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Safety of Existing Nuclear Installations

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List of external hazards to be considered in ASAMPSA_E

Reference ASAMPSA_E

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Kurt Decker & Hans Brinkman

University Vienna
NRG

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Summary :

The current report includes an exhaustive list of external hazards posing potential threats to nuclear installations. The list comprises of both, natural and man-made external hazards. Also, a cross correlation matrix of the hazards is presented. The list is the starting point for the hazard analysis process in Level 1 PSA as outlined by IAEA (2010; SSG-3) and the definition of design basis as required by WENRA (2014; Reference Levels for Existing Reactors).

The list is regarded comprehensive by including all types of hazards that were previously cited in documents by IAEA and WENRA-RHWG. 73 natural hazards (N1 to N73) and 24 man-made external hazards (M1 to M24) are included. Natural hazards are grouped into seismotectonic hazards, flooding and hydrological hazards, extreme values of meteorological phenomena, rare meteorological phenomena, biological hazards / infestation, geological hazards, and forest fire. The list of external man-made hazards includes industry accidents, military accidents, transportation accidents, pipeline accidents and other man-made external events.

The dataset further contains information on hazard correlations. 577 correlations between individual hazards are identified and shown in a cross-correlation chart. Correlations discriminate between: (1) Causally connected hazards (cause-effect relation) where one hazard (e.g., liquefaction) may be caused by another hazard (e.g., earthquake); or where one hazard (e.g., high wind) is a prerequisite for a correlated hazard (e.g., storm surge).

Visa grid			
	Main author(s) :	**Verification**	**Approval (Coordinator)**
Name (s)	K. Decker, H. Brinkman	WP21 Partners	E. Raimond
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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
Wielenberg	Andreas	GRS	WP30 coordinator
Loeffler	Horst	GRS	WP40 coordinator

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
Sauvage	Estelle	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
Brac	Pascal	EDF
Coulon	Vincent	EDF
Gallois	Marie	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
Kähäri	Petri	FKA
Karlsson	Anders	FKA

Name	First name	Organization
Ljungbjörk	Julia	FKA
Pihl	Joel	FKA
Loeffler	Horst	GRS
Mildenberger	Oliver	GRS
Sperbeck	Silvio	GRS
Tuerschmann	Michael	GRS
Wielenberg	Andreas	GRS
Benitez	Francisco Jose	IEC
Del Barrio	Miguel A.	IEC
Serrano	Cesar	IEC
Apostol	Minodora	INR
Nitoi	Mirela	INR
Groudev	Pavlin	INRNE
Stefanova	Antoaneta	INRNE
Armingaud	François	IRSN
Bardet	Lise	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
Georgescu	Gabriel	IRSN
Guigueno	Yves	IRSN
Guimier	Laurent	IRSN
Lanore	Jeanne-Marie	IRSN
Laurent	Bruno	IRSN
Ménage	Frédéric	IRSN
Pichereau	Frederique	IRSN
Rahni	Nadia	IRSN
Raimond	Emmanuel	IRSN
Rebour	Vincent	IRSN
Sotti	Oona	IRSN
Volkanovski	Andrija	JSI
Alzbutas	Robertas	LEI
Matuzas	Vaidas	LEI

Name	First name	Organization
Rimkevicius	Sigitas	LEI
Häggström	Anna	LRC
Klug	Joakim	LRC
Knochenhauer	Michael	LRC
Kumar	Manorma	LRC
Olsson	Anders	LRC
Borysiewicz	Mieczyslaw	NCBJ
Kowal	Karol	NCBJ
Potempski	Slawomir	NCBJ
La Rovere	Stephano	NIER
Vestrucci	Paolo	NIER
Brinkman	Hans	NRG
Kahia	Sinda	NRG
Bareith	Attila	NUBIKI
Lajtha	Gabor	NUBIKI
Siklossy	Tamas	NUBIKI
Caracciolo	Eduardo	RSE
Morandi	Sonia	RSE
Dybach	Oleksiy	SSTC

Name	First name	Organization
Gorpinchenko	Oleg	SSTC
Claus	Etienne	TRACTEBEL
Dejardin	Philippe	TRACTEBEL
Grondal	Corentin	TRACTEBEL
Mitaille	Stanislas	TRACTEBEL
Oury	Laurence	TRACTEBEL
Zeynab	Umidova	TRACTEBEL
Bogdanov	Dimitar	TUS
Ivanov	Ivan	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 M.	US-NRC

SUMMARY

The current report includes an exhaustive list of external hazards posing potential threats to nuclear installations. It includes both, natural and man-made external hazards. Also, a cross correlation matrix of the hazards is presented.

The list should be used as a starting point for the hazard analysis process in Level 1 PSA as outlined by IAEA (2010 b) and the definition of design basis as required by WENRA (2014).

The list is regarded comprehensive including all types of hazards that were previously cited in documents by IAEA and WENRA-RHWG. 73 natural hazards (N1 to N73) and 24 man-made external hazards (M1 to M24) are included. Natural hazards are grouped into seismotectonic hazards, flooding and hydrological hazards, extreme values of meteorological phenomena, rare meteorological phenomena, biological hazards / infestation, geological hazards, and forest fire. The list of external man-made hazards includes industry accidents, military accidents, transportation accidents, pipeline accidents and other man-made external events.

The dataset further contains information on correlated and associated hazards. 577 possible correlations between individual hazards and 82 combinations of mutually exclusive hazards (hazards which cannot apply to the plant at the same time) are identified by expert opinion and shown in a cross-correlation chart. Correlations discriminate between:

1. Causally connected hazards (cause-effect relation) where one hazard (e.g., liquefaction) may be caused by another hazard (e.g., earthquake); or where one hazard (e.g., high wind) is a prerequisite for a correlated hazard (e.g., storm surge). The identified causal links are not commutative.
2. Associated hazards ("contemporary" events) which are probable to occur at the same time due to a common root cause (e.g., drought and high temperature).
3. Hazards that occur contemporaneously by random coincidence. Such combinations cannot include hazards which are mutually exclusive (e.g., high temperature and surface ice).

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
2	Gesellschaft für Anlagen- und Reaktorsicherheit mbH	GRS	Germany
3	AMEC NNC Limited	AMEC NNC	United Kingdom
4	Ricerca sul Sistema Energetico	RSE S.p.A.	Italy
5	Lloyd's Register Consulting	LRC	Sweden
6	Nuclear Research Institute Rez pl	UJV	Czech
7	Universität Wien	UNIVIE	Austria
8	Cazzoli Consulting	CCA	Switzerland
9	Italian National Agency for New Technologies, Energy and the Sustainable Economic Development	ENEA	Italy
10	Nuclear Research and consultancy Group	NRG	Nederland
11	IBERDROLA Ingeniería y Construcción S.A.U	IEC	Spain
12	Electricité de France	EDF	France
13	Lietuvos energetikos institutas (Lithuanian Energy Institute)	LEI	Lithuania
14	NUBIKI	NUBIKI	Hungary
15	Forsmark kraftgrupp AB	FKA	Sweden
16	AREVA NP SAS France	AREVA NP SAS	France
17	NCBJ Institute	NCBJ	Poland
18	State Scientific and Technical Center for Nuclear and Radiation Safety	SSTC	Ukraine
19	VUJE	VUJE	Slovakia
20	NIER Ingegneria	NIER	Italy
22	TRACTEBEL ENGINEERING S.A.	TRACTEBEL	Belgium
23	BeL V	BeL V	Belgium
24	Institut Jozef Stefan	JSI	Slovenia
25	Institute of nuclear research and nuclear energy - Bulgarian Academia of science	INRNE	Bulgaria
26	Regia Autonoma Pentru Activatati Nucleare Droberta Tr. Severin RA Suc	INR	Roumania
27	Technical University of Sofia - Research and Development Sector	TUS	Bulgaria
28	AREXIS S.A.R.L.	AREXIS	France
	United States Nuclear Regulatory Commission	US-NRC	USA
	Tokyo Electric Power Company	TEPCO	Japan
	Japan Nuclear Safety Institute	JANSI	Japan

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GLOSSARY

IAEA	International Atomic Energy Agency
I&C	Instrumentation & Control
LOOP	Loss of Off-site Power
NPP	Nuclear Power Plant
PSA	Probabilistic Safety Assessment
SSCs	Systems, Structures and Components
UHS	Ultimate Heat Sink
WENRA	Western European Nuclear Regulators Association
WP	Work Package within ASAMPSA_E

1 INTRODUCTION

1.1 OBJECTIVE

The main objective of this technical report is to provide an exhaustive list of external hazards which form potential threats to nuclear installations. It considers both, natural and external man-made hazards.

The document further intends to provide information on hazardous events which have a significant probability to occur at the same time. Such correlated hazards may derive from causal dependencies between different hazard types, from hazards that share a common root cause, or from hazards that occur by random coincidence. We therefore developed an extensive correlation chart that indicates such causal dependencies. The chart also highlights hazards which are mutually exclusive and cannot occur at the same time.

The hazard list and the identified possible hazard combinations can be used as a starting point for the hazard analysis process in Level 1 PSA to ensure that all external threats to a nuclear installation are covered by the analysis. The process is outlined in detail by IAEA (2010 b). Both, the hazard list and the correlation chart may further be helpful for the definition of design basis values and analyses of design extension conditions as required for natural hazards and hazard combinations by the “WENRA Reference Levels for Existing Reactors” (WENRA, 2014). It may be notable that the list of natural hazards adopted by WENRA (in WENRA, 2015, Appendix 1) is identical with the list developed for ASAMPSA_E. In addition to combinations of natural and external man-made hazards WENRA further requires to include internal hazards in the analysis of hazard combinations. To facilitate such analyses, we therefore include a (non-exhaustive) list of internal hazards in Appendix B of the current report although internal hazards are not in the scope of the ASAMPSA_E project.

It is clear that not all of the hazards summarized in the exhaustive list and all possible hazard correlations uniformly apply to all nuclear sites. Site-specific screening of hazards is a necessary step in PSA. The definition of screening criteria to be used for the selection of external hazards and combinations of external hazards, however, is beyond the scope of the current report. The screening approach and the criteria to select initiating events are discussed in deliverable D30.7 (vol 2) of the ASAMPSA_E work package WP30 (Wielenberg et al., 2017).

The hazard list was further used as a basis to select a limited number of hazard types for detailed discussion with specialists of the informed scientific community outside ASAMPSA_E and the development of guidance for hazard characterisation by ASAMPSA_E (deliverable D21.3). The following hazards have been selected: seismic hazards, flooding, extreme weather (storm, extreme temperature, snow pack), lightning, biological hazards, external fire, external explosion, and aircraft crash. Earthquake and flooding have been selected as a consequence of the Fukushima Dai-Ichi accident. The other hazard types were selected according to end-users requests received after an in-depth discussion at a dedicated workshop[1] and a questionnaire sent to end-users (Guigueno et al., 2016). The strategic reasoning for selecting these specific hazards is explained in Deliverable D10.2 of ASAMPSA_E’s work package WP10 (Guigueno et al., 2016).

[1] ASAMPSA_E 1st End-Users Workshop, Uppsala, Sweden, May 26-28, 2014

1.2 DEFINITIONS

The definitions adopted in the current report are summarized in Table 1.

Table 1: Definition of key terms used in the current document

Term	Definition	Reference
External hazard	Hazards originating from sources located outside the ***site area*** of the nuclear power plant.	IAEA SSG-3 (2010)
Internal hazard (*)	Hazards originating from the sources located on the ***site area*** of the nuclear power plant, both inside and outside of the plant buildings.	IAEA SSG-3 (2010)
Site area	A geographical area that contains an authorized facility, authorized activity or source, and within which the management of the authorized facility or authorized activity may directly initiate emergency actions. This is typically the area within the security perimeter fence or other designated property marker.	IAEA Safety Glossary (2007)
Natural hazard	Natural hazards are defined as those hazards which occur in nature over which man has little or no control over the magnitude or frequency.	WENRA RHWG (2014)
Man-made hazard (**)	Hazards originating from any kind of human activity, either accidental or due to malicious acts.	
Initiating event	An identified event that leads to anticipated operational occurrences or accident conditions. This term 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.	IAEA Safety Glossary (2007)
Postulated initiating event	An event identified during design as capable of leading to anticipated operational occurrences or accident conditions. The primary causes of postulated initiating events may be human induced or natural events.	IAEA Safety Glossary (2007)

(*) Some guidance documents refer to a different interpretation of "on-site hazards": e.g., ASME-ANS (2009) lists "internal flooding", "release of chemicals from on-site storage", and "turbine missiles" among the external hazards.

(**) Malicious acts, including cyber-attacks are not considered in the current document.

1.3 THE HAZARD ASSESSMENT PROCESS AND THE HAZARD LIST

The hazard list presented in this report is the starting point of the hazard analysis process in PSA as outlined in the IAEA guide on Level 1 PSA (IAEA, 2010 b):

1. Hazard identification, including single and combined hazards;
2. Hazard screening analysis, both qualitative and quantitative;
3. Bounding assessment;
4. Detailed analysis and PSA modelling.

A very important point in this hazard analysis process is the completeness of the analysis with respect to the considered hazards. It needs to be ensured that all hazards which are site and risk relevant are identified and considered by the analyst. This hazard identification process is supported and simplified by using the exhaustive list of external natural and man-made hazards provided in this document as a starting point.

Up-to-date hazard analyses further are required to consider combinations of hazards (WENRA, 2014, Issue T; WENRA, 2015). This is due to the fact that the impact, from different combinations of hazards, may simultaneously affect different SSCs and safety functions, or the same SSCs or safety function might be affected more severely by the combined effects of different events occurring at the same time. The possible combinations of external hazards are identified based on the list of individual natural and external man-made hazards (see chapter 3, page 35).

As internal hazards are outside the scope of the ASAMPSA_E project, internal hazards are not part of the list and combinations of external and internal hazards are not discussed in this report. However, as such hazard combinations are possible and need to be included in hazard analyses (WENRA, 2014, Reference Level T3.1), we include a non-comprehensive list of internal hazards which should be considered in combination with external hazards or as consequences of external events in Appendix B.

1.4 FORMAT OF THE HAZARD LIST

During the exhaustive discussion within WP21 of the ASAMPSA_E project several formats and approaches to structure the list of external hazards have been proposed. The current report adopts the format of the hazard list published in the IAEA Safety Standard SSG-3, Annex I (IAEA, 2010 b). This format is expanded to include additional information.

The current document hazards are listed in a table format with columns referring to:

- Code (hazard number);
- Hazard : natural phenomena and man-made accidents causing the hazard;
- References : international standards or guidelines that introduce the hazard type;
- Duration (Dur.): classification of hazard duration. Duration is classified into seconds to minutes (s-m), minutes to hours (m-h), hours to days (h-d), and longer (d-l);
- Predictability and hazard progression (P&P) : predictable (e.g., by weather forecast, P) or unpredictable (U), progressing rapidly (R) or gradually (G);
- Hazard definition and hazard impact;
- Interfaces and comments: extended explanations of some uncommon natural phenomena are provided in chapter 2.2 subsequent to the table.

Information on initiating events (i.e., the potential damage caused by a hazard and its impact on the plant, SSCs or humans) are not included in the hazard list. Their identification is in general plant specific and part of the initiating event identification process of a PSA and therefore beyond the scope of the current report.

Previous external hazard lists adopted a wide variety of structures including simple alphabetic hazard lists (ASME-ASN, 2009, p. 267ff) and different thematic classifications of hazards (e.g., air based, ground based and water based natural hazards; IAEA, 2010 b). An exhaustive literature review revealed that classification schemes even differ between IAEA documents. The classification selected for the hazard list in the current report tries to adopt the logic followed in the majority of IAEA's publications. Natural hazards are therefore grossly sorted according to the general processes causing the hazards resulting in a classification into seismotectonic, hydrological, meteorological, biological, and geological hazards. The separation of seismotectonic and geological hazards is due to the generally high safety relevance of seismic hazards.

External man-made hazards are grouped into industry, military, transportation, pipeline, aircraft and other accidents. External man-made hazards which are security related (malicious acts, cyber-attack, terrorist or military attack) are not included in the list because of the public character of the documents produced within ASAMPSA_E.

The hazard list is meant to guide the analyst in identifying plant and location specific hazards. The way the list presents the hazards: grouped, alphabetically ordered, randomly listed, or otherwise is of little importance for this specific purpose. Also, the fact that some of the listed hazards (partly) overlap is not important. The purpose of the list is to ensure that the analysis does not miss a relevant hazard type. Grouping of the hazards relevant for the plant will be done during a plant and site-specific screening process as described in the ASAMPSA_E Report D30.7 (vol; 2) (Wielenberg et al., 2017).

1.5 FORMAT OF THE HAZARD CORRELATION CHART

Correlated hazards are shown in a cross correlation chart in chapter 2.4 of the report. The large number of individual natural and man-made hazards (73 and 24 hazard types, respectively) results in a large size of the chart with about 100 rows and columns. The full table is therefore included as an attachment to the report. It is also available in PDF-file format which is accessible through ASAMPSA_E's FPT server at ftp.irsn.fr.

2 LIST OF EXTERNAL HAZARD TYPES

2.1 NATURAL HAZARDS

The exhaustive list of 74 natural hazards is included in Table 2 (next pages).

Hazards are grouped into:

- Seismotectonic hazards (earthquake);
- Flooding and hydrological hazards;
- Meteorological events: extreme values of meteorological phenomena;
- Meteorological events: rare meteorological phenomena;
- Biological hazards / Infestation;
- Geological hazards;
- Forest fire (fire caused by natural causes).

Table 2 (next pages). Exhaustive list of natural hazards (73 hazard types). Explanation to columns:

Ref.: references to international standards and guidelines introducing the hazard type; [1] WENRA, 2013; [2] IAEA, 2004 a; [3] IAEA, 2003 a; [4] IAEA, 2010 a; [5] IAEA, 2003 b; [6] IAEA, 2003 c; [7] IAEA, 2003 d; [8] IAEA, 2002; [9] IAEA, 2012; [10] IAEA, 2010 b; [11] IAEA, 2004 b; [12] IAEA, 2011; [13] Kuramoto, T., et al., 2014; [14] IAEA, 2003 e; [15] USNRC, 2012. Dur.: duration of hazard phenomena classified as s-m (seconds to minutes), m-h (minutes to hours), h-d (hours to days), d-l (days and longer). P&P: Hazard predictability and hazard progression: predictable (P), unpredictable (U), progressing rapidly (R) or gradually (G). Ref: references to international standards introducing the hazard type.

Seismotectonic hazards (earthquake) [4]

Code	Hazard	Ref.	Dur.	P&P	Hazard definition and hazard impact	Interfaces and comments
N1	Vibratory ground motion (	[1] [2] [4] [10] [11] [14]	s-m	U/R	The hazard is defined by the contemporaneous impact of vibratory ground motion on all civil structures and SSCs of the plant and its surrounding.	Effects of long period ground motion and aftershocks need to be considered.
N2	Vibratory ground motion induced or triggered by human activity (oil, gas or groundwater extraction, quarrying, mine collapse)		s-m	U/R	The hazard is defined by the contemporaneous impact of vibratory ground motion on all civil structures and SSCs of the plant and its surrounding.	See explanation [N2].
N3	Surface faulting (fault capability)	[3] [4] [11]	s-m	U/R	The hazard is defined in terms of impact on the plant of coseismic fault rupture and surface displacement. It includes surface rupture at secondary faults.	See explanation [N3].
N4	Liquefaction, lateral spreading	[1] [3] [11]	s-m	U/R	The hazard is defined by the loss of shear strength of foundation soil and its effects on civil structures and underground installations such as pipes or cable trays.	See explanation [N4].
N5	Dynamic compaction (seismically induced soil settlement)	[1] [4]	s-m	U/R	The hazard is defined by the effects of soil settlement on civil structures and underground installations such as pipes or cable trays. It includes effects of seismically induced surface cracks.	-
N6	Permanent ground displacement subsequent to earthquake	[4]	d-l	U/R	The hazard is defined in terms of impact on the plant of permanent ground subsidence or ground heave due to strain release after an earthquake.	See explanation [N6]. Ground settlement (N63) and ground heave (N64) due to other geological processes is treated separately.

Flooding and hydrological hazards [1] [2] [7]

Code	Hazard	Ref.	Dur.	P&P	Hazard definition and hazard impact	Interfaces and comments
N7	Tsunami (seismic, volcanic, submarine landsliding, meteorite impact)	[1] [2] [7] [12] [14]	m-h	U/R	The hazard is defined by flooding by a series of water waves and the drawdown during the wave troughs.	See explanation [N7]. Earthquake (N1), landslide (N60, N61), and volcanic hazards (N68, N69) are treated separately.
N8	Flash flood: flooding due to local extreme rainfall	[1] [3] [6] [7] [12] [14]	m-h	U/R	The hazard is defined in terms of damage to the plant due to flooding by extreme rain.	See explanation [N8]. Damage due to rain load on structures is treated separately (N25). Note links to other meteorological phenomena.
N9	Floods resulting from snow melt	[3] [5] [6] [7] [14]	d-l	P/G	The hazard is defined by flooding caused by seasonal or rapid snow melt.	Rapid snow melt due to volcanic phenomena is treated separately (N68).
N10	Flooding due to off-site precipitation with waters routed to the site (including river floods)	[5] [7] [12] [14]	d-l	P/G	The hazard is defined in terms of damage to the plant due to flooding by waters routed to the site.	-
N11	High groundwater	[1] [12]	d-l	P/G	The hazard is defined in terms of damage to the plant due to flooding by high ground water.	-
N12	Flooding or low water level due to obstruction of a river channel (downstream or upstream) by landslide, ice, jams caused by logs or debris, or volcanic activity	[5] [7] [14]	d-l	U/G	The hazard is defined by flooding due to downstream river impoundment or by the breach of upstream river damming, and low water level due to upstream damming.	-
N13	Floods or low water level resulting from changes in a river channel due to erosion or sedimentation, river diversion	[3] [5] [7] [14]	d-l	U/G	The hazard is defined by flooding due to changes of a river channel or low water level caused by such phenomena.	Instability of the coastal area due to erosion is treated separately (N23).
N14	Flood resulting from large waves in inland waters induced by volcanoes, landslides, avalanches or aircraft crash in water basins	[5] [7]	m-h	U/R	The hazard is defined by flooding due to large waves in inland waters.	Flooding by wind induced waves is treated separately (N19).
N15	Flood and waves caused by failure of water control structures and watercourse containment failure (dam, dike, or levee failure)	[1] [3] [7] [12]	m-h	U/R	The hazard is defined by flooding due to the failure of dams, dikes, or other water containments, e.g., due to hydrological or seismic effects.	-

Code	Hazard	Ref.	Dur.	P&P	Hazard definition and hazard impact	Interfaces and comments
N16	Seiche	[1] [2] [3] [7] [14] [15]	h-d	P/G	The hazard is defined by flooding due to fluctuations of water level due to standing waves in enclosed or partly enclosed bodies of water.	See explanation [N16]. The effect of seiches may aggravate other hazard phenomena such as tsunami or tides.
N17	Bore	[5] [12]	s-m	U/R	The hazard is defined by flooding due to bore (waves travelling up a river induced by flood tide or water management).	See explanation [N17].
N18	Seawater level: high tide, spring tide	[1] [3] [6] [12] [14]	m-h	P/G	The hazard is defined by flooding due to high tide or spring tide.	-
N19	Seawater level, lake level or river: wind generated waves	[1] [3] [6] [7] [12]	h-d	P/G	The hazard is defined by flooding due to wind generated waves including long-period, short-period, and rogue waves (freak waves).	See explanation [N19] for rogue waves. Such waves are not predictable and progress rapidly.
N20	Seawater level: storm surge	[1] [3] [6] [7] [12] [14] [15]	h-d	P/G	The hazard is defined by flooding due to storm surge.	See explanation [N20].
N21	Seawater level, lake level or river: impact of man-made structures such as wave/tide breaks and jetties	[6] [12]	h-d	P/G	The hazard is defined by flooding caused or amplified by the hydrological effects of man-made structures.	-
N22	Corrosion from salt water	[10]	d-l	P/G	The hazard is defined in terms of impact on the plant of corrosion by salt water.	-
N23	Instability of the coastal area due to erosion by strong water currents or sedimentation (sea and river)	[3] [10] [12]	d-l	U/G	The hazard is defined in terms of damage to plant structures due to erosion or sedimentation by strong water currents.	-
N24	Underwater debris	[7]	h-d	U/R	The hazard is defined in terms of the damage or clogging of cooling water intake or outlet affecting the availability of the UHS. It may result from sediment load swept in by water.	The effects of ice on water intake structures is treated separately (N48).

Meteorological events: Extreme values of meteorological phenomena [3] [6] [7] [12]

Code	Hazard	Ref.	Dur.	P&P	Hazard definition	Interfaces and comments
N25	Precipitation (rain or snow), snow pack	[6] [10] [12]	h-d	P/G	The hazard is defined in terms of damage to the plant due to extreme rain or snow. It includes damage due to rain or snow load on structures.	Flooding by extreme rain (N8) or snow melt (N9) is treated separately.
N26	Extremes of air temperature (high and low)	[1] [2] [6] [7] [10] [12]	d-l	P/G	The hazard is defined in terms of impact on the plant of extremely high temperatures (e.g., the stop of ventilation function) and low temperatures (e.g., freezing of pipes).	Impact of high or low water temperature (N28) or ice is treated separately.
N27	Extremes of ground temperature (high and low)	[1]	d-l	P/G	The hazard is defined in terms of impact on the plant of high or low ground temperature, e.g., leading to freezing of pipes.	The impact of extreme soil frost is treated separately (N38).
N28	Extremes of cooling water (sea, lake or river) temperature (high and low)	[1] [10] [12]	d-l	P/G	The hazard is defined in terms of impact on the plant of high or low cooling water temperature.	Freezing (surface ice; N48) and frazil ice (N49) are treated separately.
N29	Humidity (high and low), extreme atmospheric moisture	[1] [7] [12]	h-d	P/G	The hazard is defined by the impact of moisture on the functionality of safety related equipment and electronic devices (I&C equipment), e.g., by condensation of droplets in electrical and electronic devices.	See explanation [N29].
N30	Extremes of air pressure	[1] [10]	h-d	P/G	The hazard is defined in terms of impact on the plant of high or low air pressure or of rapid pressure changes that may impact on pressure gauges (e.g., within the containment) leading to inadverted operation.	-
N31	Extreme drought: low river or lake water level	[1] [10]	d-l	P/G	The hazard is defined as an extended drought period that lowers the water level of lakes, rivers and open water basins challenging the availability of cooling or service water.	High air temperature (N26) and high water temperature (N28) are treated separately. Extremes of ground water level are treated separately (N.32)
N32	Low ground water		d-l	P/G	The hazard is defined by low ground water levels challenging the availability of cooling or service water.	-

Code	Hazard	Ref.	Dur.	P&P	Hazard definition	Interfaces and comments
N33	Low seawater level	[1] [6] [13]	h-d	P/G	The hazard is defined by the impact of low sea water level on the plant's cooling function.	The hazard includes effects of low tide, offshore winds, high air pressure, and abnormal changes in currents.
N34	Icing, freezing fog	[1] [12]	h-d	P/R	The hazard is defined in terms of the impact of ice cover caused by freezing rain or fog. It includes the loading of structures (electric power lines and switchyard) and blocking of air intakes by ice.	See explanation [N34].
N35	White frost, hard rime, soft rime	[10]	h-d	P/R	The hazard is defined in terms of impact of white frost including switchyards and power lines, and blocking of air intakes by rime.	See explanation [N35].
N36	Hail	[1] [10] [12]	m-h	P/R	The hazard is defined in terms of damage to the plant due to extreme hail. It includes damage by the impact of hailstones and hail load.	Flooding due to melting of hail are bounded by flooding due to rain and snow melt (N8, N9). Possible effects on the UHS are judged to be bounded by surface ice hazards (N48).
N37	Permafrost	[1] [11]	d-l	P/G	The hazard is defined in terms of impact of thawing and refreezing of permafrost.	-
N38	Recurring soil frost	[10]	d-l	P/G	The hazard is defined in terms of impact of soil frost, e.g., on shallow underground installations such as water pipes.	-

Meteorological events: Rare meteorological phenomena [3] [6] [12]

Code	Hazard	Ref.	Dur.	P&P	Hazard definition and hazard impact	Interfaces and comments
N39	Lightning (including electromagnetic interference)	[1] [6] [8] [10] [12] [14]	s-m	P/R	The hazard is defined in terms of damage to the plant due to lightning. The impact may be direct, causing structural damage or loss of off-site power, or indirect through an electromagnetic feeder fire started by lightning.	Fire started by lightning is bounded by external fires (N73, M 24) and internal fire analysis.

Code	Hazard	Ref.	Dur.	P&P	Hazard definition and hazard impact	Interfaces and comments
N40	High wind, storm (including hurricane, tropical cyclone, typhoon)	[1] [2] [6] [10] [12] [14]	h-d	P/G	The hazard is defined in terms of damage to the plant by the direct impact of strong winds and wind pressure.	The hazard does not include tornado (N41) due to the unique characteristics of such storms. The hazard does not include the differentiating effects of blizzard, salt spray or sandstorm. However, the wind effects of these hazards are included. Flooding by storm surge is treated separately (N20). Hazards by wind-blown missiles are treated separately (N46).
N41	Tornado	[1] [2] [10] [12] [14]	m-h	U/R	The hazard is defined in terms of damage to the plant due to tornado. It includes the effects of pressure differences and rotating wind.	The hazard is separated from other strong winds (N40) due to the special characteristics of tornados with respect to duration, wind speed, and occurrence frequency. Damage due to wind-blown missiles is treated separately (N46).
N42	Waterspout (tornadic waterspout)	[1] [14]	m-h	U/R	The hazard is defined in terms of the rotational energy. Waterspouts contain water vapour, not solid water.	See explanation [N42].
N43	Blizzard, snowstorm	[2]	h-d	P/G	The hazard is defined by the impact on the plant by wind-blown snow. It includes contamination of external high-voltage insulation in switch gear and power lines, and blocking of air intakes.	The effects of wind pressure from snowstorms are covered by the hazard high wind (N40). Snow load is treated separately (N25).
N44	Sandstorm, dust storm	[1] [7] [10] [12] [14]	h-d	P/G	The hazard is defined in terms of impact on the plant of storm-borne sand or dust and its abrasive effects. It includes contamination of external high-voltage insulation in switch gear and power lines and blocking of air intake.	The effects of wind pressure from sandstorms are covered by the hazard high wind (N40).
N45	Salt spray, salt storm	[1] [7] [10] [13]	h-d	P/G	The hazard is defined as a storm involving salt covering of plant structures and the corrosive attack by a salty atmosphere. It includes contamination of external high-voltage insulation in switch gear and power lines, and dielectric breakdown caused by salt particles.	The effects of wind pressure from salt storms are covered by the hazard high wind (N40).

Code	Hazard	Ref.	Dur.	P&P	Hazard definition and hazard impact	Interfaces and comments
N46	Wind-blown debris (external missiles)	[12]	h-d	U/R	The hazard is defined by the damage of the impacts of wind-blown debris resulting from high winds and tornado.	Typical missiles to include are cladding panels, both insulated and uninsulated aluminium, scaffolding planks, scaffolding poles, trees, and cars.
N47	Snow avalanche	[1] [10] [14]	s-m	U/R	The hazard is defined in terms of impact on the plant of avalanches.	Avalanches may be triggered by heavy snow fall or snowmelt.
N48	Surface ice on river, lake or sea	[10]	d-l	P/G	The hazard is defined in terms of the damage or clogging of cooling water intake or outlet by drift ice or thick surface ice affecting the availability of the UHS.	Frazil ice (N49) and ice barriers (N50) are treated separately.
N49	Frazil ice	[10]	d-l	P/R	The hazard is defined in terms of the impact of frazil ice on the cooling water intake or river damming.	See explanation [N49].
N50	Ice barriers	[10]	d-l	U/R	The hazard is defined in terms of impact on the plant of ice barriers, e.g., by clogging the water intake.	Flooding due to down-stream ice barriers is treated separately (N12).
N51	Mist, fog	[1] [10]	h-d	P/R	The hazard is defined in terms of impact on the plant, electric power lines, and switchyard of mist. It includes reduced visibility on site.	-
N52	Solar flares, solar storms (space weather); geomagnetic storms	[1] [8]	h-d	P/R	The hazard is defined in terms of malfunction and damage to electrical and electronic equipment by electromagnetic interference and the breakdown of the terrestrial power grid.	See explanation [N52].

Biological hazards / Infestation [1] [7]

Code	Hazard	Ref.	Dur.	P&P	Hazard definition	Interfaces and comments
N53	Marine/river/lake growth (seaweed, algae), biological fouling	[1] [7]	d-l	P/G	The hazard is defined by excessive growth of algae, seaweed, bacteria or else affecting the availability of cooling water from the UHS.	-
N54	Crustacean or mollusc growth (shrimps, clams, mussels, shells)	[1]	d-l	P/G	The hazard is defined in terms of clogging of water intake or outlet by encrusting organisms effecting on the availability of cooling water from the UHS.	-
N55	Fish, jellyfish	[1] [7] [10]	h-d	U/R	The hazard is defined by the unavailability of the UHS due to clogging of water intake by exceptional quantities of fish/jellyfish or abnormal fish population in the cooling pond.	Clogging by seaweed (N53) and biological flotsam (N58) is treated separately.
N56	Airborne swarms (insects, birds) or leaves	[1] [7]	h-d	U/R	The hazard is defined in terms of damage to the plant due to blockage of air intake by birds or blockage of ventilation systems by leaves or insects in the filters. It includes blocking of the air intake of emergency diesels.	-
N57	Infestation by rodents and other animals	[1] [7]	d-l	U/R	The hazard is defined by damage of cables or wires attacked by rodents (rats, mice), and by undermining of structures by burrowing mammals.	-
N58	Biological flotsam (wood, foliage, grass etc.)		d-l	U/R	The hazard is defined in terms of the damage or clogging of cooling water intake or outlet affecting the availability of the UHS by the accumulation of large quantities of flotsam.	-
N59	Microbiological corrosion		d-l	P/G	The hazard is defined in terms of damage to the plant by microbiological corrosion.	-

Geological hazards [1] [11]

Code	Hazard	Ref.	Dur.	P&P	Hazard definition and hazard impact	Interfaces and comments
N60	Subaerial slope instability (landslide, rock fall; including meteorologically and seismically triggered events)	[3] [10] [11] [14]	s-m	U/R	The hazard is defined in terms of impact on the plant of landslide or rock fall including possible clogging of cooling water intake or outlet affecting the availability of the UHS.	The effects of mass movements causing flooding due to the blockage of streams (N12) or by inducing tsunamis in the sea or lakes (N7) are treated separately.
N61	Underwater landslide, gravity flow (including seismically triggered events)	[10]	s-m	U/R	The hazard is defined in terms of impact on the plant of underwater landslide.	Underwater landslides may be due to above water causes, such as prolonged and intense precipitation. Underwater erosion (N23) and tsunami triggered by landslide (N7) is treated separately.
N62	Debris flow, mud flow (including seismically triggered events)	[11]	s-m	U/R	The hazard is defined in terms of impact on the plant of debris flows or mud flows. Effects may include clogging of cooling water intake or outlet structures.	Lahar hazard is treated in volcanic hazards (N68).
N63	Ground settlement (natural or man-made by mining, ground water extraction, oil/gas production)	[1] [3] [11]	d-l	P/G	The hazard is defined in terms of impact on the plant of ground settlement.	-
N64	Ground heave	[1] [10] [11]	d-l	U/G	The hazard is defined in terms of impact on the plant of ground heave.	-
N65	Karst, leeching of soluble rocks (limestone, gypsum, anhydrite, halite)	[1] [10] [11]	d-l	P/G	The hazard is defined in terms of impact to the plant of fissures, sinkholes, underground streams, and caverns caused by chemical erosion.	-
N66	Sinkholes (collapse of natural caverns and man-made cavities)	[1] [3] [11]	d-l	U/R	The hazard is defined in terms of impact on the plant of sinkholes resulting from underground collapse.	-
N67	Unstable soils (quick clays etc.)	[1]	s-m	U/R	The hazard is defined in terms of impact on the plant of unstable soils.	-

Code	Hazard	Ref.	Dur.	P&P	Hazard definition and hazard impact	Interfaces and comments
N68	Volcanic hazards: phenomena occurring near the volcanic centre	[1] [7] [9] [11] [14]	d-l	U/R	The hazard is defined in terms of impact on the plant of: volcanic vent opening; launching of ballistic projectiles; fallout of pyroclastic material such as ash, tephra, lapilli or pumice; pyroclastic flows; lava flows; debris avalanches, landslides and slope failures; lahars, maars and floods induced by snow melt; air shocks and lightning; release of gases (including 'glowing avalanches'); ground deformation; geothermal and groundwater anomalies; forest fire ignited by volcanic activity.	The large variety of volcanic phenomena necessitates separate treatment of these phenomena. Earthquakes (N1) and tsunamis triggered by volcanic activity (N7) are treated separately.
N69	Volcanic hazards: effects extending to areas remote from the volcanic centre	[1] [7] [9]	d-l	U/G	The hazard is defined in terms of impact on the plant of volcanic phenomena such as fallout of ash.	Earthquakes (N1) and tsunamis (N7) triggered by volcanic activity are treated separately.
N70	Methane seep		d-l	P/G	The hazard is defined in terms of impact on the plant of methane seeping from soils or rocks.	-
N71	Natural radiation		d-l	P/G	The hazard is defined in terms of impact on the plant of natural radiation.	-
N72	Meteorite fall	[1] [10] [13]	s-m	U/R	The hazard is defined in terms of damage to the plant due to meteorite impact (direct impact, shock waves, impact-induced vibration, and fire).	See explanation [N72]. Flooding by tsunami triggered by meteorite fall is treated separately (N7).

Forest fire

Code	Hazard	Ref.	Dur.	P&P	Hazard definition and hazard impact	Interfaces and comments
N73	Forest fire, wildfire, burning turf or peat	[7] [10]	d-l	U/R	The hazard is defined in terms of damage to plant or the loss of off-site power due to fire or threatened operator action owing to the release of smoke and toxic gases. It includes hazard due to sparks igniting other fires and combustion gas of fire.	The hazard is a possible effect of extreme meteorological conditions (high temperatures, drought or storms). Fire caused by human activity is treated separately (M24).

2.2 EXTENDED EXPLANATIONS OF UNCOMMON NATURAL PHENOMENA

[N2] Vibratory ground motion induced or triggered by human activity. Seismic ground motion caused by human activity is treated together with natural seismicity due to the identical effects of both phenomena and the difficulties which may arise to discriminate between man-made and natural events. The hazard type includes induced seismicity, which is entirely controlled by human intervention, and triggered seismicity. In the latter case human intervention causes the initiation of the seismic rupture process of a fault while the subsequent rupture propagation is controlled by natural stress. A triggered earthquake is advanced by human intervention and natural stress aggravates the ground shaking. Seismic ground motion may be triggered or induced by oil, gas or deep groundwater extraction (including both producing and empty reservoirs), geothermal heat production, liquid waste dumping in deep boreholes, quarrying and mining.

[N3] Fault capability. The displacement of the Earth's surface at a fault during an earthquake is referred to as fault capability. Coseismic displacement may occur at the master fault or splay faults which fractured during the earthquake, or by induced slip at secondary faults which are not directly related to the earthquake fault.

[N4] Liquefaction, lateral spreading. Liquefaction of soil and unconsolidated fine-grained sediment is caused by ground shaking during an earthquake. The process results from the expulsion of pore water and leads to an extreme reduction of shear strength of the soil. In such cases, soil behaves more like a liquid than a solid and is unable to carry loads. Lateral spreading refers to the down-slope flow of liquefied soil. Both phenomena may lead to base failure at the foundation of buildings and the destruction of underground infrastructure (e.g., cables, pipes and pillars).

[N6] Permanent ground displacement subsequent to earthquake. Strain release after strong earthquakes may lead to permanent ground displacement of a large area that is caused by the release of elastic deformation (strain) during the earthquake. Elastic strain accumulates in the interseismic time period between earthquakes. Well-known examples of permanent ground displacement include cases of regional costal uplift above subduction zones and thrust faults. The type of ground displacement is distinct from the displacement caused by fault capability which is restricted to the earthquake fault or secondary faults.

[N7] Tsunami. A tsunami is a series of waves (wave train) in an ocean or lake that is caused by the displacement of a large volume of a body of water by earthquake, underwater landsliding, landsliding into water, volcanic eruption, or meteorite impact. Tsunamis travel very large distances. The phenomenon that triggered the wave train may therefore have occurred far from the site where the waves arrive.

[N8] Flash flood. *"Extreme flood events induced by severe stationary storms have been considered as flash floods. Most generally, the storms inducing flash floods lead to local rainfall accumulations exceeding 100 mm over a few hours and affect limited areas: some tens to some hundreds of square kilometres. Larger scale and longer lasting stationary storm events may, however, occur in some meteorological contexts"* (Gaume et al., 2009).

[N16] Seiche. Seiches are standing waves that form in enclosed or semi-enclosed water basins due to the reflection of waves at the basin edges. Repeated wave reflections and interference of waves lead to the formation of standing waves. The superposition of waves with frequencies equal to the eigenfrequency of the basin (or multiples of this frequency) lead to resonances in the body of water and amplitude amplification. Wave initiation may be due to meteorological effects (wind, atmospheric pressure variations), seismic activity, or tsunamis.

[N17] Bore. *"A tidal bore is a series of waves propagating upstream as the tidal flow turns to rising. It forms during spring tide conditions when the tidal range exceeds 4 to 6m and the flood tide is confined to a narrow funnelled estuary. Its existence is based upon a fragile hydrodynamic balance between the tidal amplitude, the freshwater river flow conditions and the river channel bathymetry"* (Chanson, 2011). Tidal bores are characterized by strong turbulence that may lead to sediment erosion beneath the bore wave and on banks. Turbulence may further lead to scouring and sediment entrainment, and impact on obstacles (Chanson, 2011).

[N19] Rogue waves (freak wave). *"Freak waves are extraordinarily large water waves whose heights exceed by a factor of 2.2 the significant wave height of a measured wave train"* (Onorato et al., 2001). The significant wave height is defined as the mean of the largest third of waves in a wave record. Rough waves often occur as single and steep wave crests that may cause severe damage to offshore/onshore structures and ships. The formation of such waves results, among other factors, from the presence of strong currents or from a simple chance superposition of different waves with coherent phases (Onorato et al., 2001).

[N20] Storm surge. Storm surge is a coastal flood phenomenon that can result from several different types of storms such as tropical cyclones, extratropical cyclones, squall lines (a line of thunderstorms ahead of a cold front), and hybrid storms in low-pressure weather systems. Flood levels are a function of the depth of the water body, the orientation of the shoreline, the wind direction, the storm path, and tides. Two main meteorological factors contribute to storm surge: the long fetch (i.e., the length of water over which wind has blown) of winds spiralling towards the centre of the storm, and the elevated water dome drawn up by low the air pressure in the storm's centre. The second effect is responsible for destructive meteotsunamis (a tsunami-like wave of meteorological origin; Intergovernmental Oceanographic Commission, 2016).

[N29a/b] Humidity (high and low). Extremes of humidity have an impact on the cooling capacity of nuclear power plants that utilize evaporation based designs for the ultimate heat sink (e.g. mechanical draught cooling towers). Together with other parameters such as wind, precipitation, temperature, and air pressure extremes of humidity may combine to meteorological conditions representing (a) maximum evaporation potential (leading to maximum cooling water consumption) and (b) minimum water cooling (e.g. cooling capacity of the cooling tower) (IAEA, 2011).

[N34] Icing. The term refers to clear ice that precipitates from rain or fog and covers cold objects in a sheet-like mass of layered ice. Such ice covers have a higher density than ice crystals formed by frost or rime [N35] and therefore a higher potential to damage objects by loading. Examples of vulnerable structures include power lines and (high voltage) outdoor switchgears of NPPs.

[N35] White frost, hoar frost, hard rime, soft rime. The hazard type summarizes the effects of several types of ice coatings that form in humid and cold air and produce ice crystals in a greater variety of forms. Crystals freeze to the upwind side of solid objects. Rime refers to ice deposits forming from water droplets in freezing fog or mist at calm or light wind. Supercooled water drops are involved in the formation of rime. Meteorological literature distinguishes hard rime, which has a comb-like appearance and firmly adheres to objects, from soft rime, which consists of fragile and delicate ice needles. In contrast to rime, where vapour first condensates to droplets before freezing, white frost and hoar frost forms by desublimation of ice directly from water vapour. Both types of frost do not form from fog but from air of different degrees of relative humidity at low temperatures. Frost and rime is less dense than solid ice and adheres to objects less tenaciously. Their damage potential is therefore less than that of clear ice covering objects (N34, Icing).

[N42] Waterspout. A waterspout (tornado occurring over water) is a small and weak rotating column of air over water. It consists of a columnar vortex which is upwards connected to a funnel-shaped cloud. The phenomenon is mostly weaker than tornadoes on land. Most of the water contained in the funnel of a waterspout is formed by the condensation of droplets, not by sucking up water from the underlying water body. Stronger waterspouts may originate in mesocyclone thunderstorms.

[N49] Frazil ice. *"Frazil ice is generally defined as the mass of ice crystals formed in a turbulent flow which is in a supercooled condition"* (Michel, 1967). Supercooling results in a suspension of loose, randomly oriented needle-shaped ice crystals in water resembling slush. Frazil ice forms in turbulent, supercooled water (rivers, lakes and oceans) when air temperature reaches –6°C or lower. At high speeds of water currents the small ice crystals are not buoyant and may be carried into deeper water instead of floating at the surface. Continuing crystal growth may result in underwater ice adhering to objects in the water such as trash racks protecting water intake structures. This process may proceed very fast and lead to total blockage of trash bars (Daly, 1991).

[N52] Solar flares, solar storms (space weather); electromagnetic interference. A solar flare is a sudden release of extremely large energy of the Sun caused by electromagnetic phenomena within the Sun. Flares may lead to the ejection of plasma (coronal mass ejection) and particle storms (solar storms) with clouds of electrons, ions, and atoms moving through the corona of the sun into space. Such clouds may reach the Earth within hours or few days after the solar event. Massive solar flares with coronal mass ejections have a strong impact on the space weather near the Earth. They cause temporary disturbances of the Earth's magnetosphere and magnetic field causing geomagnetic storms. The latter may lead to severe disturbances of electrical systems including the disruption of communication by absorption or reflection of radio signals, and the damage of terrestrial electric power grids by moving magnetic fields that induce currents in conductors of the power grid. These currents may particularly damage transformers. Geomagnetic storms may therefore cause long-lasting breakdowns of the electrical power grid. Other effects include the heating of long conductors such as pipelines. Since solar flares affect the whole Earth the assessment of the likeliness of hazardous events is fully not site specific. Occurrence probabilities and hazard severities depend on the geographical latitude (Boteler, 2003). Direct and indirect observations of solar flares show downward-cumulative frequency distributions of fluences of solar energetic particle events (Schrijver et al., 2012).

[N72] Meteorite fall. Observations and modelling of asteroid impacts support the assumption of uniform impact distribution for all parts of the Earth independent from geographical latitude and longitude (NASA, 2014; Rumpf et al., 2015). Hazard assessments for meteorite fall therefore are not site specific. Hazard estimates may be derived from globally established correlations between the size of the impacting object (or its impact energy) and the yearly probability to hit the Earth (Bland, 2005), and the correlation between the size of the area affected by destructive phenomena and the impact energy (e.g., Collins et al., 2005).

2.3 EXTERNAL MAN-MADE HAZARDS

The exhaustive list of 24 external man-made hazards is included in Table 3 (next pages).

Hazards are grouped into:

- Industry accidents;
- Military accidents;
- Transportation accidents;
- Pipeline accidents;
- Aircraft accidents;
- Other man-made external events.

Table 3 (next pages). Exhaustive list of external man-made hazards (24 hazard types).

Explanation to columns: Ref.: references to international standards and guidelines introducing the hazard type; [7] IAEA, 2003 d; [8] IAEA, 2002; [10] IAEA, 2010 b; [13] Kuramoto, T., et al., 2014; [14] IAEA, 2003 e. Dur.: duration of hazard phenomena classified as s-m (seconds to minutes), m-h (minutes to hours), h-d (hours to days), d-l (days and longer). P&P: Hazard predictability and hazard progression: predictable (P), unpredictable (U), progressing rapidly (R) or gradually (G).

Industry accidents

Code	Hazard	Ref.	Dur.	P&P	Hazard definition and hazard impact	Interfaces and comments
M1	Industry accident: explosion	[7] [8] [14]	s-m	U/R	The hazard is defined in terms of damage to the plant resulting from explosions (deflagration or detonation) of solid substances, liquids or gases that leads to damage to the plant, loss of off-site power or threatened operator action. The damage may be due to pressure impact or impact of missiles.	This hazard is most relevant for chemical or fuel storage facilities (oil refinery, chemical plant, storage depot, other nuclear facilities). Explosions in connection with transportation (M11) and pipeline accidents (M13) are treated separately. Fire due to industrial accident is treated separately (M24).
M2	Industry accident: chemical release (explosive, flammable, asphyxiating, toxic, corrosive or radioactive substances)	[10] [14]	h-d	U/R	The hazard is defined by the impact of releases from industrial plants that lead to damage to the plant or threatened operator action owing to the release of explosive, flammable, asphyxiating, toxic, corrosive or radioactive substances.	This hazard is most relevant for chemical or fuel storage facilities (oil refinery, chemical plant, storage depot, other nuclear facilities). Hazards resulting from transportation accidents (/M12) or pipeline accidents (M14) are treated separately.
M3	Missiles from high energy rotating equipment	[8] [10]	s-m	U/R	The hazard is defined in terms of the impact of missiles from high energy rotating equipment.	-

Military accidents [8]

Code	Hazard	Ref.	Dur.	P&P	Hazard definition and hazard impact	Interfaces and comments
M4	Military facilities (permanent and temporary): explosion, projectiles, missiles and fire	[8]	s-m	U/R	The hazard is defined by the impact accidents in military facilities such as explosion, projectile generation (shrapnel), or missiles.	Chemical releases from military facilities are treated separately (M5). Fire from military facilities is treated with the fire hazard due to human/technological activity (M24).
M5	Military facilities (permanent and temporary): chemical release (explosive, flammable, asphyxiating, toxic, corrosive or radioactive substances)	[8]	h-d	U/R	The hazard is defined by the impact of releases from military facilities that lead to damage to the plant or threatened operator action owing to the release of explosive, flammable, asphyxiating, toxic, corrosive or radioactive substances.	-

Code	Hazard	Ref.	Dur.	P&P	Hazard definition and hazard impact	Interfaces and comments
M6	Military activities		d-l	P/G	The hazard is defined in terms of damage to plant resulting from military activity.	Explosion and fire induced by military action should be considered as a minimum.

Transportation accidents

Code	Hazard	Ref.	Dur.	P&P	Hazard definition and hazard impact	Interfaces and comments
M7	Ship accident: direct impact	[8] 10] [14]	s-m	U/R	The hazard is defined in terms of the direct impact of a ship.	Collisions with water intake structures and components of the UHS are treated separately (M8). The hazard does not cover consequences of releases in connection with a ship accident (explosion, pollution, intake clogging or release of toxic gases). These hazards are treated separately (M9, M11).
M8	Collisions with water intake and ultimate heat sink components (ship, pontoon, fishing net)	[7] [8] [14]	m-h	U/R	The hazard is defined in terms of damage or clogging of water intakes and UHS structures by collision with ships, pontoons, fishing nets, etc.	The hazard does not cover consequences of releases in connection with a ship accident (explosion, pollution, intake clogging or release of toxic gases). These hazards are treated separately (M9, M11).
M9	Ship accident: solid or fluid (non-gaseous) releases	[7] [8]	d-l	U/R	The hazard is defined in terms of damage or clogging of water intakes and UHS structures by impurities released into the water from a ship, such as oil spills or corrosive fluids, which could affect the availability or quality of cooling water, and its heat exchange capacity.	-
M10	Ground transportation accident: direct impact	[8]	s-m	U/R	The hazard is defined in terms of the direct impact of railway trains and wagons, road vehicles outside the site.	The hazard does not cover consequences of releases in connection with transport accidents (explosion, pollution, intake clogging or release of toxic gases). These hazards are treated separately (M11, M12).

Code	Hazard	Ref.	Dur.	P&P	Hazard definition and hazard impact	Interfaces and comments
M11	Transportation accident: explosion, fire	[8] [10] [14]	s-m	U/R	The hazard is defined in terms of damage to the plant resulting from explosion after ground transportation accidents or due to sea, lake or river transportation accidents. Damage may be due to pressure impact or impact from missiles.	Consequence of other hazards (different prime cause). Hazards due to aircraft crash (M15, M16) or pipeline accident (M13) are treated separately. Toxic effects from a chemical release are treated separately (M12).
M12	Transportation accident: chemical release (explosive, flammable, asphyxiating, toxic, corrosive or radioactive substances)	[7] [8] [10] [14]	h-d	U/R	The hazard is defined by the effects of chemical releases after ground transportation accidents or due to sea, lake or river transportation accidents that affect the plant both externally and internally, damaging or impairing safety related systems and operator action. Releases may originate from transportation accidents, spills or leakages of transported substances.	-

Pipeline accidents [8] [10]

Code	Hazard	Ref.	Dur.	P&P	Hazard definition and hazard impact	Interfaces and comments
M13	Off-site pipeline accident: explosion, fire	[8] [10]	s-m	U/R	The hazard is defined in terms of damage to the plant resulting from explosions (deflagration or detonation) after a pipeline accident (including pumping stations) outside the site. The damage may be due to pressure impact or impact of missiles.	Effects from chemical release are treated separately (M14).
M14	Off-site pipeline accident: chemical release	[8] [10]	h-d	U/R	The hazard is defined by the effects of chemical releases after pipeline accidents (including pumping stations) that affect the plant both externally and internally, damaging or impairing safety related systems and operator action.	Explosion effects from pipeline accidents are treated separately (M13).

Aircraft accidents [7]

Code	Hazard	Ref.	Dur.	P&P	Hazard definition and hazard impact	Interfaces and comments
M15	Aircraft crash: airport zone	[7] [8] [14]	s-m	U/R	The hazard is defined in terms of damage to the plant by abnormal flights leading to crashes. Damage can by caused by direct impact, explosion, missiles, fire (kerosene), smoke (toxic), and inducted vibration.	The hazard depends on flight frequencies, runway characteristics, and types and characteristics of aircrafts. The aircraft may be commercial, private or military.
M16	Aircraft crash: air traffic corridors and flight zones (military/civil/agricultural)	[7] [8] [14]	s-m	U/R	The hazard is defined in terms of damage to the plant by abnormal flights leading to crashes. Damage can by caused by direct impact, explosion, missiles, fire (kerosene), smoke (toxic), and inducted vibration.	The hazard depends on flight frequencies, characteristics of air traffic corridors, and types and characteristics of aircrafts. The aircraft may be commercial, private or military.
M17	Satellite crash	[7]	s-m	U/R	The hazard is defined in terms of damage to the plant resulting from satellite impact. Damage can be caused by direct impact, induced vibration, or shock wave.	-

Other man-made external hazards

Code	Hazard	Ref.	Dur.	P&P	Hazard definition and hazard impact	Interfaces and comments
M18	Excavation and construction work	[10] [13]	h-d	P/R	The hazard is defined in terms of impact on the plant of excavation construction work outside the site area including destructive work on cabling and piping buried underground which may lead to the breach of underground supplies or the release of explosive, flammable, asphyxiating, toxic or corrosive substances.	-

Code	Hazard	Ref.	Dur.	P&P	Hazard definition and hazard impact	Interfaces and comments
M19	Instability of the off-site power grid		h-d	U/R	The hazard is defined by the impact of disturbances coming from manipulation on the grid and switchyards from outside the site. It includes external grid disturbance leading to voltage surges.	-
M20	Industrial contamination of insulation of high voltage in outdoor switchgear and power lines		h-d	U/R	The hazard is defined by the impact on the insulation of high voltage in outdoor switchgear by industrial contaminants such as dust or chemical releases.	-
M21	Electromagnetic interference, radiofrequency interference or disturbance from off-site sources	[7] [8] [10] [14]	m-h	U/R	The hazard is defined in terms of impact of human-induced magnetic or electrical fields, and radio magnetic disturbance that could cause malfunction in or damage to safety related equipment or instrumentation.	The main examples of such fields are those attributable to radar, radio, and mobile telephone systems, or to the activation of high-voltage electric switchgears.
M22	High-voltage eddy current into ground (off-site sources)	[8]	m-h	U/R	The hazard is defined by corrosion of underground metal ground components and grounding problems.	-
M23	Flooding: malfunction or miss-management of watergate or dam	[10]	h-d	U/R	The hazard is defined in terms of damage to the plant by high level water and water waves caused by human-induced damage, malfunction or miss-management of water control structures.	The hazard may be enveloped by flood hazard caused by failure of water control structures (dam failure) caused by natural events (N15).
M24	Fire as result to human/technological activity	[10] [13]	h-d	U/R	The hazard is defined in terms of damage to the plant or loss of off-site power resulting from human-induced forest, wildland or grassland fire, or fire in urban area. It includes hazard due to sparks igniting other fires, smoke, combustion gas of fire, and heat (thermal flux).	Fire may result from industrial accident or free time activities.

3 EVENT COMBINATIONS AND HAZARD CORRELATIONS

The general approach used for the identification of a realistic set of combinations of hazards is based on a systematic check of the dependencies between all external hazards. Possible combinations of hazards are identified based on the list of individual hazards discriminating three distinct combinations of multiple hazards:

1. **Causally connected (or consequential) hazards**
   A hazardous event may result in one or more causally connected (consequential) secondary hazardous events due to a direct causal relationship between the primary and secondary event(s).

2. **Associated (or correlated) hazards**
   Multiple external hazardous events may occur as a consequence of a single underlying cause, in which case they are assumed to be correlated or associated. Such hazards are probable to occur under the same conditions and at the same time. The underlying cause (e.g., a meteorological situation) is not necessarily a hazard by itself.

3. **Hazardous combinations of independent phenomena**
   Hazards are considered to be independent if no causal connection between the phenomena exists. Independent hazardous events can only be expected to occur together by random coincidence.

Following the occurrence of an external hazardous event, the state of the plant may be compromised due to potential unavailability of some SSCs including SSCs which provide fundamental safety function to the plant, and this must be taken into account in the assessment of hazard combinations. In the case of consequential or correlated external hazards, the primary and secondary hazardous event will, by definition, occur simultaneously or within a relatively short period of time.

The analysis of event combinations uses a correlation chart that lists all natural and external man-made hazards (73 and 24 hazard types, respectively). Among the natural hazards extremes of air temperature, ground temperature, cooling water temperature, and humidity are split to list extreme highs and lows separately. This results in a correlation chart with 101 rows and 101 columns representing 5.151 possible hazard combinations. Out of these possible combinations 577 hazard correlations were identified by expert opinion. Correlations 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.

In addition to causally connected hazards and associated hazards the hazard correlation chart identifies hazards which are mutually exclusive and cannot occur at the same time. As it is presented, the correlation chart is symmetric with the line of symmetry as the diagonal line. The relationship between the causes and effects of the hazards as well as mutually exclusive hazards are only reflected in the lower left halve of the chart.

For a specific site possible combinations of hazards should be identified on the basis of the complete list of individual external hazards which apply to the site irrespective of the possible severity of each hazard. The entire list of physically possible hazards should be used for this purpose before any further screening analysis is carried out in order not to exclude hazards which in combination with other hazards have the potential to pose threats to the plant (WENRA, 2014). Hazards, that are fore instance screened out based on not reaching critical severities to challenge the physical integrity of the plant or because the hazard manifestation is within the design base, should be reconsidered in the combined assessment, as their combined loads or impacts could be challenging or even outside the design base.

Site-specific hazard assessments should also include possible combinations of external and internal hazards (WENRA, 2014; 2015). Although the latter are not in the focus of the ASAMPSA_E project a non-exhaustive list of internal hazards which should be considered in such analyses is included in Appendix B of the current report.

3.1 CAUSALLY CONNECTED HAZARDS

This type of connection between hazards refers to a cause-effect relation, where the hazardous phenomenon A triggers or may trigger the hazardous event B ("causes-effects relation", NIER, 2013; "common cause event", Kuramoto et al., 2014). The causal connections are not commutative. The hazard correlation chart discerns two types of causal connections:

1. **A may cause B**

   The relation indicates that A is not a prerequisite to B meaning that A and B can exist by themselves.

   Examples:

   Vibratory ground motion - tsunami: A strong offshore earthquake (including remote ones) may cause a tsunami; a tsunami, however, may also result from other events (landsliding, volcanic activity etc.);

   Industry explosion - wildfire: Industry accidents may under certain conditions result in wildfire but they are not the exclusive reason for wildfire.

2. **A is a prerequisite for B (no B without A).**

   The relation indicates that the event B cannot occur without A. It includes « A may cause B » meaning that A may occur without leading to B. The relation therefore does not indicate that B is an inevitable consequence of A.

   Examples:

   Vibratory ground motion - liquefaction: Soil liquefaction does not occur without earthquake shaking. The hazard must therefore be considered together with other effects of vibratory ground motion. However, not each earthquake will lead to soil liquefaction.

   Low temperature - surface ice: Surface ice on water requires a low enough temperature. Surface ice must therefore be considered together with other possible effects of low temperature.

The probabilities for causal connection type (1) may vary from any value between 0 and 1. The probability for connection type (2) is 1. The causal connections in (1) and (2) are not commutative.

Causal connections of type (1) are usually restricted by further requirements. In the listed example, liquefaction will only occur under certain conditions such as the presence of liquefiable soil, a minimum ground acceleration, and a minimum duration of the earthquake. Surface ice will be caused by appropriate combinations of low temperatures and sufficiently long periods of freezing. The limiting parameters (earthquake magnitude, earthquake duration; temperature, duration of low temperature conditions) can usually be constrained by parameters derived from the hazard assessments.

The correlation chart only lists the direct consequences of a certain hazards, causal chains and hazard cascades are not considered.

Example: a possible consequence of mismanagement of dam is flooding; further possible consequences of flooding such as biological flotsam clogging the water intake are not listed as a consequence of mismanagement of dam. Clogging by biological flotsam, however, is listed as a possible consequence of flooding.

3.2 ASSOCIATED HAZARDS

Associated hazards refer to events which are probable to occur at the same time due to a common root cause ("contemporary relation", NIER, 2013). The common root cause (e.g., a meteorological situation) may not necessarily be regarded as a hazard by itself. Examples for associated hazards are:

Cold front of a meteorological low pressure area: drop of air pressure, high wind, lightning (thunder storm), precipitation (heavy rain, hail);
High-temperature summer period: high air and ground temperature, high cooling water temperature, low ground water, drought.

Associated hazards are identified in the correlation chart. The level of correlation between the different phenomena may range from weak to strong and must be identified on a case by case basis.

3.3 HAZARDOUS COMBINATIONS OF INDEPENDENT PHENOMENA

The combinations of independent phenomena which, in combination, cause potential hazards are not specified in the correlation chart. Examples of such combinations are:

The occurrence of a earthquake *(vibratory ground motion)* during *high wind*.
Slope instability due to a combination of precipitation and vibratory ground motion.

In principal all of the possible 5.151 combinations are possible to occur by random coincidence except for the 25 cases where one hazard is a prerequisite for another hazard (A is a prerequisite for B), and for 82 hazards that – depending on the time scale – are mutually exclusive. Examples for such mutually exclusive hazards are high and low air temperature or high air temperature and surface ice.

In practise, not all of the remaining 5.044 combinations need to be considered, because combinations of hazards would be assessed only after completion of the site specific hazards screening process. The single hazards that have not been screened out at this point form the main contribution for the list of hazards whose combinations should be evaluated.

Evaluations of random combinations of independent phenomena will further limit the number of combinations to be analysed by considering the time aspect. In the case of independent hazards, each of the hazards would have to occur within a given duration of time in order to be considered as a random hazard combination. The time period in which both hazards could have an impact on the plant needs to be defined by an assessment of how long the plant may still be affected by the consequences of the first hazardous event when the second event occurs. The duration of this time period would depend on the recovery time required to address the consequences of the first event. Depending on the duration and the occurrence frequencies of both hazards in the combination, the frequency of the combination can be estimated. It is expected that this frequency will often be lower than the screening frequency used for a single hazard.

3.4 DISCUSSION OF IDENTIFIED CORRELATIONS

The close inspection of the hazard cross correlation chart reveals remarkable differences between the individual hazards in terms of the number of cross correlations with other hazards (Fig. 3-1 to 3-4). The cited figures distinguish “isolated” hazards, which do not correlate with any or only very few other hazards (e.g., biological infestation) from hazards, which are correlated or associated with a large number of other phenomena.

Examples for the latter are vibratory ground motion (correlated with 26 other hazard types), industry explosion (31 correlated hazards), and instability of the power grid (40 correlations). External man-made hazards are generally characterized by relatively large numbers of cross-correlated phenomena. This is due to the fact that many natural hazards can impact the entire site vicinity and all man-made activities in the surrounding of a NPP in the same way as the NPP itself. This is particularly evident for seismotectonic, hydrological, and meteorological phenomena. A correlation between the man-made hazards and natural hazards may therefore be regarded not very informative. It should, however, be noted that many man-made facilities will not be engineered to the same safety levels as nuclear facilities. For example, an earthquake with a ground shaking severity which is not challenging the NPP may be destructive for a chemical plant nearby which is not engineered to the same safety standard. On the other hand some man-made structures or activities may not be vulnerable to a specific natural hazard which otherwise may have a strong impact on the safety of a nuclear power plant.

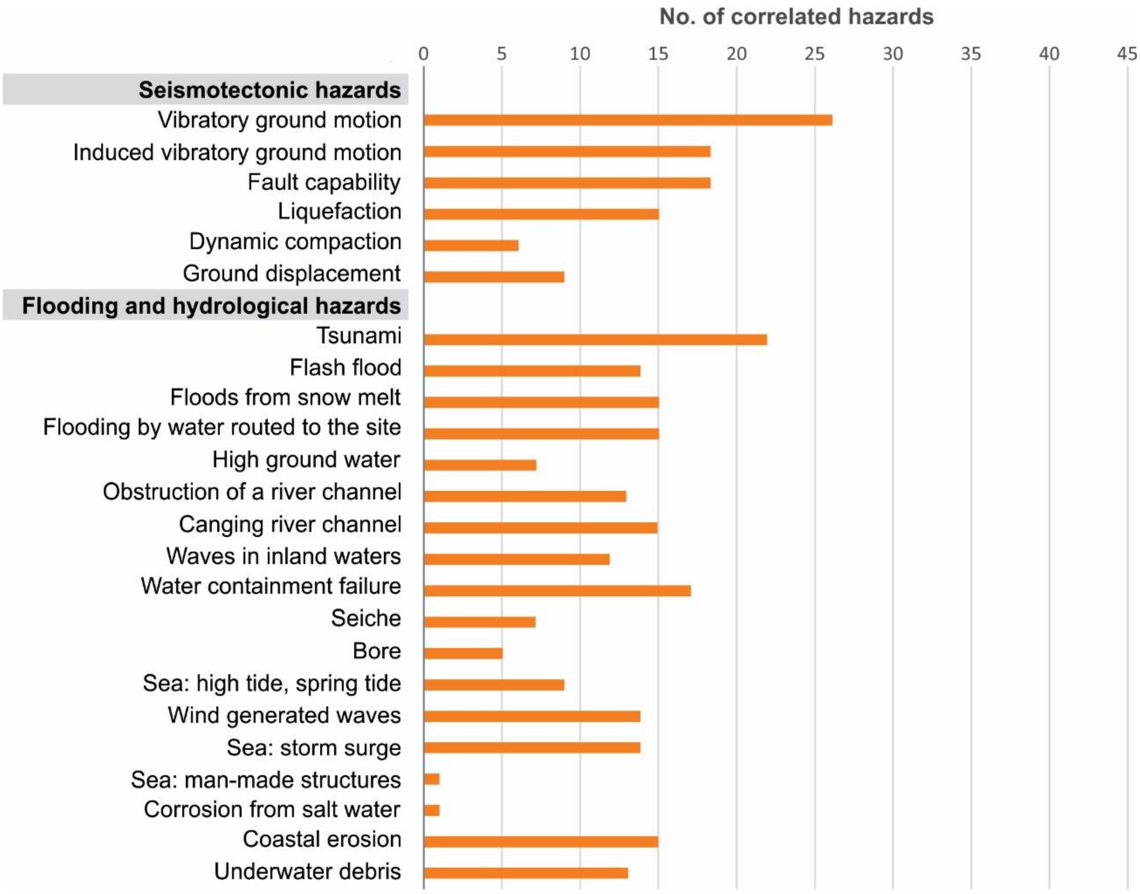

Figure 3-1: Number of hazards correlated with seismotectonic and flooding hazards.

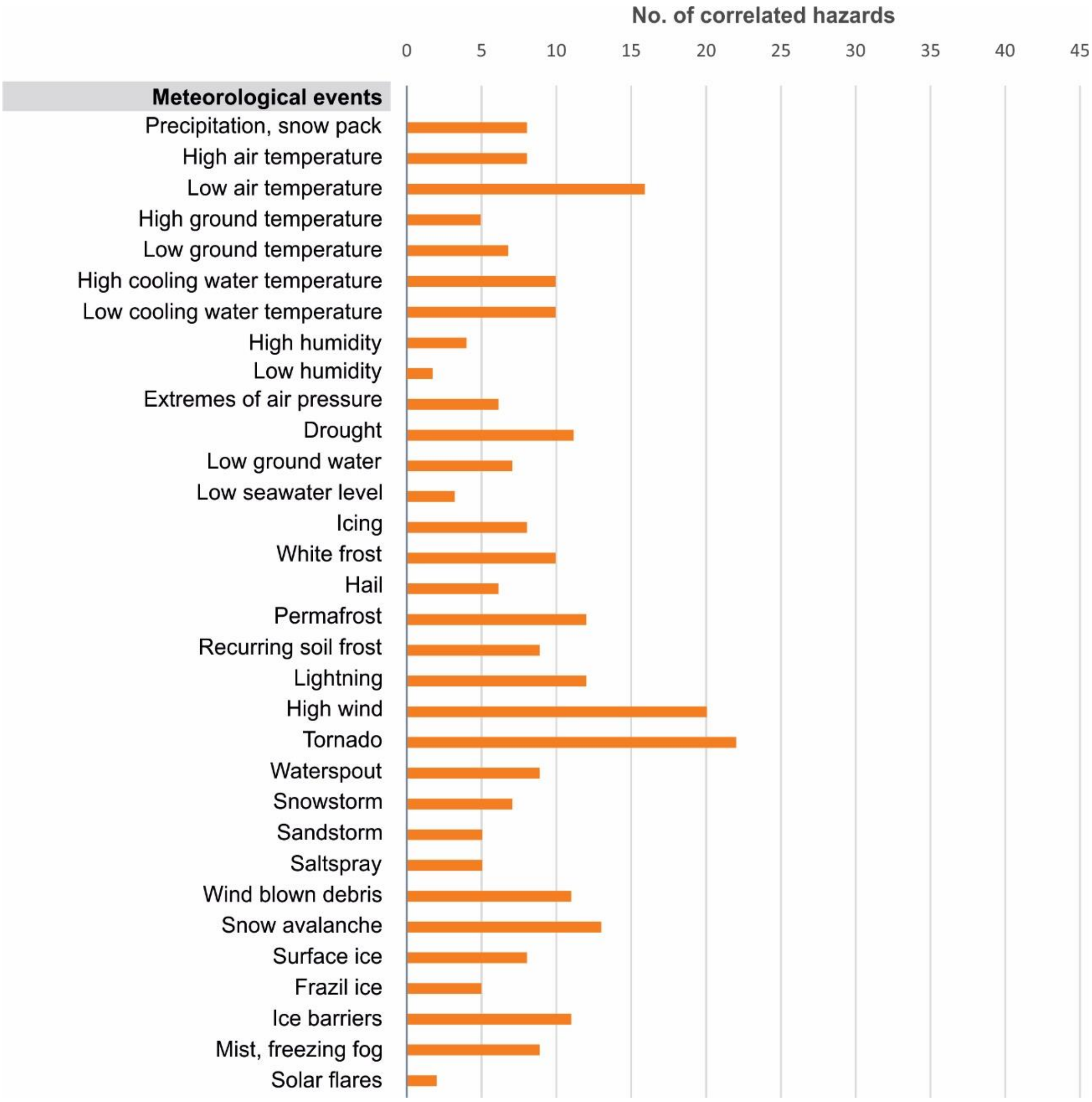

Figure 3-2: Number of hazards correlated with meteorological events.

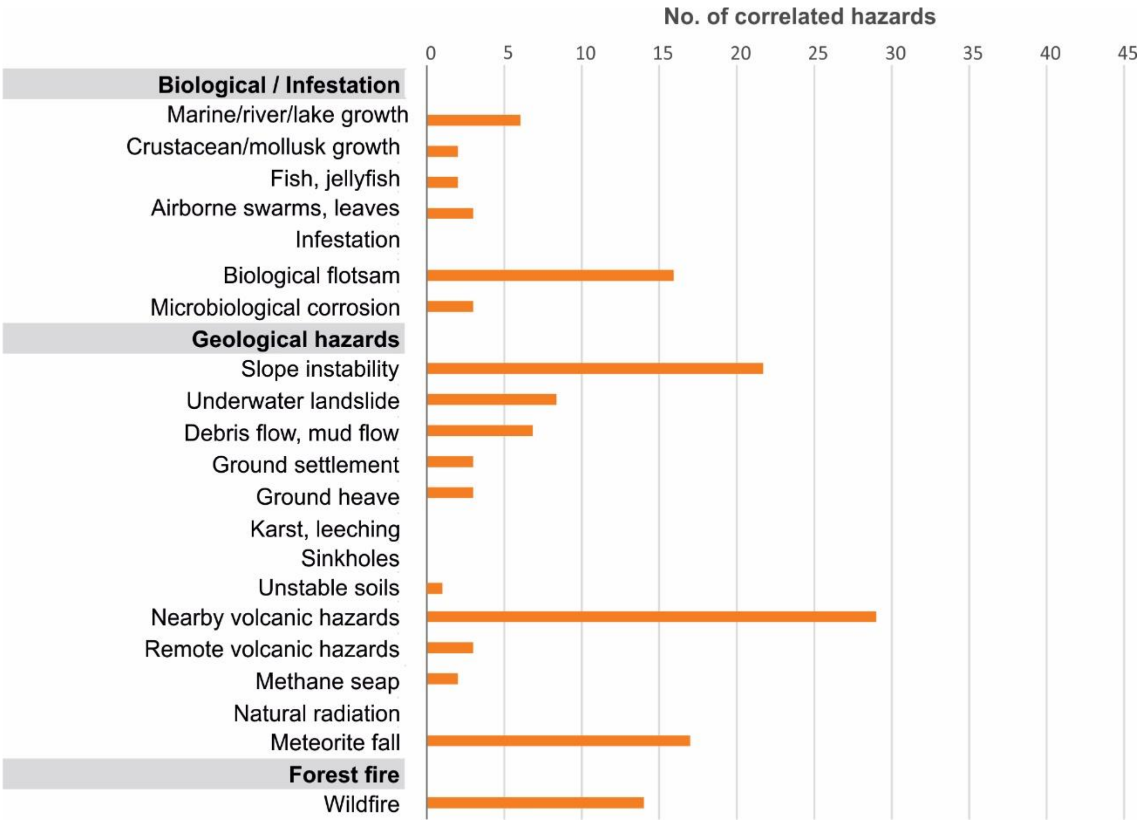

Figure 3-3: Number of hazards correlated with biological hazards, geological hazards and natural fire.

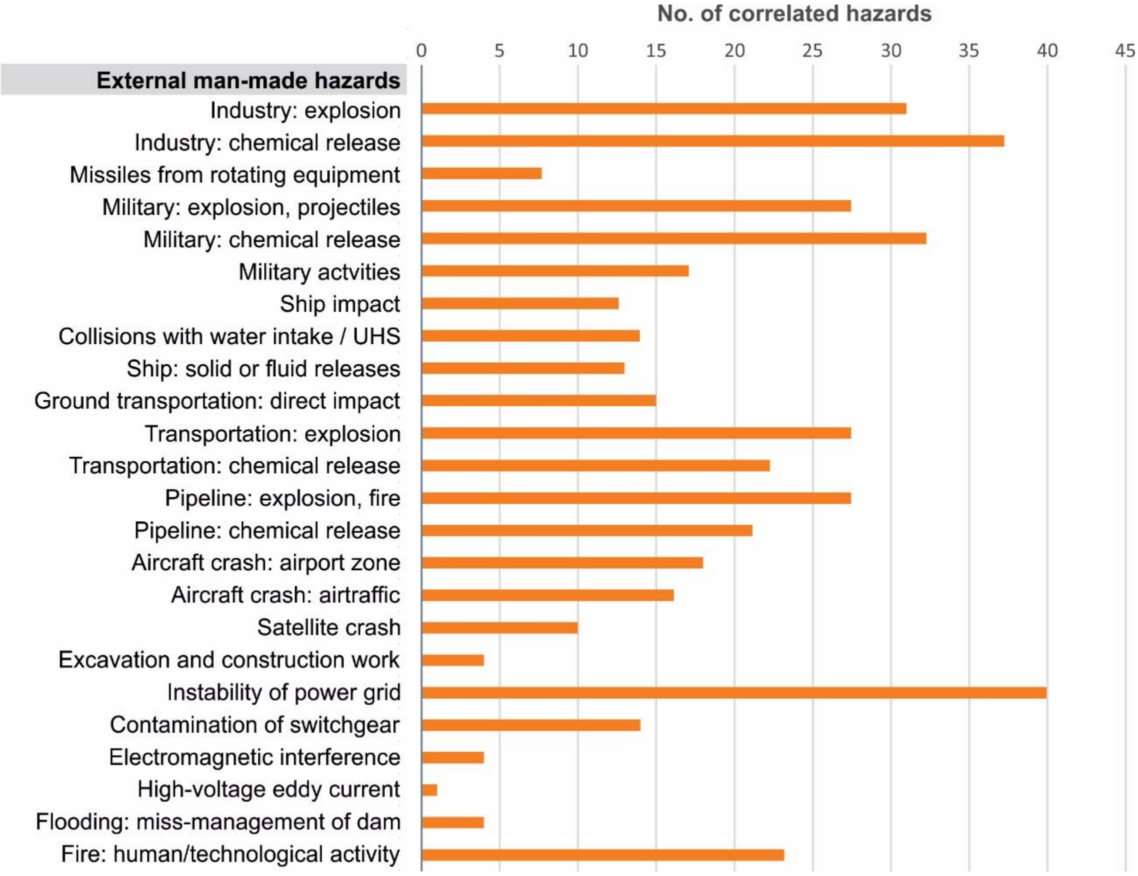

Figure 3-4: Number of hazards correlated with external man-made hazards.

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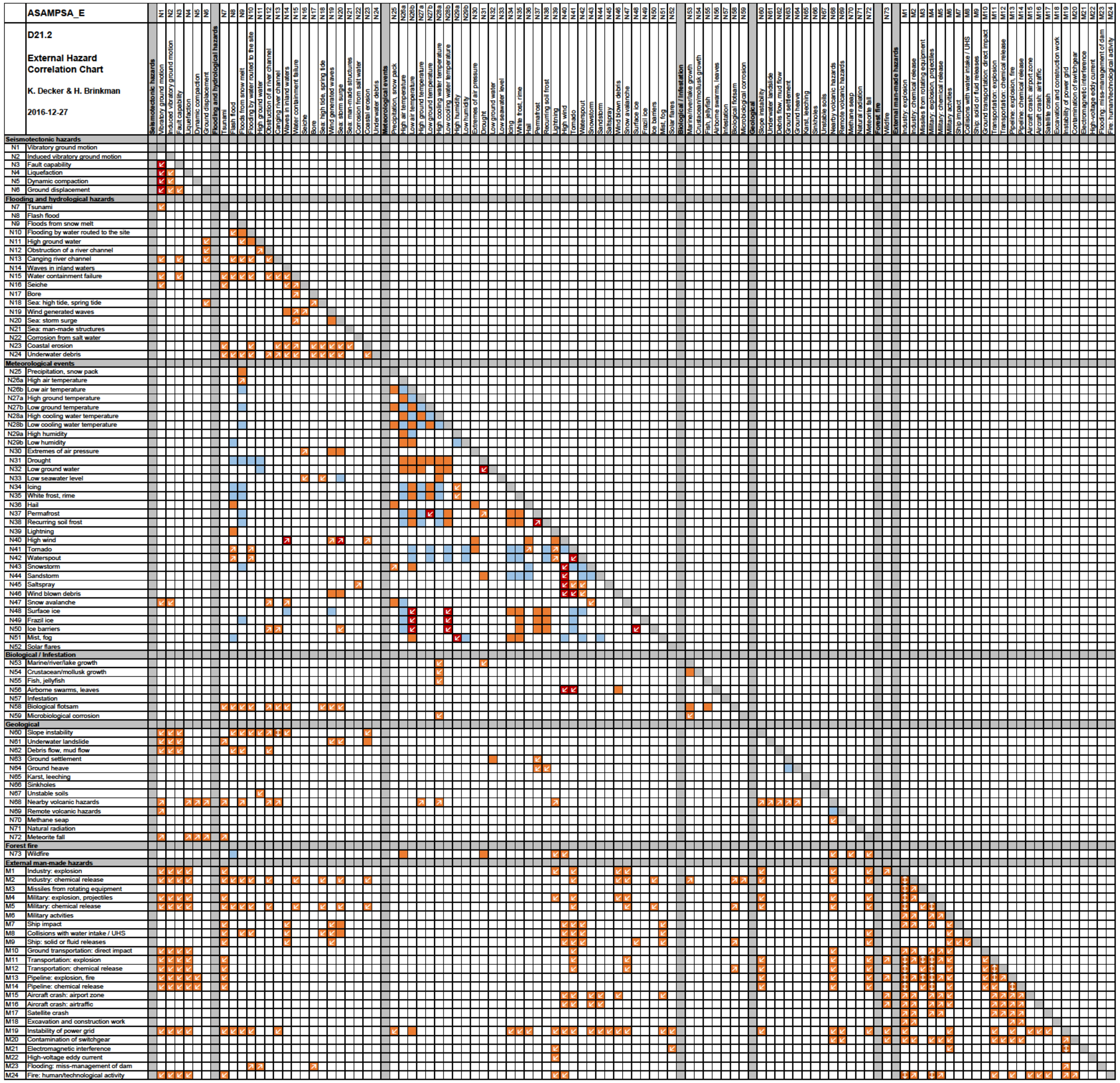
APPENDIX A: HAZARD CORRELATION CHART

Cross-correlation chart showing causally connected hazards (A may cause B, A is a prerequisite for B), associated hazards (A and B may result from the same root cause), and mutually exclusive hazards. See the legend below for the explanation of the symbols used in the table. Note that:

1. Only direct consequences of individual hazards are listed. Causal chains are not considered explicitly, but can be derived with the help of the table;
2. Combinations of independent phenomena which may cause potential hazards by their contemporaneous occurrence by random coincidence are not identified;
3. The chart is symmetric with the line of symmetry as the diagonal line. All hazard combinations are only plotted in the lower left half space of the table.

LEGEND TO THE CORRELATION CHART

A	B: f	A is prerequisite for B
A	B: c	B is prerequisite for A
A	B: f	A may cause B
A	B: c	B may cause A
A	B: ↕	A may cause B or B may cause A
A	B	Associated hazards: A and B derive from a common root cause
A	B	Hazards A and B are mutually exclusive


ASAMPSA_E
D21.2
External Hazard Correlation Chart
K. Decker & H. Brinkman
2016-12-27
Seismotectonic hazards
N1 Vibratory ground motion
N2 Induced vibratory ground motion
N3 Fault capability
N4 Liquefaction
N5 Dynamic compaction
N6 Ground displacement
Flooding and hydrological hazards
N7 Tsunami
N8 Flash flood
N9 Floods from snow melt
N10 Flooding by water routed to the site
N11 High ground water
N12 Obstruction of a river channel
N13 Canging river channel
N14 Waves in inland waters
N15 Water containment failure
N16 Seiche
N17 Bore
N18 Sea: high tide, spring tide
N19 Wind generated waves
N20 Sea: storm surge
N21 Sea: man-made structures
N22 Corrosion from salt water
N23 Coastal erosion
N24 Underwater debris
Meteorological events
N25 Precipitation, snow pack
N26a High air temperature
N26b Low air temperature
N27a High ground temperature
N27b Low ground temperature
N28a High cooling water temperature
N28b Low cooling water temperature
N29a High humidity
N29b Low humidity
N30 Extremes of air pressure
N31 Drought
N32 Low ground water
N33 Low seawater level
N34 Icing
N35 White frost, rime
N36 Hail
N37 Permafrost
N38 Recurring soil frost
N39 Lightning
N40 High wind
N41 Tornado
N42 Waterspout
N43 Snowstorm
N44 Sandstorm
N45 Saltspray
N46 Wind blown debris
N47 Snow avalanche
N48 Surface ice
N49 Frazil ice
N50 Ice barriers
N51 Mist, fog
N52 Solar flares
Biological / Infestation
N53 Marine/river/lake growth
N54 Crustacean/mollusk growth
N55 Fish, jellyfish
N56 Airborne swarms, leaves
N57 Infestation
N58 Biological flotsam
N59 Microbiological corrosion
Geological
N60 Slope instability
N61 Underwater landslide
N62 Debris flow, mud flow
N63 Ground settlement
N64 Ground heave
N65 Karst, leeching
N66 Sinkholes
N67 Unstable soils
N68 Nearby volcanic hazards
N69 Remote volcanic hazards
N70 Methane seap
N71 Natural radiation
N72 Meteorite fall
Forest fire
N73 Wildfire
External man-made hazards
M1 Industry: explosion
M2 Industry: chemical release
M3 Missiles from rotating equipment
M4 Military: explosion, projectiles
M5 Military: chemical release
M6 Military activities
M7 Ship impact
M8 Collisions with water intake / UHS
M9 Ship: solid or fluid releases
M10 Ground transportation: direct impact
M11 Transportation: explosion
M12 Transportation: chemical release
M13 Pipeline: explosion, fire
M14 Pipeline: chemical release
M15 Aircraft crash: airport zone
M16 Aircraft crash: airtraffic
M17 Satellite crash
M18 Excavation and construction work
M19 Instability of power grid
M20 Contamination of switchgear
M21 Electromagnetic interference
M22 High-voltage eddy current
M23 Flooding: miss-management of dam
M24 Fire: human/technological activity

APPENDIX B: INTERNAL HAZARDS

On-site accidents [10]: internal hazards to be considered as possible consequences of external events in extended PSA

Code	Hazard	Ref.	Hazard definition and hazard impact	Interfaces and comments
M25	Direct impact of heavy transportation within the site	[10]	The hazard is defined in terms of damage to the plant resulting from direct impact of heavy transportation within the site, but outside the plant buildings. This also includes transportation of the containment external maintenance platform.	Heavy transportation within plant buildings is analysed as part of the PSA for internal hazards.
M26	Explosion within the site	[10]	The hazard is defined in terms of damage to the plant resulting from explosions (deflagration or detonation) of solid substances or gas clouds within the site, but outside the plant buildings. It includes explosion after a pipeline rupture on the site. The damage may be due to pressure impact or impact of missiles.	The explosions within plant buildings are analysed as part of the PSA for internal hazards.
M27	Fire within the site	[10]	The hazard is defined in terms of damage to the plant resulting from fire fires affecting the site and originating from sources outside of the site, or caused by the impact of other natural events such as earthquake.	-
M28	Chemical release within the site: explosive, flammable, asphyxiating, toxic, corrosive or radioactive substances	[10]	The hazard is defined by the effects of chemical releases that affect the plant both externally and internally, damaging or impairing safety related systems and operator action.	These releases may originate from process accidents inside the plant or from leakages of substances stored within the site, but outside the plant buildings. The chemical releases from substances stored inside buildings are analysed as part of the PSA for internal hazards.

Code	Hazard	Ref.	Hazard definition and hazard impact	Interfaces and comments
M29	On-site pipeline accident: explosion, fire	[10]	The hazard is defined in terms of damage to the plant resulting from explosions (deflagration or detonation) or fire after a pipeline accident at the site. The damage may be due to pressure impact or impact of missiles.	Effects from a chemical release after on-site pipeline accident are treated separately. Explosion effects from a release outside the site are treated separately.
M30	On-site pipeline accident: chemical release (explosive, flammable, asphyxiating, toxic, corrosive or radioactive substances)	[10]	The hazard is defined by the effects of chemical releases after an on-site pipeline accident that affect the plant both externally and internally, damaging or impairing safety related systems and operator action.	Consequence of other hazards (different prime cause). Explosion effects from pipeline accidents are treated separately.

Code	Hazard	Ref.	Hazard definition and hazard impact	Interfaces and comments
M31	Excavation and construction work at the site	[10]	The hazard is defined in terms of impact on the plant of excavation work and civil construction within the site area including destructive work on cabling and piping buried underground.	-
M32	Stability of the on-site power grid		The hazard is defined by the impact of electrical current fluctuations coming from manipulation on switch yards/grid from inside the plant.	-
M33	Electromagnetic interference, radiofrequency interference or disturbance from on-site sources	[7] [8] [10]	The hazard is defined in terms of impact on the plant of human-induced magnetic or electrical fields, and radio-magnetic disturbance that could cause malfunction in or damage to safety related equipment or instrumentation.	The main examples of such fields are those attributable to radio communication and mobile telephone systems.

Code	Hazard	Ref.	Hazard definition and hazard impact	Interfaces and comments
M34	High-voltage eddy current into ground (on-site sources)	[8]	The hazard is defined by corrosion of underground metal ground components and grounding problems.	-
M35	Flooding from on-site tanks	[7]	The hazard is defined by the impact of flooding due to failure of on-site tanks.	-
M36	Missiles from other units on the site	[10]	The hazard is defined in terms of damage to the plant resulting from missiles generated by high energy rotating equipment at another unit or installation on the site.	-
M37	Internal fire spreading from other units on the site	[10]	The hazard is defined in terms of impact on the plant of fires originating in another unit on the site.	External fires are treated separately. Fires resulting as secondary effects from other external hazards are treated as part of these hazards.
M38	Internal flood and harsh environment spreading from other units on the site	[10]	This hazard is defined in terms of damage to the plant resulting from water spreading effects from other units.	-
M39	Effects of accidents at other units on the site		This hazard is defined in terms of damage to the plant resulting from explosion (e.g., hydrogen) or radioactive releases at other units of the site.	-

References (Ref.): [7] IAEA, 2003 d; [8] IAEA, 2002; [10] IAEA, 2010 b.