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Report 5: Guidance document Implementation of LIGHTNING hazards in extended PSA

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Summary :

This report is a joint deliverable of ASAMPSA_E WP21 (Initiating events modelling) and WP22 (How to introduce hazards in L1 PSA and all possibilities of events combinations). It discusses details regarding implementation of lightning assessment in extended PSA.

The report introduces feasible approach based on already existing guidelines dealing with the implementation of external hazards in L1 PSA. In general the report summarizes the lessons learnt from existing standards, existing gaps and possibility for future development with regards to scope of WP21 and WP22.

Visa grid			
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EXECUTIVE SUMMARY

The lightning (including the electromagnetic interference) is indicated with # 39 in the exhaustive list of external hazards posing potential threats to nuclear installations, in particular in the list of the Meteorological events considered in ASAMPSA_E [45]. The survey performed in the framework of ASAMPSA_E (WP10) to collect interests of the PSA the end users showed that the lightning is amongst the ten external hazards most often considered by the respondents [3]. Thence the attention to the lightning hazard is within the scope of the extended PSA and its role in the safety of the nuclear power plant is underlined in this report.

This report is a joint deliverable of ASAMPSA_E WP21 (Initiating events modelling) and WP22 (How to introduce hazards in L1 PSA and all possibilities of events combinations), which are intended:

- to examine characteristics and modelling of lightning in PSA,
- to identify and promote exchanges of some good practices on the implementation of lightning in L1 PSA.

This report includes the End-Users recommendations given in WP10 and results from discussions at the 1st End-Users Workshop, Uppsala, Sweden, May 2014 [3], questionnaire survey and discussions at the Final End-Users Workshop, Vienna, Austria- September 2016 [4].

ASAMPSA_E PARTNERS

The following table provides the list of the ASAMPSA_E partners involved in the development of this document.

1	Institute for Radiological Protection and Nuclear Safety	IRSN	France
5	Lloyd's Register Consulting	LR	Sweden
12	Electricité de France	EDF	France
17	NCBJ Institute	NCBJ	Poland
19	VUJE	VUJE	Slovakia
27	Technical University of Sofia – Research and Development Sector	TUS	Bulgaria

CONTENT

LIST OF ABBREVIATIONS

AC	Alternating Current
BO	Brought high voltage waves (Overvoltage)
BPS	Bank Pumping Station
CDF	Core Damage Frequency
CG	Cloud To Ground
DC	Direct Current
DG	Diesel Generations
DPD	Discrete Probability Distributions
DSG	Design Safety Guide
EES	Electric Energy System
EL	Economic Loss
EMC	ElectroMagnetic Compatibility
EMI	ElectroMagnetic Interference
EMIn	ElectroMagnetic Induction
EMP	ElectroMagnetic Pulse
ESIn	ElectroStatic Induction
I&C	Instrumentation And Control
I/O	Input / Output
IEC	International Electrotechnical Commission
LA	Loss of Activity
LCH	Loss of Cultural Heritage
LEMP	Lightning Electromagnetically Pulse
LL	Loss of Life
LLS	Lightning Location Systems
LOOP	Loss Of Off-Site Power
LPL	Lightning Protection Level
LPS	Lightning Protection System
LPS	Loss of Public Services
LV	Low Voltage
MCS	Minimal Cut Sets or Monte Carlo Simulation
MoM	Method Of Moments
NDC	Nph Design Category
NFPA	National Fire Protection Association
NPH	Natural Phenomena Hazards
NPP	Nuclear Power Plant
OSY	Outdoor Switch Yard
PDF	Probability Density Functions
PLC	Programmable Logic Controller
POS	Plant Operational State
PSA	Probabilistic Safety Assessment
PSF	Performance Shaping Factor

PSHA	Probabilistic Seismic Hazard Analysis
PSR	Periodic Safety Review
SBO	Station Black Out
SFP	Spent Fuel Pools
UPS	Uninterruptible Power Supply

DEFINITIONS

Event Tree Analysis	An inductive technique that starts by hypothesizing the occurrence of basic initiating events and proceeds through their logical propagation to system failure events. • The event tree is the diagrammatic illustration of alternative outcomes of specified initiating events. • Fault tree analysis considers similar chains of events, but starts at the other end (i.e. with the 'results' rather than the 'causes'). The completed event trees and fault trees for a given set of events would be similar to one another.
Fault Tree Analysis	A deductive technique that starts by hypothesizing and defining *failure events* and systematically deduces the *events* or combinations of *events* that caused the *failure events* to occur. • The fault tree is the diagrammatic illustration of the *events*. • *Event tree analysis* considers similar chains of *events*, but starts at the other end (i.e. with the 'causes' rather than the 'results'). The completed *event* trees and fault trees for a given set of *events* would be similar to one another.
Cliff Edge Effect	In a nuclear power plant, an instance of severely abnormal plant behaviour caused by an abrupt transition from one plant status to another following a small *deviation* in a plant parameter, and thus a sudden large variation in plant conditions in response to a small variation in an input.
Design Basis	The range of conditions and *events* taken explicitly into account in the *design* of a *facility*, according to established criteria, such that the *facility* can withstand them without exceeding *authorized limits* by the planned *operation* of *safety systems*.
Design Basis External Events	The *external event(s)* or combination(s) of *external events* considered in the *design basis* of all or any part of a *facility*.
External Event	An event originated outside a nuclear power plant that directly or indirectly causes an initiating event and may cause safety system failures or operator errors that may lead to core damage or large early release. Events such as earthquakes, tornadoes, and floods from sources outside the plant and fires from sources inside or outside the plant are considered external events. By historical convention, LOOP not caused by another external event is considered to be an internal event. According to NUREG 2122, the term external event is no longer used and has been replaced by the term external hazard.
External Hazard Analysis	The objective is to evaluate the frequency of occurrence of different severities or intensities of external events or natural phenomena (e.g., external floods or high winds).
Fragility	The fragility of a structure, system or component (SSC) is the conditional probability of its failure at a given hazard input level. The input could be earthquake motion, wind speed, or flood level.
Fragility Analysis	Estimation of the likelihood that a given component, system, or structure will cease to function given the occurrence of a hazard event of a certain intensity. • In a PRA, fragility analysis identifies the components, systems, and structures susceptible to the effects of an external hazard and estimates their fragility parameters. Those parameters are then used to calculate fragility (conditional probability of failure) of the component, system, or structure at a certain intensity level of the hazard event. • Fragility analysis considers all failure mechanisms due to the occurrence of an external hazard event and calculates fragility parameters for each mechanism. This is true whether the fragility analysis is used for an external flood hazard, fire hazard, high wind hazard, seismic hazard, or other external hazards. For example, for seismic events, anchor failure, structural failure, and systems interactions are some of the failure mechanisms that would be considered.
Fragility Curve	A graph that plots the likelihood that a component, system, or structure will fail versus the increasing intensity of a hazard event. • In a PRA, fragility curves generally are used in seismic analyses and provide the conditional frequency of failure for structures, systems, or components as a function of an earthquake-intensity parameter, such as peak ground acceleration. • Fragility curves also can be used in PRAs examining other hazards, such as high winds or external floods.

Hazard	The ASME/ANS PRA Standard defines a hazard as “an event or a natural phenomenon that poses some risk to a facility. • Internal hazards include events such as equipment failures, human failures, and flooding and fires internal to the plant. • External hazards include events such as flooding and fires external to the plant, tornadoes, earthquakes, and aircraft crashes.”
Hazard Analysis	The process to determine an estimate of the expected frequency of exceedance (over some specified time interval) of various levels of some characteristic measure of the intensity of a hazard (e.g., peak ground acceleration to characterize ground shaking from an earthquake). The time period of interest is often taken as 1 year, in which case the estimate is called the annual frequency of exceedance.
Human Reliability Analysis	A structured approach used to identify potential human failure events and to systematically estimate the probability of those events using data, models, or expert judgment.
Initiating Event	An identified *event* that leads to *anticipated operational occurrences* or *accident conditions*. • This term (often shortened to ***initiator***) is used in relation to *event* reporting and *analysis*, i.e. when such *events* have occurred. For the consideration of hypothetical *events* considered at the *design* stage, the term *postulated initiating event* is used.
Loss of Offsite Power (LOOP)	The loss of all power from the electrical grid to the plant. In a PSA/PRA, loss of offsite power (LOOP) is referred to as both an initiating event and an accident sequence class. As an initiating event, LOOP to the plant can be a result of a weather-related fault, a grid-centered fault, or a plant-centered fault. During an accident sequence, LOOP can be a random failure. Generally, LOOP is considered to be a transient initiating event.
Structures, Systems and Components (SSCs)	A general term encompassing all of the elements (items) of a *facility* or *activity* which contribute to *protection and safety*, except *human factors*. • ***Structures*** are the passive elements: buildings, vessels, shielding, etc. • A ***system*** comprises several *components*, assembled in such a way as to perform a specific (active) function. • A ***component*** is a discrete element of a *system*. Examples of components are wires, transistors, integrated circuits, motors, relays, solenoids, pipes, fittings, pumps, tanks and valves.
Severe accident	A type of accident that may challenge safety systems at a level much higher than expected.
Screening	A process that distinguishes items that should be included or excluded from an analysis based on defined criteria.
Screening criteria	The values and conditions used to determine whether an item is a negligible contributor to the probability of an accident sequence or its consequences.
Sensitivity Analysis	A quantitative examination of how the behaviour of a *system* varies with change, usually in the values of the governing parameters. • A common approach is parameter variation, in which the variation of results is investigated for changes in the value of one or more input parameters within a reasonable range around selected reference or mean values, and perturbation *analysis*, in which the variations of results with respect to changes in the values of all the input
Uncertainty	A representation of the confidence in the state of knowledge about the parameter values and models used in constructing the PRA. OR Variability in an estimate because of the randomness of the data or the lack of knowledge.
Uncertainty Analysis	An *analysis* to estimate the uncertainties and error bounds of the quantities involved in, and the results from, the solution of a problem.

1 INTRODUCTION

1.1 CONTEXT

Safety reports and probabilistic safety analysis are included amongst safety licensing documentations for nuclear facilities. External hazards including extreme meteorological events may have an important impact on nuclear safety. One of these meteorological events is a strong atmospheric discharge - lightning.

Figure 1-1 Lightning

The survey performed in the framework of ASAMPSA_E (WP10) to collect interests of the PSA the end users showed that the lightning is amongst the ten external hazards most often considered by the respondents [3]. Thence the attention to the lightning hazard is within the scope of the extended PSA and its role in the safety of the nuclear power plant is underlined in this report.

The potential importance of this hazard comes from the high frequency of its occurrence. For instance a study for the territory of Bulgaria shows that the number of recorded lightning strikes over the area of Kozloduy NPP (within a radius of about 50 km) for three-month period (June, July and August) of 2005 and 2006, was around 3000-4000 (mainly in noon and afternoon hours) [38].

Based on the latest predictions of worldwide climatology panels regarding global warming, importance of lightning topic could be more and more relevant [8]. The increase of average temperatures could lead to more frequent and intensive storms which are the main sources of lightning. Increasing frequency of storms and lightning could lead to a situation where lightning power could exceed the limits defined by standards applied for electromagnetic compatibility to ensure appropriate protection against impact of lightning. For example, in [1] are presented reviews of studies for an increase in lightning activity by 12% (or 10%) due to a rise in global warming by 1°C. There is an assumption that average earth temperature due to global warming could be increased to nearly 4°C by year 2100, which could ultimately lead to increasing lightning activity by 48%. That could be disputable taking into account other existing information based on climate model, which conclude to a decrease of lightning activity because of a stabilization of atmosphere, as compared to more violent events, and higher lightning currents, or higher extreme lightning currents.

The impact of lightning due to direct (ground) flash strikes and the resulting secondary effects could have serious consequences on the nuclear power structures and systems, due to the digital and low-voltage analogic systems. Lightning protection is becoming increasingly important. Digital systems have the potential to be more vulnerable than older analogic systems, to the resulting power surges and electromagnetic interference (EMI) when lightning hits facilities or power lines.

The protection of Nuclear Power Plants against the consequences of lightning strike is of importance, as it is shown for example, in the studies held by the High Voltage Technique Laboratory (HVT) of TUS in Kozloduy NPP in Bulgaria. The research made by HVT Laboratory of Technical University of Sofia (TUS) is devoted to improve lightning protection and reduce surges in the internal network and relay protection circuit of Kozloduy NPP in Bulgaria [42].

Some of the equipment of HVT Lab is shown in Figures 1-2 and 1-3.

Figure 1-2 Impulse voltage generator IP 7.5 / 750 kV

Figure 1-3 Spheres MKF 75

In accordance with the general requirements and needed components of the lightning protection system of NPP, shown in Figure 1-4, from HVT Lab. of TUS is carried out "Study the existing lightning protection of all buildings and facilities of the NPP Kozloduy" [42].

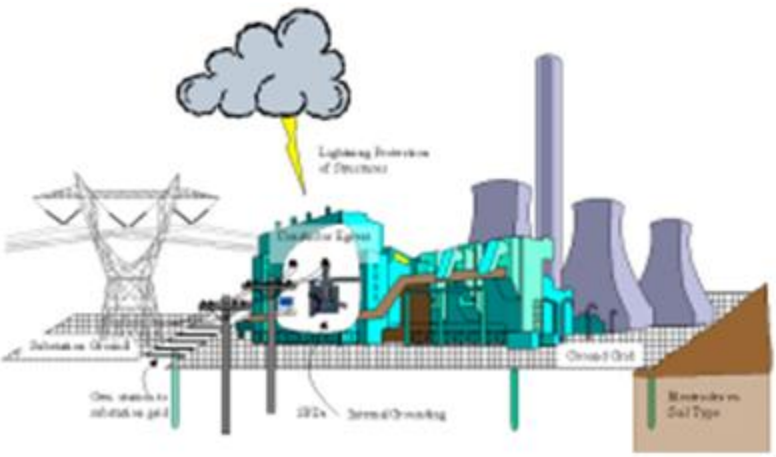

Figure 1-4 Issues for lightning protection in generating stations

Key lightning protection issues focus on:

1 Overall grounding plan

2 Quality of lightning protection system (LPS)

3 Quality of filtering and grounding of conductors that egress LPS

4 Cable routing within the facility

5 Correct selection and placement of surge protection devices (SPDs) throughout the facility

6 Grounding of the instrumentation and control (I&C) components

7 Protection of equipment from electromagnetic surges

In the general study the laboratory has developed issues 2 and 5, and for surge protection of voltage transformer (VT) secondary circuit's has developed tasks 5, 6 and 7 of the recommended key tasks listed above.

There were modelled of disconnectors switching under electrical voltage 400 kV. Similar processes are under the influence of lightning in a direct or near lightning strikes. The transients' wave voltage was measured with amplitude reaching 2,5 kV at terminals of the VT (Figure 1-5). The measured amplitudes of the input voltage of the relay protection are 250-300 V with a short duration (Figure 1-6).

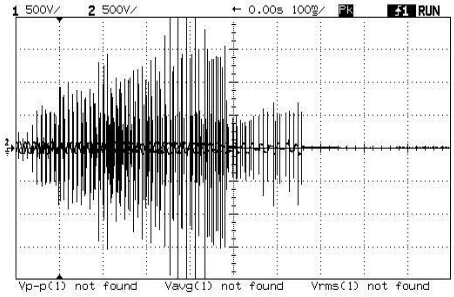

Figure 1-5 Wave voltage with amplitude until 2.5 kV

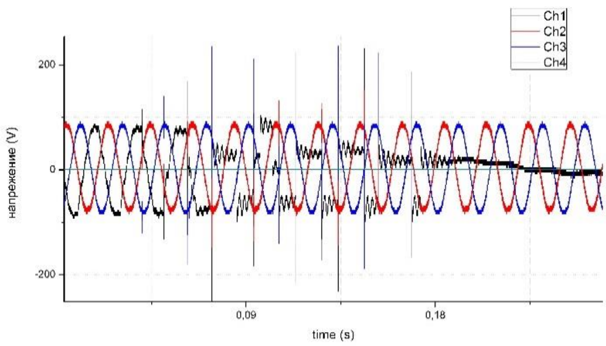

Figure 1-6 Amplitudes of the input voltage of the relay protection 250-300 V

1.2 OBJECTIVE, SCOPE AND STRUCTURE OF THE REPORT

The aim of this report is to describe the phenomenology of lightning, its effects and potential impact on nuclear safety, and to examine how to introduce this phenomenon in PSA if necessary. This report discusses possible initiating events related to lightning and their parameters.

Based on our knowledge, this topic is not covered by any known specific guidance addressing the issue of electromagnetic interference (EMI) caused by atmospheric discharges. However this report is developing a systematic framework on implementation of lightning hazard and its modelling in L1 PSA.

The structure of this report is built as follows:

- Section 2 presents the lessons learnt from operational experience.
- Section 3 presents the basic requirements of L1 PSA for NPP concerning external hazards which are valid for lightning hazard and discussed the position of existing standards compare to these requirements.
- Section 4 introduces general phenomenology of lightning, including lightning effects.
- Section 5 deals with the data necessary for the assessment of the frequency and magnitude of lightning strikes as well as for evaluation of the impact of lightning on NPP. This section also briefly discusses topic of plant database to support lightning hazard analyses.
- Section 6 presents a basic methodology for lightning hazard assessment as well as the approach to evaluate impact of lightning on plant equipment. This section forms the background for PSA fragility analysis. Within this section, the topic of hazard combinations is discussed.
- Section 5 deals with correlated hazards and combinations of hazards, especially important for NPP.
- Section 7 presents some methods for identification and assessment of hazards combinations, applicable for NPP.
- Section 8 is devoted to multi-unit assessment for lightning hazard,
- Section 9 discusses the development of event and fault trees in a lightning PSA
- Section 10 is about L2 PSA considerations

2 LESSONS LEARNED FROM PAST EVENTS

The lightning is one of the three most common causes of events caused by external hazards in nuclear power plants [7]. Figure 2-1 and Figure 2-2, taken from [7] illustrate distribution of external events in Germany and France caused by variety of external hazards.

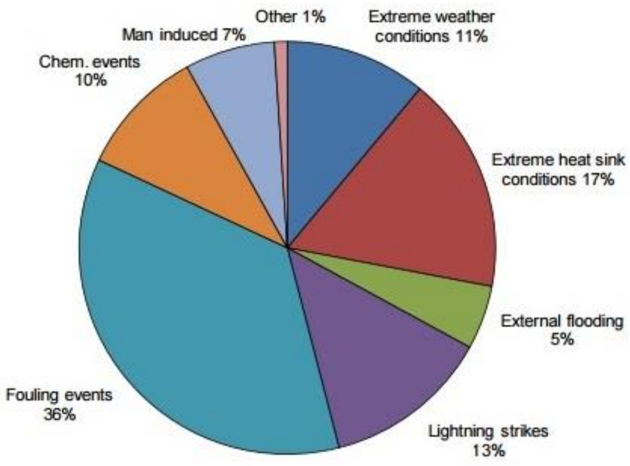

Figure 2-1 Distribution of external hazard related events in Germany

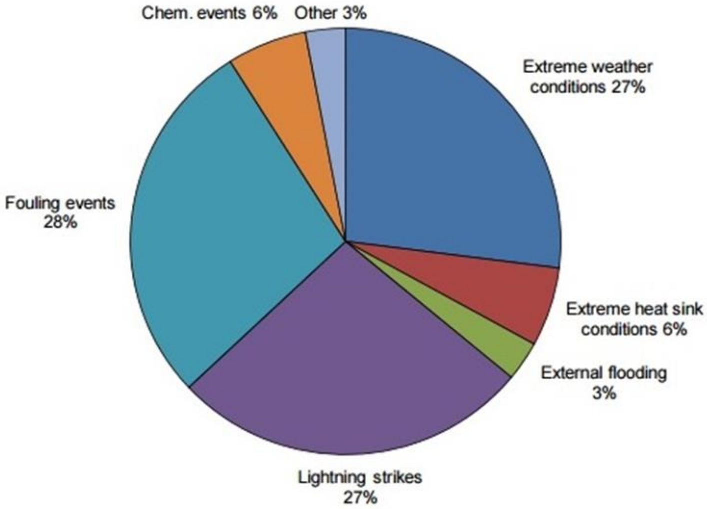

Figure 2-2 Distribution of external hazard related events in France

The information presented in both figures provides a distribution of external hazards. A more precise analysis of the events corresponding to 13 % and 27 % lightning strikes in Germany and France, must be held to understand for instance, which part of these lightning strikes have affected some NPPs in the both countries. Thence the consideration is to what extent it is necessary to examine lightning hazards in the PSA? And on the other hand is this available or can it be collected enough information for detailed development of the lightning hazards in the PSA?

Examples of lightning consequences are given in the study on the lightning risk assessment evaluation on French NPPs [48]. This study covers 30 years of observation (1980-2012) for 19 large industrial nuclear sites and reports a very important number of material damages (~ 50000 structures per year). From all registered incidents, 116 incidents produced an impact on the process, but without material damage (e.g. activation of safety power source) and 51 incidents are associated to material damage (e.g. destruction of equipment). In the same time, there are no human registered injuries and no fire ignition due to lightning. So, if for this study apply the risk assessment method of the international standards for lightning protection (e.g. IEC 62305-2) which evaluate the lightning risk on buildings and structures [44], the risk will refer to one third of the lightning events. Statistically, it can be seen as an average of 1.7 lightning per year with risk for material damage in nuclear power plant (NPP), which is significantly higher frequency than calculated by the 'Improved EDF's method' indicated in [48] and the 'Standard method' (classical application of IEC 62305-2). Information on the 'Improved EDF's method' and on the differences between "improved method" and "classical method" is given in Appendix 19.

Some safety significant events caused by the lightning in Europe or in other countries (ASAMPSA_E [5])-) are shown in the Table 2-1. Even very distant lightning events may cause electrical disturbances (e.g. Sweden 13/06/2008).

Table 2-1. Description of some safety significant events caused by the lightning

Date (DD/MM/YYYY)	Country	Type of Reactor	Brief description of the hazards	Brief description of the consequences for the NPP
23/02/1967	Germany	BWR		Lightning strike in the network, strong voltage dip, in the further course of events, Rupture of a steam line
06/06/1982	Germany	PWR		Failure of the turbine-generator control system and other electronic and electrical systems, short-term emergency power
29/05/1983	Germany	BWR		Triggering a RESA and other reactor safeguards
04/05/1986	Germany	PWR		Triggering of the 220 kV power supply and emergency power
13/06/2008	Sweden	BWR	Grid disturbance due to Lightning (50-60 km out in the grid)	Trip of reactor coolant pumps Risk for dry-out
13/07/2012	Sweden	BWR	Grid disturbance due to Lightning	The event shows that an external event can cause electrical disturbance within the plant.
1993-2013	USA	BWR	Reactor trip, LOOP, containment isolation, Reactor trip, LOOP	

Very indicative examples to illustrate the lightning hazards for the purposes of PSA are the lightning consequences in NPPs of Forsmarks Kraftgrupp AB, presented during the 1st End-Users Workshop of ASAMPSA_E in Uppsala, Sweden, May 26-28, 2014 [63]. The described events are the following:

- **Loss of external power and loss of** power supply from 2 of 4 **diesel generators** Forsmark 1 (25 July 2006)
- **Lightning strike** tripped all eight main circulation pumps at Forsmark 2 (13 June 2008)
- **Lightning strike** causing voltage transient in station AC net Forsmark 3, (13 July 2012)
- **Loss of two phases of the external grid** during outage shutdown with loss of decay heat removal (30 May 2013)

Information for lightning consequences in NPPs of Forsmarks Kraftgrupp AB (2006-2013) is given in Appendix 18.

3 PSA REQUIREMENTS AND STANDARDS

The basic requirements for L1 PSA are given in many guidelines and national regulatory guides, e.g. the publications [9], [17]. In this report it is appropriate to display the stages in accordance with the Section 6 of [9] general methodology for internal and external hazards, as follow:

a. Collection of initial information on internal and external hazards;
b. Hazard identification, including single and combined hazards;
c. Hazard screening analysis, both quantitative and qualitative;
d. Bounding assessment;

e. Detailed analysis.

Basic requirements on L1 PSA and above stages have to be applied for lightning in the extended PSA. Overall picture of analysis process from [9] is applied to lightning hazard and is presented in Figure 3-1.

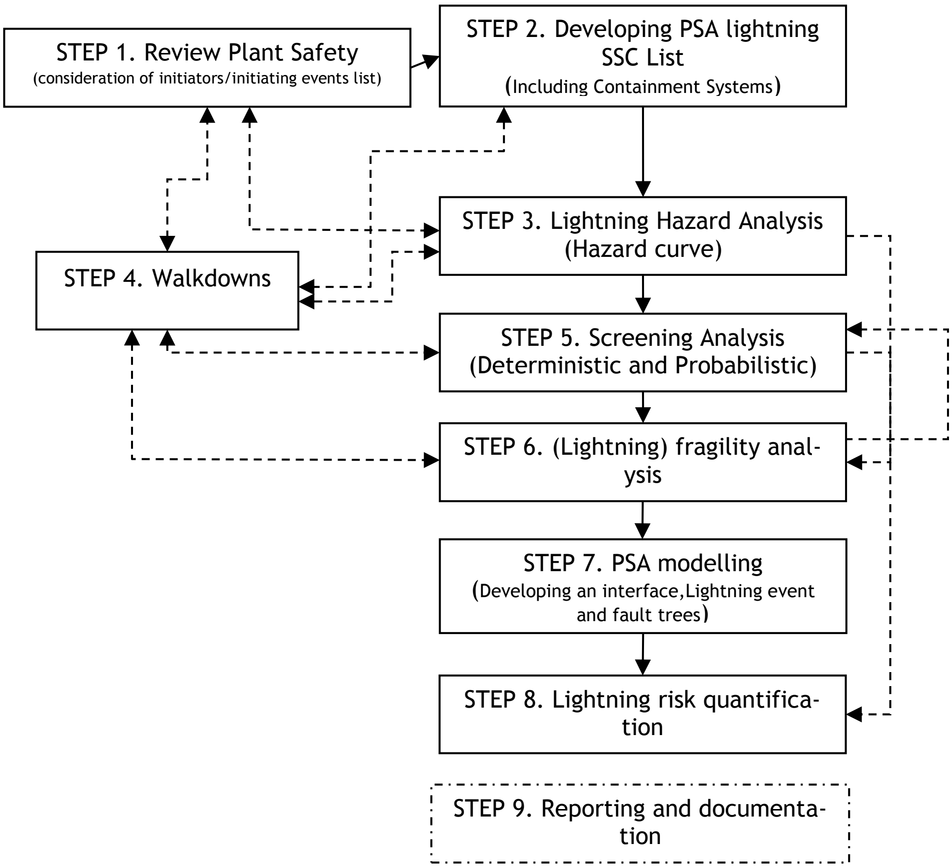

Figure 3-1 Logical diagram for lightning PSA

Until now there is no established new, improved standard as recommended in [48]; however the methodology for assessing the risk of lightning, including for large industrial sites as nuclear sites, should adhere to the current IEC 62305-2 standard.

The standard IEC 62305-2 objectives are:

- evaluate the frequency of dangerous events,
- evaluate the needs of lightning protection,
- define lightning protection,
- evaluate the residual risk, and
- comply with standard or regulations,

Damage caused by lightning are associated with respective losses (damages), which are subdivided into:

i. loss of life (LL);
ii. loss of public services (LPS);
iii. loss of cultural heritage (LCH);
iv. economic loss (EL) - buildings, outdoor facilities and the contents are property networks for public services and loss of activity (LA).

The loss of species LL, LPS and LCH are considered as loss of social values, and the loss of species EL and LA - as pure economic losses.
These losses are not fully relevant to nuclear power plants safety analysis and should be adapted, as far as still valid and should be used IEC 62305-2. It is not expected these types of loss to be maintained in the next revision of the standard in 2018.

An approach for extended PSA guidance using only the existing IEC 62305 would not be not very suitable, especially for covering the ASAMPSA_E end-users' needs and in perspective for more widely applicable document. One reason is that there are different critical points of view on the standards [45] and now more than 100 published lightning protection codes and standards are in use within countries. Different documents of USA Department of Energy, USA National Fire Protection Association (NFPA) and other are modified [44], [47] etc. Therefore a comparative approach is used in the current Guidance, in addition to KTA 2206 (2009-11), which is applied in Germany, France and other countries.

The KTA 2206 (2009-11) [61] defined the method, requirements and parameters for the protection of the electrical facilities in nuclear power plants against impermissible adverse effects from a lightning strike. For that aim, the lightning protection system has to comprise two subsystems:

i. Exterior Lightning Protection system which consists in all measures and equipments provided for catching and grounding the lightning current.

ii. Interior Lightning Protection system which consists in all measures and equipments provided against the effects of the lightning strike on conductive installations and electrical facilities inside structures and structural components, including the measures for the reduction and limitation of surge voltages.

The requirements with respect to dimensioning the lightning protection of structural components of the NPP shall be specified with regard to the electrical facilities contained in these structural components, or more precisely the lightning protection system has to be differentiated concerning the importance of the electrical facilities for the safety of the NPP, namely by category. The following protection categories shall therefore be assigned to the individual buildings (structural components):

i. Level 1 protection category applies (is required) to buildings that contain electrical facilities relevant to safety, and also is required to buildings that contain facilities of the plant-operation related instrumentation and control if their malfunction might lead to impermissible adverse effects in safety-related plant components.

ii. Level 2 protection category applies to all other buildings, and as supplement to the KTA 2206 – Level 2 protection category has to be required for all other buildings at the NPP site and around, where could be caused correlated lightning hazards.

In addition to the application of KTA 2206 in design of new nuclear plants or in case of revision of the existing lightning protection system of NPP in operation, for further improvement of the level protection of NPPs against impact of lightning should be involved evaluation of lightning hazards in extended PSA, and to be developed regulatory guidance to address design and implementation good practices for lightning protection systems in NPPs.

It is very important, while considering the implementation of lightning hazards in extended PSAs to make a realistic link between the objectives of an extended PSA and the methodological approaches to implement lightning hazards. Realistic evaluation of the lightning hazard contribution to the overall risk presented by a plant shall be the main point of any PSA guidance. Assessment of lightning as an independent risk for NPP requires lengthy observations about its impact on individual systems of the plant under real conditions and further data for a representative analysis and conclusion.

4 GENERAL PHENOMENOLOGY OF LIGHTNING

Lightning is the natural equalization of charge potential between various regions of a cumulonimbus cloud and also the surface of the earth. Typically, the lower region of the cloud becomes negative and this, in turn, induces positive charging of the earth's surface below the cloud. When the charge potential between becomes large enough to break down the normally resistive characteristic of the air, i.e. when the intensity of the electric field between the cloud and the earth reaches the critical value (about 30 kV/cm), a lightning strike occurs. When considering the lightning as hazard for nuclear facilities, different international standards and national regulations can be used as basis. The series of IEC 62305-1 to -5 and KTA 2206 (2009-11) [61] are particularly recommended.

There are different types of lightning to be considered, defined in accordance with IEC 62305-1 [10] and IEC 62305-2 [11], as follow:

- ***cloud-to-ground lightning (CG) -*** discharge that is comprised of one or more cloud-to-ground lightning strokes that propagate from cloud to ground or vice-versa and lead to a net transfer of charge between cloud and ground;
- ***cloud lightning (IC) -*** discharge occurring within or among thunderclouds (intracloud), or between thunderclouds (intercloud), or between cloud and air, without a ground termination;
- ***first return stroke -*** first stroke to ground of a cloud-to-ground lightning discharge (the stepped leader and attachment process precede the first return stroke);
- ***subsequent stroke -*** subsequent stroke to ground that follows a previous (return) stroke in the same flash;
- ***multiplicity -*** number of first and subsequent strokes in a cloud-to-ground lightning flash.

Note: Concerning the terminology could be mention that the standards use the both "stroke" and "strike". IEC 62305-1 uses stroke, but KTA 2206 (2009-11) uses strike. IEEE Std 998-1996 uses the both - concerning the distance uses "strike distance (S) », and concerning the current uses «return stroke current (Is)».

Usually the lightning strike is multiple and multiplex. After the first stroke there are an average of 3-4 other strokes (sometimes their number is several tens), with typical time interval between them of about 50 ms. The mechanism of the stepped leader permits the discharge to develop to the huge distances [65], [66].

The main relevant lightning strokes of this report are those that occur from cloud to ground.

The front of the lightning current is shown in Figure 4-1.

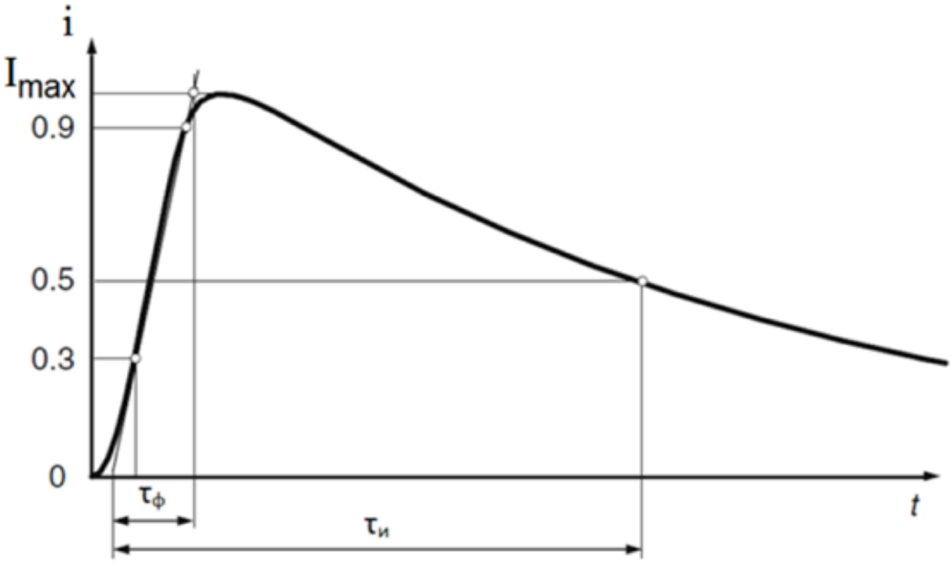

Figure 4-1 Front of the lightning current

The main common characteristics of the lightning strike are:

- Current as high as 300 kA, but the average value is around 20 kA. For design of lightning protection of explosive danger objects the computing value considered is 200 kA.
- The steepness (di/dt) of the front of the lightning current curve is usually 5-10 kA/ µs, sometime it reaches 80 kA/ µs and for computing value 60 kA/ µs is considered. In IEC 62305-1, for calculation, 3 types of lightning waves are defined:
  - Positive first stroke (di/dt not significative)
  - Negative first stroke (di/dt=100kA/µs)
  - Negative subsequent stroke (di/dt=200kA/µs)
- The main return stroke is approximately 30 microseconds in duration.
- In average there are 3 or 4 return strokes per lightning strike.
- Typical lightning duration is 20 - 50 milliseconds, but sometime the total duration of repeated lightning reaches 1.5 s.
- The wave period of the lightning current is usually 1.5-10 µs, but sometime reaches 20-100 µs and the computing value considered is 50 µs.
- Temperature can reach almost 50000 °C, but usually is around 20000 °C.

Lightning severity is characterized by different parameters:

- peak current,
- current derivative,
- specific energy,
- charge.

The standard KTA 2206 [61] proposes the following steps:

a) deriving and specifying lightning strike characteristics from the measurement results of actual lightning strikes;

b) evaluating specific experiments with pulse generators that simulate lightning strikes by inducing voltage pulses into cables and conductors of existing nuclear power plants which are already protected by defined and relevant lightning protection measures;

c) specifying analytical procedures for the determination of that portion of the lightning current that must be considered for the induced voltage pulses;

d) evaluating results from analytical and numeric procedures regarding the lightning-based voltage pulses induced into cables of cable ducts and into ground-routed cables.

Similar as in IEC 62305-1 (shown above) 3 types of lightning waves are defined for calculation, shown in the Table 4-1 for the specified lightning current parameters (In the Fig.4-1 above the symbols τ_1 and τ_2 are indicated as $\tau_ф$ and $\tau_и$.):

Table 4-1. Parameters for the lightning current pulse

Lightning	***Parameter***	***Symbol***	***Unit***	***Value***
Positive initial lightning strike	crest value of current	IB	kA	200
	average current gradient	IB/τ_1	kA/µs	20
	front time ($\tau_ф$)*	τ_1	µs	10
	time of half-value ($\tau_и$)*	τ_2	µs	350
	impulse charge	Qi	C	100
	specific energy	W/R	MJ/Q	10
Negative initial lightning strike	crest value of current	IB	kA	100
	average current gradient	IB/τ_1	kA/ µs	100
	front time	τ_1	µs	1
	time of half-value	τ_2	µs	200
Negative subsequent lightning strike	crest value of current	IB	kA	50
	average current gradient	IB/τ_1	kA/ µs	200
	front time	τ_1	µs	0.25
	time of half value	τ_2	µs	100

Each characteristic is connected to one or several lightning effects on installations. For example, charge is connected to erosion and piercing, specific energy to temperature rise, peak current to magnetic field, induced voltages, ground voltage rise, etc.

Usually the basic characteristics of lightning impact accepted are the intensity of the discharge and the peak current, in kA, respectively absolute peak current, because of two possible polarizations charges. Discharge with greater intensity is due to the large peak current very well detectable from sensors system of meteorological stations. In general, intensity maps enabling to asses expected lightning intensity can be easily produced. As an example, the Figure 4-2 shows lightning strokes between the cloud and ground, at peak current greater than 200 kA, in the Slovak Republic and the surrounding area for the years 2002 to 2010.

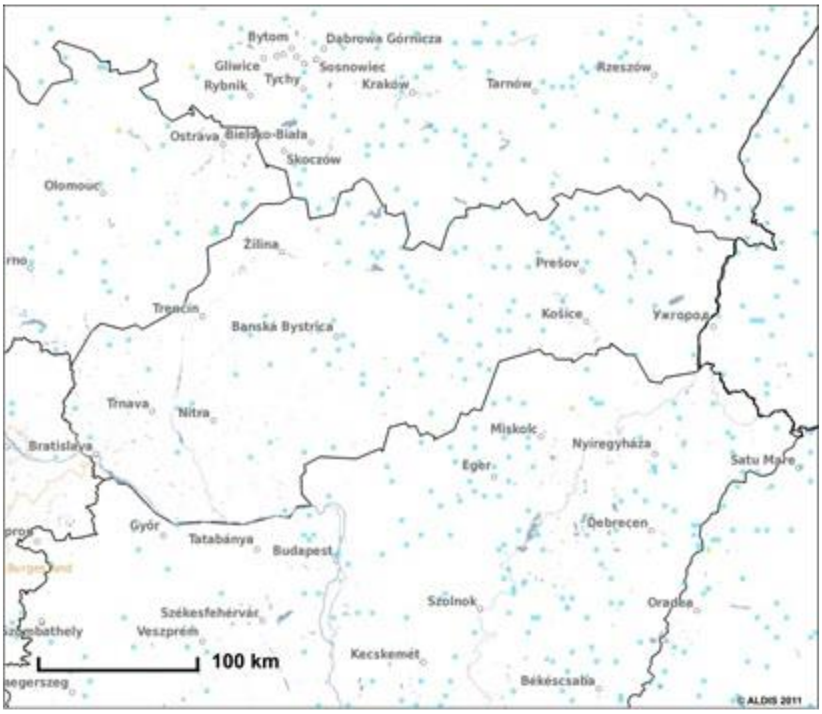

Figure 4-2 Lightning between the cloud and ground at peak current greater than 200 kA in the Slovak Republic and the surrounding area for the years 2002 - 2010

Lightning damage falls into two main categories:

- **Physical damage** (results into direct lightning hits/strikes or primary effects) - fire and destruction of structures. More precisely, physical damage could appear also from the consequence of sparking due to overvoltage coming from external lines (so called indirect effects). The most common technology for dealing with this effect is to divert the strike energy to a properly grounded lightning rod or cabling system - lightning protection system (LPS).
- **Failure to electrical and electronic systems** – This type of failures are approximately 1000 times more likely to occur than physical damage for any given facility. Secondary effects are the damages caused to sensitive electronic devices, electrical networks and systems. The most commonly observed effects are:
  - Direct Energization - due the Electromagnetic Induction (EMIn). It is the most obvious and potentially damaging secondary effect of lightning. A strike on the electrical cabling or other conductive pathways routed to a facility can introduce dangerous currents leading to energy surges into equipment connected at both ends of the pathway. Although the strike may be a considerable distance from the facility, it may be easily introduced into that facility by cabling, rail-road tracks or even utility piping. Common surge suppression technology is not generally effective against this effect of lightning.
  - Electro Magnetic Pulse (EMP) - Electrostatic Induction (ESIn) is forming near field coupling. An enormous electromagnetic field is usually developed in areas adjacent to the strike path at the moment of discharge. As a result, high currents (several kA) can develop along any electrically conductive paths to the ground within the area affected by this field. Such fields can also be developed in all lightning strikes including Cloud - To - Cloud events that do not directly contact earth. Elimination of these common effects cannot be always accomplished through conventional grounding systems. In IEC 62305-1, EMP is generally defined Lightning Electromagnetically Pulse

(LEMP) - all electromagnetic effects of lightning current via resistive, inductive and capacitive coupling that create surges and radiated electromagnetic fields.

- Ground Potential Rise - This effect is formed by resistive coupling that occurs when a ground potential gradient forms in areas adjacent to the earth contact point of a cloud to ground strike. Low Side Surge is the result of such effect and it is easily the most common point of introduction of damaging energy into sensitive control and monitoring circuitry. During a lightning induced Ground Potential Rise event, the ground reference point that electronic systems critically depend on diversion of “excess” energy that can actually become a source of this energy. Commonly relied on protective devices and their connected grounding systems are simply not designed to handle lightning related energy and may actually become the pathway for this destructive energy to enter into the system. If an ideal low impedance single point grounding system existed in the facility, then resistive coupling due to Low Side Surge would not be an issue.

Practically lightning could cause several types of fault, for instance, disturbances in the voltage, frequency or phase angle that could affect electrical output and equipments of the NPPs.

In practical terms related to safety of nuclear facilities, it is very important to consider the lightning hazard depending on the degree of consequences of the lightning impact on the electrical supply needed for the normal safe operation of the NPPs and also in the case of accident conditions.

At nuclear facilities, it is important to understand how lightning hazards are considered in the original design of the NPP and what protections are designed against lightning hazards, The kinds of protections are described in KTA 2206 (2009-11) [61]. If at specific NPP, other standard or regulation is used, then it could be compared with KTA 2206.

To summarize the above given points:

- **the lightning does not have to strike directly a facility to cause real damage.**
- **protection currently in place may be appropriate for normal surges caused by load switching and utility transients, but could not be effective against extreme lightning. Inappropriate protection may even put system equipment at greater risk by providing a pathway through sensitive equipment.**
- **to provide highly reliable protection, a lightning protection system design must address direct strikes, energization of all incoming lines, Electro-Magnetic Pulse, and the effects of Ground Potential Rise.**

The first step of the analysis is then to determine the list of all events that can be induced by lightning strike. Analysts shall review the plant safety systems and fundamental safety function from the viewpoint of lightning strike.

This step shall take into account effect of direct and nearby lightning flashes on SSCs. Failures are caused mainly by the effects of lightning overvoltage’s on electrical and electronic which is induced by effects of lightning current and voltage. Every SSC exposed by the natural influences of lightning discharges and their electromagnetic fields may be damaged.

This step should be focused on two basic areas:

- potential internal events - this part covers mainly
  - offsite power disturbances
  - spurious reactor trip and loss of one or several safety trains - potential impact of lightning strike on I&C or power supply systems

  - loss of one or several safety trains without reactor trip- potential impact of lightning strike on I&C or power supply systems
  - malfunction in operation of main control room
  - internal fires and explosions (flammable and explosive tanks etc.)
- potential external events - this part should be based on results of external hazard analysis such as external industry and external fires.

5 DATABASE ON LIGHTNING PHENOMENA

This section deals with creating a database for lightning hazards which is necessary for the assessment of the frequency and magnitude of lightning as well as for evaluation of the impact of lightning on the plant. This section also briefly discusses topic of plant database to support lightning hazard analyses.

5.1 LIST OF DATA REQUIRED FOR HAZARD ASSESSMENT

Basic data that are necessary to perform estimation of frequency are data describing lightning quantities and features of plant regarding lightning effects.

Lightning strikes can be described by isokeraunic maps, providing information about distribution of lightning intensities for area of interest.

Lightning strikes parameters are usually derived from keraunic local level (keraunic local number), i.e. of the average number of storm days per year in the locality. Meteorological institutes keep statistics storms in shape of isokeraunic curves, which are the flowlines of such places on the map that have the same number of storm days per year. Examples of isokeraunic maps of the Slovak Republic describing average storm days per year is shown in Figure 5-1 and the similar map of Bulgaria in Figure 5-2. It is assumed that the distribution of recorded parameters is described by normal distribution (of random variables). This assumption can be demonstrated by many publicly available data, e.g. [30]. Consequently based on the distribution of storm days, it is possible to assess the probability of occurrence particular parameters describing features of lightning strikes as stated in the standard IEC 62305, detailed in section 6.1.

Figure 5-1 Isokeraunic map of the Slovak Republic

Figure 5-2 Isokeraunic map of Bulgaria

Such maps, as in Figure 5-1 and Figure 5-2, can be used as input to assess lightning strike density [44]; relevant data are shown in Table 5-1.

Table 5-1 Map referred in: Transmission and Distribution Electrical Engineering [47]

Average number of storm days per Year	Number of flashes per km^2 per Year (Mean)	Number of flashes per km^2 per Year (Limits)
5	0,2	0,1 to 0,5
10	0,5	0,15 to 1
20	1,1	0,3 to 3
30	1,9	0,6 to 5
40	2,8	0,8 to 8
50	3,7	1,2 to 10
60	4,7	1,8 to 12
80	6,9	3 to 17
100	9,2	4 to 20

The lightning strike density in Bulgaria depends on intensity of lightning activity [41] as shown in Table 5-2.

Table 5-2. Lightning strike density in Bulgaria

Intensity of lightning activity hours per year	10 - 20	20 - 40	40 - 60	60 - 80	> 80
Flashes per km^2 per Year	1,5	3	6	9	12

According to a French study known as *the lightning risk assessment evaluation on French nuclear power plants* [48] the thunderstorm activity was defined by the keraunic level (Nk) i.e. "the number of days per year when we heard the thunder". In France, Météorage calculates a value equivalent to keraunic level, the number of thunderstorm days, from measurements of the lightning detection network. For each city, this number is calculated from the 'Lightning Database', which represents an average over the last 10 years. The mean number of stormy days in France is 11.30.

The criterion of number of thunderstorm days is not necessarily characterizing the importance of thunderstorms. Indeed a single lightning strike or a violent storm will be recognized in the same way. The best representation of thunderstorm activity is the density of arcs (Da), which is the number of arcs of lightning per km² per year. The lightning detection network used by Météorage allows direct measurement of this magnitude. The average value of the density of arcs, in France, is 1.59/ km^2/year.

The density of flashes (Df), generally used in normative term, can be deduced from the density of arcs by the following formula:

$$Df = Da / 2.1$$

The French study shows that 50% of lightning strikes have intensity lower than 50 kA and 99% lower than 200 kA. According to the last French definitions, the lightning occurrence is characterized by the « Ground flash density » Ng given by lightning location systems (LLS), without referring to « keraunic level » Nk used in the past. Nk is now derived from Ng (with Nk=Ng/10) since a long time, and in the next edition of the 62305 standard, Nk is expected to totally disappear from the standard. If there are no local LLS to evaluate Ng, like in desert or ocean, the ground flash density will be derived from satellite data's available all over the word.

The average number of lightning strikes in Europe, according [16] is ranging from 0.1 to 4 per km^2 per year. The highest annual average per km^2 per year in mountain areas to 7.9 lightning strikes is shown on Figure 5-3. There are major differences between months during the year. The largest number, up to 42 strokes in the month of July is shown on Figure 5-4.

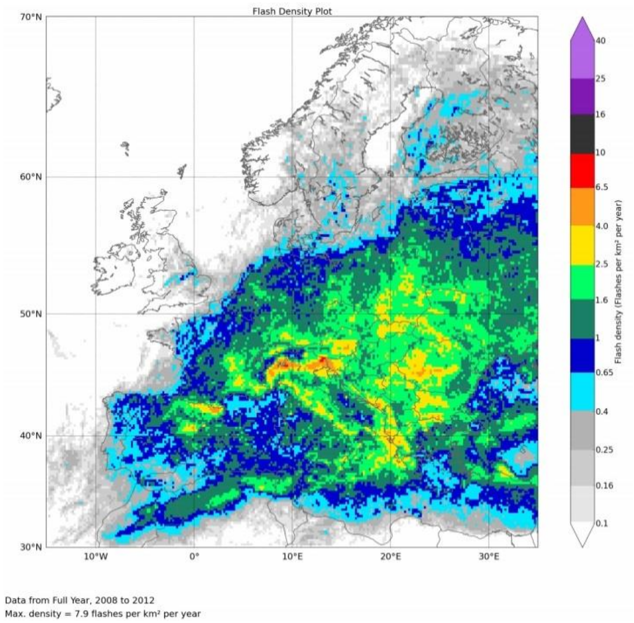

Figure 5-3 Annual detected lightning flash density

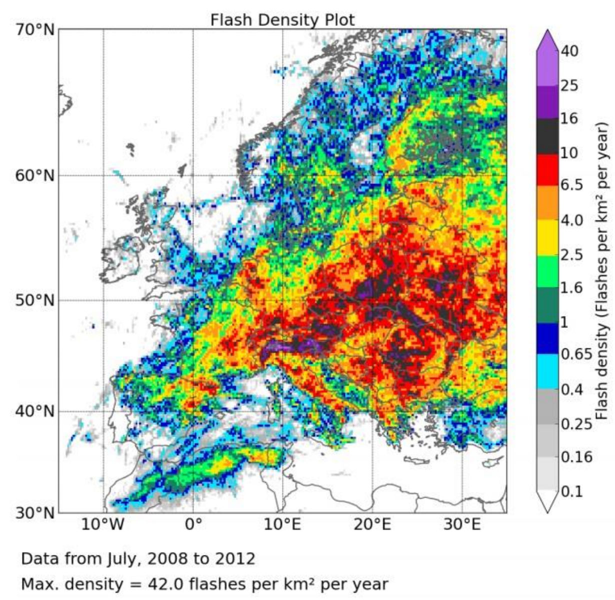

Figure 5-4 Detected lightning flash density for July

Finally in order to assess frequency of lightning strikes and to evaluate their effects, following category of data are required:

- Basic data: ground flash density per km^2 (or per another reasonable square unit which is suitable for further analysis) having particular magnitude (e.g. current peak, charge, specific energy etc.). Basic data should be site specific.
- Supplementary data: they are formed by additional internal and external data. Internal supplementary data are represented by layout of civil structures containing sensitive equipment as well as surrounding structures that can be affected by lightning impact, list of sensitive equipment's whose failures affect plant safety function and design and qualification of lightning protection system. Internal supplementary data should also contain location of outside objects that use or store flammable, explosive or poisoning materials.

  External supplementary data should cover list of external natural formations (forest, flammable fields) and industrial facilities where fires and/or accident could be induced by lightning strike and those are capable of affecting nuclear safety and/or performance of the plant/facility of interest.

The pre-conditions, its parameters and a uniform data taxonomy used in the formulas to evaluate lightning impact are summarized in the Table 5-3.

Table 5-3 List of basic data (parameters)

Nomenclature	Parameter description	Unit
$f(i_p)d_i$	The fraction of lightning flashes that have first return stroke peak currents (i_p) in the interval between i and i+d_i.	
h	Height of the structure	m
i_p	Peak current (prospective return-stroke peak current)	A
i(t)	Current pulse	A
N_g	Ground flash density - number of lightning flashes that strike a unit area in a given region in a year	[km^2 x $year^{-1}$]
T_d	Number of thunderstorm days - thunderstorm day is normally defined as the local calendar day in which thunder is heard by meteorological observers	
R	Attractive radius - R=f(i_p, h)	m
	Derivative of the magnetic field of electromagnetic field generated by first and subsequent return strokes	T/m

An important note is that among these selected basic parameters (Table 5-3) and also among the all 13 lightning parameters (quoted in table 3 of IEC 62305-1), a very few have available regional statistics. This shortcoming should be gradually eliminated with the development of lightning monitoring network.

5.2 EXTERNAL DATA SOURCES

In accordance with the recommendations of IEC 62858:2015 [41], the lightning density based on lightning location systems should be applied as primary input parameter for the evaluation of the lightning risk on buildings and structures using the methods of the IEC 62305-2 (Protection against lightning – Risk management) [11].

The lightning ground flash density N_G is defined in the Table 5-1 above. The number of lightning flashes to ground [km^2 *x* $year^{-1}$] is derived from data provided by LLS – network of lightning sensors that work together to detect and geolocate lightning events within the area of the system's coverage.

IEC 62858 defines the minimum level of quality acceptable for LLS. The lack of common rule for defining requirements either for their performance, or for the elaboration of the measured data, requests the application of measures to make reliable and homogeneous values of N_G obtained from LLS in various countries, like these presented in IEC 62858 [44]. Motivations for that are:

- the International Standard IEC 62858:2015 was approved by CENELEC as a European Standard without any modification, and
- IEC 62858:2015 is implemented at national level in EU on 09 June 2016 by publication of an identical national standard or by endorsement.

The application of the method based on the lightning ground flash density $N_{G,}$ requires lightning data from LLS for at least ten years and taking into account the changes in the global meteorology, the newest data used is not older than five years.

The value of the median location accuracy of LLS for CG strokes shall be better than 500 m in all regions in the territory over which N_G has to be computed, i.e. the grid should be with cells finer than 1 km x 1 km, by central position of the sensor in every cell.

In accordance with the IEC 62858 the lightning data (N_G in km^2 *x* $year^{-1}$) have to be evaluated as a raster map and the grid size shall be chosen in such a way that the dimensions of each cell (A_{cell} - area in km^2) and the number of years (T_{obs} - observation period in years) considered both comply with the minimum requirements obtained from Formula (3.2-1), as follow:

$$N_G \; x \; T_{obs} \; x \; A_{cell} \geq 80 \qquad (3.2\text{-}1)$$

i.e. following poisson distribution and the law of rare events, thus obtaining an uncertainty of less than 20% at 90% confidence level. In order to avoid edge effects for the smallest cell (which should be such that it contains at least 80 flashes), the N_G value shall be obtained by integrating a finer sub-grid of 1 km *x* 1 km resolution.

The performance characteristics of LLS can be evaluated using variety of techniques [43] which are more suitable for the studies of lightning properties, i.e.:

- network self-reference,
- video camera studies,
- inter comparison among networks.

In a further discussion for application of the above presented method for definition of the lightning ground flash density NG on the basis of lightning data from LLS, could be included also additional considerations, for examples:

- the locations of the LPS to be defined on the basis on the recommended in [51] distance between an LPS down-conductor and the protected object in air, which should be greater than D*air* given in meters:

$$D_{air} = 0.12Z + 0.1l \qquad (3.2\text{-}2)$$

where

Z is the impedance of LPS grounding system under direct lightning strike conditions and l is the distance between the point of interest and the LPS grounding system. For a point in the immediate vicinity of ground surface, $l \approx 0$ this reduces to $D_{air}=0.12Z$ (m)

- the distance between the LPS grounding system and buried metallic services to be greater than Dsoil given in meters by

$$D_{soil} = I\ Z/\ Eb \qquad (3.2\text{-}3)$$

where

I (kA) is the lightning peak current, and *Eb* (V/m) is the breakdown electric field in the soil.

Other theories for lightning striking distance versus return-stroke peak current are presented in the Figure 5-5.

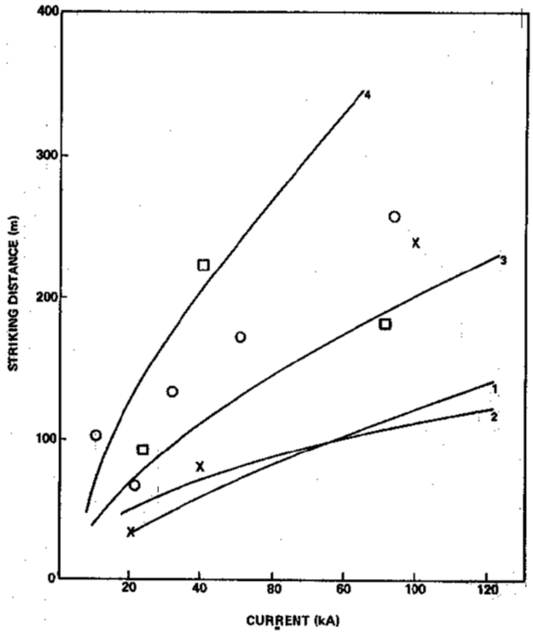

Figure 5-5 Striking distance versus return-stroke peak current

Curve 1, Golde (1945); Curve 2, Wagner (1963); Curve 3, Love (1973); Curve 4, Ruhling (1972)

x - theory of Davis (1962);
o - estimates from two-dimensional photographs by Eriksson (1978);
□ - estimates from three-dimensional photography by Eriksson (1978), adapted from Golde (1977) and Eriksson (1978).

So far as one or a combination of these techniques can be used for evaluation of performance characteristics of given LLSs, it is important that the identification and consideration of the influenced factors for strengths and weaknesses of the methods used in order to obtain reliable estimates of LLS performance characteristics.

Other approach for data gathering is to use the plant specific data for installations affected by lightning, which are the ideal, but have to be used only as partial data source, having low statistical significance, to determine frequency of lightning induced initiating events, it means events caused by direct or indirect strikes near power lines [14] etc.

Further options are formed by using isokeraunic maps or results of specific lightning measures that are produced by local meteorological institutes. Such data can provide histograms of annual frequency (lightning strike density) versus lightning intensity (peak current).

Last, the less desirable option is usage of generic data.

Sources of supplementary data containing information regarding safety significant equipment including their localization and lightning protection system can be found in plant detailed design documentation.

Sources of supplementary data providing information regarding external industrial facilities and natural formation (that can trigger lightning induced initiating event) are formed by external hazard analyses.

5.3 PLANT DATABASE

Plant database should integrate all data that are necessary to assess lighting hazard. Usage of database is not a necessary condition to perform hazard analysis. However such database facilitates central maintenance of all relevant data, helps to keep data consistency and integrity (i.e. ensures that all members of lightning team use the same data sources) and can provide significant support in documentation process.

Based on experience (due to the small overall number of occurrences) further it is recommended to monitor the area around the nuclear facility at least within 50 km, taking into account some examples, for instance in Sweden (Table 2-2), that even very distant lightning events may cause electrical disturbances.

6 LIGHTNING HAZARD ASSESSMENT METHODOLOGIES

This section introduces a basic methodology to evaluate parameterized frequency of lightning strikes as well as the approach on how to evaluate the impact of the lightning strike on plant's equipment. This section forms the back-ground data for fragility analysis. It considers reservation/understanding for incomplete detailed coverage from the basic methodology of the lightning effects. No existing methodologies assess the probability of all effects of the lightning. The approach in this report could be developed hereafter with ramification for each effect, how far it is useful and reliable about safety aspects.

Taking into account the ASAMPSA_E end user review comments, representative assessment of each lightning effect should use different types of models when best estimate data are lacking or when large uncertainties exist and there is a risk for outliers, as it is certainly the case with the different effects of lightning.

By considering each models, the attention have to be directed to design criteria or boundary conditions, specified for all or almost all external hazards and internal hazards, for barriers and safety system as well as for many non-safety systems important to safety.

Lessons learned from real events indicate clearly that the consequences of several external events are strongly related to the status and operability of non-safety systems.

From significant number of non-safety systems that have specific probability, as per Forsmark NPP, to fail in different kind of external events, for the lightning followings are underlined:

- External power supply and
- Non-safety classed power supply systems.

Both could certainly and with high probability be affected by lightning strike near to the NPP.

For such lightning cases one of the most important work for identifying initiating event scenarios in a PSA are to identify secondary failures during lightning that can initiate Common Cause Initiator (CCI) events which initiate scram and also degrade safety functions.

Some important comments have to be done on uncertainties for lightning PSAs.

The probability analysis of the lightning hazards is a new area with not enough suitable data. In general, the lightning damages are very limited and without any consequence on safety. The greater uncertainties are in variability of lightning (striking point and characteristics of lightning current) and the great difficulty is to demonstrate that there is no "weak point" in the lightning protection and that consequences will be always limited and acceptable. That's why, in practice, one may rely with greater confidence on engineering judgments and expert opinions.

Nevertheless, it is needed to specify uncertainties and to estimate any degree of conservatism implemented in the PSA parameters and shown in the result presentation of a lightning PSA, before any risk application. Practical problem for such assessment is that usually the available lightning data are too limited, hence for each specific NPP it is from to collect all possible lightning data observed in the country for possible long period back, a priori assuming that almost all of recorded lightning in the country could happen near NPP.

No doubt that the quality of lightning (uncertainties) data is a big challenge for lightning PSA development and will have to considered in PSA applications.

Process of considering lightning events in PSA faces two fundamentally different types of variability. First of them is fundamental to the phenomenon parametrization - annual frequency occurrence of event having particular magnitude. Second variability can be formed by incomplete knowledge about the representation and evaluation of impact of lightning - fragility analysis.

This section covers both frequency assessment and fragility analysis.

6.1 PARAMETRIZATION AND LIGHTNING STRIKE FREQUENCY ASSESSMENT

This section covers two basic areas i.e. frequency assessment and robust screening.

Characterizing a complex hazard phenomenon by a single parameter like frequency is generally inadequate. For example even if map presented in the next figure provides information describing lightning distribution this information is insufficient to evaluate potential impact of lightning strike on a particular facility.

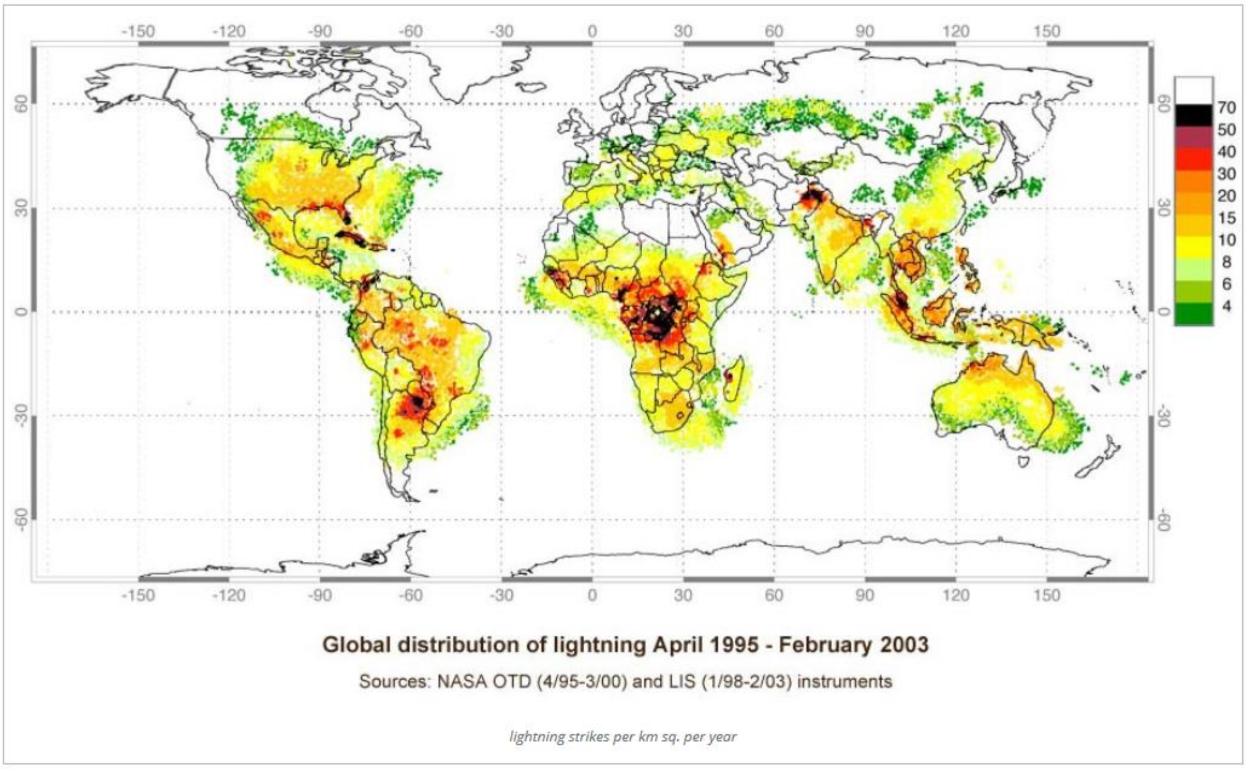

Figure 6-1 Global distribution of lightning April 1995 - February 2003

Effects of lightning are connected to following parameters, described in Table 3-3 above:

- N_g (ground flash density)
- Imax (peak current)
- Di/dt (current derivative)
- W (specific energy)
- Q (charge)

The basic parameters that are used to describe lightning hazard and form input for the response analysis are N_g and i_p. They are usually presented in the form of a hazard curve. Such hazard curves can be based on generic or plant specific data. The uncertainties in the intensities values are represented by developing a family of hazard curves having assigned probability to each hazard curve. The summation of probabilities assigned over the family of hazard curves is unity.

In general it is assumed that N_g has normal distribution and i_p lognormal distribution. These theoretical distributions of lightning parameters are very useful and effective around average values. But for higher values of lightning parameters, they get false because they tend to zero at infinity, but it is known that the real values of lightning are finite because of the limited thickness of troposphere.

So, the event analysis using classical values of lightning parameters is possible with these lognormal distributions, but not to evaluate extreme events frequencies. The latter should be treated another way.

6.1.1 DEVELOPMENT OF GENERIC HAZARD CURVE

Generic hazard curve relies on number of storm days or on generic values of N_g, e.g. table 3.3. Peak current i_p can be based on IEEE data -Figure 6-2 from [18]. It is noted that this curve is valid only to 200 kA.

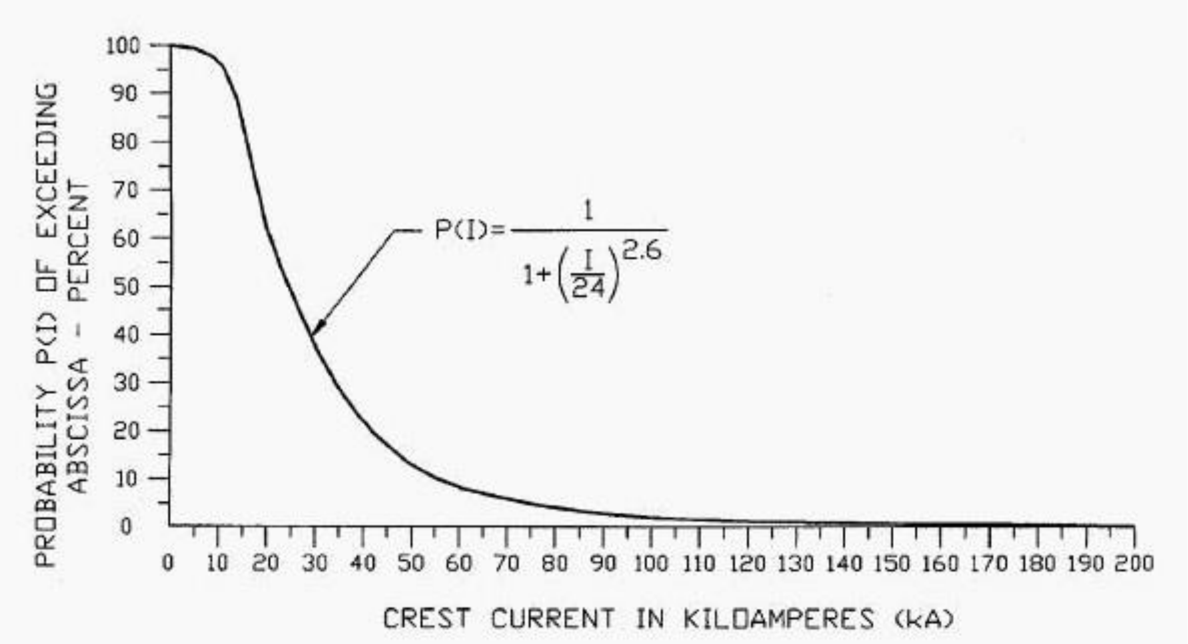

Figure 6-2 Probability of stroke current exceeding abscissa for strokes to flat ground

Better estimation can be achieved by the peak-current distribution of negative ground flashes suggested by IEEE, obtained by Berger can be approximated by two straight lines (when plotted by probability) intersecting at 20 kA. The median value of strokes to Overhead Ground Wires (OHGW), conductors, structures, and masts is usually taken to be 31 kA (Anderson, 1987).

Typical output of lightning hazard curve is presented in the picture shown in Figure 6-3.

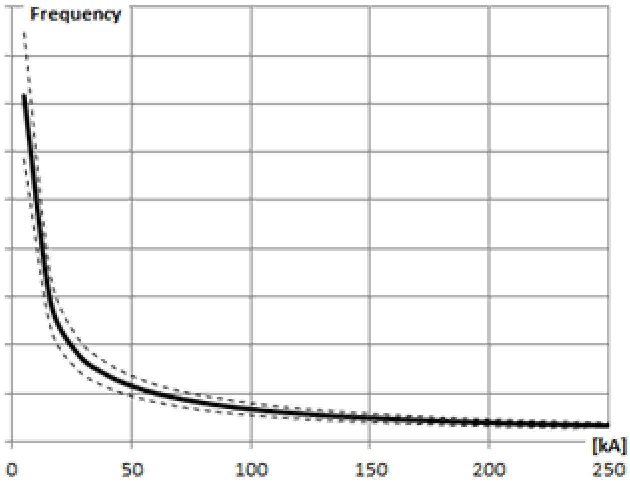

Figure 6-3 Curve of exceedance frequency versus lightning intensity

Hazard curve can be generally expressed in terms of a limited number of discrete ranges of variables.

In general frequency of initiating event for particular interval from discretized hazard curve will be expressed as follow:

$$F_{i_n} = P_n \cdot \sum_{j=0}^{N} Q_{j_n}$$

Where

F_{in} Frequency of i[th] initiating event for n[th] bin of discretized hazard curve

P_n Frequency of occurrence n[th] CI from discretized hazard curve

Q_{jn} Conditional probability of damage of j[th] by n[th] CI which leads to initiating event F_i; e.g. see E-1.

6.1.2 DEVELOPMENT OF SPECIFIC HAZARD CURVE

The lightning strike frequency assessment can be based on site specific data or on appropriate generic data.

The assessment based on site specific data can use the approach consists from direct evaluation if there is available plant history, i.e. number of failures over number of all events. It is obvious that this one is a rare and hardly applicable case requiring rich plant history and specific equipment for lightning registering.

In the assessment based on generic data, the basic inputs for hazard analysis are lightning strike density (e.g. per km^2) and data describing lightning intensity. Such estimations should take into account quality and efficiency of registration stations, e.g. 80% efficiency introduces substantial variability into gathered data. These data are organized into histograms containing intensity of lightning strikes versus annual frequency. Such data enables interval estimations frequency as well as bound estimation of intensity. In this case the lightning damage potential can be expressed by lightning intensity and current in kA, and consists in processing of the site specific meteorological data.

6.2 FRAGILITY ANALYSIS

The fragility analysis generally is considered as conditional probability that one or all components will be damaged by impact of lightning, or in particular from specified phenomenon of lightning, but the aim of lightning fragility analysis within this report is mainly to estimate conditional probability of occurrence of particular initiating event determined.

However, it is obvious that (under scope of this report) such event can be evoked only by lightning damage of particular components. Given the different possible effects of a lightning strike due to different phenomena (IEM; direct strike; EMIn; ESIn), should be further develop how to assess the fragility of all important enough components for safety, if is possible for each type of phenomena. For instance for one component (e.g. cable), should be clarified what are the specific features to analyse the fragility at a given level of lightning intensity. In addition the efficiency of the protection system as a function of type and fragility of components and peak current value shall be clarified.

Conditional probability of SSC failure (P_{cf}) can be expressed as:

$$P_{cf} = F_s \cdot P_{i_p} \qquad \text{E-1}$$

Where

F_s represents frequency probability that SSC or relevant area is affected by lightning strike (or lightning strike side effect) having particular i_p

P_{ip} represents probability that SSC is damaged by effect evoked by lightning current i_p

There are discussions concerning the applicability of the IEC 62305, in particular should be or not rely on 62305-2 risk assessment for NPPs sites. The cited reasons of the basis of experience of EDF [44] are:

i. IEC 62305-2 doesn't address safety related questions;

ii. IEC 62305-2 calculations are not adapted for nuclear sites. EDF compared 62305-2 risk assessments with experience and real damages on its nuclear fleet, and published the results in ICLP 2014 in Shanghai [44]. The conclusion there is that the standardized calculation overestimated the risk of a factor 100 to 1000, and consequently that 62305-2 risk assessment could not be used on nuclear sites to evaluate risk, nor to select lightning protection, because identified weaknesses are just calculation artefacts.

It is possible in the next edition of IEC 62305-2 (2018), nuclear power plants to be retired from the scope of the standard, but for the present there is no common ground to reject the application of existing IEC 62305-2.

Following sections introduce probabilistic approach based mainly on the individual parts of the IEC 62305 which are [10], [11], [12], [13] and [14].

Lightning current limit i_p of high-risk considered by quoted standards is 200 kA, which is also indicated in almost all available literature as the most likelihood case covering 99% of lightning strikes. This limit is also taken as design the basis for lightning protective measures, e.g. earthing, shielding etc. Even if those 99% are not strictly scientifically proven, the use of such a high value of 200 kA design brings security to the protection.

6.2.1 ASSESMENT OF PROBABILITY THAT SSC OR RELEVANT AREA IS AFFECTED BY LIGHTNING STRIKE

Assessment of probability that SSC is affected by lightning strike or lightning strike side effect having particular i_p, depends on location of SSCs of interest. SSCs can be located on terrain as pipe and grid lines or are built in civil structures as I&C systems. If we assume ground flash density used to develop hazard curve is distributed over basic unit area uniformly[1] than frequency / probability that relevant area A is affected by lightning strike can be estimated as

$$F_s = F_{i_{pI}} \cdot A \qquad \text{E-2}$$

Where

$F_{i_{pI}}$ frequency of lighting strike having peak current i_p

A relevant area

If F_s for alone building in flat terrain is estimated then modified approach based on IEC 62305-2, Annex A [11], can be used where A is replaced by so called effective area A_e.[2]

$$A_e = length \cdot width + 6 \cdot height \cdot (length + width) + 9\pi \cdot (height)^2$$

There is two basic cases: relevant SSC can be located in or part of civil structure which is protected against direct strike or SSC is in area which is unprotected against direct strike, e.g. heating pipe line, small tanks etc.

Consequently:

A. If SSC is located in area which is not protected against direct lightning strike then F_s estimation is based on equation E-2

B. If SSC is located in area which is protected against direct lightning strike then F_s estimation is still based on equation E-2 but i_p can be adjusted according level protection features -Table 6-1

It is necessary to take into account that lightning protection as such is based on IEC requirements. IEC distinguishes 4 levels of protections and uses several methods as rolling sphere and angle methods.

Table 6-1 Positioning of air terminals according to the protection levels defined by the IEC standards

Protection level	Critical minimum prospective return stroke peak current (kA)	Efficiency of protection (%)	Rolling sphere method: sphere radius, *R* (m)	Protective angle method for different heights of terminals: protective angle, α (°)				Mesh method: maximum distance, *D* (m)
				20	30	45	60	
I	3	99	20	25	*	*	*	5
II	8	97	30	35	25	*	*	10
III	10	91	45	45	35	25	*	15
IV	16	84	60	55	45	35	25	20

*Not defined.

[1] However; considering uniform distribution can be in some cases unreasonable due to geometry of civil structures because tallest structure will attract more flashes, i.e. it can lead to underestimation of some structures and to overestimatiom flates part of examined area.

[2] Document [43] presents equation $A_e = length \cdot width + 2 \cdot height \cdot (length + width) + \pi \cdot (height)^2$

A structure lightning protection system based on level I would not allow a return stroke peak current larger than 2.9 kA to penetrate the lightning protection system. The corresponding currents for levels II, III, IV are 5.4, 10.1 and 15.7 kA, respectively. Further text brings basic information regarding typical lightning protection systems.

Protection zones formed by high buildings

In general different altitude of each building in the examined area will attract a variety of lightning, depending on their intensity. This can create protection zones, where the taller buildings (chimney, cooling tower) download lightning current through its air-termination system (see figure 6-8) and thus prevent either direct threat to an important object or mitigate the effects of electromagnetic fields on the building with sensitive equipment. A good guide can be found in [18].

Several methods are published to calculate this strike distance (protection area), in other words the length of the upward discharge, e.g.:

Darveniza [20]	$S = 2 \cdot i_p + 30 \cdot \left(1 - e^{-\frac{i_p}{6,8}}\right)$	
Love [19]	$S = 10 \cdot i_p^{0.65}$	
Whitehead [23]	$S = 9.4 \cdot i_p^{2/3}$	
IEEE [21]	$S = 8 \cdot i_p^{0.65}$	E-3
Suzuki [22]	$S = 3,3 \cdot i_p^{0.78}$	

It is obvious that results calculated with the higher ip can differ significantly. Therefore, it is recommended to use E-3 by standards.

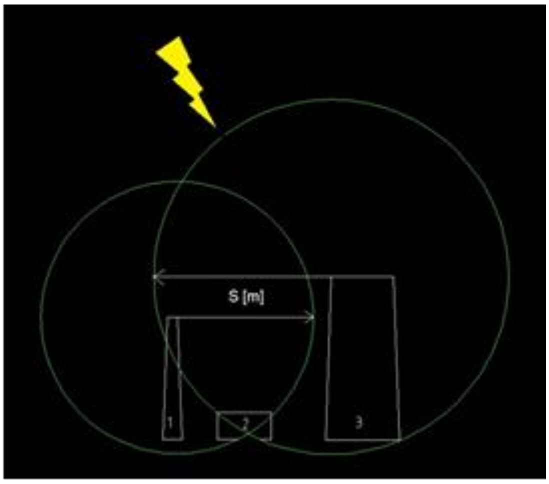

Figure 6-4 Protective features of neighbouring buildings

1-chimney, 2-building containing sensitive equipment, 3-cooling tower

In such way, one can determine the size of the protection zone. Above presented picture demonstrates a protective effect of neighbouring buildings. Graphical representation of the size of the radius of the protective sphere in dependency on lightning intensity is shown in the next chart.

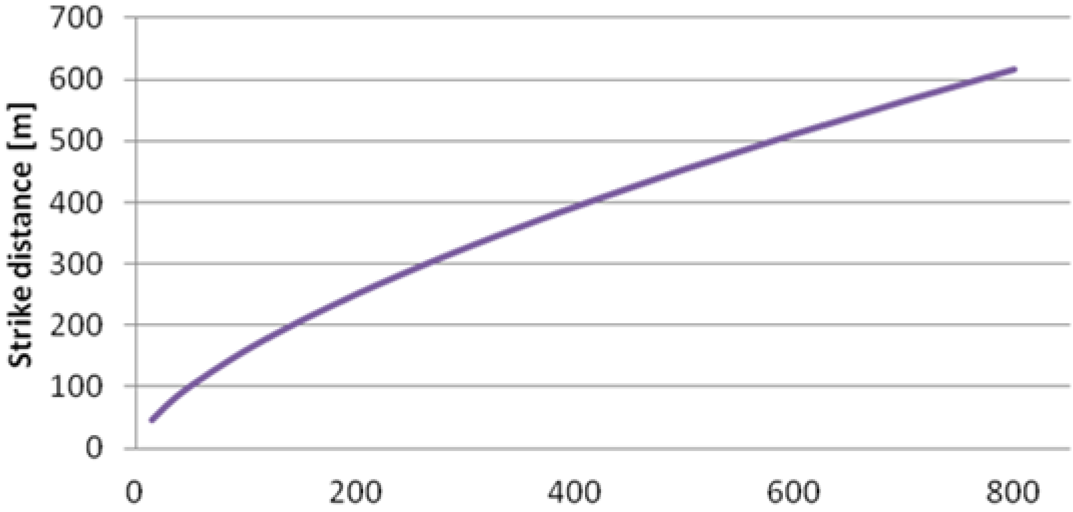

Figure 6-5 Strike distance dependence on the ip [kA]

This assumption can be used to screen cases when sensitive buildings can be hit by direct lightning strike, independent that these are in the protection zone of the others high buildings and the air-common protection zone is not interrupted.

Side effect of such protective features is that the level of electromagnetic field created by a lightning strike to neighbouring building will be around and inside of building containing sensitive equipment much lower. On the graph, can be seen attenuation of the intensity of the magnetic field depending on the distance from the strike point.

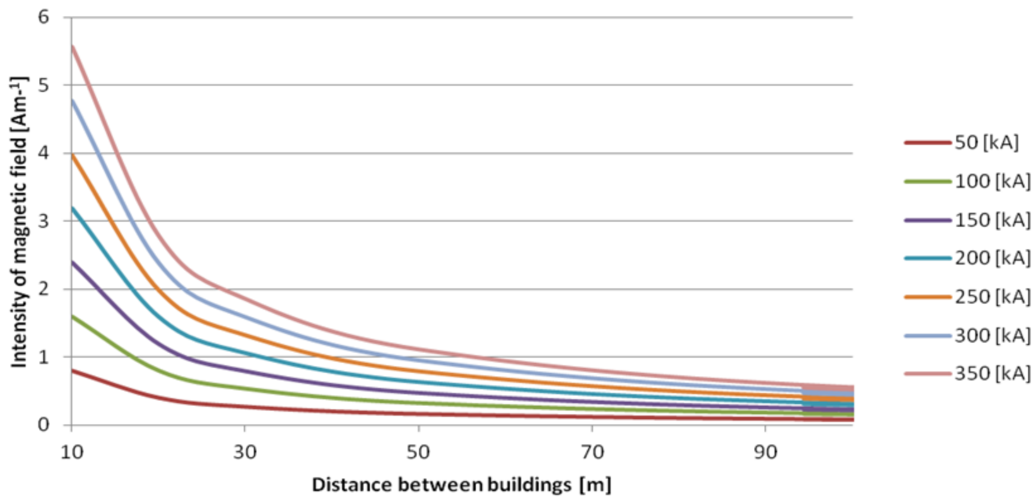

Figure 6-6 Intensity of magnetic field as a function of the distance between buildings

This graph demonstrates decrease of the intensity of the magnetic field depending on the (air) distance according intensity lightning. This effect ensures fast decreasing magnetic field created by lightning to the design level event if initial strike exceeded more than 200 kA. However, necessary conditions are appropriate level of lightning protection system.

This attenuation depends on the construction of the building itself (e.g. building material steel or reinforced concrete etc.).

Rolling sphere and Protective angle

Almost in all countries, e.g. Bulgarian regulation [41], those methods are used. Their application is fully driven by IEC standards. In general rolling sphere and Protective angle/cone methods are used to determine position and height of the air termination rods.

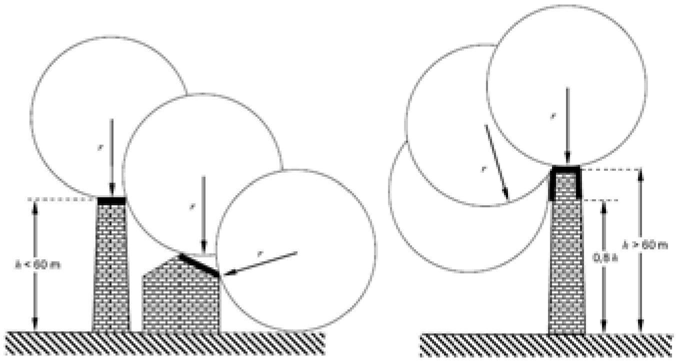

Figure 6-7 Determination of lightning zone by method of the "notional/fictitious rolling sphere"

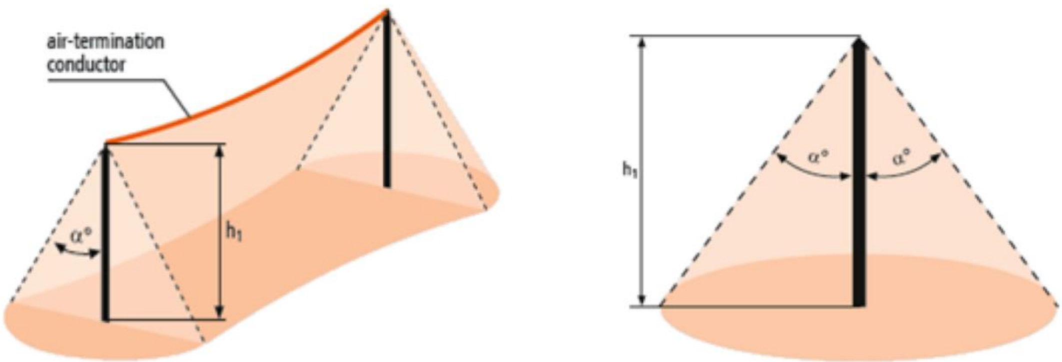

Figure 6-8 Protective angle/cone - Volume protected by an air-termination conductor

When assessing the risk from lightning, the level of the lightning protection depends on two components:

- R_D - component related to direct lightning strikes on the protected object, referring to physical damage as a result of dangerous arcing at the site, leading to a fire or complete or partial demolition of buildings and outdoor facilities;

- R_I - component related to direct lightning strikes on networks for public services related to the protected object, referring to physical damage (fire or total or partial destruction resulting from dangerous arcing between internal fittings and metal parts, which are usually located at the input of public service networks in the protected object) arising from lightning currents carried through or incoming public service networks.

The calculation of the needed level of the lightning protection is dependent on the calculated value of R_D for the relevant types of the damages.

Table 6-2a Level of the lightning protection

Levels of the lightning protection	Value of R_D
I	0,02
II	0,05
III	0,1
IV	0,2

According to HSE (Failure Rate and Event Data for use within Risk Assessments (28/06/2012) [53] the following formula is used to calculate the number of dangerous events for the structure:

$$N_D = L_{gfd} \times A \times F_{loc} \times 10^{-6}$$

where:

L_{gfd} = lightning ground flash density (/km^2/year)

F_{loc} = location factor of the structure (see table below)

A = area of interest (m^2).

The value of the correction factor F_{loc} is:

- 0.25 - Surrounded by higher objects or trees
- 0.5 - Surrounded by objects or trees of the same height or smaller
- 1.0 - No other objects in the area
- 2.0 - No other objects in the area and on top of a hill or knoll

HSE [53] includes two additional items in the above Table 4.2a, namely shown in Table 4.2b.

Table 6-2b Level of the lightning protection

Levels of the lightning protection	Value of R_D
I	0,02
II	0,05
III	0,1
IV	0,2
Air-termination system conforming to LPS I and a continuous metal or reinforced concrete framework acting as a natural down-conductor system.	*0,01*
Metal roof or an air-termination system, possibly including natural components, with complete protection of any roof installations against direct lightning strikes and a continuous metal or rein-forced concrete framework acting as a natural down-conductor system.	*0,001*

The radius of the notional/fictitious rolling sphere is determined depend on the level of the lightning protection:

Table 6-3 Radius of the notional/fictitious rolling sphere

Levels of the lightning protection	Radius of the notional/fictitious rolling sphere, m
I	20
II	30
III	45
IV	60

The approach for estimation of probability of failure of relevant components used in [41] is similar as presented in the section 4.2.2.

One other approach for definition of the protection zones of high buildings is demonstrated in KTA 2206 [61]. The lightning current parameters specified in Table 4-1 above together with the next Table 6-4 shall be used as basis for demonstrating the protection against lightning-based power surges.

Table 6-4 Parameters for longer duration lightning currents

Height of Structure (Type of Lightning)	*Parameter*	*Symbol*	*Unit*	*Value*
h > 60 m	charge of the longtime current	Qi	C	400
	duration of the longtime current	t	s	0.5
h < 60 m	charge of the longtime current	Qi	C	200
	duration of the longtime current	t	s	0.5

Then, for above defined Level 1 protection category – applies (is required) to buildings that contain electrical facilities relevant to safety, and also is required to buildings that contain facilities of the plant-operation related I&C if their malfunction might lead to impermissible adverse effects in safety-related plant components, the determination of the Lightning-strike Protected Areas of Level 1 Protection Category Buildings comprises:

i. Determination of the lightning-strike locations and the lightning-strike protected areas by the rolling sphere method using a radius of 20 m. By this method must be considered that the electrical equipment located outside of the determined lightning-strike protected area may be subject to direct lightning strikes with a reduced crest current value.

ii. The design of protective measures with respect to their maximum current conductivity may be based on the crest current value of an initial lightning strike at the radius of the lightning sphere in accordance with Table 6-5

Table 6-5 Correlation of the crest current values to the lightning sphere radius

Radius of Lightning Sphere	*Corresponding Crest Current Value of the Initial Lightning Strike*
20 m	3 kA
30 m	6 kA
45 m	10 kA
60 m	16 kA

6.2.2 ESTIMATION OF PROBABILITY OF FAILURE OF RELEVANT COMPONENTS

Based on E-1 the purpose is to estimate value of P_{ip} representing probability that SSC is damaged by effect evoked by lightning current i_p. Generally two methods can be used:

- Approach based on IEC
- Analytical approach.

6.2.2.1 Approach based on IEC

Approach based on IEC brings significant simplification of work. This approach is based on the assumption that evaluated object has implemented appropriate lightning protection level which was discussed in section 6.2.1. IEC approach can be used only for the cases when i_p does not exceed 200 kA. Consequence of IEC approach usage is that probability of damage is the same for i_p in range $\langle 0; 200)$ kA.

IEC use risk categories R that correspond with P_{i_p} from E-1.

The primary cause of damage is the lightning current depending on the location of the flash. The standard [11] states four strike locations and three kinds of damages. Consequently combination of targets and kind damages can evoke several types of losses. For the purpose of this report are relevant only following of them:

R_B - damage caused by hazardous sparking inside the building, which can initiate fire or explosion – covers the case of lightning strike to the analysed building

R_C - failure of internal systems due to LEMP – covers the case of lightning strike to the analysed building

R_M - failure of internal systems due to LEMP – covers the case of lightning strike near analysed building

R_V - damage caused by the lightning current transmitted over or along the inlet of utility networks – covers the case of lightning strike near analysed building

R_W - failure of internal systems due to surges induced into the supply line and transferring into the building – covers the case of lightning strike near analysed building

R_Z - failure of internal systems due to surges induced into the supply line and transferring into the building – covers the case of lightning strike close to the lines (structures) connected to the analysed building

Each of the mentioned items, R_B, R_C, R_M, R_V, R_W, R_Z, can be estimated by the using following equation:

$$\boldsymbol{R_x = N_x \cdot P_x \cdot L_x} \qquad \text{E-4}$$

where:

Nx – the number of dangerous events per year, i.e. frequency of event assessed in section 3.1

Px – the likelihood of damage of buildings internal structures which is evaluated according standard [11] and depends on level of building LPS as well as on LPS of individual devices, quality of shielding, design of ground system etc.

Lx – resulting loss term wraps further individual factors that influence potential damage.

Equations to estimate particular R are:

$$R_B = N_D \cdot P_B \cdot L_B$$

$$R_C = N_D \cdot P_C \cdot L_C$$

$$R_M = N_M \cdot P_M \cdot L_M$$

$$R_V = (N_L + N_{Da}) \cdot P_V \cdot L_V \qquad \text{E-5}$$

$$R_W = (N_L + N_{Da}) \cdot P_W \cdot L_W$$

$$R_Z = (N_I - N_L) \cdot P_Z \cdot L_Z$$

Further details can be found in [11] and its specific annexes. Various free software utilities based on this standard to facilitate calculations can be used, e.g. "IEC Risk assessment calculator" or "Lightning risk assessment calculations" and more.

The previous approach enables quite convenient and fast evaluation of potential impact on lightning event. However, such evaluations can be far conservative because they do not take into account intensity of lightning (i.e. any category of LPS protections has the same effect on the results of evaluation of R_x, without considering real value of electro-magnetic field induced by lightning) and are much suitable for screening purposes.

4.2.2.2. Analytical approach

If area of interest cannot be screened out, detailed fragility analysis shall be performed. However this analysis is a very specific activity that should be performed by trained electro-engineers.

Lightning creates a very wide frequency range electromagnetic field. Calculations propagation and attenuation field contains lots of parameters (e.g. Frequency, current, impedance permeability, holes on the panels, use of shielding, grounding etc.).

Basic method to carry out such work can be described as follows:

The estimation of magnetic inductance evoked by lightning strike is obtanined by the following equation.

$$M_I = {}^{I_p}/_{2\pi \cdot d} \qquad \text{E-6}$$

where:

I_p - Intensity current of lightning strike

d - distance

A reduction in magnitude of electromagnetic field strength is commonly referred to as Magnetic Field Attenuation. This reduction can be measured and expressed by decibels (dB). When shielding materials are introduced they provide this magnetic field attenuation by absorption, reflection, scattering and dispersion.

Calculated magnetic field attenuation can be represented as:

$$Attenuation(dB) = 20Log\frac{E_1}{E_2} \qquad \text{E-7}$$

where:

E1 = Field intensity generated on one side of the shield.

E2 = Field intensity received on the other side of the shield.

Of course this assessment is a complex topic; indeed, without providing some attenuation data equation E-7 is unusable. Therefore, it is important to consider how to solve this topic at least for some specific cases.

The application of the IEC 62305-2 in the methodology above may not guarantee absolute coherence of terms, concepts, etc., for example flat terrain and corrections to the heights of buildings, but this standard allows enough good assessment for practice nowadays.

However, the above approach is a great simplification. The description of other different methods can be find in [24] to [28]. Based on these documents, one cansay that there is no standardized procedure to calculate life expectancy (or expectation for damage) of the surge protection device and each manufacturer offers his own method based on his experience for calculation life expectancy (or damage).

In addition, it is possible to use, for example, the individual parts of IEC EN 61000 family. The main directive for EMC is Directive 2004/108/EC [29] relating to electromagnetic compatibility and repealing Directive 89/336/EEC and its modifications Directive 92/31/EEC, Directive 93/68/EEC [CE Marking], Directive 91/263/EEC [TTE/SES].

7 CORRELATED HAZARDS AND COMBINATION OF HAZARDS

7.1 COMBINATIONS IDENTIFICATION

Background for this analysis here could be the segmentation of the correlations proposed in D21.2 [45] in two groups:

i. Causally connected hazards (cause-effect relation) where one hazard may cause another hazard; or where one hazard is a prerequisite for a correlated hazard.

ii. Associated hazards that are probable to occur at the same time due to a common root cause.

The physical essence of the phenomena lightning is connected with the violation of the balance in the distribution of electrical charges in the atmosphere, usually in the condition of storm. A strong upward air flows with an intense condensation of water vapor and spray water droplets accumulate electrical charges in the clouds, increasing the intensity of the electric field.

Therefore a storm activity is a prerequisite for a correlated lightning hazard, but the storm is not always followed or accompanied by lightning.

In its turn the lightning strikes very often cause large spectra of external initiating events like accidents of industrial facilities, wild fires, power grid disturbances, etc. [45], [46] and similar internal events on NPP site also.

So, practically the lightning almost always is in a chain of causally connected hazards and usually is in the middle or somewhere in the chain of the hazards.

Of course the lightning has to be considered and in the second group of the associated hazards which are probable to occur at the same time due to a common root cause, for instance the storm can cause apart from lightning and flooding. More comprehensively, the lightning can be accompanied by another danger for the NPP site, for instance storm in the vicinity of the NPP causes lightning and at the same time there is flooding at the NPP site due to other reasons upriver on the banks of which is located the NPP. This combination could be considered as combination of independent phenomena, i.e. it is a supplement to the correlation chart presented in D21.2 [45] where are not specified such combinations.

The assessment of the number of hazards correlated with meteorological events in D21.2 [45] is 12 for the lightning. This makes the lightning the fourth in the list of the most correlated hazards (after high wind, tornado and low air temperature), i.e. the lightning usually should be considered in combination with other hazards for NPP, including in the extended PSA.

The explanation for the gaps concerning the lightning hazard in the correlation chart presented in D21.2 (there for lightning is shown only associated hazard with flash flood –both events derive from common root cause) is that in the chart are listed only direct consequences of individual hazards, and are not considered causal chains, as is usually the case of lightning combinations of other hazards.

Nevertheless, generally for the purpose of PSA, the main hazards that should be considered as correlated/combined with lightning events, are the following:

- heavy rain and wind due to storm activity,
- forest fires,
- agriculture fires (stubble, bale of hay, feeds, etc.),
- transport fires and explosion on the roads located nearby to the NPP site,
- pipeline explosion and fires,
- internal fires induced by direct lightning strike or as a side effect of indirect strike,
- releasing of poisoning substances, etc.

This has to be underlined that an accident of industrial facilities which failure as result of lightning can affect safety systems and conditions of the analyzed NPP.

Concerning combinations of external events in general, there is not enough evidence of simple correlation between lightning strike and induced external events. May be a partial exception is formed by wild fires, but ignition of wild fire by lightning strike depends on many factors as season, humidity etc. Concerning the correlation between the lightning strike and induced internal events of NPP site, it cannot for sure to be claimed, even back, if there are failures or low efficiency of the lightning protection which is implemented at the plant.

Example for confirmation of this understanding could be found in the Regulatory Approach for Fire Protection in NPPs of Germany [62]. This approach is based on German Guide “Probabilistic Safety Assessment (PSA) for Nuclear Power Plants” and its supplementary technical documents on PSA Methods and Data (from 2005), nuclear KTA fire protection standards which have been updated accordingly in the recent past, the enhanced nuclear standards “Fire Safety in NPPs” – KTA 2101 (2) and in correspondence with KTA 2206 (2009-11) Design of Nuclear Power Plants against Damaging Effects from Lightning [61].

This approach underlined following event combinations of anticipated events and consequential fires which have to be considered:

i. Component failures and consequential fire including high energetic faults of electric and mechanic components as well as of pressurized pipework and vessels

ii. Plant internal explosion and consequential fire (with additional requirements in KTA 2103 standard on explosion protection)

iii. Earthquake and consequential fire (with additional requirements in KTA 2201 standard series on seismic protection)

iv. Lightning and consequential fire (with additional requirements in KTA 2206 standard on lightning protection)

With accent to the nuclear safety, independently, but simultaneously occurring fires and other anticipated events have to be considered as follows:

- "Directly" (i.e. 1 week) after an anticipated event fire protection means needed to ensure the required function of those items important to safety after such an event have to be made operable again or replaced by suitable other means
- For the following anticipated events these requirements are assumed to be met: internal or external electromagnetic interference (EMI).

Obviously, assuming this a good approach with focus to nuclear facilities as priority have to be assess how lightning hazard is considered in the design of NPP and relevantly in the PSA for the specific NPP.

A storm can produce several lightning strikes that simultaneously hit several relevant safety targets, but even if lightning activity is well mapped, there is no known case of some storm that produced several simultaneous lightning strikes in small area. On other hand taking into account:

i. Practically from different lightning' effects (primary and secondary) and several types of fault can be affecting the electrical net and equipment of NPPs as disturbances in the voltage, frequency or phase angle. Relevant effects have to be considered also for the electronic and computer systems, communication systems and digital I&C systems.

ii. Usually the lightning stroke is multiple (not a single discharge and several discharges one after another) and multiplex or a lot more strokes (sometimes their number is several tens) and the mechanism of the stepped leader permits the discharge to develop to the huge distances [65], [66]. Hence it may not have multiple simultaneous lightning near one NPP, but in almost all cases there will be multiple strokes by a storm caused lightning,

And finally the impact of the lightning should be considered as a combination of hazards, especially as effects to the electronic and computer systems, communication systems and digital I&C systems of the NPP.

Not so thorough, simplified and more restricted in the general case of PSA could be accepted that the lightning event does not require specific consideration regarding correlation and combination of hazards. In order to simplify the PSA could be consider for instance if the electronic and computer systems, communication systems and digital I&C systems of the NPP have very good protection systems and to consider the lightning as hazard only for mechanical damage of the constructions. But in specific cases, when there are conditions around the plant characterised with availability of forests or technical facilities which can have a fire hazard, different methods should be used for the assessment of hazard combinations.

7.2 METHODS FOR THE ASSESMENT OF HAZARDS COMBINATIONS

7.2.1 INTERNAL FIRES AND RELEASING OF POISONING SUBSTANCES

Fires induced by direct lightning strikes can occur if when large oil cooled transformers and their lines or storages of flammable or explosive substances are hit, e.g. hydrogen storages. Conditional probability of such fires can be assessed on using so called geometric probability if density of lightning is known. The same methods can be used for releasing of poisoning substances.

Conditional probability of fires ignited by side effects of lightning can be assessed by using guideline given in [11] concretely by R_B, see section 6.2.2.1.

7.2.2 ACCIDENTS OF INDUSTRIAL FACILITIES

Assessment of conditional probabilities of Accidents of industrial facilities requires considering the same methods as are discussed within sections 3 and 4 (e.g. accident of relevant industrial facility can be induced wild fire that was induced by lightning).

7.2.3 FOREST FIRES

The forest fires form quite complex topic because occurrence and sustainability of lightning ignited fires depend on many factors – environmental variables that are used in various mathematical models applied to predict lightning fire occurrence. It should be noted that topic of "forest fire" can be freely extend in many other area where natural fuel can be ignited by lightning strike, for instance in the agriculture areas [31].

Based on resources quoted in this part, common models to predict lightning fire occurrence are ordinary least squares regression, binary logistic regression, cellular automaton, weights-of-evidence, generalized linear, negative binomial regression models etc. Most of these models have their limitations for general application. Examples of environmental variables are:

- daily average maximum temperature in the day period before the ignition [°C]
- rainfall in the 3 days before the ignition [mm]
- daily average relative humidity in the day period before the ignition [%]
- daily average wind speed [m/s]
- number of strikes on the day of the ignition
- lightning current intensity for all strikes [A]
- neutralized charge amount for all strikes [C]
- return stroke duration [ms]
- lightning energy for all strikes [J]
- category of forest fuel type of ignition
- topography defined by Altitude [m], Slope[%] and Aspect [%]

Further details could be found in different references [32] to [35]. The information from them shown that forest fires form specific topic and probability of forest fire ignited by lightning strongly depends on seasonal and local conditions. For example there is power-law relationship between the size of the area burnt, A, and how often fires of that size occur [34]:

There is indicated that lightning-fires account for about 90% of the total area burnt during the available period of data, even though they only account for about 30% of the total number of fires which occurred. This disproportionality can (partly) explained by difficult access to the fireplaces in mountain terrain.

Interesting general observation is that the average chance of fire per stroke is thus estimated to be ~0.4%, which represents an average chance of fire per flash of ~0.6%, given that there are about 1.5 strokes per lightning flash on average (in studied case) [34]. This value is within the typical range of values reported for other parts of the world by giving average values data for Canada 2%, British Colombia in Alberta 0.07%, Finland 0.015% [33], [36]. However, there is none general common method how to estimate general probability of lightning induced fires and regional research shall be always performed. As example this statement is demonstrated in the map shown on Figure 9-3.

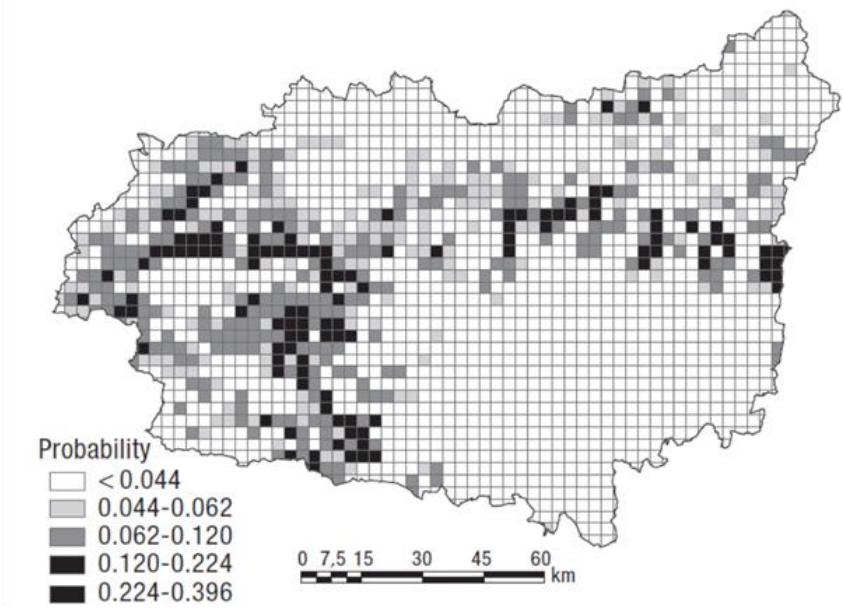

Figure 9-3 Spatial distribution of the probability of occurrence of lightning-induced fires in the province of León for the 2002-2007 periods (Probabilities were based on the logistic model)

7.2.4 METHODS FOR HAZARD COMBINATIONS

In terms of hazard combination frequency evaluation, the nature of combination has to be taken into account. As it was derived in D21.2 [45]: "Hazard c*orrelations discriminate between: (1) causally connected hazards (cause-effect relation) where one hazard may cause another hazard; or where one hazard is a prerequisite for a correlated hazard, (2) associated hazards which are probable to occur at the same time due to a common root cause*" and in additional, hazard combinations of independent phenomena have been denoted.

Subject to its applicability not specifically and totally exhaustive for study of hazard combinations, here below are presented two known methodologies, adapted for lightning hazards, as follow:

7.2.4.1 IAEA Fault Sequence Analysis (FSA) Methodology

IAEA developed a complementary safety analysis FSA methodology and supporting tool to assist in evaluation of the impact of extreme events on NPPs [54] [55]. This method utilised both probabilistic and deterministic safety assessment methods to gain the insights of robustness of plant protection including impact on SSCs against the extreme external hazards and its combinations. The method also considers combined load conditions resulting from the simultaneous occurrence of these hazards. Fundamentally, the FSA method incorporates 'stress test' principles that have been performed in Europe after Fukushima accident. The method considers sufficiency of defence-in-depth provisions, including various dependencies, safety margins, application of specific design features, cliff edge effects, multiple failures, prolonged loss of support systems and the capability of safety important systems for long term operation [55].

After the Fukushima accident, the FSA method was addressed to answer of the question - are current safety analysis approaches sufficiently comprehensive and consistent to reveal possible Fukushima-like scenarios, specifically for instance:

- To consider the effects of combined hazards
- To consider obstacles for human interactions and issues in emergency procedures relating to the specific conditions caused by extreme events
- To address all possible functional dependencies including also those ones between front-line and support systems (component cooling, instrumentation & control, power supply) and operability under adverse environmental conditions
- To address long-term accident sequences
- To consider connections and interactions between plant buildings, compartments, and components, etc.

To avoid the gaps in the existing safety assessment methodologies, the methodology should be capable of satisfying number of points for to be improved the safety assessment, namely:

i. Comprehensively address functional dependencies, component operability and feasibility of human interactions under adverse conditions caused by extreme events.
ii. Effectively address the impact of combined hazards.
iii. Utilize the outcomes of the existing safety assessment studies (DSA and PSA) avoiding known limitations.
iv. To be flexible in terms of using the data on component operability:
    - Using design basis data for component operability limits as starting point,
    - Crediting safety margins, where justifiable.
v. To be understandable by technical specialists who are not PSA-specialists.
vi. To be efficient in terms of time and effort to be spent.

In the case for assessment of a nuclear plant protection against extreme events, in particular lightning, the focus has to be on the assessment of the available safety margins at NPP remaining after the hazard had occurred. Generally, the assessment with FSA method is aimed at estimating the robustness of relevant safety systems and the continued presence of the defence-in-depth principle for load cases that exceed the design basis.

The logical models constructed in Level 1 internal initiating events PSA identify the fault sequences that start from a potential initiating event and proceed to core damage through possible failures of components needed to mitigate the accident. These logical models could be applied also in Level 1 PSA concerning external hazards, in particular lightning, and have to take account:

- The safety functions of criticality control and residual heat removal,
- Combinations of safety systems and other equipment that could operate to perform these safety functions,
- Support systems that are required for operation of front line systems,

- Support systems that are required for operation of other support systems (e.g. cooling water is required for operation of power supply system), and
- Required operator actions.

So, the PSA's logical models can be used to analyse the fault sequences that could occur following an extreme event – Lightning, and they form a basis of the FSA method.This method comprises five major analysis steps illustrated in Figure 7-1 [55] slight modified here for external initiating events.

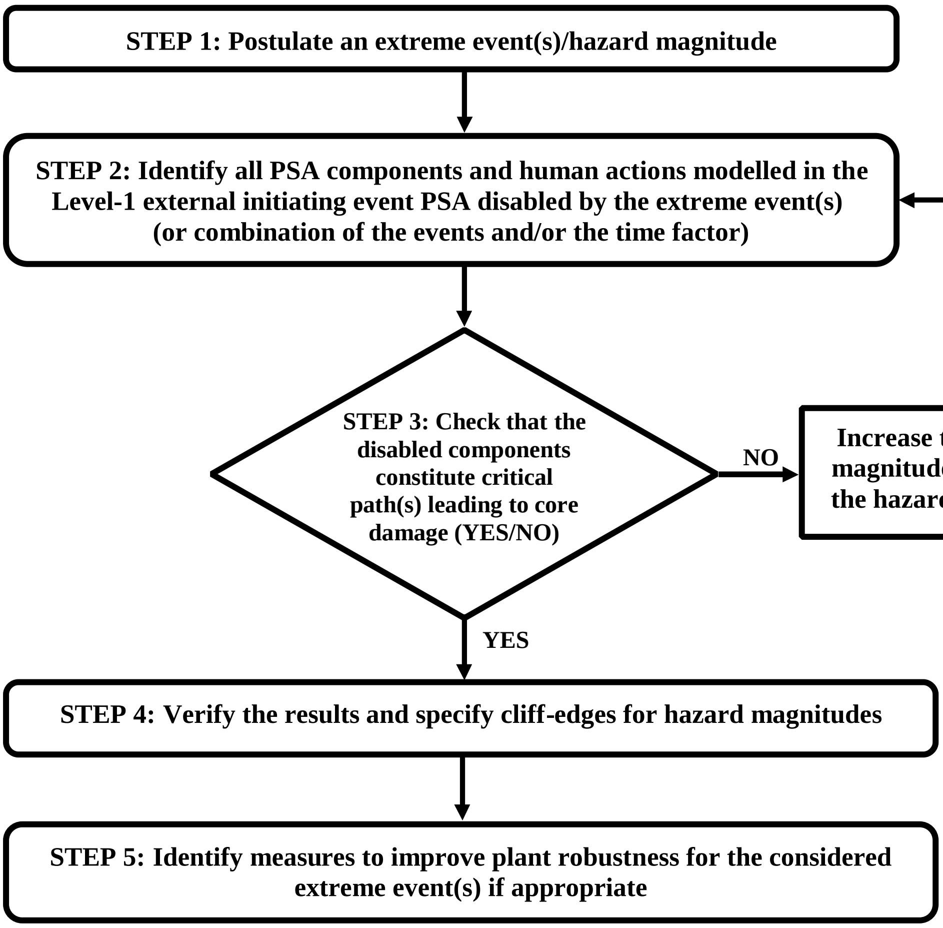

Figure 7-1 Fault Sequence Analysis Steps

Briefly, in the case of extreme event – lightning, these steps are described below.

Step 1: The lightning to be considered in the scope of the analysis and associated magnitudes of the parameters (current, overvoltage, intensity of the electromagnetic field, etc.) of the hazard. The assessment starts with the analysis of lightning as individual hazard that form the design basis for the facility and then all credible combinations of correlated hazards are considered.

Step 2: As basis all PSA components and human actions modelled in the Level 1 internal initiating events PSA are identified. The components, which could be affected by lightning in the NPP' vicinity, are selected. This step requires a significant amount of information to be prepared:

- *The PSA component list (including human actions): this information is directly taken from the PSA model available for the facility.*
- *Information on component elevations and location on the site of the plant and in buildings/compartments: this information is needed to identify the sensitive to the effects of lightning components and elements. The main sources of this information are the plant drawings and the information that could be obtained from external and internal hazards walkdowns.*

Step 3: The MCSs (Minimal CutSets) selected from the PSA model are reviewed to identify whether at least one MCS could be found between all components and human actions represented in this analysis will be damaged from the postulated lightning, When at least one MCS is identified it means that core damage is expected for the specified ex-treme event [55] . At this step, also the damage of structures housing the components or compartments from where human actions should be performed is analysed. Components or human actions are assumed failed in case of structure damage.

If no single MCS is found, a slight increase in the magnitude of the parameters of the hazard(s) is defined and again the process iterates from Step 2.

When at least one MCS is identified, it means that core damage is expected for the specified extreme event.

Step 4: At this step, firstly a more precise magnitude of the hazards failing critical combinations of components is obtained by slight decrease of the hazard magnitude and verifying the result obtained by repeating Step 3. The final hazard magnitude represents a cliff edge.

Then the following verification of critical failure combinations is performed:

- *The technical validity of the sequences leading to core damage is assessed. It should be clearly understood and documented that accident sequences identified with the FSA method do really cause core damage.*
- *It is verified that the list of MCSs used in the analysis is sufficiently complete and there is no accident sequence leading to core damage for the extreme event below the identified 'limiting extreme event'[4]. This verification could be done by explicit modelling in PSA of the particular set of SSCs and human actions surviving the extreme event considering the operability limits specified earlier. In the PSA model, the survived SSCs and human actions are set to 'FALSH' and the PSA model is re-quantified. The requantification should not reveal any new MCSs leading to core damage. Otherwise these MCSs should be added to the list of MCSs and the process should be repeated from Step 2.*

Step 5: Finally, the accident scenarios leading to core damage are analysed in detail to identify what plant improvements could be implemented (e.g. improvement of common lightning protection, additional protection of the sensitive components, etc.). In addition, it may be relevant to re-visit emergency procedures and severe accident management guidelines.

For performing FSA concerning lightning is necessary for specific NPP to consider the opportunity to apply the software 'Fault Sequence Tool for Extreme Event' (FAST-EE) developed by the IAEA to provide support while performing analyses of NPPs' robustness in terms of the ability of the plant to withstand different extreme events, including natural hazards and combined hazards.

There are two versions of the FAST-EE software: the first one is designed for the inputs (MCSs) generated by RISKSPECTRUM and the second version is designed for the inputs (split fractions and cause tables) generated by RISKMAN.

The application of FSA method and supporting tools are implemented at Goesgen-Daeniken NPP, Switzerland and Medzamor NPP, Armenia. The methodology is the entirety described in IAEA paper [55].

7.2.4.2 Extreme Event Analyzer (EEA) Methodology

Lloyd's Register Consulting (LRC), in cooperation with IAEA, has further developed the FSA method [56]. LRC developed a value added tool (ExtremeEventAnalyzer (EEA)) to systematically analyze the accident scenarios not explicitly addressed in the design extension conditions using integrated deterministic and probabilistic approaches. The tool has incorporated lesson learned from FSA methodology developed by IAEA, which has been verified by application on Goesgen-Daeniken NPP (Switzerland) and Medzamor NPP (Armenia).
This method utilises an internal initiating events PSA model for assessing the impact of extreme events, including the consideration of hazard susceptibility limits of SSCs and impact of extreme external hazards. This PSA model can be used for example to analyse extreme events and combinations of extreme events and their impact on safety functions and the ability for the nuclear power plant to withstand extreme events with regard to core integrity.
In EEA method, a number of extreme events (including credible combinations) can be postulated, for example seismic, water levels, extreme temperature, weather conditions etc. The extreme event analysis is linked directly to the PSA model (in RiskSpectrum) to ensure that the whole PSA model is included in the evaluation of the impact of the event or combinations of events. The EEA perform re-quantification of the PSA model including the hazard susceptibility limits of the SSCs. The outcome of the analysis is to [56] and [57]:

- identify sensitive scenarios for extreme events;
- analyse simultaneous extreme events;
- prove robustness of plant design, for individual components and for buildings.

In correspondence with the Fault Sequence Analysis Steps of FSA method shown in Figure 6-1, below is a list of sequential steps to perform while using the EEA method to identify scenarios sensitive for extreme events [56]:

1. determine what hazards to include ; this will be site specific and screening criteria may be applied,
2. determine the components, buildings that can be susceptible to the hazards ; plant data collection and plant walkdowns are important inputs,
3. determine initiating events which can be triggered by the hazard,
4. determine the magnitudes of hazards that will fail the components, the buildings and trigger the initiators,
5. generate the minimal combinations of events given the occurrence of a hazard or combinations of hazards.

For the purpose of the lightning hazard assessment, taking into account that usually the lightning stroke is multiple and multiplex from number of strokes and the impact of the lightning should be considered as a combination of hazards, especially as effects to the electronic and computer systems, communication systems and digital I&C systems of the NPP, is very suitable to use the EEA method because the MCSs produced from the EEA can be generated considering only lightning or together with other hazards and they ~~to~~ represent the combinations of events that would lead to core damage.

Then the quantification in the PSA model could be done in the following way:

i. Basic events representing components that fail due to the lightning or in combination with other hazards are set to probability 1.0.
ii. All other basic events in the PSA model are set to FALSE.
iii. MCSs are generated.

If no MCS are generated, it means that there is no accident scenario due to lightning or correlated hazards leading to core damage, based on the PSA model and the defined susceptibilities for components, buildings and initiators, which would lead to core damage, due to the hazard(s).

EEA method and tool is utilised in a benchmarking study "Extreme Event Analysis – an application of RiskSpectrum EEA at Armenian NPP" is performed under co-operation project between LRC, Nuclear and Radiation Safety Center (NRSC) and Armenian Nuclear Power Plant (ANPP). The purpose of the study was to perform a comprehensive and systematic assessment of robustness and vulnerability of NPPs against the impact of extreme events using EEA method and tool. The EEA method, result and conclusion of this benchmarking study are presented in [57].

The example given in [56] for initiating event: 'Loss of Off Site Power' (LOOP), external power is lost, reactor scrammed (emergency shutdown), is suitable to be presented here as similar example for EEA method application, considering that it is very likely to occur LOOP due to lightning strike in the area of NPP and subsequent fire, namely:

Example with hazards: ***Lightning and fire***

Lightning:

Negative subsequent strike (di/dt=200kA/µs) -> A & B fail

Fire:

External ->E & K fail

Internal -> D & E & K fail

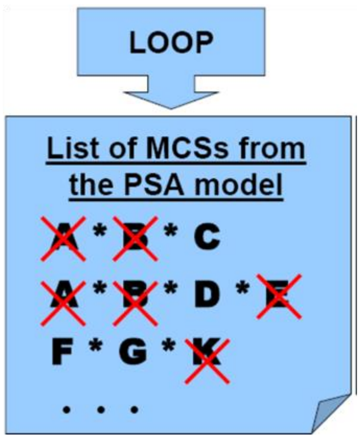

Figure 7-2 Scenario 1: Negative subsequent lightning strike and External fire

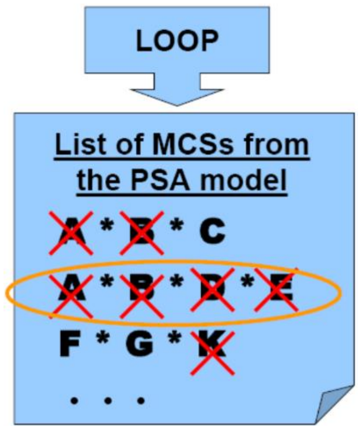

Figure 7-3 Scenario 2: Negative subsequent lightning strike and Internal fire

Figure 7-2 shows that the plant is protected against the combination of negative subsequent lightning strike and external fire, while Figure 7-3 show a scenario where the plant is not protected in the case of combination of negative subsequent lightning strike and internal fire (one MCS where all components will be disabled by the hazards' combination is identified).

Once the scenarios leading to core damage are found, the very important process of verifying that these are indeed critical begins. This has to be done by looking at each lighning scenario in detail and clearly understanding that it really causes core damage. There may also be that some combinations are the effect of conservative assumptions.

With the scenarios identified it is clear which safety functions, buildings, etc. to improve with regard to lightning protection improvement, components (electronic and computer systems, communication systems and digital I&C systems of the NPP) locations, etc., if necessary. When the measures have been identified it is easy to evaluate again to verify that it has had its desired effect. If there are no measure that can be taken, a weakness in the plant design has been identified.

8 MULTI-UNIT ASSESSMENT FOR LIGHTNING HAZARD

After the Fukushima Daiichi NPP accident, the consideration of the special aspects of multi-unit accidents became especially important as well as the need for improved assessment of accident propagation to other units and the relevant measures for their prevention and protection.

The multi-unit impact of the lightning assessment depends on two factors:

1) Location of the lightning strike and the resulting effects on the nuclear power structures and systems
2) Categories of lightning damage falls and most commonly observed effects

A qualitative assessment of their importance for potential multi-unit hazard of the all effects of the lightning is presented in Table 8-1.

Practically, for each specific NPP this qualitative assessment could be confirmed or modified taking into account the location of the units, distances between them, types and characteristics of the internal networks, lightning protections of the units, relay protections, components etc.

So, the multi-unit is a special case for assessment in lightning PSA at least for two reasons:

i. conventional lightning protection systems for multi-buildings have to cover special requirements of the standards and regulations if the designer wants to achieve a high level of protection on one hand and to minimize the investment on the other hand.

ii. the nuclear unit has to be consider not simply as a building when we consider lightning in PSA, taking into account not only potential fire danger sources, but also the potential damage of the containment in case of direct lightning strike (fire and destruction of structure) and/or safety system in case of an unsuccessful lightning protection.

The implementation of lightning hazard on multi-unit sites in the extended PSA has to be coordinated with the SAM strategy of the specific NPP.

Table 8-1 Possibility for impact, probability for and potentially degree of the lightning' hazard in multi-unit case of assessment

	Location of the lightning strike and resulting effects on the nuclear power structures and systems	Categories of lightning damage falls and most commonly observed effects				Probability for affected more than one unit in multi-unit NPP from one or more one effects of the lightning	Potentially degree of the lightning hazard for more than one unit in multi-unit NPP, in case of lack, ineffective or loss of lightning protection
		Physical damage from direct lightning strikes/ primary effects - fire and destruction of structures	Failure to electrical and electronic systems of NPP in case of lack, ineffective or loss lightning protection				
			Direct Energization due the Electromagnetic Induction (EMIn)	Electro Magnetic Pulse (EMP) due the Electrostatic Induction (ESIn)	Ground Potential Rise		
1	Lightning strikes directly on the buildings and facilities, including outdoor switchyard (OSY) at the NPP site	NO affected multi-unit as buildings, but could be affected by lightning strike on OSY	YES, affected multi-unit	YES, affected multi-unit	YES, affected multi-unit	very high	high
2	Lightning strikes outside of the plant, but fall on transmission lines high voltage related OSY at the NPP	NO physical damage but could be affected multi-unit by loss of out-side power for the whole NPP	YES, affected multi-unit	YES, affected multi-unit	NO affected multi-unit	high	medium
3	Lightning strikes outside of the plant not directly affected transmission lines high voltage related OSY, but with the resulting effects impacted on transmission lines high voltage related OSY and hence impacted on the nuclear power structures and systems at the plant site.	NO physical damage but could be affected multi-unit through internal power network, in case of lack, ineffective or loss lightning protection	YES, affected multi-unit through internal power network	YES, affected multi-unit through internal power network	NO affected multi-unit	high - medium	medium - low
4	Lightning strikes outside of the NPP without directly lightning strikes on the transmission lines high voltage related OSY, and without the resulting effects impacted on transmission lines high voltage related OSY, but affected with lightning strikes or with resulting effects other buildings, facilities and lines, including communications lines, long steam and heat pipelines and other systems entering the plant site, and hence could impacted on the nuclear power structures and systems at the plant site.	NO affected multi-unit	YES, affected multi-unit through internal networks	YES, affected multi-unit through internal networks	NO affected multi-unit	an average - low	low

9 LIGHNING EVENT AND FAULT TREES

The aim of this task is in accordance with [9] to outline basic progression of accident scenarios as well as to determine specific human actions if appropriate.

It is assumed that majority of work will be adapted from PSA for internal event (e.g. success criteria etc.). In such case event trees will have quite simple structure and trees for particular initiating events will require only reactor trip and heat removal.

It is assumed that majority of initiating event will not require development of specific fault trees to adapt PSA model on lightning condition. This assumption is based on fact that any lightning strike can put out of order limited number of components. So it is sufficient only to set affected component to fault state. This customization of model can be done by using configuration files or boundary condition sets (depends on the used software)

It is also assumed that external initiating events induced by lightning strike will not use specific event trees. In this case frequencies estimated in step 4 will be added to particular frequencies used within analysis of external hazards and external hazard analysis will be re-evaluated.

10 L2 PSA CONSIDERATIONS

Few considerations on L1-L2 PSA interface are provided in Appendix section 15. No specifities can be highlighted for lightning hazards L2 PSA in comparison with existing practices.

11 CONCLUSION

The report introduces a systematic framework to evaluate hazards caused by lightning event including correlated hazards. From this framework, feasibility of lightning hazards implementation in extended PSA can be discussed.

From the “state of the art” knowledge, the methods, equations, data, standards, exposed above as engineering technics in the general case, can be applied for the design of lightning protection or to improve them.

Nevertheless, the presented fragility analysis methodology is based mainly on IECs and does not take into account lightning intensity effects. Further effort can be useful to improve available methods for fragility analysis in case of lightning.

For extended PSA, analysis of lightning damages from NPP experience and additional methodologies for the theoretical possible damages of lightning on safety functions would be useful for the quantification of initiating events frequency of occurrence or assessment of the accuracy or uncertainty of the results. In addition, assessment of wild fire frequency induced by lightning is seen as a topic for further development.

The above mentioned weakness of current lightning methodology, namely:

- fragility analysis methodology does not take into account lightning intensity effects,
- qualification and quantification of possible damages of lightning on safety functions,
- missing assessment of wild fire frequency induced by lightning,

should be defined rather as "open-issues" on one hand, and on other hand as important directions for further improvement of the methodology for lightning hazard assessment and its PSA.

Further after finalisation of this ASAMPSA_E project, it might be needed to define more ambitious objective concerning the lightning hazards as an independent risk for NPP for probabilistic evaluation and for lightning protection of NPPs with identification of the weaknesses of a NPP with regards to lightning and definition of relevant improvements. In this case new advanced methodologies shall be searched, which will minimise the number of opened issues in lightning hazard and its PSA.

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15 APPENDIX - EXISTING GUIDANCE USEFUL FOR LIGHTNING PSA

Some of existing guidance's for hazards in general and lightning hazards in particular are shown here in the table. More general analysis is available in [1] or [2].

Reference	WA1	WA2	WA3	WA4	Remarks
IAEA SSG-3 Date?	x	x	x		General
IAEA - A Methodology to Assess the Safety Vulnerabilities of Nuclear Power Plants against Site Specific Extreme Natural Haz-ards, 2011	x				Extreme Natural Hazards /weather, Seismic, Flood
NUREG/CR-2300, Volume 2 PRA Date?	x	x			General
IAEA-TECDOC-1511 Date?	x	x	x		General
WENRA Issue O Date?	x	x			All External Events
NEA/CSNI/R(2009)4	x		x		Non-Seismic Haz-ard
SKI, Report 02:27 Date?	x	x			Non-Seismic Ex-ternal Events
10CFR 50.54(f) Date?	x				All External Events
IEC 62858:2015 Lightning density based on lightning location systems (LLS) – General principles					Lightning
EUR 2001 "Volume 2 Generic Nuclear Island Requirements. 2.1 Safety requirements. 2.17 PSA Methodology. Revision D"	x	x			General
WENRA RHWG, Safety of New NPP Designs - March 2013		x			General
WENRA "Position paper on Periodic Safety Re-views (PSRs)", March 2013			x		General
NRC Handbook "Risk Assessment of Operational Events - Revision 1.03", August 2009			x		General
IAEA-TECDOC-1341 Date?			x		General
HSE Safety Assessment Principles for Nuclear Facilities 2006 , Revision 1			x	x	General
IAEA NS-R-3 Date?			x		General
EPRI 1022997 Date?			x		General External Hazards
WENRA-RHWG, Guidance Document Issue T: Natural Hazards. Date?			x		Natural Hazard
ONR Technical Assessment Guide - External Hazards. T/AST/013 - Issue 4, July 2011				x	General

WA1 - Impact on the SSCs modelled in L1 PSA event trees
WA2 - Impact on Human Reliability Assessment modelling in L1 PSA

WA3 - Site impact modelling in L1 PSA event trees

WA4 - Link between external initiating events of PSA and NPP design basis conditions (only IE frequency)

16 APPENDIX – INTERFACE LEVEL 1 – LEVEL 2 PSA

This appendix provides recommendations regarding the definition of Plant Damage States (PDSs), which are used as boundary conditions in the Level 2 analyses, for the lightning initiators groups that have been identified to be of most interest by the end-users groups after collection and discussion of results from the ASAMPSA_E end-users survey [3]. The general discussion on definition of PDSs and protocols and recommendations for performing PSA are to be found in the ASAMPSA2 guidelines ([58] and [59]).

Most of the discussion is the same for each of the external events initiator groups, according to experience gained from performing and/or reviewing complete and integrated analyses, and therefore the sections are given for completeness and to make the discussion self-contained for each initiator group and with small variations from each other, according to initiator group expected consequences. The only exception is for the "biological infestation" group, for which no specific analysis has been performed to date. For this group, guesses are given, on the basis of potential (or known) infestation incidents.

Definition of Plant Damage States (PDS) for lightning initiating events

Since the definition of, and collection of data for the PDSs are tasks that may fall upon different teams that perform the analyses (Level 1 and Level 2 teams), this section is intended primarily for Level 2 experts.

It must be stressed, as was done for analyses of internal events [58] and [59]), that this task involves close interaction between the teams performing the analyses. Level 2 personnel has knowledge about what boundary conditions are necessary for characterization of accidents after core damage, and Level 1 personnel knows how accidents progressed up to that point and why core damage occurred. Therefore, this part of the works profits from feedback and potentially iterative work between the two teams in the course of defining the PDSs.

To this point, it is recommended that the Level 2 team in general takes cognizance and understands thoroughly the definition of systems success criteria used in the Level 1 study, and in particular for accidents initiated by lightning events, what are the potential initiator-dependent systems failures (failure of systems that occurred as a direct impact from the initiator) and –independent failures (failure of systems that may have occurred after accident initiation, at a time that for the most part cannot be specified by Level 1 analyses).

It is also strongly recommended that the Level 2 team familiarizes themselves with the results of Level 1 in terms of individual accident sequences or Minimal CutSets (MCSs) that show the chain of failures (initiator, dependent systems failures, component failures, and operator errors) that ended in core damage. Operator errors in Level 1 are of particular importance for Level 2 analyses if operator interventions that could be considered as part of SAMGs are introduced in Level 1 in conjunction with interventions that are part of EOPs. This is the case for instance for containment venting, initiation of containment sprays, or initiation of firewater (or equivalent emergency system) injection in the RCS prior to core damage in BWR plants. The danger is that these systems may be over-credited in Level 2, if accident progression to the time of core damage is not thoroughly understood by the Level 2 teams.

In addition, it is also strongly recommended that the Level 2 team responsible for the definition of PDSs understand the role of auxiliary systems (such as compressed air, auxiliary and component cooling water systems) in the process of preventing core damage in particular accident scenarios, since these systems may fail as dependent on the initiator, without immediate failure of the primary safety systems.

The definition of PDSs that has been used for the internal events analysis has to be verified for applicability to Level 1 accident sequences that are initiated by lightning events. The combination of dependent and independent systems failures due to lightning events-induced sequences may require the definition of additional PDSs that were not considered possible for internal events. Finally, operators may be required to perform actions (such as venting of the containment prior to core damage) that would not be considered under accidents initiated by internal events and that change the status of the containment before the beginning of Level 2 analyses.

Preliminary discussion of this topic within WP40 has led to the conclusion that for the purpose of “presentation of results” and “analysis of results” (especially for importance analysis) it is strongly suggested to include one additional characteristic in the definition of PDSs that describes the group of initiators. Apart from this additional information, the traditional PDS characteristics seem to be suitable also for lightning events characterization.

Additional characteristics with particular importance for L2 PSA do not seem to be needed.

As a preliminary conclusion of the present document it seems that – apart from the initiating event itself – no additional PDS characteristics are needed.

17 APPENDIX - HAZARD ASSESSMENT AND PSA TOOL - EXAMPLE

RiskSpectrum® HazardLite [60] (hereafter called ***HazardLite***) is a light tool for assessing hazard risks, e.g. earthquake, tsunami, extreme weather etc. This tool could be modified for assessing lightning hazard risk. The input to ***HazardLite*** includes definition of initiating events ranges, hazard curves and fragilities. The output is an excel workbook containing the results in form of Basic Events. This excel file can be imported into RiskSpectrum® PSA for further analysis. In addition, if the Monte Carlo method is selected in the analysis, a series of text files will also be generated for uncertainty analysis in RiskSpectrum® PSA.

A probabilistic safety assessment of an external hazard is different from analysis of internal events e.g. seismic hazards. The differences are mainly that:

- The hazard (the initiator of the sequence) spans over a continuous range
- There is relation between the hazard and the failure of equipment (fragility). The stronger the external hazard e.g. earthquake, the more likely the equipment will fail. Respectively from the impact of the stronger lightning is more likely the equipment of the switchyard, relay systems, electronic and communication systems to be failed.
- This is relevant also for other types of hazards, e.g. tsunami, extreme weather hazards.

HazardLite uses an EXCEL workbook to store the input necessary for fragility calculations of components over discreet ranges of peak ground accelerations, which are considered to be the initiating events. To capture the full uncertainty inherent in our knowledge, families of both hazard curves and fragility curves are used.

To capture the uncertainty of hazard curves, several hazards curves may be entered and each curve is given a probability, or weight, that it is the actual hazard curve. To capture the uncertainty of the fragility curve for each component, the user must enter the median acceleration where the component is expected to fail (called Am), the logarithmic standard deviation (called β_R) which represents the random variability of the fragility, and the logarithmic standard deviation (called β_U) which represents the uncertainty in the actual shape of the fragility curve. Fragility curves are modelled as lognormal probability distributions.

The hazard curves (and the fragility curves) are divided into discrete intervals by the analyst. In the PSA model, each of these intervals needs to be represented. ***HazardLite*** will generate the input necessary, with regard to hazard frequencies within each interval and fragilities to be used within each interval. These basic events are intended to be used as initiating events (frequency events) and as component failure in the PSA model (normal basic events in the fault tree structure).

It shall be noticed that fragilities may be grouped and combined. Grouping of equipment is performed to reduce the amount of necessary seismic fragility events and it represents OR-structures of components that need to be treated as fragilities. Combinations may be relevant when several fragility events are found in the same MCS. The reason for this is that the convolution approach used in ***HazardLite*** is more exact if the convolution is performed for the events together, rather than performing the convolution individually and then combining them in a MCS.

In the quantification, each of the defined intervals is subdivided into a number of sub-intervals. The chosen amount of subintervals is 100 in ***HazardLite***.

Within each interval the hazard frequency, as well as the fragility for each component is calculated. The calculation of the fragility is convoluted with the frequency, to account for differences in the interval (both the hazard curves and the fragility curve will change value within the interval).

The quantification algorithm is described by following:

- Point estimate calculation
- Quantification of the hazard frequency, the initiating events
- Fragility
- Calculation of fragility for group of events
- Calculation of fragility for combination of events
- Uncertainty calculation
- Quantification of hazard
- Quantification of fragility

Quantification of hazard, initiating events, point estimate calculation

HazardLite is calculating the frequency for the hazard by calculating the average frequency taking into account the weight of the hazard curve. The hazard frequencies are calculated by subtracting the exceedance frequency at the upper hazard boundary from the exceedance frequency corresponding to the lower boundary. Thereby a frequency within each interval is calculated. The calculation of hazard frequency is also performed for each sub-interval, since these frequencies are required for the convolution of hazard and fragility. Logarithmic interpolation is used when the definition of the interval does not match the user defined input data for the hazard curve.

Fragility

The HazardLite is used earthquakes as an example to illustrate how it works.

The fragility calculation is based upon following formula [1]:

$$f' \quad = \Phi\left(\frac{ln\left(\frac{a}{A_m}\right)+\beta_U\cdot\Phi^{-1}(Q)}{\beta_R}\right) \qquad (1)$$

Where:

$\Phi()$ is the standard Gaussian cumulative distribution

a is the PGA

A_m is the median capacity of the component

β_R is the random variability (the randomness wrt the earthquake)

β_u is the state of knowledge uncertainty (uncertainty of fragility curve shape)

Q is the confidence that the conditional probability of failure, f, is less than f´ for a given peak acceleration a.

A mean fragility curve can be calculated by replacing β_R by following

$$\beta_C = \sqrt{\beta_R^2 + \beta_U^2} \qquad (2)$$

in the equation above and to set β_U to zero [1]. Then following equation can be defined:

$$f = \Phi\left(\frac{ln\left(\frac{a}{A_m}\right)}{\beta_C}\right) \quad (3)$$

This equation is used in ***HazardLite*** to calculate the mean fragility (e.g. at a given PGA a).

Since the fragility is representing a range of PGAs, and over this range the hazard frequency is also changing, and the cut sets including fragilities will always include one hazard and at least one fragility, the proper calculation would be to integrate them over the interval (over which the hazard is defined). However, the calculation in RiskSpectrum PSA/RSAT does not allow for such evaluations and thereby the calculation of the fragility must take this into consideration. The calculation of the individual component fragility convolution is described below, and the calculation of groups and combinations is described in a separate section.

Assume following cut set

H_1, F_1, B

Where H_1 is the frequency in an interval, F_1 is the failure probability of a component in the same interval, and B is an independent failure probability.

If H_1 and F_1 are calculated independently with regard to the frequency and probability within the interval, this will not necessarily yield the same result as the mean value computed by

$$\frac{1}{x}\int_0^x h(x) \cdot f(x)\ dx \quad (4)$$

And the mean value from the integral above is the correct mean value. Therefore ***HazardLite*** does the convolution through a numerical integration, and then divides it by the frequency in the interval. In this way a weighted fragility estimate is calculated, and when it is multiplied with the hazard frequency in the MCS again, it will yield the same result as if the integration would have been performed for the MCS itself.

To put it in formula, F_i the failure probability of the component due to seismic fragility in interval i is calculated by:

$$F_{i,h_k} = \frac{\sum_{j=1}^{100}(h_{ij} \cdot f_{ij})}{\sum_{j=1}^{100} h_{ij}} \quad (5)$$

Where:

$F_{i,hk}$ is the fragility calculated for interval i based on hazard curve k

h_{ij} is the hazard frequency for interval i, sub-interval j

f_{ij} is the fragility calculated for the interval i, sub-interval j

The value of the fragility f_{ij} is calculated at the upper end of the sub-interval, which is a slightly conservative approach taken. The probability is calculated by formula (3).

The fragility (failure probability) is calculated for each individual hazard curve as basis, and then the fragility (failure probability) results to be used in the PSA for the interval are calculated by multiplying the weight of the hazard curve with the $F_{i,hk}$ of that specific curve. The raw data are the hazard curves, and thereby these should be used as the basis for the convolution. The fragility (failure probability) for the component is calculated by:

$$F_i = \sum_{k=1}^{n} F_{i,h_k} \cdot W_{h_k}$$

Where:

W_{hk} is the weight of hazard curve k

$F_{i,\,hk}$ is the fragility in segment I for hazard curve hk

Component groups and combinations

A component groups is defined as a set of components that are grouped together and instead of representing them individually, they are represented as a group. These events could be considered to be represented under an OR-gate.

The quantification of the fragility for each component is according to the methodology above, but instead of representing each value in the PSA model by a basic event, they are combined according to following formula:

$$F_{Group} = 1 - \prod_{i=1}^{n} (1 - F_i)$$

Combination

A combination is defined as a set of basic events that are found in the same MCS. The process described above for components and groups of components generates a convolution of the hazard and the fragilities over the hazard range. This process is used to, as accurately as possible; calculate the values that should be produced by the MCS analysis whenever the cut set includes the hazard (which it should always do in the hazard analysis) and a fragility. However, when a cut set contains more than one fragility the convolution is no longer correct.

HazardLite gives the user the possibility to specify combination of events. There can be a prohibitively large number of combinations, so the process is intended to be used for the events that may have impact on the results.

The combinations defined are calculated simultaneously as the individual basic events, to ensure consistency of values used (e.g. with regard to uncertainty simulations – same value must be used for $fA(i)$ (failure probability A in internal i) both when the individual basic event is computed and the combination event).

The combinations are intended to be included in the analysis using MCS post processing, replacing the events in the cut set by the combinations. The difference in results when applying combinations and not for individual MCS may be significant, and hence it is recommended to use the combinations for event combinations of importance.

Uncertainty calculation

The uncertainty calculation is built by the same methods as presented above. The equations are slightly different, when it is no longer the mean value that is computed.

The method is:

- Randomly select one of the hazard curves (according to its weight)
- Randomly select one of the fragility curves in the group of fragility curves (for each component)
- Calculate the hazard frequencies for all defined intervals
- Calculate the fragilities for all intervals, under the condition of the selected hazard curve (convolute with the selected hazard curve only)

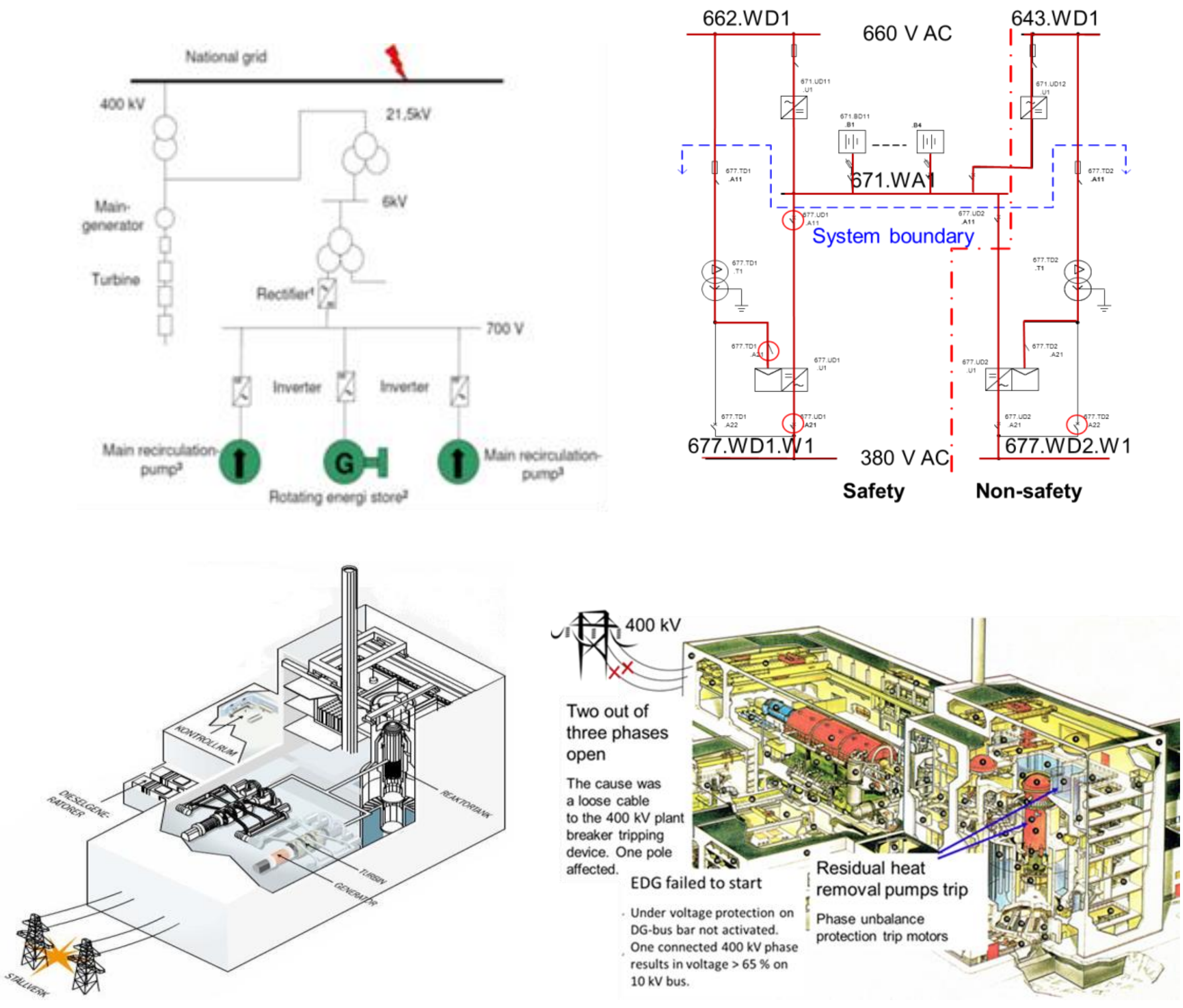
- Calculate Component groups and combinations
- Perform next sampling

18 APPENDIX – FORSMARK CASE STUDY – DESIGN, ASSESSMENT OF EXTERNAL EVENTS

18.1. Lightning consequences in NPPs of Forsmarks Kraftgrupp AB, 2006-2013

Indicative examples to illustrate the lightning hazards for the purposes of PSA are the lightning consequences in NPPs of Forsmarks Kraftgrupp AB, presented during the 1st End-Users Workshop of ASAMPSA_E in Uppsala, Sweden, May 26-28, 2014 [63]. The discribed events and the consequences are listed here and relevant shown in the next figures 1, 2, 3 and 4:

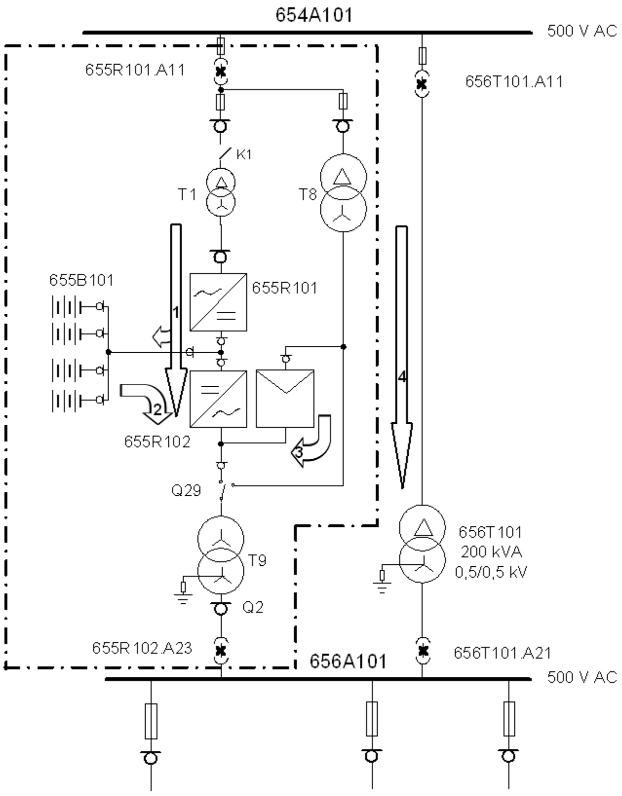
- **Loss of external power and loss of** power supply from 2 of 4 **diesel generators** Forsmark 1 (25 July 2006)
- **Lightning strike** tripped all eight main circulation pumps at Forsmark 2 (13 June 2008)
- **Lightning strike** causing voltage transient in station AC net Forsmark 3, (13 July 2012)
- **Loss of two phases of the external grid** during outage shutdown with loss of decay heat removal (30 May 2013)



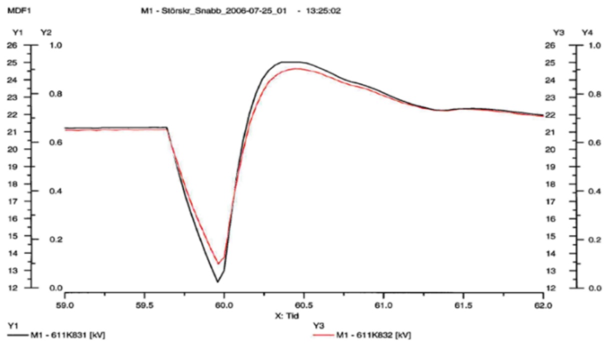
Figures 1, 2, 3 and 4: Events and the consequences in NPPs of Forsmarks Kraftgrupp AB, 2006-2013

Tuesday July 25th, 2006 initiated a planned change in the 400 kV switchyard. Upon opening the sectional disconnector has evolved an arc (protection relay is blocked in accordance with instructions) The situation is illustrated in Figures 5 (a), 5 (b) and 5 (c) as Initial event (the Loss of external power and loss of power supply from 2 of 4 diesel generators Forsmark 1) - (near SBO – Station Black-Out).

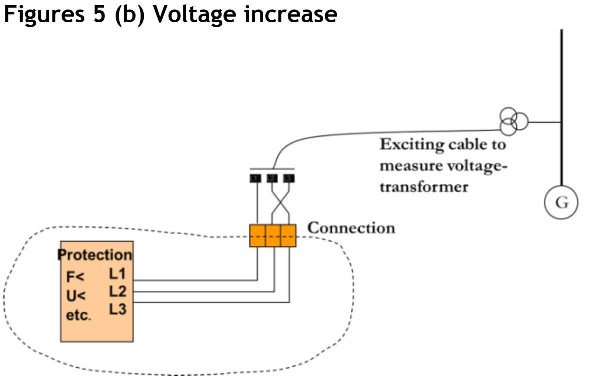
Figure 5 (d) represents some examples of other electrical phenomena and fault affecting the Forsmarks NPP.



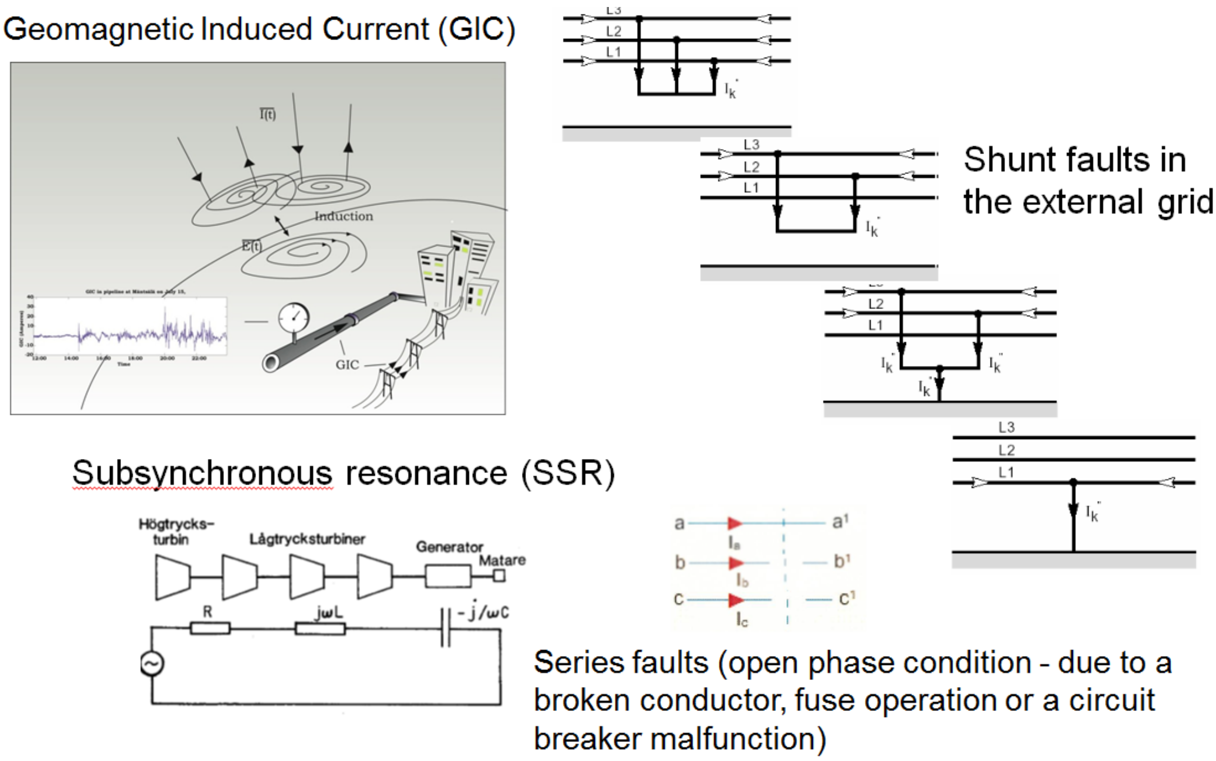
Figures 5 (a) Problem with selectivity



Figures 5 (b) Voltage increase



Figures 5 (c) New realy protection with new functionality



Figures 5 (d) Other electrical phenomena and faults affecting the Forsmarks NPP – examples

The generalization for the events and the consequences in NPPs of Forsmarks Kraftgrupp AB are:

- Simplified: The design an analysis is made with the grid voltage to be either zero (< 65 % internal) or one (nominal voltage):
  - Actual events have shown that it can be voltages between
- Several type of fault that can be affecting the plant:
  - Disturbances in the voltage, frequency or phase angle
- Analysis at different plant/units electrical operational condition:
  - Main grid (400 kV grid)
  - House load
  - Stand-by source (70 kV grid with gas turbine)
  - Outage
- The events is initiated:
  - Man-made – lack of analysis at renewal or at maintenance
  - Weather phenomena as lightning, which initiate shunt faults
  - Ageing – lack of maintenance or renewal
- PSA studies should include a more diverse modelling of internal and external electrical events

18.2. Methodology for design and assessment general for external events

The example refers a methodology for design and assessment general for external events [64] as experience of Forsmark applicable in particular for lightning as single event/hazard or in combination with other correlated and/or associated hazards – with some notes in brackets (*note for the lightning's*) below.

Assessments of frequencies of loads from External events are based on data from real events (exist for about 100 years – depending on which kind of external events) and is implemented in **three groups** with extrapolation of data for:

i. periods beyond the existing map of data **up-to 10^{-4}/year** (can be based on complementary data from history documents or signs)
ii. periods **beyond 10^{-4}/year of data up-to 10^{-6}/year** (no real references exists - data have to be developed based methods for extrapolations or other methodologies)
iii. periods **beyond 10^{-6}/year** (– if possible at all)

Existing historical data related to external event can in most cases be tracked back with real measured data covering the last 100 years. The accuracy of the measurement is in most cases usable for develop statistical tables.

Some weaknesses for the data covering the last 100 years are:

- in the data can be lack of data that represent the specific local site,
- all data not fully describe the nature of measured extreme values as the rate of changes before and after the maximum values are reached.

In many cases both local as well as national program today have increased:

- Place/Points for measurements – including the real plant
- Frequency of recording data as well as storing measured data

For this category is generalized that:

- Existing data give data with low and for PSA purposes acceptable uncertainties.
- Ongoing measurement programs will reduce the uncertainties even more.

The **three groups** indicated above are described as follow:

i. periods beyond the existing map of data **up-to 10^{-4}/year** (can be based on complementary data from history documents or signs)

Existing historical data related to external event can in most cases not be tracked back to 100 years by real measured data (*especially for the lightning*). By information given about extreme weather in other historical books and documents it is possible to have a hint of any extreme external event that have causes harm or destruction to the population or to the society.

As no real measurements exist the uncertainties in data is very high (*especially for the lightning*). The historical data will not cover all events perhaps not even the worst cases. This fact will also make the data uncertain.

By developing of different kind of models representing the different kinds of external events it is possible to give complementary knowledge about both best estimate data for the parameter as well as the uncertainties (*in the most of lightning cases it is too difficult*). Research in understanding historical changes will reduce the uncertainties.

<u>CONCLUSIONS for this category:</u>

Existing data for this period give data that can be used to develop some maximum and minimum values for extreme weather conditions but these includes certain degree of uncertainties data are still usable for PSA purposes but include uncertainties that is higher than for most other data. The PSA have to treat these data with specific attention.

Use of models and better understanding of external event will in the future reduce the uncertainties. It will probably last many years before a drastic reduction of uncertainties will affect data within this range of frequencies.

ii. periods **beyond 10^{-4}/year of data up-to 10^{-6}/year** (no real references exists - data have to be developed based methods for extrapolations or other methodologies)

There exist no historical data related to events within the frequency range of 10-4/year to 10-6/year. The only way to develop data related to this event frequency will be to use certain methods or models that extrapolate data from periods with higher frequencies. There exist different theories to perform such extrapolation.

Different theories result in very different outputs related to best estimate data and therefore also on the uncertainty band. Foreseen climate changes will also affect which possible range of data will occur (*for the lightning as is indicated above, due to global warming the average earth temperature could be increased to nearly 4°C by year 2100, which could ultimately lead to increasing lightning activity by 48%*).

In this range it is also possible that specific outliers of data could exist that represent one specific case giving extreme amplitude to the event.

<u>CONCLUSIONS for this category:</u>

There exist no data and existing methods for extrapolation gives large variation of data and uncertainties. It will be of importance to periodically re-assess data in this category to include new knowledge related to climate-changes.

Data with large variation of data and uncertainties have to be handled with extreme care if it shall give useful outputs to PSA-results and for application of PSA in decision making.

iii. periods **beyond 10^{-6}/year** (– if possible at all)

With existing knowledge it is not possible to develop useful data for PSA or for deterministic assessment related to external events with frequency less than 10^{-6}/year not even using different kind of models. For this category the effects of climate changes will probably influence the possible loads in ways that cannot be foreseen today (*hardly a lightning it will be able to predict and beyond*).

<u>CONCLUSIONS for this category:</u>

No useful data or models exist to develop useful data within frequencies lower than 10^{-6}/year.

A summary of the positions given above (i, ii and iii) is presented with the next Figure 6, as follow:

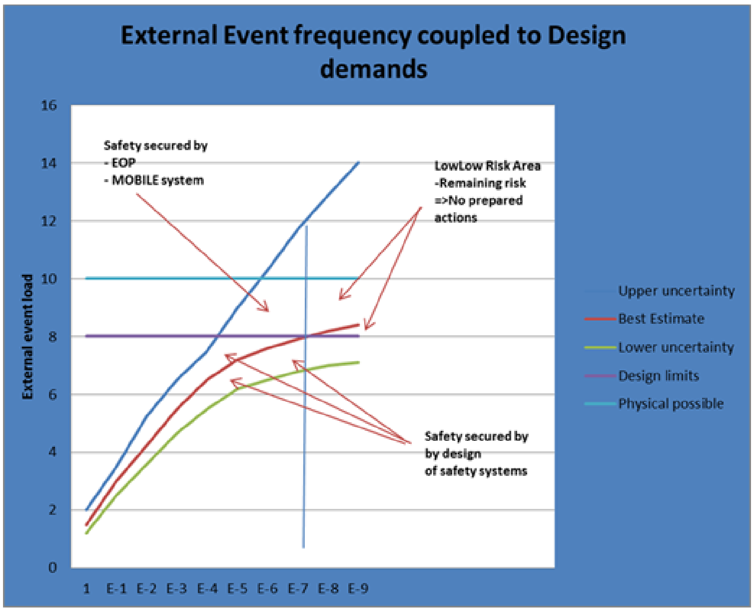


Figure 6 External Event frequency coupled to Design demands

The conclusions related design of NPPs depending of limits within the figure is:

1) Design of Nuclear Power Plants to protect against negative effects of external events is based on identifying a design limit for all or most of the external events. The design limit or limits are used to specify demands on structures and components to withstand the loads up to at least the design limits. This will secure that safety systems will be operable under such loads.

In most cases the design limits are selected to cover all loads up to

- best estimate level of loads up to 10^{-4}/year with some extra margin,
- best estimate data of loads up to 10^{-6}/year (if possible to specify).

This will result in low or very low probabilities for core damages and radioactive releases for events within this frequency range.

2) As the uncertainties related to amplitudes of loads for external events above 10^{-6}/year to 10^{-7}/year is very large the chosen design limits to cover 10-6/year event will not cover all possible loads within the range of 10^{-6}/year or even higher frequencies.

It will be a good practice to identify the loads that are above the design limits and within the uncertainty band for event covering 10^{-7}/year-events. Consequences of events within these ranges shall be assessed.

3) To protect against negative effects related to core damages and radioactive releases for extreme loads within this category of events the basic design shall be complemented by using mobile equipment, Emergency Procedures (EOP) and Accident Management Guidance (SAMGs) that can reduce the negative effects of these events.

4) Consequences for PSA

It will be of importance to develop a strategy for PSA related to the above characteristics of external events, in two categories:

i. PSA cover only external events up to frequencies for which safety systems are used to protect against core damages. This means that no loads above design limits. This PSA shall not include Mobile systems, EOPs or SAMGs.

ii. PSA cover external events with high degree of uncertainties including loads above the design limits. For this category it will be of importance that the PSA includes enhancements from Mobile systems, EOPs or SAMGs.

The best solution will be to develop both types of PSAs and use them for different kind of assessments.

And a supposition for events with lowers frequencies -**10^{-7}/year to 10^{-9}/year**

Event with extreme low probabilities or extreme outliers of events will not be possible to include in any kind of assessment or design program. It will be impossible to describe both direct and indirect effects of these events.

Severe accident management guidelines (SAMG) can give common recommendation on how the emergency organisation shall cope with such kinds of events.

19 APPENDIX – INFORMATION FOR THE IMPROVED EDF'S METHOD FOR LIGHTNING ASSESSMENT [48]

Since 2008, a new French regulation*, dealing with lightning protection of classified installations for environment protection, imposed to realize:

- A risk assessment in accordance with IEC 62305-2 (edition 1 of 2006) to evaluate the risks, define the needs of protection and the associated level required
- A technical study to design the protections
- Installation, and control of the protection devices
- A logbook to register all lightning related events on the sites (storm, damage, periodic control, etc.)

Risk assessment, design study, installation and control of protection devices should be made by certified professionals. Two labels of certification were created and approved by the administration (Qualifoudre and F2C). EDF obtained a Qualifoudre certification to continue to carry out risk assessment studies on nuclear sites in accordance with classified installations regulation.
In 2012, a new edition of the French regulation defining general rules for design and operation of nuclear facilities was published. It requires that:

- In section 3.5: Internal hazards taken into account in safety analysis report should include EMI (electromagnetic interferences)
- In section 3.6: External hazards taken into account in safety analysis report should include lightning and EMI (electromagnetic interferences)

The nuclear regulation doesn't enforce any method or standard to achieve these demonstrations. It requires being aware of the best knowledge and practices in the words to achieve the best reasonably possible protection level. It also requires that:

- Every method, tool or calculation used in the analysis should be validated, and used in the scope of the validation with an acceptable accuracy
- An experience feedback should be organized and analyzed to improve the system and knowledge. It means huge consequences in the way to deal with lightning protection in the future. As far as the lightning experience feedback is already good, it will probably not change very much the nature and the level of the lightning protections, but surely, it will completely change the way the need of protection will be evaluated, and the way that a good level of safety is achieved will be justified.

The differences between "improved method" and "classical method" are listed below:

- Ng: EDF use a more local Ng inferred from French lightning location system (LLS) operated by Météorage instead of standard County values. Météorage furnishes Ng for all townships. The average surface of a township in France is around 15 km².

- Collection areas: EDF did not use the location factor Cd to calculate collection area of building. Instead, EDF developed dedicated software, called CAPTSURF under Autocad ©. The calculation method is similar to the approach of former IEC guide 61662. The intersections of collection areas of adjacent buildings are divided between these buildings, and the surface of collection area is at least equal to the surface of the building itself. But the difference with IEC guide 61662 is that calculation are computed in 3D.
- LPS: EDF assumed that the metallic or reinforced structure of building is a LPS based on natural components. The lightning protection level (LPL) has been estimated by experts, and taken into account in the calculation.
- Cables protection: EDF estimated an attenuation coefficient linked to cable routing in accordance with the literature [7]. EDF considered 3 types of cable routings: cable accompanied with a grounding conductor with regular connection to earthing system (0.25), cable in a metallic cable tray (0.01), cable in a covered metallic cable tray (0.005).

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* Decree from January 15, 2008 “Lightning protection for classified installations for environmental protection”