ASAMPSA_E SEVENTH FRAMEWORK PROGRAMME	Advanced Safety Assessment Methodologies: extended PSA	EURATOM

"NUCLEAR FISSION "

Safety of Existing Nuclear Installations

Contract 605001

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

- *This version of the report will be submitted to a peer rewiew*
- *The conclusions of the review will be discussed during the ASAMPSA_E workshop with PSA End-Users (12-14th Sept. 2016)*
- *The report will then be improved before the end of the project (31st Dec. 2016)*

Reference ASAMPSA_E

Technical report ASAMPSA_E / WP21 & WP22 / D21.3 & D22.2-3-5/ 2016-23

Reference IRSN PSN/RES/SAG/2016-00189

Authors

I.Ivanov (TUS), P. Simurka (VUJE), J. Prochaska (VUJE), P. Brac (EDF), D. Vasseur (EDF), P. Duquerroy (EDF), C. Trouilloud (EDF), M. Kumar (LRC), S. Potempski (NCBJ), T. Vinot (IRSN), J. Espargilliere (IRSN)

Period covered: from 01/01/2015 to 31/12/2016		Actual submission date: 31/05/2016	
Start date of ASAMPSA_E: 01/07/2013		Duration: 42 months	
WP No: 21/22	Lead topical coordinator :		His organization name :

Project co-funded by the European Commission Within the Seventh Framework Programme (2013-2016)		
Dissemination Level		
PU	Public	No
RE	Restricted to a group specified by the partners of the ASAMPSA_E project	Yes
CO	Confidential, only for partners of the ASAMPSA_E project	Yes

ASAMPSA_E Quality Assurance page

Partners responsible of the document : TUS, VUJE, EDF, LRC, NCBJ, IRSN	
Nature of document	Technical report
Reference(s)	Technical report ASAMPSA_E/ WP21 & WP22 / D21.3 & D22.2-3-5/ 2016-23 Rapport IRSN-PSN-RES/ SAG/2016-189
Title	Report 5: Guidance document - Implementation of LIGHTNING hazards in extended PSA
Author(s)	I.Ivanov (TUS), P.Simurka (VUJE), J.Prochaska (VUJE), P.Brac (EDF), D. Vasseur (EDF), P. Duquerroy (EDF), C.Trouilloud (EDF), M. Kumar (LRC), S. Potempski (NCBJ), T. Vinot (IRSN), J. Espargilliere (IRSN)
Delivery date	31-05-2016
Topical area	Level 1 PSA, Lightning Hazard, Lightning PSA
For Journal & Conf. papers	No

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).

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. Main outcome of this report is focused on development of extended lightning PSA discussing details regarding implementation of such extended PSA.

Visa grid

	Main author(s) :	**Verification**	**Approval (Coordinator)**
Name (s)	I.Ivanov, P.Simurka et.al.	M. Kumar	E. Raimond
Date	10-05-2016	10-05-2016	31-05-2016
Signature			

MODIFICATIONS OF THE DOCUMENT

Version	Date	Authors	Pages or paragraphs modified	Description or comments
Draft 01	11/11/2015	Peter Simurka, Ivan Ivanov	All	
Draft 02	22/11/2015	Peter Simurka, Ivan Ivanov	All	
Draft 03	20/02/2016	Peter Simurka, Ivan Ivanov	All	
Draft 04	30/03/2016	P.Simurka, I.Ivanov , M. Kumar, J.Prochaska	All	
Draft 04	10/05/2016	I.Ivanov , J.Prochaska, P.Simurka, P.Brac, D. Vasseur, P.Duquerroy, C.Trouilloud, M. Kumar, S. Potempski	All	
For external review	31/05/2015	E. Raimond	All	Approval review. Editorial comments. The report still needs further improvement (see indications in the text). In particular the applicability of existing norms in the context of PSA shall be discussed during the review process.

LIST OF DIFFUSION

European Commission (scientific officer)

Name	First name	Organization
Passalacqua	Roberto	EC

ASAMPSA_E Project management group (PMG)

Name	First name	Organization	
Raimond	Emmanuel	IRSN	Project coordinator
Guigueno	Yves	IRSN	WP10 coordinator
Decker	Kurt	Vienna University	WP21 coordinator
Klug	Joakim	LRC	WP22 coordinator until 2015-10-31
Kumar	Manorma	LRC	WP22 coordinator from 2015-11-01
Wielenberg	Andreas	GRS	WP30 coordinator until 2016-03-31
Löffler	Horst	GRS	WP40 coordinator WP30 coordinator from 2016-04-01

REPRESENTATIVES OF ASAMPSA_E PARTNERS

Name	First name	Organization
Grindon	Liz	AMEC NNC
Mustoe	Julian	AMEC NNC
Cordoliani	Vincent	AREVA
Dirksen	Gerben	AREVA
Godefroy	Florian	AREVA
Kollasko	Heiko	AREVA
Michaud	Laurent	AREVA
Hasnaoui	Chiheb	AREXIS
Hurel	François	AREXIS
Schirrer	Raphael	AREXIS
De Gelder	Pieter	Bel V
Gryffroy	Dries	Bel V
Jacques	Véronique	Bel V
Van Rompuy	Thibaut	Bel V
Cazzoli	Errico	CCA
Vitázková	Jirina	CCA
Passalacqua	Roberto	EC
Banchieri	Yvonnick	EDF
Benzoni	Stéphane	EDF
Bernadara	Pietro	EDF
Bonnevialle	Anne-Marie	EDF

Name	First name	Organization
Brac	Pascal	EDF
Coulon	Vincent	EDF
Gallois	Marie	EDF
Henssien	Benjamin	EDF
Hibti	Mohamed	EDF
Jan	Philippe	EDF
Lopez	Julien	EDF
Nonclercq	Philippe	EDF
Panato	Eddy	EDF
Parey	Sylvie	EDF
Romanet	François	EDF
Rychkov	Valentin	EDF
Vasseur	Dominique	EDF
Burgazzi	Luciano	ENEA
Hultqvist	Göran	FKA
Karlsson	Anders	FKA
Ljungbjörk	Julia	FKA
Pihl	Joel	FKA
Loeffler	Horst	GRS
Mildenberger	Oliver	GRS
Sperbeck	Silvio	GRS

Name	First name	Organization
Tuerschmann	Michael	GRS
Wielenberg	Andreas	GRS
Benitez	Francisco Jose	IEC
Del Barrio	Miguel A.	IEC
Serrano	Cesar	IEC
Apostol	Minodora	ICN
Nitoi	Mirela	ICN
Groudev	Pavlin	INRNE
Stefanova	Antoaneta	INRNE
Andreeva	Marina	INRNE
Petya	Petrova	INRNE
Armingaud	François	IRSN
Bardet	Lise	IRSN
Baumont	David	IRSN
Bonnet	Jean-Michel	IRSN
Bonneville	Hervé	IRSN
Clement	Christophe	IRSN
Corenwinder	François	IRSN
Denis	Jean	IRSN
Duflot	Nicolas	IRSN
Duluc	Claire-Marie	IRSN
Dupuy	Patricia	IRSN
Durin	Thomas	IRSN
Georgescu	Gabriel	IRSN
Guigueno	Yves	IRSN
Guimier	Laurent	IRSN
Lanore	Jeanne-Marie	IRSN
Laurent	Bruno	IRSN
Pichereau	Frederique	IRSN
Rahni	Nadia	IRSN
Raimond	Emmanuel	IRSN
Rebour	Vincent	IRSN
Sotti	Oona	IRSN
Volkanovski	Andrija	JSI
Prošek	Andrej	JSI
Alzbutas	Robertas	LEI
Matuzas	Vaidas	LEI
Rimkevicius	Sigitas	LEI
Häggström	Anna	LRC
Klug	Joakim	LRC
Kumar	Manorma	LRC
Olsson	Anders	LRC
Borysiewicz	Mieczyslaw	NCBJ

Name	First name	Organization
Kowal	Karol	NCBJ
Potempski	Slawomir	NCBJ
La Rovere	Stephano	NIER
Vestrucci	Paolo	NIER
Brinkman	Hans (Johannes L.)	NRG
Kahia	Sinda	NRG
Bareith	Attila	NUBIKI
Lajtha	Gabor	NUBIKI
Siklossy	Tamas	NUBIKI
Morandi	Sonia	RSE
Caracciolo	Eduardo	RSE
Dybach	Oleksiy	SSTC
Gorpinchenko	Oleg	SSTC
Claus	Etienne	TRACTEBEL
Dejardin	Philippe	TRACTEBEL
Grondal	Corentin	TRACTEBEL
Mitaille	Stanislas	TRACTEBEL
Oury	Laurence	TRACTEBEL
Zeynab	Umidova	TRACTEBEL
Yu	Shizhen	TRACTEBEL
Bogdanov	Dimitar	TUS
Ivanov	Ivan	TUS
	Kaleychev	TUS
Holy	Jaroslav	UJV
Hustak	Stanislav	UJV
Jaros	Milan	UJV
Kolar	Ladislav	UJV
Kubicek	Jan	UJV
Decker	Kurt	UNIVIE
Halada	Peter	VUJE
Prochaska	Jan	VUJE
Stojka	Tibor	VUJE

REPRESENTATIVE OF ASSOCIATED PARTNERS (External Experts Advisory Board (EEAB))

Name	First name	Company
Hirata	Kazuta	JANSI
Hashimoto	Kazunori	JANSI
Inagaki	Masakatsu	JANSI
Yamanana	Yasunori	TEPCO
Coyne	Kevin	US-NRC
González	Michelle	US-NRC

EXECUTIVE SUMMARY

The lightning (including the electromagnetic interference) on one hand 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: rare meteorological phenomena, as part of the List of external hazards to be considered in ASAMPSA_E [43]. On other hand the survey in the frame of WP10 between the end users shown that the lightning is amongst the ten external hazards most often considered by the respondents [38]. 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 scope of this report is to provide guidance on implementation of LIGHTNING hazards in extended level 1 PSA. This report is a joint deliverable of WP21 (Initiating events modelling) and WP22 (How to introduce hazards in L1 PSA and all possibilities of events combinations) which aims:

- to update the list, characteristics and modelling of the already introduced external hazards in the existing guidance, in particular with the lightning hazards;
- to identify and promote exchanges of some good practices on the implementation of external events in L1 PSA and
- to outline the approach, structure and content as basis and in a perspective development of extended PSA, in particular to LIGHTNING.

Further, the objective of the complete WP21 and to a greater extent WP22 is to discuss good practices for the introduction of relevant modelling for external hazards in an existing (internal events) L1 PSA (event trees).

This report also includes the END USER recommendations given in WP10 and is intended to next external review before the final description for the aim of ASAMPSA_ E project.

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	LRC	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	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

These definitions come from IAEA and US NRC safety glossaries. Some harmonization will be done between all ASAMPSA_E reports in final versions.

This will be updated in the final version of the report.

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.

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].

Ref	WA1	WA2	WA3	WA4	Remarks
IAEA SSG-3	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	x	x			General
IAEA-TECDOC-1511	x	x	x		General
WENRA Issue O	x	x			All External Events
NEA/CSNI/R(2009)4	x		x		Non-Seismic Haz-ard
SKI, Report 02:27	x	x			Non-Seismic Ex-ternal Events
10CFR 50.54(f)	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			x		General
HSE Safety Assessment Principles for Nuclear Facilities 2006 , Revision 1			x	x	General
IAEA NS-R-3			x		General
EPRI 1022997			x		General External Hazards
WENRA-RHWG, Guidance Document Issue T: Natural Hazards.			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)

1 INTRODUCTION

Safety reports and probabilistic safety analysis are included amongst safety licensing documentations for nuclear facilities. External hazards including extreme meteorological events play important roles in nuclear safety. One of the meteorological events is a strong atmospheric discharge - lightning.

Figure 1-1 Lightning

The importance of this hazard increased taking into account the high frequency of its occurrence. For instance the study for the territory of Bulgaria shows that the number of recorded lightnings 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 around 3000-4000 lightnings (mainly in noon and afternoon hours) [33].

One indicative example for the lightning hazard is the study on the lightning risk assessment evaluation on French NPPs [46] on the basis of 30 years of observation (1980-2012) on 19 large industrial nuclear sites refers for very important number of 'structure per year' - material damages (~ 50000 structure per year) and human risk: around 25000 structure per year (about 50% of the buildings are not occupied). From all registered incidents, 116 incidents are with impact on the process, but without material damage (e.g. activation of safety power source) and 51 incidents are with 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, for this study the risk assessment method addresses one third of the lightning events [42]. Statistically, it can be seen as average 1.7 lightnings per year with risk for material damage in nuclear power plant (NPP). Significant times higher is frequency of such events calculated with the Improved EDF's method and much higher with the Standard method (classical application of IEC 62305-2).

Comment : the applicability of current IEC 62305-2 standard (and future improved standard IEC 62305-2 as recommended in [46]) in the context of PSA shall be discussed during the report review phase. See also appendix1.

Based on latest predictions of worldwide climatology panels regarding global warming importance of lightning topic can be more and more relevant [6]. Increasing of average temperature leads to the more frequent and intensive storms that are main lightning sources. Increasing storm frequency including intensity and frequency of lightning can lead to the situation when lightning power can exceeds the limits defined by standards applied for electromagnetic compatibility are used to ensure appropriate protection against impact of lightning. For example, an article [1], indicate an increase in lightning activity by 12% (or 10%) in the warming of 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 theory based on climate model conclude on a decrease of lightning activity because of a stabilization of atmosphere, rather than with more violent events, and higher lightning currents, or higher extreme lightning currents.

The impact of the lightnings due to direct (ground) flash strikes and the resulting secondary effects can have serious consequences on the nuclear power structures and systems. With the advent of digital and low-voltage analogue systems in NPPs, lightning protection is becoming increasingly important. These systems have the potential to be more vulnerable than older, analogue systems to the resulting power surges and electromagnetic interference (EMI) when lightning hits facilities or power lines [34].

For further improvement of the level protection of NPPs against impact of lightnings could be developed by implementation of lightning hazards in extended PSA together with regulatory guidance to address design and implementation practices for lightning protection systems in NPPs.

It is very important to consider the implementation of lightning hazards in extended PSAs to make one realistic link between the objectives of an extended PSA and the methodological approaches to implement lightning hazards.

The strong expectation from End-users that guidance documents should make the link between the definition of the top level objectives of a PSA (i.e. its intended uses and applications) and the choice of methods and tools to execute the different tasks and solve the identified issues.

As precondition for development the present guidance document, with the above presented methodology, is the understanding for introduction of the lightning hazards in the envelope of the overall risk evaluation in the extended PSA, i.e. realistic is to have an evaluation of the lightning hazard contribution to the overall risk presented by a plant. 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.

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, of course shall be searched new advanced methodologies which will minimise the number of opened issues in lightning hazard and its PSA.

1.1 OBJECTIVES

The aim of this report is to describe the phenomenology of lightnings, their effects and potential impact on nuclear safety, as well as to outline the guide to deal with this phenomenon in PSA. This report discusses possible initiating events related to lightning and their parameters.

Whereas (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.

This topic shall consider general lightning phenomenas and its consequences at NPPs, as discussed in the four cases below:

i. Lightning strikes directly on the buildings and facilities, including outdoor switchyard (OSY) at the plant site and the resulting effects on the nuclear power structures and systems.

ii. Lightning strikes outside of the plant, but fell on transmission lines high voltage related OSY at the plant and the resulting effects on the nuclear power structures and systems.

iii. 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.

iv. Lightning strikes outside of the plant 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.

More limited, without considerations outside the standardized vocabulary of IEC 62305, the contents of the Guidance document, could cover only lightning on the NPP site, which can be divided in four sources of damage - on buildings, near buildings, on services (pipes, telecom lines, Low Voltage (LV) power lines) and nearby services. Under consideration can be only 3 types of lightning effects - touch and step voltage, physical damage on structure and overvoltage on electrical or electronic systems.

An approach for the aims of the Guidance for the extended PSA with limitation only in the frame of the existing IEC 62305 is not very suitable, especially for covering the end-users' needs and in perspective for more widely applicable document. Some of reasons are – there are different critical point of views on the standard [43], now more than 100 published lightning protection codes and standards are in use by various countries and by agencies within countries, different documents of US Department of Energy, USA National Fire Protection Association (NFPA) and other are modified [44], etc.

1.2 SCOPE

The scope of this report covers objective stated in previous section as follows:

- Section 2 introduces general phenomenology of lightning, including lightning effects, operational experience and induced hazards. Basic requirements on L1 PSA concerning external hazards, valid and for lightning are summarized presented also here.
- Section 3 deals with database creating which is necessary for assessment of the frequency and magnitude of lightnings as well as for evaluation of the impact of lightning on the plant. Section also briefly discusses topic of plant database to support lightning hazard analyses.
- Section 4 presents basic methodology for lightning hazard assessment as well as the approach how to evaluate impact of lightning on plant equipment. This section forms background for PSA fragility analysis. Within this section the topic of hazard combinations is discussed also.
- Section 5 deals with correlated hazards and combinations of hazards.
- Section 6 presents some methods for assessment of hazards combinations.
- Section 7 provides examples of best practices.
- Section 8 is devoted to implementation of extended lightning PSA

2 GENERAL PHENOMENOLOGY OF LIGHTNING

This section introduces general phenomenology of lightning including lightning effects and operational experience.

2.1 BRIEF DESCRIPTION OF GENERAL PHENOMENOLOGY

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 occurs. There are different lightning, defined in accordance with IEC 62305-1 [5] and IEC 62305-2 [6], 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.

The main relevant lightnings of this report are those occurred from cloud to ground. Common lightning strike characteristics are:

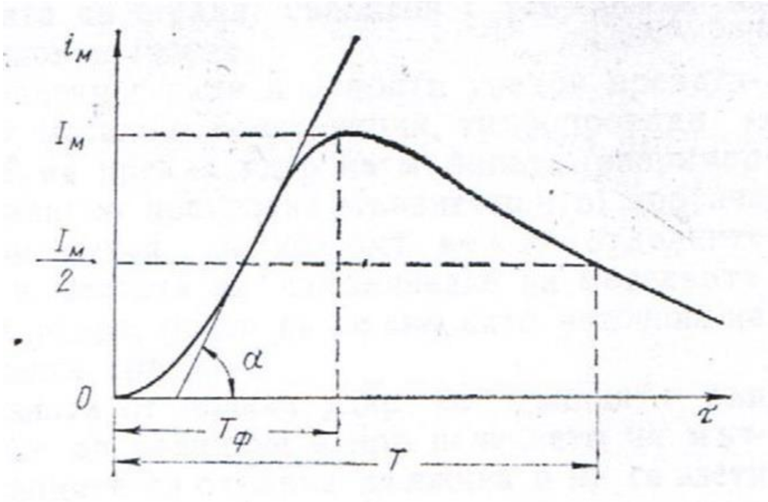

Figure 2-1 Front of the lightning current

- 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 is considered 200 kA.
- The steepness (tgα) of the front of the lightning current curve usually is 5-10 kA/ µs, sometime reaches 80 kA/ µs and for computing value is considered 60 kA/ µs. In IEC 62305-1 for calculation are defined 3 types of lightning waves:

- 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
- It is observed 4 – 16, but in average there 3-4 return strokes per lightning strike
- Typical lightning duration is 20 - 50 milliseconds, but sometime the total duration of repeated lightning reaches the total duration of repeated lightning reaches 1.5 s.
- The wavelength of the lightning current is usually 1.5-10 μs, but sometime reaches 20-100 μs and the computing value is considered 50 μs.
- Temperature can reach almost 50000 °C, but usually is around 20000 °C.

Lightning severity is characterized by different parameters:

- peak current
- urrent derivative
- specific energy
- charge

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 as basic characteristics of lightning impact accepted 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 easy produced. As an example, the Figure 2-2 shows 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.

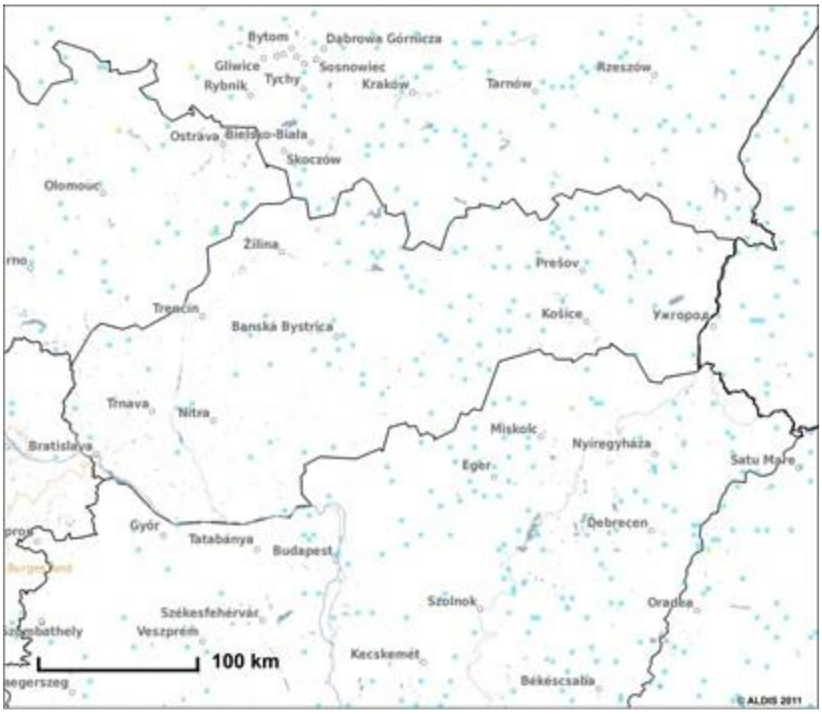

Figure 2-2 Lightning between the cloud and ground at peak current greater than 200 kA in the Slovak Republic and the surrounding area for the years 2002 - 2010

It should be noted, however, that generally is very complicated and hazardous to wrong conclusions to estimate number or probability of extreme values of lightning characteristics. Each estimate of probability of extreme values of lightning characteristics has to be accompanied by information for the sources of the data, method of the calculations and with explanation for the limits of this estimation.

For extreme peak current, for example, there are at least 2 ways to estimate the number of lightning flash greater than 200kA:

- the first method is an extrapolation of lognormal probability based on Cigré (Electra n°41 and 69).
- the second is LLS data's

The both are quiet right on average current values, but false for higher current values and that they overestimate number of high values for different reasons.

Lightning damage falls into two main categories:

- **Physical damage** (as results mainly of so called direct lightning hits/strikes or primary effects) - fire and destruction of structures. More precise, 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** - They 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 conduc-

tive 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, railroad tracks or even utility piping. Common surge suppression technology is not generally effective against this effect of lightning.

- Electro Magnetic Pulse (EMP) - due the 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 ground within the area affected by this field. Such fields can be also 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. IEC 62305-1 instead EMP defined generally 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 upon for diversion of “excess” energy can actually become a source of this energy. Commonly relied upon 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 the system. If an ideal low impedance single point grounding system existed in the facility, then resistive coupling due to Low Side Surge would be a non-issue.

Practically from lightning several type of fault that can be affecting the electrical net and equipment of NPPs as disturbances in the voltage, frequency or phase angle.

In practical terms, relating to safety is very important the lightning hazard to be considered in the extended PSA depend of the degree of the consequences of the lightning impact to the electric supply needed for the normal safe operation of NPPs and also in cases of accident conditions. Such analysis could be more general from theoretical point of view but at least should be consider the most probable possible, presenting cases. Such possible cases, for instance for the conditions of Kozloduy NPP in Bulgaria, are presented here and they are representative for a lot of other European NPPs:

a) Loss of off-site power (LOOP)

Loss of the off-site power is defined as interruption to all the connections with the NPP with Electric Energy System (EES).

The Kozloduy site is connected to the EES of Bulgaria at the OSY at voltage levels of 400 kV, 220 kV and 110 kV. Cross connections between these are made through transformers. The total number of the transmission lines to which the Kozloduy site can be connected is 17, among which 13 are transit lines and four are radial ones. Normal and safety buses of VVER 1000 Units 5 and 6 are powered from the main generator, through the auxiliary transformers. A standby power supply is provided from OSY-220 kV. The second standby power to the units is provided from the standby power supply busbars of the other power unit (Unit 5 is powered from Unit 6 and vice versa). Off-site power supply to the bank pumping stations is provided from OSY-220 kV, and the redundancy is provided from the Bukyovtsy substation of 110 kV.

Generally, a design solution for LOOP is to transfer the house load to the reserve lines from the 220 or 110 kV power grids. The switchover is automatic. If the 110 kV grid is available but the automatic switchover fails, operators can make the connection manually.

In principle, house load operation is possible as the first defence line against the loss of the 400 kV grid connections. However, the plant tested the house-load capability and came to the conclusion that this mode of operation is rather unstable and therefore is not considered by the plant as a reliable source for emergency situations.

If this automatic switchover is successful, the plant can continue the house-load operation. If the main grid, back-up grid or house-load operation are not possible, the plant safety buses are powered from the Diesel Generations (DGs). Each train of the emergency power supply system is capable of ensuring a safe shutdown state in all design basis accidents.

The Bank Pumping Station (BPS) has DG, which supply the emergency service water pumps, shaft pumping stations, fire annunciation installation and fire extinguishing in the BPS and their supporting systems. The BPS is equipped with two DG sets. Two accumulator batteries are installed in the BPS to guarantee uninterrupted power supply to the most important consumers.

The Spent Fuel Pools (SFPs) rely essentially on the same cooling and electric supply systems as the reactor.

b) Loss of off-site power and loss of the ordinary back-up Alternating Current (AC) power sources

Each of VVER 1000 Units 5 and 6 has one additional independent DG with nominal power of 5.2 MW. These DGs are located in a container located on a platform, 1m above ground and belong to Class-4 equipment in accordance with OPB-88/97, and in seismic category 2. The Additional DGs are in hotstand-by mode. These DGs can power consumers to allow for heat removal from the primary as well as the secondary systems total fuel and oil reserve of additional DGs ensure continuous operation for more than 4 days.

c) Station Blackout (SBO)

In case all AC power is lost, the accumulator battery can supply Direct Current (DC)/AC power to the category-1 safety buses, i.e. for which uninterruptible power supply (UPS) shall be ensured. There are three batteries ensuring 3x100% redundancy at each Unit. In addition to the station batteries with discharge time of 10 hours, there is a common plant accumulator battery, which powers a computer-based information system, and which can be charged from the additional DG.

Other very important aspect of the lightning hazard which has to be considering in the extended PSA refers to the relevant effects on the electronic and computer systems, communication systems and digital I&C.

The topic of lightning can be essential for nowadays plants widely using digital Instrumentation and Control (I&C). Microprocessors and integrated circuits are subject to weakening damage from reverse electrical energy as little as one micro joule comparing with wires that withstands several kJ. Even if modern electronic systems include intricate circuitry designed to filter such transients, there is a limit to their effectiveness. If the effective surge is large enough, as in a lightning related event, damage can occur and performance will be affected. When the accumulated damage reaches a critical level, the component will fail. Unpleasant point of this conclusion is that lightning effects could form common cause failure which could put out of operation several or all control trains. If extreme lightning strike occurs than Computer Systems, Programmable Logic Controllers (PLCs), Input/Output (I/O) cards could demonstrate symptoms of degraded performance as unexplained data loss, errors in data transmission for networked systems, bios errors, system slowdowns, erratic behavior, unexplained lockups operation, reboot of computer systems etc.

To summarize 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.**

2.2 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 [5]. Below given pictures, Figure 2-3 and Figure 2-4, overtaken from [5] illustrate distribution of external events in Germany and France caused by variety of external hazards.

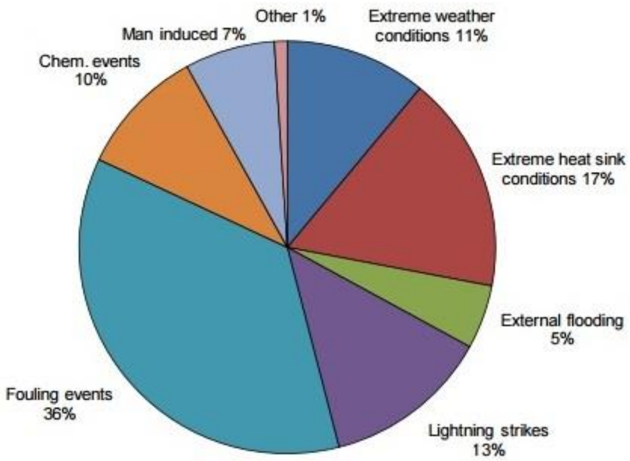

Figure 2-3 Distribution of external hazard related events in Germany

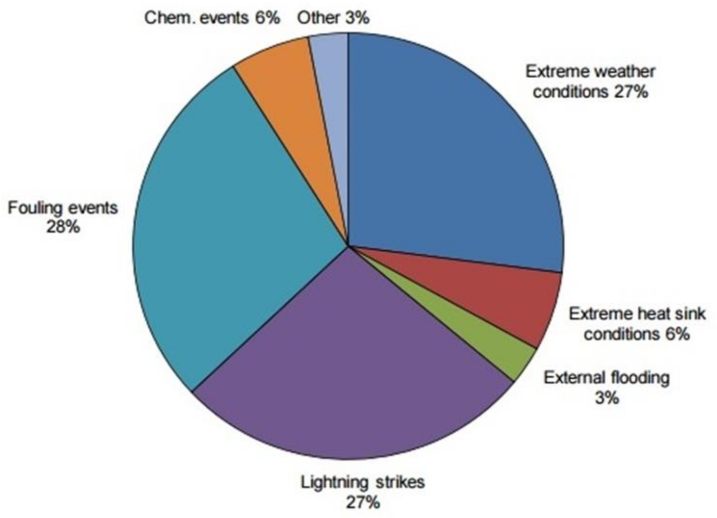

Figure 2-4 Distribution of external hazard related events in France

The illustrated information in the both figures could be considered only as fact for distribution of external hazards, but will be very useful one more precise analysis of the events relevant to 13 % and 27 % lightning strikes in Germany and France, 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 an examination of 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?

Further, more consideration is needed on where are the lightning hazards as assessment of the end users in the list of the hazards needed for involvement in the extended PSA? Undisputable the lightning hazards should be subject of the extended PSA because the survey in the frame of WP10 between the end users shown (Figure 2-5) that the lightning is among the ten external hazards most often considered by the respondents [35].

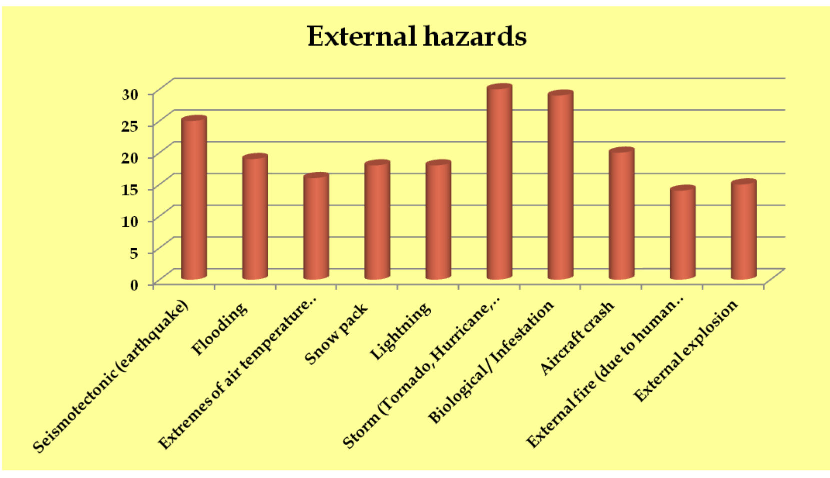

Figure 2-5 Distribution of external hazard related events from ASAMPSA_E End-Users survey

Some safety significant events caused by the lightnings in Europe or in other countries (ASAMPSA_E - WP10 - D10 3 - high amplitude external hazards) 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 lightnings

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	

2.3 BASIC REQUIREMENTS ON L1 PSA

The basic requirements on L1 PSA are given in many good practices agency guidelines and national regulatory guides, e.g. the publications [7], [15] and other. In this report it is appropriate to display the stages in accordance with the Section 6 of [7] 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.

Another, widely used framework of lightning risk assessment accepts the standard IEC 62305-2 objectives, e.g.:

- 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,

which should include hazard analyses, but for this purpose basic data describing lightning distribution, lightning parameters and some supplementary datas are needed. Supplementary data 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 which failures affect plant safety function and design and qualification of lightning protection system. Internal supplementary data should 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 that which fires and/or accident can could be induced by lightning strike and are capable of affecting nuclear safety and/or performance of the plant / facility of interest.

The analysis of the lightning hazards in the extended PSA should include and the assessments of the damages, standardized with IEC 62305-2 i.e. there are necessary also data for the all type of damages. 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 expected these types of loss to be not maintained in the next revision of the standard in 2018.

3 DATABASE ON LIGHTNING PHENOMENA

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

3.1 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 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 3-1 and the similar map of Bulgaria in Figure 3-2. 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. [28]. 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 4.1.

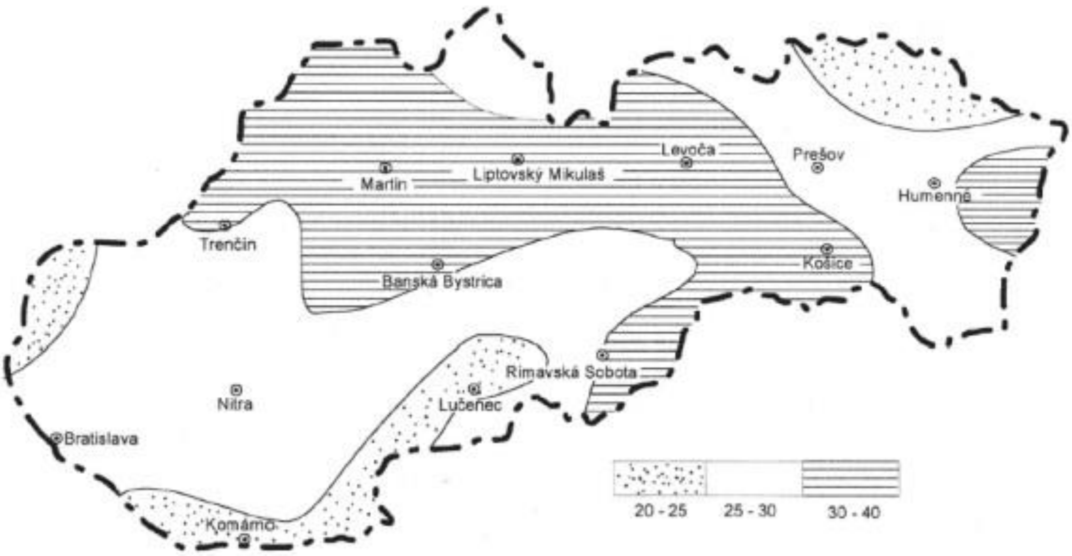

Figure 3-1 Isokeraunic map of the Slovak Republic

Figure 3-2 Isokeraunic map of Bulgaria

Such maps, as in Figure 3-1 and Figure 3-2, can be used as input to assess lightning strike density. For the Slovak Republic it is shown in

Table 3-1 Map referred in: Transmission and Distribution Electrical Engineering [39]

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 depend of intensity of lightning activity [36] is shown in Table 3-2.

Table 3-2. 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 [45] the thunderstorm activity has long been defined by the keraunic level (Nk) that is to say "the number of days per year where 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 and represents an average over the last 10 years. The mean number of stormy days in France is 11.30.

The criterion of the number of thunderstorm days does not characterize 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 km^2 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/ km2/year.

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

$$Df = Da / 2.1$$

The French study [45] shows that 50% of lightning strikes have an intensity lower than 50 kA and 99% higher NCI-200 kA.

According 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 totally to be disappear from the standard. If there are no local LLS to evaluate Ng, like in desert or ocean, the ground flash density

The average number of lightning strikes in Europe, according [14] 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 3-3. 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 3-4.

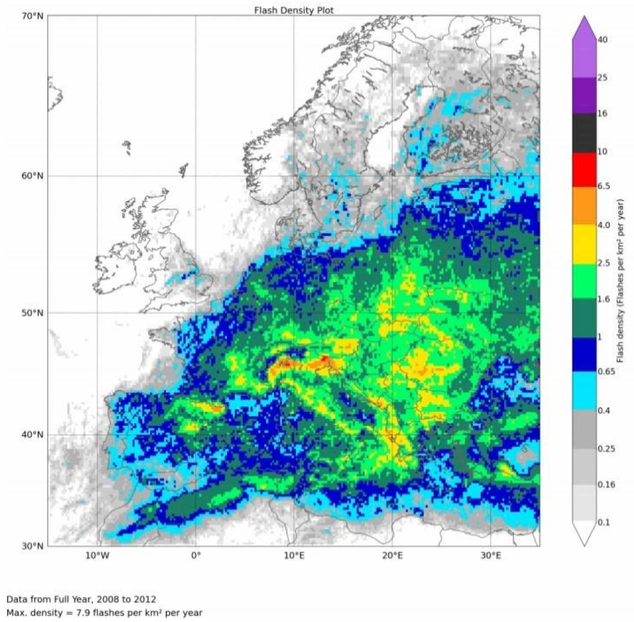

Figure 3-3 **Annual detected lightning flash density**

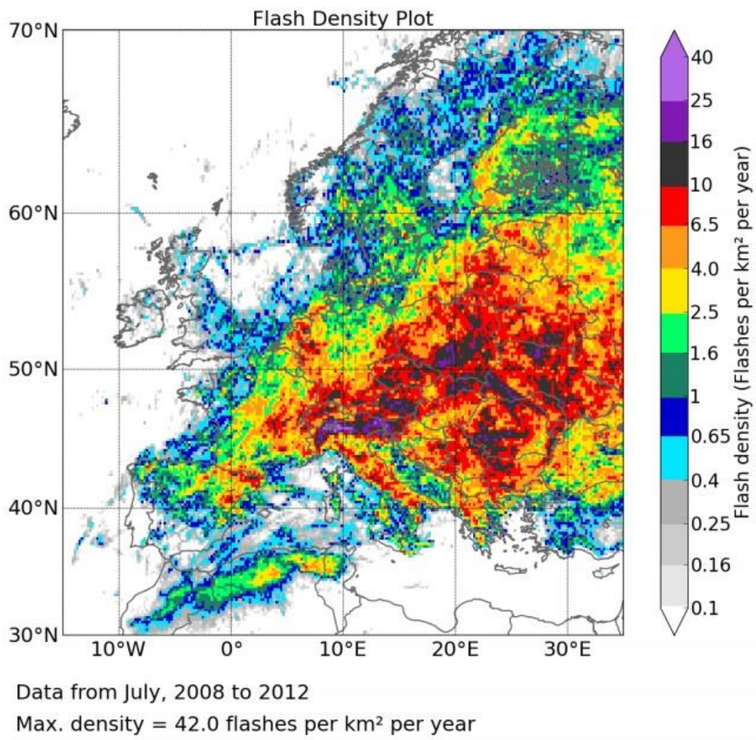

Figure 3-4 Detected lightning flash density for July

Finally in order to be able 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: These data provide description of safety relevant components or external facilities / formation that can produce lightning induced initiating events. Supplementary data shall be plant specific.

As a precondition to be defined and introduced an uniform data taxonomy which to be used in formulas that evaluate lightning impact, could be summarized the basic data in Table 3-3 as follows.

Table 3-3 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	
i_p	Peak current (prospective return-stroke peak current)	
i(t)	Current pulse	
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 - $R=f(i_p, h)$	
	Derivative of the magnetic field of electromagnetic field generated by first and subsequent return strokes	

Important note is that among these selected basic parameters (Table 3-1) 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 network monitoring lightning.

3.2 EXTERNAL DATA SOURCES

In accordance with the recommendations of the International Electrotechnical Commission (IEC) in the IEC 62858:2015 [39], 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) [6].

The lightning ground flash density N_G is defined in the Table 3-1 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.

As far as IEC 62858 defines minimum level of quality acceptable for LLS, in this document is appropriate indication of some basics. The lack of common rule for defining requirements either for their performance or for the elaboration of the measured data request the application of measures to make reliable and homogeneous the values of N_G obtained from LLS in various countries, like these presented in IEC 62858 [39]. Motivations for that are also:

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

For application of the method based on the lightning ground flash density N_G there are required lightning data from LLS for a least ten years and taking into account the changes in the global meteorology, the newest data used not being 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 x1 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 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 (2.2-3), 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 a LLS can be evaluated using variety of techniques [38] mong which more suitable for studies of lightning properties are:

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

In one 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, as the next both:

- the locations of the LPS to be defined on the basis on the recommended in [46] distance between an LPS down-conductor and the protected object in air, which should be greater than *Dair* 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 *Dair*=0.12*Z* (m)

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

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

where

I is the lightning peak current, and *Eb* is the breakdown electric field in the soil.

Other theories for lightning striking distance versus return-stroke peak current are presented in the Figure 3-6.

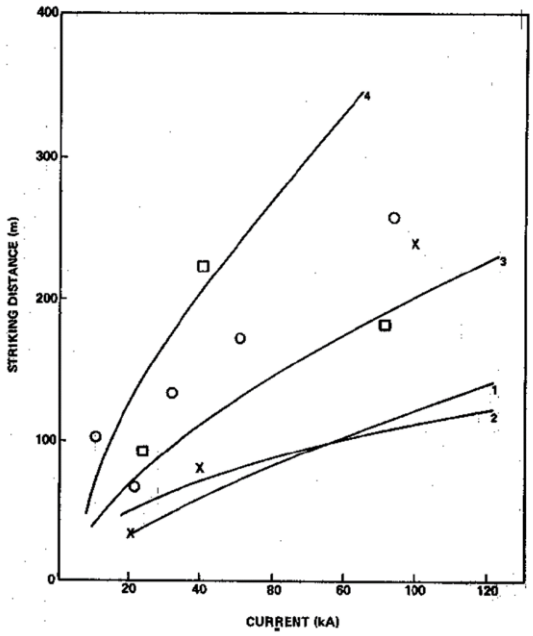

Figure 3-5 Striking distance versus return-stroke peak current

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 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 [9] etc.

Farther 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 detail 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.

3.3 PLANT DATABASE

Plant database should integrate all data that are necessary to assess lighting hazard. Usage of database is not 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 50 km, taking into account some examples, for instance in Sweden (Table 2-1), that even very distant lightning events may cause electrical disturbances.

4 LIGHTNING HAZARD ASSESSMENT METHODOLOGIES

This section introduced basic methodology to evaluate parameterized frequency of lightning strikes as well as the approach how to evaluate the impact of the strike on plant' equipment, i.e. this section forms background 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.

In general it is recognized that the degree of uncertainty in estimating risk due to accidents caused by lightning events tends to be greater than that associated with other accident-initiating events that have been analyzed. Some uncertainties stem from less experience in analysing this kind of event and have to say the probability analysis of the lightning hazards is one relatively new area, also no enough full or suitable data – in the most of time the damage from lightning 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 practically may rely with greater confidence on engineering judgments and expert opinions.

In the lightning hazard assessment methodology for the aim of the extended PSA the potential consequences have to be in the front of the attention, but in the selection of lightning events for a detailed risk analysis have to accent also to the frequency of occurrence and magnitude of the lightning. The results of the lightning event analysis will be used as input to the PSA in defining initiating events, in developing event and fault trees for accident-sequence and system analysis, and in quantifying accident sequences.

The scope and time consumption of analysis suggested here for lightning event is commensurate with the overall objectives of this document, and presented current state of the art in analysing risks from lightning events. Since such analyses are still in a developmental stage, it can be expected that the methods used in the analysis of lightning events can undergo significant changes as the PSA community gains experience in the treatment of lightning events in PSAs.

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 rep-presentation and evaluation of impact of lightning - fragility analysis.

This section covers both frequency assessment and fragility analysis.

4.1 PARAMETRIZATION AND LIGHTNING STRIKE FREQUENCY ASSESSMENT

This section covers two basic areas. They are 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 particular facility.

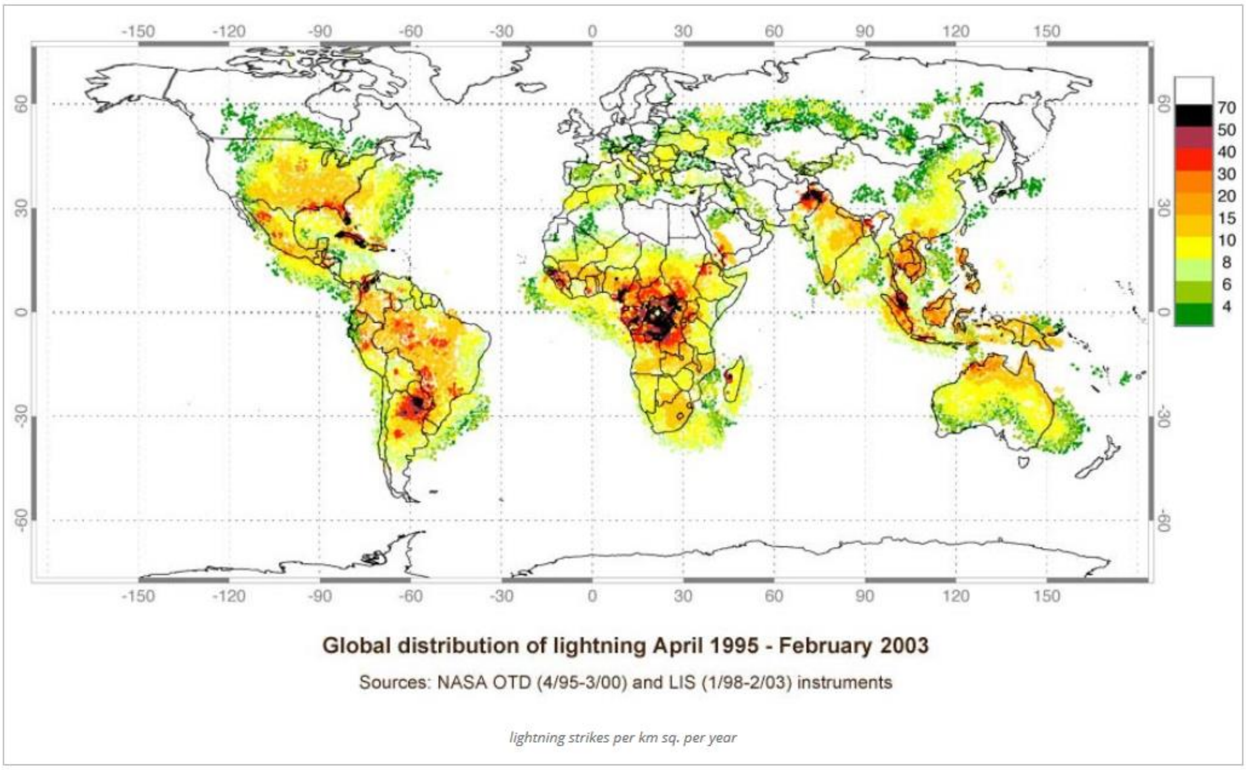

Figure 4-1 Global distribution of lightning April 1995 - February 2003

Effects of lightning are connected to following parameters, described in Table 3-1 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 know that the real values of lightning are finite because of the limited thickness of troposphere.

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

4.1.1 DEVELOPMENT OF GENERIC HAZARD CURVE

Generic hazard curve relies on number of storm days or on generic values of N_g, e.g.table 3.1. Peak current i_p can be based on IEEE data –Figure 4-2 from [16]. It is noted that this curve is valid only to 200 kA.

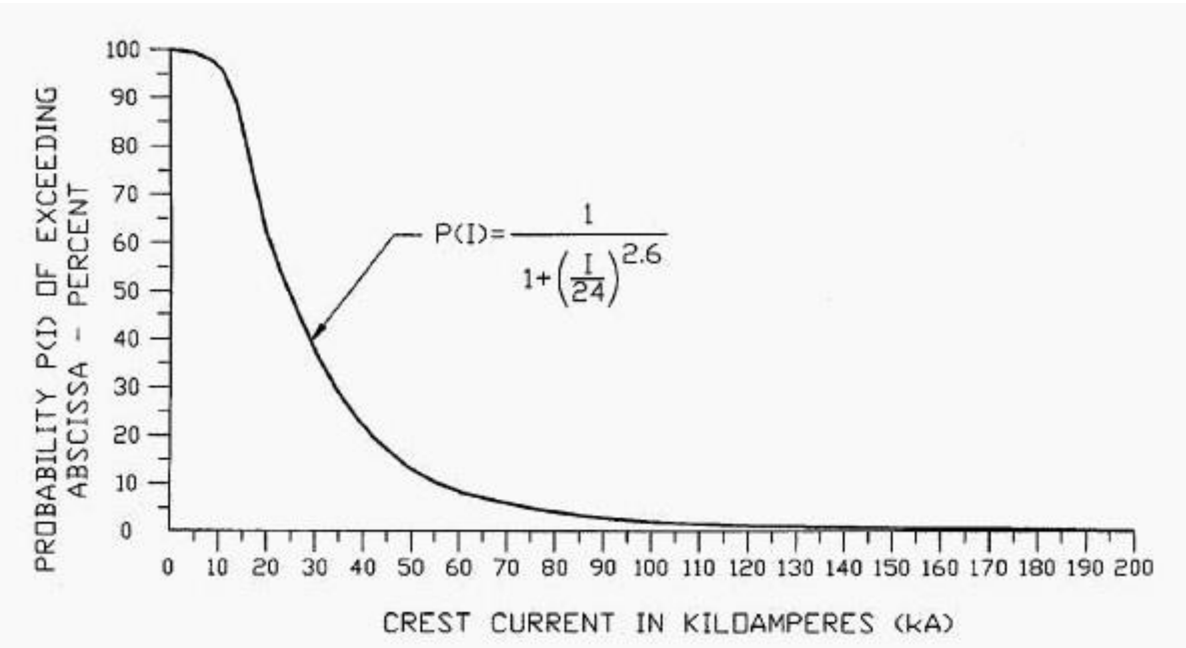

Figure 4-2 Probability of stroke current exceeding abscissa for strokes to flat ground

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. According to this description, for $i_p \le 20$ kA the median value is 61.1 kA and the standard deviation is $\sigma_{\ln_{i\_}} = 1.33$ for $i_p > 20$ kA, the median value is 33.3 kA and the standard deviation is $\sigma_{\ln_{i\_}} = 0.605$.

Typical output of lightning hazard curve is presented in the picture shown on Figure 4-3.

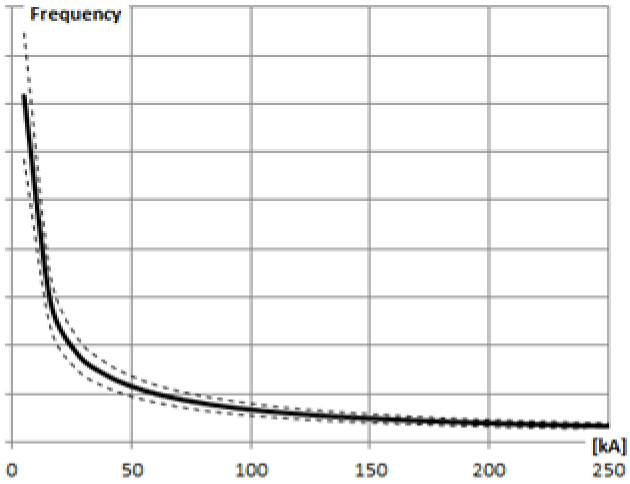

Figure 4-3 Curve of exceedance frequency versus lightning intensity

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

4.1.2 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 km2) and data describing lightning intensity. Such estimations should take in 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.

4.2 FRAGILITY ANALYSIS

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

$$P_{cf} = F_s \cdot P_{ip}$$

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

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 [42] are:

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

ii. IEC 62305-2 calculation are not adapted for nuclear sites. EDF compared 62305-2 risk assessment with experience and real damages on its nuclear fleet, and published the results in ICLP 2014 in Shanghai [42]. The conclusion there is that the standardized calculation overestimated the risk of a factor 100 to 1000, and consequently that 62305-2 risk assemement could not be use 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 no common ground to reject the application of existing IEC 62305-2, though perhaps the overestimated risk means reinsurance with resized protection. It can be noted, at that time EDF is still working with the first edition of IEC 62305-2 (2006) in accordance with French regulation [42].

Following sections introduce probabilistic approach based mainly on the individual parts of the IEC 62305 as are, [5], [6], [7], [8] and [9].

Lightning current limit i_p of high-risk considered by quoted standards is 200 kA, which is also indicated in the most of the 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 those 99% are not strictly scientifically proven, the use of such a high value of 200 kA design brings more security of the protection.

4.2.1 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

[1] In general P_{cf} function of stress F_s and propable damageP_{i_p}. If the process of lightning flashes is treated as homogeneous and stationary then can be expressed as $P_{cfexact} = 1 - e^{-F_s \cdot P_{i_p}}$.
With the assumption that product $F_s \cdot P_{i_p} \ll 1$; $P_{cfexact} \approx P_{cf}$.

unit area uniformly[2] than frequency / probability that relevant area A is affected by lightning strike can be estimated as

$$F_s = F_{i_{pl}} \cdot A \quad \text{E-2}$$

Where

$F_{i_{pr}}$ 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 [9], can be used where A is replaced by so called effective area A_e.[3]

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

There will be 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 4-1

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 4-1 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.

2 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.

3 Document [41] 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 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 [13].

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

Darveniza [18]	$S = 2 \cdot i_p + 30 \cdot \left(1 - e^{-\frac{i_p}{6,8}}\right)$	
Love [17]	$S = 10 \cdot i_p^{0.65}$	
Whitehead [21]	$S = 9.4 \cdot i_p^{2/3}$	
IEEE [19]	$S = 8 \cdot i_p^{0.65}$	E-3
Suzuki [20]	$S = 3,3 \cdot i_p^{0.78}$	

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

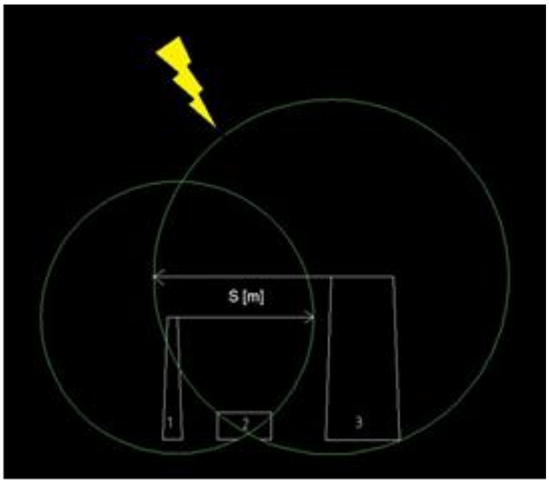

Fig. 4-4 Protective features of neighbouring buildings

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.

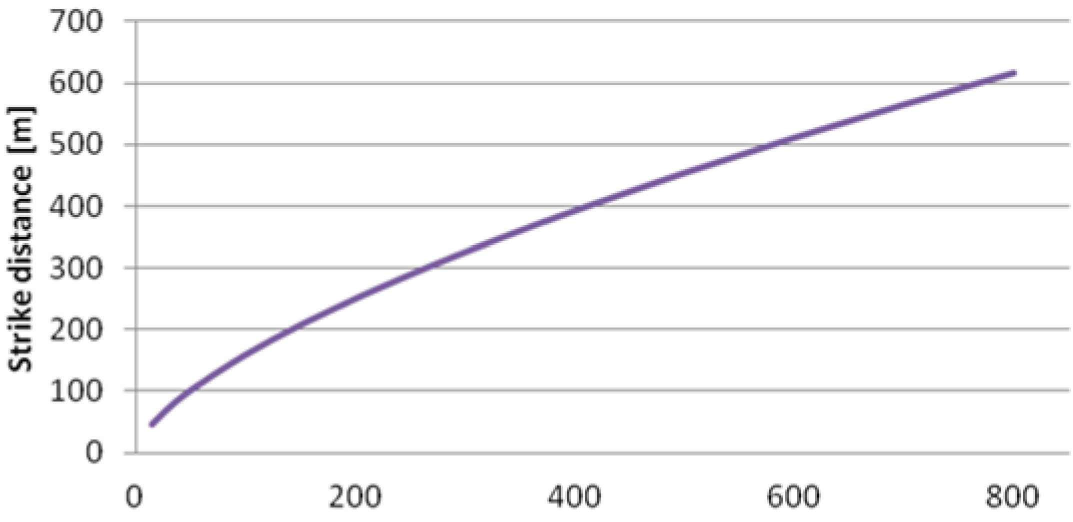

Fig. 4-5 Strike distance dependence on the ip [kA]

This way can use to screen cases when the sensitive buildings; that are in the protection zone of the others high buildings; will be hit by direct lightning strike. But this assumption holds only in case if there is no common air-termination system.

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 you can see attenuation of the intensity of the magnetic field depending on the distance from the strike point.

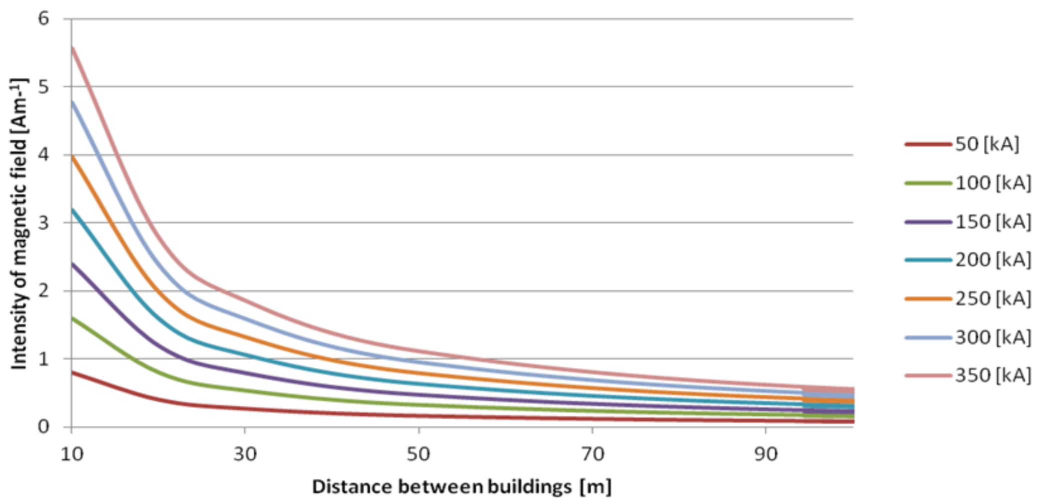

Fig. 4-6 Intensity of magnetic field as a function of the distance between buildings

Presented graph demonstrates decreasing of the intensity of the magnetic field depending on the (air) distance according intensity lightning. This effect ensures fast decreasing magnetic field crated by lightning to the design level event if initial strike exceeded more than 200 kA. However; necessary conditions is 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 [36], 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.

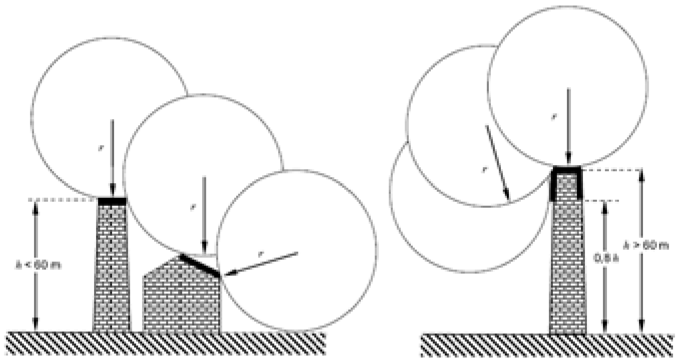

Fig. 4-7 Determination of lightning zone by method of the "notional/fictitious rolling sphere"

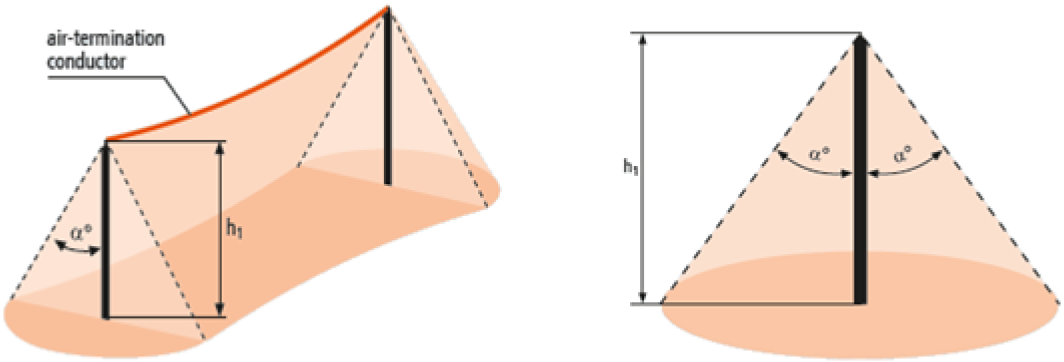

Fig. 4-8 Protective angle/cone - Volume protected by an air-termination conductor

When assessing the risk from lightning, the level of the lightning protection is determined depend of two components:

- RD - 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;

- RI - 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 be-tween 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 4-2a 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) [47] 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 [47] includes two additional items in the above Table 4.2

Table 4-2b 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 of the level of the lightning protection:

Table 4-3Radius 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 [36] is similar as presented in the section 4.2.2.

4.2.2 ESTIMATION OF PROBABILITY OF FAILURE OF RELEVANT COMPONENTS

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

- Approach based on IEC
- Analytical approach

4.2.2.1 Approach based on IEC

Approach based on IEC brings significant simplification of work. This approach is based on assumption that evaluated object has implemented appropriate lightning protection level which was discussed in section 4.2.1. 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 $\langle 0; 200 \rangle$ kA.

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

The primary cause of damage is the lightning current depending on the location of the flash. The standard [9] 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 the 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:

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

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 [9] 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:

$$R_B = N_D \cdot P_B \cdot L_B$$
$$R_C = N_D \cdot P_C \cdot L_C$$
$$R_M = N_M \cdot P_M \cdot L_M$$
$$R_V = (N_L + N_{Da}) \cdot P_V \cdot L_V$$
$$R_W = (N_L + N_{Da}) \cdot P_W \cdot L_W$$
$$R_Z = (N_I - N_L) \cdot P_Z \cdot L_Z$$

Further details can be found in [9] 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.

Above presented 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 can be not screened out detailed fragility analysis shall be performed, however this analysis forms 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 a shielding, grounding ....).

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

Estimation of magnetic inductance evoked by lightning strike (see also Figure 3 7):

$$M_I = {}^{I_p}/_{2\pi \cdot d} \quad \text{3-16}$$

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:

$$Attenuation(dB) = 20Log\frac{E_1}{E_2} \quad (4\text{-}1)$$

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 complex topic; this one is not trivial topic, however without providing some attenuation data 3-17 is unusable. May be could be more 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 to 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, above presented approach forms great simplification. Description of different methods could be find in the information sources which given resources demonstrates not trivial nature of such kind of analyses [19]. [20], [21], [22] and [23]. Of them can be summarized that there is no standardized procedure to calculate life expectancy (or expectation for damage) of the surge protection device and each manufacturer offers their own method based on their experience for calculation life expectancy (or damage).

In addition, is possible to use, for example, the individual parts of IEC EN 61000 family. The main directive for EMC is Directive 2004/108/EC [27] 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].

5 CORRELATED HAZARDS AND COMBINATION OF HAZARDS

/this chapter need improvement in the final version/

Lightning strikes are in general a consequence of storm activity. On the one hand lighting strikes can induce large spectra of external initiating events like accidents of industrial facilities, wild fires, power grid disturbances etc…[43], [44].

The following hazards can be listed as correlated/combined with lightning events:

- heavy rain and wind due to storm activity,
- internal fires induced by direct lightning strike or as a side effect of indirect strike,

- releasing of poisoning substances,
- forest fires,
- accident of industrial facilities which failure can affect safety conditions of the analyzed plant,
- agriculture fires (stubble, bale of hay, feeds, etc.),
- transport fires explosion on the roads located nearby to the NPP site, etc.
- pipeline explosion.

In general, there is none evidence of simple correlation between induced events and lightning strike. May be that partial exception is formed by wild fires, but ignition of wild fire by lightning strike depends on many factors as season, humidity etc.

A storm can produce several lightning strikes that simultaneously hit several safety relevant targets, but even if lightning activity is well mapped, there are no known case of some storm that produced several simultaneous lightning strikes in small area [to be discussed during the report review].

It could be accepted that in the general case of PSA, the lightning event does not require specific consideration regarding correlation and combination of hazards. In specific cases, when there are conditions around the plant characterised with availability of forests or technical facilities which can have a fire hazard, could be used different methods for the assessment of hazard combinations. [to be discussed during the report review].

6 METHODS FOR THE ASSESSMENT OF HAZARDS COMBINATIONS

/this chapter need improvement in the final version/

Previous section determined the main possible combinations of hazards induced by lightning, namely: Internal fires, Releasing of poisoning substances, Forest fires and Accidents of industrial facilities.

6.1 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 [9] concretely by R_B, see section 4.2.2.1.

6.2 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).

6.3 FOREST FIRES

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.

6.4 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 [43]: "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.

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 [52] [53]. 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 [53].

The application of FSA method and supporting tools are implemented at Goesgen-Daeniken NPP, Switzerland and Medzamor NPP, Armenia. The methodology is described in detail in IAEA paper [53].

Extreme Event Analyzer (EEA) Methodology

Lloyd’s Register Consulting (LRC), in cooperation with IAEA, has further developed the FSA method [54]. 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 utilise 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. 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 [54] [55]:

- identify sensitive scenarios for extreme events;

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

Below is a list of sequential steps to perform while using the EEA method to identify scenarios sensitive for extreme events [54]:

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.

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.

7 BEST PRACTICES (EXAMPLES)

/this chapter need improvement in the final version – other examples/

This report describes how lightning events are selected for detailed evaluation in a PSA including discussion the methods used to evaluate their frequency and effects.

It is assumed that the basic PSA methods and procedures for internal events presented in the many internationally accepted standards are generally applicable to all risk contributors, including external events, like lightning.

However, there are several specific aspects for setting establishing separate specialized guidelines reflecting those specific aspects. Most important, the analysis of lightning events requires the use of specialized methods to address important factors not usually encountered in the analysis of the internal events. These include the assessment of frequency of occurrence versus magnitude for lightning events and the modelling of component and structure failure in terms of variables that describe physical interactions.

Because we are dealing with relatively new area having limited experience, there can be introduced only a few general recommendation as follows.

If lightning events are deemed to significantly contribute to the overall plant risk, work on analytical models and data collection should be enhanced in the future. Refined results may eventually reduce the uncertainties. In the meanwhile, a detailed peer review of the assumptions, models, and input-parameter values is necessary to achieve consistency between different PSA studies relying heavily on engineering judgment in the treatment of lightning events.

Since a risk analysis of a lightning event would interact in many of the PSA elements generic to any risk contributor, there is an aim to modularize the steps risk-analysis procedure for lightning events so as to avoid overlaps on event and fault tree levels.

As practical case is mentioned here the research [37] to improve lightning protection and reduce surges in the internal network and relay protection circuit of Kozloduy NPP made by High Voltage Technique Laboratory (HVT

Lab.) of Technical University of Sofia (TUS) in Bulgaria. Some of the equipment of HVT Lab is shown in Figures 7-1 and 7-2.

Figure 7-1 Impulse voltage generator IP 7.5 / 750 kV

Figure 7-2 Spheres MKF 75

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 7-3). The measured amplitudes of the input voltage of the relay protection are 250-300 V with a short duration (Figure 7-4).

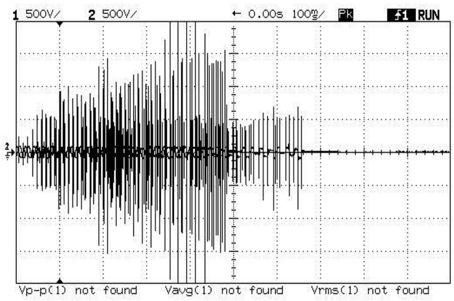

Figure 7-3 Wave voltage with amplitude until 2.5 kV

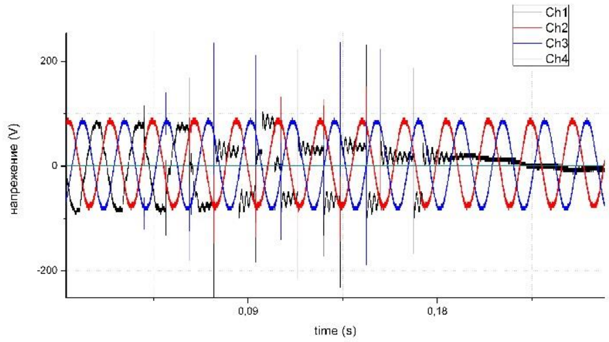

Figure 7-4 Amplitudes of the input voltage of the relay protection 250-300 V

There are other research of HVT Lab of TUS in Kozloduy NPP and defined recommendations for improvement of the lightning protection system of the plant.

8 EXTENDED LIGHTNING PSA

In addition to the basic requirements on L1 PSA summarized in [7], [15] etc. specific information is provided in this section. Overall picture of analysis process from [4] is presented here as Figure 8.1.

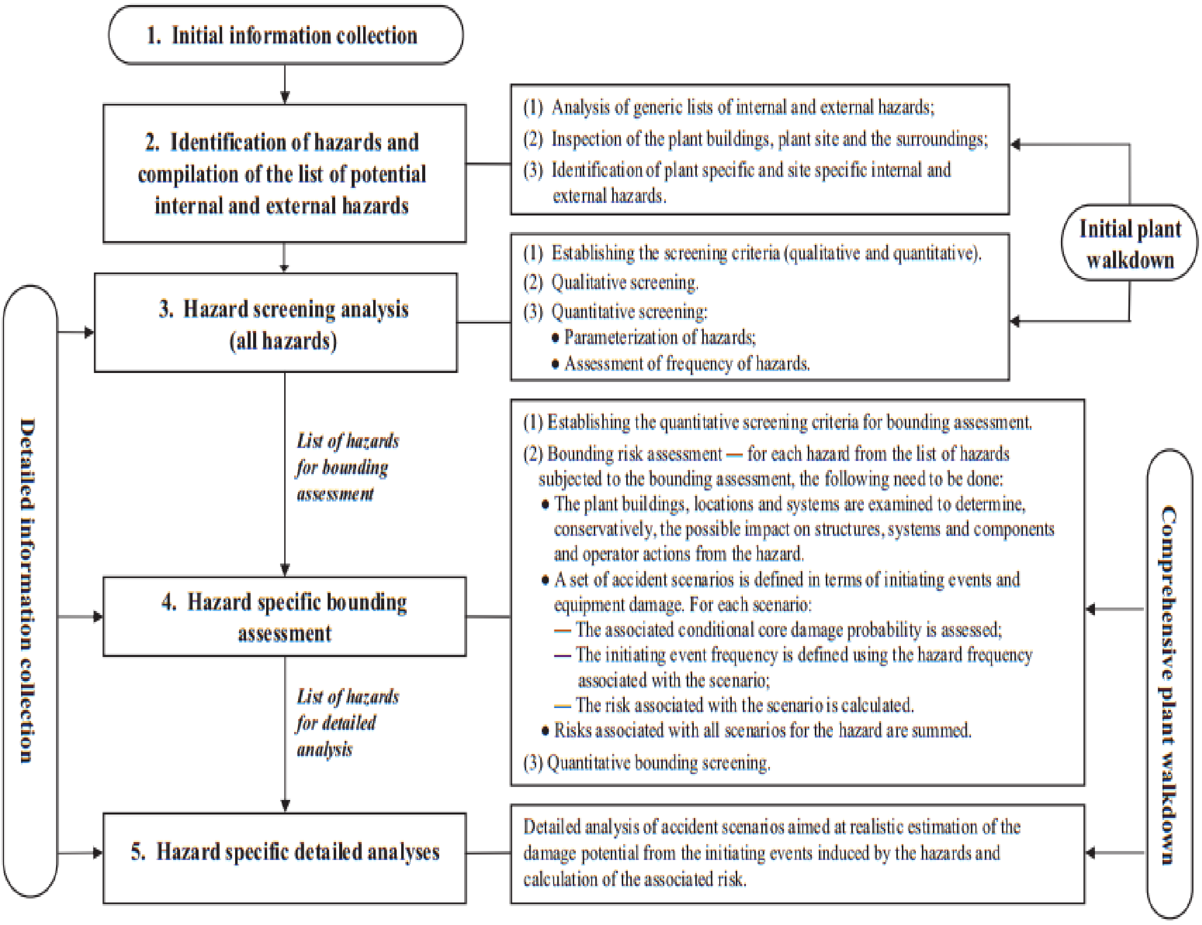

Fig. 8-1 Overall picture of analysis process for internal and external hazards, [7]

Based on general description, mainly in [7], methodology to evaluate impact of lightning event can be outlined into following logical sequence of steps.

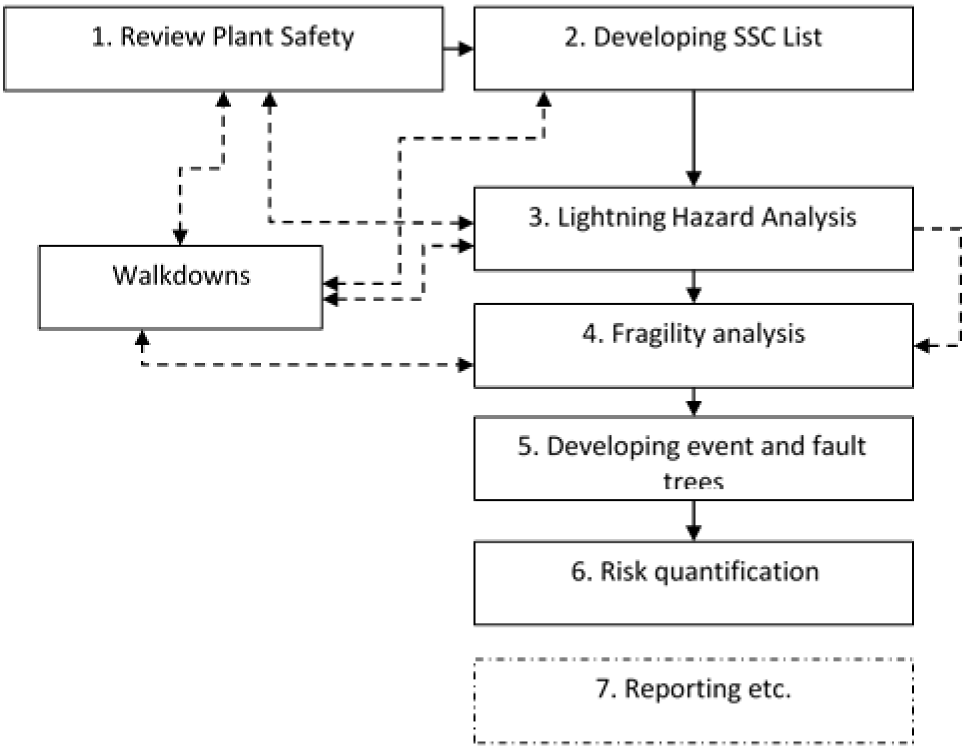

Fig. 8-2 Logical diagram for lightning PSA

8.1 STEP 1 - REVIEW PLANT SAFETY

The aim of this step is to determine list of all events that can be evoked 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 damage with certain probability P_{cf}, see section 4.2.

This step should be based 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 mainly influence of external industry and external fires.

This step corresponds with items 1 and 2 in and work should consider information presented in section 3. Outputs of this step are:

- list of internal and external (initiating) events that can threat plant safety
- general information like list of relevant plant buildings including information about their lightning protection
- lightning protection levels (LPL) and lightning protection zones (LPZs) of particular structures.

8.2 STEP 2 - DEVELOPING SSC LIST

Input of this step is result of step 1. Aim of this step is collection of detailed information (in the greatest extent possible) to be able to perform fragility analysis. Work should on one hand take into account that the lightning protection is most of time based on protection at building level, and on the other hand, to use as background PSA for internal events, internal fire and explosion analysis, external hazard analysis and plant design basis.
Outputs of this step are:

- list of plant internal SSCs that if affected by direct lightning strike or lightning strike side effects can trigger events determined in step 1 including data regarding location, shielding, earthing, lightning protection (if appropriate), design data etc.
- more detailed description of external events if appropriate input data to evaluate impact of wild fires etc.

8.3 STEP 3 - LIGHTNING HAZARD ANALYSIS

Aim of this step is to estimate lightning hazard curve. Work is based on information presented in section 4.1.

Inputs of this step are data described in section 3 and output of this step is plant hazard curve. It is convenient to approximate hazard curve by finite number of discrete intervals (e.g. doublets containing CI versus probability).

8.4 STEP 4 - 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 within step 1.

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 shall be clarified the efficiency of the protection system as a function of type and fragility of components and peak current value.

Work is based mainly on methods described in section 4.2.

Exception is formed for the often occurring combination “lightning – forest fire” indicated in section 6.3. 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 [29].

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 finding in different references [27], [28], [30] and [31]. 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 [29]:

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) [29]. 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% [31]. 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 8-3.

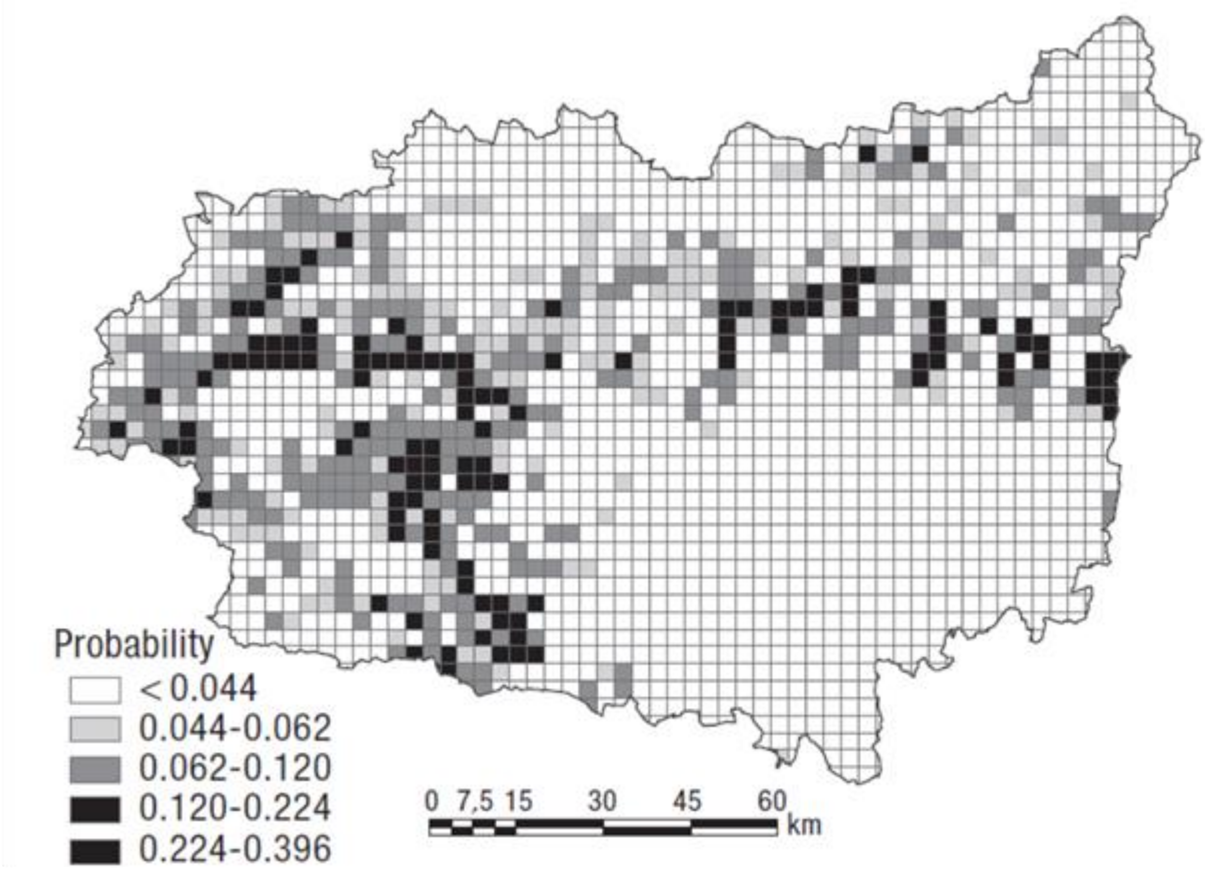

Figure 8-3 Spatial distribution of the probability of occurrence of lightning-induced fires in the province of León for the 2002-2007 periods (Probabilities were based on the logistic model)

Finally, output of Fragility analysis step is formed by frequencies of lightning induced initiating events. In general frequency of any considered internal initiating event for particular interval from discretized hazard curve will be expressed as follow:

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

Where

F_{in} Frequency of ith initiating event for nth bin of discretized hazard curve

P_n Frequency of occurrence nth CI from discretized hazard curve

Q_{jn} Conditional probability of damage of jth by nth CI which leads to initiating event F_i; initiating, e.g. see E-1.

Frequencies of external events caused by lightning strike will be estimated similarly as frequencies for internal events. As it was mentioned exception will be formed by wild fires (this topic was discussed in previous text).

8.5 STEP 5 - DEVELOPING LIGHNING EVENT AND FAULT TREES

The aim of this task is in accordance with [7] 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.

8.6 STEP 6 - RISK QUANTIFICATION

The aim of this step is to quantify risk (core damage frequency for L1 PSA) by appropriate integrating of the lightning hazard (what is done within step 5).

Based on the work performed within steps 1 to 5 quantification of lightning PSA is standard activity like in PSA for internal events.

8.7 STEP 7 – L1 PSA REPORTING

Reporting is standard part of any PSA which aim is to provide comprehensive and traceable documentation of the work.

8.8 L2 PSA CONSIDERATIONS

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

9 CONCLUSION

/The conclusion has to be discussed during the End-Users review process/

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.

10 LIST OF REFERENCES

[1] ASAMPSA_E - Summary report of already existing guidance on the implementation of External Hazards in extended Level 1 PSA - Technical report ASAMPSA_E / WP22 / D22.1 / 2015-11 - Reference IRSN PSN/RES/SAG/ 2015-00235

[2] ASAMPSA_E - Bibliography – Existing Guidance for External Hazard Modelling - Technical report ASAMPSA_E / WP21 / D21.1 / 2015-09 - Reference IRSN PSN-RES/SAG/2015-00082

[3] ASAMPSA_E - Synthesis of the initial survey related to PSAs End-Users needs - Technical report ASAMPSA_E/WP10/D10.2/2014-05 - Reference IRSN PSN-RES/SAG/2014-00193

[4] Projected increase in lightning strikes in the United States due to global warming, David M. Romps, Jacob T. Seeley, David Vollaro, and John Molinari, Science 14 November 2014: 851-854. [DOI:10.1126/science.1259100]

[5] JRC Scientific and policy reports, European Clearinghouse: Report on External Hazard related events at NPPs, Summary Report of an European Clearinghouse Topical Study, Benoit Zerger, Manuel Martín Ramos, Miguel Peinador Veira, 2013

[6] EUROPEAN COMMISSION, DIRECTORATE-GENERAL, REGIONAL POLICY, Policy development, Conception, forward studies, impact assessment, REGIONS 2020 THE CLIMATE CHANGE CHALLENGE FOR EUROPEAN REGIONS, Brussels, March 2009, DIRECTORATE GENERAL FOR REGIONAL POLICY BACKGROUND DOCUMENT TO COMMISSION STAFF WORKING DOCUMENT SEC(2008), 2868 FINAL REGIONS 2020, AN ASSESSMENT OF FUTURE CHALLENGES FOR EU REGIONS.

[7] IAEA SSG-3 Development and Application of Level 1 Probabilistic Safety Assessment for Nuclear Power Plants, 2010

[8] IEC 62305-1:2010, Protection against lightning - Part 1: General principles

[9] IEC 62305-2:2010, Protection against lightning - Part 2: Risk Management

[10] IEC 62305-3:2010, Protection against lightning - Part 3: Physical Damage to Structure and Life Hazard

[11] IEC 62305-4:2010, Protection against lightning - Part 4: Electrical and Electronic Systems within Structures

[12] IEC 62305-5:2013, Protection against lightning - Part 5: Services

[13] NUREGICR-6579, BNL-NUREG-52536, Digital I&C Systems in Nuclear Power Plants, Risk-Screening of Environmental Stressors and a Comparison of Hardware Unavailability With an Existing Analog System, Manuscript Completed: December 1997, Date Published: January 1998, M. Hassan, Brookhaven National Laboratory, W.E. Vesely, Science Applications International Corporation

[14] Natural Hazards and Earth System Sciences, A European lightning density analysis using 5 years of ATDnet data, G. Anderson and D. Klugmann, 11 April 2014

[15] PRA Procedures Guide: A Guide to the Performance of Probabilistic Risk Assessments for Nuclear Power Plants (NUREG/CR-2300), J.W. Hickman, et al. January 1983

[16] IEEE Std 998-1996; IEEE Guide for Direct Lightning Stroke Shielding of Substations; Substations Committee of the IEEE Power Engineering Society; Approved 19 April 1996 - IEEE Standards Board; Approved 11 September 1996 - American National Standards Institute

[17] Anderson, J. G., Section 12 of Transmission Line Reference Book 345 kV and Above, 2nd Ed. Rev. Palo Alto, Calif.: Electric Power Research Institute, 1987

[18] Darveniza, M., Popolansky, F., and Whitehead, E. R., "Lightning Protection of UHV Transmission Lines, "Electra, no. 41, pp. 39–69, July 1975

[19] IEEE Working Group, "A simplified method for estimating lightning performance of transmission lines," IEEE, Transactions on Power Apparatus and Systems, vol. PAS-104, no. 4, pp. 919–932, 1985. NEW BIB "46a" IEEE Working Group, "Estimating lightning performance of transmission lines II—Updates to analytic models," IEEE Transactions on Power Delivery, vol. 8, No. 3, pp. 1254–1267, July 1993

[20] Suzuki, T, Miyake, K., and Shindo, T, "Discharge path model in model test of lightning strokes to tall mast, "IEEE Transactions on Power Apparatus and Systems, vol. PAS- 100, no. 7, pp. 3553–3562, 1981

[21] Whitehead, E. R., "CIGRE Survey of the Lightning Performance of Extra-High-Voltage Transmission Lines, "Electra, no. 33, pp. 63–89, Mar. 1974

[22] Djalel, D., Hocine, L.; Study and characterization of the transient electromagnetic field radiated by lightning, Published in: Power Engineering, Energy and Electrical Drives (POWERENG), 2013 Fourth International Conference; ISSN : 2155-5516; INSPEC Accession Number: 13860723; Publisher: IEEE

[23] Lijun Jin ; Ganwen Lu ; Jian Mei ; Lu Han ; Yuzhuo Shen; Research on the characteristic for the dielectric of building and the material of grounding by lightning stroke; Published in: Properties and Applications of Dielectric Materials, 2009. ICPADM 2009. IEEE 9th International Conference, ISBN: 978-1-4244-4367-3, Publisher: IEEE

[24] Yingqiang Wang ; Wang Pan ; Jiaqing Chen ; Wenchun Liao ; FDTD analysis of the three dimensional magnetic field distribution inside a building under direct lightning stroke; Published in: Lightning (APL), 2011 7th Asia-Pacific International Conference, Print ISBN: 978-1-4577-1467-2, Publisher: IEEE

[25] Zhang Wei ; Zhao Zhi-bin ; Gu Shan-qiang ; Xiang Nian-wen ; Analysis of magnetic fields radiated by lightning strikes to a building, Published in: Lightning (APL), 2011 7th Asia-Pacific International Conference, Print ISBN: 978-1-4577-1467-2, Publisher: IEEE

[26] Panicale, Barbosa, Impulsive currents and voltages induced into loops due to nearby lightning, Published in: Lightning Protection (XI SIPDA), 2011 International Symposium, Print ISBN: 978-1-4577-1898-4, Publisher: IEEE

[27] DIRECTIVE 2004/108/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 15 December 2004 on the approximation of the laws of the Member States relating to electromagnetic compatibility and repealing Directive 89/336/EEC; L 390/24

[28] L. Bums, R. Decker, The Distribution of Cloud to Ground Lightning Strike Intensities and Associated Magnetic Inductance Fields near the Kennedy Space Center, 2002

[29] United States Department of Agriculture, Forest Service, "A Model for Predicting Lightning-Fire Ignition in Wildland Fuels" (1979). Wildfires. Paper 5. http://digitalcommons.usu.edu/govdocs_wfires/5

[30] Feng Chen, Yongsheng Du, Shukui Niu, Jinlong Zhao, Modeling Forest Lightning Fire Occurrence in the Daxinganling Mountains of Northeastern China with MAXENT, Forests 2015, 6(5), 1422-1438, 2015

[31] F. Castedo-Dorado, J. R. Rodriguez-Perez, J. L. Marcos-Menendez, M. F. Alvarez-Taboada, Modelling the probability of lightning-induced forest fire occurrence in the province of León (NW Spain), Forest Systems 2011 20(1), 95-107, 2011

[32] A. J. Dowdy, G. A. Mills, Atmospheric states associated with the ignition of lightning-attributed fires, The Centre for Australian Weather and Climate Research, CAWCR Technical Report No. 019, 2005

[33] J. Podur, D. L. Martell, F. Csillag, Spatial patterns of lightning-caused forest fires in Ontario, 1976–1998, Ecological Modelling 164 (2003) 1–20, 2002

[34] M.P. Plucinki, A review of wildfire occurrence research, CSIRO Ecosystem Science and CSIRO Climate Adaptation Flagship, 2012

[35] M. Larjavaara, Climate and forest fires in Finland – influence of lightning-caused ignitions and fuel moisture, The Finnish Society of Forest Science, 2005

[36] EUROPEAN “STRESS TESTS” FOR NUCLEAR POWER PLANTS. National Report of Bulgaria, Nuclear Regulatory Agency, December 2011.

[37] NUREG/CR-6866, ORNL/TM-2001/140. Technical Basis for Regulatory Guidance on Lightning Protection in Nuclear Power Plants, U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001, NRC Job Code W6851, July 2005.

[38] Ivanov I., List of external and internal hazards to be considered in extended PSAs, ASAMPSA_E 1st End-Users Workshop, Uppsala, Sweden, May 26-28, 2014.

[39] ORDINANCE № 4 from December 22, 2010 for lightning protection of buildings, outdoor facilities and open spaces, (SG. 6, 2011), Bulgaria.

[40] Nakov P., I. Ivanov, Some examples of research to improve lightning protection and reduce surges in the internal network and relay protection circuit of the NPP made by High Voltage Technique Laboratory (HVT Lab.) of Technical University of Sofia (TUS) in Bulgaria, TU-Sofia, 2014.

[41] The Institution of Engineering and Technology, Lightning Protection, ISBN 978-1-84919-106-7, 2010

[42] IEC 62858:2015 Lightning density based on lightning location systems (LLS) – General principles.

[43] ASAMPSA_E- List of external hazards to be considered in ASAMPSA_E - Technical report ASAMPSA_E/WP21/D21.2/2015-10 - IRSN PSN-RES/SAG/2015-00082 K.Decker, H. Brinkman.

[44] ASAMPSA_E - Report 6: Guidance document MAN-MADE hazards and ACCIDENTAL AIRCRAFT CRASH hazards modelling and implementation in extended PSA - Technical report ASAMPSA_E/WP21&WP22/D21.3 & D22.2-3-6/2016-24-reference IRSN PSN/RES/SAG/2016-00173

[45] Colin Bayliss, Colin R. Bayliss, Brian J. Hardy, Transmission and Distribution Electrical Engineering, Elsevier, 2012 - Technology & Engineering.

[46] P.Duqueroy, C.Miry, P.Seltner. Lightning risk assessment evaluation on French nuclear power plants, 2014 International Conference on Lightning Protection (ICLP), Shanghai, China. Conference Proceedings, 2014.

[47] C. Bouquegneau, A Critical View on the Lightning Protection International Standard, Faculte Polytechnique de Mons, rue de Houdain, Belgium.

[48] R. Kithil, New International Standard for Lightning Protection, IEC 62305, US National Lightning Safety Institute.

[49] Direction des risques accidentels, Le risque foudre et les Installations Classées pour la Protection de l'Environnement, INERIS, septembre 2001.

[50] V. Rakov, Lightning Discharge and Fundamentals of Lightning Protection, Journal of Lightning Research, 2012, 4, (Suppl 1: M2) 3-11.

[51] HSE (Failure Rate and Event Data for use within Risk Assessments (28/06/2012).

[52] Kuzmina I., Lyubarskiy A., El-Shanawany M., An Approach for Systematic Review of the Nuclear Facilities Protection against the Impact of Extreme Events (Proceedings of the Nordic PSA Conference – Castle Meeting 2011, 5-6 September 2011, Stockholm, Sweden).

[53] Kuzmina I., Lyubarskiy A., Hughes P., Kluegel J., Kozlik T., Serebrjakov V., The Fault Sequence Analysis Method to Assist in Evaluation of the Impact of Extreme Events on NPPs (Proceedings of the Nordic PSA Conference – Castle Meeting 2013, 10-12 April 2013, Stockholm, Sweden)

[54] Sörman J., Bäckström O, Yang L., Kuzmina I., Lyubarskiy A., El-Shanawany M., Method for analysing extreme events, PSAM 12, June 2014, Honolulu Hawaii.

[55] Kumar M., Sörman J., Bäckström O., Tool for extreme events analysis, IAEA technical meeting 7-11 July 2014, Vienna.

[56] Best-Practices Guidelines for L2PSA Development and Applications, Volume 1 - General, Reference ASAMPSA2, Technical report ASAMPSA2/ WP2-3-4/D3.3/2013-35, IRSN-PSN/RES/SAG 2013-0177, dated 2013-04-30.

[57] Best-Practices Guidelines for L2PSA Development and Applications, Volume 2 - Best practices for the Gen II PWR, Gen II BWR L2PSAs, Extension to Gen III reactors, Reference ASAMPSA2, Technical report ASAMPSA2/ WP2-3-4/D3.3/2013-35, IRSN-PSN/RES/SAG 2013-0177, dated 2013-04-30.

[58] Lloyd's Register Consulting, RiskSpectrum HazardLite, User guide version 1.1.0, 26th February 2015, Sweden.

11 LIST OF TABLES

12 LIST OF FIGURES

13 APPENDIX 1 – LIGHTNING RISK SAFETY ASSESSMENT (SOME COMMENTS FROM IRSN)

/This appendix may be suppressed in the final version if the discussion on norms applicability is improved/

For the lightning risk safety assessment, the buildings with the following characteristics have to be considered:

- a risk of radioactive material release;
- a risk of fire or explosion;
- a risk of failure of equipment important for the safety of the installation (safety targets).

The standards of the CEI 62305 (ref. 1 to 4) series give the state-of-the-art regarding protection against lightning, to be used to determine the protective performance levels[4]. For a nuclear facility, some input parameters have to be carefully chosen such as "lightning flashes frequency" [flashes/year.km²], "fire risk of the building", "provisions to mitigate the fire consequences" and "type of hazard associated to a lightning initiated accident scenario" as they have a major influence on the level of protection selected for the buildings to be protected. However, if these standards may be sufficient to protect conventional buildings, the analysis has to be completed for a nuclear safety demonstration. Indeed, these standards involve risk acceptability criteria and introduce a probability of casualties in case of lightning. Their implementation then leads to a minimum level of protection but does not achieve the highest level of protection requested for a nuclear facility; as well, the adequacy of the protection devices against lightning is not justified and the consequences of an uncaptured lightning strike are not assessed. For example, a system of protection against lightning rated "level IV" (the lowest level of protection) only captures 80% of lightning strikes. Thus, for a nuclear safety demonstration, these standards have to be completed regarding:

- the list of safety targets to be protected against lightning effects;
- consequences assessment on equipment in case of an uncaptured lightning strike;
- safety analysis of incidental or accidental scenarios occurring with an uncaptured lightning strike.

Concerning the necessary provisions to mitigate the lightning consequences, in addition to the technical analysis required by the CEI 62305, the licensee also have to justify the performance of these provisions regarding:

- the control measurements to check the correct equipotentialization of the facility earthing system. The correct connection of this system to the site earthing system shall also be checked;
- the protection against electric or electrostatic sparks of conducting elements (ducts, power lines…) entering the building; if necessary, following the CEI 62305 standards, connections between these conducting elements and the earthing system are requested. The connections shall be put in place where the elements penetrate the building.

[4] Four protective performance levels (I, II, III and IV) are defined in the CEI 62305-1 standard. For each level, minimal and maximal values for the lightning current are given. The maximal value is used for the design of the protection devices and the minimal value is used to size the virtual sphere representing the protection zone.

Finally, regular checks and tests of all the elements providing the lightning protection shall be mentioned in the operating procedures of the facility.

References:

1. International standard CEI 62305-1:2010 - Protection against lightning – Part 1: General principles
2. International standard CEI 62305-2:2010 - Protection against lightning – Part 2: Risk management
3. International standard CEI 62305-3:2010 - Protection against lightning – Part 3: Physical damage to structures and life hazard
4. International standard CEI 62305-4:2010 - Protection against lightning – Part 4: Electrical and electronic systems within structures

14 APPENDIX 2- WP40 – Level 2 PSA contribution: Interface Level 1 – Level 2

1 Forword

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 ([56] and [57]).

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.

2 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 [56] and [57]), 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.

15 APPENDIX 3- HAZARD ASSESSMENT AND PSA TOOL

/This appendix has been provided by LRC – Other examples of tools can be added during the external review/

RiskSpectrum® HazardLite [58] (hereafter called ***HazardLite***) is a light tool for assessing hazard risks, e.g. earthquake, tsunami, extreme weather etc. 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.
- 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]:

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

Where:

Φ() 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

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

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

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

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:

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

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

<u>**Component groups and combinations**</u>

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