the reference flow. With some site configurations, a higher water level can be reached with a lower flow rate than the reference flow; in such cases, the reference level is the level associated with this lower flow rate.

In the case of a water course with installed equipment, account needs to be taken of the operation and behaviour of the equipment under the flood conditions in question (management rules during a flood, structures reaching full capacity, structure deterioration, etc.).

The proximity of the site to a confluence of water courses may mean that the flooding analysis has to take account of this confluence.

#### 3.2.2 Failure of a water-retaining structure

The analysis of the failure scenarios concerns water-retaining structures that lie across water courses. In some cases, the volume and location of lakes and retaining structures that are not in water courses may justify treating the associated structures in accordance with the recommendations in this section.

For a water-retaining structure that lies across a water course, the failure with the most serious consequences for the site is postulated. The reference level associated with the failure of this structure is the maximum level on the site resulting from propagation of the

flood wave. The study of the RFS will consider the water course on which the site is located and the different valleys opening out into the area around the site.

With some site configurations, a higher water level can be reached with a lower flow rate than the reference flow; in such cases, the reference level is the level associated with this lower flow rate.

In the case of a water course with installed equipment, account needs to be taken of the operation and behaviour of the equipment under the flood conditions in question (management rules during a flood, structures reaching full capacity, structure deterioration, etc.).

The proximity of the site to a confluence of water courses may mean that the RFS analysis has to take account of the effect of the wave backing up into each tributary.

#### 3.2.3 Chop

The reference chop is the field of waves resulting from a hundred year wind (upper limit of the 70% confidence interval) propagated on a thousand year flood (upper limit of the 70% confidence interval).

It is characterised by a significant wave height, a representative period (e.g. the mean period or significant period) and a dominant direction of propagation.

The duration of the RFS is worked out from statistics for the duration of episodes of strong winds.

#### 3.3 RFSs to be taken into account for coastal sites

There are three further RFSs to consider: sea level, waves and seiche. The situations defined below are not adequate for covering sites located beside the Mediterranean sea.

#### 3.3.1 Sea level

The reference high sea level is the sum of:

- the maximum height of the theoretical tide,
- the thousand year set-up, due to storm surge (upper limit of the 70% confidence interval), amplified to take account of uncertainties with the evaluation of rare set-up resulting from outliers,
- the change in mean sea level extrapolated until the next safety review.

As an alternative to the first two, a statistical analysis of the tide levels and set-up may be carried out to work out the probability of the cumulative water level for the two phenomena being exceeded (joint probability method), considering a ten thousand year return period. This approach should use a satisfactory statistical extrapolation model for outliers and include an estimate of the sampling uncertainty that will be covered by the reference sea level.

The reference high sea level also takes account of the risk of seiche under the conditions defined below.

#### 3.3.2 Waves (ocean waves and chop)

Working out the wave conditions at a maritime site in principle combines ocean waves (also known as 'swell'), generated by wind a long distance away from the site and propagated outside the area where they are generated, and waves stirred up by local wind (also known as 'wind sea', or 'chop' in the case of waves generated over a small area).

The reference waves are worked out from the hundred year significant height wave conditions (upper limit of the 70% confidence interval) determined offshore at the site and propagated over the reference sea level. In this case, it is recommended that the swell and the wind sea are not separated, and the analysis is performed on the total wave height data.

Depending on the exposure and configuration of the site, the analysis can be simplified by working out the preponderance of the contribution made by the ocean waves or the local wind effects (wind sea or chop depending on the site configuration) to the total wave height.

In particular, where the local wind effects dominate over the ocean waves because of the configuration of the site or existing structures, a reference chop is used. This is defined by the chop resulting from a hundred year wind (upper limit of the 70% confidence interval) propagated over the reference sea level.

The duration of this RFS is worked out from sea level variations due to the tide.

#### 3.3.3 Seiche

The risk of a seiche occurring is analysed on the basis of the past experience available, for example through the operation of an existing installation or measurements of the sea level. If the risk of a seiche occurring is identified in coastal installations (port basin, water inlet or outlet channels), the phenomenon is taken into account when calculating the reference sea level. As a first approach, the reference sea level can be increased by an amount corresponding to the estimate of the height of the annual seiche (statistical or empirical estimate depending on the available data).

#### 3.4 Additional considerations

#### 3.4.1 Tsunami

Tsunamis are generated by seismic or volcanic sources or sources linked to landslides under the sea or on the coast. An earthquake can cause a tsunami only if it is in shallow water and is of a sufficiently high magnitude. For example, the thresholds for triggering a tsunami alert in the Pacific are a magnitude of 6.5 for a local bulletin, 7.6 for a regional alert and 7.9 for a large-scale alert. In the case of a landslide, experience shows that the volume of the collapse is the most important parameter. A tsunami can develop locally (a few kilometres from the source) for collapse volumes of the order of 100,000 m<sup>3</sup>, regionally (a few tens or hundreds of kilometres from the source) for volumes of around 1 km<sup>3</sup>, or even on a transoceanic scale for larger volumes (of the order of a hundred km<sup>3</sup>). No geological structure that could cause a major tsunami has been identified close to the Atlantic coast of metropolitan France (more specifically the coasts of the Atlantic, the English Channel and the North Sea).

Based on seismic and sea level monitoring over the last 50 years, neither historical information nor data related to high seawater level on the Atlantic coast of metropolitan France has been linked with any certainty to an Atlantic tsunami. In a similar way to the studies of seismic hazard, historical analyses have been carried out to extend the observation period. These involve analysis of the literature to identify observations that could be linked with tsunamis: fluctuation of water levels on the coast and particularly in ports, related, for example, to an earthquake. Witness reports compiled from the 18th century to the present day record around 15 events attributed with some degree of uncertainty to tsunamis. In all cases, the effects were no more than the flooding of gently sloping coasts, the beaching of light vessels and slight damage to less substantial buildings close to the coast. More significant damage and the highest sea levels were observed during storms causing high instantaneous sea levels, sometimes coinciding with high tides and accompanied by swell.

Tsunamis are independent of high tides and storms; taking account of the conjunction of a tsunami and the sea level RFS is therefore not justified.

In view of the exclusion of Mediterranean sites from the scope of section 1.3.5, the tsunami risk is considered to be covered by the sea level and wave RFSs.

#### 3.4.2 Specific case of estuary sites

Estuary sites are affected by both the sea and rivers.

Maritime influence

The RFSs defined in section 3.3. are worked out using the assumption that at the estuary entrance the maritime conditions defined for sites beside the sea (reference sea level and reference waves) apply, combined with a hundred year local wind (upper limit of the 70%)

confidence interval) and a mean river flow. The duration of these RFSs is worked out from sea level variations due to the tide.

River influence

The RFSs defined in section 3.2. are worked out with the following adaptations.

For the 'flood on a large watershed' RFS, the reference situation is determined without applying the 15% increase mentioned in section 3.2.1 and based on a maximum level for the theoretical tide.

For the 'failure of a water-retaining structure' RFS, the reference situation is determined based on a mean high water level (tidal coefficient 70).

For the 'chop' RFS, the reference situation is determined based on a mean high water level (tidal coefficient 70).

# **4 FLOOD PROTECTION**

#### 4.1 Specific features of a flood

A flood can affect several or indeed all the installations on a site. It can therefore simultaneously affect several lines of defence.

A flood can also affect the environment of the site: depending on the extent and duration of the phenomena that cause it, a flood can isolate the site and cause the loss of support functions (external electricity supply, telecommunications, external emergency services, discharge devices, etc.).

The action of the water can be static or dynamic or both. Dynamic effects include, for example, the erosion of embankments, banks and dykes, changes in the turbidity of the water, debris jams and floating bodies. This can affect the availability of some equipments.

A flood can also be accompanied by other phenomena (lightning, wind, etc.).

However, depending on what causes it, a flood can sometimes be anticipated through the use of early-warning systems, and the site configuration can also be adapted in advance.

# 4.2 Protection principles

For each RFS considered, protection measures are introduced to ensure that any safety functions that might be affected can be maintained. For existing installations, including installations being dismantled, protection of the safety functions should be judged in the light of the potential consequences for safety if they fail.

The physical and organisational protection measures of:

- sites,
- buildings containing systems or components involved in the maintenance of safety functions in the situation under consideration,
- the rooms containing these systems or components within the buildings,
- the systems or components themselves within these rooms,
- provide several lines of defence.

As far as possible, these lines of defence should be independent.

The specific features of floods are taken into account when defining and designing these measures. The level of protection shall be suited to the hazards presented by the installation. Depending on what causes the flood and the type of protective measures, an event of greater intensity than the RFS could produce a cliff-edge effect. A cliff-edge effect is present when, starting from the RFS, a slight worsening of the flood situation (e.g. a water level that runs over a protective dyke) leads to a signification deterioration of the safety functions. For each RFS, any potential cliff-edge effect should be found and analysed.

As far as the safety functions that need to be maintained in a flood are concerned, the installation is designed on the basis of the defined RFSs. In addition, the design and dimensions of the protective systems shall take account of:

- safety objectives of the installation,
- results of the analysis of cliff-edge effects,
- any foreseeable changes in climate during the anticipated life of the installation in question.

The approach to protection taken should notably take account of the possibility of damage or effects (fire, mechanical impact, etc.) caused by the situation in question.

# **5 CONCLUSION**

The Blayais event and the following studies showed the limits of the I.2.e BSR and the opinion of the GPR has led the French Nuclear Safety Authority (ASN) to launch its revision. The Guide which supersedes and replaces the I.2.e BSR will be applicable to all type of nuclear installations except waste repository in deep geological formations. After several years of preparation, a draft guide was approved by the advisory committees for nuclear reactors (GPR) and for nuclear installations (GPU) in May 2012. The Guide should be edited by ASN at the end of the year.

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The Guide is dedicated to protection against design basis flood. However, as it points out keys parameters in the domain, it has been also useful for current activities on beyond desing flood in the framework of Stress-Tests.