IAEA SAFETY STANDARDS SERIES

Meteorological Events in Site Evaluation for Nuclear Power Plants

SAFETY GUIDE

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INTERNATIONAL
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IAEA SAFETY STANDARDS

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METEOROLOGICAL EVENTS IN SITE EVALUATION FOR NUCLEAR POWER PLANTS

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FOREWORD

by Mohamed ElBaradei
Director General

One of the statutory functions of the IAEA is to establish or adopt standards of safety for the protection of health, life and property in the development and application of nuclear energy for peaceful purposes, and to provide for the application of these standards to its own operations as well as to assisted operations and, at the request of the parties, to operations under any bilateral or multilateral arrangement, or, at the request of a State, to any of that State's activities in the field of nuclear energy.

The following bodies oversee the development of safety standards: the Commission on Safety Standards (CSS); the Nuclear Safety Standards Committee (NUSSC); the Radiation Safety Standards Committee (RASSC); the Transport Safety Standards Committee (TRANSSC); and the Waste Safety Standards Committee (WASSC). Member States are widely represented on these committees.

In order to ensure the broadest international consensus, safety standards are also submitted to all Member States for comment before approval by the IAEA Board of Governors (for Safety Fundamentals and Safety Requirements) or, on behalf of the Director General, by the Publications Committee (for Safety Guides).

The IAEA's safety standards are not legally binding on Member States but may be adopted by them, at their own discretion, for use in national regulations in respect of their own activities. The standards are binding on the IAEA in relation to its own operations and on States in relation to operations assisted by the IAEA. Any State wishing to enter into an agreement with the IAEA for its assistance in connection with the siting, design, construction, commissioning, operation or decommissioning of a nuclear facility or any other activities will be required to follow those parts of the safety standards that pertain to the activities to be covered by the agreement. However, it should be recalled that the final decisions and legal responsibilities in any licensing procedures rest with the States.

Although the safety standards establish an essential basis for safety, the incorporation of more detailed requirements, in accordance with national practice, may also be necessary. Moreover, there will generally be special aspects that need to be assessed on a case by case basis.

The physical protection of fissile and radioactive materials and of nuclear power plants as a whole is mentioned where appropriate but is not treated in detail; obligations of States in this respect should be addressed on the basis of the relevant instruments and publications developed under the auspices of the IAEA. Non-radiological aspects of industrial safety and environmental protection are also not explicitly considered; it is recognized that States should fulfil their international undertakings and obligations in relation to these.

The requirements and recommendations set forth in the IAEA safety standards might not be fully satisfied by some facilities built to earlier standards. Decisions on the way in which the safety standards are applied to such facilities will be taken by individual States.

The attention of States is drawn to the fact that the safety standards of the IAEA, while not legally binding, are developed with the aim of ensuring that the peaceful uses of nuclear energy and of radioactive materials are undertaken in a manner that enables States to meet their obligations under generally accepted principles of international law and rules such as those relating to environmental protection. According to one such general principle, the territory of a State must not be used in such a way as to cause damage in another State. States thus have an obligation of diligence and standard of care.

Civil nuclear activities conducted within the jurisdiction of States are, as any other activities, subject to obligations to which States may subscribe under international conventions, in addition to generally accepted principles of international law. States are expected to adopt within their national legal systems such legislation (including regulations) and other standards and measures as may be necessary to fulfil all of their international obligations effectively.

EDITORIAL NOTE

An appendix, when included, is considered to form an integral part of the standard and to have the same status as the main text. Annexes, footnotes and bibliographies, if included, are used to provide additional information or practical examples that might be helpful to the user.

The safety standards use the form 'shall' in making statements about requirements, responsibilities and obligations. Use of the form 'should' denotes recommendations of a desired option.

The English version of the text is the authoritative version.

CONTENTS

1. INTRODUCTION

BACKGROUND

1.1. This Safety Guide was prepared under the IAEA programme for safety standards for nuclear power plants. It supplements the IAEA Safety Requirements publication on Site Evaluation for Nuclear Facilities[1] which is to supersede the Code on the Safety of Nuclear Power Plants: Siting, Safety Series No. 50-C-S (Rev. 1), IAEA, Vienna (1988).

1.2. The present Safety Guide supersedes two earlier Safety Guides: Safety Series No. 50-SG-S11A (1981) on Extreme Meteorological Events in Nuclear Power Plant Siting, Excluding Tropical Cyclones and Safety Series No. 50-SG-S11B (1984) on Design Basis Tropical Cyclone for Nuclear Power Plants.

OBJECTIVE

1.3. The purpose of this Safety Guide is to provide recommendations and guidance on conducting hazard assessments of extreme and rare meteorological phenomena. This Safety Guide provides interpretation of the Safety Requirements publication on Site Evaluation for Nuclear Facilities and guidance on how to fulfil these requirements. It is aimed at safety assessors or regulators involved in the licensing process as well as designers of nuclear power plants, and provides them with guidance on the methods and procedures for analyses that support the assessment of the hazards associated with extreme and rare meteorological events.

SCOPE

1.4. This Safety Guide discusses the extreme values of meteorological variables and rare meteorological phenomena, as well as their rates of occurrence, according to the following definitions:

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[1] Site Evaluation for Nuclear Facilities, Safety Standards Series No. NS-R-3, IAEA, Vienna (in preparation).

(a) Extreme values of meteorological variables such as air temperature and wind speed characterize the meteorological or climatological environment. These variables are measured routinely over a network of fixed stations by international, national, local or private meteorological services. These measurements are usually normalized (such as data collected on wind speed, which are normalized to a given height). The extreme values, associated with the annual probabilities of being exceeded, are derived from the measurements.
(b) Rare meteorological phenomena. These are phenomena that occur infrequently. Thus at any particular station, the instruments used for routine measurements would rarely register characteristics of these phenomena. Rare meteorological phenomena, which are highly complex, are usually scaled in terms of their intensity. These intensity values may be expressed in terms of either a qualitative characteristic such as damage or a quantitative physical parameter such as wind speed.

1.5. The meteorological variables considered in this Safety Guide whose extreme values are to be evaluated are those associated with wind, precipitation, snow pack, temperature and seawater level.

1.6. The rare meteorological phenomena considered in this Safety Guide are tornadoes, tropical cyclones and lightning. Lightning is not a rare event; however, data on parameters relevant to lightning are not routinely recorded, and it is therefore not possible to derive any corresponding extreme values. For this reason, lightning appears under 'rare events' in the present Safety Guide. Other meteorological phenomena that should be considered owing to their possible impact on plant safety, but which are not explicitly discussed in this Safety Guide, are blizzards, dust and sand storms, drought, icing and hail.

1.7. The meteorological phenomena that should be taken into account for the assessment of atmospheric dispersion of radioactive releases are discussed in the IAEA Safety Guide on Dispersion of Radioactive Material in Air and Water and Consideration of Population Distribution in Site Evaluation for Nuclear Power Plants [1].

1.8. A major possible consequence of the meteorological phenomena addressed in the present Safety Guide is flooding, which is addressed in another IAEA Safety Guide [2].

1.9. The results of the site evaluation should be used for the design of a plant as described in the Safety Requirements publication on the Safety of Nuclear Power Plants: Design [3] and its related Safety Guides. In particular, guidance for a design safe against the consequences of meteorological phenomena is given in a related IAEA Safety Guide [4].

STRUCTURE

1.10. The general approach in terms of the scope and detail of the information to be collected, the investigations to be performed and quality assurance are presented in Section 2. Section 3 provides information on the development of a database for both determining extreme values of meteorological variables and characterizing rare meteorological phenomena. Hazard determination on the basis of extreme values is discussed in Section 4, while determination of the hazard for rare meteorological phenomena is dealt with in Section 5.

2. GENERAL APPROACH TO HAZARD ASSESSMENT

2.1. The extreme values of the meteorological variables and the rare meteorological phenomena listed below should be investigated for every nuclear power plant site:

— wind, precipitation, snow pack, temperature and seawater level;
— tornadoes, tropical cyclones and lightning.

2.2. The meteorological and climatological characteristics of the region around the site should be investigated as described in this Safety Guide. The size of the region to be investigated, the type of information to be collected and the scope and detail of the investigations should be determined on the basis of the nature and complexity of the meteorological and geographical environment of the area in which the site is located. In practice, the time extension for data collection is limited by the availability of the data.

2.3. Since climate change is increasingly topical, due attention should be paid to global warming and its possible consequences in relation to the meteorological hazards considered in this Safety Guide; their possible effects during the lifetime of the plant should accordingly be described.

2.4. In all cases, the scope and detail of the information to be collected and the investigations to be undertaken should be sufficient to determine the design bases for protection against meteorological hazards at or near the site. In order to combine the effects of different meteorological variables properly, information on the temporal distributions of meteorological variables should also be obtained[2].

2.5. The collection of data should continue during the lifetime of the plant, including during decommissioning and safe storage, so as to permit the possible reassessment of the protection against meteorological hazards; for instance, in periodic safety reviews.

2.6. A quality assurance programme should be established and implemented to cover those items, services and processes affecting safety that are within the scope of this Safety Guide. The quality assurance programme should be implemented so as to ensure that data collection, data processing, field and laboratory work, studies, evaluations and analyses, and all other activities necessary to achieve the objectives of this Safety Guide are correctly performed.

3. INFORMATION AND INVESTIGATIONS NECESSARY (DATABASE)

DATABASE FOR EXTREME VALUES OF METEOROLOGICAL VARIABLES

3.1. Routinely collected data on meteorological variables provide long term records for analysis to determine extreme values. The specifications for the necessary instrumentation and for its installation are given in publications of the World Meteorological Organization. For phenomena that occur frequently at a site, the corresponding statistics should be determined from records of observations under standard conditions.

Off-site sources of meteorological data

3.2. For evaluating extreme meteorological variables, data should be collected over a long period of time at appropriate intervals for each proposed site. Since locally

[2] For this purpose, the characterization of all meteorological parameters as random processes, with given auto- and cross-correlation functions, would be desirable. However, simpler approaches, such as the specification of duration (persistence) above fixed intensity levels and mean rate of up-crossings, may assist in establishing adequate load combination criteria.

recorded data are not normally available for most proposed sites, an assessment should be made of the data available from meteorological stations or substations in the region. Long term data from the station where the site conditions are most representative for the variable concerned or alternatively the records of various neighbouring meteorological stations shown to belong to the same climatological zone should be processed, so as to furnish more robust estimates of the necessary statistical parameters. The first approach may be accomplished by making comparisons with similar data obtained in an on-site programme for the collection of short term meteorological data.

3.3. In general, it is preferable to choose the beginning date for the yearly time interval for data analysis to be at a time of year when the meteorological variable concerned is not at the peak or valley of a cycle. Such a yearly cycle is termed a 'meteorological year' and the resulting data series are denoted as, for example, annual extreme velocities and temperatures. This approach should be applied particularly to extremes of precipitation and temperature.[3]

3.4. An appropriate averaging timescale of the parameter should be chosen so as to provide data relevant for the design of the plant.

3.5. The one extreme event for the year should be identified and tabulated for each year in order to perform the calculation of extreme statistics. The long term data should preferably cover a minimum period of 30 years. If the period of the available data set is shorter, the size of the sample should be increased by retaining all values above a given threshold instead of a single maximum value per year (renewal method), so as to compensate for the larger uncertainty. The extreme values corresponding to various annual probabilities of being exceeded are derived from these data; an associated confidence interval should be provided.

3.6. Catalogues that itemize specific meteorological and climatological data collected around the world are available. Similarly, the meteorological services of States generally publish data collected. Information collected at government supervised meteorological stations normally includes data on wind, temperature and precipitation. Potential users of these data should be aware of the fact that measurements conducted by different organizations do not necessarily follow the

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[3] In considering extreme maximum temperature, it is most appropriate to define the meteorological year as beginning in the winter; conversely, in considering extreme minimum temperature, the meteorological year should begin in the summer.

same procedures; this necessitates careful evaluation and adjustment of the data before processing. For instance, the standard 10 m height for wind velocity measurements is often not observed at meteorological stations.

3.7. A report on the results of the analyses should include a description of each meteorological station (type of device, calibration, quality and consistency of the records), its geographical location and setting, and its environmental conditions. Any adjustment to the data should be duly justified in the report.

3.8. In some parts of the world, mesoscale numerical models are available that can simulate the airflow at regional and local scales and focus on a given area. If such models are available and validated, they should be used in the meteorological site evaluation.

On-site meteorological programme

3.9. During site evaluation an on-site meteorological investigation programme should be initiated for evaluating the site characteristics in relation to atmospheric dispersion phenomena, as recommended in Ref. [1]. This programme should include measurements along a vertical line on the site, by means of instrument masts and equipment for measuring the wind and temperature profiles.

3.10. Even if there is indirect evidence that long term measurements made at adjacent meteorological stations may be considered representative of the proposed site, the data obtained during the short period of site evaluation should be used for assessing the influence of specific site conditions in the determination of the extreme values of meteorological variables. Comparative analysis of on-site and adjacent off-site records should be carried out to validate the use of the off-site data.

3.11. During the operational stage the long term data records obtained from the on-site meteorological investigation programme should be used for confirmation of the meteorological parameters used for design bases. These records should also be used in the event of a reassessment of the protection against meteorological hazards.

DATABASE FOR RARE METEOROLOGICAL PHENOMENA

3.12. Events characterized as rare meteorological phenomena are unlikely to be recorded by a standard instrument network owing to their low probability of occurrence at any single point and the destructive nature of the phenomena, which may damage standard instruments or produce unreliable recordings on them. For rare phenomena, the extreme wind velocity should be determined from conceptual models of the phenomenon, coupled with statistics on the rate of occurrence and the intensity of the event at the site.

3.13. Two types of data should be collected for rare meteorological phenomena:

(1) Data systematically assembled by specialized organizations in recent years. The data in this group will include data on more events of lower intensity and will be more reliable than historical data.
(2) Historical data, obtained from a thorough search of information sources such as newspapers, historical records and archives. From data of this type, and by using a qualitative scaling system for each phenomenon, a set of events and their associated intensities may be collected for the region. These data are likely to be:
    (i) Very scarce in the range of low intensity events;
    (ii) Dependent on population density at the time;
    (iii) Subjectively classified at the time of their occurrence, thus making it difficult to assign the appropriate intensity level in each case.

3.14. On occasion a comprehensive collection of data and information obtained soon after the occurrence of the event may be available. This could include measured values of variables, eyewitness accounts, photographs, descriptions of damage and other qualitative information that were available shortly after the event. Such detailed studies of rare real events help in constructing a model for their occurrence and may contribute, in conjunction with a known climatology for a particular region, to determining the design basis event for that region. Often the actual area affected by a rare meteorological phenomenon is comparatively small, which makes the accumulation of relevant and adequate data extremely difficult to achieve in practice.

4. HAZARD DETERMINATION ON THE BASIS OF EXTREME VALUES

GENERAL PROCEDURE

4.1. The general procedure for determining the hazard from an extreme meteorological variable comprises the following steps:

(a) A study of the representative data series available for the region under analysis and an evaluation of its quality (completeness and reliability);
(b) Selection of the most appropriate statistical distribution for the data set;
(c) Processing of the data to evaluate moments of the distribution function of the variable under consideration (expected value, standard deviation and others if necessary), from which the mean recurrence interval (MRI) values and associated confidence limits may be derived.

4.2. Extreme annual values of meteorological variables constitute random variables, which may be characterized by specific probability distributions[4]. In principle, the data set should be analysed with probability distribution functions appropriate to the data sets under study. Among these, the asymptotic extreme value distributions described in the Annex are widely used: Fisher–Tippett Type I (Gumbel), Type II (Fréchet) and Type III (Weibull). This implies that sufficient information needs to be available to allow determination of which distribution best fits the data. The Fisher–Tippett distributions may be used in graphical form, which results in a straight line when plotted on a special template; the curvature at the extreme end may indicate that data from two populations of events are present in the data set.

4.3. Data processing should account for the possible non-stationarity of the stochastic process under consideration, which may reflect climatic changes among other phenomena. Data for design purposes should describe this possible non-stationarity with its confidence interval.

4.4. Caution should be exercised in attempting to fit an extreme value distribution to a data set representing only a few years of records. If extrapolations are carried out over very long periods of time by means of a statistical technique, due regard should be given to the physical limits of the variable of interest. Care should also be taken in extrapolating to time intervals well beyond the duration of the available records (such as for 'return' periods greater than four times the duration of the sample). The extrapolation method should be documented.

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[4] Variables derived from continuous random processes, such as the temperature or wind velocity at a site, should be studied to determine whether they are stationary or present either trends or transient behaviour. In the former case, which is normally assumed in dealing with meteorological variables, detectable cycles may exist, such as the daily or yearly cycles of temperature or wind velocity. The peak within such a cycle constitutes a new random variable, designated the 'extreme value' of the associated variable (extreme daily temperature, extreme annual wind velocity).

EXTREME WINDS

Data sources and data collection

4.5. Measurement techniques for recording maximum wind speed vary from State to State. The general tendency is to record average values for a given constant duration, such as 3 s gusts, 60 s or 10 min (averaging time is a characteristic of the database). Processing of the data for the evaluation of extreme wind statistics should be carried out by the best methods available; in particular, the data set should be standardized to uniform averaging time periods and to uniform heights and soil surface roughness, and corrected for local topographical effects.

4.6. Not all wind data are collected at the same height above the ground. The height may vary from station to station; even for one station, data may be collected at different heights in different periods. In these cases the data should be normalized to a standard height (usually 10 m above ground level) using profiles with an adjustable coefficient suited to the local roughness. However, for tall structures, winds at higher altitudes may be more appropriate.

4.7. If parts of the wind data set have been derived with different averaging periods, the data should be normalized to a constant averaging duration. When appropriate, the wind speed values to be used should be those associated with the time durations determined to be critical for the design.

4.8. Strong winds may be caused by several different meteorological phenomena, such as extended pressure systems (EPSs), certain cumulonimbus cloud formations (thunderstorms or downbursts), föhn, flows induced by gravity and other local phenomena. Extreme annual wind velocities produced by each of these phenomena constitute random variables that should be analysed separately. Depending on sources and on national customs, EPSs may also be designated as extra-tropical storms, extra-tropical depressions or extra-tropical cyclones.

Statistical analysis

4.9. Studies have indicated that in most locations the extreme wind velocities caused by a single meteorological phenomenon, for instance EPS winds, are better fitted by a Type I law. For mixed wind series, i.e. series unclassified by storm type, there is no clearly preferred distribution. The most appropriate distribution should be selected on a case by case basis. If there is information that suggests a potential for meteorological phenomena such as tropical or extra-tropical (EPS) storms, an appropriate design basis event for each of these phenomena should be evaluated.

4.10. The aforementioned studies are conducted for the magnitude of the wind velocity, thus ignoring wind orientation. The statistical characterization of the extreme wind velocities, with account taken of the wind orientation, should be performed by grouping the data in sections, for example in octants, which leads to more complete models.

Data for design purposes

4.11. The extreme wind speed should be characterized by its probability of being exceeded in reference time intervals; these probabilities and reference time intervals should be appropriate for the purpose of plant design. As an indicator of wind hazard, the expected extreme wind speed and its confidence interval for the lifetime of the plant should be determined.

PRECIPITATION

Data sources and data collection

4.12. Data routinely collected and used for analyses of extreme precipitation generally include the maximum 24 h precipitation depth. Records based on shorter averaging times contain more information and should under certain circumstances be preferred[5]. The analysis should preferably use data from those stations equipped with a continuously recording rain gauge such as a weighting or tipping bucket type gauge. However, if the network of continuously recording stations is too sparse, the use of data from a network of non-continuously recording stations should be considered.

4.13. When the results of extreme precipitation analyses are reported, a description of the meteorological stations and the geographical setting should be included. Any adjustment to the data should be presented in conjunction with the results of the analyses.

4.14. A regional assessment of the precipitation regime should be made to ascertain whether the site is climatologically similar to those of surrounding meteorological stations. Such an assessment is made in order to select the stations most appropriate

[5] Note that for short averaging periods very intense precipitation can occasionally be observed from certain cloud cell systems, which would be smoothed out if a 24 h averaging period were used. This may be the case particularly in areas where there is extreme rainfall because of the orographic conditions.

to provide the long term data series for analysis. The selection process should consider, but should not be limited to, micrometeorological characteristics, mesoscale systems and topographic influences. Consideration should also be given to any supplemental data collected in an on-site measurement programme.

4.15. In cases where there is no continuously recording network in the site vicinity, but where precipitation totals for fixed intervals exist for stations not climatologically different from the site, similarity concepts may be employed. With this method a general statistical relationship is applied to estimate the maximum event that will occur in a specified averaging period, such as 24 h, from a known set of sequential measurements made over another averaging interval, such as 3, 6 or 12 h.

Statistical analysis

4.16. In general, analyses of maximum precipitation for longer periods (of the order of 24 h or more) have resulted in good fitting of the data with the Type I (Gumbel) distribution. Analyses of maximum precipitation for shorter periods, however, have resulted in good fitting of the data with the Type II (Fréchet) distribution. (This is confirmed by recent approaches based on fractal theory.) The time period for which it is appropriate to change from one type of distribution to the other can vary from location to location as a function of the climatology. Multiple analyses for varying time periods should be made for the construction of precipitation intensity–duration curves.

4.17. For short averaging periods, very intense precipitation events (possible outliers), particularly in areas that experience extreme rainfall because of orographic conditions, may occasionally be observed in the records. Such effects should be taken into account in calculating the corresponding statistics. Caution should be exercised in dealing with outliers in the data set. These points represent extremes of the events in the data set, but may be significantly greater in magnitude than the other values. In some cases the statistical approach should be discarded and only an estimated upper bound of the precipitation should be considered based on an analysis of physical phenomena.

4.18. For a time interval of the order of 12–48 h, an evaluation should be made to determine which distribution (such as Gumbel or Fréchet) best fits the data. Few guidelines are available, but points that should be considered include:

(a) The range of values of data points within the data,
(b) The nature of the system producing the maxima of the data set,
(c) The possible use of a mixed distribution when precipitation may be due to more than one meteorological phenomenon.

Data for design purposes

4.19. For the future evaluation of the design basis precipitation, the variable to be considered is the amount of precipitation during various periods of time. This subsection deals in general with precipitation in the liquid phase, or with the liquid equivalent of solid precipitation, and does not discriminate between the solid and liquid phases.

4.20. As is the case for other meteorological variables that can be measured during sufficiently long periods of time, the precipitation hazard may be evaluated by standard statistical analysis of the observed records. It should be characterized by its probability of being exceeded in reference time intervals; these probabilities and reference time intervals should be appropriate for the purpose of plant design. As an indicator of precipitation hazard, the expected extreme value in 24 h and its confidence interval for the lifetime of the plant should be determined. In addition, for the evaluation of local effects at the plant or in the surrounding area, shorter averaging periods should be used.[6]

4.21. Procedures for evaluating the precipitation hazard depend on numerous factors, such as: the meteorological characteristics responsible for heavy rainfall at any particular site; the amount, type and quality of meteorological data; the topographic features; and the possible effects of meteorological and topographic factors on the duration of rainfall and on the selection of the critical drainage area. Since the factors involved are practically unique for each site under consideration, no single, detailed, step by step general procedure can be given. Meteorologists familiar with extreme rainstorm climatology should carry out the corresponding studies according to the best methods available.

EXTREME SNOW PACK

4.22. The load on a structure due to the snow pack will depend on both snow depth and packing density. These two parameters can be combined conveniently by expressing snow depth in terms of a water equivalent depth.

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[6] In some States, deterministic approaches of the greatest depth of precipitation possible over a drainage basin are used. All these methods present large uncertainties and the derived estimates should be treated with caution.

Data sources and data collection

4.23. If snowfall occurs in the region concerned in such an amount that its load may be important for the structural design, a regional assessment should be made of the snowfall distribution. Satellite photographs taken after snowstorms at the site may be helpful in this task. The variables to be considered for such an evaluation should include wintertime precipitation, snowfall and snow cover. The data set should be selected to represent the summer to summer year in order to include each annual maximum event.

4.24. In cold regions where snow on the ground may persist for long periods, caution should be exercised in estimating the design basis snow pack since snow compaction will vary from place to place. The meteorological station selected should be one that has a comparable topographical position to that of the proposed site (so, for example, data from a meteorological station on a south facing slope should not be used in considering a nuclear power plant on a north facing slope).

4.25. In mountainous regions where the density of a meteorological network is such that the values measured at the station may differ significantly from the values at the site, a site specific evaluation should be carried out. Sites should be evaluated case by case, with account taken of any local factors (such as neighbouring structures and topography) which may possibly have an influence on the snow load.

Statistical analysis

4.26. For the evaluation of the design basis snow pack, the Gumbel or Fréchet distributions or the log–normal distribution may be used. To allow for the occurrence of years without snow, the analysis should be performed by weighting the frequency of snow years for the period of record.

Data for design purposes

4.27. In regions where snow may represent a significant load factor in the design of plant structures, a design basis snow pack should be determined. The total snow pack in terms of its water equivalent is the variable to be considered. The snow pack should be characterized by its probability of being exceeded in reference time intervals. These probabilities and reference time intervals should be selected to be appropriate for purposes of plant design. As an indicator of snow pack hazard, the expected extreme value and its confidence interval for the lifetime of the plant should be determined.

4.28. In developing a design basis snow pack, another factor to be considered is the additional weight of the rain which can be incorporated into the snow pack; therefore, the water equivalent weight of the snow pack should be supplemented by a rainfall which has a low probability of being exceeded.[7]

EXTREME TEMPERATURES

Data sources and data collection

4.29. Temperatures are recorded continuously at some recording stations and at frequent intervals at other stations. At secondary locations, at least daily maximum and minimum temperatures are recorded.

4.30. A description of each meteorological station from which data are obtained and its geographical setting should be included in the report of the analysis.

4.31. An on-site measurement programme should be conducted for obtaining the site data for comparison with data from existing meteorological stations in the region. By means of such a comparison, it is possible to identify stations for which the meteorological conditions are similar to those for the site and for which long term records are available. This similarity should be verified by means of the on-site programme.

4.32. The daily maximum and minimum temperatures (extreme values of the instantaneous temperature in a day) represent the data set from which the extreme annual values are normally selected for prediction purposes. These values form data subsets which are commonly analysed to yield extreme value statistics. Note that improved approaches (renewal methods) are based on enlarged subsets that, in addition to the yearly maxima, retain the subsequent ordered values (second and third maximum values, provided that they are not correlated). These enlarged subsets should be made available. Moreover, estimates of the duration that the temperature remains above or below given values (persistence) may be needed for plant design purposes, and this should accordingly be taken into account in data collection.

4.33. As is done in analysing other meteorological phenomena, the beginning of the meteorological year should be selected so as not to coincide with a season during which the temperature attains an extreme value. This will avoid arbitrary assignment to different years of the data from a single such season.

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[7] In one State, the 48 h winter probable maximum precipitation is added to the snow pack.

Statistical analysis

4.34. Extreme temperatures generally follow the Gumbel distribution. The temperature records should be properly processed in order to characterize statistically the persistence of temperature above or below specified levels.

Data for design purposes

4.35. The design should accommodate the effects of temperature extremes, and the statistical analyses should provide the necessary data in forms usable for such purposes, in analogy to what should be done for other variables. The persistence of very high or very low temperatures is a factor that should be considered.

SEAWATER LEVEL

4.36. The seawater level close to a plant at a coastal site is influenced by:

- — changes in average sea level induced by climate changes (or other phenomena);
- — the astronomical tide;
- — storm surges coming from the open sea, potentially amplified by local strong winds;
- — wind waves;
- — human made structures such as tide breaks and jetties.

When the plant is located in an estuary, the river's discharge is an additional pertinent factor.

Data sources and data collection

4.37. Sea level is generally recorded hourly by tide gauges at harbours. In several States such data have been recorded for more than a hundred years (the measurements are in the charge of hydrographic services, which often depend on navies). Such data should be carefully collected, mindful of the fact that historic data can be affected by natural or human induced changes in the coastal area.

4.38. Concerning storm surges, the representativeness of collected data for the site under consideration should be assessed by the use of a model validated for the region.

4.39. Data on the heights of wind waves are collected by meteorological services. A parameter used for the description of these waves is one third of the height of the highest waves. The standardization of these data should be clearly documented.

4.40. In the absence of reliable statistical data for storm surges and wind waves, information from another site should not be relied upon because similarity of sites is very difficult to ascertain without a thorough investigation. The outputs of meteorological models (appropriate for the description of these phenomena) should be regarded as an alternative source of statistical data. These models should be validated for the region against collected data that are in close physical relation with storm surges, such as wind or pressure. Possible similarities with other sites should be thoroughly investigated and validated.

Statistical analysis

4.41. In general, analysis of extreme storm surges and of extreme wind waves is performed using classical methods, such as the Gumbel distribution, for the assessment of extreme values. The renewal method should be used to take account of historical events.

Data for design purposes

4.42. The expected average level of the seawater for the lifetime of the plant should be appropriately documented, with its confidence interval.

4.43. The extreme storm surge and the extreme high of the wind waves should be characterized by their probabilities of being exceeded in reference time intervals; these probabilities and reference time intervals should be appropriate for purposes of plant design. As an indicator of hazard, the expected extreme storm surge and the expected extreme height of wind waves for the lifetime of the plant should be determined together with their confidence intervals.

5. HAZARD DETERMINATION FOR RARE METEOROLOGICAL PHENOMENA

INTRODUCTION

5.1. This section describes methods for establishing the hazard for rare meteorological phenomena such as tornadoes or waterspouts, tropical cyclones and other events. These events may also result in flooding in certain circumstances. The method can be summarized as follows:

(a) The potential in the region for each phenomenon is assessed. If there is a potential, the regional climatology is evaluated, and the intensity and frequency of occurrence of the phenomenon under consideration are determined.
(b) The relevant physical parameters associated with different intensities of the phenomenon are identified.
(c) The probability of each phenomenon at the specific site is determined as a function of the intensity level of the phenomenon, or an appropriate model for the phenomenon in the region is constructed.
(d) The design basis phenomenon corresponding to a specified probability of exceedance value is evaluated.

TORNADOES

5.2. Tornadoes are generally described as violently rotating columns of air, usually associated with a storm. Waterspouts are similar to tornadoes but they form over large water bodies under more homogeneous surface conditions. If tornadoes or waterspouts strike buildings or structures of a plant, damage may be caused by the following:

(a) The battering effect of very high winds,
(b) The sudden pressure drop which accompanies the passage of the centre of a tornado,
(c) The impact of tornado generated missiles on plant structures and equipment.

Furthermore, tornadoes may induce floods and consequently may be the cause of additional indirect damage.

Data collection

5.3. Tornado phenomena, identified by appropriate local names, have been documented around the world. Information over as long a period of time as possible should be collected in order to determine whether there is a potential for the occurrence of tornadoes in the region.

5.4. If the possibility that tornadoes may occur in the region is confirmed, a more detailed investigation should be performed to obtain suitable data for the evaluation of a design basis tornado.

5.5. An intensity classification scheme similar to that developed by Fujita–Pearson should be selected. This system is a combination of the Fujita F scale rating for wind speed, the Pearson scale for path length and the Pearson scale for path width. The classification of each tornado is based on the type and extent of damage. Descriptions and photographs of areas of damage provide additional guidance for the classification of the tornado.

Compilation of tornado inventory

5.6. Reports of tornadoes occurring in the region should be collected and the tornadoes should be classified. From this, a regional tornado inventory should be compiled in the form of a 'tornado catalogue'. A region of the order of 100 000 km^2 centred at the site should be considered for this purpose.

5.7. Classification of each tornado should include the intensity (F scale), path length, path width and path direction. Information is generally available only for that portion of the occurrence for which the tornado was in contact with the ground. It is difficult to take into account those tornadoes that do not come into contact with the ground at all, or to assign an effective damage for the lifted part of a tornado which touches the ground intermittently. This may result in an underestimate of the probability of interaction with tall structures.

5.8. Correct interpretation of tornado reports collected from the public may be difficult. If the description of a tornado is vague, the F scale intensity class should be assigned conservatively. For the evaluation of the design basis tornado described in this section, the path area (path width and path length) and the intensity (F scale) are very important.

5.9. For the evaluation of the design basis tornado, a region which is climatologically homogeneous and which exhibits uniform tornado characteristics should be selected. The region may be divided into subregions, and for each subregion the frequency of occurrence of tornadoes should be evaluated and compared in order to assess the homogeneity of the zone and the conservatism of the choice of frequency for the region.

Data for design purposes

5.10. The probability per annum that a particular site will experience tornado wind speeds in excess of a specified value should be derived from a study of the tornado inventory. Tornadoes are classified in terms of their physical characteristics, such as maximum wind speed (intensity) and damage area (path length and path width).

5.11. After determination of the design basis tornado, which is scaled by wind speed, a tornado model should be selected in order to evaluate, by the best method available, the other parameters such as the tangential velocity, the maximum rotational wind velocity, the radius to the maximum wind velocity and the pressure drop. Tornado generated projectiles should also be specified.

TROPICAL CYCLONES

5.12. The approach that should be adopted for design measures against tropical cyclones relies on the determination of a probable maximum tropical cyclone (PMTC), which is covered by the present Safety Guide.[8] General methods are given for the evaluation of the relevant parameters of the PMTC. These methods depend on the results of theoretical studies on the tropical cyclone structure and make use of a large amount of data.

5.13. The distribution of heavy rains in tropical cyclones and its estimation and the effects of tropical cyclones on flooding require special consideration. General criteria, not specifically related to tropical cyclones, are presented in the Safety Guide on flood hazards [2].

Description of the phenomenon

5.14. A tropical cyclone consists of a rotating mass of warm humid air, one kilometre to several hundreds of kilometres in diameter. The atmospheric pressure is lower near the centre and could be less than 90 kPa in a well developed severe tropical cyclone. In the northern hemisphere the winds of a cyclone spiral inwards towards the centre in an anticlockwise sense, whereas in the southern hemisphere the rotation is clockwise. Well developed tropical cyclones have widespread areas of thick cloud cover, extending to great heights, together with bands of torrential rain and violent winds. The strongest winds (which may reach 100 m/s) blow in a tight band around the eye of a tropical cyclone.[9] The eye is a region of light winds and lightly clouded sky, usually circular or elliptical in shape and ranging from a

[8] It should be borne in mind that, in spite of this accepted terminology, the event is not characterized by purely probabilistic methods.

[9] A tropical storm is similar to a tropical cyclone but of lower intensity. A tropical storm corresponds to a maximum wind velocity lower than 33 m/s.

few kilometres to over 150 km in dimension. The wind speeds increase abruptly near the outer edges of the eye, called the eye wall, and then diminish gradually with distance from the wall.

5.15. Although the winds in a tropical cyclone frequently exceed 50 m/s, the cyclone's translational movement is much slower. For example, in the northwest Pacific ocean, the movement would typically be towards the west or northwest at about 4–5 m/s, but other directions and speeds up to and above 15 m/s are not uncommon.

5.16. The physical processes and energy transformations occurring in tropical cyclones are extremely complex and are not yet fully understood. Essentially, a tropical cyclone is a vast heat engine whose source of energy is the warm sea, providing water vapour which releases latent heat when it condenses and forms rain.

5.17. Tropical cyclones are warm core storms. Since the warm air in the core is lighter than its surroundings, the surface pressure there is lower, and such differences in the surface pressure produce the familiar pattern of circular isobars. Air starting to move towards the low pressure centre is deflected because of the rotation of the earth and spirals inwards. It should be noted that tropical cyclones do not form near the equator (5°N latitude to 5°S latitude).

5.18. It is generally known that for a tropical cyclone to form and persist, three conditions must be fulfilled:

(1) The sea must be warm, with a surface temperature of over 27°C.
(2) Moist air at low levels must converge inwards over a large area.
(3) The air flow at very high levels must be outwards so that circulation can be sustained.

5.19. Tropical cyclones have various names, depending on their severity and the regions in which they occur. What in the Atlantic is described as a hurricane is essentially the same phenomenon as what in the Bay of Bengal, the Arabian Sea and the southwest Indian Ocean is called a severe cyclone or in the western north Pacific a typhoon.

5.20. Although tropical cyclones occur much more rarely than severe EPSs, their impact is sufficiently important to most States concerned to merit a continual reassessment of their threat to coastal areas. The major damage from these storms results from inundations by tide surges accompanying the disturbances and generally occurs some distance away from the centres of the cyclones. On exposed shorelines, destruction normally begins with erosive scouring and battering by large breaking waves, the effects of which may extend inland with a rising tide to attack a plant's foundations and to cause structural damage to the lower floors of buildings.

5.21. In general, tropical cyclones occur most frequently in the western Pacific. They also form in the north Indian Ocean (Bay of Bengal and Arabian Sea), the south Indian Ocean, the south Pacific, the west Atlantic and off the northwest coast of Australia. Tropical cyclones are also frequent in the eastern Pacific but their trajectories remain mainly over the ocean. The occurrence of cyclones is strongly modulated by the southern oscillations: more in the Pacific, fewer in the Atlantic, in El Niño years. This phenomenon is related to the occurrence, every few years, of unusually warm ocean conditions along the tropical west coast of South America, which affect the local weather and create far field anomalies in the equatorial Pacific, Asia and North America. The southeast Atlantic and the central Pacific are not affected by these disturbances. Coastal areas of Brazil are reported to have been subjected to tropical cyclones roughly once every hundred years. There are indications of a steady increase in the temperature of surface water in the oceans, which may theoretically result in an increase in both the rate of occurrence and the intensity of tropical cyclones around the world.

Collection of information

5.22. In view of the available data as a whole, it may be said that a great deal is known about the characteristics of the movement of tropical cyclones and their effects on land and sea, but meteorological measurements at the surface and in the upper air in tropical cyclones are still inadequate in terms of either area coverage or record period.

5.23. As stated, studies of tropical cyclones have generally been handicapped by a lack of data. Early developments in establishing international observation networks have been slow and stations on islands in oceans are few and far between. Tropical cyclones form and exist mostly over oceans, and it is a particularly difficult task to obtain sufficient data to enable a detailed analysis to be made of their thermal and dynamic features. When a tropical cyclone moves over land, it is usually in a weakening stage, and observations even from a relatively dense land observation network may not be representative of the characteristics of an intensifying or intense steady state tropical cyclone.

5.24. In recent years, high resolution images from orbiting and geostationary meteorological satellites have become readily available to many national meteorological services. Such images provide valuable information for the detection and tracking of tropical disturbances, the estimation of their intensity and the derivation of the wind field at cloud level. Nevertheless, the number of parameters for tropical cyclones that can be measured accurately is still too low to permit reliable descriptions to be given of the basic physical processes involved.

5.25. Reports from reconnaissance aircraft provide important information about tropical cyclones. Data from such reports have been used extensively, in conjunction with conventional synoptic data and autographic records, to throw light on the three dimensional structure of the core regions of tropical cyclones. Observations by aircraft reconnaissance for intense tropical cyclones are carried out near the coasts of Japan, China (Taiwan) and the Philippines, while detailed analyses are made of all the extreme storms along the Gulf of Mexico and the east coast of the United States of America.

5.26. The following data on the storm parameters for tropical cyclones should be collected:

- — minimum central pressure;
- — maximum wind speed;
- — horizontal surface wind profile;
- — shape and size of the eye;
- — vertical temperature and humidity profiles within the eye;
- — characteristics of the tropopause over the eye;
- — positions of the tropical cyclone at regular, preferably six hourly, intervals;
- — sea surface temperature.

5.27. Values of some of these parameters are generally available in published reports and from databases, summaries or papers by national or international meteorological services or by research institutes. However, some of the data may not be available for a specific region, and recourse should be made to other sources such as radar observations, satellite imagery, special reconnaissance reports, case studies and press reports.

5.28. For the determination of the 'extreme' values of some of the variables, the 'highest' and 'lowest' values that have been recorded should be ascertained. Since synoptic observations are made at discrete time intervals, some of these values may be determined by the use of autographic records from land based locations or ships at sea. If autographic data are insufficient, data on some parameters, such as the maximum winds or the peripheral pressure of a tropical cyclone, should be estimated from synoptic maps.

5.29. For the purposes of applying certain methods, an overall picture should be obtained of the normal or 'undisturbed' conditions prevailing in the region when a cyclone occurs. To this end, climatological charts or analyses depicting the following fields should be examined:

— sea level pressure;
— sea surface temperature;
— temperature, height and moisture (dew points) at standard pressure levels and at the tropopause.

5.30. Most of the tropical cyclone data used for the development of the PMTC are associated with storms over open waters and, strictly speaking, the methods are only applicable to open coastal sites. For inland locations, the effects of topography and ground friction should be examined and quantified. In addition, it is known that polewards moving storms generally lose their quasi-symmetrical tropical characteristics and assume the structure of EPSs with well marked thermal contrasts. In considering the site evaluation for facilities at higher latitudes, modifications should therefore be made to the criteria developed for coastal sites.

Cyclone modelling

5.31. In spite of the availability of aircraft reconnaissance data accumulated over the past 20 years, the time variations of a few of the pertinent tropical cyclone parameters over a period of a few hours are still little known, so the PMTC is assumed to be in a steady state. Substantial changes in the inner core region from hour to hour have been noted in some mature tropical cyclones.

5.32. In order to determine the applicability of a model for a particular site, the local conditions, the peculiarities of the site and the historical data should be carefully evaluated and should be supplemented by means of measurements made with suitable instrumentation installed at the site so that comparisons with surrounding areas may be made. Whenever possible, case studies should also be made in order to determine the characteristics of tropical cyclones that have traversed the vicinity. All known tropical cyclones that have passed within 300–400 km of the site should be included in the study.

5.33. It is possible that the methods based on a physical model for cyclones developed for a certain region cannot be transposed to another region without appropriate modifications. Because of the rarity of very severe tropical cyclones, coupled with the scarcity of observations in the intense part of the storms, the physical characteristics of cyclones in different regions are not completely known, and these uncertainties should be taken into account in the modelling.

Probable maximum tropical cyclone

5.34. For the purposes of the application of the methods discussed in this Safety Guide, a PMTC is a hypothetical steady state tropical cyclone having a combination of values for meteorological parameters chosen to give the highest sustained wind speed that can reasonably occur at a specified coastal location. From the values of the meteorological parameters a PMTC should be derived and used to compute the maximum surge at coastal points, on the assumption that the PMTC approaches along the most critical track.

5.35. The methods for evaluating the PMTC are still undergoing development so that caution should be exercised in carrying out the evaluation. In this regard, modern techniques of determining some of the tropical cyclone parameters on the basis of observations made by aircraft and satellites have experienced a significant evolution and should be considered for application.

Data for design purposes

5.36. The maximum credible wind speed at the site should be specified. This value should be compatible with those resulting from available data recorded at the site or at nearby stations. Likewise, other features of interest for design, such as the vertical profile of the wind velocity or the duration of the wind intensity above specified levels, wind borne projectiles or surges should also be described.

LIGHTNING

5.37. Lightning transients exhibit extremely high voltages, currents and current rise rates. Damage is usually categorized as either direct or induced (indirect). The extreme electric field created under certain circumstances produces point discharges and can cause breakdown (a conductive path) in all but the most robust of insulators. Once a path has been established for the return stroke, currents of tens to hundreds of kiloamperes flow.

5.38. While it is impossible to predict exactly when and where lightning will strike, statistical information collected over the years can provide some indication of the areas with the highest probability of lightning activity as well as the seasons and times of day when such activity is most likely to occur. It should be noted that lightning is an unpredictable transient phenomenon with characteristics that vary widely from flash to flash and whose measurement is difficult.

5.39. A commonly used method of presenting data on the occurrence of lightning is the isokeraunic map. Contour lines depict the number of thunderstorm days per month or year that a particular region can expect to experience. These maps are based on weather service records over an extended period of time (30 years for example). A thunderstorm day is defined as any day during which a trained observer hears thunder at least once. Although these maps are regularly referred to by persons who perform risk analyses for structures and systems that are vulnerable to lightning, they are a poor indicator of actual lightning activity. This is because one thunderstorm day will be noted whether a single thunderclap or 100 are heard on that particular day. In addition, recent studies indicate that thunder was not heard for 20–40% of lightning flashes detected.

5.40. While the probability of lightning striking in a particular area is often evaluated from statistically determined values from isokeraunic map data based on thunderstorm days, such calculations should be viewed with caution. Despite this caveat concerning the use of isokeraunic maps of thunderstorm days, they may be useful in providing a rough idea of the relative incidence of lightning in a particular region. A general rule, based on a large amount of data from around the world, estimates the earth flash mean density to be 1–2 cloud to ground flashes per 10 thunderstorm days per square kilometre. New techniques and associated networks are now in use in many States for detecting individual cloud to ground lightning flashes and for archiving data. This more recent database, if available for the site area under evaluation, can be used to supplement the thunderstorm day data and thus to provide a more realistic assessment of lightning risk for the nuclear power plant site.

Annex

DISTRIBUTIONS OF EXTREME VALUES

A–1. In the analysis of extreme values, the general asymptotic extreme value distribution is widely used:

$$\text{For } k = 0,\ F(x) = \exp\left[-\exp\left(-\frac{x-\xi}{\alpha}\right)\right]$$

$$\text{For } k \neq 0,\ F(x) = \exp\left[-\left(1-k\frac{x-\xi}{\alpha}\right)\right]^{1/k}$$

These distributions are known as Type I (Gumbel), Type II (Fréchet) and Type III (Weibull) Fisher–Tippett laws, corresponding to $k = 0$, $k < 0$ and $k > 0$, respectively.

A–2. The Type I law, $k = 0$, known as Gumbel's distribution, can also be written as:

$$\xi = x + \alpha\{[-\ln F(x)]\} = x + \alpha u, \text{ in which } u = \ln[-\ln F(x)].$$

Plotting x against u gives a straight line. This property enables a visual check to be made of the extent to which a data set fits the Gumbel distribution.

A–3. Similarly, special probability paper is available for the Type II (Fréchet) and Type III (Weibull) distributions, in which the corresponding distribution is plotted as a straight line and may therefore be used to inspect visually the fit of the data to the proposed distribution.

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