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Proceedings of the Workshop on Uncertainties in the Assessment of Natural Hazards (Excluding Earthquakes)

19-21 April 2022

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NUCLEAR ENERGY AGENCY

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NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

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The mission of the NEA is:

– to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes;

– to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management and decommissioning, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS (CSNI)

The Committee on the Safety of Nuclear Installations (CSNI) addresses Nuclear Energy Agency (NEA) programmes and activities that support maintaining and advancing the scientific and technical knowledge base of the safety of nuclear installations.

The Committee constitutes a forum for the exchange of technical information and for collaboration between organisations, which can contribute, from their respective backgrounds in research, development and engineering, to its activities. It has regard to the exchange of information between member countries and safety R&D programmes of various sizes in order to keep all member countries involved in and abreast of developments in technical safety matters.

The Committee reviews the state of knowledge on important topics of nuclear safety science and techniques and of safety assessments, and ensures that operating experience is appropriately accounted for in its activities. It initiates and conducts programmes identified by these reviews and assessments in order to confirm safety, overcome discrepancies, develop improvements and reach consensus on technical issues of common interest. It promotes the co-ordination of work in different member countries that serve to maintain and enhance competence in nuclear safety matters, including the establishment of joint undertakings (e.g. joint research and data projects), and assists in the feedback of the results to participating organisations. The Committee ensures that valuable end-products of the technical reviews and analyses are provided to members in a timely manner, and made publicly available when appropriate, to support broader nuclear safety.

The Committee focuses primarily on the safety aspects of existing power reactors, other nuclear installations and new power reactors; it also considers the safety implications of scientific and technical developments of future reactor technologies and designs. Further, the scope for the Committee includes human and organisational research activities and technical developments that affect nuclear safety.

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The members of the Nuclear Energy Agency (NEA) Working Group on External Events (WGEV) acknowledge the significant contributions of those individuals who had a key role in the conduct and success of the NEA's Workshop on Uncertainties in the Assessment of Natural Hazards (Excluding Earthquakes). Additional thanks are extended to Taehee Kim, Technical Secretary of the WGEV, and Mihaela Brunette, NEA Assistant, in support of the workshop and the preparation of these proceedings.

This report was approved at the 73rd meeting of the NEA Committee on the Safety of Nuclear Installations (CSNI) on 6 June 2023 (as recorded in the "Summary Record of the 73rd Meeting of the CSNI" [NEA/SEN/SIN(2023)1] [not publicly available]).

Workshop / session chairs and rapporteurs

John Perdikaris	Ontario Power Generation (OPG), Canada Workshop and Wrap-up Session Chair
Gernot Thuma	Gesellschaft für Anlagen-und Reaktorsicherheit (GRS), Germany Session 1 Chair and Session 3 Rapporteur
Minkyu Kim	Korea Atomic Energy Research Institute (KAERI) Session 2 Chair
John Nakoski	United States Nuclear Regulatory Commission (NRC) Session 3 Chair
Taehee Kim	Nuclear Energy Agency (NEA) Session 1 Rapporteur
Vincent Rebour	Institut de Radioprotection et de Sûreté Nucléaire (IRSN), France Session 2 Rapporteur

Presenters and panel members

Yann Richet	IRSN, France
Tomas Jelinek	Swedish Radiation Safety Authority (SSM), Sweden
Antti Mäkelä	Finnish Meteorological Institute (FMI), Finland
Catalin Obreja	Environment and Climate Change Canada (ECC)
Peter Siegmund	Royal Netherlands Meteorological Institute (KNMI), Netherlands
Claire-Marie Duluc	IRSN, France
Joseph Kanney	NRC, United States
Sato Taichi	Nuclear Regulation Authority (NRA) Japan
Marc Levitan	National Institute of Standards and Technology (NIST), United States

Table of contents

List of abbreviations and acronyms

CRIEPI	Central Research Institute of Electric Power Industry
CSNI	Committee on the Safety of Nuclear Installations (NEA)
ECC	Environment and Climate Change Canada
FEPC	Federation of Electric Power Companies
FMI	Finnish Meteorological Institute
GCMS	Global climate models
GR	Gutenberg–Richter (law)
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit gGmbH (Germany)
IAEA	International Atomic Energy Agency
ICCS	Independent core cooling systems
IDF	Intensity duration frequency
IRSN	Institut de Radioprotection et de Sûreté Nucléaire (French Institute for Radiological Protection and Nuclear Safety [ASNR since January 2025])
KAERI	Korea Atomic Energy Research Institute
KNMI	Royal Netherlands Meteorological Institute
NEA	Nuclear Energy Agency
NIST	National Institute of Standards and Technology (United States)
NRA	Nuclear Regulation Authority (Japan)
NRC	Nuclear Regulatory Commission (United States)
ONR	Office for Nuclear Regulation (United Kingdom)
OPG	Ontario Power Generation (Canada)
PFHA	Probabilistic flood hazard assessment
PTHA	Probabilistic tsunami hazard assessments
SSM	Swedish Radiation Safety Authority
WENRA	Western European Nuclear Regulators' Association
WGEV	Working Group on External Events (NEA)

Executive summary

The Nuclear Energy Agency (NEA) Working Group on External Events (WGEV) was established by the Committee on the Safety of Nuclear Installations (CSNI) in June 2014 with the aim of improving the understanding and treatment of external hazards in order to support the continued safety performance of nuclear installations and improve the effectiveness of regulatory practices in NEA member countries. Based on its work with respect to different natural hazards, such as coastal flooding, riverine flooding and high winds, the WGEV identified a common challenge: uncertainties related to hazard assessments. Therefore, a two-phased task on "uncertainties in the assessment of natural hazards (excluding earthquakes)" was proposed to, and accepted by, the CSNI. Phase 1 of this task is intended to provide an overview of the types of uncertainties that need to be considered depending on the type of natural hazard, the data sources and the assessment approaches.

To facilitate the compilation of a report on the sources of uncertainties, it was decided to convene an international workshop shortly after the beginning of this activity. More specifically, the purpose of the workshop was to gather information on: i) sources of uncertainties affecting all assessments of natural hazards; ii) sources of uncertainties relevant to specific hazards; iii) sources of uncertainties related to the input data for the assessment; and iv) sources of uncertainties specific to certain assessment methods. The workshop was organised into three technical sessions, covering the spectrum of hazards within the scope of this activity (extreme temperatures, heat sink effect, lightning, snow, site flooding, and high winds), and an opening and wrap-up session. Each technical session consisted of a set of presentations followed by a panel discussion. In the wrap-up session, the rapporteurs and session chairs summarised the main insights and key messages from the technical session. Based on these summaries, the workshop chair identified the following common themes regarding uncertainties affecting all natural hazard assessments:

- Major uncertainties are related to historical climate conditions as well as bathymetric and topographic data. These uncertainties have a temporal and spatial component.
- The limited length of records for relevant meteorological and hydrological data (with maximum record length of 100 to 150 years) leads to significant uncertainties in the extrapolation to rare events.
- The data collection procedure itself is also a source of uncertainties. To evaluate the suitability of the data for a given purpose several questions need to be answered, e.g.:
    - What exactly has been measured? For which event type can the measurements be considered representative? Which methods and instruments were applied? Where were the measurements taken, at what time intervals and with what integration time? How accurate are the measurements? How good is the quality of the data?
- Besides these data-related uncertainties, there are also epistemic (lack of knowledge) and aleatory (random scatter) uncertainties related to the assessment approaches:
    - Stochastic/statistical approaches require an extrapolation of the recorded data to high return periods (in the order of $10^{-4}/a – 10^{-6}/a$). Besides the limited length

of records mentioned above, the assumptions that must be made with respect to plotting positions, statistical distributions, fitting procedure, etc. contribute to the overall uncertainty of the results.

- o Deterministic hazard assessments based on numerical simulation models are likewise subject to uncertainties resulting from assumptions and simplifications that have to be made.

From these common themes, the following recommendations were derived on how to better integrate the consideration of uncertainties into natural hazard assessments:

- Since many sources of uncertainty are related to data, the data basis for hazard assessments should be improved. The incorporation of additional data sources, such as airborne, satellite or radar measurements, helps to expand the pool of available data.
- Historical data and paleo data are other sources of information that should be used to improve hazard assessments (if they are accessible). Although their inclusion introduces other uncertainties in the analysis, they can provide valuable information on extreme events not covered by measurements.
- As improving the data basis mainly serves to reduce sampling uncertainties, understanding of the phenomenological aspects of natural hazards should be improved to reduce model uncertainties.
- A better understanding of the effects of climate change on natural hazards needs to be developed. This holds in particular for those processes that do not depend on global climate change in a direct manner (e.g. frequency and intensity of rainfall events or storms) and need to be assessed on a regional (not global) scale.
- Although it is not possible to eliminate risk, the understanding of the risk can and should be enhanced by improving the hazard assessment methods.
- In addition to protection measures, a mitigation approach should be applied to natural hazards.

The insights regarding the sources of uncertainties identified in the workshop will be used to guide the further work of the WGEV regarding uncertainties. In particular, the various sources of uncertainties identified during this workshop will be addressed in a forthcoming technical report entitled “Uncertainties in the Assessment of Natural Hazards (Excluding Earthquakes) Phase 1: Sources of Uncertainties”.

Another insight from the workshop is that developing more detailed and complex models of natural hazards and performing comprehensive uncertainty assessments allows epistemic uncertainties to be better quantified, which is an advantage over simpler models. In other words, the increasing complexity of models and uncertainty evaluations leads to an increase of the “known unknowns”. In contrast, simpler models are associated with more “unknown unknowns” (low fidelity).

1. Introduction

1.1. Background

In June 2014, the NEA Committee on the Safety of Nuclear Installations (CSNI) decided to establish the Working Group on External Events (WGEV) to improve the understanding and treatment of external hazards to support the continued safety performance of nuclear installations, as well as the effectiveness of regulatory practices in NEA member countries. The WGEV constitutes a forum of experts for the exchange of information and experience on external events in member countries, thereby promoting co-operation and maintaining an effective and efficient network of experts.

At its 68th meeting, the CSNI approved a recommended task on "uncertainties in the assessment of natural hazards (excluding earthquakes)", to be pursued by the WGEV. This task is split into two phases: Phase 1 on "sources of uncertainties" and Phase 2 on "methods to deal with uncertainties". The overall objective of the two phases is to develop an understanding of the state of practice with respect to the consideration of uncertainties in natural hazard assessments. Phase 1 is intended to provide an overview of the types of uncertainties that need to be considered, depending on the type of natural hazard, the data sources and the assessment approaches. Based on a review of documents containing lists of external hazards published by the International Atomic Energy Agency (IAEA), the Western European Nuclear Regulators' Association (WENRA), the United States Nuclear Regular Commission (NRC), the Office for Nuclear Regulation (ONR), the Swedish Nuclear Power Inspectorate (SKI) and the project team of Advanced Safety Assessment Methodologies: Extended PSA (ASAMPSA_E), the following natural hazards were selected for consideration in this task:

- extreme temperatures (e.g. low/high temperatures, frost, ice cover, ice dams);
- heat sink effects (e.g. drought, low lake/river/sea water level);
- lightning;
- snow (e.g. snowpack, snow loads, drifting snow);
- flooding (e.g. precipitation, flooding caused by landslides or dam/dike failures, high tide, seiche, storm surge, tsunami, waves);
- high winds (e.g. extreme winds and tornadoes, hail, hurricane, sandstorm).

To facilitate the development of a report that i) outlines the spectrum of uncertainties to be taken into account, ii) summarises the relevant characteristics of these uncertainties, and iii) provides a bibliography of the pertinent literature, it was decided to convene an international workshop near the beginning of this activity. Due to travel restrictions related to the COVID-19 pandemic, the decision was made to hold the workshop online, from 19 to 21 April 2022.

1.2. Objectives of the workshop

Whereas previous workshops organised by the WGEV were held towards the end of the task to share and discuss the insights gained with a broader audience, the objective of the Workshop on Sources of Uncertainties in the Assessment of Natural Hazards (Excluding Earthquakes) was to collect information that would serve as input to the corresponding task on uncertainties.

More specifically, the purpose of this workshop was to gather information on:

- sources of uncertainties affecting all assessments of natural hazards;
- sources of uncertainties relevant to specific hazards;
- sources of uncertainties related to the input data for the assessments;
- sources of uncertainties specific to certain assessment methods.

1.3. Organisation of the workshop

The workshop was organised into three technical sessions, covering the spectrum of hazards within the scope of this activity, in addition to an opening and wrap-up session, as follows:

- Opening session
- Session 1: Extreme temperatures, heat sink effect, lightning, snow and statistical methods
- Session 2: Site flooding
- Session 3: High winds
- Wrap-up session

Each technical session consisted of a set of presentations followed by a panel discussion. A total of 14 presentations (on scientific and technical issues) were given in the technical sessions and the opening session.

In the wrap-up session, the rapporteurs and session chairs summarised the main insights and key messages from the technical sessions, followed by a wrap-up of the essential insights from the whole workshop by the workshop chair.

The workshop was open to anyone who wished to participate. The WGEV reached out to subject matter experts from a wide range of organisations. As a result, the participants included experts from regulatory authorities and their technical support organisations, research organisations, universities, operating organisations, and industry associations (see Appendix A for a list of the workshop participants).

The detailed workshop agenda is provided in Appendix B.

2. Summary of the Workshop on Uncertainties in the Assessment of Natural Hazards (Excluding Earthquakes)

The workshop consisted of an opening session, three technical sessions that featured participant presentations followed by panel discussions, and a wrap-up session in which the main insights and key messages were summarised. The contributions presented were devoted to uncertainties in hazard assessments for various natural hazards, including snowfall, lightning, high temperatures, intense precipitation, riverine and coastal flooding, tsunamis, tornadoes, and tropical storms, as well as uncertainties related to deterministic and probabilistic hazard assessment methods.

2.1. Opening session

The workshop was opened by the workshop chair, Mr John Perdikaris (Ontario Power Generation [OPG], Canada), who welcomed the participants, introduced the chairs of the technical sessions and gave an overview of the priorities and challenges of the workshop. Mr Gernot Thuma (Gesellschaft für Anlagen- und Reaktorsicherheit gGmbH [GRS], Germany) explained the background and the purpose of the workshop (as outlined in Sections 1.1 and 1.2 of these proceedings). After the formal opening of the workshop, the first technical presentation introduced the topic of uncertainties:

- General comments on sources and types of uncertainties: Mr Yann Richet (Institut de Radioprotection et de Sûreté Nucléaire [IRSN], France):

  The presentation addressed the general treatment of uncertainties in safety analyses performed by IRSN (supplemented by an example for a flooding assessment on the Loire River) and the challenges of extreme value analyses.

2.2. Session 1

This session was devoted to a set of natural hazards that have received relatively less attention than earthquakes, flooding and high winds in the field of nuclear safety engineering, and the general problems regarding the statistical analysis of hazards. In particular, snowfall, lightning, high temperatures and the challenges related to downscaling of climate projections were addressed.

The following presentations were made:

- Sources of uncertainties in snowfall assessment connected to independent core cooling requirements, Mr Tomas Jelinek (Swedish Radiation Safety Authority [SSM], Sweden):

  The presentation described the analyses performed regarding precipitation in connection with the construction of independent core cooling systems at Forsmark and Oskarshamn Nuclear Power Plants. The analyses showed that the different climate parameters are subject to various major uncertainties. For those associated with the large-scale circulation of the atmosphere, such as temperature and precipitation, there is a relatively robust basis for carrying out assessments. Rather, the challenge for these parameters is analysis of the unusual events, where, by definition, there is no large statistical basis. Available measurement series normally allow an extrapolation to a couple of hundred years. For longer return periods, uncertainty increases drastically. Also, it was noted that a long return period does not mean that an extreme event will only occur well into the future, but that there is a lower likelihood that it will occur at any time in the future.

- Sources of uncertainties in lightning occurrence and parameters, Mr Antti Mäkelä (Finnish Meteorological Institute [FMI], Finland):

  Lightning is one of the most frequent natural hazards and causes various kinds of damage and loss. This presentation introduced the main sources of uncertainty in lightning occurrence, especially regarding lightning protection assessments.

- Uncertainties induced by statistical methods: downscaling – Example: intensity duration frequency (IDF) curves, Mr Catalin Obreja (Environment and Climate Change Canada [ECC]):

  Global climate models (GCMs) are an attempt to mimic and predict climate at a planetary scale. Stability criteria within current modelling approaches impose a large spatial mesh (hundreds of kilometres). This data must have a local representation (on the scale of tens of kilometres) in order to be used locally, e.g. at a city/regional level. The process of downscaling the data in itself induces uncertainties and errors on top of those that exist due to the limitations of observational time series. This presentation described one such process.

- Sources of uncertainties in extremely high temperatures in the Netherlands, Mr Peter Siegmund (Royal Netherlands Meteorological Institute [KNMI], Netherlands):

  On 25 July 2019, record high temperatures of more than 40°C were observed in the Netherlands. This presentation discussed the factors that contributed to the high temperatures and to what extent such factors could lead to even higher temperatures.

The main insights from the presentations and subsequent discussions can be summarised as follows:

- As part of the verification for the independent core cooling systems (ICCS) of the Swedish nuclear power plants, precipitation events (including snowfall) of different durations with exceedance probabilities of up to 10^{-6}/a were assessed. To obtain sufficiently long time series, data were extrapolated from measurements at relatively distant meteorological stations (e.g. 70 km in the case of Forsmark). In addition, expected climate change up to 2045 has also been taken into account. Due to the extrapolation based on sparse data and the limited knowledge regarding the effects of climate change on rare precipitation events, the results of the investigations are subject to considerable uncertainties.
- Lightning is another hazard that is difficult to quantify. While the number of lightning strikes can be determined relatively well by today's lightning locating systems, the associated lightning parameters, such as the peak current, can usually only be derived indirectly. This is because direct strikes on dedicated measuring equipment are rare. This leads to considerable uncertainties, especially when inferring maximum credible lightning currents. Based on theoretical considerations, it can be deduced that currents of up to 800 kA cannot be ruled out. However, it is not yet clear how often and under which boundary conditions such extreme lightning may occur.
- In the summer of 2019, record temperatures of more than 40°C were measured in southern Netherlands. An investigation of this event and the boundary conditions responsible for it identified essential factors that contributed to the unusually high

temperatures that included: i) the temperature in the source region of the warm air masses (Sahara); ii) the rapid transport of the air to the north due to the prevailing wind currents; iii) the sinking of the air masses (warming due to pressure increase); iv) the dry soil (little evaporative cooling); and v) the sunny weather due to a high-pressure situation. It was also concluded in the analysis that since all factors were almost "ideal", significantly higher temperatures (more than 1 to 2°C) hardly seem possible for the affected region.

- In general, changes in individual meteorological parameters can be expected in the future due to climate change. While the large-scale trends for temperature development can be determined with relative certainty (apart from the uncertainties of the emission scenarios that are the basis of these types of assessments), this is not the case for other parameters, such as precipitation intensities and wind speeds, as well as regional/local climate impacts. Since only the regional/local climate impacts are relevant for hazard analyses of nuclear installations, the determination of these impacts is a major source of uncertainty in the analysis of meteorological and hydrological hazards.

In the panel discussion, the following aspects emerged as essential (which were also repeatedly discussed in Session 2 and Session 3 as they are relevant for all site-specific assessments of natural hazards):

- The appropriate consideration of uncertainties plays an important role in nuclear safety since: i) very rare events have to be considered; ii) the planning horizon for new nuclear installations is increasing (for new nuclear power plants, interim storage facilities and the operating phase of waste repositories, it is on the order of 100 years); and iii) climate change brings additional uncertainties with it.
- The main sources of uncertainty fall into two broad categories:
    - Limitations of available data: In addition to the relatively short time span covered by measurements (approximately 50 to 150 years, depending on the hazard), the question of the extent to which the measured data are representative for the site plays a significant role. This applies on the one hand spatially, if data from distant measuring stations have to be transferred to the site, and on the other hand temporally with regard to the instrumental records. Here the question arises as to whether the recorded period was actually "typical" for the meteorological and hydrological conditions of the region or whether the recent past happened to be relatively benign. In addition, measuring stations may fail or be completely destroyed during extreme events, so that no meaningful data may be available for the relevant rare events in particular.
    - Methods and statistical models: Since models are not reality itself, but only an approximation of it, they are necessarily associated with uncertainties. Assumptions and simplifications have to be made. Since more uncertain variables are included in complex models than in simple models, they usually result in numerically larger uncertainties. However, this does not justify the conclusion that simpler models provide more reliable results. In general, the opposite is the case, since the simple models tend to "mask" the underlying uncertainties. More accurate modelling, on the other hand, leads (ideally) to a better understanding of the geophysical processes and thus de facto reduces the uncertainty.

Key messages

- Uncertainties play an ever-increasing role in nuclear safety due to:
    - the need to consider very rare events;
    - extended planning intervals for nuclear projects;
    - the potential effects of climate change.
- The major sources of uncertainties are related to:
    - limitations of the available data
      (e.g. length of time series, spatial/temporal representativeness);
    - statistical models/assessment methods
      (models are only a representation of reality).
- A better understanding/systematic consideration of uncertainties is needed.
    - This may increase uncertainties "numerically" but de facto the uncertainty is reduced because of increased knowledge.
- Uncertainties in hazard assessment should not be considered independent from protection/mitigation measures.

2.3. Session 2

This session was devoted to the uncertainties related to flood hazard assessments. Coastal and riverine flooding had been the subject of previous tasks by the WGEV. Whereas these tasks were focused on the hazard assessment approaches themselves, in this workshop the uncertainties associated with the assessments were discussed.

The following presentations were made:

- Sources of uncertainty – Flooding – WGEV activities, Mr John Nakoski (United States Nuclear Regulatory Commission [NRC], United States):

  This presentation gave an overview of previous WGEV activities related to flooding. The corresponding body of work consists of two surveys with subsequent workshops addressing severe weather and storm surge as well as riverine flooding. In the framework of these activities, various uncertainties related to input data and assessment methods were identified.

- Sources of uncertainties from the French experience on coastal and riverine flooding, Ms Claire-Marie Duluc (Institut de Radioprotection et de Sûreté Nucléaire [IRSN], France):

  The presentation described the variety of sources of uncertainties associated with riverine and coastal flooding. For each phenomenon, it is possible to identify four main steps in the hazard assessment (defining the phenomena involved, collecting data, performing statistical extrapolation and, often, doing a numerical simulation of flooding effects around the site of interest). The presentation illustrated typical sources of uncertainties associated to each of these steps, by referring to French regulation and practice in safety studies.

- Sources of uncertainty in probabilistic flood hazard assessment (PFHA), Mr Joseph Kanney (United States Nuclear Regulatory Commission [NRC], United States):

  Separating uncertainty into aleatory variability and epistemic uncertainty is a useful exercise, but these concepts are unambiguous only within a given analytical/modelling framework. Important sources of uncertainty vary with scale and setting (e.g. site scale, watershed scale) as well as analysis approach (e.g. statistical vs simulation) and flooding metric of interest. Interactions between multiple flooding mechanisms introduce complexity and additional uncertainty.

- Uncertainty in flood risk modelling, Mr John Perdikaris (Ontario Power Generation [OPG], Canada):

  Uncertainty exists in all aspects of flood risk modelling and can vary both temporally and spatially. Uncertainty analysis gives forecasters and emergency managers a level of confidence in the prediction results. In addition, it provides a level of confidence in modelling phenomena that are difficult to quantify. The more complex the models the greater the (numerical) uncertainty. In view of this fact, better risk communication is needed to meet the public demand for more precise and detailed solutions.

- Developing an assessment method for the uncertainty of the Tsunami Occurrence Models, Mr Taichi Sato (Nuclear Regulatory Authority [NRA], Japan):

  This presentation provided an overview of work by Sugino and Abe (submitted) and described their efforts to improve the reliability of probabilistic tsunami hazard assessments (PTHAs) for earthquake-induced tsunami. Sugino and Abe's proposed method allowed them to express the impact of both epistemic and aleatory uncertainty in terms of the number of hazard curves. Sugino and Abe also established probabilistic models and conducted PTHA for three factors – the scaling law for earthquake magnitude, the Gutenberg–Richter (GR) law, and patterns of non-uniform slippage distribution. Their work demonstrated that the uncertainty of the scaling law for earthquake magnitude has the largest impact.

- Sources of uncertainties highlighted by flooding events in Germany, Mr Gernot Thuma (Gesellschaft für Anlagen- und Reaktorsicherheit gGmbH [GRS], Germany):

  In July 2021, severe flooding of urban areas next to small/medium rivers occurred in the western parts of Germany. Depending on the assessment method, estimates of the exceedance frequency of these events range between 10^{-2}/a and 10^{-4}/a. This highlights the fact that any approach to determining the water level of a rare flood event is subject to significant uncertainties. The specific sources of uncertainty vary depending on the applied methodology.

The main insights from the presentations and subsequent discussions can be summarised as follows:

- Flooding of a site can be caused by very different events. These include, for example, local heavy rainfall, river flooding due to rainfall and snowmelt on a regional scale, the failure of sewer systems, seiches, wave run-up, storm surges and tsunamis. Incidental or causally linked combinations of floods due to different causes are also conceivable.

- When analysing such flooding hazards, the data basis (amount of available data, quality and representativeness for the site), the statistical models (e.g. choice of statistical distribution and possible unrecognised trends), and the hydrological or hydraulic models (e.g. with regard to saturation of the soil, representation of the topography / bathymetry or soil roughness) are to be regarded as sources of possible uncertainties. Whether the individual uncertainties have to be considered as aleatory variability (random scatter) or epistemic uncertainty (lack of knowledge of the underlying processes/inadequacy of the models) depends, among other things, on the chosen analysis method.
- As in the case of meteorological impacts, rare flooding events with exceedance frequencies on the order of 10^{-4}/a to 10^{-6}/a have to be inferred from a limited observation period of a few decades. The potential influence of climate change makes the extrapolation even more difficult. Therefore, improving the database is considered one of the most important steps to reducing uncertainties. With regard to floods, historically documented events and findings from geological investigations (e.g. paleogeographic information) should therefore also be taken into account during the hazard assessment.
- The approaches to probabilistic flood hazard assessment (PFHA) developed in France and the United States, in particular, are potentially good ways of taking uncertainties into account systematically and quantitatively. However, it should be noted that this is also possible in principle for deterministic studies (e.g. through sensitivity studies).

Key messages

- Uncertainty exists in all aspects of flood risk modelling and can vary both temporally and spatially.
- Aleatory and epistemic uncertainties should be considered for site flooding.
- Combinations of flooding phenomena/mechanisms should be considered.
- Climate change remains an additional uncertainty, among others, for coastal and riverine flooding.
- For low frequency but high consequence events, such as tsunamis, an assessment of the uncertainties is of utmost importance in order to improve the reliability of PTHA.

2.4. Session 3

This session was devoted to uncertainties related to high winds such as tropical cyclones, extratropical depressions and tornadoes. These types of hazards had also been discussed in another workshop recently organised by the WGEV.

The following presentations were made:

- WGEV activities on high wind and tornado – hazard assessment and protection of NIS, Mr Vincent Rebour (Institut de Radioprotection et de Sûreté Nucléaire [IRSN], France):

  This presentation gave an overview of the WGEV activities on high winds and tornadoes. Like the WGEV flooding activities, they consisted of a survey and workshop. The key messages – in particular from the workshop – were that occasionally severe events occur in unexpected locations, measuring wind speeds in severe storms is difficult and almost impossible for tornadoes/small-scale storms, small-scale events are particularly difficult to characterise and forecast, and severe weather forecasting is probabilistic (i.e. subject to uncertainties) by nature.

- Identifying deterministic phenomenological based sources of uncertainty in the US related to high winds, Mr Marc Levitan (National Institute of Standards and Technology, NIST, United States):

  This presentation explored uncertainties for multiple types of high wind events, including straight line winds, tropical winds and tornadic winds. Specific topics that were addressed included wind measurement uncertainties, estimation vs. measurement of wind speeds, incomplete records, and changes in surface roughness during a high wind event.

- Probabilistic high wind hazard assessment focused on the sources of uncertainties, Mr Minkyu Kim (Korea Atomic Energy Research Institute [KAERI], Korea):

  In Korea, a probabilistic high wind hazard assessment was conducted using a logic tree for a nuclear power plant site. Using the logic tree and the Monte Carlo technique, the wind speeds from simulated typhoons and probable maximum wind speeds were estimated.

The main insights from the presentations and subsequent discussions can be summarised as follows:

- The methods for hazard analysis with regard to wind loads are generally not as extensively investigated as those for earthquakes and flooding. In many countries, conventional civil engineering standards are used for this purpose in the nuclear field as well. Countries that are confronted with frequent, very strong winds due to their specific climatic conditions, e.g. the United States (hurricanes and tornadoes) and Korea (typhoons), represent an exception to a certain extent. In general, specific procedures exist in these countries.
- There is also a significant difference in the methods used for different types of storms. While the hazard analysis for extratropical depressions is usually based on a statistical evaluation of wind speed measurements, the determination of severe tropical cyclones (referred to as hurricanes or typhoons, depending on the region) is usually carried out by means of simulations. In Korea, for example, such studies are carried out using Monte Carlo simulations and the assumptions made in the analysis are recorded in a logic tree.
- The fact that different types of high winds (large-scale low-pressure areas, downbursts associated with thunderstorms, tornadoes, slope winds, etc.) contribute to the overall hazard of a site is a source of uncertainty insofar as the different types are each characterised by different hazard curves (wind speed occurrence probability relationships). It follows from this fact that, depending on the exceedance frequency considered, different types of high winds dominate the hazard. Conversely, this also means that a distribution function that fits the measured data well (i.e. the frequent "weaker" wind events) is not necessarily representative of the rare "strong" events. Thus, the extrapolation of “weak” wind events does not necessarily cover all “strong” events. In principle, a separation of the measurement data according to the causal wind types would be desirable, but this is often not possible due to the limited data basis and the (missing) meta-information of the measurements required for this purpose.

- For small-scale wind events, such as downbursts and tornadoes, reliable measurement data are very difficult to obtain. This is due mainly to the low probability of such a small-scale event hitting a measurement station and, when it does, the measuring station and equipment are often destroyed.
- Another uncertainty factor – as with the other impacts discussed so far – is climate change. While for some regions and types of high winds it seems that climate change is leading to an increase in extreme events (e.g. typhoons in Korea), similar trends are not apparent for other regions and wind types (e.g. tornadoes in Canada and the United States). Global climate projections are often not meaningful in this context, as wind effects are mostly determined by local meteorological and topographical conditions. Thus, there is still a need for research in this respect.

Given the multiple sources of uncertainty in hazard assessment for high wind events, it is important to know how the underlying data were obtained and how they are to be interpreted. This applies to the measurements themselves, i.e.:

- the types of wind events recorded;
- the effects of signal processing on the measurements;
- the sampling rate of the measurements;
- the exact location of the measurement; and
- any changes at the measurement station over time.

It also applies to the representativeness of the measurement location for the nuclear site under consideration.

Key messages

- Data is a common source of uncertainties for wind hazard assessments. Uncertainties are related to:
    - measurements from instrumentation;
    - the translation of data from measurement sites to nuclear installation sites;
    - historical records.
- Different storm types dominate at different return periods:
    - therefore, it is important to understand the data source when looking at effects on sites.
- The local conditions of measurement sites are a common source of uncertainties for various natural hazards. This is related to:
    - surface roughness, topography, land use, etc.
- Changing conditions during extreme events can affect wind speeds and impacts.

2.5. Wrap-up session

In the wrap-up session, the rapporteurs summarised the content of the presentations and panel discussions of the three technical sessions addressing the relative current state, the identified challenges and possible ways forward. Their reports were followed by key messages from the chairs of the corresponding sessions as outlined in the previous sections of these proceedings.

Based on these summaries, the workshop chair identified common themes regarding uncertainties affecting all natural hazard assessments and gave recommendations on how to better integrate the consideration of uncertainties in these assessments.

Common themes

- Major uncertainties are related to historical climate conditions as well as bathymetric and topographic data. These uncertainties have a temporal and spatial component.
- The limited length of records for relevant meteorological and hydrological data (with maximum record lengths of 100 to 150 years) leads to significant uncertainties in the extrapolation to rare events.
- The data collection procedure itself is also a source of uncertainties. To evaluate the suitability of the data for a given purpose, several questions need to be answered, e.g.:
    - What exactly has been measured? For which event type can the measurements be considered representative? Which methods and instruments were applied? Where were the measurements taken, at what time intervals and with what integration time? How accurate are the measurements? How good is the quality of the data?
- Besides these data-related uncertainties, there are also epistemic (lack of knowledge) and aleatory (random scatter) uncertainties related to the assessment approaches:
    - Stochastic/statistical approaches require an extrapolation of the recorded data to high return periods (in the order of 10^{-4}/a – 10^{-6}/a). Besides the limited length of records mentioned above, the assumptions that have to be made with respect to plotting positions, statistical distributions, fitting procedure, etc. contribute to the overall uncertainty of the results.
    - Deterministic hazard assessments based on numerical simulation models are likewise subject to uncertainties resulting from assumptions and simplifications that have to be made.

Recommendations

- Since many sources of uncertainties are related to data, the data basis for hazard assessments should be improved. The incorporation of additional data sources, such as airborne, satellite or radar measurements, helps to expand the pool of available data.
- Historical data and paleo data are other sources of information that should be used to improve hazard assessments (if they are accessible). Although their inclusion introduces other uncertainties in the analysis, they can provide valuable information on extreme events not covered by measurements.
- As improving the data basis mainly serves to reduce sampling uncertainties, understanding of the phenomenological aspects of natural hazards should be improved to reduce model uncertainties.
- A better understanding of the effects of climate change on natural hazards needs to be developed. This holds in particular for those processes that do not depend on

global climate change in a direct manner (e.g. frequency and intensity of rainfall events or storms) and need to be assessed on a regional (not global) scale.

- Although it is not possible to eliminate risk, the understanding of the risk can and should be enhanced by improving the hazard assessment methods.
- In addition to protection measures, a mitigation approach should be applied to natural hazards.

3. Conclusions

The focus of this workshop was on collecting information on potential sources of uncertainties in the assessment of natural hazards (excluding earthquakes) to facilitate the compilation of a technical report on this issue. Regarding this objective, a wealth of information was obtained. Given the differences in maturity of the hazard assessment approaches for the range of natural hazards considered, more specific information could be obtained with respect to uncertainties related to flooding and high winds compared to, for example, lightning or snowfall.

Besides some sources of uncertainties that are specific to certain hazards, many natural hazard assessments are affected by the same – or at least very similar – uncertainties. These common sources of uncertainties are related to two major areas, data and assessment methods, as outlined in the wrap-up session. The insights regarding the identified sources of uncertainties will be used to guide the further work of the WGEV regarding uncertainties. In particular, the various sources of uncertainties identified during this workshop will be addressed in the technical report entitled “Uncertainties in the Assessment of Natural Hazards (Excluding Earthquakes) Phase 1 Sources of Uncertainties”. Therefore, an extensive list of the identified sources of uncertainties is not included in these proceedings. Some examples are addressed in the previous sections on the technical sessions and the wrap-up session.

Another insight from this workshop is that developing more detailed and complex models of natural hazards and performing comprehensive uncertainty assessments allows epistemic uncertainties to be better quantified, which is an advantage over simpler models. In other words, an increase in the complexity of models and uncertainty evaluations leads to an increase in the “known unknowns”. In contrast, simpler models are associated with more "unknown unknowns" (low fidelity).

Appendix A. List of registered participants

AUSTRIA	HOSSAIN, Shaheed	BOKU University
BELGIUM	REGA, Jo	Tractebel Engie
CANADA	KIM, Duck	Environment and Climate Change Canada (ECC)
	LEI, Shi Zhong	Canadian Nuclear Safety Commission (CNSC)
	OBREJA, Catalin	ECC
	PERDIKARIS, John	Ontario Power Generation (OPG)
	YALAOUI, Smain	CNSC
CZECHIA	KRIZ, Antonin	State Office for Nuclear Safety
FINLAND	MÄKELÄ, Antti	Finnish Meteorological Institute (FMI)
	MARJAMÄKI, Marko	Radiation and Nuclear Safety Authority (STUK)
	VARPASUO, Pentti E.	AFRY
FRANCE	AMPHOUX, Audrey	Électricité de France (EDF)
	DULUC, Claire-Marie	Institute for Radiological Protection and Nuclear Safety (IRSN)
	FOUET, Fabrice	IRSN
	GRAMMOSENIS, Laurence	EDF
	GUINARD, Luc	EDF
	REBOUR, Vincent	IRSN
	RICHET, Yann	IRSN
GERMANY	THUMA, Gernot	Gesellschaft für Anlagen- und Reaktorsicherheit gGmbH (GRS)
HUNGARY	SIKLOSSY, Tamas	Nuclear Safety Research Institute (NUBIKI)
ITALY	LOMBARDO, Calogera	Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA)
JAPAN	CHOI, Byunghyun	Japan Atomic Energy Agency (JAEA)
	IDEI, Yukiyoshi	Nuclear Regulatory Authority (NRA)
	KIYOTAKA, Takito	JAEA
	MARUYAMA, Yu	Central Research Institute of Electric Power Industry (CRIEPI), Nuclear Risk

		Research Center (NRRC) JAEA
	NAKAJIMA, Masato	CRIEPI NRRC
	NISHIDA, Akemi	Japan Nuclear Safety Research Center (NSRC) JAEA
	SAKAI, Toshiaki	CRIEPI
	SATO, Taichi	NRA
	TAKADA, Tsuyoshi	JAEA
	YAMANAKA, Yasunori	Federation of Electric Power Companies (FEPC) Atomic Energy Association (ATENA)
	YOSHIDA, Tomoaki	NRRC, CRIEPI
	YUYAMA, Ayumi	CRIEPI
KOREA	AHN, Kwang-Il	Korea Atomic Energy Research Institute (KAERI)
	HA, Jeonggon	KAERI
	HAHM, Daegi	KAERI
	JANG, Seunghyun	KAERI
	KIM, Min-Kyu	KAERI
	LEE, Kwan-Hee	Korea Institute of Nuclear Safety (KINS)
	PARK, Junhee	KAERI
NETHERLANDS	CARELSEN, Stef	Authority for Nuclear Safety and Radiation Protection (ANVS)
	SIEGMUND, Peter	Royal Netherlands Meteorological Institute (KNMI)
ROMANIA	DRAGUSIN, Mitica	National Institute for Research and Development in Physics and Nuclear Engineering
	STRASSER, Gabriel Valeriu	S.N. NUCLEARELECTRICA S.A. – Cernavoda Nuclear Power Plant
RUSSIA	SOKOLNIKOV, Mikhail	Southern Urals Biophysics Institute
SPAIN	GARCÍA DE LA VARGA, Alberto	Spanish Nuclear Safety Council (CSN)
SWEDEN	BENNEMO, Lars	Swedish Nuclear Power Inspectorate (SKI)
	JELINEK, Tomas	SKI
SWITZERLAND	SCHWAB, Andreas	Swiss Federal Nuclear Safety Inspectorates (ENSI)
TÜRKIYE	GUNGOR, Gorkem	Ministry of Energy and Natural

		Resources (ETKB)
	KARACA, Gökhan	ETKB
	NART, Merve	ETKB
	ÜNVER, Hatice Nur	Nuclear Regulatory Authority, Türkiye (NDK)
UNITED KINGDOM	IVES, Thomas	Office for Nuclear Regulation (ONR)
UNITED STATES	FERRANTE, Fernando	Electric Power Research Institute (EPRI)
	GILBERTSON, Anders	United States Nuclear Regulatory Commission (NRC)
	HUMBERSTONE, Matthew	NRC
	KANNEY, Joseph	NRC
	LANE, John	NRC
	LEVITAN, Marc	National Institute of Standards and Technology (NIST)
	LLINDEMAN, Ashley	EPRI
	NAKOSKI, John	NRC
	REISI FARD, Mehdi	NRC
	SMITH, Curtis L.	Idaho National Laboratory (INL)
	YEILDING, Dale	NRC
IAEA	LEE, Hyunwoo (Heanu)	International Atomic Energy Agency (IAEA)
NEA	KIM, Taehee	Nuclear Energy Agency (NEA)
	KUMAGAI, Yuji	NEA
	MORITA, Shin	NEA

Appendix B. Workshop agenda

TUESDAY, 19 APRIL 2022

12:00 – 12:55	**INTRODUCTORY SESSION**
	Session chaired by ***John Perdikaris – Workshop Chair (OPG, Canada)***
12:00 – 12:15	**INTRODUCTION OF THE OUTLINE OF THE WORKSHOP THAT INTRODUCES THE CHAIR ON EACH SESSION WITH THE DISCUSSION ON THE PRIORITIES AND CHALLENGES** John Perdikaris (OPG, Canada)
12:15 – 12:30	**OVERVIEW THAT INCLUDES BACKGROUND, THE PURPOSE OF THE WORKSHOP AND EXPECTED OUTCOMES BASED ON THE DRAFT TR** Gernot Thuma (GRS, Germany)
12:30 – 12:55	**GENERAL SOURCES AND TYPES OF UNCERTAINTY** Yann Richet (IRSN, France)
12:55 – 13:15	***Coffee break***
Session 1	**EXTREME TEMPERATURES, HEAT SINK EFFECT, LIGHTNING AND SNOW AND STATISTICAL METHODS**
13:15 – 16:35	Session chaired by ***Gernot Thuma (GRS, Germany)***
13:15 – 13:45	**SOURCES OF UNCERTAINTIES IN SNOWFALL ASSESSMENT CONNECTED TO INDEPENDENT CORE COOLING (ICC) REQUIREMENTS** Tomas Jelinek (SSM, Sweden)
13:45 – 14:15	**SOURCES OF UNCERTAINTIES IN LIGHTNING OCCURRENCE AND PARAMETERS** Antti Mäkelä (FMI, Finland)
14:15 – 14:45	**UNCERTAINTIES INDUCED BY STATISTICAL METHODS: DOWNSCALING – EXAMPLE: INTENSITY DURATION FREQUENCY (IDF) CURVES** Catalin Obreja (ECC, Canada)
14:45 – 15:15	**(FOR SESSION 2) SOURCES OF UNCERTAINTIES HIGHLIGHTED BY FLOODING EVENTS IN GERMANY** Gernot Thuma (GRS, Germany)
15:15 – 15:35	***Coffee break***
15:35 – 16:35	**PANEL DISCUSSION**

16:25 – 16:35	**CHAIR WRAP-UP (KEY MESSAGES)** John Perdikaris (OPG, Canada) *one item for session 1 "Sources of uncertainties in extremely high temperatures in the Netherlands" would be on Day 2

WEDNESDAY, 20 APRIL 2022

12:00 – 12:05	***DAY 1 OVERVIEW*** John Perdikaris (OPG, Canada)
12:05 – 12:35	**(FOR SESSION 1) SOURCES OF UNCERTAINTIES IN EXTREMELY HIGH TEMPERATURES IN THE NETHERLANDS** Peter Siegmund (KNMI, Netherlands)
Session 2	**SITE FLOODING**
12:35 – 16:45	Session chaired by ***Minkyu Kim (KAERI, Korea)***
12:35 – 13:05	**SOURCES OF UNCERTAINTY – FLOODING – WGEV ACTIVITIES** John Nakoski (NRC, United States)
13:05 – 13:35	**SOURCES OF UNCERTAINTIES FROM THE FRENCH EXPERIENCE ON COASTAL AND RIVERINE FLOODING** Claire-Marie Duluc (IRSN, France)
13:35 – 13:55	***Coffee break***
13:55 – 14:25	**SOURCES OF UNCERTAINTY IN PROBABILISTIC FLOOD HAZARD ASSESSMENT (PFHA)** Joseph Kanney (NRC, United States)
14:25 – 14:55	**UNCERTAINTY IN FLOOD RISK MODELLING** John Perdikaris (OPG, Canada)
14:55 – 15:25	**DEVELOPING AN ASSESSMENT METHOD FOR THE UNCERTAINTY OF THE TSUNAMI OCCURRENCE MODELS** Taichi Sato (NRA, Japan)
15:25 – 15:45	***Coffee break***
15:45 – 16:35	**PANEL DISCUSSION**
16:35 – 16:45	**CHAIR WRAP-UP** Minkyu Kim (KAERI, Korea) *one item for session 2 "Sources of uncertainties highlighted by flooding events in Germany" would be on Day1

THURSDAY, 21 APRIL 2022

12:00 – 12:05	***DAY 2 OVERVIEW*** John Perdikaris (OPG, Canada)
Session 3	**HIGH WINDS**
12:05 – 14:45	Session chaired by ***John Nakoski (NRC, United States)***
12:05 – 12:25	**WGEV ACTIVITIES ON HIGH WIND AND TORNADO - HAZARD ASSESSMENT AND PROTECTION OF NIS** Vincent Rebour (IRSN, France)
12:25 – 12:55	**IDENTIFYING DETERMINISTIC PHENOMENOLOGICAL BASED SOURCES OF UNCERTAINTY IN THE US RELATED TO HIGH WINDS** Marc Levitan (NIST, United States)
12:55 – 13:25	**PROBABILISTIC HIGH WIND HAZARD ASSESSMENT FOCUSED ON THE SOURCES OF UNCERTAINTIES** Minkyu Kim (KAERI, Korea)
13:25 – 13:45	***Coffee break***
13:45 – 14:35	**PANEL DISCUSSION**
14:35 – 14:45	**CHAIR WRAP-UP** John Nakoski (NRC, United States)
14:45 – 15:25	***Coffee break***
Session 4	**WRAP-UP SESSION**
15:25 – 16:45	Session chaired by ***John Perdikaris (OPG, Canada)***
15:25 – 16:25	**RAPPORTEURS' REPORTS (SUMMARY) + KEY MESSAGES FROM CHAIRS** Rapporteurs / Session Chairs
16:25 – 16:45	**FINDINGS, CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK** John Perdikaris (OPG, Canada)