Screening of External Hazards in Belgium

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Abstract: Screening methodology has been developed and applied to the list of natural and man-made external hazards to both Belgian sites (Tihange and Doel) in order to identify relevant external hazards. Adequate screening criteria, based on the best international practices, have been defined. They consist of two groups: qualitative and quantitative. Qualitative criteria are based on general characteristics of the hazard (e.g. severity, rate of progression/development) and its relevance to the site (e.g. distance). The quantitative criteria, on the other hand, focus on the frequency of occurrence and potential contribution to the core damage frequency (CDF) of a plant.

As the result, it was concluded that most of the hazards do not represent considerable risk to the nuclear power plants in Belgium. Some hazards were screened out based on the results of existing deterministic studies. A deep analysis of potential consequences was performed for other hazards, which allowed to screen them out. Finally, four families of hazards cannot currently be screened out: Seismic phenomena, Loss of main heat sink (MHS), Loss of off-site power and External flooding.

Keywords: PRA, PSA, External Hazards.

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1. INTRODUCTION

The Western European Nuclear Regulators Association (WENRA) published in 2006 – updated in 2007 and 2008 – a set of Safety Reference Levels (RLs) for operating nuclear power plants (NPPs). The RLs are agreed by the WENRA members and reflect expected practices to be implemented in the WENRA countries.

After the TEPCO Fukushima Daiichi nuclear accident, an update has been published in 2014 [1] considering the lessons learned, including the insight from the EU stress tests as well as IAEA safety requirements being under updating for the same reason.

According to WENRA RLs 2014 [1] Issue O “Probabilistic Safety Analysis (PSA)”:

- RL O1.1 “For each plant design, a specific PSA shall be developed for level 1 and level 2, considering all relevant operational states, covering fuel in the core and in the spent fuel storage and all relevant internal and external initiating events. External hazards shall be included in the PSA for level 1 and level 2 as far as practicable, taking into account the current state of science and technology”;

- Footnote 58 “[…] Adequate screening criteria shall be defined in order to identify the relevant initiating events and operational states”.

This paper describes the methodology of screening and its application to the list of natural (N1-N73, [2]) and man-made (M1-M24, [3]) external hazards to both Belgian sites (Tihange and Doel). In addition, this document provides details of calculations performed in order to support application of quantitative criteria for certain hazards.

2. METHODOLOGY

2.1. Qualitative Screening Criteria

Table 1 is primarily based on a research report developed by the Nordic PSA Group (NPSAG), SKI 02:27, described in [4] (original publication [5]). It was however adapted (by using different elements or recommendations within the document [4]) in order to account for the Belgian context and the current best international practice, also mentioned in [4].
Hazards can be screened out if one or more of the following criteria apply:

Table 1 – Qualitative criteria

Code	Element	Description	Source
QL-1	Distance	The event cannot occur close enough to the site and its relevant surroundings during future decades	EXT-B1[6]: Criterion 3 SKI[5]: Criterion 1, Criterion 3
QL-2	Inclusion	The event shall be included into the definition of another event	EXT-B1: Criterion 4 SKI: Criterion 2
QL-3	Severity	The event has a damage potential that is less or equal to another event that the plant is already designed for	EXT-B1: Criterion 1 SKI: Criterion 5
QL-4	Slow/ Predictable	The anticipation time of the event is long or the increase rate of the strength of the event is low enough that there is sufficient time to eliminate the source of the threat or provide an adequate response. This criterion is applied to slow and predictable phenomena, which can be timely detected and they are monitored	EXT-B1: Criterion 5 SKI: Criterion 6
QL-5	Initiating Event	The effects of the estimated maximum strength of the event do not exceed the design basis documented or the endurance based expert estimate. This means that the event does not cause: A) during power operation at least a need for controlled shut down or scram and does not require the actuation of front-line systems B) during shutdown losses of safety systems required during shut down C) the sole consequence is a transient already modelled in the internal events PSA model. One must check that it takes into account the hazard; if not, an evaluation of the hazard frequency must be done.	SKI: Criterion 8
QL-6	Frequency	The hazard has a significantly lower mean frequency of occurrence than another hazard that has been screened out, and the hazard could not result in worse consequences than the other screened out hazard	EXT-B1: Criterion 2 ENSI-A05/e: 4.6.1.d

2.2. Quantitative Screening Criteria

The quantitative criteria below are not intended to be sharp lines, as suggested in NextEra Energy feed back[*], but instead judgment should be made regarding how far above these point values the risk could be screened out based on the conservative nature of the specific analysis. Hazards can be screened out if either one or both criteria apply:

Table 2 – Quantitative criteria

Code	Element	Description	Source
QN-1	Initiating Frequency	The frequency of the hazard is less than $<10^{-6}$/year, unless there is evidence that this frequency is near a 'cliff edge' effect or a potential design vulnerability has been identified; if so, the hazard may be screened out if the frequency is $<10^{-7}$/year	EPRI [4], based on EXT-C1: Criterion B, taking into account EPRI recommendations
QN-2	Plant Damage	Hazards can be screened out if the CDF is ~ 10^{-7}/r-year. The hazards that also impact containment function, can be screened out if additionally the LERF is ~10^{-8}/r-year	EPRI [4], NextEra Energy feed back

Criteria can be applied by order of relevance: QL-1, QL-5, QL-4, QL-3, QN-1/2, and QL-2. The most obvious hazards are screened out first, by narrowing the list down to those ones, which require quantification or are included/treated within existing studies.

3. HAZARD CONSIDERED FOR TIHANGE AND DOEL SITE

This section considers the natural and man-made external hazards for the sites of Tihange and Doel.

3.1. Hazards not physically possible at the site

Hazards listed in this chapter are screened out by criteria QL-1 Distance: events cannot occur close enough to the site and its relevant surroundings during future decades.

This group contains hazards not applicable to both sites: N3 Surface faulting, N6 Permanent ground displacement, N13 Changes in river path, N37 Permafrost, N44 Sandstorm, N47 Snow avalanche, N60 Slope instability, N61 Underwater landslide, N62 Debris/mud flow, N64 Ground heave, N65 Karst, leaching of soluble rocks, N66 Sinkholes, N67 Unstable soils (quick clays), N68 Volcanic hazards: near centre, N69 Volcanic hazards: remote centre, N70 Methane seep, M4 Military: explosion, projectiles and M6 Military activities.

Some hazards are not physically possible at one site only. For example, coastline or tidal river related hazards (N16 Seiche, N17 Bore, N18 Seawater, high tide, N20 Seawater, storm surges, N21 Seawater, human made structures, N22 Corrosion salt water, N23 Instability coastal area, N33 Low seawater level and N45 Salt spray and tsunami) are inapplicable to the river site (Tihange), whereas hazards related to a typical river site (N12 Obstruction of the river, N15 Water control structure failure and M23 Flooding: miss-management of dam, Extreme drought) are not applicable to Doel.

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[*] Taking into account approach followed by NextEra Energy [4]. NextEra performed an external hazard screening analysis in 2013 and provided a feedback to EPRI on the use EPRI 1022997. This feedback was considered when establishing the quantitative criteria for the Belgian sites. Notably, quantitative criteria are not considered as sharp lines, but the order of magnitude is considered.

Most of the hazards were screened out either by obvious facts (e.g. Permafrost, Sandstorm or Snow avalanche) or by existing deterministic studies. For some however, additional analysis has been performed. One of them is volcanic hazard.

IAEA reference [7], Table 1, specifies different screening distances depending on the volcanic phenomenon. The highest screening distance of 300 km for active volcanoes is related to Tephra fallout (i.e. volcanic ash). The West-Eifel Volcanic Field in Germany is located within a radius of 300 km of the Belgian plants (about 125 km from Tihange and about 225 km from Doel). All other phenomena (atmospheric phenomena, pyroclastic currents, debris avalanches…) have screening distances of 80 km or less.

By studying the Volcanic Eifel Laacher See formation [8], it was concluded that the vast majority of the ashes were deposited in the vicinity of the volcano. Furthermore, as the Eiffel volcano is located in the south-east of Tihange, and the dominant wind direction in Tihange is directed SW-NE, there is a low risk of a large ash deposit at the site of Tihange.

As there is a low risk of the eruption in combination with a low ash deposit chance, the potential risk for the Belgian NPP from the volcanic activity is screened out.

3.2. Hazards, which cannot cause an initiating event

This section describes external hazards, which cannot cause a PSA initiating event (screening criteria QL-5). These events can have an impact on plant safety, but, from a PSA point of view, there is no credible path that leads to core damage as a result of this event's occurrence.

The effects of the estimated maximum strength of the event do not exceed the design basis documented or the endurance based expert estimate. The following hazards where identified for both sites: N29 Humidity, N30 Extreme air pressure, N32 Low groundwater, N51 Mist, fog, freezing fog, N56 Airborne swarms, N71 Natural radiation, M3 Missiles from rotating equipment, M10 Ground transportation: direct impact, M13 Pipeline: explosion, fire.

In addition, a group of hazards, which are applicable to Doel, was demonstrated not to be able to cause an initiating event: N11 High ground water, N21 Seawater, human made structures, N22 Corrosion salt water, N33 Low seawater level, N45 Salt spray.

3.3. Slow/Predictable

The anticipation time of the event is long or the increase rate of the strength of the event is low enough (QL-4). For the following hazards it was demonstrated that there is sufficient time to eliminate the source of the threat or provide an adequate response for both sites N26 Extreme air temperature, N27 Extreme ground temperature, N28 Extreme cooling water temperature, N38 Recurring soil frost, N53 Biological fouling, N57 Infestation rodents.

Due to specificity of the soil near the Doel site Ground settlement and Instability of coastal area can occur, but due to a slow nature of these hazards, they were screened out based on QL-4.

3.4. Severity of the hazard

A hazard can be screened out based on QL-3 if an event has a damage potential that is less or equal to another event that the plant is already designed for. The impact of hail is enveloped by other phenomena such as: tornado induced missiles and aircraft crash and snow load in regard to the dead weight on top of the buildings.

In addition, this criterion is applicable to the hazards linked to the nature of a nearby body of water:

- At the Tihange site, the following hazards can induce the elevation of the river water level: N12 Obstruction of the river, N15 Water control structure failure and M23 Flooding: miss-management of dam. The maximal increase of the water level is lover that the design basis for flood protection wall around the site.

- For the Doel site, the maximal credible water level increase due to the following hazards is sufficiently below a level that can represent any risk to the plant: N7 Tsunami, N14 Large induced waves, N16 Seiche, N17 Bore.

3.5. Quantitative screening

The following hazards were screened out based on their low frequency of occurrents and/or low contribution to the CDF: N2 Ground motion human triggered, M18 Excavation construction work, N41 Tornado, N42 Waterspout, N72 Meteorite fall, M1 Industry: explosion, M11 Transportation: explosion and M24 Fire: human/technological activity, M2 Industry: chemical release, M5 Military: chemical release, M12 Transportation: chemical release and M14 Pipeline: chemical release, M15 Aircraft crash: airport zone and M16 Aircraft crash: air traffic, M17 Satellite crash.

References to the existing studies have been made for many of the hazards in this category in order to support their screening. Details of calculations performed for the additional hazards are shown below:

3.5.1. Meteorite fall

Small meteorites (meteors) entering the Earth’s atmosphere are a fairly common phenomenon. However, the absolute majority of them are disintegrated without big pieces ever reaching the earth surface. The disintegrated pieces can damage cars or roofs of the houses, damage is local and limited. Almost all the kinetic energy of small meteorites is lost in the atmosphere. For example, the Chelyabinsk meteor entered Earth's atmosphere over Russia on 15 February 2013. It had a diameter approximately 20 meters and the atmospheric impact was equivalent to approximately 500 kilotons of TNT (30–40 times more energy than was released from the atomic bomb detonated at Hiroshima) And yet the only real damage consisted in a collapsed old factory’s roof and broken windows [9].

Damage to the objects located on the earth surface increases drastically with the size of the meteorite. The threshold for a meteorite to create a crater on Earth’s surface is around 100 meters (Based on $\rho = 2600\ \text{kg/m}^3$; v = 17 km/s; and an angle of 45°)[10]. An impact with such parameters occurs less than once every 5200 years. An energy release at the epicentre is equivalent to 3.8 Mt of TNT. The blast wave can create moderate destruction of the civilian buildings in a radius 24.8 km. Given the Earth’s surface ($5.1 \cdot 10^8\ \text{km}^2$), assuming the radius of the nuclear site 1 km, it is possible to calculate the probability of such an impact occurring within the area with potential safety related consequences:

$$P = \frac{\pi \cdot (24{,}8 + 1)^2}{5{,}10 \cdot 10^8} = 4{,}1 \cdot 10^{-6} \tag{1}$$

The frequency of such event will be:

$$F = \frac{4{,}1 \cdot 10^{-6}}{5200} = 7{,}9 \cdot 10^{-10}\ 1/ry \tag{2}$$

Based on the low frequency of occurrence, meteorite impact is therefore screened out.

3.5.2. Satellite crash

The near-Earth space orbits are full of uncontrolled man-made objects. Space debris (often referred to as junk, waste, trash) includes old satellites, spent rocket stages, and fragments from disintegration, erosion, and collisions. In the 56 years of spaceflight, some 15 000 tons of man-made space objects have re-entered the atmosphere without causing a single human injury to date. Every year 100 to 150 tons of these objects re-enter the atmosphere. [11]. They usually fully burn down in the upper layers of the atmosphere. However, it has been recorded that some percentage of bigger pieces can reach the Earth's surface. Damage to property is therefore feasible. According to the NASA Orbital Debris Program Office, there have been no confirmed instances of serious property damage or injury caused by crashing debris in 40 years.

Conservatively assuming that 150 tons of space debris cause a complete destruction on a combined area of 1 km^2 and given the surface area of Earth (510.1 million km^2), a probability that such impact happens at the nuclear site in Belgium is below 2E-09 /r-year.

3.5.3. Ground motion human triggered and Excavation construction work

Construction works at the site can triggered a temporary displacement of non-bunkered buildings. As a result, normal working conditions for safety related equipment can be compromised.

A CDF contribution of events of this type can be estimated by using the following reasoning and assumption:

- Failure rates of all equipment in the impacted building are increased by factor of 10.

- It is assumed that the major damage to the structural integrity of non-bunkered buildings due to construction works does not happen more than once during the operation time of a unit. In other words, the frequency of occurrence is not higher than $2{,}5 \cdot 10^{-2}$ /year for the Belgian units. This assumption is based on the reasoning that after a major deformation or collapse of a building, on-site works will be stopped or significantly modified.

- CDF contribution of this event is estimated by the formula:

$$\Delta CDF = F * \Delta CCDP = F * (CCDF - CDF\ basis) * \Delta t \qquad (3)$$

F – Frequency of occurrence (1/year), Δt – time of disruption of the normal operation, (year), CCDF – conditional CDF, given the increased failure rate.

The calculations of the CDF increase due to such events resulted in values significantly lower than the established quantitative criteria.

3.5.4. Lightning

A nuclear power plant has numerous structures, systems, and components that are susceptible to lightning strikes. Based on experience feedback from the commercial NPPs in the US [12], it is possible to approximate lightning CDF in Belgium.

Lightning-related events from 1992 - 2003 were analyzed and grouped into categories. The search for lightning-related occurrences from 1992-2003 uncovered a total of 66 events. The main two categories with PSA related consequences are:

- 21 events of Loss of Offsite Power were registered. A loss of off-site power occurs when any transmission line connecting the plant to the power system is disconnected by circuit breakers. A plant typically has more than one off-site power source. Plants are also required to have on-site backup sources, such as diesel generators, to provide sufficient power to safely shut down the plant in case of a total loss of offsite power. Unlike the previous periods, examination of the events in the 1992 - 2003 period did not uncover any loss of off-site power events that subsequently resulted in plant equipment damage. 91% of LOOP events were resolved within 30 min.

- The second category involves events that resulted in a reactor trip but did not involve any equipment damage. Reactor trips that also resulted in equipment and emergency safety function actuation, i.e., pump or valve actuation, also fall under this category. 18 events fall in this category.

The total number of reactor-years between 1992 and 2003 is 1226, for 106 US commercial reactors in operation during that period. Based on the number of recorded events and a total number of reactor-years during that period, frequencies of lightning induced reactor trip, short- and long-term LOOPs for the referenced US plants were estimated.

In general, density of lightning occurrence in the US is significantly larger than in Belgium: density greater than 10 flashes/km^2/year. The average number of lightning strikes in Belgium amounts to 1,19/km^2/year [13]. For the region of Tihange a value of 1,76/km^2/year (above the Belgian average) is considered. Therefore, the frequency of lightning induced events is respectively 5,68 (for Tihange) and 8,4 (for Doel) times less frequent than for the referenced plants in the US.

Frequency of above mentioned events (reactor trip, short- and long-term LOOPs) were adjusted to the Belgian context (by applying the correction coefficients). Core damage frequency was calculated based on those frequencies by making use of the internal events PSA model. The obtained results are below or of the order of magnitude of the quantitative criteria QN-2 (10^{-7} /r-year).

3.5.5. Solar storm

Severe disturbances caused by solar storms in the upper layers of our atmosphere can have a serious impact on power lines. Additional currents can overload the electric grid system to trigger voltage collapse, or worse, damage a significant number of transformers. For example, a severe geomagnetic storm struck Earth in 1989. It caused a nine-hour outage of Hydro-Québec's electricity transmission system. Solar storms of this magnitude are frequent, but their consequences are very local.

Historical records of solar events suggest that a reasonable range for the average return period for an extreme geomagnetic storm is 100-250 years. Based on information from historical aurora records, the mid-point estimate for the return period of a Carrington-level event is 150 years. This event can result in a loss of offsite power at many places around the globe. Frequency of such an event is $6{,}67\cdot10^{-3}$ /ry, (consistent with [14] and [15]). An additional coefficient is applied to account for a probability that a given solar storm that hits the Earth, will severely impact the Belgian NPPs (in the first approach, this coefficient was assigned a value of 0,1, based on engineering judgement, and it can be an object of further refinement). This coefficient mainly depends of two factors: duration of the storm and proximity to the magnetic poles. In fact, probability of being impacted is not uniform around the globe. It is very high near the magnetic poles and falls sharply near the equator. In addition, if the storm happens during the night and lasts less than 24 hours, it is possible that there will be no impact on the NPPs.

For Doel 1&2 the frequency was split between LT LOOP and ST LOOP in proportion 1 to 9. The values of the obtained results (by making use of the internal PSA event models) are of the order of magnitude of the quantitative criteria QN-2 (10^{-7} /r-year).

3.6. Inclusion

3.6.1 Inclusion in internal flooding

Internal flooding PSA considers generic rupture frequencies, i.e. it comprises various types of ruptures, without distinguishing their origins. N59 Microbiological corrosion and M22 High-voltage eddy current were identified as corrosion inducing mechanisms, implicitly taken into account in the internal flooding PSA. In addition, consequences of high ground water were assumed not to be more penalizing than the pipe rupture in the underground galleries, already studied as a part of internal flooding project. Thus, these hazards can be screen-out based on criteria QL-2.

3.6.2 Loss of main heat sink

The only safety significant consequence of the events listed in this section is loss of raw water. In principle, a series of measures has been put in place (filters, gratings, an alternative water supply, etc.) in order to minimize potential risks. The following hazards have been identified: N24 Underwater debris, N31 Extreme drought, N48 Surface ice on river, N49 Frazil ice, N54 Crustacean or mollusk growth, N55 Fish, jellyfish, N58 Biological flotsam, M7 Ship impact, M8 Collisions with water intake / UHS, M9 Ship: solid or fluid releases

The conservative margin of the generic values currently used in the PSA model is assumed to cover these hazards.

3.6.3 Loss of off-site power

The following hazards have been identified as the ones which have a potential of inducing a loss of off-site power events: N34 Icing, N35 White frost, N36 Hail, N39 Lightning, N40 High wind, storm, N43 Blizzard, N46 Wind blown debris, N52 Solar flares/storms, N73 Forest fire, wildfire, burning turf (for Tihange only), M19 Stability of power grid, M20 Contamination of switchgear, M21 Electromagnetic interference.

The conservative margin of the generic values currently used in the PSA model is assumed to cover these hazards.

3.6.4 External flooding

The design basis flood for Doel site is based on a model that combines high tides, storm surges and wind waves (N18, N19, N20).

In case of Tihange, N8 Flash flood, N9 Snow melt, N10 Off-site precipitation, N19 Seawater, wind waves, N25 Precipitation (rain and snow), Dam failure or mismanagement are considered during the definition of the design basis flood

4. CONCLUSION

Adequate screening criteria were defined in order to identify the relevant initiating events and operational states. Based on these screening criteria, a list of 97 external natural and man-made hazards was screened in order to identify those hazards that are relevant for the risk of the Belgian units as determined with the PSA (in accordance with WENRA Safety Reference Levels 2014, Issue O). It appeared that, most of the hazards do not represent considerable risk to the nuclear power plants in Belgium. In order to apply the qualitative criteria, supporting deterministic study were used, whenever applicable. Quantification of initiating frequencies and impact on Core Damage Frequency (CDF) has been calculated for the hazards, which cannot be screened out based of qualitative criteria.

Four families of hazards cannot currently be screened out:

- Seismic phenomena (vibratory ground motion and liquefaction);
- Loss of main heat sink;
- Loss of off-site power;
- External flooding.

Consequences of certain hazards are already present in the current PSA models. Generic frequencies are used without crediting individual hazards. A typical example is loss of main heat sink. A number of external hazards can induce it:

- Underwater debris;
- Crustacean or mollusk growth, Fish, jellyfish;
- Biological flotsam;
- Ship impact, Collisions with water intake and Ship: solid or fluid releases;
- Frazil ice, Ice barriers and surface ice on river;
- Extreme drought (Tihange).

Quantification of individual contributions of these hazards is complicated due to absence of reliable data.

Similarly, loss of off-site power can be induced by various causes. The current generic frequency is assumed to cover these reasons:

- Stability of power grid;
- Contamination of switchgear;
- Electromagnetic interference;
- Meteorological conditions (High wind, storm, Blizzard, Wind blown debris, Icing, White frost, Hail);
- Lightning, Solar storm;
- Forest fire (Tihange).

The contribution of Lightning and Solar storm was assessed. The CDF contribution exceeds the value of 10^{-7} /r-year (QN-2 criteria) for certain units, but their estimated frequencies only represent approximately 19% and 4% compared to the current generic frequency for LOOP used in the model.

Further analysis is foreseen within Electrabel/Tractebel in order to define the most practicable and justified methodology to be used to evaluate the contribution of the retained external hazards to the overall risk profile of the plant.

This is in line with the WENRA RL O1.1 (2014) that specifies the following:

"*If not practicable, other justified methodologies shall be used to evaluate the contribution of external hazards to the overall risk profile of the plant*".

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