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METEOROLOGICAL AND HYDROLOGICAL ASPECTS OF SITING AND OPERATION OF NUCLEAR POWER PLANTS

VOLUME I: METEOROLOGICAL ASPECTS

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FOREWORD

Meteorology and hydrology play an important role in the understanding of the basic criteria for the siting of nuclear power plants and in applying protective measures for their operation. In order to provide advice on this matter, the WMO Secretariat, at the request of the Executive Council, arranged for the preparation of a Technical Note aimed at practising meteorologists and hydrologists of countries faced with the task of installing nuclear power plants.

This Technical Note, which is composed of two volumes, dealing with meteorological and hydrological aspects respectively, has been prepared in close cooperation with the International Atomic Energy Agency (IAEA). Each volume is so conceived as to stand on its own and be complementary to the relevant internationally accepted guidance material prepared by IAEA.

The present volume, which deals with meteorological aspects and constitutes Volume I of the Technical Note, was prepared by Dr B. Bringfelt (Sweden) (Chapters 1 and 2) and Dr. B. Zalcman (USA) (Chapter 3) and was reviewed by Dr A Junod (Switzerland).

On behalf of the World Meteorological Organization, I should like to express my appreciation to all who contributed to the preparation of this volume.

G.O.P. OBASI
Secretary-General

Geneva, 1985
SUMMARY

The present volume has been prepared to provide guidance to Meteorological Services concerning the contributions they can make to solving problems of safety in the siting and operation of nuclear power plants (NPP). It describes methods of acquisition, presentation, interpretation and use of meteorological data in this special field of application.

The introduction in Chapter 1 explains the scope of the volume and gives a brief review of the role of meteorology in the different stages of NPP siting and operation.

Chapter 2 sets out detailed guidance on the meteorological services to be provided. The first part of the chapter gives a general description of the planning and implementation of a local meteorological investigation for the evaluation of diffusion characteristics (including details on instrumentation, data collection and processing and the use of atmospheric-diffusion models). This is followed by a review of the meteorological studies needed in the various stages of siting and operation (i.e. site survey, final site selection, site qualification, normal operation, emergency situations). Each of these stages is treated in turn, indicating the methodology to be followed, the need for meteorological data normally available on a routine basis, the requirements for special observations and the use of diffusion models. Some examples of computation are included.

Damaging meteorological phenomena and extremes of certain meteorological elements may have significant implications for safety and should be duly accounted for in the structural design of an NPP. In view of its importance, a separate chapter (Chapter 3) is devoted to this aspect. Guidance is given on the collection, selection and statistical analysis of data and on the determination of design-basis values of extreme wind, precipitation, snow pack and temperature. Of the severe meteorological phenomena, the tornado is discussed in considerable detail, and a shorter treatment is given of probable maximum floods at river and coastal sites. To facilitate the practical application of methods described in the text, Annex I contains a discussion of the statistics of extremes, with examples.
**RESUME**

Le présent volume a été préparé pour guider les Services météorologiques au sujet des contributions qu'ils peuvent apporter à la solution des problèmes de sécurité dans le choix de l'emplacement et l'exploitation des centrales nucléaires. On y trouvera une description des méthodes d'acquisition, de présentation, d'interprétation et d'emploi des données météorologiques dans ce domaine spécial d'application.

L'introduction du chapitre 1 donne des explications sur la portée du volume ainsi qu'un bref aperçu du rôle de la météorologie aux différents stades du choix de l'emplacement et de l'exploitation des centrales nucléaires.

Le chapitre 2 contient des conseils détaillés sur l'assistance météorologique à assurer. La première partie du chapitre donne une description générale de la planification et de la mise en œuvre d'une enquête météorologique locale pour évaluer les caractéristiques de diffusion (notamment des détails sur les instruments, le rassemblement et le traitement des données et l'emploi de modèles de la diffusion dans l'atmosphère). Vient ensuite un aperçu des études météorologiques nécessaires aux divers stades du choix de l'emplacement et de l'exploitation (par exemple, enquête relative au site, choix définitif du site, critères auxquels doit répondre le site, exploitation normale, situations d' urgence). Chacun de ces stades est étudié successivement et l'on trouve des indications sur les méthodes à suivre, les données météorologiques dont on doit normalement disposer dans des circonstances courantes, les observations spéciales indispensables et l'emploi de modèles de la diffusion. On y trouvera aussi des exemples de calcul.

Les phénomènes météorologiques qui risquent de causer des dommages et les conditions extrêmes de certains éléments météorologiques peuvent avoir des conséquences importantes pour la sécurité et il doit être dûment tenu de son importance, cet aspect de la question a été traité dans un chapitre distinct (chapitre 3). Des directives sont données concernant le rassemblement, le choix et l'analyse statistique des données ainsi que pour déterminer les valeurs de base dont il faut tenir compte au stade de la conception pour des conditions extrêmes de vent, de précipitation, d'enneigement et de température. Parmi les phénomènes météorologiques dangereux, les tornades font l'objet d'un examen très détaillé tandis que la question des crues maximales probable des cours d'eau et des emplacements côtiers y est traitée plus brièvement. Pour faciliter l'application pratique des méthodes décrites dans le texte, l'annexe I contient une discussion des statistiques des cas extrêmes, avec des exemples.
Резюме

Настоящий том подготовлен с целью предоставить руководящий материал метеорологическим службам относительно вклада, который они могут внести в решение проблем безопасности при выборе места для строительства и эксплуатации атомных электростанций (АЭС). В этом томе описываются методы получения, представления, интерпретации и использования метеорологических данных в этой специальной области их применения.

Во введении к главе 1 даётся описание информации, содержащейся в томе, и приводится краткий обзор её роли, которую играет метеорология на различных стадиях выбора места для строительства и эксплуатации атомных электростанций.

В главе 2 даётся подробное описание метеорологического обслуживания. В первой части главы даётся общее описание планирования и проведения местных метеорологических исследований для оценки характеристик диффузии (включая подробную информацию по приборам, сбору и обработке данных и использованию моделей атмосферной диффузии). Это описание сопровождается обзором метеорологических исследований, необходимых на различных стадиях выбора места и эксплуатации (т.е. обследование участков строительства АЭС, окончательный выбор места, определение пригодности места, обычная эксплуатация, непредвиденные ситуации). Каждая из этих стадий в свою очередь рассматривается с указанием применяемой методологии, потребности в последующих метеорологических данных, потребностях в специальных наблюдениях и использования диффузионных моделей. Приводятся некоторые примеры расчетов.

Метеорологические явления, присоединяющие ущерб, и экстремальные значения некоторых метеорологических элементов могут иметь значительное влияние на безопасность и должны учитываться должным образом при проектировании атомной электростанции. Отдельная глава (глава 3) посвящена этому аспекту с точки зрения его важности. Приводится руководящий материал по сбору, отбору и статистическому анализу данных и по определению при оценке проектирования экстремальных значений ветра, осадков, толщины снежного покрова и температуры. Очень подробно рассматривается такое метеорологическое явление, как тornado, и даётся более краткое изложение возможного максимального наводнения в результате разлива рек и на морском побережье. С целью облегчения применения на практике методов, приведенных в тексте, в приложении I содержатся статистические данные экстремальных значений с примерами.
RESUMEN

El presente volumen se ha preparado para proporcionar directrices con el fin de que los Servicios Meteorológicos puedan contribuir a resolver los problemas relacionados con la seguridad de las centrales de energía nuclear por lo que atañe a su emplazamiento y funcionamiento. En el presente volumen se exponen los métodos para adquirir, presentar, interpretar y utilizar los datos meteorológicos en esta esfera especial de aplicación.

En la introducción del Capítulo I se explica el contenido del presente volumen y se expone un breve resumen de la función que incumbe a la meteorología respecto a las diferentes etapas de emplazamiento y funcionamiento de estas centrales.

En el Capítulo 2 se dan directrices pormenorizadas sobre los servicios meteorológicos que deberán proporcionarse a este respecto. En la primera parte del capítulo se describe, en términos generales, la forma de planificar y llevar a cabo una investigación meteorológica sobre el lugar de emplazamiento con el fin de evaluar las características de difusión (datos sobre instrumentos, concentración y proceso de datos y utilización de modelos de difusión atmosférica). Esta primera parte va seguida de un examen de los estudios meteorológicos que es necesario realizar en las diversas fases del emplazamiento y funcionamiento (esto es, estudios relativos al lugar de emplazamiento, selección del emplazamiento final, calificación del emplazamiento, funcionamiento en condiciones normales, situaciones de emergencia). El volumen se ocupa sucesivamente de cada una de estas etapas, indicándose los métodos aplicables, las necesidades de datos meteorológicos corrientes normalmente disponibles, las necesidades de observaciones especiales y la utilización de modelos de difusión. También se dan algunos ejemplos de operaciones de computación.

Algunos fenómenos meteorológicos perniciosos y la severidad de determinados elementos meteorológicos pueden afectar de una manera significativa a las condiciones de seguridad y, por esto, deben tenerse debidamente en cuenta para diseñar la estructura de la central de energía nuclear. En vista de su importancia, se dedica a este aspecto un capítulo aparte (Capítulo 3). Se dan también directrices sobre la concentración, selección y análisis estadístico de datos y sobre la determinación de los valores extremos de los vientos y de la precipitación, el manto de nieve y la temperatura como base del diseño de la central. Entre los fenómenos meteorológicos severos, se estudia el tornado con notable pormenor y se tratan más brevemente los valores probables máximos de las crecidas en los emplazamientos situados en las cuencas fluviales y en las costas. Con objeto de facilitar la aplicación práctica de los métodos que se exponen en el texto, se incluye el Anexo I que trata de estadísticas de valores extremos, con ejemplos.
CHAPTER 1

INTRODUCTION

1.1 GENERAL

This volume contains an introductory and general text devoted primarily to meteorologists in those national Meteorological Services engaged in the siting and operation of nuclear power plants (NPPs). The aim is to describe, in a practical way, the use of meteorology in solving problems of health and environmental safety in the siting and operation of one NPP. Reference will be made to sciences and techniques used by meteorologists in order to make their results useful.

A general review is given of all related problems in their individual context. Detailed and more specific guidance should be sought in the other literature referred to. The IAEA safety guide No. 50-SG-33 Safety Guide on Atmospheric Dispersion in Nuclear Power Plant Siting contains direct practical solutions to many specific problems and is referred to and in part summarized in this volume. It is stressed that, at the national level, conventional meteorological data should be made available by the national Meteorological Service, whose responsibility in planning and performing meteorological investigations is pointed out.

Even if the emission from an NPP in normal operation is small, as is the probability of an accident, the effects of the present or potential releases must be duly treated as some radioactive materials are very poisonous. (There is also a global impact, where the contributions from all NPPs should be added together but this aspect will not be treated in this volume.) Radiological safety recommendations are therefore very rigorous in comparison to those for "conventional" pollution. The basic recommendations of the International Commission on Radiological Protection (ICRP), concerning the effects of ionizing radiation, are found in ICRP (1977). The recommendations contain the dose-limitations system for radiation protection, including the requirements for the protection of the public. Based on these recommendations, the basic safety standards for radiation protection (IAEA Safety Series No. 9) are being revised in co-sponsorship with IAEA, ILO, NEA and WHO. Publication is expected within the next few years.

With respect to the release limits of radioactive material to the environment, the ICRP publication No. 29 provides guidance on the general methodology and modelling necessary for that purpose (ICRP, 1979). Furthermore, the IAEA Safety Series Nos. 45 and 57 also provide guidance on the general methodology to be applied.

In safety analysis, every link in the chain from release to consequence should be given a thorough examination in which conservatism should be the keynote. The radiological effects should be estimated (e.g. in specified types of emergency or in normal operation) compared with the ICRP recommendations. The safety analysis should be made for each of the various stages discussed in paragraphs 1.2.1.1 - 1.2.1.5 below: site survey, final site selection, site qualification (NPP design input), normal operation and emergencies.
Many central environmental problems have to be solved by meteorologists in co-operation with reactor technicians, measurements and data-systems engineers and data-processing specialists. It is therefore necessary that meteorologists and the national Meteorological Services take an active part in dealing with the environmental problems in NPP siting and operation.

The entire safety analysis should be performed at least twice: once by the proposing organization, which develops the detailed information; and again by the licensing agency, which critically reviews every step. In this last procedure, the information should be sent to various bodies for criticism, including the national Meteorological Service, which should give advice to the regulatory body about, for example, the suitability of the proposed site from the point of view of the meteorological environment or about a special meteorological investigation to be made before approval of the site.

Subjects will be considered such as the development of methods for the use of standard meteorological data and the study of micro- and mesometeorological conditions in the surroundings of an NPP with reference to modern dispersion-modelling techniques.

Methods for presentation and interpretation of relevant meteorological information are indicated. The desirable length of record and interpolation of missing data on the basis of data from nearby routine weather stations are discussed.

It should be mentioned that the advent of the atomic energy industry provided a major focal point for the development of air-pollution meteorology, since it was realized that prediction and control in advance of radioactive impact on the environment were essential in this new field. Air-pollution meteorology is a branch of the science of meteorology which deals with the study of the effects of atmospheric phenomena on airborne pollutants. The results of reaction and deposition are usually included, since they interact very strongly with the pure dispersion. Simply stated, the role of the air-pollution meteorologist is to evaluate the effects of weather and terrain on the concentration of the effluent as it travels from source to receptor.

Extreme meteorological phenomena like hurricanes, tornadoes and strong winds in general may cause damage to the NPP. The meteorological service of the applicant should collect data and then study, investigate and propose a suitable design basis. The meteorological service of the regulatory body, taking into account the advice of the national Meteorological Service, will review the proposal, approve the design basis or request additional research (see section 1.2.2).

The necessity to consider the extreme meteorological conditions and phenomena in site selection must be mentioned. General practical recommendations on these aspects are given in this volume. Reference should also be made to the IAEA Safety guide 50-SG-D11A Extreme Meteorological Events in Nuclear Power Plant Siting, Excluding Tropical Cyclones.
As indicated above, the present volume will not treat:

(a) Global effects of man-made radioactivity;
(b) Effects of more than one NPP site in a region, such as the possible addition of radioactive doses and climatic modification.

1.2 THE ROLE OF METEOROLOGY AS AN ENVIRONMENTAL SCIENCE IN THE SITING AND OPERATION OF A NUCLEAR POWER PLANT

Meteorology is an indispensable tool in consequence and risk analyses for NPP siting and operation. Meteorological knowledge must be used in an active way in planning and evaluating the local meteorological investigations at every NPP site, i.e.:

(a) Effects of the NPP on the environment; and
(b) Effects of the environment on the NPP.

The work under (a) mainly consists in assessing the atmosphere as a pathway for the transport of radioactive releases from the NPP to the environment. The movement of gases and particles is largely governed by the motions of the atmosphere. Atmospheric motions dictate the paths to be followed by airborne contamination; others determine the extent to which the contaminants will be diluted.

Most releases originate from sources in the first hundred metres above ground and virtually all receptors are located in this layer. Much meteorological development for the atomic energy field has, therefore, dealt with the lowest hundred metres of the atmosphere, from which it is possible to predict what concentrations will occur from a given release in normal operation or an emergency. Hot releases, which will occur in major NPP accidents, however, may rise to several hundreds of metres. (See further section 2.2.5.)

Chemical reactions, radioactive decay and deposition of the contaminant on the ground play important roles. These phenomena are harmful and can affect concentrations at some distance from the source since, during the transport up to that distance, they may remove or add specific contaminants to the plume. Such effects on the concentration values are important, especially at large distances from the source. In mesoscale dispersion modelling (transport distances 10-300 km) due regard must be paid to these phenomena, as well as to other purely meteorological effects which have greater importance such as: vertical wind shear, circulation patterns like land and sea breezes and weather changes during the transport from source to receptor.

In estimating the effects of an airborne radioactive release, three main problems should be considered (these are discussed in Chapter 2):

- Airborne radioactive concentration near ground level;
- External radiation from the release;
- Radioactive fall-out on surfaces.
CHAPTER 1

The work concerning the effects of the environment on the plant (see (b) above) deals with extreme meteorological conditions and phenomena. In this case, the design basis should be identified and the plant protected against the extreme meteorological event. This is usually done using historical data to evaluate the design basis with probabilistic or deterministic methods.

1.2.1 Problems in the separate stages of NPP siting and operation

The role of meteorology in the successive stages of NPP siting and operation will be discussed below. The stages were defined above in the general introduction.

1.2.1.1 Site survey

At first, several regions or sites will be compared. The result will be the selection of a few suitable sites, which will be studied further for final site selection. Some sites or regions may have to be excluded because, for instance, of flooding or geological faults. The choice of suitable sites will also depend on non-safety-related factors such as the availability of land, water, transport, distance from a high-voltage network, ease of site preparation and heat-dissipation facilities.

The choice also depends on a comparative assessment of the potential of the air over the sites to dilute radioactive releases in normal NPP operation or accidents and on routine meteorological statistics from the area and other information if available, e.g. specially collected data. Usually, no meteorological measurements are made solely for the purpose of site preselection.

1.2.1.2 Final site selection

At this stage, a few sites have usually been selected and considered as suitable and the final site has to be chosen from among them. If there are specific problems with one or more sites such as complex population distribution or physical characteristics, special meteorological measurements should be made in order to ascertain whether the site has the sufficient potential for the transport and dilution of a radioactive release. These studies may involve long series of observations at the site and detailed research into some of the characteristics of the environment. These studies may often have to continue for as long as a few years before the final site is selected.

Population distribution, together with unsuitable meteorological characteristics, may represent an exclusion factor (see further section 1.4.2.2).

1.2.1.3 Site qualification (NPP design input)

In order to establish suitable design input for the NPP such as location and height of chimneys and cooling towers, meteorological investigations are necessary. Problems involved in avoiding downwash of emitted plumes must be studied before a suitable design can be established.
1.2.1.4 Normal operation

Meteorological dispersion models play an important role in mapping the concentration and dosage field in the environment in normal operation. Meteorological statistics from the site should be used to obtain average concentrations over a certain time interval as well as the probability of high hourly values, for example.

The biological consequences of the absorption by man of radio-nuclides through air, water and other media are then used to evaluate doses to individuals and the population as a whole.

1.2.1.5 Emergency situations

In not-too-weak winds, an emergency release will pass over a populated area minutes to hours after the release. Warnings with instructions such as to remain indoors with fastened windows could therefore be issued beforehand.

The deposition (wet or dry) of the cloud will cause a coverage which may remain hazardous for years. Evacuation of contaminated areas may then be decided on the basis of measurements of the radiation from a coverage. Meteorological information is necessary in assessing these measurements.

In an emergency situation, three degrees of meteorological assistance may be defined (regarding time-scales and quality of information delivered):

(a) Very quick and rough information (no meteorologist is present);

(b) Quick but somewhat more detailed information (meteorologist is present);

(c) Elaborate dispersion calculations (which could be made months after the emergency has occurred).

The current direction of movement and the rate of diffusion of the release have to be evaluated very quickly. Rapid information is necessary in order that the radiological monitoring organization may establish the actual extent of the environmental contamination.

The necessary information has to be deduced by a meteorologist from the measurements at the site or even from a suitably located routine weather station. In order to make this procedure rapid and reasonably accurate, such use of current meteorological data should be included in the emergency service organization. This system should be prepared by making case-study diffusion experiments well before the reactor starts operation. The system must also include a fast, direct contact with a meteorological service, so that the relevant meteorological parameters can be forecast and, subsequently, the future path and spread of the release.

Forecasts are especially important for:

(a) Prolonged emergency releases;
(b) When there is a possibility to postpone a necessary release; and

(c) When it is known that there will be a release in, for example, two hours.

At a coastal site, a weather forecast can provide information about the time and place of return to the coast of a release which has drifted out over the water. In such a case, the need for accuracy may sometimes be greater than that for rapidity.

A meteorologist provided with adequate data can offer considerable help in the case of an accident by making quantitative estimates of the extent and severity of the contamination. Moreover, his services are of great use in the post facto analyses of an accident. The results may be used to indicate contaminated agricultural areas, for example, and to deduce the magnitude of the release according to the observed contamination levels.

The investigations and measures to be made in preparatory studies and in an emergency depend very much on the type of site. (See further section 1.4.1 and Chapter 2.)

1.2.2 Role of the national Meteorological Service (NMS), the meteorological services of the applicant and the regulatory body

It is advisable to include atmospheric diffusion experts in the organization of both the applicant and the regulatory body at a very early stage of site selection. It will subsequently be the responsibility of the applicant to collect the information and instigate studies and research and that of the regulatory body to review proposals, taking into account the advice of the NMS concerning existing routine meteorological statistics and special measuring data at the sites studied.

In NPP siting, there is a need for information about the climate of the site and the possibility to make local weather forecasts. It is therefore necessary to contact the NMS at an early stage to learn how to obtain the relevant information. The NMS also knows how to treat historical records from weather stations. Further, the duty of an NMS is to follow and store all information about the quality, representativity, history and the previous work of the weather stations. An NMS can also provide the climatic information with accompanying services, such as arranging the information for special purposes. Special weather measurements or observations have often been made earlier at a given location for another industrial project. In most cases, the NMS is best informed about such material, while the safety experts of the NPP often do not know about such previous meteorological work.

Meteorological investigations performed by the applicant at a site should be used to establish criteria for final selection concerning the design of the plant. It is important that the regulatory body, taking into account the advice from the NMS, stresses the need for early special meteorological investigations if specific design data are required.

An important task of the applicant is the installation and maintenance of the meteorological instruments for studying the site before selection thereof and during the operation of the plant. The regulatory body is responsible for approving the instruments and their installation and the
entire measuring programme, including maintenance and data processing, taking into account the advice of the NMS which may be charged with inspecting the equipment prior to and during its operation.

As regards disaster preparedness, a weather forecast service (usually associated with the NMS) must be ready to take an active part in training and to serve immediately in a real emergency (see also section 1.2.1.5).

1.3 LEVEL AND KIND OF KNOWLEDGE NEEDED TO DEAL WITH METEOROLOGICAL ASPECTS AND DIRECTLY RELATED AREAS

In this section, scientific knowledge needed to deal with the meteorological aspects of NPP siting and operation are discussed, together with the technical abilities that are required to implement in the field the inquiries and measures proposed by the scientists.

1.3.1 Meteorology

In order to meet the requirements of the meteorological assessments and services at an NPP, a meteorologist must be engaged within the applying organization as project leader, who is responsible for meteorological research, including the operation of the technical equipment involved. This meteorological project leader must be an air-pollution meteorologist, engaged either half- or full-time until normal operation has started and possibly later, depending on the tasks raised by the safety organization.

The person in question must be educated and trained in general meteorology and especially in the theoretical and practical aspects of air-pollution dispersion studies and modelling, as well as theoretical and practical experience of meteorological instruments used in the lower atmosphere. To be an instrument specialist or a purely theoretical meteorologist is not sufficient. The meteorological project leader should therefore take a general view and be able to engage the necessary personnel to assist in solving special problems. He (or she) should normally be recruited by the national Meteorological Service or a university. At least one person with similar qualifications to those of the meteorological project leader should be included in the staff of the regulatory body and be charged with reviewing the proposals, studies and investigations of the applicant.

Meteorological personnel familiar with the emergency plan for the site must participate in any training or drill arranged by the regulatory body. Such personnel should also be available in the Meteorological Service which, according to section 1.2.2, should be responsible for the forecasting needed in training as well as in a real emergency.

1.3.2 Health physics

The experts in health physics engaged in the environmental safety analyses must be able to use the results obtained by the meteorologists, and must therefore co-operate closely with them.
1.3.3 Techniques of field measurements and inquiries

The planning of the local meteorological investigation should be made by a person having experience of meteorological instruments and data-transmission and -acquisition systems. This person should take an active part in the calibration and installation work in the laboratory and at the site and should be familiar with the requirements for the positioning of meteorological sensors, such that they will not be disturbed by other structures. The planning, calibration and installation work shall be followed by the meteorological project leader and approved and inspected by the regulatory body.

During the local meteorological investigation and also later during normal NPP operation, it is necessary that a person be responsible for the maintenance system conceived to obtain the desired joint data recovery (see section 2.1.2.1). This person would be responsible for the technical inspection and repair of the meteorological sensors, cables, boxes, recorders, data-processing systems, etc.

The case-study measurements such as smoke experiments or remote-sensing studies must be planned by an air-pollution meteorologist.

1.3.4 Data handling

The specification and ordering of the transmission and acquisition systems should be made in close co-operation with an expert in data processing. The data handling and processing should be designed by this expert in co-operation with the meteorological project leader, as well as plans for the statistical methods and dispersion models. The final calibration curves for the meteorological sensors should be reviewed by the meteorologist.

The routine checks of the data continuously collected during the meteorological investigation should be made under the regular supervision of a person in possession of excellent judgement as to the viability of meteorological data records.

1.3.5 Need for scientific assistance from other fields

If outside help is needed to meet the requirements given above, it may be necessary to appeal abroad for experts, technical equipment and computer capability. Useful standard computer programs for statistical processing and dispersion-model calculations are available and programs appropriate to the problems at the site may be recommended by the staff of an experienced meteorological service.

When ordering the technical equipment, it is important to ensure that the appropriate service can subsequently be carried out quickly. The data-transmission and -acquisition systems should therefore be ordered from an electronics company with a service organization in the country.

1.3.6 Organization of meteorological services

Detailed advice on how to organize the applicant's and regulatory body's meteorological services and other specific problems may be requested from international organizations such as WMO and TERA.
1.4 STUDY OF LOCAL METEOROLOGICAL CONDITIONS

Diffusion characteristics and the frequency of extreme meteorological conditions vary widely from one site to the next. Climatic regions also vary as to locations within the same climatic region. The variations of the latter depend greatly on local site features such as coasts, rivers, valleys and built-up areas. As a result of these differences, the methods of performing the necessary meteorological assessments and services may also vary widely between sites.

1.4.1 Review of different investigations needed at various sites to meet the requirements of the meteorological assessments and continuing services

Since the types of site are greatly diversified, no definitive statements can be made of the meteorological investigations which must be made at any one site. While only a general review will be presented, it is possible, however, to specify the requirements of the meteorological investigation.

There are two main purposes of local meteorological investigations at NPP sites:

(a) Evaluation of diffusion characteristics in normal NPP operation, which should be used to:

(1) Estimate probability-consequence relationships for various concentrations or doses;

(2) Give estimates for the NPP design such as information on required chimney height;

(b) Evaluation of diffusion in emergencies, which should be used to:

(1) Predict the path of an emergency release and the resulting concentration and contamination levels;

(2) Analyse the consequences of an historical emergency release;

(3) Estimate probability-consequence relationships regarding various types of accidents and meteorological situations.

While (a) is achieved mainly by making continuous measurements for one year or more and using these data in diffusion models (the results should be made valid for several years in order to obtain a climatologically representative picture), (b) is achieved by using data from the continuous measurements as well as from additional preparatory case-studies of diffusion in complicated weather situations. In both cases, data from suitable routine weather stations have to be included in the analyses.

The influence of site characteristics on the kind and amount of measuring equipment, the duration of the continuous measurements and the kind of data analyses in the various stages of NPP siting and operation is
discussed below. (Further details are given in Chapter 2.) The more complex
the site, the more the investigations that are needed. At some sites it may
not be possible to predetermine the extent and type of investigation and
preparatory investigations will be necessary.

In some of the stages listed below, the most important
meteorological measurements at the site are usually performed on a high
meteorological mast with instruments at various levels. When making such
measurements on a continuous basis, it is necessary to design and protect the
instruments according to the conditions that may occur at the site. For
example, in sites subject to heavy icing, it is necessary to protect the
meteorological sensors against falling ice by the use of shields.

The data collected are usually processed by a computer and the
results concerning concentration or dose values have to be obtained by the use
of dispersion models.

1.4.1.1 Site_survey

In a site survey, there may be several regions or sites to be
compared and the meteorologist may be required to state which is/are the most
suitable for NPP siting. If the sites to be studied are in flat terrain, they
may have similar diffusion conditions and similar positions in relation to
population centres. The former must be established by thorough study of
climatic data from weather stations which are representative for the sites.
Comparisons of air-pollution potential should be made for the regions
concerned.

A site survey is usually made without special meteorological data
but, if any special measurements have already been made for other purposes,
such results should, of course, be used. Simplified diffusion models should
be used to compare the suitability of different sites but the limitations of
such models at complex sites must be noted.

If data from a nearby routinely operated weather station are to be
used, the representativity of that station for the site must be investigated.

The occurrences of extreme meteorological conditions and phenomena
should be compared.

On the basis of these preliminary investigations, the various
sites can be ranked according to their suitability from a meteorological point
of view.

1.4.1.2 Final site_selection

When the final site is selected it is on the understanding that
the following requirements have been satisfied:

(a) The air over the site should have a sufficient potential to
carry away and dilute releases in normal operation;

(b) The diffusion of emergency releases should be known
sufficiently well for indicating the broad lines of the
meteorological part of the emergency plan;
Engineering solutions to the design problems must exist, which satisfy the meteorological requirements of the site.

When investigating whether these requirements have been fulfilled, a comparison is made of dispersion-model estimates, based on meteorological data from the site, with the recommendations of the ICRP concerning the effects of ionizing radiation (see section 1.1). The results should be valid for a period of several years and then conventional meteorological data have to be used as much as is feasible. In addition to conventional data, one year of mast data must be regarded as the minimum even at a simple site.

The meteorological project leader may decide either at the beginning or after studying some of the data collected, however, that more than one year of data will be necessary in order to ascertain whether the above requirements will be met. It can also be decided whether measurements at other masts or ground stations are necessary or indeed case-studies using tracer or remote-sensing techniques. Moreover, after making mast measurements for some time, technical difficulties arise, with resulting erroneous or missing data. In all these cases a judgement and recommendation from the meteorologist about more extensive measurements have to be respected by the applicant and other authorities concerned.

The amount of local material (e.g. mast data) required depends on the degree of correlation between the local material and the material for the same period from the nearest station of the conventional meteorological network. Even with five years of data, the correlation between the local measurements, and the standard data may be very bad, in which case, a good climatic description of the site cannot be made. There might well be a good correlation for mundane meteorological situations but for special meteorological situations, which are critical for dispersion conditions, there might be no correlation at all. It is the responsibility of the meteorologist to ensure that this material is produced in the sufficient quantity. The aspects mentioned above should be treated by the meteorologist in one or more interim reports.

The applicant often requires the final conclusions from the meteorological data to be made at a prescribed date, in which case, the meteorological project leader could state that such an obligation cannot be undertaken because technical problems concerning the measurements could emerge or the meteorological features of the site could show that an extended measuring programme would be necessary. It would, however, be considered reasonable at least to promise that, after a three-year period, a statement would be issued about the usefulness of the data collected thus far, together with a recommendation as to whether the measurements have to continue or not. These aspects will also be treated in Chapter 2.

If proximity of the site to agricultural or populated areas is an important factor, meteorology is one of the means used to ascertain the measures to be taken to ensure adequate safety in an emergency. Techniques for computing concentration and deposition after long-range travel (up to 100 km or more) then have to be used. Such mesoscale dispersion-modelling techniques will be discussed in section 2.1.6.4.

At a complicated site, meteorology may rank as an exclusion factor but the final choice of site is not based solely on meteorological characteristics. A site might be undesirable from a meteorological point of view.
but other considerations may lead to its being chosen. In such a case, it is necessary to establish that engineering design safeguards exist to offset completely the meteorological drawbacks of the site. An example of this (considering diffusion in the air) will be given in section 1.4.1.3. It is also necessary to establish confidently that the NPP construction will withstand the extreme meteorological conditions which may occur.

1.4.1.3 Site qualification (NPP design input)

As mentioned above, many of the design problems have been considered already in the selection of the final site. Usually, no further meteorological measurements besides those made in the selection stages are necessary but more detailed diffusion-model calculations or wind-tunnel studies may be required in order to determine the necessary dimensions of chimneys and cooling towers. The influence of buildings and terrain has to be taken into account.

In a deep valley, tracer, balloon or remote-sensing studies may be carried out. The results can be used in a diffusion model or the air trajectories coming from various release heights examined. Such experiments might show how high the chimney has to be built in order to avoid direct impact of radioactive gases on the valley sides. As mentioned in section 1.4.1.2, such investigations should already have been included in the final site selection in order to find out whether reasonable design solutions exist.

1.4.1.4 Normal operation

Before starting operation of an NPP, the following meteorological requirements must be fulfilled:

(a) For the planned releases in normal operation, estimated probability-consequence relationships for the concentration or doses in the environment must have been established;

(b) The emergency plan, including the meteorological part, has to be operative.

This implies that there should be a minimum of one year of satisfactory, continuous meteorological data from at least one high mast at the site. From comparisons with a series of data over several years from a routine weather station, evaluated meteorological and concentration statistics that are representative for the site must be available. If there are complex surroundings, there may be no routine weather station with statistics representative for the NPP site and additional years of data have to be recorded at the site.

Several case-studies using, for example, smoke releases simulating accidental radioactive clouds should be made in poor dispersion conditions. In a flat site, such experiments have to be made primarily in strong inversion conditions. In complex terrain, experiments must also be made in other weather situations. The results from these studies have to be used for constructing the meteorological part of the emergency plan.

During normal operation, a certain number of key meteorological parameters must be recorded in preparation for an emergency. (See further sections 2.2.4 and 2.2.5.)
If high-release processes or experiments are carried out during normal operation, they should be accompanied by rigorous meteorological control and the meteorological information used as a guide to radiological measurements in the environment of the site.

The results mentioned above have to be developed in most cases with the assistance of dispersion models.

1.4.1.5 Emergency situations

The development of the meteorological part of the NPP emergency plan has been reviewed above. This development has to be made before the start of normal operation and the system must be operative during the whole NPP lifetime.

In an emergency situation, it is necessary to take quickly the following steps:

(a) Ascertain the amount, duration and height of the release;
(b) Ascertain the current and future weather at the site;
(c) Use these results to determine the current and future contamination field in the environment;
(d) Guided by these results, perform direct radiological measurements in the environment;
(e) Based on the information obtained in the steps (a) to (d) above, decide which measures to take at the nuclear plant and in the region contaminated.

The current weather conditions have to be described by a set of key meteorological parameters. Which are relevant depends on the height of the release and in some cases also the type of weather. To maintain the emergency preparedness, the current key parameter values must be recorded continuously and kept available in the reactor control room during the NPP lifetime. Parallel transmission of the data to a weather service and an authority responsible for emergency preparedness is desirable (see further section 2.2.5).

The current values of the key data have to be used in a meteorological system in order to provide a fast indication of the path and dispersion of the release and the resulting contamination field in the environment. At a complicated site, a larger number of key parameters must be recorded, the character of which depends on the type of site: if it is one in a deep valley with other, lateral valleys, it may be necessary to use wind data in these valleys; at a coastal site, it may be necessary to use temperature and wind data at certain inland stations.

In an emergency, forecasts should be made by a weather service and interpreted in co-operation with the emergency headquarters. Forecasts should be made on the relevant key parameters and yield areas which will be contaminated some hours later. The forecaster must be thoroughly familiar with the local meteorology of the site.
Once an emergency is over, it may be necessary to analyse the consequences of the release. The meteorological data which were valid for the period of the release should be critically re-examined as well as the applicability of the dispersion models used. The radiological data collected during or after the release should be used in a critical way in order to check and validate the dispersion-model calculations. It is possible to obtain a picture of the areas contaminated and their degree of contamination as well as to estimate the magnitude of the release. This post facto analysis must be made, taking thorough account of the particular meteorological conditions at the site.

1.4.2 Review of problems occurring at various kinds of site

1.4.2.1 Diffusion characteristics

In regions with complex topography, water surfaces or built-up areas, the analysis of atmospheric diffusion is very difficult. Because of the great variety of conditions, a generalized treatment is not possible, since the flows will be extremely site-dependent. Reliance should be placed on detailed studies such as those from multiple meteorological towers and tracer studies.

Relevant atmospheric dispersion models will be discussed in section 2.1.6.

Examples of sites with special effects on atmospheric diffusion are:

(a) Sites in complex terrain such as:
   (i) Narrow valleys;
   (ii) Hills;

(b) Coastal sites in general, and especially those with:
   (i) Complex topography e.g. a mountain or ridge inland;
   (ii) An island beyond;
   (iii) Another coast beyond the water;

(c) Sites not far from built-up areas.

The effects of these types of site will be discussed below.

Examples of local meteorological effects in regions of complex topography are:

(a) Mountain and valley winds caused by heating or cooling of air on mountain slopes;

(b) Föhn winds with warm and dry descending air in the lee of a mountain or ridge;

(c) Increased cloudiness and precipitation owing to orographic effects, i.e. air forced upwards along a mountain slope;
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(d) Channeled flows in valleys;

(e) Persistent stable layers in low terrain.

In a valley, for example, potential for the transport and dilution of air pollutants is small because persistent inversions may occur. A radioactive release should then stay in the valley for a long time. Winds in valleys tend to be channeled up- or down-valley. The up-valley winds are generally associated with unstable and down-valley winds with stable meteorological conditions.

As an example of terrain-influenced flow, Figure 1 comprises a map with stability mean wind roses from a meteorological investigation lasting 2.5 years at a reactor site in hilly terrain.

Only cases with ground-based inversion have been selected. Two wind roses are given from the main mast at heights of 36 and 122 m. Wind roses from the ten-metre level of five surrounding meteorological stations are also given. They are situated in a valley extending SSW-NNE and a marked terrain influence on the wind roses can be seen. The wind roses from 10 and 36 m indicate the possible travel directions of releases in the valley and from the chimney respectively. The reactor was built in a room excavated within a mountain.

A release in a valley may, especially in inversion conditions, flow slowly down the valley and can later change its direction of movement when it finds its way into the general prevailing wind. In fact, the local direction of the wind in a valley may well be opposite to the prevailing wind above the mountain ridges. In such a case, in an emergency, the consequences of using current wind data from a nearby airport may be catastrophic for predicting the direction of movement of the release in a valley.

In the wake of a mountain or ridge, the air often descends and this will cause the undesired downwash of a plume.

In some weather situations, and at sites with only slightly complex terrain, the dispersion pattern can be quite complicated. The photograph in Figure 2 shows the spread of a smoke release in a strong ground-based inversion: the site is a coastal one and the hills and ridges are only five to ten metres high.

Complicated meteorological effects occur at coastal sites even if the topography is quite flat. Such effects include:

(a) Land- and sea-breeze effects caused by unequal heating or cooling of the water and land surfaces;

(b) Building-up of an internal boundary layer as the air blows over the "new" surface. This holds also for inland sites near a marked boundary between two regions of different ground roughness (See Munro and Oke, 1975);

(c) Systematic vertical motions in air which has passed a coastline. Large descending motions are likely to occur in air flowing from warm land out over colder water.
Figure 1 - Map of the terrain around a reactor site. Wind roses for cases of ground-based inversion have been inserted.
Figure 2 - Diffusion in extremely strong ground-based inversion
A release which has drifted out over the water can later move landwards and strike the coast at some distance from the site if a sea breeze has started but also in a general change of wind direction. If the sea-breeze circulation is well-developed and the prevailing wind is weak, a release which has at first travelled inland with the sea breeze may later travel aloft out to sea and strike the coastline coming from the sea.

At a coastal site, the values of dispersion parameters (for use in a diffusion model) are usually based on observations or measurements made in the air mass over the site. When the air leaves the coastline, the values of the dispersion parameters may change, owing to the build-up of a new boundary layer. As pointed out above, this effect can also be present at an inland site.

In suitable weather conditions, an elevated release will travel over water in a thin concentrated layer. When arriving over a land mass, the plume may be diffused vertically down to the ground, especially if the land mass is rough or has a structure of heat sources creating buoyant turbulence. In a city, for example, high concentrations may result from a somewhat distant source beyond a water surface.

The descending motions mentioned under item (c) above may appreciably increase the concentrations occurring on islands outside a source at the coastline. These effects have been discussed by Briggs (1975) and Angell et al. (1975).

Built-up areas also influence the diffusion conditions. One such effect has been mentioned above. Others include convergent air motions and circulations over cities where pollutants may accumulate. A review of urban meteorology has been given by Oke (1974).

Regard must be made to deposition of radioactive material. Both dry and wet deposition may be strongly site-dependent. As pointed out in IAEA (1980), precipitation is not always widespread and may be patchy. The local orographically influenced precipitation pattern may expose areas on mountain slopes to wet deposition. In showery conditions, a radioactive release may remain undepleted for some distance and then a strong fall-out will occur because of the intense precipitation falling through the radioactive plume. This is probably the weather situation which can give the largest fall-out per unit surface area some distance away.

The general diffusion conditions are also variable from one climatic region to another. The frequencies of unfavourable values of air-pollution dispersion indices such as wind speed and mixing height (or combinations thereof) may vary considerably. Such variations have primarily been established in studies of air-pollution potentials, where various regions of a country have been compared. The most important data used in these studies are radiosonde statistics. Large variations between different regions in the frequency of low mixing heights have been found. (See Holzworth, 1972.)

Such data can provide, primarily, information on the air-pollution potential for spread over mesoscale distances (10-300 km). Local diffusion conditions vary from one region to another and, naturally, between various parts of the world. The frequency indicator of various classes of turbulence (which can give values of the dispersion parameters) vary according to the climatic region. The frequency of unstable conditions, therefore, is generally higher in low rather than high latitudes.
1.4.2.2 Extreme meteorological conditions

The occurrence of extreme meteorological conditions (strong wind, intense rainfall, etc.) as well as extreme phenomena (tornadoes and hurricanes) varies considerably throughout the world. In some parts, tornadoes and hurricanes do not occur and strong winds, etc., arise from the "common weather", where cyclones, fronts and thunderstorms play the major role.

In all parts of the world, the occurrence of extreme meteorological conditions has to be studied. In certain exposed sites, the consequences of a not-too-heavy storm may be severe. It must be emphasized that a totally different type of information is needed to evaluate the effects of extreme meteorological conditions as compared to diffusion problems. There is a qualitative difference between these two kinds of information with the result that even quite satisfactory information on diffusion conditions may be useless for the evaluation of extreme meteorological conditions.

The kind of information needed to evaluate diffusion conditions is similar whatever the climatic region of site. On the other hand, the evaluation of extreme meteorological conditions requires a different and more specific kind of information according to climatic region and kind of site. Thus, the duration, intensity and character of a tropical cyclone may greatly depend on the region studied. In addition, even in the same climatic region, the consequences of extreme meteorological conditions may be different in rural and urban areas, e.g. as regards runoff conditions.

Potential consequences of man-made constructions may be great. In the case of a dam upstream of an NPP sited in a valley, for example, the runoff of heavy rainfall is directed by the forestation of the areas upstream. There is a need, therefore, for information on land use in addition to climatic data.

In coastal sites in some parts of the world, the flooding effects of the tide must be added to the effects of a storm. These effects are treated in Volume II of this Technical Note.

In IAEA (1984) methods are given for determining NPP design bases for occurrences of specific meteorological phenomena such as tornadoes. Methods are also provided for determining extreme values for atmospheric variables such as temperature.

Chapter 3 of this present volume describes the kind of information that is needed in different climatic regions of the world in order to assess the effects of extreme meteorological conditions.
CHAPTER 2

PRACTICAL GUIDANCE FOR METEOROLOGISTS IN CHARGE OF THE METEOROLOGICAL ASSESSMENTS AND CONTINUING SERVICES

2.1 GENERAL FRAME AND TOOLS

At any given site, various types of investigation have to be carried out according to the stages of development treated in sections 1.2 and 2.2. As mentioned in section 1.1, the objectives of the meteorological part are to provide the meteorological information and assistance needed in these stages of development. In this section, the general principles and factors common to the various stages of development will be discussed. As mentioned in Chapter 1 (see section 1.4.1), there are two main purposes of a local meteorological investigation at an NPP site:

(a) Evaluation of diffusion in normal NPP operation; and

(b) Evaluation of diffusion in emergency situations.

(a) will be achieved by making meteorological measurements during periods covering a wide range of diffusion conditions and by determining the average frequencies of these conditions. This is usually solved by making special continuous measurements during one year or more. Later, these data have to be used in diffusion models.

(b) will be achieved by using data from the special continuous measurements and also data from additional special case-study measurements of diffusion in complicated weather situations. In using these two kinds of data for establishing the meteorological part of the emergency service for operation of the NPP, a minimum number of key parameters are obtained, sufficient for describing the spread of an emergency release. These key parameters have to be recorded and the values made easily accessible during the lifetime of the NPP.

In order to achieve these goals, expertise is necessary in meteorological measurements, data processing and atmospheric diffusion (see Chapter 1) as well as in the following:

- Meteorological instruments and one or more instrument towers;
- Data-transmission and -collection systems,
- Data-processing techniques;
- Diffusion models;
- Computers and computer programs.

In some cases, remote-sensing equipment may be useful. The types and requirements of these skills will be described in the following sections.
In estimating the effects of airborne radioactive releases, atmospheric dispersion models can be used only as one step in the process. Usually, such a model is used for evaluating the following features:

(a) The concentration near ground-level;
(b) The vertical concentration profile;
(c) The deposition on the Earth's surface.

As a second step, the results of (a) can be used to calculate the exposure or the integral of the concentration over a specified time interval. The results of (b) can be used to compute the external radiation from a passing cloud.

Some kinds of emergency releases are supposed to contain a large number of long-lived radioactive nuclides. This means that the radioactive fall-out at the Earth's surface (see (c) above) may cause an increased level of radiation, compared to the background level, which may last for many years after the emergency. These aspects are treated in greater detail in Slade (1968).

Before proceeding to the final step, i.e. calculating the dose equivalent, the radio-isotopes involved must be specified and, if possible, their chemical form and their appearance such as air concentration or layer deposited on the surface and the material exposed. (See ICRP, 1977 and 1979.)

2.1.1 How to plan and implement a local meteorological investigation

The meteorological investigation must be planned well in advance. The types of measurement must be chosen according to the type of site (see Chapter 1).

During the site survey (comparison between various alternative sites), it is necessary to study data from routine weather stations (see further section 2.2.1.2). The usual way is to compare statistics giving the air-pollution potential in various regions. In doing so, a stability classification scheme (based on Pasquill's original work) is usually applied to standard surface-weather data. It is also possible to compare various regions using radiosonde data. In the types of comparison mentioned above, due account should be made of local differences in terrain structure and vicinity to water surfaces. It is advantageous to make a plan for the possible future special measurements at each alternative site. Thus, when the final site has been selected, decisions concerning instruments and the ordering thereof will be rendered faster.

The special continuous measurements should start as early as possible, so that they can be utilized for designing the plant, e.g. determination of chimney heights. Sufficient material should be available for the site to be fully characterized.

In order to obtain more realistic diffusion conditions, it is preferable not to make the special case-study measurements, e.g. smoke studies in inversion conditions, until the main buildings of the plant have been erected. On the other hand, the emergency plan (including the meteorological part) has to be complete before the reactor is put into operation.
The emergency plan will demand certain key meteorological parameters (selected from the continuous data) to be recorded permanently during the lifetime of the NPP. These key parameters can be selected only after a thorough analysis of the case-study measurements and the continuous data.

When the applicant has decided upon the local siting and external design of the NPP structures, the meteorological project leader must be informed immediately, since the planning of the local meteorological investigation is directly dependent thereon. Similarly, if the applicant changes his plans, the meteorologist must be informed immediately. For example, after some time, the planned position of a cooling tower could be changed. If the position of the meteorological mast is not changed accordingly, it may well happen that the continuous mast data, which normally provide key information for emergency preparedness, become useless because of disturbances from the cooling-tower wake. Generally, it is necessary for the meteorologist to be cautious about such disturbing effects on the meteorological measurements.

The following questions have to be answered in planning a meteorological investigation at a new NPP site:

(a) What type of continuous measurements should be made?
(b) Is more than one meteorological mast necessary?
(c) What levels should be chosen for the meteorological sensors?
(d) Is there a need for surrounding simpler sites with other meteorological stations providing concurrent measurements?
(e) What sites should be chosen for the mast and stations?
(f) What can be said about the necessary length of the local meteorological investigation?
(g) Is there a need for special measurements or case-studies?
(h) What is the accuracy necessary in the various measurements and how will the data be presented?

Some general answers to these questions are given below:

(a) The type of measurement is dependent on the practical method chosen to evaluate dispersion. An important task here is the determination of stability in terms of or as a function of one or more meteorological parameters or turbulence indicators. These procedures are inherent in the type of diffusion model which can be used. It is, therefore, important to choose the type of model as early as possible in view of site characteristics and practical circumstances (see section 2.1.6 and 2.2). The methods using the standard deviation of wind direction for determining the values of the
Types and positioning of sensors will be discussed in section 2.1.4. Some comments on the sampling and averaging of data will be given in section 2.1.2.3:

(b) It is considered necessary to have at every site at least one meteorological mast giving continuous data. In complicated sites, two or more masts may be necessary. The site terrain must be thoroughly examined before planning the meteorological investigation and the number, type and position of the meteorological stations must be decided. In some cases, measurements should be made at more than one location; for example, where effects of sea breeze may be important, consideration should be given to an additional meteorological mast farther inland for evaluating the overland sea-breeze diffusion régime characteristics;

(c) In general, the meteorological sensors should operate at heights representative for the plume.

At a site where the atmospheric conditions affecting dispersion are not complex (complex and simple sites are discussed in section 1.4.2.1) and important changes in wind speed or direction within a limited space do not occur, it is sufficient to record wind speed and direction at the following levels measured at a single mast:

(1) At 10 m for comparing and correlating the wind data at the site with those of the national meteorological station network; and

(11) At certain levels covering the plume elevation in various atmospheric conditions. This is determined in each case by the release height and the plume rise.

As mentioned above, various practical methods exist to evaluate dispersion. Each method requires meteorological data of some kind, such as temperature gradient (from temperature at two or more levels) or wind-direction fluctuations at one level. These methods will be discussed in section 2.1.6.2.

The meteorological mast must be high enough for information to be collected in a height interval covering the plume. However, at a complex site, information may be needed from higher levels. In such a case and in that of a very tall chimney, the mast may become very expensive. Sodar may then
be used to give wind data at sufficiently high levels. Complementary case studies may give information on what equipment and siting should be used.

At a complex site, a larger number of measuring levels are required than at a simple site. It is often impossible at the outset to determine the minimum number of levels necessary for the permanent measurements for the emergency service. It may be advantageous to start with a rather extensive measuring programme consisting of both continuous measurements at many levels and case-study measurements. These will be evaluated before enacting the emergency plan and selecting the final key parameters and the minimum necessary measuring levels for the emergency service (see section 2.2.5);

(d) In simple sites, no surrounding meteorological stations will be necessary. In coastal sites, such stations located at various distances inland are of great value to evaluate, for example, the penetration of sea breezes. In a valley such stations may give valuable data on circulation systems and valley winds. Study of the data taken in the special measurements may show that fewer or no additional stations are necessary for the emergency service;

(e) Generally, the main meteorological mast should be sited at approximately the same elevation as the finished plant grade. All meteorological masts or stations should be sited so that reactor buildings, cooling towers or other local structures will have little or no influence on the measurements. Especially in the case of a wind-direction variance sensor, it must be ensured that the record will not be disturbed by turbulence from local structures (see also section 2.1.4 and IAEA, 1980);

(f) In simple sites, the local meteorological investigation must last for a minimum of one year. It is considered necessary that all seasons of the year are covered.

As is pointed out in section 2.1.3.1, more complicated sites may require a longer series of continuous data. At the outset, when trying to judge the necessary length of the special continuous measurements, the historical data from nearby routine synoptic and climatological stations must be studied. If there are other, similar nuclear sites with special measurements, the earlier comparisons made there may be utilized. At complicated sites, conclusions about the period necessary for collecting data from nearby routine meteorological stations should be drawn only with caution. Thus, meteorological data in a series of years from a nearby routine station may show rather similar characteristics from year to year, whilst data from the site itself may show larger year-to-year variations.
In some of these cases, further years of continuous measurements will be necessary. In others, data from different masts or case-studies will give the best information (see items (b) and (h)).

The decision about the length of the special continuous measurements involves combining several years of data from a routine station. This will be discussed further in section 2.1.3.2. It would be advantageous to make an interim study after, say, two years of the continuous data in order to judge if more data will be needed. For example, at a simple site, the results may indicate that the conditions are much the same as in another similar site studied earlier. An important conclusion is, therefore, that the same period of continuous data is needed as for the earlier site. In making the interim study, it must be realized that the need for more data depends on the representativeness of those of the first period.

(g) There are cases where the continuous mast measurements should be complemented and compared with special concurrent measurements. These short-term data have to be compared with the long-term data from the mast and routine weather data (section 2.1.3.2) in order to obtain a relation to be used operationally in emergency situations, for example. Some of these aspects will be discussed below.

At each site there is a stability limit, such that for stable conditions there is an irregular picture of dispersion of a ground-level or low-level release from a building. The cloud will then spread as a more or less irregular disk. The cloud will slowly follow valleys and remain in low terrain. The cloud may remain in the neighbourhood of the site for hours. At a flat site, the stability limit is very high, i.e. strong inversion. In hilly terrain, or in a valley, only slightly stable conditions are sufficient to obtain an irregular diffusion pattern.

At every site at least 10 case-studies should be made for the purpose of characterizing the flow during stable or weak wind conditions. These problems are treated in greater detail in section 2.2.5.

There may be reasons for investigating the path of a release into a sea-breeze circulation; at a coastal site, a release which has drifted out to the sea may later return to the coast.

Special studies of transport and diffusion in the 100 - 500 m layer should be made, if it is considered essential to evaluate problems of very great emergencies when hot plumes with thermal rise are released.

In these and case-study situations, soundings and balloon tracings (tetroons) and sodar measurements over continuous periods can be used (see section 2.1.5). At a coastal site,
a sodar operating several kilometres inland can give information about the diffusion conditions and their variation with distance inland.

The need for special measurements should be judged by an experienced meteorologist, who may merely express an opinion thereon. If the site has special features, however, such as complex terrain, or is in proximity to a coastline, giving reason to suppose that the meteorological conditions are complicated, then the meteorologist should already press strongly for special measurements in the preselection stage:

(h) Questions about accuracy and methods of presentation will be discussed below. It is strongly recommended that decisions about accuracy and data presentation are made at the start, when the meteorological investigation is planned.

2.1.2 Data collection

At the site-survey stage, usually only routine weather data are available, but all existing data sources should be considered. In the later stages, a local meteorological investigation will be required at the site. The bases of such a local meteorological investigation are:

(a) Data defining the following parameters:

(i) Air temperature;
(ii) Airflow (wind direction, associated speed and duration);
(iii) Low-level mixing height;
(iv) Precipitation (for estimation of deposition and depletion);
(v) Humidity.

These data should be obtained concurrently to determine their frequency and duration;

(b) Data required for indication of turbulence:

(i) Air temperature and temperature-lapse rate;
(ii) Solar radiation or cloud amount during the day and cloud amount or net radiation at night;
(iii) Wind-direction fluctuations;
(iv) Wind speed at different heights.

(One or more of the above may be required, depending on the model chosen.)
2.1.2.1 **Sources of data**

During site preselection the following sources of data may be available:

(a) Synoptic weather data or climatological data from surface stations;

(b) Radiosonde data;

(c) Sometimes, the national Meteorological Service or another institution has collected or presented data which might be used to compare air-pollution potential in various regions. The influence of local features (valleys, mountains, coast, etc.) on diffusion, strong winds or strong precipitation may have been investigated. Useful mast or other data may exist from investigations at earlier NPP sites or for other purposes as well as weather radars with facilities for precipitation measurements (see Collier, 1981).

The data under (a) and (b) will be termed *routine meteorological data*. In some countries, surface data are collected by an automatic station network (see section 2.1.2.3). In subsequent stages, data will be available from the local meteorological investigation. For the special continuous measurements extending over one year or more, data will be provided by sensors on a mast (and in some cases surrounding stations or sodars) and transmitted onto magnetic tapes or strip charts. In the special case-study measurements, data will be taken in complicated weather situations (see sections 2.1.1 and 2.2.5).

The part of the continuous-measurement data which will be selected as key meteorological data for the emergency service (see section 2.2.5) must be accessible at all times in the reactor control room for use during plant operation. Data for the latest hours must be directly visible on a strip chart, alphanumerical or graphical display terminal or typewriter output. For emergency service it is also possible to use automated systems as microcomputers or minicomputers (see section 2.2.5). In general, the meteorological data can be directly used and stored in a special computer or in the main computer of the NPP.

Meteorological instruments and systems of data transmission and acquisition should be selected and maintained (see section 2.1.4) so as to provide at least an annual 90 per cent joint data recovery. Annual 90 per cent joint recovery means that values of all measured meteorological parameters should exist concurrently 90 per cent of the time in one year. The use of redundant sensors and/or recorders may be another way of achieving the 90 per cent data recovery goal.

If the data from a meteorological mast have to be used for estimating ambient concentrations in potential emergency cases, it is preferable to have instantaneous values or short-term averages taken at regular time intervals within each hour. Data on wind direction, wind speed and temperature profile should then be collected a minimum number of times per hour. Usually, at least 12 sets of values per hour should be taken (i.e. every five minutes).
It is necessary to measure a set of values in a vertical temperature profile in a rapid sequence, i.e. within a time period of the order of 0.1 T where T is the time constant of the temperature sensors (see WMO, 1983(a)). This is because the turbulent temperature fluctuations in time are often much larger than the differences between various levels at any one moment. If fast-response wind vanes are used (see section 2.1.6.2), there should be a continuous record of the fluctuations.

The requirements of collection frequency and averaging of data, etc. are discussed further in section 2.1.3.1. The instruments must be designed so as to fulfil these requirements.

2.1.2.2 Accuracy of data

The minimum accuracy required of instruments to be used in meteorological studies of atmospheric dispersion in NPP sites is given in IAEA (1980).

2.1.2.3 Technical handling of data

During the local meteorological investigation, the continuous data from the masts and surrounding simpler stations (if any) should be subject to quality control and validation. Data should be checked continuously at least once a week both by internal comparison and by comparison with external data. Continuous data-quality control and validation take considerable time and effort but are worthwhile since the failures discovered in sensors, transmission and acquisition systems can be corrected at an early stage and thus will no longer cause errors in the records. The correction of such errors already present in the material is more difficult and expensive. A complete programme for data-quality control and validation covers regular checks of data just stored in the final medium and also regular maintenance of the sensors, transmission and acquisition systems.

The following action should be taken:

(a) Internal comparison of the data: this should be made by simple manual comparisons and also by statistical methods at least once a week. If a data-logger with a programmable microprocessor is used for the measurement, some data quality-control algorithms can be used to extract a set of fresh data for specially programmed continuous checks. This is very effective and quick but has a real value only if the data to be checked are taken from the final medium such as the magnetic tape or disk. Thus, for data from a high mast, there could be an erroneous message in, for example, the cases when:

(i) Wind speed does not increase with height;

(ii) There is too large a deviation in a comparison between two wind-speed sensors at the same level, at wind directions when both sensors are similarly exposed to the wind;
(iii) A temperature or wind-speed value diverges more than 1°C (5 m s⁻¹) from both the preceding and following values;

(iv) The reference voltages in the data-logging system are not within prescribed limits.

Statistical error checks may also be made automatically in recording the data. Such checks are discussed in WMO (1968);

(b) Comparison of recorded data with external data such as routine weather data. It is desirable for a person trained in weather observations to make these checks. Maintenance covers quick repair and correction of failures discovered in sensors and transmission or acquisition systems. A regular technical service of these systems is also necessary (see sections 1.2.2 and 2.1.4.4).

Regional Air Pollution Study (Hern and Taterka, 1977) contains details involved in quality control from an operational point of view.

All continuous data should be stored at least every hour in an easily accessible manner, e.g. on magnetic tape, as the data may have to be used repeatedly for various purposes such as diffusion-model calculations.

Storage of hourly average values in a well-documented manner is usually sufficient for most model applications but for certain applications, such as investigations of gustiness or other special climatological studies, storage of each value recorded is necessary. It may also be considered favourable in general to store the original data and, therefore, advantageous to store both the original data (e.g. five-minute values) and the hourly averages formed from them. The techniques to form hourly averages from the originally measured values are discussed in section 2.1.3.

If the routine data are taken from automatic weather stations, they should be integrated with the data from the special continuous measurements into one system, thus making all meteorological data basically computer-accessible. Advantages of such a system are that:

(a) The comparison of the time series from the routine and special measurements is greatly facilitated;

(b) The use of all data for dispersion calculations is facilitated;

(c) Error checking by comparison of the different types of data can be made automatically and continuously.

2.1.3 Data processing

In section 2.1.2 the method of collecting data to obtain appropriate hourly values was described. The calculation of such values is discussed below. The hourly data must be treated such that the results can be used for evaluating the diffusion characteristics both in normal operation and in the case of an emergency release.
It may be necessary to analyse data in case-studies with a finer sampling rate than that of once an hour. For example, there may be a sudden change of wind direction due to the passage of a sea-breeze front (see also section 2.2.5).

- NPP releases can be divided into the following categories:
  - Routine releases;
  - Emergency releases.

Statistics to be used for estimating diffusion of these releases can be divided into:

(a) General climatological statistics;
(b) Statistics for use in diffusion models;
(c) Statistics of results from diffusion models.

Important parts of these statistics have to be generated from the data taken on an hourly basis in the special continuous measurements of most sites, the analyses of emergency releases have to use data from case-studies in poor dispersion conditions.

2.1.3.1 Statistical techniques

First, the determination of average values of parameters over regular (usually hourly) intervals will be discussed. Obtaining good hourly average values requires instruments which integrate (accumulate) over an hour. This may be the case for the variables' acquired wind path, radiation energy or precipitation.

When the instruments give instantaneous values (with different time constants for different instrument types - see section 2.1.4), the calculation of the hourly average value can be made on a sampling basis only. This can be done in various ways, depending on the desired accuracy of the average value.

Sometimes, there are given N values taken at a constant time interval, such as five minutes, and from these the arithmetic mean of these values is \( \bar{x} \). The corresponding error of the hourly average value will then be larger and in some cases much larger than \( \sigma / \sqrt{N} \).

This expression for the error (see WMO, 1966(a) and Panofsky and Brier, 1958) holds only when the N values used are independent of each other. The correct factor with which to reduce N cannot be stated generally. The reduction will depend on the character of the autocorrelation function for the meteorological element in question and also on the time constant of the sensor and recording system used.

For wind, temperature (including differences) and humidity, it is possible to form an average for a 10 - 15 minute period and to use this as an estimate of the one-hour average. Because of the large variation possible within an hour, this method must be used with care.
If wind direction is given by a scale with a jump (e.g. by values ranging from 0° to 359°) there is a difficulty in calculating average wind directions, when the direction is close to north (0°). Before averaging, account must be taken of this, e.g. by transforming a set of given directions (e.g. 359°, 350°, 001° to 359°, 350°, 361°). Another way of solving the problem is to form averages of individual wind vectors, taking into consideration both wind direction and speed. With the use of certain models, it is preferable to use such vector representation.

There are methods for estimating the plume standard deviation parameters $\sigma_y$ and $\sigma_z$ which use a record of the fluctuations of wind direction at plume level. Methods to obtain such parameter values representing sampling times of one hour are discussed in section 2.1.6.2.

The statistical techniques as regards section 2.1.3, item (a), are directly related to the method of presentation and these aspects are discussed in section 2.1.3.3. In estimating the uncertainty of a frequency table or histogram, it is possible to use the statistical parameters in the frequency distribution, such as the mean, standard deviation, variance and skewness (see WMO, 1966(a)). This generally requires a random sample, i.e. the data collected are mutually independent, but this, unfortunately, is seldom the case for meteorological data.

About item (b) it should be mentioned that, usually, the statistics for use in diffusion models are based on hourly values. Most diffusion models in practical use such as the Gaussian models base their calculations on hourly meteorological data (or shorter) and furnish concentration values for the same sampling time.

For item (c), to calculate concentration statistics of hourly values during, for example, one year, use can be made of tables showing frequencies of various meteorological classes, such as wind speed, wind direction and stability. If rainout or washout is treated, precipitation classes should also be taken into account. Such tables are given in IAEA (1980). For a fixed receptor point, the model can calculate the concentration for each meteorological class. Using the frequencies of these classes for a specified period makes the relevant frequency distribution of hourly concentration values possible. This method will work only when the meteorological classes are sufficiently small, such as wind direction to 2° etc., otherwise the frequency distribution will miss the critically high concentrations, which are only possible in very restricted meteorological conditions. This method can also be used to calculate the long-term (one or more years) mean concentration in a fixed location. (See Slade, 1968 and Högström and Smedman-Högström, 1978.)

In consequence, analyses for routine and emergency releases often need concentration statistics for sampling times longer than one hour. Some aspects of these problems are treated in IAEA (1980). Meteorological statistics cannot be translated by model calculations into concentration statistics as simply as described above. If, for example, statistics of average concentrations over 24 hours are required, it is necessary in principle to start by listing hourly meteorological data consecutively. If the model calculates the concentration for each consecutive hour during, for instance, a year, then it will be possible to form statistics of concentrations averaged over 24 hours. Such a treatment generally needs a computer.
In a fixed location in the vicinity of a continuous source or source complex, a limit concentration value for a given percentile can be calculated as a function of the sampling time (see example in section 2.2.4.5). This is also possible for a point at a fixed distance moving so that, for each sampling period, it is in the sector of the most frequent wind direction. From such a curve the probability may be inferred that a certain concentration will be exceeded for a given sampling time.

These functions depend, in a complex way, on release height, number and grouping of sources, the location of the receptor point (fixed or moving), and climatic conditions such as the frequency and persistence of wind direction. However, in performing model calculations on consecutive meteorological data, it will be found, for simple sites (e.g. sites with homogeneous and non-complicated terrain), that the average concentration values over the longer sampling periods, e.g. one or two months, will show very small mutual scatter. A meteorological investigation over one year may well be sufficient for obtaining meteorological statistics for diffusion purposes.

In a situation where the curves showing concentration as a function of sampling time will level out to a constant concentration value, for sampling times of the order of two months and more, the following useful consequence arises: frequency data of meteorological classes for one year (thus no consecutive data) are sufficient to interpolate approximate curves for sampling times between one hour and one year. This interpolation must be made whilst being aware of the general shape of the curve: its asymptotic behaviour for example. Concentration values for one-hour sampling times and the concentration value for the asymptote have to be calculated at the beginning.

At complicated sites, one year of data will not suffice, since even the mean yearly concentrations may vary. The asymptotic value may be reached for a sampling time longer than one year. It is not easy to establish this without making long-term special measurements at the site. The use of statistics of standard weather data may lead to the wrong conclusions at complicated sites but data from multiple masts or case studies may give important information (see also Chapter 1 and section 2.1.1).

2.1.3.2 Combining different sets of data

The data from special continuous measurements, usually recorded hourly during at least one year, should be related to a series of several years of data from one or more nearby routine weather stations in order to determine the long-term diffusion conditions (see also sections 2.1.1 and 2.1.3.1).

The data from the special continuous measurements are of a character directly suited for evaluating dispersion. They have been designed for use in a special stability-classification scheme intended to fit a diffusion model. Data from a routine weather station can also be used for stability classification systems like methods of the Pasquill-Gifford type. For the period of the special continuous measurements, it is possible to compare the stability classes formed from the mast data with the classes derived from the routine station. This can provide a simple tool for computing approximate long-term concentration statistics. Before performing that study, it must be confirmed that the routine station is suitably located and that its data are of sufficient quality. Limitations of methods of the
Pasquill-Gifford type should also be borne in mind in this context (see further section 2.1.6.2).

The data of the special continuous measurements at the site are usually recorded once an hour. Most weather stations, however, provide data every three hours or less and this difference in relation to the continuous data has to be taken into account. Data taken regularly every six hours, for example, do not represent the whole night and day, since some hours with specific diffusion conditions, such as the hours around sunrise in some parts of the year, will not be covered. This effect may be compensated for, on a long-term basis, by comparing the data from the period with concurrent measurements at the NPP site and at the weather station.

General methods, from a climatological point of view, for solving the problems of reducing data from different weather stations to a common period are given in WMO (1983(b)).

If (a) continuous data are taken at a NPP site during one year, for example, and (b) routine data are taken at a nearby weather station over several years, it may be possible to extrapolate long-term weather statistics representative for the NPP site. Judging what is the necessary and adequate length of the special continuous measurements at the site is not a minor matter.

The concept of obtaining relevant climate statistics at the site is based on the fact that a relationship can be established between the high-density data from the site ($y_n(t)$) and conventional meteorological data from nearby routine stations ($x_n(t)$).

Hence:

$$y_n(t) = f(x_n(t)) + \varepsilon_n(t)$$

where: $\varepsilon_n(t) = \text{the expected error}$.

$y_n(t)$ and $x_n(t)$ would not necessarily be directly measured quantities but suitable transformations, e.g. stability classes estimated by bulk formulas.

Using the relationship established, the long series from the routine meteorological station can be used to estimate climate statistics at the site. If the model structure is linear and known a priori, an optimal measurement length can be stated (Mehra, 1976). This is often not the case, however, and no general rule for optimal sampling length can be applied. In the latter case, some guidance can be given but would not be strictly objective. It is fairly easy to suggest what is the necessary length but more difficult to judge what is an adequate period:

(a) The absolute minimum period must be considered as one year. This is the shortest necessary time in which to obtain a representative sample, i.e. including the different seasons;

(b) The sampling period must be made as long as possible. Since measurements, data collecting and processing are costly, the financial constraints will naturally set the upper limit;
Replicate sampling (i.e. using longer and longer sampling periods and comparing the resulting error in the model as a function of its parameters and the sample length) might provide adequate information. The idea of forward-validating and cross-validating (Hjort and Holmqvist, 1981) would probably be useful;

Subjective criteria (i.e. criteria which might be difficult to specify in statistical terms) would have to be considered. Not every situation needing a judgement can be foreseen. For example, a year of measurements may contain so many extreme meteorological conditions that the year is not a representative sample;

If the site is considered as complex and the relation between routine meteorological statistics and the high-density data from the site is less well-defined than usual, then a basic data sample of more than one year might be necessary;

If a complete study has been made for one site, using model calculations based on the data from the special continuous measurements, it is possible, as a first approximation, to apply the result on another site provided that:

(i) Both sites are simple and similar;

(ii) The source configuration is similar.

A correction factor must then be applied, having regard to differences in factors such as release height. Also, a critical comparison of the meteorological statistics taken at the two sites must be made.

Various kinds of general meteorological statistics can be formed from the continuous mast data. Tables or diagrams can be given on a monthly, seasonal or annual basis or of the total period of measurements. The length and number of suitable periods for such divisions should depend on the climatological features, such as seasonal variations.

Examples of such statistical representations are:

(a) Wind tables or roses for an entire period or for a specified meteorological class. IAEA (1980) contains an example of a wind- and direction-frequency table for a specified class of stability and precipitation;

(b) Frequency tables or histograms of a variable, e.g. stability (here can be shown the number or percentage of cases (hours) in various intervals during a given period);

(c) Tables or histograms showing time series (the frequency of ground-based inversions at an NPP site can be shown for each month).
Various ways of presenting meteorological data are given in WMO (1983(b)). The presentation of results from diffusion models is treated in section 2.1.6.

2.1.4 Meteorological instruments for NPP purposes - siting and maintenance

IAEA (1980) contains general advice on how the sensors should be positioned in relation to terrain features in order to obtain data representative of the site conditions for later use in meteorological studies of atmospheric dispersion. This information is assumed to be known here as well as the required characteristics of the instrumentation system to be used. The WMO Guide to Meteorological Instruments and Methods of Observation (WMO-No. 8) describes various types of meteorological instruments and measuring methods.

It is extremely worthwhile to use best-quality equipment as regards mast, sensor holders, sensors, shieldings and transmission and logging devices since repair costs and the time-consuming and expensive correction of errors in the records are thereby reduced (see section 2.1.2.3). Preference should be given to equipment which has been sufficiently tested and which withstands long-term operation in difficult conditions.

2.1.4.1 Meteorological masts

The site of the mast should be chosen to minimize the influence of structures and natural obstacles on the meteorological measurements. In planning for the mast and its equipment, the following should be kept in mind:

(a) The mast dimensions must allow room for climbing and for installation work;

(b) The mast should be equipped with landings beneath the sensor levels in order to facilitate installation and maintenance work;

(c) In order to minimize turbulent wake effects on the wind sensors, the mast must be of an open type and the positions and dimensions of cable bearers must be chosen carefully. The positioning of a junction box at a height similar to that of a wind or temperature sensor must therefore be avoided. If an accuracy of wind data within ± 10 per cent in speed and ± 5° in direction is needed for the complete 360° of azimuth, the use of two sets of speed and direction sensors 180° apart must be considered. For recommendations concerning the mounting of wind sensors, see Gill, Olsson, Sela and Suda (1967);

(d) The presence of the mast has been found to affect downwind thermometers more than upwind ones, especially in strong incoming radiation (see Gash and Stewart, 1975). Thus, as stated above for the wind sensors, the use of two sets of temperature sensors 180° apart should be considered;

(e) Flexibility in the sensor bracket and sensor connection system is preferred to facilitate sensor-level alterations;
(f) At sites with heavy icing conditions, the sensors must be protected against falling ice by special shields;

(g) Heating of sensors with moving parts must be considered at sites with icing and hoar-frost conditions;

(h) Internal heating of junction boxes must be considered at moist sites or at low-signal levels (e.g. bridge-coupled temperature sensors);

(i) The mast and the guy wires must be satisfactorily earthed for protection against lightning;

(j) The junction box at the mast base or at the data-logger site must be equipped with lightning-surge dissipators (e.g. vacuum lightning protectors and/or solid-state transient suppressors).

It is also necessary to observe legislation concerning electrical installations and the protection of workers. Good planning may be obtained from the department of the telecommunications administration which deals with erecting masts.

2.1.4.2 Sensors

(a) Wind direction

The wind-direction vane consists of two subassemblies: the vane and the signal generator. To avoid position preference at low speeds, the vane must be well balanced and the vertical vane axis must be well adjusted.

A good vane with not too much overshoot and a reasonably fast response is characterized by a long vane arm with a proportionally short counter-weight arm. Care should be taken to ensure that the bearings and signal generator have low starting and running frictional torques. The choice of signal generator depends on the type of logger or recorder used. Potentiometers, torque transmitters, digital code disks, variable capacitors and inductors are often used.

Special fast-response wind vanes are sometimes used for determining the values of the diffusion parameters. The standard deviation of the wind direction can be calculated automatically on site from a fast record (see WMO, 1977). A brief description of some commercially available wind vanes is given by Mazzarella (1972);

(b) Wind speed

Cup and propeller anemometers are commonly used for the determination of wind speed and consist of two subassemblies: the rotor and the signal generator. The angular velocity of a cup rotor is directly proportional to the wind speed. Close to the starting threshold, however, deviations from linearity may occur. All cup anemometers
overestimate the wind-speed average since the cup rotor accelerates more quickly with an increase in wind than it decelerates in a decreasing wind (Schrenk, 1929). An examination of this matter shows that the difference of wind-speed average between various types of commercially available cup and propeller anemometers exposed to fluctuating winds is 10 per cent (Lamboley and Viton, 1977). It is therefore necessary to make a careful choice of wind-speed sensor to meet the sensor characteristics given in section 2.1.2.2. Calibration characteristics must also be used in processing data from the special continuous measurements.

A good cup rotor is characterized by:

(i) The semi-conical shape of its cups;
(ii) The beaded edges of the cups;
(iii) The large ratio of cup diameter to the diameter of the circle described by the cup centres;
(iv) Its light weight.

(Meteorological Office, UK, 1956)

The choice of signal generator depends on the type of logger or recorder used. Alternating- or direct-current generators, mechanical, optical or magnetic pulse generators are often used. Special three-dimensional anemometers are sometimes used for determining atmospheric turbulence structure (Hopkirk and Ravussin, 1976). Other types of anemometer are two- or three-dimensional sonic anemometers and vortex anemometers.

For short-time turbulence studies, a hot-wire anemometer can be used. This is a very sensitive instrument but, since the wire is rather fragile and the calibration not stable, the instrument can only be used for special short-term measurements during good weather conditions.

A brief description of some commercially available wind-speed sensors is given by Mazzarella (1972);

(c) Wind speed and direction measurement with sodar

With Doppler sodar, an active instrument using reflection of sound waves in turbulent layers of the atmosphere, it is possible to obtain wind profiles up to an altitude of 500 m. The range is limited by absorption of the acoustic waves in water vapour (typical range is 300 m with a height resolution of 20 m). The presence of turbulent air is required to obtain echoes from the different layers.

An intercomparison of sodar systems was performed in the Low-level Intercomparison Experiment, Boulder, Colorado, 1979
(see Kaimal et al., 1980). Another comparison of four systems is described by Gaynor et al. (1983). See also Gland (1982);

(d) Temperature and temperature difference

To fulfil the sensor characteristics given in section 2.1.2.2, it is necessary to use a motor-aspirated radiation shield of good quality in order to protect the sensor from solar and terrestrial radiation. The radiation effects of various types of thermometer shields are described by McKay and McTaggart-Cowan (1977).

Since continuous aspiration is required to ensure proper measurements, some failure-warning detector must be installed in the system. This failure detector is usually a flow-actuated vane with a reed switch whose contact will close whenever airflow ceases.

The platinum resistor sensor is recommended because of its calibration stability. The sensor can be bridge-coupled or constant-current-coupled in a four-lead connection. The four-lead connected sensor allows simpler installation and calibration. Observe that the calibration characteristics of each sensor must be used when processing data.

In temperature-difference measurements, there are advantages in recording the absolute temperatures of the levels and then calculating the differences. A system of direct recording is more difficult to calibrate when it is installed in the mast:

(e) Humidity

There are various types of humidity sensor, e.g. human-hair sensors, thin-film capacitors, lithium-chloride sensors, dry- and wet-bulb sensors. Generally applicable recommendations of a choice of sensor for NPP purposes cannot be given; the sensor type must be chosen individually, according to local conditions at the site. A detailed review of different techniques is given by Ruskin (1963);

(f) Precipitation

For automated systems, some type of tipping-bucket precipitation gauge is recommended. The output from the sensor is in general a reed switch or microswitch. The contact closures from the switch are counted by a digital counter. Some tipping-bucket sensors are also equipped with heaters for measurements during winter conditions. To reduce loss of the collected precipitation from evaporation it is necessary to equip the heaters with proportional temperature control;

(g) Solar radiation

Sensors for measuring solar-radiation energy can be classified as thermal detectors and photoelectric detectors.
In the thermal detector, the radiant energy is transferred into heat energy. The main types of thermal detectors are calorimeters, thermopiles and bolometers. For NPP purposes, the thermopile detector and the photoelectric detector are recommended: both have an electrical output. The spectral sensitivity of the thermopile detector, however, is less dependent on the wavelength of the radiation. A detailed description of solar-radiation sensors is given by Coolson (1975):

(h) Net radiation

There are many types of net radiometer but the most accurate type, the ventilated, unshielded radiometer, cannot be used for NPP purposes.

Shielded sensors with thermopiles are recommended. The blackened surfaces should be shielded by polyethylene hemispheres through which both long- and short-wave radiation can pass. It is recommended that the hemispheres be inflated by dry air or nitrogen gas to keep them free of condensation moisture. A detailed description of radiation sensors is given by Coolson (1975).

2.1.4.3 Data-logger and recorders

2.1.4.3.1 Planning the logging and display system

When planning the data-logging and display system it is important to pay attention to the local meteorological investigation in order to achieve a system suited both to special continuous measurements and the special case-study measurements. It is also important to consider the need for the sensors and the logging system. The accuracy and resolution of the logging system must be at least of the same class as the best sensor connected to the system. There are many loggers and recorders commercially available for industrial and scientific purposes. When choosing the equipment, the need for the following facilities must be considered:

(a) Surge protection;

(b) Suitable sensor interfaces in order to avoid loss of accuracy;

(c) Suitable number of analogue and digital inputs with sufficient resolution;

(d) Suitable scanning frequency, possibilities to change frequency, individual frequency for the sensors;

(e) Built-in check of scanner and amplifier functions;

(f) Possibilities to adapt sensor calibration curves;

(g) Suitable routines for calculation of averages, possibility to change averaging intervals;
Display terminal and (or) typewriter;

Display output (magnetic tape or disk) and on-line transmission to a central computer;

Possibilities to alter the logger system into a display system when the period of continuous measurements is finished and the emergency service measurement period starts;

Possibilities to connect the logger to a computer program for automatic evaluation of diffusion in normal NPP operation and in emergency situations.

An example of a measuring and display system for NPP purposes

Two identical, separated sensor systems, one connected to a microprocessor-controlled data-logger with magnetic tape-recorder output and a display terminal for operator communication, the other connected to a strip-chart recorder for back-up purposes. The magnetic tape-recording format must be compatible with the central computer;

When the final emergency plan is enacted and the key parameters and minimum measuring levels for the emergency service are chosen, the microprocessor logger is programmed to calculate and display corrected and averaged values to the key parameters;

The data from the latest hours are displayed on the display terminal, now sited in the reactor control room. The display terminal is either an alphanumerical or graphical CRT display. Data from the back-up system are recorded by the strip-chart recorder. The magnetic tape recorder is still connected to the system in order to store the key parameters.

Maintenance

The meteorological instruments and the logging equipment should be maintained to provide at least an annual 90 per cent data recovery. It is not possible to give any generally applicable recommendations; the maintenance programme for individual parts of the measurement system must be adapted to local weather conditions and to the recommendations of the manufacturers and suppliers of the equipment.

Maintenance operations should generally include:

Calibration of sensors;

Cleaning and lubrication of moving parts;

Cleaning of thermometers, radiation shields, radiation, humidity and precipitation sensors;

Checking the functions in the logging system.
2.1.5 Special measurement techniques

Remote-sensing techniques have been the subject of increasing interest in recent years. Some systems are already operational and commercially available for use in monitoring atmospheric parameters. Several new systems are expected to become available shortly, improving the possibilities of three-dimensional mapping of the atmosphere. Remote-sensing will facilitate continuous monitoring of atmospheric parameters, e.g. at an NPP site.

Remote-sensing from satellites has an indirect interest in connection with the siting and operation of NPPs, e.g. improved possibilities for accurate weather forecasting and monitoring regional impacts of releases from NPPs. (A summary and an extensive list of references regarding this latter aspect can be found in Kunhel et al., 1975; see also Collier, 1981.)

Laser techniques, including lidar (light detection and ranging) can be used for remote monitoring of aerosols and gases (released as tracers, for example), wind speed and direction and humidity in the lower atmosphere. Although still rather expensive and not generally available commercially, measuring systems based on laser techniques should be considered when planning meteorological investigations at NPP sites. A review of available techniques, including an extensive list of references can be found in Hinkley (1976).

Sodars (sound detection and ranging) are today in operational use for measuring the structure of the lower atmosphere. Sodars do not directly measure the temperature profile of the atmosphere but rather record continuous information about turbulent temperature fluctuations in the lower atmosphere. Most operational sodar systems in use are intended to monitor the mixing height on a continuous basis. With the addition of Doppler systems, sodars can also be used for the remote monitoring of winds (see section 2.1.4.2).

Remote-sensing systems for measurements or continuous monitoring of precipitation, winds and stability in the lower atmosphere based on radar (see Chadwick et al., 1976 and Wilson et al., 1976) and radiometers for measurements of temperature are already available. A review of different techniques for ground-based remote-sensing is given by Little (1981). In planning a measuring and monitoring programme at a potential or selected NPP site, these new technologies should be considered. Up-to-date information can be found in professional journals.

Photography of smoke releases has for a long time been used to study atmospheric diffusion (see Pasquill, 1974 and Högström, 1964). Most experiments have been used for measuring the rate of widening of a regular smoke plume in a uniform wind. Högström's method has been used to determine the standard deviations \( \sigma_y \) and \( \sigma_z \) at two reactor sites. This and other references most often describe techniques of establishing the spread of an elevated release undisturbed by local effects caused, for example, by buildings or topography. The behaviour of a ground-level release or a disturbed elevated release is more complicated. Local effects are much more important for ground-level releases than for elevated releases. Studies based on ground-level releases should, therefore, be used at a new site, especially if the site is not quite flat and uniform. This is especially useful for predicting the spread of emergency releases (see sections 2.1.1 and 2.2.5). Generally, local influences on diffusion are small in turbulent
and unstable conditions, and most pronounced in inversion conditions. Such studies should, therefore, be made primarily in inversion conditions.

Pilot balloon techniques using optical theodolites for determining winds at various levels are commercially available but limited for use to conditions of good visibility.

Rawinsonde techniques using optical theodolites for determining winds at various levels are commercially available for wind soundings in all weather conditions. Mobile rawin/radiosonde systems are also commercially available.

Tetroons (constant-level balloons) for determining air trajectories are commercially available as well as various tracking systems.

Wiresonde systems (captive balloons) are commercially available. They are often designed as kite balloons of about two cubic metres volume, with a motor-driven winch. Various types of meteorological sensor can be used.

Radiosonde sounding systems are used at upper-air stations but some mobile systems are also available. Special low-level sounding systems based on slowly ascending radiosondes are available for use in the boundary layer. Special electrically-driven radiosondes for wiresonde applications are commercially available.

Various types of smoke rocket systems with stereographic photography of the smoke trails have been developed. Several low-altitude rocket systems giving integrated measurements of the low-altitude winds, temperatures and humidity are commercially available.

Several temperature-measuring systems with variable shielding and recording equipment are available for mobile application.

2.1.6 Atmospheric diffusion models

In the literature, a large number of atmospheric diffusion models are described. Every model formulation contains several parameters and the values to use must be known. These parameter values have often to be adapted specially to the model formula in use, and they are of crucial importance to the resulting concentration. Parameters of the following types have to be specified (see sections 2.1.6.2 - 2.1.6.6):

(a) Dispersion parameters or coefficients;
(b) Parameters describing plume rise and downwash at chimneys and neighbouring structures such as buildings;
(c) Parameters for decay or build-up of radioactive contaminants;
(d) Parameters describing deposition and chemical transformation of pollutants.

2.1.6.1 Choice of model

It is important to realize that no one model has a general application. For each application, various alternative models should first be studied.
The model chosen must be:

(a) Possible to use with regard to available economic resources;
(b) Well-suited for the application;
(c) Able to use the meteorological data to hand;
(d) Readily available for use (including computer facilities);
(e) Able to treat the source types involved;
(f) Able to pay due regard to relevant terrain type and complexity;
(g) Able to work on the time- and space-scales involved;
(h) Able to furnish concentration values relevant for the sampling time in question.

In applications at new NPP sites, it is often possible to choose the model at an early stage and plan the measurements and data structure for favourable use in the model (see section 2.1.1).

It is necessary to know what application a model has and what applications it does not have. Too often, a model is used without any appropriate study of its applicability to the problem at hand. For various applications, section 2.2 will discuss useful or necessary model studies. Reference will be made to the appropriate model types described in the present section and suggestions given for further study.

In sections 2.1.6.2 - 2.1.6.3 the so-called Gaussian models and their requirements will be discussed. They are the most widely used for calculating dispersion up to about 10 km from the source. There are specific situations, however, where Gaussian models may fail, such as complex terrain, coastal sites, and cases with very tall chimneys, mesoscale dispersion, chemical transformations, deposition of pollutants and under urban influence. Some of these problems will be discussed in sections 2.1.6.4 - 2.1.6.6.

For more complex models, years of work are often required to construct an individual model and make it practicable. Even if it is preferable to adopt another model, several months of co-operative training are then required, concerning both theoretical bases and practical computer problems.

2.1.6.2 Practical methods of evaluating dispersion

The largest group of dispersion models in practical use is the Gaussian models. (The basic Gaussian formula is given below.) Before using such a model, the appropriate values of the dispersion parameters $\sigma_y$ and $\sigma_z$ must be determined. In operative use, the steps are as follows:

(a) Determine the actual atmospheric stability in terms of or as a function of one or more of certain indicators of the atmospheric turbulence;
(b) Use the stability value in a suitable method to determine the actual values of the dispersion parameters $\sigma_y$ and $\sigma_z$;

(c) Use the values of $\sigma_y$ and $\sigma_z$ together with other meteorological data (primarily wind speed) and source data (primarily source strength and effective height) in a Gaussian formula to calculate the concentration values.

These steps will be briefly discussed below.

(a) Determination of atmospheric stability

As mentioned in section 2.1.1, the type of meteorological measurements should depend on the type of turbulence indicator adopted. These turbulence indicators are discussed by Slade (1968) and IAEA (1980). A brief review of some useful parameters follows:

(i) Temperature lapse rate

This is the vertical temperature gradient in the ambient atmosphere, obtained by the measurement of temperature at two or more levels;

(ii) Wind-direction fluctuation

This parameter directly reflects the effect of turbulence. It can be evaluated from wind-direction records which show different widths of trace for different stability conditions;

(iii) Solar elevation, cloudiness and wind speed

The usual method is to apply a scheme of the type described by Turner (1970) to data from standard surface weather stations. The parameters used as input are wind speed, cloud cover, cloud type and solar elevation. The output is a stability class, usually termed from A to F.

Useful computer models exist in various countries and the choice thereof depends on the nature of the data and the adaptability of the program and data to the computer. A practical method for stability class estimates is the so-called STAR computer program of the National Climatic Data Center in the USA. The data base for the program is the standard hourly (or three-hourly) weather observation using Pasquill's classification scheme as shown in Slade (1968) (Table A.1 on page 406 thereof).

Methods to obtain stability classes from surface weather data have also been developed by Klug (1969);
Comparisons between stability classification systems using surface data and mast or sounding data have been made by Portelli (1976) (see also section 2.1.3.2);

(iv) Richardson number

This is one of the basic parameters used in several atmospheric dispersion experiments (see Slade, 1968). It reflects the imbalance between thermal and mechanical turbulence and requires the measurements of the vertical gradients of temperature and wind speed. The latter gradient is, however, difficult to record on a routine basis;

(v) Bulk Richardson number

This is similar to the Richardson number but requires only measurements of the wind speed at one level and is therefore easier to record on a routine basis;

(b) Determination of dispersion parameter values

The following methods to determine the values of the dispersion parameters may be used (most of them are also discussed in IAEA, 1980):

(i) Simplified methods

These are used in various countries and primarily in cases where specific site data on the diffusion conditions do not exist. Often, one of the methods discussed below is used in a simplified way. Thus, extrapolation of $\sigma_y$ and $\sigma_z$ values may be made regarding the source height or roughness of the new site to be studied;

(ii) Methods of the Pasquill-Gifford type

Six categories of stability are used as input termed from A to F (see (a) (iii) above). The $\sigma_y$ and $\sigma_z$ values are obtained as functions of downwind distance for each category. Graphs exist in the literature for various kinds of surface (see Gifford, 1976 and IAEA, 1980);

(iii) Temperature lapse rate methods

These methods use the vertical temperature gradient between two levels to characterize both $\sigma_y$ and $\sigma_z$. A comparison between the temperature lapse rate and the Paquill-Gifford stability class is given in IAEA, 1980. The method is not reliable for unstable conditions as has been shown by Briggs and McDonald (1978);
(iv) Wind-fluctuation method

Values of $\sigma_y$ and $\sigma_z$ can be obtained by measuring the standard deviation of the fluctuations of the horizontal and vertical wind direction respectively. The method has been described by Slade (1968) and Pasquill (1974) and requires fast continuous recording of the wind-direction components and a device for calculating the standard deviation (see section 2.1.4.2). Some countries use such systems in their network of automatic weather stations.

There are difficulties in designing wind vanes sensitive to low wind speeds and yet resistant enough to difficult field conditions. Disturbing wake turbulence from the mast or other structures must also be considered;

(v) Split sigma method

This method uses the horizontal wind-direction fluctuations (see (iv) above) to evaluate $\sigma_y$ and the vertical temperature gradient (see (iii) above) to evaluate $\sigma_z$.

In stable conditions with rather large $\sigma_y$ (due to meandering motions), this method gives better values than the temperature lapse rate method, whilst the evaluation of $\sigma_y$ in unstable conditions is less certain.

The measurements are rather simple, since no vertical wind fluctuations are recorded but disturbing wake effects on the wind vane must be considered (see also (iv) above);

(vi) Methods based on temperature lapse rate and wind speed

These methods use the bulk Richardson number. This indicator is superior to the temperature gradient alone, since it considers both mechanical and thermal turbulence. Also, the measurements are relatively simple to perform continuously. A system in operative use has been developed by Högström (1964) and Högström and Smedman-Högström (1978);

(vii) Scaling method in convective conditions

In convective conditions, there are two scaling parameters by which values of $\sigma_y$ and $\sigma_z$ can be calculated:

- The mixing layer height $z_l$;
- The scaling velocity $w$ related to the surface heat flux.
These parameters can be estimated from routine meteorological data or from more elaborate data such as radiation fluxes. A short description is found in Hanna et al. (1982) and a practical application to tall chimney dispersion is given by Weil et al. (1982).

Draxler (1979) compares methods (ii) and (vi) and finds the dispersion given by a Pasquill-Turner stability class from routine airport data will most likely be different from calculations using mast data several kilometres away. This is ascribed to different locations. It is also known that method (ii) derived from homogeneous surface conditions will not work at a coastline, for example.

Irwin (1983) compared different methods to calculate $\sigma_y$ and $\sigma_z$ for both surface and elevated releases. Field data from 11 different sites were used in this comparison.

In many cases (e.g. convective conditions) the distribution of plume material may not be Gaussian, but, as described above, modern results can be used to deduce $\sigma$ values giving proper concentrations when used in the Gaussian formula. The reason for doing so is purely practical.

The methods given above do not take into account source effects on the diffusion. These effects will be treated in the coming sections;

(c) Calculation of concentration values

The basic Gaussian formula for computing a concentration from a continuous point source of strength $Q$ (ci s$^{-1}$) in a wind speed of $U$ (m s$^{-1}$), measured at plume level, is obtained from the assumption of a double Gaussian expression

$$\chi(x,y,z) = \frac{Q}{2\pi\sigma_y\sigma_z U} \exp \left[ -\frac{1}{2} \left( \frac{y^2}{\sigma_y^2} + \frac{z^2}{\sigma_z^2} \right) \right]$$  (2.1)

where: $\chi$ = concentration of the effluent at a point $(x, y, z)$;

$Q$ = source strength, i.e. the rate at which the effluent is released;

$U$ = horizontal wind speed at source level.

The co-ordinate system is such that the origin $(0, 0, 0)$ is at the source. The $x$-axis is in the mean downwind direction. The $y$-axis is in the horizontal crosswind direction and the $z$-axis is in the vertical. The dispersion parameters $\sigma_y$ and $\sigma_z$ are the standard deviations of distributions of concentrations at distance $x$ in the
horizontal crosswind and vertical directions, respectively. The Gaussian plume model has been described, inter alia, by Hanna et al. (1982).

From equation (2.1), formulae have been derived from a number of special applications and a review is given in Slade (1968).

Paquill (1974) discusses various functional forms for the distribution of material in a plume. He finds that the Gaussian form is reasonably accurate in most applications. Furthermore, it is simple to use and almost all literature data of standard deviations assume this form.

The Gaussian model discussed here is stationary, i.e. it assumes that a continuous plume is spread in a uniform wind. During each time interval used (usually that of one hour in length), the meteorological data specify the stationary situation and the concentration is calculated at a specified location. By combining several hours, concentration statistics may be formed.

It must be pointed out that most methods suffer from the weakness that they are valid in principle only for a site where there is uniform and homogeneous terrain. At a coastal site, for example, the methods give parameter values based on the air volume or weather parameters observed at the site itself. When leaving the coastline, these characteristics may change and other dispersion parameter values will be valid. These problems may be solved by making special case-studies and/or by making measurements on one or more meteorological masts at various distances from the coastline. (See Chapter 1 and section 2.1.1.) Apart from these limitations, the methods listed above are valid up to about ten kilometres.

2.1.6.3 **Source effects**

The basic Gaussian formula gives the contribution from one single point source from which approach the treatment of most other source types can be derived. In the case of one NPP unit in normal operation, the continuous plume usually comes from a single chimney. In the transport and spread history of a plume, there is an initial phase which is controlled by the source characteristics. There are three source factors which influence both the path and spread of the plume:

(a) The effluent may have an initial buoyancy (either positive or negative), which will cause the plume to rise or sink. Buoyancy (which is most often formed by an excess heat of the release); will also cause some initial dispersion;

(b) The effluent may enter the atmosphere with initial vertical momentum, which will cause it to rise;

(c) In release from a stack or a building there may be a downwash (a lowering of the plume trajectory) combined with
some initial widening. These effects occur especially at high wind speeds.

2.1.6.3.1 Effects of initial buoyancy and momentum

Of these effects, the rise of chimney plumes has been the most extensively studied. Briggs (1975) gives a detailed review of current plume-rise models and Hanna et al. (1982) give a summary. There are various special cases as regards source and meteorological conditions. A separate formula often holds for each case, and it must be specified very clearly what the conditions are that must be fulfilled before a special formula can be used.

In a weak wind, a hot plume may rise hundreds of metres. For most conditions, the maximum ground-level concentration is approximately inversely proportional to the square of effective stack height. Therefore, the dependence of ground-level concentration on plume rise is substantial.

At least three types of plume rise have been treated in the literature:

(a) Final plume rise, considered to be constant as of a certain distance;

(b) Plume rise after a fixed transport distance (or time);

(c) Plume rise at the distance of maximum ground-level concentration.

Some of the discussion below follows the lines of Briggs (1975).

At large distances, where the plume is expected to have levelled off, it is practical to use some formula for the final rise (see definition (a)). Such a formula, however, must be derived with great care and considering physical principles.

Definition (a) has been frequently used but, in most observations, the plume has not yet levelled off when it is lost sight of. This may lead to different reports on plume rise even for the same plume, depending on measuring technique. This explains much of the inconsistency as to the plume-rise values observed and the formulae derived.

It may also be useful to consider plume rise as a function of downwind distance, in which case definition (b) must be adopted. Thus, the consideration of downwind distance in experimental plume-rise data has unified the data and made it possible to put forward formulae more generally valid in the special cases mentioned above. This definition is also the most useful when concentrations and their statistics are to be calculated in prescribed fixed locations.

The third definition (c) is useful for calculating the maximum ground-level concentration for a specified plume and meteorological situation. It is more difficult to use in calculating concentration statistics since, for instance, the downwind distance to the maximum ground-level concentration varies with the meteorological situation.
Plume-rise estimates should refer to a sampling time of half an hour to one hour. Shorter estimates will be very uncertain, since the real values will have a large scatter owing to short-term variation in vertical wind speed. In longer estimates, changing meteorological conditions will have disturbing effects.

Plume rise has been thoroughly examined by Briggs (1975). His theoretical formulae for plume rise contain coefficients whose values must be established from experimental plume-rise data and associated data on source and environmental conditions. For a neutrally stratified atmosphere Briggs gives plume rise as being dependent on both the vertical momentum flux $F_m$ and the buoyancy flux $F$ of the source:

$$
\left[ \frac{3}{\beta_1^2} \frac{F_m}{U} t + \frac{3}{2\beta_2^2} \frac{F}{U} t^2 \right]^{\frac{1}{3}}
$$

(2.2)

where: $U =$ wind speed; and $\beta_1$ and $\beta_2 =$ coefficients that have to be experimentally determined.

Equation (2.2) gives the rise, $Z$, as an increasing function of transport time, $t$. At small values of $t$ the effect of the momentum flux dominates. It is possible to calculate at what time (distance) buoyancy starts to dominate. If the chimney gas has the same density and temperature as the ambient air, there is only a momentum rise (jet plume). Usually, only one of these two effects needs to be considered. In cases where both effects have an approximately equally large influence on the rise, the equation may be simplified by using only the effect giving the lowest rise, especially if a conservative concentration estimate is required.

Equation (2.2) holds for a plume in a moderate-to-strong wind. The plume is a bent-over plume, i.e. its axis is assumed to be approximately horizontal. This is the most usual case in practical application and will be discussed below. Equations also exist, however, for the rise in a calm atmosphere, when a vertical plume axis is assumed. Equation (2.2) gives the rise in the first stage, when only the plume's own turbulence is active, after which comes a rather abrupt transition to the second stage.

The pure buoyancy rise in the first stage of a bent-over plume in a neutral atmosphere is, according to equation (2.2), proportional to:

- 2/3 power of downwind distance;
- $-1$ power of wind speed; and
- 1/3 power of buoyancy flux.

For emissions with heat capacity and mean molecular weight close to those of air, the buoyancy flux is proportional to the heat emission rate.

The corresponding pure momentum rise is proportional to:

- 1/3 power of downwind distance;
- 2/3 power of ratio between efflux velocity and wind speed; and
- 2/3 power of stack diameter.
Briggs (1975) discusses methods for calculating the rise of non-buoyant plumes (jets) from stacks. The non-buoyant plume is the most common in normal NPP operations and in the small and medium-size accidents. He gives criteria for when the first stage is finished and the transition occurs. At this point, for practical application, he states that the final rise has been reached and the plume levels off. He gives equations for this final rise in neutral conditions for a buoyant plume and a jet. For buoyant plumes, however, there is evidence that the plume also continues to rise after the transition and for accurate concentration estimates, where no conservatism is aimed at, attention should be paid to this additional rise.

In major NPP accidents a buoyant plume is possible, where buoyancy is a result of radioactive decay (see Gifford, 1967).

At large distances, the stratification of the atmosphere is quite important for the rise and the meteorological situation (site data plus routine weather data such as vertical soundings) must be studied.

Briggs (1975) gives a tentative method of evaluating buoyant-plume rise in convective conditions (applied by Weil et al., 1982). More observations are needed to validate this method. Methods are given for calculating rise through an arbitrary density (temperature) profile including the important case of limited rise into an elevated stable layer.

2.1.6.3.2 Downwash effects

The effects of stack and building downwash are to pull down the plume and to make it wider. The early trajectory of a plume emitted close to a building is important for the nearby air quality such as at fresh-air intakes (Slade, 1968) and also for ground-level concentrations.

To make a general rule for downwash is difficult, since there is a large variety of possible source and meteorological conditions. There are also coupling effects between the various types of downwash. Thus, stack downwash may increase the risk for building downwash.

(a) **Stack downwash**

Rules for stack downwash give the sinking of the plume axis below the top of the stack. The crucial factor for the occurrence of stack downwash of a non-buoyant plume is the ratio $R$ of exit velocity to ambient wind speed. Wind-tunnel studies indicate that downwash is slight, provided this ratio is larger than 1:5. When $R$ is smaller than 1:5, downwash does not necessarily imply a descent of the plume below the level of the stack top. The result will be a somewhat lower plume, still subject to plume rise. For very small ratios such as $R = 0.5$, the plume can be brought down across the entire back of the chimney and may come to the ground and penetrate into buildings at the base of the chimney. A practical formula for stack downwash is given by Hanna et al. (1982).

For a buoyant plume, the requirement for the size of the ratio $R$ for avoiding downwash is smaller. Downwash criteria
may be described by combining $R$ with the efflux Froude number (see Briggs, 1969). Practical rules for this case have not been published, as far as is known.

(b) Building downwash

In windy conditions, materials released from a building or an adjacent short stack will be mixed in the turbulent lee wake. A method of correcting the Gaussian dispersion equation in this case is given in IAEA (1980). Huber (1977) examines a few modifications that can be incorporated into the Gaussian plume model to account for the enhanced dispersion resulting from wake effects.

The behaviour of a plume from a short stack adjacent to a building is dependent on the ratio of stack-gas velocity to wind speed. The greater the wind speed, the shorter is the downwind distance at which the plume will be deflected towards the ground. In weak winds the plume may leave quite unaffected by the building (see Culkowski, 1967).

Many wind-tunnel experiments have been made on building downwash. In some cases, the results can be used for practical estimates at similar structures (see Davies and Moore, 1964; Slade, 1968; Snyder and Lawson, 1976; Huber and Snyder, 1976; Vincent, 1977; and Wilson and Netterville, 1978).

In practice, it is desirable to avoid building downwash fully by keeping the plume away from the lee wake. This can be achieved if the stacks are high enough. The famous 2.5 times rule* has long been used. In many cases, it is too conservative and more refined rules are described by Hanna et al. (1982), who also discuss problems with sources upwind of buildings.

Before applying a downwash rule, its origin and its applicability to the site characteristics (building dimensions) at hand have to be examined.

A user-oriented computer program (Spalding, 1981), can be used for calculating airflows near prescribed structures such as buildings.

There is also a stability dependence of the behaviour of a plume in a building wake. The turbulent exchange across the line separating the building wake and the ambient air is weakest in stable conditions. In an inversion, therefore, the upper edge of the plume will follow the contour of the wake and the upper edge may descend for the first 100-200 m downwind. From that distance onwards, the height of the upper edge will increase proportionally the instability.

* This rule says that building downwash is avoided if the stack is at least 2.5 times the height of the building.
2.1.6.3.3 Application of source effects in dispersion models

It is possible to apply the results discussed above directly in a Gaussian dispersion model and when several consecutive hours or meteorological classes are treated. For each hour or class, the appropriate values of wind direction, wind speed and stability have to be used, together with the data on the source and neighbouring structures to calculate the effective height of the plume. These effects can then be taken into consideration in the final result for a fixed location which may be a monthly mean concentration value or a cumulative frequency distribution of hourly concentration values, etc. (see sections 2.1.3.1 and 2.1.6.7).

IAEA (1980) gives methods to calculate short-term (one-hour) and long-term concentrations having regard to the initial widening of the plume because of building wake effects, when the effective plume height is given as zero. These methods are applicable to materials mixed uniformly in the turbulent wake created by the ambient airflow around the building and are valid for releases from leaks in the building and in windy conditions and from stacks lower than twice the height of the building (short stacks).

When there are two or more units in a site, the separation L between the chimneys will play a role for the concentration field up to a certain distance and the total concentration is obtained by adding together the contributions from each source. One approach is to draw isopleths of concentration for various wind speeds and stabilities and then to orient these according to wind direction. Multiple-source Gaussian models are also available for such a case (see NATO/CCMS, 1975).

For calculating concentrations beyond the distance mentioned above, the sources may be treated as a single source. This distance depends on the ratio between L projected on a line perpendicular to wind direction and \( \sigma_y \). Knowing the function \( \sigma_y \) of distance and the tolerable error in the concentration value, it is easy to determine the above-mentioned distance.

2.1.6.4 Modelling techniques for mesoscale problems

The plume models described above are applicable within about 10 km of the source where data on \( \sigma \) values exist. For modelling concentration and deposition at mesoscale distances (between about 10 and 300 km from the source), new problems arise, which can often be ignored in work on the local scale.

Such problems are:

(a) Non-stationarity of meteorological elements during the time of transport, e.g. a gradual change in wind direction will cause a curved trajectory;

(b) Non-homogeneity of meteorological elements in space. Such effects occur in complex terrain and in transition zones between various kinds of surface. Examples are mountain-valley winds, land and sea breezes, urban circulations and systematic vertical motions in flow from land out over water;
(c) Increase with distance of the effects of vertical wind speed and direction shears;

(d) The importance of mixing height for the ground-level concentration increases with distance;

(e) The deposition to the ground removes material from the plume. When concentration values at large distances are to be calculated it may be important to consider this process (see section 2.1.6.6);

(f) Physical and chemical processes and radioactive decay may remove 'old' contaminants in the plume and create 'new' ones. The consequences of these processes increase with transport time (see section 2.1.6.6).

Some model types and their applicability to these problems will be discussed below. Only diffusion from a point source will be treated. A review of mesoscale modelling has been given by Hanna et al. (1982).

2.1.6.4.1 Plume models

There is very little information about the spread to mesoscale distances in the mixed layer. Some data for $\sigma_y$ can be found in Slade (1968). Pasquill-Gifford curves for plume $\sigma_z$'s have been extrapolated to mesoscale distances but this is not recommended by Pasquill and Gifford.

The plume model can be applied to the mesoscale effect of vertical wind-direction shear on the lateral spread (lateral = horizontally at right angles to wind speed). This effect can be neglected within some kilometres from the source but may become quite dominating at large distances. (See further Smith, 1965 and Pasquill, 1974.) In general, plume models should not be used at mesoscale distances since data on $\sigma_y$ and $\sigma_z$ do not exist. Also, processes such as deposition must be treated by other methods (see below).

2.1.6.4.2 Solution of the diffusion equation

This method is useful in mesoscale problems where the vertical concentration profile is known not to be Gaussian. The basic step is to solve the equation for diffusion in two of three dimensions. In two dimensions, there is one vertical ($z$) and one downwind-directed horizontal co-ordinate ($x$) and the release from an infinite line source along the y-axis is assumed to be diffuse in the vertical $x$-$z$ plane.

In closing the equation a $k$-formulation may be used, where $k$ stands for the diffusion coefficient. (See Pasquill, 1974.) For a two-dimensional model there is a $k$-formulation ($k_z$) only in the vertical (and sometimes along-wind, $k_x$), while for three dimensions, the $k$-theory can be used for describing the lateral diffusion also ($k_y$).

The value of $k_z$ and its variation with height and the wind profile have to be determined from experimental studies and/or results from dynamical boundary-layer models. (See Mellor and Yamada, 1974.) Hanna et al. (1982) give a review of the problems encountered in using the diffusion equation.
After solving the two-dimensional diffusion equation, the horizontal crosswind diffusion may sometimes be introduced by a Gaussian distribution. It is possible to use either a stationary or a non-stationary equation. The stationary equation is suitable for statistical studies, based on hourly values such as when the model is used to calculate a cumulative-frequency distribution or a yearly value of deposition from continuous sources. The non-stationary, time-dependent equation may be suitable for the evaluation of an emergency release, which is necessary for adequately describing the influence, during transport, of the diurnal course of meteorological variables. This equation is also suitable to describe time-dependent chemical reactions or radioactive decay.

In describing dry deposition, the deposition velocity has to be included in the boundary conditions of the model.

In a few simplified cases the diffusion equation may be solved analytically. Solutions for more general cases can only be obtained by finite difference methods where various numerical schemes are used for solving the diffusion equation. Computerized numerical methods are now by far the most frequently used. A pseudo-spectral method to solve the diffusion equation has been used to calculate diffusion and dry deposition form a point source.

2.1.6.4.3 Trajectory and puff models

Such models can be used for transport studies on all scales. In mesoscale transport, the wind field is often non-homogeneous. The curved transport path is described by trajectory analysis. This requires continuous analyses of the wind field. (See Henrikson, 1971 and Nordlund, 1976.) This calculation of transport path is common to all trajectory models. In other respects, the model procedures must be designed for the problem type, where crucial aspects are duration of the release, stationarity and sampling time. Special procedures must be developed for chemical processes, radioactive decay and deposition. This has been done so far mostly for larger scales.

The advective transport terms in the diffusion equation can also be treated by the Lagrangian 'particle-in-cell' (PIC) method, in which a collection of particles representing concentration is followed by the calculation of the particle trajectories. Teuscher and Hauser (1974) give a description of the basic PIC model. Application of this method to complex terrain has been done by Anthes et al. (1976).

To describe plumes in curved wind fields a puff model may be useful. Hanna et al. (1982) give a review of puff diffusion with application to field experiments. Mikkelsen et al. (1980) describe a puff model for use in mesoscale distances.

2.1.6.5 Modelling techniques for complex topography, low wind speeds and fumigation

The effects of these situations on ground-level concentration may be strong for both small and large distances.
(a) Complex topography

Hanna et al. (1982) give a review of air-pollution meteorology in complex terrain. A stability parameter used to classify the flow is the internal Froude number. By this parameter it can be judged if the flow is around the hills at constant height or over them.

Simple rules for the spread of a plume over a mountain have been issued by the US Environmental Protection Agency. More advanced models are difficult to use practically but Pielke et al. (1983) have tried. Such a model can give results which are drastically different but often more realistic. (To describe plumes in curved wind fields, a puff model may be advantageous—see section 2.1.6.4.3 above.)

Section 2.1.1 discussed measurements to be made at sites with complicated topography. It was found that the dispersion of a ground-level release was most complicated in inversion conditions. If such dispersion pictures are established in a number of case studies, it is possible to evaluate the later spread after inversion break-up, when the diffusion is simpler and may be calculated by a Gaussian model to give dosage values from the passing plume. The dispersion picture found in the inversion can then be used to specify the type of source to be used (area or line source). A model for diffusion of a ground-level release suitable for this case is given by Högström (1964);

(b) Low wind speeds

Primarily, the wind speed should be studied at the height of release and spread of the plume. In this context it should be pointed out that in inversion conditions there may be a calm in the lower metres but a strong wind at 100 m, for example, even over quite flat terrain.

Low wind-speed diffusion studies such as Van der Hoven (1976) and Wilson et al. (1976) show that the lateral diffusion parameter $\sigma_y$ (taken over about one hour) is much larger, also over flat terrain, than predicted by standard Pasquill-Gifford curves, owing to increased horizontal meandering of the plume. The value of the vertical diffusion parameter $\sigma_z$ is dependent on the surface roughness.

The NATO/CCMS (1975) report contains models applicable to low wind and calm conditions. Briggs (1975) discusses the behaviour of chimney plumes in calm conditions;

(c) Fumigation

This term refers to the mixing downwards to the ground of material concentrated aloft in stable air which occurs when the ground is warmed by solar radiation or when air flows from a cold to a warmer surface. General information is
given in Slade (1968) and a method to estimate ground-level concentration is found in Turner (1970).

Special consideration should be given to fumigation at coastal sites where it may last for several hours; special measurements and modelling techniques are available. Most fumigation models give the inland ground-level concentration from a tall stack at the shoreline. Such a model is described by Meroney et al. (1975). Another model has been tested against concentration data inland by Misra (1980). Deardorff and Willis (1982) describe and test a fumigation model incorporating application to flow over a lake and time-averaged concentrations.

2.1.6.6 Removal and deposition

Mechanisms where a contaminant is removed from the air are:

(a) Wet deposition;
(b) Dry deposition;
(c) Chemical transformation;
(d) Radioactive decay.

Deposition to the ground or vegetation may be important and harmful in a reactor accident. The basic theory for dry and wet deposition and depletion of a Gaussian plume is given by Slade (1968). More recent findings are reviewed by Hanna et al. (1982). The simplest way to estimate dry deposition is to calculate the concentration near the ground and to multiply it by the deposition velocity. Beyond a certain distance, plume depletion and reduced concentrations resulting from deposition have to be considered.

A Gaussian plume model corrected for dry deposition and consequent plume depletion is described by Hosker (1974). Models of this kind must be used with care in cases with vertical concentration gradients near the ground such as stable conditions and at large distances. For wet deposition, most models used in an NPP context assume equal rain intensity over the entire time and area concerned. (See IAEA, 1980.)

Studies have also been made of the effect of showers of limited lifetime and of their travel path (see Ritchie et al., 1976), where the redistribution of deposited material owing to runoff is also studied.

The washout of pollutants by precipitation has been discussed by Slinn (1977).

Data on dry-deposition velocities are given in a large number of reports. The value may vary widely with atmospheric stability, wind speed and surface conditions, even for the same vapour or aerosol. For particles, the deposition velocity is also highly dependent on the particle-size distribution. In IAEA (1978), information is given on methods and techniques for analysing particle-size distributions. McMahon and Denison (1979) give data on deposition velocities to grass of particles of various sizes. A
review of deposition of gases and particles to plants has been made by Hosker and Lindberg (1982). Values of dry-deposition velocity for various fission products are given by Gifford and Pack (1961/1962); Beattle and Bryant (1970); Barry and Chamberlain (1963); and Chamberlain and Chadwick (1965).

2.1.6.7 Presentation of results

The method of presenting results from a diffusion model is determined by the problem to be solved. Some typical methods of presentation are:

(a) The average concentration over a long period such as one year. This may be given at a fixed point or as a map of the concentration field. This representation may be used in consequence analyses, when a linear relation between concentration or dose and consequence is assumed;

(b) Statistics of concentration values averaged over one or more specified sampling times. Such statistics may be presented in various ways, such as:

(i) Giving the values in a consecutive time series;

(ii) Giving a cumulative-frequency distribution, i.e. a curve showing the probability of exceeding various concentration values, which enables any percentile value judged appropriate to be chosen;

(iii) Giving a map of the value of the 99 percentile (the value exceeded by one per cent of the time averages), or some other percentile judged to be appropriate;

(iv) Giving the limit concentration value corresponding to a fixed percentile as a function of the sampling time (see section 2.1.3.1);

The three latter presentations may be used in consequence calculations, if it is considered that there is a threshold concentration for which only higher values are supposed to be harmful;

(c) Presentation of the time average at a fixed distance in the most polluted sector. This sector is allowed to move from one averaging period to another.

The results of model calculations are often used in further studies, e.g. to estimate probability-consequence relationships for emergency cases (see USNRC, 1975) or to calculate population doses for emergency and normal operation.

2.2 Meteorological requirements for the various stages of siting and operating an NPP

The following table gives a summary of the studies to be made in the various stages (further details will be given in the following sections):
<table>
<thead>
<tr>
<th>Stage</th>
<th>Existing routine meteorological data measurements</th>
<th>Local meteorological investigation</th>
<th>Special continuous measurements</th>
<th>Special case-study measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Site survey (comparative studies)</td>
<td>Must be used.</td>
<td>If data exist they should be utilized.</td>
<td>At least one year of site data from one or more levels depending on site complexity</td>
<td>In complex sites, smoke or tracer studies should be made.</td>
</tr>
<tr>
<td>2. Final site selection</td>
<td>Must be used.</td>
<td>At least one year of site data from two or more levels</td>
<td>In complex site or design, smoke tracer studies should be made either on full scale or in a wind-tunnel.</td>
<td></td>
</tr>
<tr>
<td>3. Site qualification (NPP design input)</td>
<td>Suitable data should be used together with special continuous data.</td>
<td>At least one year of analysed data should exist when starting normal operation. During normal operation some key parameters must be recorded.</td>
<td>When starting normal operation, the results from such measurements should have been utilized for constructing the emergency plan.</td>
<td></td>
</tr>
<tr>
<td>4. Normal NPP operation</td>
<td>See above.</td>
<td>At least one year of analysed data concerning the path and spread of the release.</td>
<td>The current values of the key parameters should be used.</td>
<td></td>
</tr>
<tr>
<td>5. NPP emergencies situations</td>
<td>A weather service must give forecasts concerning the path and spread of the release.</td>
<td></td>
<td></td>
<td>See above.</td>
</tr>
</tbody>
</table>
2.2.1 Site survey

2.2.1.1 Methodology

For the site survey, a list of existing routine and special meteorological data should be prepared.

When selecting a site for an NPP, there are a lot of factors to be considered, such as the occurrence of special meteorological conditions. In an early stage of NPP siting, however, meteorological information is not usually at hand and one is often, therefore, completely restricted to routine weather data. Judgements of the diffusion conditions at the sites have to be made from general statistics: radiosonde statistics and synoptic weather data can be used to compare air-pollution potential of different regions.

Data should be used in a simplified diffusion model to estimate concentration values. Assuming homogeneous conditions in the whole region, average concentrations can be calculated at different distances from the source. Different regions can be compared and ranked by these simplified methods. A review of topographical features affecting transport and diffusion of releases in the immediate vicinity of and farther away from the site has also to be made. By simplified methods it is also possible to make a rough estimate of deposition conditions around the site. Together with factors like population distribution and land use, a first selection of suitable NPP localizations can be made.

2.2.1.2 Use of routine meteorological data

Usually at this stage, studies requiring meteorological information have to be based only on routine meteorological data such as synoptic weather data and aerological data (see section 2.1.2). These data can be used for a comparison of the general climatological conditions in different regions. The climatological parameters of principal interest are wind speed, wind direction, atmospheric stability, temperature, precipitation, humidity and fog. Frequencies of values of a single climate element and of simultaneous values of several elements should be calculated. All the above elements, except atmospheric stability, are directly observed at every synoptic station.

In comparing statistics of atmospheric stability and air-pollution potential for various regions, the usual method is to apply a system based on routine surface weather data such as cloudiness and wind speed. (See turbulence indicator (a) (iii) in section 2.1.6.2.) It is also possible to compare air-pollution potential in various regions using radiosonde data. (See Holzworth, 1972 and 1974.) At this and later stages it may be necessary to evaluate wind speed at higher levels from routine surface-wind data. Such a method has been described by Högström et al. (1978) using detailed information about the surrounding ground roughness to evaluate the wind profile up to about 200 m. The method applies only to comparatively flat, rural terrain.

2.2.1.3 Use of special meteorological data

A site survey must usually be made without utilizing any special meteorological data but if special measurements have been made for other purposes in the region, the results shall, of course, be used in assessing the general climatological conditions.
2.2.1.4 Use of diffusion models

Only simplified diffusion models are applicable in the site-survey stage, because the model calculations in most cases must be based on routine weather data, which are usually not specific for the NPP site.

Generally, a crude concentration statistic such as a long-term average is required at various locations for a given rate of emission assumed constant and a number of NPP sites to be compared. Often, comparisons with other variables such as population distribution have to be made at the sites studied.

The simplest models use a wind rose and some average stability class assumed constant in time and space. Systems calculating stability classes from routine weather data have been described above and in section 2.1.6.2.

Brun et al. (1973) present a method using results from tracer experiments at about 20 sites. A probabilistic presentation of concentration was developed. The values were weighted with the measured or estimated wind rose and the results extrapolated up to 100 km.

One useful model is the so-called box model. An example of its application is given in section 2.2.1.5 below.

2.2.1.5 Applications

Simplified methods for describing dispersion conditions are often useful for any type of site. A connection between source data and meteorological data can be obtained in a simple way by utilizing a box model (see Figure 3): part of the atmosphere above the site is supposed to be enclosed in a box, in which there is a vigorous mixing.

\[
C = \frac{t \cdot Q}{x \cdot y \cdot z}
\]

Figure 3 - Box model

One side, y, is chosen perpendicular to the stationary mean wind and the other side, x, along-wind. The vertical dimension, z, is the height to the lowest inversion layer in the atmosphere. Assuming the rate of emission in the box to be Q, and that it takes the air t time to pass the box, the average concentration C in the box will be:
Further, if the average wind speed is \( u \) and \( y = 1 \) length unit, then

\[
\frac{C}{Q} = \frac{1}{u z}
\]

This is valid only for a location within an extended region with area sources but it may also be used for a point source in a first comparison between various alternative sites. The numerical values cannot then be used as absolute numbers but only for a comparison between various sites. For sources of height comparable to \( z \) the method may fail.

In using meteorological statistics for various sites (usually radiosonde data), the method may in practice result in a comparison of percentile limits of \( u z \). Holzworth (1972) gives practical numerical examples of using this method.

### 2.2.2 Final site selection

#### 2.2.2.1 Methodology

In the survey stage, a small number of the sites originally considered were selected for further investigation. In selecting the final site, therefore, it must be certain that the NPP can be so designed as to fulfill the basic safety standards for radiation protection in the environment of the site concerned. On the basis of the results form the survey stage, it can be determined what further investigations are desirable for final selection. Such special investigations at a small number of sites are required, particularly for describing the unfavourable air-transport and diffusion conditions arising in complex terrain, coasts and neighbouring populated areas. The need for special investigations is also dependent on distance to, and representativity of, existing routine weather stations.

A complementary investigation needed for final site selection may consist of at least one year of continuous measurements at surface level or at several levels for a mast (depending on site complexity). Parameters of interest are wind speed, wind direction and atmospheric stability, e.g. temperature profile in the mixing layer. The complementary investigation may also include case-study measurements.

For sites likely to be selected for NPPs, it may be recommended already at this stage to start the measurements at several levels, since this will be required for the site qualification. These measurements must be planned so that the data can be used in suitable computer models to form a picture of the transport and diffusion patterns. Conventional meteorological instruments are discussed in section 2.1.4, while existing special measurement techniques, and diffusion models are described in sections 2.1.5 and 2.1.6 respectively.

It is important that a site investigation is planned in such a manner that the measured data will be applicable for later requirements (see sections 2.2.3 - 2.2.5).

#### 2.2.2.2 Use of routine meteorological data

Sometimes, the existing routine meteorological data used for preselection are sufficient for final selection too, such as when the surroundings of the site are simple (concerning topography and land-sea
distribution) and when there is some representatively situated routine weather station in the neighbourhood. In complex sites, routine weather data can be used for complementing special data taken at the site, for example in making a short period of special data climatologically representative (see section 2.1.3.2). Climatological parameters of interest are the same as in site preselection.

2.2.2.3 Use of special meteorological data

When meteorological conditions at the site are complex, it is necessary to make local measurements including smoke or tracer experiments to establish an adequate dispersion assessment. This is particularly desirable in poor dispersion situations. Examples of such unfavourable situations are a channeled flow in a narrow valley, prevailing wind direction towards a nearby heavily populated area and unfavourable atmospheric dispersion conditions over long periods. In some cases, it is enough to have one year of measurements at one level to decide whether the site is suitable for an NPP location (see section 2.1.2) but in other cases, many years of local measurements and/or data from more levels are needed.

At great heights, mast data of the releases are not sufficient and balloon soundings are useful (see section 2.1.1). It may also be advantageous to make remote-sensing measurements (see section 2.1.5), e.g. sodar can be used to record data continuously. These data may be used to evaluate the frequency and persistence of elevated inversions.

2.2.2.4 Use of diffusion models

If no special measurements are available, the same simplified models as those for the preselection stage have to be used (see section 2.1.6.2).

The special investigations to be made at complex sites or in poor dispersion situations can be utilized to obtain an idea of the dispersion conditions. Comparisons may also be made with other sites. At this stage, useful models should pay regard to local geographical and topographical features as much as possible. (For further information on suitable models see section 2.1.6.)

2.2.2.5 Applications

If there is a special investigation made at the site, the applications are of the same type as in the normal operation stage (see 2.2.4.5). If no such data exist, the application will be the same as in site preselection.

2.2.3 Site qualification (NPP design input)

2.2.3.1 Methodology

For site qualification, the characteristics of the site must be identified in order to gain input to the solution of the design problems. For this purpose it is necessary to have, for every kind of site, at least one year of data from several levels at the site. These data and existing routine meteorological data used in suitable diffusion-model calculations should give the input for determining the necessary dimensions of chimneys, cooling towers, etc.
In model calculations, it is important to take into account the influence of building and terrain structures on the behaviour of a release (see section 2.1.6). Wind-tunnel studies are also useful, especially for investigating the effects of complex structures on the local behaviour of a release. Another effect is the interaction between different plumes, e.g. when a chimney plume moves into a cooling-tower plume. A review of meteorological effects on cooling systems is given in section 2.3. The dimensions of a cooling tower are partly determined by the normal air temperature and humidity at the site (see section 2.3). The dimensions of structures such as walls must be determined by solidity calculations, so that they withstand the extreme meteorological phenomena which can occur at the site (see Chapter 3).

2.2.3.2 Use of routine meteorological data

For calculating necessary chimney heights, statistics of wind and stability are needed. The statistics must be climatologically representative for the site which, ideally, means that they are based on several years of measurements therefrom (see section 2.2.3.3). In most cases, however, routine meteorological data from an adjacent weather station must be used, combined with the special site data (see section 2.1.3).

With regard to stability, it is also desirable to use measurements from an adjacent upper-air station.

2.2.3.3 Use of special meteorological data

At least one year of special site data from two or more levels should be used. The statistics based on these data can, if necessary, be corrected by means of a longer period of conventional meteorological data at an adjacent routine weather station in order to obtain climatologically representative statistics (see section 2.1.3.2). The shape of the meteorological statistics needed depends on what diffusion model is used.

Smoke or tracer studies should be made if a complex design is planned (with, for example, risk of downwash) or at sites in complex terrain in order to investigate, for example, minimum necessary chimney height. Wind-tunnel studies may be used, especially in complex design plans.

2.2.3.4 Use of diffusion models

Diffusion models can be utilized for determination of chimney heights, cooling-tower sizes and siting of different sources relative to each other and to large buildings. Most often used in this connection are the Gaussian models. Account must be taken of the joint effects of, for example, different sources, plume rise and downwash (caused by buildings, chimneys or terrain). A description of useful models is given in section 2.1.6.

2.2.3.5 Applications

Model calculation of the median relative concentration at various distances in direction 280° is made for two values of effective chimney height. (See Figure 4.)
Figure 4 - Model calculation of the median relative concentration. Normal operation; release time one year; cumulative frequency for 50% of all hours; bearing 280°; effective chimney height 50 m and 100 m.
After that, the following relation is used:

\[
\text{rate of emission} \times \text{relative concentration} = \text{Bq s}^{-1} (\text{s m}^{-3}) = \text{actual concentration} \frac{\text{Bq}}{\text{m}}
\]

Knowing the rate of emission and specifying a value of effective chimney height, the actual concentration picture should be converted to the proper radiological effects and be compared to the standards of the ICRP (see section 2.1). Using comparisons for some chimney-height values, the minimum acceptable chimney height should be chosen, having taken downwash effects and plume rise into consideration.

The model calculations were made for various meteorological classes and the result was obtained after weighing by the frequencies of these classes.

2.2.4 Normal NPP operation

2.2.4.1 Methodology

An NPP in normal operation also has a need for meteorological information. There is a demand for maintaining a satisfactory preparedness for emergency situations and for authorities to control the observance of existing prescriptions. There is also a need for meteorological control in planned high-release processes or experiments.

Meteorological data should be used to assess how the continuous release is dispersed in the surroundings of the NPP and to obtain the probability of occurrence for concentrations and doses of radioactive material released routinely. Calculations should be made of average doses over different time-scales (from one hour up to the whole NPP lifetime), depending on what effects are being considered with regard to human beings and the environment. The total radioactive dose over the whole NPP lifetime (dose commitment) gives a measure of the total environmental impacts of the radioactive releases, where not only the immediate effects are considered.

When the NPP operation is started, it is necessary to have meteorological statistics that are climatologically representative for the site. In some cases the statistics obtained in the design stage or earlier are sufficient. The statistics should be based on comparisons of at least one year of data from a local meteorological investigation at the site and several years of data from a weather station (see section 2.1).

When the NPP is in normal operation, continuous measurements which are necessary for emergency preparedness can be used some years later to make the meteorological statistics more representative. The environmental doses from an NPP in normal operation should be calculated afterwards, according to meteorological and source data at the site for the period passed.

2.2.4.2 Use of routine meteorological data

Long-term (several years) meteorological data from one or more adjacent routine weather stations can be used to make the short-term (e.g. one year) mast measurements at the site climatologically representative (see section 2.1.3.2). The routine weather stations used can be surface and
upper-air. Another important use of routine weather data is for checking the continuous measurements.

2.2.4.3 Use of special meteorological data

Special continuous meteorological measurements at the site should be made during at least one year to determine the local meteorological conditions and to calculate the climatologically representative statistics. This material should be analysed at the start of normal operation.

Special case-study measurements are required for the construction of the emergency plan, which has to be operative at the start of normal NPP operation.

The influence of topographical and other features in the neighbourhood of the site on the meteorological conditions can be determined by means of tracers, constant-level balloons or photography of smoke releases (see section 2.1.5).

Making analyses of concentrations and doses from routine releases requires frequency distributions of wind direction and wind speed for different stability classes. For effluent subject to washout, it will also be necessary to take into account precipitation classes. Wind direction, wind speed and precipitation are measured directly and stability can be determined, for example, by temperature-difference measurements. The required accuracy of data is discussed in section 2.1.2.2.

2.2.4.4 Use of diffusion models

The most common method for computation of concentrations from a continuous point source is the use of a Gaussian model.

Decay of the radioactivity in the cloud and depletion by dry and wet deposition can be taken into account (see section 2.1.6). In complicated sites and when studying long-range transport, modifications must be made to compensate for the space and time variations of the relevant meteorological parameters (wind speed and direction, atmospheric stability). Concentrations from long-term routine releases can be estimated using techniques discussed in section 2.1.6.

The climatological statistics discussed in the earlier sections should be analysed and stored so that they can be used as input data to the diffusion model. The model can then compute probabilities of different concentration values at different sampling times and distances from the source and comparisons can be made with the results from other NPPs having other climatological and topographical conditions. An example is given below.

2.2.4.5 Applications

In the following example (see Figure 5) a Gaussian model has been used to describe the diffusion of a constant unit radioactive release. Consecutive hourly data over 32 months from a mast on wind direction, wind speed and stability have been used. Stability has been calculated using a bulk Richardson number (see section 2.1.6.2). The time mean concentrations have been formed at fixed locations according to the principles discussed in section 2.1.3.1.
Asymptotic concentration value

Figure 5 - Three percentile limits of the time mean concentrations

\[ \frac{1}{t_0} \int_0^{t_0} x \, dt \]

depend on the sampling time \( t_0 \).
- Summer half year;
- Distance 5 000 m;
- Bearing 0°;
- Release height 87 m;
- Percentiles 50%-----------------------
  10%-----------------------
  1%-----------------------
2.2.5 NPP emergency situations

2.2.5.1 Methodology

In an emergency situation, there is an immediate need for a realistic picture of the path and spread of the release and, later, for an estimate of the resulting concentrations and doses.

To achieve this, an immediate characterization is necessary of, firstly, the amount, duration and height of the release and, secondly, the actual weather conditions.

In an emergency situation, the current weather conditions at the site are often characterized by some meteorological key data (see section 2.2.5.3), which have to be recorded continuously during the lifetime of the NPP. Which parameters are relevant depends on the location of the release, source effects such as plume rise and the current weather conditions. To know which parameters are relevant in the different release cases, some investigations must be made at the site before starting the operation of the reactor. This investigation should also include detailed mapping of the influence of buildings and local topographical and geographical features on the diffusion of the radioactive cloud. Such an investigation can be made, for example, by smoke or tracer studies (see section 2.1.5). Several experiments must be made covering different heights of release and different weather situations. It is important to cover extreme weather situations which give poor diffusion conditions. The number of experiments depends also on the complexity of the site (see section 2.2.5.3).

Quick and accurate information about the path and spread of an emergency release can be achieved by using results from preparatory model calculations for a limited number of diffusion regimes (see section 2.2.5.4). The results of these calculations can be put together to form an easy-to-handle manual, which will here be called a dispersion catalogue (see section 2.2.5.5). Current or forecast meteorological data may be used when entering this catalogue and the course of the radioactive cloud will be predicted.

Forecasts based on the actual meteorological conditions are usually relevant only for a short time and must be repeated at least once an hour. It is also necessary to forecast the spread over long distance and of long-term releases. Forecasts are made by a meteorological service and in an emergency, the service should have a meteorologist familiar with the key meteorological information needed. If possible, forecasts should be made of the relevant key meteorological parameters for direct use in the dispersion catalogue of the emergency plan.

It may be technically possible to delay a radioactive release for perhaps ten hours. In such and other cases a forecast of wind direction will be of great value, hence knowledge of a frontal passage or other similar weather changes may be important.

There is a risk of erroneous forecasts and of forecasts which will be changed after some time. In this context, it is important that the data given to the weather service from the meteorological station at the NPP are
reliable. The best means of finding out and correcting shortcomings and error sources is to perform realistic emergency exercises involving all parts concerned.

Meteorological data should be used in diffusion models as a tool to estimate probability-consequence relationships for emergency releases (see USNRC, 1975).

In sections 1.4.2.1 and 2.1.6.6 the problem of precipitation scavenging was discussed. The fall-out of a radioactive cloud at the ground by a shower, for example, may be very strong and it is therefore recommended that cases of deposition by precipitation be investigated and included in the dispersion catalogue.

2.2.5.2 Use of routine meteorological data

In an emergency situation, it is important to establish contact immediately with a meteorological service to obtain information about prevailing and expected weather conditions in the immediate region. From this service, a forecast of rapid changes in the weather (e.g. frontal passages) can be promulgated, which are often associated with precipitation and great changes of wind direction and speed. The weather forecasts can also be used to predict the key parameters for calculation of concentrations and doses in the neighbourhood of the NPP. If there is a good, representative routine meteorological station in the immediate neighbourhood of the site, meteorological observations from that station can be used in the emergency plan. Routine weather data will be especially important in emergencies where the special data are lacking, erroneous or insufficient (see further section 2.2.5.6).

2.2.5.3 Use of special meteorological data

For a quick and adequate forecast of the dispersion of an emergency release, the reactor control room must contain, firstly, a continuous record of some key meteorological parameters and, secondly, a description of the radioactive cloud dispersion in some meteorological classes which are defined by the key parameters (see section 2.2.5.5). Continuous meteorological data at different levels can be suitably received from a mast. Relevant meteorological parameters for this purpose are wind direction, wind speed and a stability indicator (see sections 2.1.1 and 2.1.6). How many and what levels should be used are determined by the investigation mentioned in section 2.2.5.1. This investigation, which also contains some measurements for mapping the local site features, makes it possible to define key parameters for any release case and any weather type (see section 2.2.5.5).

One way of making a catalogue that describes the radioactive cloud dispersion at any emergency situation is to conduct a number of smoke experiments using aerial photography in different meteorological conditions. The investigation should contain experiments with release from different levels, e.g. ground level, the roof of the reactor building and the chimney. The meteorological conditions can be determined from mast or aerial measurements or a remote-sensing technique. Special measurement techniques are discussed in further detail in section 2.1.5. It is very important to conduct experiments in complicated weather situations, i.e. those which make for high ground-level concentrations and those in which concentrations depend largely on local features (buildings, topography). It may be necessary to carry out
experiments with ground-level releases and a stable atmosphere. A comparison of smoke dispersion and actual wind and stability makes it possible to define a number of meteorological classes with different dispersion characteristics.

When the emergency release is hot, a considerable plume rise may take place and information will be needed at heights above the mast (see sections 2.1.1 and 2.2.5.5).

In an emergency, radar may be used to localize areas of precipitation and wet fall-out (see section 2.1.5).

2.2.5.4 Use of diffusion models

At most sites, a Gaussian model is enough for making a dispersion catalogue. In topographically complicated sites and for larger transport distances, it is desirable to use a more sophisticated model. (For the use of models for various applications, see section 2.1.6.) The model calculations must be made by computer at the time of the accident or, for a limited number of well-defined weather types, in advance.

The results from diffusion-model calculations predict the course of an emergency release and the resulting concentration and contamination levels, and also assist in calculating probability-consequence relationships for emergency releases.

In a special emergency case, the results from the dispersion catalogue (manual or automatic) have to be supported by direct radiological measurements. The model computations would then give an initial indication of the site where the measurements should be made.

Another important use of diffusion models is for analysis after an emergency has passed (emergency post-analysis) which can be more thorough than one made in the busy duration (hours or days) of the emergency. For example, a deposition model may be used to calculate which areas in the surroundings have been most heavily contaminated by the emergency release. This may be used as guidance for radiological measurements when promulgating restrictions, such as for milk deliveries (see also next section).

2.2.5.5 Methods to make results useful in an emergency situation

As it is desirable to minimize the manual calculations, exposure maps for a standard or unit amount of release and a limited number of dispersion classes should be immediately available in case of need. The dispersion classes may be defined by the atmospheric stability and the level of release. In special cases, however, some calculations must be made, e.g. when taking into account the actual amount of release, to ascertain the ground-level concentrations and exposures.

In an emergency situation, the diffusion régime must be quickly and simply determined from the current values of the key parameters (dispersion catalogue). In the reactor control room, therefore, there may be a map with movable overlays, one for each diffusion type, showing the current concentration field. After multiplication by the exposure time it is also possible to obtain the radiation exposure (see Slade, 1968). In the following discussion and examples, only the exposure defined in curies per second per cubic metre (arising from air concentration x time) will be discussed.
In the case of an accident release, the following steps connected with meteorology have to be taken:

(a) Find out the level of release and estimate the amount of release;

(b) Read the current meteorological data relevant for dispersion from the release level and make the calculations needed to obtain averages of at least 30 min for the relevant meteorological parameters;

(c) Determine the current dose configurations by means of the dispersion catalogue and put this dose chart on a map over the region;

(d) Perform direct radiological measurements using the model calculations as guidance;

(e) Decide if any preventive steps are necessary within the exposed region.

If any procedures are executed by a computer (see below), the site personnel should be apprised of limitations and possible errors.

In the early stage of an emergency situation, these procedures have to be carried out by the site personnel. They should be trained in the use of a very simple type of dispersion catalogue. Example 1 in section 2.2.5.6.1 illustrates such a simple system. Later, there will be the assistance of a meteorologist familiar with diffusion estimates. This person might be available at the meteorological service or in some centrally assembled emergency group. In this case, a moderately detailed type of catalogue could be used (see Example 2 in section 2.2.5.6.2).

The first mentioned, simplest version of a dispersion catalogue cannot give adequate concentration dose estimates in complicated situations with:

- Weak winds;
- Ground-based inversion;
- Complicated topography;
- Land/sea and mountain-valley circulations;
- Extended source;
- Addition of geographical dosage fields over several hours.

This version must, therefore, be considered as giving very conservative results.

A more elaborate version of the catalogue to be used with the assistance of an air-pollution meteorologist as stated above can give a more exact evaluation, where it is possible to have special classes with a
complicated type of diffusion as in a ground-based inversion and concentration estimates should be evaluated from special case-studies.

The type of key data (see section 2.2.5.1) should be determined and, in order to make forecasts for the complicated situations listed above, it is generally advisable to include at least two levels of wind speed and direction as key data.

Hot emergency releases cannot be treated by the kinds of dispersion catalogue discussed above as the plume rises considerably owing to its large rate of heat emission. The key data from an ordinary mast will, in such a case, be insufficient.

The handling of the dispersion catalogue in an emergency is usually manual but it is desirable to automate handling by means of a computer. The presentation of the dose charts is made on a display with a geographical map in the background, whereby the actual amount of release, the wind speed and the wind direction can be used. The calculations could also use a continuous scale of atmospheric stability. Making the calculations by a computer gives a safer, quicker forecast of the dispersion course of an accident release. It is possible to initialize the system so that it will automatically read the current key meteorological data, make the necessary calculations and present the result as isolines on a map. It is necessary to have some back-up system for the calculations which can consist either of another computer system or of a manual dispersion catalogue.

In the analysis of an emergency release, methods to obtain the maximum information from existing data are needed. At a certain stage, for example, data may exist on air concentration from an indicating group at three locations at three different times and as much information as possible is required about the three emitted quantities so far and the location of the area contaminated. In such a case, an automated system is very useful.

An automated system can also include factors which are especially difficult and time-consuming to operate in a manual system such as:

- Treatment of emergency cases where there is a time-dependent history of the spread of the release. One example of the usefulness of dynamic boundary-layer models is a sea-breeze circulation;

- Assessment of various types of radioactive impact such as ground-level deposition patterns of specific isotopes or time when the inhalation dose will occur (time for cloud passage).

Some general practical views on meteorological preparedness are given below:

(a) It should be pointed out that the reliability of a meteorological forecast varies with the weather situation: the measures and recommendations must be decided from individual cases after consultation with the weather service and a considerable security margin should already be added at the beginning;
(b) In preparing emergency training, a suitable past weather situation should be selected. During the course of the scenario, successive meteorological forecasts should be given to the decision-making authorities. It is important to make this forecast sequence as "realistic" as possible, e.g. by changing the forecast at some stage of the scenario;

(c) Forecasts for the air layer up to 500 m are not usually included in the routine of a weather service. It is difficult to forecast wind changes of several degrees or metres per second, hence a great uncertainty in forecasting the movement of a radioactive cloud. The general instructions to the weather service should concern emergency releases. The following material should be available in the meteorological office and could be included in the dispersion catalogue:

- Maps and tables or curves to facilitate calculations of the transport and spread (especially lateral cross-wind spread or dispersion angle) of radioactive clouds in the air layer up to about 500 m for various sites and stability characteristics;

(d) The meteorological equipment at the NPP site should be checked regularly and rigorously and the meteorological data continuously recorded. The data should also be transmitted automatically to certain external locations such as a weather service and the emergency headquarters;

(c) All forecasters should be instructed and trained for emergency situations. They should know, for example, where to obtain the relevant meteorological data for each NPP site, where masts are located, etc.

2.2.5.6 Applications

A dispersion catalogue is an instrument for obtaining a quick description of the transport and diffusion of a radioactive release in an emergency situation. An idea of how meteorological information can be used will be given in Examples No. 1 and 2 below.

2.2.5.6.1 Example No. 1.- General description of a very simple type of dispersion catalogue

The input in operative use is:

(a) Amount of material released;

(b) Source characteristics;

(c) Wind direction;

(d) Wind speed;

(e) A specification of the type of severity of the radioactive impact to be considered.
Figure 6 is placed on a map with the circle at the reactor site extending along the wind direction. A, B and C are three characteristic lengths giving the dimensions of the area of impact, which have to be estimated from meteorological and source conditions. The type and severity of impact (e) also have an influence. Thus, if a very small concentration makes an impact, a large area will be influenced.

A gives the dimension of the area of impact close to the reactor site and is estimated from data (a), (b) and (e) above; B and C give dimensions of the area of impact on a larger scale; B is the length of the area of impact in the direction of the wind; C is the width of the area perpendicular to the wind. B and C have to be estimated primarily from (a), (d) and (e).

In preparing the system A, B, and C may be calculated for various values of (a), (b), (d) and (e). The limitations of this type of system are discussed in section 2.2.5.5.

2.2.5.6.2 Example No. 2 - Example of a moderately detailed type of dispersion catalogue

This catalogue is intended to give guidance as to the diffusion of a non-heated radioactive emergency release into the environment of the reactor (up to 20 km) and consists of three parts:

(a) Chimney release (not given in this example);

(b) Release from upper part of reactor building (not given in this example).

(c) Release from lower part of reactor building (see Figures 7, 8 and 9).
Figure 7 - Release from lower part of reactor building: flowchart for establishment of plume type
Figure 8 - Stability index, $\lambda$
Figure 9 - Stability index, λ.
After having established the elevation above ground of the opening of the release, establish what part to use and calculate half-hourly averages of the relevant meteorological parameters:

A. The plume type has now been established. The corresponding ground-level dose pattern can be found on one of the five maps given in Figure 10.

The figures on the dose maps refer to the estimated radioactive dose (Ci s⁻¹ m⁻³) provided that the release is 1 Ci and wind speed is 1 m s⁻¹. The actual configuration is obtained by multiplying all figures by the actual release and dividing by the actual wind speed at the height of 24 m. The actual configuration is then placed on a map (of the same scale) of the region around the NPP in such a way that the ring is placed on the release point and the plume axis in the wind direction;

This procedure is valid for an exposure time between 15 minutes and one hour. For longer periods, an isoline configuration has to be derived for each hour. Each isoline pattern is directed in the hour's wind direction and the isoline systems are added.

B. No dose maps are given. In this extreme inversion case, the release starts by extending at low level to a flat disk of diameter 1-3 km. In calm conditions the release will remain over low terrain for many hours. When the wind speed increases, the release will move away in a broad plume in the direction of the wind at 24 m level.

As an illustration, a release from the lower part of the reactor building and the current meteorological values are supposed to be as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>12 m</th>
<th>24 m</th>
<th>48 m</th>
<th>96 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>14.0</td>
<td>14.0</td>
<td>14.2</td>
<td>13.5</td>
</tr>
<tr>
<td>Wind speed</td>
<td>-</td>
<td>3.2</td>
<td>-</td>
<td>4.2</td>
</tr>
<tr>
<td>Wind direction</td>
<td>-</td>
<td>92°</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The so-called plume type can now be determined by the flowchart. In this special case, the flowchart is used as follows:

- Is temperature lowest at 48 m? No;
- Calculate $\Delta T_0 = T_{12} - T_{96}$: in this case $\Delta T_0 = 0.5 ^\circ C$;
- Is $\Delta T_0 > 1.0$? No;
Figure 10 - Emergency release from lower part of reactor building: dose maps for five stability classes
• Calculate $\Delta T = T_{12} - T_{48}$. In this case $\Delta T = -0.2^\circ C$.

• Determine stability index from Figure 9 by means of the values of $\Delta T$ and $U_{96}$.

• What is the value of $\lambda$? In this case $\lambda = 1.6$.

• The plume type of this $\lambda$-value is 1.5, which can be characterized as being slightly stable. The corresponding dose map is given in the dispersion catalogue.

In the example above of a moderately detailed dispersion catalogue, the stability index $\lambda$ in Figures 8 and 9 is $\lambda = 10 \log R_B$ where $R_B$ is the bulk Richardson number (see section 2.1.6.2. (b) (vi)) derived from

$$R_B = 10^3 \left( \frac{\Delta T}{\Delta z} + 1 \right) / u_f^2$$

where: $\frac{\Delta T}{\Delta z}$ = the vertical temperature gradient in $^\circ C$ per 100 m; and $u_f$ = the speed in m s$^{-1}$ of the wind above the friction layer at 500 - 1 000 m above the ground.

2.3 ASSESSMENT OF METEOROLOGICAL EFFECTS OF COOLING SYSTEMS

Complete information on the environmental effects of cooling towers is found in Cooling Tower Environment (1974). Some remarks and references are also given in IAEA (1980).

There are two major environmental effects of cooling towers at NPP sites:

(a) Meteorological effects of the tower or its emission;

(b) Effects of the cooling tower or its emission on the radioactive plume from the NPP.

The most important effect under (a) is the visible water droplet plume found at wet cooling towers. Mention may be made here of fog formation near the ground, which is found primarily at wet, mechanical-draught cooling towers. At modern high, wet natural-draught towers, ground fog may be expected only occasionally at most sites in cases of strong winds (see Spurr, 1974), when the plume is submitted to downwash (see also Junod et al., 1972).

At wet cooling towers, there are shadowing effects from the water droplet plume. The length of this plume depends on the weather conditions and especially relative humidity (see Barber et al., 1974). Important here also is the rise of the usually buoyant plume (see Briggs, 1975). The visible plume may also reduce the number of hours of sunshine (see Bøgh et al., 1972).

Effects of complex terrain, such as valley winds, may change the path of the visible plume. The wet plume from a cooling tower may influence, for example, the local winds in a narrow valley (see Junod et al., 1972).
If there are several cooling towers close to each other, their plumes may join together, which may increase the length of the visible plume (Barber et al., 1974) and also increase the plume rise (see Cooling Tower Environment, 1974 and Briggs, 1975). If there is a high enough total energy flux from several adjacent cooling towers, a Cumulus cloud may be induced in a suitably stratified atmosphere (see Fortak, 1977).

As regards (b) above, not much published information is available. Some comments and references are given in IAEA (1980) about the effect of a cooling tower - in and out of operation - on the pathway and making of a radioactive plume from an NPP.

The deposition pattern of radioactive material from the NPP plume may be changed as a result of:

(a) A change in the vertical plume path;

(b) The plume mixing and interacting with water droplets.

Some remarks and references about cooling ponds and lakes are given in Cooling Tower Environment (1974). A review of references about emissions from cooling towers has been made by Schneider (1982).

2.4 SOURCES OF SCIENTIFIC AND TECHNICAL ADVICE

The meteorological project leader described in section 1.3.1, may obtain general or specific advice from WMO and IAEA. Advice may also be obtained from some foreign or domestic expert body with practical experience of the problem. Reference to such a body may also be obtained from WMO or IAEA.

Much of the information concerning the climatology of the region or the site can naturally be found only within the country itself, as is also true for the quality and representativity of nearby weather stations, problems in making weather forecasts for the region and maybe also the choice of an adequate dispersion model.

The meteorological project leader should also be responsible for the technical part of the local meteorological investigation. The technical planning of the meteorological investigation should be made with the assistance of an engineer suitably experienced in meteorological instruments, data-transmission and -acquisition systems. Such a specialist may be found in the national Meteorological Service. If not, the choice should be made with the advice of WMO or IAEA.

As regards the equipment of the mast (lightning shelters, shielding of transmission cables, heating of sensors and cable boxes, etc.), advice can be obtained from the appropriate telecommunications services.
CHAPTER 3

METEOROLOGICAL CONSIDERATIONS FOR EXTREME VARIABLES AND PHENOMENA

3.1 INTRODUCTION

The design and operation of a nuclear power plant should incorporate the effects of rare and extreme meteorological events. Meteorological variables may attain values having significant implications for safety and should be included in the design of safety-related structures by the establishment of appropriate design criteria. The values of such design bases may be derived from routinely recorded meteorological variables or from the analysis of rare occurrences of severe meteorological phenomena.

In order to assess the impact of the air environment on the plant, methods are provided for determining extreme values for meteorological variables and for establishing the design-basis events for specific phenomena.

3.2 GENERAL FRAME AND TOOLS

In this chapter, which closely follows the IAEA safety guides on meteorological extremes (IAEA, 1981 and 1984), the extremes of meteorological variables and extreme meteorological phenomena are treated in accordance with the following steps:

(a) Description and classification of the events and variables with regard to their effects on safety;

(b) Identification of data source and collection of data;

(c) Analysis of meteorological variables such as air temperature to determine their design bases and identification of the design basis phenomenon event e.g. the design-basis tornado;

(d) Definition of the design-basis value for the variable or of the design basis for the phenomenon (such as pressure drop and maximum wind speed of the design-basis tornado).

In the following sections, the general procedures for evaluating the design bases of extreme meteorological variables and phenomena are outlined. The procedures are then presented in detail for each variable or phenomenon considered.

The variables characterizing the meteorological environment dealt with in this chapter are wind speed, atmospheric precipitation and temperature. The extreme meteorological phenomena discussed here are the tornado and, briefly, the meteorological input to river and coastal flooding. Detailed procedures for estimation of maximum floods are given in WMO (1969 and 1981) for river sites and in IAEA (1983(b) and 1984) for coastal sites.
3.2.1 Description and classification

Extreme meteorological events are classified into two categories for use in this chapter. The assessment procedures differ for the extreme meteorological variables (EMV) and the extreme meteorological phenomena (EMP).

Extreme meteorological variables are those routinely measured parameters which have the potential to attain values having significant implications for safety and should be taken into account in the design by establishing appropriate design bases.

Extreme meteorological phenomena are complex systems which occur infrequently and the maximum values of whose characteristics are rarely measured at a particular location by the instruments used for routinely measured variables. These phenomena should be taken into account in the design by establishing appropriate design bases for the phenomena.

3.2.2 Data sources and selection

For an evaluation of an EMV, data collected over a long period of time and of an appropriate frequency are needed for each proposed site. Since locally measured data are not normally available for most proposed sites, an assessment should be made of the data available from the continuously manned or continuously recording meteorological stations or substations in the region. Those stations which provide long-term data most representative of site conditions for the variable should be selected. This can generally be accomplished by making comparisons with concurrent data obtained as a result of a near-site short-term meteorological data-collection programme. If no clearly representative long-term station can be identified, then the long-term off-site data are adjusted conservatively and may be used to approximate conditions for the site, provided that the adjustment is based on a statistical comparison of short-term near-site and off-site data.

A catalogue that itemizes the specific meteorological and climatological data collected throughout the world is available (WMO, 1965, 1970 and 1972). This survey details the type of data collected as well as their storage and retrieval media, i.e. paper tape, punched card, or magnetic tape. (Also under preparation by WMO is a comprehensive computerized catalogue of information on climatological and radiation stations, data sets and archives, published data and historical and proxy data for climate research. The catalogue is being developed under the World Climate Data Information Referral Service (INFOCLIMA) project of the World Climate Data Programme.) Similarly, the national Meteorological Services generally publish the parameters for which data are collected and their format, together with an inventory of available data. Data collected at government-supervised meteorological stations normally include (at least) information on wind, temperature and precipitation. Measurements and observations made at meteorological stations are usually published monthly and annually.

The one extreme event for the year should be identified and tabulated for each year in order to perform the extreme statistics calculation. The long-term data base should be a 30-year period of record or longer. In some cases, it will be necessary to accept a data set measured over a shorter period but the resulting extreme-value estimate has an inherently larger uncertainty.
Extreme meteorological phenomena are unlikely to have the maximum values of their characteristics recorded by a fixed instrument network because of their low probability of occurrence at a point, their random distribution within a region and the destructive nature of the event. It is probable that standard instruments will suffer damage or produce unreliable recordings with the passage of such phenomena.

Two categories of data may be collated for an investigation of extreme meteorological phenomena. Official data systematically assembled by specialized organizations in recent years will include a spectrum of intensities; these data should provide the most reliable information. Data obtained from an ensemble of non-scientific record-keeping groups generally provide information on the high-intensity events; local government records, newspaper accounts and even religious records can provide useful information on the most damaging events. The latter type of data is generally dependent on population density, is scarce in the range of low-intensity events and, usually, only provides qualitative information making intensity scaling extremely difficult.

On rare occasions, a comprehensive collection of data may have been made soon after the occurrence of an event. These data could include measured values of variables, eye-witness accounts, photographs, damage descriptions and other qualitative information which were available shortly after the event. Such detailed studies of rare events help in constructing a model of the phenomenon and, in conjunction with the known climatology of a particular region, may contribute to determining the design-basis event for that region.

3.2.3 Design bases

Design bases are derived from extreme values of meteorological variables and from variables associated with extreme meteorological phenomena. Design bases are established to have a sufficiently low probability of exceedance which is based on their effects on safety if not incorporated in the design.

To determine the design basis for extreme meteorological variables, a reference time interval and an acceptable probability of exceedance within that time interval should have been specified. These parameters are determined on the basis of the implication for safety of the meteorological variable and of the margin of safety adopted for the variable in the design. Two approaches may be specified, depending on the unique environmental conditions in the region, and national practice.

In the first approach, a value of the meteorological variable having a specified mean recurrence interval (MRI) is evaluated with the methodology presented in Annex I. The MRI selected is the reference time interval and the associated extreme value is termed the expected extreme event. The margin of safety in the design reflects permissible limits for normal operation and anticipated operational occurrences.

In the second approach, a value of the meteorological variable is determined which has a selected low probability of exceedance in the reference time interval (usually the lifetime of the plant) which is termed the low probability extreme event. An equivalent mean recurrence interval may then be determined by the use of the methods outlined in Annex I. The extreme value
corresponding to this mean recurrence interval can be evaluated with the methodology outlined in the other parts of Annex I. The margin of safety in the design reflects limits for accident conditions.

For either method, the extreme may be pessimized by a quantity related to the standard deviation for the MRI. This adjustment takes into account the sampling error in the estimation as outlined in Annex I.

For evaluating the design basis for extreme meteorological phenomena, two basic methodologies are available: one is based on the knowledge of the fundamental physical characteristics of the phenomena (a deterministic method) and the other on the statistical analysis of the historical data (a probabilistic method). The choice of method depends on the degree of understanding of the relevant phenomena for the region of the site and on the completeness of the historical data, in both quality and quantity. If sufficient information exists to enable the use of both methods, it would be prudent to verify the predictions of one with the other.

Deterministic methods are based on physical relationships or on the use of models which may be empirical to describe the system. For a given input or a set of initial and boundary conditions, the model will predict a single value or a set of values to describe the state of the system. To obtain extreme or conservative estimates, extreme or conservative values of the input parameters have to be used.

Probabilistic methods are concerned with the statistical analysis of historical events to evaluate an extreme event with a given probability of non-exceedance.

3.3 CONSIDERATIONS IN THE VARIOUS STAGES OF SITING AND OPERATING A NUCLEAR POWER PLANT

The design-basis meteorological input in the site-evaluation process is not a governing factor. Nuclear power plants are designed to withstand some degree of magnitude of extreme meteorological events to retain an acceptable level of operational integrity. The design-basis evaluations dealt with in this chapter, therefore, are not considered of consequence beyond the construction phase of the nuclear power plant (i.e. the routine or emergency operation phases).

The main stage where extreme meteorological events can play a significant screening role in determining an acceptable site is the site-survey stage. The contribution of the susceptibility of a site region to extreme phenomena or unusually negative extreme values of meteorological variables is important for comparative purposes. This information alone is, however, insufficient to disqualify a site from the selection process.

3.3.1 Site survey

During the site-survey stage, existing routine and special meteorological information should be inventoried from those sources which can characterize the site. The type of information and its quantitative nature are dependent on the category of extreme event, frequency of discrete events of a given magnitude and implications for safety at proposed sites.
For evaluating extreme meteorological variables, data collected over a long period of time (a climatological record: 30 years) and of an appropriate frequency (every hour, every day, etc.) are needed for each proposed site. Locally measured data are not generally available for most proposed sites. An assessment should therefore be made of those locations for which information is available to select those which provide long-term data most representative of the proposed sites for each variable in question. This can generally be achieved by comparing the results of a near-site short-term meteorological data-collection programme with similar data for the same period of record at a long-term fixed meteorological station.

Detailed meteorological information is generally unavailable for extended record periods to describe adequately the magnitude of the characteristics of extreme phenomena. Because of their destructive nature which may damage even rugged equipment, such events are unlikely to be recorded reliably by fixed instrument networks. Values less than the peak value of an element of the phenomenon or sporadic records due to inadequate instrument response or instrument failure make dependence on actual records inappropriate. An inventory of extreme phenomena occurrences should be compiled from information assembled by specialized organizations (primarily the national Meteorological Service) which conduct damage surveys subsequent to the occurrence. Longer-term information of a more qualitative nature may need to be collected from other accounts such as newspapers and church and local records.

The extent to which assessments should be considered at the site-survey stage is determined by the relative extremes expected at proposed sites and whether such sites are in phenomena-prone regions. Substantial differences should only become apparent if proposed sites have unique mesoscale features or climatic characteristics which differ substantially.

### 3.3.2 Site selection

Extreme meteorological events generally play a minor role in site selection. Rather, the inputs from such evaluations are crucial in the design of critical structures to withstand or endure the elements. Most site-selection studies are conducted within a region of similar climatic features. The extent to which sites exhibit a wide disparity in magnitude of expected or low probability extreme values of meteorological variables or a disparity in susceptibility to extreme meteorological phenomena will determine the relevance of this element in the site-selection process.

### 3.4 EVALUATION OF EXTREME VARIABLES

The general approach for deriving extreme values of meteorological variables to be incorporated into the design of a nuclear power plant has been outlined in earlier sections. This section provides details for specific variables on data sources and selection, statistical analyses, and the evaluation of design-basis values.

#### 3.4.1 Extreme winds

##### 3.4.1.1 Data sources and collection

Wind speeds are generally measured and recorded routinely at continuously manned or continuously recording meteorological stations and form the principal data concerning extreme winds.
Measurement techniques for recording maximum wind vary from country to country. In general, the maximum values are recorded for a given constant duration, i.e., maximum three-second gust (Shellard, 1965); maximum 60 seconds sustained wind speed (Kintanar, 1975). Alternatively, in some countries, wind run instrumentation (such as a triple register) is used to record the shortest time of a fixed-distance traversal of wind, i.e., fastest mile (Thom, 1968) or fastest kilometre. Special processing of the data may be necessary for the evaluation of extreme-wind statistics. It may be necessary to standardize the data base to uniform averaging time periods and uniform heights.

3.4.1.2 Selection of the data set

A near-site measurement programme will help identify nearby stations having long-term records which are representative of the meteorological conditions of the proposed site. To establish representativeness, a comparison should be made between the site data - if available - and the data from the meteorological stations in the region to identify one or more stations which exhibit wind patterns and climatological and physical characteristics similar to those of the site.

All reliable data available from the representative stations should be used in the extreme-statistics analysis. It is desirable to have data for a climatological period of 30 years or more.

Where it is possible to identify a representative station, a conservative interpretation of the available data from the more representative stations should be performed by an experienced meteorologist, allowing for the physical characteristics of the site.

Not all wind data are collected at the same height above the ground; this may vary from station to station and, on some occasions, even data of the same stations are collected at different heights during different periods in the data record. In these cases the data should be normalized to a standard height (usually ten metres above ground-level) using a method of the type outlined in Annex II. This type of method can also be used to evaluate wind speeds at different heights.

A portion of the data set of wind speeds may need to be derived from data records with different averaging times (fastest mile, three-second gust, etc.). In these cases, the data should be normalized to a constant averaging time (duration). The appropriate wind-speed values to be used for the design are those associated with the time durations determined to be critical for the structures (natural frequency of the structures) which may differ in character from the data base. Studies have shown that wind-speed values can be statistically correlated with the averaging time, utilizing a gust-factor relationship.

3.4.1.3 Statistical analysis

This section provides guidance on the selection of the type of statistical distribution that best fits the wind-data set. The factors to be considered are the magnitude and general variability of the data, the nature of the physical processes producing the maximum of the data set and the possible use of non-homogeneous (mixed) distribution when it is apparent that the data set does not fit a single distribution.
In some cases, the data set will have to be analysed for both Fisher-Tippett distributions (Gumbel and Frechet), and a mixed version. This requires that sufficient data are available for each segregated portion of the distribution to determine which analysis most appropriately fits the data at the upper quantile levels (the most relevant region for the evaluation of extremes). If information exists that exhibits a potential for extreme phenomena such as extreme tropical or extreme extra-tropical storms, an appropriate design-basis event for these phenomena should be evaluated.

Studies have indicated that for the majority of locations, the Gumbel distribution generally fits the data well (Lieblein, 1974; Simiu and Filliben, 1975(a) and (b). This is especially true for inland locations with homogeneous data sets. In coastal areas that experience high winds from tropical systems, however, as well as moderate winds from extra-tropical systems, data have been successfully considered in the Gumbel, Fréchet, and mixed Fréchet distributions (Thom, 1968; Simiu, et al., 1979).

3.4.1.4 Design basis

This section outlines the procedures for establishing the design basis wind speeds. In the first of the two methods discussed in section 3.1.3, the expected extreme wind speed associated with the reference time interval is determined and the permissible limits for normal operation and anticipated operational occurrences are used in the design.

In the second method a low-probability extreme wind speed is evaluated which has a defined probability of being exceeded in the reference time interval.* The design limits used are those adopted for accident conditions.

If the design-basis values are evaluated by extrapolating over very long periods of time by means of a statistical technique, due regard should be given to the physical limits of the variable that can be experienced in the area of interest. One should also exercise care in extrapolating to time intervals well beyond the period of record utilized to determine the estimate.

3.4.2 Extreme precipitation

For the evaluation of extreme precipitation, the variable considered is the amount of the precipitation for varying periods of time, including the liquid equivalent of solids. In this section, no discrimination is made between the solid and liquid forms of precipitation.

Two distinct variables are used for extreme precipitation. The first, dealt with in this section, defined as the extreme precipitation for a particular site, is associated with a specific mean recurrence interval (MRI), and is evaluated using probabilistic methods. This statistical method may be used to provide necessary design information on precipitation at the NPP site, such as total depth of accumulation, site drainage, roof runoff, water loading and snow pack. The second, briefly dealt with in section 3.4.2, is a deterministic approach involving the modelling of an event, the probable

* In some countries, the reference time interval is taken to be the lifetime of the plant and the defined probability is $10^{-2}$ to $10^{-3}$. 
maximum precipitation (PMP), which would result in an estimated depth of water for a given duration, drainage area, and time of year for which there is virtually no risk of exceedance. This PMP is used mainly in the evaluation of the design-basis flood (see WMO, 1969).

3.4.2.1 Data sources and collection

Data routinely collected for extreme-precipitation analysis generally include maximum 24-hour precipitation amount. It should be noted that this parameter should be the running 24-hour total rather than a daily total. The analysis should therefore preferably use data from those stations equipped with a continuously recording raingauge, such as a weighing or tipping-bucket type (WMO, 1983(a)). If the continuously recording station network is sparse, however, data from a dense network of non-recording stations should be considered.

Continuously recording station information should be used to evaluate the spectrum of time periods. An objective with multiple time-period evaluations is the construction of a series of precipitation depth-versus-duration curves appropriate for the site.

3.4.2.2 Selection of the data set

A regional assessment of the precipitation régime should be made to ascertain the climatological homogeneity of the site with surrounding meteorological stations. Such an assessment is made in order to select the most appropriate station(s) providing the long-term data series needed for analysis. The selection process should consider, but not be limited to, micrometeorological characteristics, mesoscale systems and topographical influences. Consideration should be given to the supplementary data collected during a near-site short-term measurement programme, if available.

In certain cases, a continuously recording precipitation network does not exist in the vicinity of the site but precipitation totals for fixed intervals do exist for climatologically similar stations. In these cases, similarity concepts may be employed whereby a general statistical relationship may be applied for estimating the maximum event occurring in a specified average period, e.g. 24 hours, from a set of sequential measurements made over any averaging interval up to and including the specified interval (see Annex III).

3.4.2.3 Statistical analysis

In general, analyses of maximum precipitation for long durations of 24 hours or more fit the Gumbel distribution (Hershfield, 1961). Analyses of maximum precipitation for short durations of 24 hours or less fit the Fréchet (Fisher-Tippett Type II) distribution (Jenkinson, 1955). The duration associated with this transition in the type of distribution varies from location to location as a function of the climate. Multiple analyses for varying durations would allow for the construction of precipitation depth-versus-duration curves.

For short sampling periods, excessive precipitation can be observed from intense systems and the resulting statistics may need to be adjusted (Rodda, 1967). Such difficulties arise particularly in areas that experience extreme rainfall owing to orographic conditions.
For a time interval of 12-48 hours, an evaluation must be made to
determine which of the Gumbel or Fréchet distributions best fits the data.
Few guidelines are available and experience is the general rule, but items to
be considered are:

(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 one
distribution does not fit the data well.

The mixed distribution can be useful in treating particular events
that can be distinguished by the precipitation-generating mechanism.

3.4.2.4 Design Basis

This section outlines the procedures for establishing design-basis
precipitation values to be used in designing the drainage system of the site
and the roofs of structures.

The expected extreme precipitation associated with an appropriate
reference time interval* is used in designing the roofs of structures. The
low-probability extreme precipitation is evaluated for the design of other
items such as critical drainage systems. The associated probability level and
the reference time interval are selected on the basis of the relevance of the
precipitation to safety.

3.4.3 Extreme Snow Pack

The load from snow pack on a structure depends 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.

3.4.3.1 Data Sources and Collection

The water equivalent (WMO, 1983(a)) is routinely recorded at most
continuously manned meteorological stations. This variable is defined as the
water-equivalent depth of freshly fallen snow. Data on such variables can be
obtained from the national Meteorological Services. The water equivalent of
snow cover is obtained from melted core samples from undisturbed locations.

3.4.3.2 Selection of the Data Set

If such an amount of snow falls in the region that its load may be
significant for the structural design, a regional assessment should be made of
the snowfall distribution to determine which meteorological station is most
representative. The variables to be considered for such an evaluation should
include winter-time precipitation, snowfall and snow cover. The data set
selected should represent the summer-to-summer year to include each annual
maximum event.

* In some countries, a reference time interval of 50-100 years is used.
It should be noted that, in extremely cold regions where snow on the ground may persist for very long periods, caution should be exercised in estimating the design-basis snow. Snow compaction varies from place to place and this should be taken into consideration. The meteorological station should represent a comparable topographical position, e.g. data from a meteorological station on a south-facing slope should not be used when considering an NPP on a north-facing slope.

In mountainous regions where the density of a meteorological network is such that the values measured at the station may be significantly different from the values of the site, a site-specific evaluation is necessary. The problems of wind-induced drifts and blizzard conditions cannot be treated in a statistical manner. Such problems should be evaluated on a case-by-case basis.

3.4.3.3 Statistical analysis

For the evaluation of the design-basis snow pack, the Gumbel or Fréchet distribution (Ghiocel and Lungu, 1975) or the log-normal distribution (Thorn, 1965 and 1966) may be used. In areas where snow is not an annual event, it is unlikely that the snow load would have a significant bearing on the design load. However, to accommodate such non-snow years, the analysis should be performed by weighing the frequency of snow years for the period of record.

3.4.3.4 Design basis

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 water equivalent is the variable to be considered. For the design-basis snow pack the expected extreme snow pack with an appropriate reference time interval is normally used and in the design the usual permissible limits for normal operation and anticipated operational occurrences are used.

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. Being a winter-time occurrence, the water-equivalent weight of the design-basis snow should be supplemented by a rare precipitation (rain) event.

3.4.4 Extreme temperatures

3.4.4.1 Data sources and collection

Temperature data are collected at continuously manned or continuously recording meteorological stations. In addition, maximum and minimum daily temperatures are recorded at other locations. The specifications for the instrumentation and the requirements for its installation are given in

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1 In some countries, a reference time interval of 50-100 years is used.

2 In one country, the 48-hour winter probable maximum precipitation is added to the snow pack (USNRC, 1978).
detail by WMO (WMO, 1983(a)). The routinely collected data generally form the basis for extreme-temperature analysis.

It should be noted that maximum and minimum thermometers are typically housed in a standard louvered shelter up to two metres off the ground, sufficiently shielded from direct and reflected solar radiation.

3.4.4.2 Selection of the data set

The daily maximum and minimum temperatures for an entire year represent the data subset from which the extreme annual value should be selected to characterize the annual maximum and minimum daily temperature. When considering a high or low temperature extreme, the beginning of the meteorological year should not coincide with a season during which the temperature attains the extreme value. This avoids splitting a single season which contains the extreme value over two successive yearly intervals. Consideration should be given to the supplementary data collected during a near-site short-term measurement programme, if available.

3.4.4.3 Statistical analysis

Extreme temperatures generally follow the Gumbel distribution (Vestal, 1961; Gumbel, 1942) but the concept of extreme values can be wrongly applied if periods shorter than one year are considered (Gringorten, 1962). Caution should be exercised in attempting to fit the extreme-value distribution to a data set representing a season or less.

3.4.4.4 Design basis

The design should incorporate the effect of temperature extremes and the statistical analyses provide the data in usable form for such purposes. The persistence of very high or low temperatures is a factor which may need to be taken into consideration.

3.5 EVALUATION OF EXTREME PHENOMENA

The following sections describe methods for establishing the design bases for extreme meteorological phenomena. The phenomena considered relevant for inclusion in the design of a nuclear power plant are the family of spouts and other events that may result in flooding. The spout (WMO, 1966(b)) can be land- or water-based: for the sake of consistency, the land-based spout is here termed the tornado. Meteorological events that may result in flooding can be differentiated and should be categorized.

The two events that may produce flooding at nuclear power plant sites are: (a) extreme precipitation at most river sites; and (b) wind-driven swells at coastal sites. River and coastal flooding have been discussed in great detail elsewhere, hence they are dealt with only in general terms here.

The methods used to evaluate the design bases for extreme meteorological phenomena involve several steps. These include:

(a) Evaluation of the potential for the phenomenon to exist in the region;
(b) Evaluation of the regional climatology to determine the frequency of occurrence of the phenomenon and degree of intensity;

(c) Identification of the governing physical parameters associated with higher intensity events;

(d) Determination of the probability of the phenomenon striking the site with a given intensity (or greater) or, if inadequate data exist, construction of an appropriate model therefor;

(e) Evaluation of the design-basis event which corresponds to the established design-basis probability value;

(f) Evaluation of the design bases for the event.

3.5.1 Design-basis tornado

The methods used for evaluating the design-basis tornado (DBT) provide a spectrum of probabilities from which the level of severity of an assigned design basis probability value (DBPV) can be determined, i.e. for a site, the probability of occurrence of a tornado having a greater severity than the DBT will be less than a given probability level, the DBPV.

The probability of a site experiencing tornado wind speeds in excess of the DBPV in any year is derived from an assessment of the tornado inventory in conjunction with a tornado risk model. Tornadoes are classified in terms of their frequency and location of occurrence and their related physical characteristics, such as maximum wind speed and damage swath.

The type of model and tornado inventory are interconnected. The scope and detailed specification of the tornado inventory will depend on the method adopted. Also, the method adopted will depend on the specificity of detail in the tornado inventory.

3.5.1.1 General description

Tornadoes are generally described as being violently rotating columns of air, usually associated with a storm. Waterspouts are similar to tornadoes but they generally form under more homogeneous atmospheric conditions in close proximity to large bodies of water.

Tornadoes or waterspouts striking buildings or structures of a nuclear power plant may cause damage by:

(a) The battering effect of very high wind speeds and the wind pressure induced by the translational winds;

(b) The sudden pressure drop which occurs as the vortex of a tornado passes an obstacle, such as a building. The pressure drop may be as high as 0.2 atm and will act explosively if a building is not sufficiently vented to allow rapid equalization of the internal and external pressures;
3.5.1.2 **Collection of information**

Data on tornadoes have to be compiled to determine whether a potential exists for the occurrence of one in a given region.

Tornadic phenomena, identified by appropriate local names, have been documented all around the world, although no authoritative inventory of tornado occurrences around the world for a fixed period of time has yet been prepared. An attempt to collate reports of tornado-like events was made for a four-year period (1963-1966) from documents and other literature (Fujita, 1973). The resulting map, Figure 11, should be taken as a tentative description of tornado-prone areas. The figure should not be interpreted as identifying tornado risk-free areas; it should be noted that this figure demonstrates the data-population bias associated with reporting such events. Those areas associated with a higher frequency of tornado incidence are generally those areas for which well-developed meteorological monitoring networks exist.

If the possibility exists for tornadoes to occur in the region, further steps will need to be taken to collate the information in an acceptable form for analysis; these steps are outlined in the following sections. In most areas it is unlikely that this information will be sufficiently detailed to complete the analysis. In this case, it may be necessary to transpose the site to an area with a similar climatic régime where sufficient data do exist. Detailing the similarity of climatic zones, air-mass types, overrunning synoptic situations, moisture environments and other factors, affords the opportunity for such an assessment. Such similarity assessments should be made to ascribe conservatively estimated characteristics of the design-basis tornado.

3.5.1.3 **Preparation of an inventory**

The information collated for the region in which the site lies needs to be stratified to differentiate the total data population. Classification schemes are used to describe the characteristics of each tornado of which the most widely used is known as the FPP Scale (a combination of the Fujita F-scale rating for maximum wind speed; the Pearson P-Scale for path length; and the Pearson P-Scale for path width). This classification scheme is detailed in Annex IV.

Each tornado occurring in the region should be classified by intensity and damage swath. The information available is generally only for that portion of the event when the tornado is in contact with the ground. It is difficult to take into account those tornadoes which do not come in contact with the ground at all or to assign an effective damage rating for the lifted portion of a tornado which touches the ground intermittently. For tall structures, this may result in underestimating the probability of interaction. In the case of a skipping tornado, a path length of 1/4 of the total path length is adopted and for tornadoes reported as having only "touched down", a value of 1.6 km is conservatively assumed for the path length (Abbey and Fujita, 1975).
Figure 11 - Tornadic phenomena expected to occur over a four-year period (partially based on records from 1963 to 1966 (after Fujita, 1973)
The proper interpretation of tornado reports collected from the general public will present a problem. If the tornado description is vague it is recommended that the F-scale intensity class should be assigned conservatively. Duplication reporting will require scrutiny in the case of multiple tornadoes. For the evaluation of the design-basis tornado, as will be illustrated in the following sections, specification of the path area (path width and path length) and intensity (F-scale) become critical.

For evaluation of the design-basis tornado a global region should be chosen which encompasses the site, is climatologically homogeneous and exhibits uniform tornado characteristics. These factors generally dictate a typical region of a 3° by 3° longitude by latitude square. The region may be divided into subregions (local region) and, for each subregion, the frequency of occurrence of tornadoes may be evaluated. These local regions may be compared to assess the homogeneity of the global region and the degree of conservatism in the choice of occurrence frequency for the regions.

Some conservatism is inherent in this method. One factor contributing to the over-estimation arises from the practice of assuming the maximum wind speed along the entire trajectory. Another conservative factor arises from assigning the maximum width value to the entire path length.

3.5.1.4 Evaluation methods for determining the design-basis tornado

Several methodologies are available to establish the characteristics of the DBT. The scope and level of detail available for the tornado inventory will in some cases depend on the method adopted; in most cases, however, the method adopted will depend on the specificity of the inventory.

Two methods are presented which can be used to evaluate the DBT. The first method, referred to as the AEC Tornado Risk Model (for want of a better title) is based on a point strike-probability relationship (Thom, 1963) and a wind-speed probability relationship. The second method, referred to as the IDR Tornado Risk Model (McDonald et al. 1975), is a more realistic examination of the problem.

The AEC model should be used primarily when the tornado inventory is seriously lacking in information regarding damage and ground contact. This method is an effective screening technique to compare regional tornado characteristics. The IDR model could only be used when comprehensive tornado information exists for each occurrence in the inventory. Although a vast improvement on the former method, the inventory used to establish the design basis should be of sufficient duration to ensure its representativeness.

3.5.1.4.1 AEC tornado risk model

One of the available tornado risk models is presented by Markee et al. (1974). The AEC model was an initial attempt to quantify the tornado hazard as applied to nuclear power plants. Three basic steps are involved in the methodology:

(a) Calculation of the probability of the site being struck by a tornado;
(b) Determination of the probabilities of wind speeds greater than given thresholds in the region of the site;

(c) Assumption of the level of risk associated with the design basis probability value (DBPV) to yield the DBT maximum wind speed.

3.5.1.4.2 Tornado strike-probability relationship

A site region, selected on the basis of meteorological and physiographical homogeneity, is defined to permit the assessment of the strike-probability relationship. The tornado strike probability can be determined from the frequency of occurrence of tornadoes in the global region, the mean path area of tornadoes in the region and the area of the global region.

The strike-probability relationship is determined from (Thom, 1963):

\[ P_s(n) = 1 - (1 - \frac{a}{A})^n \]  \hspace{1cm} (3.1)

where: \( P_s(n) \) = the probability that the location will experience at least one tornado strike per year;

\( a \) = mean path area of the tornado inventory;

\( A \) = area of the global region; and

\( n \) = mean number of tornadoes in a period of time, t, (generally one year) in the global region.

Therefore, if:

\[ n = \frac{N_t}{y} \]  \hspace{1cm} (3.2)

where: \( N \) = the total number of occurrences of tornadoes for the global region tornado inventory;

\( y \) = the years of record of the tornado inventory;

then:

\[ P_s(t) = 1 - (1 - \frac{a}{A})^{\frac{N_t}{y}} \]  \hspace{1cm} (3.3)

where: \( P_s(t) \) = the probability that the location will experience at least one tornado strike in t years.

This can be approximated by the following, if \( t = 1 \):

\[ P_s(t) = \frac{na}{A} \]  \hspace{1cm} (3.4)

3.5.1.4.3 Wind-speed probability relationship

The probability of experiencing a wind speed in the region of the site that is greater than or equal to some magnitude can be obtained from
the intensity-frequency distribution of the tornado inventory. The aggregate frequencies of occurrence of events in excess of wind-speed class values can be translated directly into a probability function. These elements provide a functional relationship of the form:

$$\log (V_i) = S(Z_i) + M$$ \hspace{1cm} (3.5)

where: $V_i$ = threshold wind speed for a discrete intensity class, $i$, which is normally distributed;

$Z_i$ = the value of the random variable, $V_i$, having the standard normal distribution;

$S, M$ = standard deviation and mean based on a least-squares linear-regression analysis.

This can be transposed to a functional relationship in the form of a continuous cumulative distribution function:

$$P(V_1) = f(V_1)$$

This can be extended to be:

$$f(V_1) = \frac{1}{\sqrt{2\pi} S} e^{-\frac{1}{2} \left( \frac{V_1 - M}{S} \right)^2}$$ \hspace{1cm} (3.7)

3.5.1.4.4 Assumption of risk level

The maximum wind speed associated with the design-basis tornado is determined from the intensity probability and strike probability. For the purpose of this risk model, the assumption is implied that the two probability relationships are independent variables; a simplifying and non-conservative assumption that was predicated on the specificity of the available tornado inventory.

The design-basis tornado wind speed is obtained from the following expression:

$$P(V_1) = \frac{DBPV}{P_s(t)}$$ \hspace{1cm} (3.8)

where: $DBPV$ = the specified assigned probability value not to be exceeded by the occurrence probability of the design-basis tornado.

3.5.1.4.5 IDR tornado risk model

Another of the available tornado risk models is presented by McDonald et al. (1975) and discussed by Abbey and Fujita (1975). The Institute for Disaster Research model attempts to be realistic as it accounts for gradations of damage across the damage swath. Four basic steps are involved in the methodology:

(a) Determination of an area-intensity relationship for a global region surrounding the site;
(b) Determination of an occurrence-intensity relationship for a local region surrounding the site;

(c) Calculation of the probabilities of a point within the local region experiencing wind speeds in a given wind-speed interval;

(d) Determination of the probability of wind speeds greater than a given threshold in the local region.

3.5.1.4.6 Area-intensity relationship

A global region, selected on the basis of meteorological and physiographical homogeneity, is defined to permit the assessment of a mean-damage area by intensity relationship. Mean-damage area and wind speed can provide a functional relationship based on the tornado inventory of damage characteristics for the region. This relationship can take the form:

\[
\log (a_i) = c' \log (V_i) + k'
\]

where: 
- \( a_i \) = mean damage path area for a discrete intensity class, \( i \);
- \( V_i \) = median wind speed for the intensity class;
- \( c' \), \( k' \) = constants based on least-squares linear-regression analysis.

The FPP tornado scale is conducive to this type of determination, providing damage-area (path width and path length) and maximum wind-speed (intensity class) information for each event.

3.5.1.4.7 Occurrence-intensity relationship

A local region, wholly within the global region and in which the site lies, is defined to permit an assessment of an occurrence by intensity relationships. The aggregate frequencies of occurrence of events in excess of wind-speed class values are determined from a tornado inventory for the local region. These elements provide a functional relationship of the form:

\[
\log (n_i) = c^* u_i + k^*
\]

where: 
- \( n_i \) = cumulative frequency of occurrence of events in excess of a threshold wind speed, \( u_i \);
- \( u_i \) = threshold wind speed for a discrete intensity class, \( i \);
- \( c^* \), \( k^* \) = constants based on a least-squares linear-regression analysis.

To develop this relationship, the tornado inventory need not be tabulated by characteristics other than maximum wind speed. It is likely that a longer period of record could be available, characterized by this single parameter (e.g. F-scale for wind speed) than for multiple parameters which include damage area. An extended data base would also be desirable as the area in the local region may be significantly smaller than the global region in which it lies.
The frequency distribution of the tornado inventory may exhibit more than a monotonic characteristic. This may be especially true for inventories collected for sparsely populated regions as low intensity events may go unreported. In this case, it may be necessary to segregate the inventory so that two or more functional relationships are evaluated.

Ultimately, the relationship is expressed in an annualized frequency distribution by intensity class. It is this mean annual distribution by class, λ, that is used in the risk model.

3.5.1.4.8 Wind-speed probability relationship

The probability of experiencing a wind speed in the local region that is greater than some threshold speed incorporates the area- and occurrence-intensity relationships with a combined Rankine vortex scheme for the wind-speed profile. This scheme provides the mechanism for incorporating the gradations of wind speed and, therefore, damage associated with a tornado.

Figure 12 illustrates the relationships of the damage area exposed to wind speeds of a given magnitude, assuming the profile is of the combined Rankine type. The mean damage area in this risk model is assumed to be the extent of damage from wind speeds equal to or greater than 33.5 m s⁻¹.

In order to relate the area- and occurrence-intensity relationships to the wind-speed probability, the wind-speed profile was used to develop an expression for the gradation of wind speeds. The area within the damage path that experiences wind speed, \( V_j \), in a tornado with a maximum wind speed, \( V_i \) (e.g. F-scale) is given in the form:

\[
 a_{ij} = \frac{33.5 \cdot a_i (V_{j+1} - V_j)}{(V_{j+1}) (V_j)} \quad \text{when} \quad j < i \tag{3.11}
\]

and

\[
 a_{ij} = \frac{33.5 \cdot a_i}{V_j} \quad \text{when} \quad j = i \tag{3.12}
\]

where: \( a_{ij} \) = area within the damage path that experiences wind speeds \( V_j \) in a tornado with a maximum wind speed of \( V_i \) where \( i \) is the intensity class; and

\( a_i \) = mean damage path area for a discrete intensity class, \( i \), obtained from the area-intensity relationship.

The probability that a point in the local region will experience a wind speed of some magnitude, \( P(V_j) \), is given in the form:

\[
P(V_j) = \frac{\sum_{i=j}^{n} \lambda_i a_{ij}}{\lambda} \tag{3.13}
\]
Figure 12 - Damage area exposed to wind speeds in the interval $j$ (after McDonald et al., 1975, in Abbey, 1976)
where: \( A \) = area of the local region;

\( \lambda_i \) = mean annual frequency of occurrence of tornadoes in the local region for a discrete intensity class, \( i \), obtained from the occurrence-intensity relationship;

\( n \) = class interval containing the highest tornado wind speed considered.

3.5.1.4.9 Probability of exceeding wind speed

The probability that a point in the local region will experience a wind speed greater than or equal to \( V_j \) is given as:

\[
P_E(V_j) = \sum_{j=j}^{n} P(V_j) \tag{3.14}
\]

The spectrum of probabilities can easily be obtained for the risk model by a plot of wind speed versus probability.

3.5.1.5 Design bases for the tornado

A simple model provides the means to evaluate other parameters (rate of pressure drop and total pressure drop) associated with the design-basis tornado. This model is given in the form (Hoecher, 1961; Markee, et al. 1974):

\[
\frac{\Delta p}{dt} = \frac{V_T}{R_m} \rho V_m^2 \tag{3.15}
\]

where:

\( \frac{\Delta p}{dt} \) = rate of pressure drop;

\( V_T \) = translational speed of the tornado;

\( R_m \) = radius of maximum rotational wind speed;

\( \rho \) = density of air;

\( V_m \) = maximum rotational wind speed;

and

\[
\Delta p \approx \rho V_m^2 \tag{3.16}
\]

where: \( \Delta p \) = total pressure drop

These relationships are obtained from the cyclostrophic wind equation. In this case, it is used to describe the balance between the inward radial pressure force and the outward centrifugal force present in a tornado.

To evaluate the total pressure drop and the maximum rate of pressure drop the radius of maximum rotational wind speed \( R_m \) and the maximum translational wind speed \( (V_m \text{ and } V_T \text{ respectively}) \) have to be evaluated. In the USA, \( R_m \) has been assumed to be about 50 m for intense tornadoes.
The maximum rotational wind speed and the maximum translational wind speed have been derived from the hypothesis that for intense tornadoes the ratio remains constant and is given by:

\[
\frac{V_m}{V_T} = \frac{290}{70}
\]  

(3.17)

Using a similar procedure, but based on local characteristics of the tornado, the rate and the total pressure drop may be evaluated for a given site region.

### 3.5.2 Meteorological considerations for the probable maximum flood at river sites

The probable maximum precipitation is the estimated precipitation amount for a given duration, drainage area and time of year and for which there is virtually no probability of exceedance; within the limits of hydrometeorological knowledge and techniques for the PMP for a given duration and drainage area, it approximates that maximum which is physically possible.

The methodology for determining the probable maximum flood on rivers for a given PMP is detailed in Volume II of this Technical Note (WMO, 1981). The meteorological considerations relevant to the evaluation of the probable maximum precipitation as input to the probable maximum flood are given in detail in comprehensive guides on the subject (WMO, 1973; NERC, 1975; ANSI, 1976; Hershfield, 1977; USNRC, 1980 and IAEA, 1983).

#### 3.5.2.1 Preparation of precipitation-data inventory

The meteorological data to be collected and examined for a probable maximum precipitation evaluation should include:

(a) Historical data on precipitation over the drainage basins of the relevant water bodies;

(b) Storm-precipitation records, depth-area-duration data and any available isohyetal maps for severe historical storms which have affected the drainage basin of the site;

(c) Historical data on snow cover and snowmelt.

A scheme for checking for systematic and transformation errors should be established.

#### 3.5.2.2 Evaluation of the probable maximum precipitation

Procedures for evaluating the probable maximum precipitation depend on numerous factors which include the meteorological characteristics responsible for heavy rainfall at any particular site, the amount, type and quality of meteorological data, the topographical features and their relationship to the critical drainage size and rainfall duration. Because the factors involved are almost unique for each site under consideration, no single detailed stepwise procedure can be given for the evaluation. Meteorologists familiar with extreme rainstorm climatology should carry out
the studies that are necessary. For detailed guidance, examples and summaries are given in WMO (1973) for a variety of procedures and methods that have been used in a number of countries.

3.5.3 Meteorological considerations for the probable maximum flood at coastal sites

Several dynamic mechanisms can result in significant flooding at coastal locations. These mechanisms include tropical storms, extra-tropical storms, the tsunami and seiches. In the limited discussion that follows, it is only the probable maximum tropical cyclone that is presented. Guidance is provided in great detail in IAEA (1983b and 1984) which are devoted to the coastal environment and in USWB (1959) and USNWS (1968 and 1979).

3.5.3.1 General description

The tropical cyclone is characterized by a vast rotating mass of warm, humid air one hundred or several hundreds of kilometres in diameter and a well-marked pressure difference between its centre and its periphery. Since the source of energy for the cyclone is the warm sea providing water vapour which releases latent heat while condensing and forming rain, tropical cyclones are generally formed and their energy expended on sea surfaces. Tropical cyclones can cause damage through flooding by heavy rain and/or surges and battering from extreme winds.

The effect of the tropical cyclone at the nuclear power plant site is, therefore, a matter of concern for coastal and near-coastal sites. Section 3.3.2 discussed methodologies for considering extreme precipitation. Details for evaluating the origin of the cyclone, its properties and areas of occurrence are provided in IAEA, 1984.

3.5.3.2 Design basis

For planning and designing hydrological protection of an NPP at a given site, design values pertaining to the most extreme winds (and possibly precipitation), which are the result of a tropical cyclone, are necessary. A probable maximum tropical cyclone is postulated for this purpose, containing a combination of meteorological parameters giving the highest sustained wind speed occurring at the specified location. The most important meteorological factor in determining the maximum winds is the central pressure or the lowest pressure in the eye of the cyclone, termed $P_0$. The difference between the sea-level pressure at the storm centre $P_0$ and that at the periphery of the cyclone $P_W$ is used as an index for characterizing the cyclone intensity or the severity of the wind. Other factors that are needed in determining the wind field are the radius of the maximum wind, the translational speed and the direction of movement of the cyclone relative to the coastline.

Two methods for determining $P_0$ are in use, a probabilistic method dealing with the statistical analysis of historical records and a deterministic method based on fundamental physical laws applied to observed data.
ANNEX I

STATISTICS OF EXTREMES

1. Introduction

The following discussion of the statistics of extremes gives examples of methods to be used in the evaluation of the extreme values of the meteorological parameters important to the safety of nuclear power plants. Comprehensive theoretical discussions of the statistical techniques are available (Gumbel, 1954; Gumbel, 1958 and Lieblein, 1954). In the following, a practical procedure is presented without any attempt to demonstrate the underlying theories. The user requiring additional information is directed to the references.

2. Extreme-value probability distributions

The "extreme value distribution" is based on the following: let \( X_1, X_2, X_3, \ldots, X_p \) be a random set of data from a normal distribution. If we take several such sets, the average values of each also follows a normal distribution. Each set has two extreme values - a minimum value and a maximum value. These extremes do not follow a normal distribution. The distribution followed by these is called an extreme-value distribution. An extreme-value distribution may, however, be applied to the extremes of any random data set (i.e. not necessarily to the extremes of a normal distribution) but the data set must be stationary, i.e. the data should not exhibit any long-term trend or periodicity.

Three extreme-value distributions have been used to describe data sets of extreme values of populations of data, referred to as the Fisher-Tippett distributions (Fisher and Tippett, 1928). Two of these distributions are practical for use in evaluating the meteorological variables under consideration. The Fisher-Tippett Type I distribution is commonly referred to as the Gumbel distribution. The Fisher-Tippett Type II distribution, with the location parameter assumed to be zero, is commonly referred to as the Fréchet distribution.

The formula for the Gumbel distribution (Type I) is given by (Simiu and Filliben, 1975(b)):

\[
P_G(x) = e^{-e^{-\left(\frac{x_G - \alpha_G}{\beta_G}\right)}}
\]

(I.1)

where: \( P_G(x) \) = the probability of non-exceedance of \( X \);

\( \alpha_G \) = a location parameter;

\( \beta_G \) = a scale parameter.
The formula for a Fisher-Tippett Type II distribution is given by:

\[ P_{\text{II}}(X) = e^{- \frac{X - \alpha_{\text{II}}}{\beta_{\text{II}}}} \]  

(1.2)

where:  
- \( \alpha_{\text{II}} \) = a location parameter;  
- \( \beta_{\text{II}} \) = a scale parameter;  
- \( \gamma_{\text{II}} \) = tail-length parameter.

The Fréchet distribution is the Type II distribution with the location parameter equal to zero and is given by:

\[ P_{\text{F}}(X) = e^{- \frac{X_{\text{F}}}{\beta_{\text{F}}}} \]  

(1.3)

where:  
- \( \gamma_{\text{F}} \) = a shape parameter;  
- \( \beta_{\text{F}} \) = a scale parameter.

The Fréchet distribution is the logarithmic transformation of the Gumbel distribution. There is the following correspondence between two variables \( X_{\text{G}} \) and \( X_{\text{F}} \) of the Gumbel and Fréchet distributions respectively.

\[ X_{\text{F}} = e^{X_{\text{G}}} \]  

(1.4)

If \( P_{\text{G}}(X_{\text{G}}) = P_{\text{F}}(X_{\text{F}}) \)  

(1.5)

then \( \beta_{\text{F}} = e^{\alpha_{\text{G}}} \)  

(1.6)

and \( \gamma_{\text{F}} = \beta_{\text{G}}^{-1} \)  

(1.7)

The data set and the results of the extreme-probability analysis are generally presented in graphical form using the extreme-probability papers, which are constructed in such a way that a straight line is obtained for the observed cumulative frequencies of data sets which fit the corresponding distribution, i.e. the reduced variate-versus-data value is a straight-line relationship.

On the extreme-probability paper for a Gumbel distribution the variate \( X_{\text{G}} \) is expressed as a function of the reduced variate:

\[ Y_{\text{G}} = \frac{X_{\text{G}} - \alpha_{\text{G}}}{\beta_{\text{G}}} \]
(see equation I.1) and on the extreme-probability paper for a Fréchet distribution, the variate $X_F$ is expressed as a function of the reduced variate:

$$Y_F = -\gamma_F \ln \left( \frac{X_F}{\beta_F} \right)$$

(see equation I.2). The probability $P_G(Y_G)$ or $P_F(Y_F)$ and the MRI are also represented for each corresponding value of $Y_G$ or $Y_F$.

The type of extreme distribution recommended for some meteorological variables are presented in Table I.1.

### Table I.1

**Probability distribution types for meteorological variables**

<table>
<thead>
<tr>
<th>Meteorological variable</th>
<th>Extreme-probability distribution type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme winds</td>
<td>Gumbel, Fréchet, or mixed Fréchet</td>
</tr>
<tr>
<td>Extreme precipitation (long-term)</td>
<td>Gumbel</td>
</tr>
<tr>
<td>Extreme precipitation (short-term)</td>
<td>Fréchet or mixed</td>
</tr>
<tr>
<td>Extreme temperature</td>
<td>Gumbel</td>
</tr>
<tr>
<td>Extreme snow</td>
<td>Gumbel, Fréchet or log normal</td>
</tr>
</tbody>
</table>

3. **Concept of mean recurrence interval**

A mean recurrence interval (MRI) is defined as the mean time between the occurrence of two events that are equal or greater than a given magnitude. This is frequently called the "return period". Since the term does not imply any averaging, however, it can be interpreted incorrectly, whereas the MRI has a specific connotation; the MRI concept will, therefore, be used throughout this annex.

The relationship between probability of non-exceedance per year, $Q(X)$, and mean recurrence interval is defined as (Gumbel, 1958):

$$MRI = [1 - Q(X)]^{-1}$$  \hspace{1cm} (I.8)

where: $Q(X)$ = the probability of non-exceedance of $X$.

An event with an MRI of N years (meaning that, on average, it will be exceeded every N years) is often referred to as an "N-year event". It is
possible to evaluate the probability that a given N-year event will be exceeded within a given number of V years on average, or vice versa (Vestal, 1961; Crutcher and Nicodemus, 1975; Newberry and Eaton, 1975). This relationship is as follows:

\[ P(X_{N,V}) = 1 - Q(X_N)^V \]  

(I.9)

where: \( Q(X_N) \) = the probability of non-exceedance of \( X_N \) in one year;

\( P(X_{N,V}) \) = the probability of occurrence of an event greater than or equal to \( X_N \) in \( V \) years.

For example, the probabilities with which an event of a given magnitude and an MRI of 100 years, \( X_{100} \), will occur within 50, 100 or 1000 years may be found from Table 1.2; the probability of occurrence of the 100-year event, \( X_{100} \), in 50, 100 and 1000 years is 39.5, 63.4 and 99.9 per cent respectively.

From equations I.8 and I.9, the following relation can be obtained:

\[ P(X_{N,V}) = 1 - (1 - \frac{1}{N})^V \]  

(I.10)

with \( V \) set equal to \( N \), equation I.10 may be approximated by:

\[ P(X_{N,V}) = 1 - e^{-\frac{V}{N}} \]  

(I.11)

which means that the N-year event has an average probability of being exceeded of 63 per cent in \( N \) years.

The concept that the MRI is the mean of all expected N-year events around which a normal or log-normal distribution exists for the Gumbel and Fréchet distributions, respectively, should be kept clearly in mind.

4. Plotting position formulas

The results obtained from using the extreme-value statistics technique are generally presented in graphical form using extreme-probability paper (equations I.1 and I.2). Various plotting procedures have been used, but the method most often employed starts from the data in their observed order \( X_i (i = 1, N) \). These are then ranked according to their relative magnitude (lowest to highest for a maximum analysis and the reverse for a minimum analysis) to obtain a new set \( X_m (m = 1, N) \). Finally, the associated probability plotting positions \( \Phi(m) \) are computed using the following equation:

\[ \Phi(m) = \frac{m}{N + 1} \]  

(I.12)

where: \( \Phi(m) \) = the probability plotting position of \( X \) with the rank \( m \);

\( N \) = the sample size of data set;
m = rank of the given parametric value "X" (rank being the consecutive integers associated with a parameter position based on relative magnitude).

Each data point of the observed data may not be plotted on the suitable extreme-probability paper (Gumbel or Fréchet) as a function of the associated probability plotting position \( \phi(m) \).

5. Data processing with order-statistics approach

The order-statistics approach treats the property of the ordered data sets obtained by ranking the data in increasing or decreasing order of relative magnitude for a maximum and minimum calculation, respectively. This method has been recommended for use by the World Meteorological Organization and by various national agencies for climatological analyses of extreme events (WMO, 1966(a)). The bulk of the discussions in this and the following sections is derived from that WMO publication and from the original work (Lieblein, 1954).

The purpose of data processing with an order-statistics method as presented here is to provide a particular extreme-value distribution which best fits the data set and the confidence interval as a function of the variate.

The evaluation of this theoretical extreme-probability distribution should be performed in such a way that the resulting standard deviations for all the data points are minimized. A numerical value which expresses how well each point of the theoretical curve fits the data is the efficiency, \( E_p \). In the following sections, no attempt is made to explain the theory and only one procedure (Lieblein technique) is presented to perform the extreme-value calculation. Practical examples are given for several meteorological variables.

5.1 The time period and the time sequence

5.1.1 Time period related to each data point

Each data point to be used in the analysis is the maximum or minimum of a particular subsample of the data observed in a particular time period, e.g. the one maximum or minimum of the daily temperatures observed in a year. The data set of the extremes of N years are used for the analysis. The underlying assumptions for the subsamples is that the maximum or minimum event in the period during which the subsample is collected (e.g. one year for the example given) does indeed represent the extreme of large samples (Gumbel, 1954; Gumbel, 1958; Lieblein, 1954). In meteorology, the natural cycle of a year as the sample size is conducive and generally sufficient for consideration of a given variable but caution should be exercised in considering variables (such as extreme 14-hour snowfall) for regions that do not experience occurrences frequently every year. Attempts to consider shorter data periods (less than a year) tend to decrease the sample size to the point that a proper extreme-value distribution no longer holds for the resulting data set. Such decomposition of the distribution is due to improper use of extreme-value theory rather than failure of the theory.
TABLE I.2

Occurrence probability \( P(X_N,Y) \) of an event equal to or greater than the \( N \)-year event in \( Y \) years

<table>
<thead>
<tr>
<th></th>
<th>2</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>50</th>
<th>100</th>
<th>200</th>
<th>500</th>
<th>1,000</th>
<th>2,000</th>
<th>5,000</th>
<th>10,000</th>
<th>100,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.750</td>
<td>0.360</td>
<td>0.190</td>
<td>0.097</td>
<td>0.040</td>
<td>0.020</td>
<td>0.010</td>
<td>0.004</td>
<td>0.002</td>
<td>0.001</td>
<td>0.000</td>
<td>0.0002</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.969</td>
<td>0.672</td>
<td>0.409</td>
<td>0.226</td>
<td>0.096</td>
<td>0.049</td>
<td>0.025</td>
<td>0.010</td>
<td>0.005</td>
<td>0.002</td>
<td>0.001</td>
<td>0.0005</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.999</td>
<td>0.893</td>
<td>0.651</td>
<td>0.401</td>
<td>0.183</td>
<td>0.096</td>
<td>0.049</td>
<td>0.020</td>
<td>0.010</td>
<td>0.005</td>
<td>0.002</td>
<td>0.0010</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0.999</td>
<td>0.878</td>
<td>0.641</td>
<td>0.332</td>
<td>0.182</td>
<td>0.095</td>
<td>0.039</td>
<td>0.029</td>
<td>0.010</td>
<td>0.004</td>
<td>0.002</td>
<td>0.0020</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.995</td>
<td>0.927</td>
<td>0.636</td>
<td>0.395</td>
<td>0.222</td>
<td>0.095</td>
<td>0.049</td>
<td>0.025</td>
<td>0.010</td>
<td>0.005</td>
<td>0.0050</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>0.999</td>
<td>0.994</td>
<td>0.867</td>
<td>0.631</td>
<td>0.394</td>
<td>0.181</td>
<td>0.095</td>
<td>0.049</td>
<td>0.020</td>
<td>0.010</td>
<td>0.0010</td>
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</tr>
<tr>
<td>200</td>
<td>0.999</td>
<td>0.982</td>
<td>0.866</td>
<td>0.633</td>
<td>0.390</td>
<td>0.181</td>
<td>0.095</td>
<td>0.039</td>
<td>0.020</td>
<td>0.0020</td>
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</tr>
<tr>
<td>500</td>
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<td>0.993</td>
<td>0.918</td>
<td>0.632</td>
<td>0.394</td>
<td>0.221</td>
<td>0.095</td>
<td>0.049</td>
<td>0.0099</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,000</td>
<td>0.999</td>
<td>0.993</td>
<td>0.865</td>
<td>0.632</td>
<td>0.394</td>
<td>0.181</td>
<td>0.095</td>
<td>0.039</td>
<td>0.020</td>
<td>0.00995</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2,000</td>
<td>0.999</td>
<td>0.982</td>
<td>0.865</td>
<td>0.632</td>
<td>0.330</td>
<td>0.181</td>
<td>0.095</td>
<td>0.039</td>
<td>0.020</td>
<td>0.01980</td>
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<td></td>
</tr>
<tr>
<td>5,000</td>
<td>0.999</td>
<td>0.993</td>
<td>0.918</td>
<td>0.632</td>
<td>0.393</td>
<td>0.393</td>
<td>0.393</td>
<td>0.393</td>
<td>0.4877</td>
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<td>0.993</td>
<td>0.865</td>
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<td>0.09516</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.1.2 Time sequence of the data points

The Lieblein technique requires that the data set be carefully maintained in the original time order of the climatological series. If the data are not available in the original order of occurrence, the data should be randomized by some acceptable unbiased method. This technique can employ an accepted random number generator or table to assign a random identifier to each number within the data set. The procedure then followed is to rank the random number identifiers in an increasing or decreasing order. By this means, the data are sufficiently randomized. Unfortunately, two independent analyses with the same data set can produce significantly different results. It is, therefore, very important that the data set be maintained in the original order of occurrence whenever possible.

6. Evaluation of the Gumbel distribution

This section provides guidance for applying the order-statistics approach to variables which follow the Gumbel distribution of extreme values.

6.1 Selection of subgroups

The N elements of the basic data set are partitioned into k subgroups of m elements each. If N is not a multiple of k, then there will be a remainder of m (e.g. if a data set consists of 23 elements and it is divided into three groups of six elements each, k = 3, m = 6, the remainder group includes five elements, m' = 5). This appears more complicated than it actually is: to simplify matters, combinations of k, m, and m' which yield the maximum efficiency for each combination of k, m, and m' for sample sizes up to 50 are given in Table I.3. The efficiency, $E_p$, of the analysis depends upon this choice of k. Efficiency is the main parameter by which the partition is optimized and, thus, the variance is minimized.

6.2 Evaluation of the estimates

A set of proportionality factors can be obtained from the selected values of k, m, and m' as follows:

$$\bar{t} = \frac{kmN^{-1}}{t}$$  \hspace{1cm} (I.13)

$$t' = \frac{m'N^{-1}}{t'}$$  \hspace{1cm} (I.14)

$$\bar{q} = \frac{t^{2k^{-1}}}{q}$$  \hspace{1cm} (I.15)

$$q' = (t')^2$$  \hspace{1cm} (I.16)

where the t values are the proportionality factors to be used in the determination of the estimators $\alpha_G$ and $\beta_G$ and the q values are the proportionality factors to be used in the determination of the variance (and the standard deviation).

Here, the (k,m) group will be called the main subgroup and the m' group will be called the remainder subgroup.
### TABLE I.3

**Partitioning scheme for optimization of efficiency**

<table>
<thead>
<tr>
<th>N</th>
<th>(k)(m) + m'</th>
<th>Efficiency (P(x) = 0.99)</th>
<th>N</th>
<th>(k)(m) + m'</th>
<th>Efficiency (P(x) = 0.99)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>-</td>
<td>26</td>
<td>(4) (6) + 2</td>
<td>.799</td>
</tr>
<tr>
<td>2</td>
<td>(1) (2) + 0</td>
<td>.540</td>
<td>27</td>
<td>(4) (6) + 3</td>
<td>.813</td>
</tr>
<tr>
<td>3</td>
<td>(1) (3) + 0</td>
<td>.687</td>
<td>28</td>
<td>(4) (6) + 4</td>
<td>.819</td>
</tr>
<tr>
<td>4</td>
<td>(1) (4) + 0</td>
<td>.750</td>
<td>29</td>
<td>(4) (6) + 5</td>
<td>.827</td>
</tr>
<tr>
<td>5</td>
<td>(1) (5) + 0</td>
<td>.803</td>
<td>30</td>
<td>(5) (6) + 0</td>
<td>.832</td>
</tr>
<tr>
<td>6</td>
<td>(1) (6) + 0</td>
<td>.832</td>
<td>31</td>
<td>(5) (5) + 6</td>
<td>.808</td>
</tr>
<tr>
<td>7</td>
<td>(1) (4) + 3</td>
<td>.727</td>
<td>32</td>
<td>(5) (6) + 2</td>
<td>.805</td>
</tr>
<tr>
<td>8</td>
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<td>33</td>
<td>(5) (6) + 3</td>
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</tr>
<tr>
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<td>(5) (6) + 4</td>
<td>.823</td>
</tr>
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<td>36</td>
<td>(6) (6) + 0</td>
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</tr>
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<td>(7) (6) + 0</td>
<td>.832</td>
</tr>
<tr>
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<td>.832</td>
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<td>(8) (5) + 3</td>
<td>.793</td>
</tr>
<tr>
<td>19</td>
<td>(3) (5) + 4</td>
<td>.793</td>
<td>44</td>
<td>(7) (6) + 2</td>
<td>.812</td>
</tr>
<tr>
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<td>45</td>
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<td>.821</td>
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<td>(7) (6) + 4</td>
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<tr>
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<tr>
<td>23</td>
<td>(3) (6) + 5</td>
<td>.826</td>
<td>48</td>
<td>(8) (6) + 0</td>
<td>.832</td>
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<tr>
<td>24</td>
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<td>.832</td>
<td>49</td>
<td>(9) (5) + 4</td>
<td>.799</td>
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<tr>
<td>25</td>
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<td>.803</td>
<td>50</td>
<td>(8) (6) + 2</td>
<td>.814</td>
</tr>
</tbody>
</table>
The next step is to express the elements of the main subgroup into a matrix. In this matrix, the elements in each individual row are rearranged from the original time order to increasing order \( X(k,m) < X(k,m+1) \) as follows (a main subgroup of 30 elements has been used for this example):

\[
\begin{array}{ccccccc}
X(k,m) & 1 & 2 & 3 & 4 & 5 & 6 \\
1 & x_{11} & x_{12} & x_{13} & x_{14} & x_{15} & x_{16} \\
2 & x_{21} & x_{22} & x_{23} & x_{24} & x_{25} & x_{26} \\
3 & x_{31} & x_{32} & x_{33} & x_{34} & x_{35} & x_{36} \\
4 & x_{41} & x_{42} & x_{43} & x_{44} & x_{45} & x_{46} \\
5 & x_{51} & x_{52} & x_{53} & x_{54} & x_{55} & x_{56} \\
\end{array}
\]

The next step is to obtain the sum of each column of the rearranged matrix:

\[
S_j = \sum_{i=1}^{k} x(i,j) \quad \text{(where } j = 1, 2 \ldots m \text{)}
\]

The distribution parameters \( \bar{\alpha}_G \) and \( \bar{\beta}_G \) can now be calculated with the following formula:

\[
\bar{\alpha}_G = \frac{1}{k} \sum_{j=1}^{m} a_{mj} S_j \quad \text{(I.17)}
\]

\[
\bar{\beta}_G = \frac{1}{k} \sum_{j=1}^{m} b_{mj} S_j \quad \text{(I.18)}
\]

where \( a_{mj} \) and \( b_{mj} \) are given in Table 1.4.

If a remainder group exists (\( m' \neq 0 \)), the procedure will be the same as for the main subgroup in obtaining \( \bar{\alpha}_G \) and \( \bar{\beta}_G \) and a similar procedure is followed for obtaining \( \bar{\alpha}_G' \) and \( \bar{\beta}_G' \) considering the case \( k = 1 \). The values for the estimators \( \bar{\alpha}_G \) and \( \bar{\beta}_G \) for the whole group are then obtained from the following relations:

\[
\bar{\alpha}_G = t \bar{\alpha}_G + t' \bar{\alpha}_G' \quad \text{(I.19)}
\]

\[
\bar{\beta}_G = t \bar{\beta}_G + t' \bar{\beta}_G' \quad \text{(I.20)}
\]

In the absence of a remainder group \( \bar{\alpha}_G = \bar{\alpha}_G' \) and \( \bar{\beta}_G = \bar{\beta}_G' \).
Table of order statistics weights $a_{mj}$ and $b_{mj}$ where $j = m$ or $m'$

<table>
<thead>
<tr>
<th>m or m'</th>
<th>$a_{2j}$</th>
<th>$a_{3j}$</th>
<th>$a_{4j}$</th>
<th>$a_{5j}$</th>
<th>$a_{6j}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>.656320</td>
<td>.510998</td>
<td>.418934</td>
<td>.355450</td>
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<tr>
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<td>.255714</td>
<td>.263943</td>
<td>.246282</td>
<td>.225488</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>.153680</td>
<td>.167609</td>
<td>.165620</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.108824</td>
<td>.121054</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.058350</td>
<td>.083522</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.048867</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>m or m'</th>
<th>$b_{2j}$</th>
<th>$b_{3j}$</th>
<th>$b_{4j}$</th>
<th>$b_{5j}$</th>
<th>$b_{6j}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-.721348</td>
<td>-.630541</td>
<td>-.558619</td>
<td>-.503127</td>
<td>-.459273</td>
</tr>
<tr>
<td></td>
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<td>.255816</td>
<td>.085903</td>
<td>.006534</td>
<td>.035992</td>
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<td>.374725</td>
<td>.223919</td>
<td>.130455</td>
<td>.073199</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.145807</td>
</tr>
</tbody>
</table>

A value of the reduced variate $Y_p$ may now be associated to each value of $X_p$ through the following equation for the Gumbel distribution:

$$Y_p = \frac{X_p - \alpha_G}{\beta_G}$$  \hspace{2cm} (I.21)

The probability may then be evaluated using equation I.1 and the MRI by equation I.8.

6.3. **Evaluation of variance, efficiency and standard deviation**

The variance associated with a specific value of $X_p$ can be determined from $\bar{q}$ and $q'$ (equations I.15 and I.16) and $Q_m$ and $Q_{m'}$, as given by the expression $Q_j$ in Table I.5. The variance is assembled based on the proportionality factors in the form:

$$\text{var} (X_p) = \bar{q} Q_m + q' Q_{m'}$$  \hspace{2cm} (I.22)

All variances may be related to a theoretically specified lower boundary known as the Cramer-Rao lower boundary $Q$. The ratio between $Q_{LB}$ and $\text{var} (X_p)$ is the efficiency, $E_p$: 
where:

\[ Q_{LB} = Q_0 N^{-1} \] (1.24)

and \( Q_0 \) is given in Table 1.5.

### TABLE 1.5

Variance determinators for \( Q_j \) where \( j = m \) or \( m' \)

<table>
<thead>
<tr>
<th>( j = m ) or ( m' )</th>
<th>( A_j )</th>
<th>( B_j )</th>
<th>( C_j )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>.71186</td>
<td>-.12864</td>
<td>.65955</td>
</tr>
<tr>
<td>3</td>
<td>.34472</td>
<td>.04954</td>
<td>.40226</td>
</tr>
<tr>
<td>4</td>
<td>.22528</td>
<td>.06938</td>
<td>.29346</td>
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<td>5</td>
<td>.16665</td>
<td>.06798</td>
<td>.23140</td>
</tr>
<tr>
<td>6</td>
<td>.13196</td>
<td>.06275</td>
<td>.19117</td>
</tr>
</tbody>
</table>

\[ Q_{LB} = Q_0 N^{-1} \]

where: \( Q_0 = (.60793 Y_p^2 + .51404 Y_p + 1.10566) \beta_G^2 \)

The standard deviation, \( \sigma_p \) for each data point \( X_p \) can be obtained from:

\[ \sigma_p = (\text{var} \ (X_p))^{1/2} \] (1.25)

The standard deviation \( \sigma_p \) may now be plotted for each \( X_p \) on extreme-probability paper obtaining the shape of the confidence limit.

Then if the sampling distribution of \( X_p \) is approximately normal:

(a) The \( X_p \pm 1\sigma_p \) confidence interval will represent the limits within which the 68.27 per cent of the events having a particular MRI would fall for the maximum analysis case;
(b) The $X_p + 1\sigma_p$ upper confidence limit will represent the value which will not be exceeded by 84.13 per cent of the events having a particular MRI.

(c) The $X_p + 2\sigma_p$ upper confidence limit represents the value which will not be exceeded by the 97.72 per cent of the events having a particular MRI (for $X_p + 3\sigma_p$ the percentage is 99.87).

An example of a Gumbel distribution calculation is presented in section 9.

7. Evaluation of the Fréchet distribution

The relationship between the Gumbel and the Fréchet distributions has been presented in section 2 of this annex, equations 1.1 to 1.7. To evaluate the estimators related to a Fréchet distribution for a given data set $(X_{Fi}, i = 1, N)$ the data should be transformed to simplify data handling for the data points $(X_{Fi})$, the natural logarithm of each value is determined i.e., $X_{Gi} = \ln X_{Fi}, i = 1, N$. Each of all the other steps of data handling for these $X_{Gi}$ are, therefore, the same as mentioned in the previous section for the Gumbel distribution. A prime objective is obtaining the estimators $\alpha_G$ and $\beta_G$ of the distribution function $\gamma_{GP}$ of the transformed data set. The location and scale parameters of the Fréchet distributions are obtained using equations I.6 and I.7 repeated here:

$$\beta_F = e^{\alpha_G} \quad \text{(I.26)}$$
$$\gamma_F = \beta_G^{-1} \quad \text{(I.27)}$$

The confidence bandwidth or standard deviation, $\sigma_p$ is evaluated using the following equation valid for the Gumbel distribution:

$$X_{gp}(\pm \sigma_p) = \alpha_G + \beta_G \gamma_{GP} \pm 1\sigma_p \quad \text{(I.28)}$$

The $X_{gp}$ must now be transformed back to the actual $X_{fp}$ value as:

$$X_{fp} = e^{X_{gp}} \quad \text{(I.29)}$$

obtaining:

$$X_{fp}(\pm \sigma_p) = e^{(\alpha_G + \beta_G \gamma_{gp} \pm 1\sigma_p)} \quad \text{(I.30)}$$

In the case of the Gumbel distribution, the upper and lower confidence limits are equidistant from the MRI value. In the case of the Fréchet distribution, logarithms of the confidence limits are equidistant from the logarithms of the MRI value. An example of a Fréchet distribution calculation is presented in section 10.

8. Mixed distribution

Certain meteorological parameters and corresponding extreme-value data are generated by different phenomena. A typical example would be tropical and extra-tropical generated winds (ANSI, 1972) with the possible addition of associated convective winds. Similarly, it may be appropriate to treat precipitation generated by various phenomena as a "mixed"
distribution. The method for analysis of such distributions is to segregate each data set according to its generating phenomenon, then weight the MRI and the confidence band for each quantile probability level, $Y_p$, by the segregated data population to the total population. For example, if in a 30-year data base, 20 of the extreme events were generated by an A-type mechanism and the remaining 10 by a B-type mechanism, then two discrete calculations would be made, one for each generating mechanism, and the results are combined weighting the A results by 20/30 and the B results by 10/30.

9. Gumbel distribution example calculations

The Gumbel distribution can be applied for both extreme maximum and minimum analyses. Two examples are presented to illustrate the application of the Lieblein technique for maximum and minimum evaluations.

9.1 Maximum extreme value calculation

This example considers an evaluation for an annual extreme maximum daily temperature (°C). A 36-year data base is provided in sequential order in Table I.6. Using the plotting position formula of equation I.12, the data were ranked so that they could be plotted on Gumbel-type extreme-probability paper (see equation I.1). From Table I.3, the partitioning of the data base provides a six-by-six matrix.

From Table I.4, the weights are selected for a subgroup size with six elements. Table I.7 provides the proportionality factors and illustrates the maximum ordered ranking within each subgroup, the summation, and application of element weights. The resulting calculation is first expressed in terms of the reduced variate and then the probabilistic expression. Either of these equations can be used to determine the magnitude of various quantile levels.

Table I.8 provides the predicted event ($X_p$) as a function of the probability level ($P(X_p)$), the reduced variate ($Y_p$) or the return period (MRI). This table also provides the computed one, two, and three σ confidence bands. The results of the calculation are illustrated in Figure I.1 for the computed line of best fit and the ±$1\sigma_p$ confidence band.

9.2 Minimum extreme value calculation

This example considers an evaluation for an annual extreme minimum daily temperature (°C). A 31-year data base is provided in sequential and ranked order in Table I.9. From Table I.3, the partitioning of the data base provides a five-by-five matrix for the first 25 samples and a remainder group of six.

From Table I.4, the weights are selected for subgroups with five and six elements. Table I.10 provides the proportionality factors and illustrates the minimum ordered ranking within each subgroup, the summation for the main subgroups, and the application of element weights. The expressions derived from the main subgroup and remainder subgroup calculations are then combined based on the proportionality of sample size.

Table I.11 provides the predicted events and confidence bands. The results of the calculation are illustrated in Figure I.2 for the computed line of best fit and the ±$1\sigma_p$ confidence band.
### TABLE 1.6

**Data set - extreme maximum daily temperature**

<table>
<thead>
<tr>
<th>Original data</th>
<th>Ranked data</th>
<th>Plotting position</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>37.80</td>
<td>32.20</td>
<td>.02703</td>
<td>1</td>
</tr>
<tr>
<td>38.30</td>
<td>32.80</td>
<td>.05405</td>
<td>2</td>
</tr>
<tr>
<td>37.20</td>
<td>33.30</td>
<td>.08108</td>
<td>3</td>
</tr>
<tr>
<td>38.90</td>
<td>33.30</td>
<td>.10811</td>
<td>4</td>
</tr>
<tr>
<td>41.70</td>
<td>33.90</td>
<td>.13514</td>
<td>5</td>
</tr>
<tr>
<td>37.80</td>
<td>33.90</td>
<td>.16216</td>
<td>6</td>
</tr>
<tr>
<td>42.20</td>
<td>33.90</td>
<td>.18919</td>
<td>7</td>
</tr>
<tr>
<td>37.80</td>
<td>34.40</td>
<td>.21622</td>
<td>8</td>
</tr>
<tr>
<td>33.90</td>
<td>35.00</td>
<td>.24324</td>
<td>9</td>
</tr>
<tr>
<td>36.10</td>
<td>35.00</td>
<td>.27027</td>
<td>10</td>
</tr>
<tr>
<td>37.20</td>
<td>35.00</td>
<td>.29730</td>
<td>11</td>
</tr>
<tr>
<td>35.60</td>
<td>35.00</td>
<td>.32432</td>
<td>12</td>
</tr>
<tr>
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<td>35.00</td>
<td>.35135</td>
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<td>35.00</td>
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<tr>
<td>35.60</td>
<td>35.00</td>
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<td>15</td>
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</tr>
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<td>.97297</td>
<td>36</td>
</tr>
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</table>
### A. SUBGROUP SIZES AND PROPORTIONALITY FACTORS

\[ N = 36 = k \cdot m + m' = 6 \cdot 6 + 0 \]

\[ t = k \cdot m/N = 1.00000 \]

\[ q = t^2/k = .16667 \]

\[ k = 6 \quad m = 6 \quad m' = 0 \]

### B. MAIN SUBGROUPS

Weights \( a_{mj} \) and \( b_{mj} \)

<table>
<thead>
<tr>
<th>( j )</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_{6j} )</td>
<td>0.35545</td>
<td>0.22549</td>
<td>0.16562</td>
<td>0.12105</td>
<td>0.08352</td>
<td>0.04887</td>
</tr>
<tr>
<td>( b_{6j} )</td>
<td>-0.45928</td>
<td>-0.03599</td>
<td>0.07319</td>
<td>0.12673</td>
<td>0.14953</td>
<td>0.14581</td>
</tr>
</tbody>
</table>

Observations \( X(k.m) \) ordered from \( j = 1 \) to \( j = m \)

<table>
<thead>
<tr>
<th>SUBGROUP</th>
<th>1</th>
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<th>4</th>
<th>5</th>
<th>6</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>37.20</td>
<td>37.80</td>
<td>37.80</td>
<td>38.30</td>
<td>38.90</td>
<td>41.70</td>
</tr>
<tr>
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<td>33.90</td>
<td>35.60</td>
<td>36.10</td>
<td>37.20</td>
<td>37.80</td>
<td>42.20</td>
</tr>
<tr>
<td>3</td>
<td>33.90</td>
<td>34.40</td>
<td>35.00</td>
<td>35.00</td>
<td>35.60</td>
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<td>35.00</td>
<td>37.20</td>
<td>37.20</td>
<td>38.30</td>
</tr>
</tbody>
</table>

TOTAL: 203.80 209.50 213.90 218.80 222.30 239.40

\[
X_p = \frac{a_{mj}}{S_j/k} + \frac{b_{mj}}{S_j/k} Y_p = 35.31 + 1.73 Y_p
\]

\[
F(X_p) = \exp\left(-\exp\left(-\left(\frac{X_p - 35.31}{1.73}\right)\right)\right)
\]
### TABLE 1.8

**Predicted events with confidence bands**

<table>
<thead>
<tr>
<th>Probability level</th>
<th>Return period</th>
<th>Reduced variate</th>
<th>Predicted event</th>
<th>Confidence bands</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.682</td>
<td>.954</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Upper</td>
<td>Lower</td>
</tr>
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<td>.367</td>
<td>35.94</td>
<td>36.28</td>
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</tr>
<tr>
<td>.8000000</td>
<td>5</td>
<td>1.500</td>
<td>37.91</td>
<td>38.45</td>
<td>37.37</td>
</tr>
<tr>
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<td>10</td>
<td>2.250</td>
<td>39.21</td>
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Figure I.1 - Extreme maximum daily temperature - example of Gumbel distribution calculation
## TABLE I.9

**Data set - Extreme minimum daily temperature**

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TABLE I.10
Gumbel-type minimum-value analysis

A. SUBGROUP SIZES AND PROPORTIONALITY FACTORS

\[ N = 31 = k \cdot m + m' \]
\[ t = (k \cdot m) / N = 0.80645 \]
\[ t' = (m') / N = 0.19355 \]
\[ k = 5 \]
\[ m = 5 \]
\[ m' = 6 \]

B. MAIN SUBGROUPS

Weights \( a_{mj} \) and \( b_{mj} \)

\[
\begin{array}{cccccc}
  j = & 1 & 2 & 3 & 4 & 5 \\
  a_5j = & 0.41893 & 0.26428 & 0.16761 & 0.10882 & 0.05835 \\
  b_5j = & -0.50313 & 0.0653 & 0.13045 & 0.18166 & 0.18448 \\
\end{array}
\]

Observations \( X_{(k,m)} \) ordered from \( j = 1 \) to \( j = m \)

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\[
\bar{X}_p = (a_{mj}, S_j/k) + (b_{mj}, S_j/k) \quad \bar{Y}_p = -26.98 -3.57 \quad \bar{Y}_p \quad a_G \quad b_G
\]

REMAINDER SUBGROUP

Weights \( a_{m'j} \) and \( b_{m'j} \)

\[
\begin{array}{cccccc}
  j = & 1 & 2 & 3 & 4 & 5 & 6 \\
  a_6'j = & 0.35545 & 0.22549 & 0.16562 & 0.12105 & 0.08352 & 0.04887 \\
  b_6'j = & -0.45928 & -0.03599 & 0.07319 & 0.12673 & 0.14953 & 0.14581 \\
\end{array}
\]

Observations \( X_{m'} \) ordered from \( j = 1 \) to \( j = m' \)

\[
\begin{array}{cccccc}
  j = & 1 & 2 & 3 & 4 & 5 & 6 \\
  1 & -27.70 & -29.90 & -31.00 & -34.90 & -34.90 & -35.50 \\
\end{array}
\]

\[
X'_{p} = (a_{mj}', S_{j'}) + (b_{mj}', S_{j'}) \quad \bar{Y}'_{p} = -30.60 -3.29 \quad \bar{Y}'_{p} \quad a_G' \quad b_G'
\]

C. ESTIMATORS

\[
X_p = t \cdot \bar{X}_p + t' \cdot X'_p = -27.68 -3.52 \quad \bar{Y}_p \quad a_G \quad b_G
\]

\[
F(X_p) = \exp(-\exp(-((X_p + 27.68)/-3.52)))
\]
10. **Fréchet distribution example calculation**

The Fréchet distribution is a "bounded" distribution and can only be applied for an extreme maximum analysis. The example presented considers the evaluation for an annual extreme maximum one-minute wind speed (m s\(^{-1}\)). To demonstrate the application of the method given in Annex II as well, the data presented were collected at two different measurement heights.

A 38-year data base is provided in sequential order in Table I.12 with the resulting wind speeds normalized to a uniform height using equation II.1 with \( \alpha \) equal to 0.14 (1/7). The data to be used for the calculation and the ranked data to be plotted (see equation I.2 for Fréchet-type extreme probability paper) are given in Table I.13. In order to perform the evaluation the data are transformed by taking the natural logarithm of each sample; the transformation is given in Table I.14.

From Table I.3, the partitioning of the transformed data base provides a six-by-six matrix for the first 36 samples and a remainder group of two. From Table I.4, the weights are selected for subgroups with two and six elements. Table I.15 provides the proportionality factors and illustrates the maximum ordered ranking of the transformed data within each subgroup, the summation for the main subgroup and the application of element weights. The expressions derived from the main subgroup and remainder subgroup calculations are then combined, based on the proportionality of sample size. Also given is the complimentary expression relating the Gumbel version to the Fréchet version following the discussion of equations I.3 to I.7.

Table I.16 provides the predicted events and confidence bands. It should be noted that these were determined using the evaluation in the Gumbel form and transforming the estimates using equations I.28 to I.30. The results of the calculation are illustrated in Figure I.3 for the computed line of best fit and the ±1\( \sigma \) confidence band.
Figure I.2 Extreme minimum daily temperature - example
### TABLE I.11

Predicted events with confidence bands

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### TABLE I.12

Normalization of sample data to uniform height (10 m)

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<td>25.90</td>
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<td>.89744</td>
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<td>18.80</td>
<td>38.40</td>
<td>.92308</td>
<td>36</td>
</tr>
<tr>
<td>26.80</td>
<td>38.40</td>
<td>.94872</td>
<td>37</td>
</tr>
<tr>
<td>20.60</td>
<td>46.40</td>
<td>.97436</td>
<td>38</td>
</tr>
</tbody>
</table>
### TABLE 1.14

**Transformation of Fréchet samples to Gumbel samples**

<table>
<thead>
<tr>
<th>Original data</th>
<th>Natural logarithm of original data</th>
<th>Original data</th>
<th>Natural logarithm of original data</th>
</tr>
</thead>
<tbody>
<tr>
<td>28.7</td>
<td>3.3569</td>
<td>19.8</td>
<td>2.9857</td>
</tr>
<tr>
<td>38.4</td>
<td>3.6481</td>
<td>21.1</td>
<td>3.0493</td>
</tr>
<tr>
<td>30.8</td>
<td>3.4275</td>
<td>32.5</td>
<td>3.4812</td>
</tr>
<tr>
<td>23.2</td>
<td>3.1442</td>
<td>30.4</td>
<td>3.4144</td>
</tr>
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<td>3.6481</td>
<td>28.7</td>
<td>3.3569</td>
</tr>
<tr>
<td>30.4</td>
<td>3.4144</td>
<td>22.8</td>
<td>3.1268</td>
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<td>27.8</td>
<td>3.3250</td>
<td>19.2</td>
<td>2.9549</td>
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<tr>
<td>32.5</td>
<td>3.4812</td>
<td>38.0</td>
<td>3.6376</td>
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<tr>
<td>27.8</td>
<td>3.3250</td>
<td>24.1</td>
<td>3.1822</td>
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<tr>
<td>23.6</td>
<td>3.1612</td>
<td>32.2</td>
<td>3.4720</td>
</tr>
<tr>
<td>24.9</td>
<td>3.2149</td>
<td>27.3</td>
<td>3.3069</td>
</tr>
<tr>
<td>20.7</td>
<td>3.0301</td>
<td>26.8</td>
<td>3.2884</td>
</tr>
<tr>
<td>46.4</td>
<td>3.8373</td>
<td>23.2</td>
<td>3.1442</td>
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<td>3.1612</td>
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<td>3.0007</td>
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<td>24.0</td>
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<td>2.9339</td>
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<td>21.9</td>
<td>3.0865</td>
<td>25.9</td>
<td>3.2542</td>
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<tr>
<td>27.4</td>
<td>3.3105</td>
<td>18.8</td>
<td>2.9339</td>
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<td>3.4275</td>
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<td>3.2884</td>
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<tr>
<td>19.0</td>
<td>2.9444</td>
<td>20.6</td>
<td>3.0253</td>
</tr>
</tbody>
</table>
STATISTICS OF EXTREMES

TABLE I.15

Fréchet-type maximum value analysis

A. SUBGROUP SIZES AND PROPORPORTIONALITY FACTORS

\[ N = 38 \cdot k \cdot m + m' \]
\[ t = k \cdot m / N = 0.94737 \]
\[ t' = m' / N = 0.05263 \]
\[ K = 6 \]
\[ m = 6 \]
\[ m' = 2 \]

B. MAIN SUBGROUPS

Weights \( a_{mj} \) and \( b_{mj} \)

<table>
<thead>
<tr>
<th>j</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_{6j} ) =</td>
<td>0.35545</td>
<td>0.22549</td>
<td>0.16562</td>
<td>0.12105</td>
<td>0.08352</td>
<td>0.04887</td>
</tr>
<tr>
<td>( b_{6j} ) =</td>
<td>-0.45928</td>
<td>-0.03599</td>
<td>0.07319</td>
<td>0.12673</td>
<td>0.14953</td>
<td>0.14581</td>
</tr>
</tbody>
</table>

Logarithm of observations \( X(k,m) \) ordered from \( j = 1 \) to \( j = m \)

<table>
<thead>
<tr>
<th>SUBGROUP</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.14</td>
<td>3.36</td>
<td>3.41</td>
<td>3.43</td>
<td>3.65</td>
<td>3.65</td>
</tr>
<tr>
<td></td>
<td>3.03</td>
<td>3.16</td>
<td>3.21</td>
<td>3.33</td>
<td>3.33</td>
<td>3.48</td>
</tr>
<tr>
<td></td>
<td>3.09</td>
<td>3.16</td>
<td>3.18</td>
<td>3.31</td>
<td>3.43</td>
<td>3.48</td>
</tr>
<tr>
<td></td>
<td>2.94</td>
<td>2.99</td>
<td>3.05</td>
<td>3.36</td>
<td>3.41</td>
<td>3.48</td>
</tr>
<tr>
<td></td>
<td>2.95</td>
<td>3.13</td>
<td>3.18</td>
<td>3.31</td>
<td>3.47</td>
<td>3.64</td>
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<tr>
<td></td>
<td>2.93</td>
<td>2.93</td>
<td>3.00</td>
<td>3.14</td>
<td>3.25</td>
<td>3.29</td>
</tr>
</tbody>
</table>

TOTAL 18.09 18.73 19.04 19.87 20.54 21.37

\[ \bar{X}_p = (a_{mj} \cdot S_j / K) + (b_{mj} \cdot S_j / k) \]

REMINDER SUBGROUP

Weights \( a_{m'j} \) and \( b_{m'j} \)

<table>
<thead>
<tr>
<th>j</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_{2j} ) =</td>
<td>0.91837</td>
<td>0.08363</td>
</tr>
<tr>
<td>( a_{2j} ) =</td>
<td>-0.72135</td>
<td>0.72135</td>
</tr>
</tbody>
</table>

Logarithm of observations \( X_{m'} \), ordered from \( j = 1 \) to \( j = m' \)

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.03</td>
<td>3.29</td>
</tr>
</tbody>
</table>

\[ X_{p'} = (a_{m'j} \cdot S_j') \]

C. ESTIMATORS

\[ X_p = t \cdot X_p + t' \cdot X_{p'} = 3.16 + 0.19 Y_p \]

\[ F(X_p) = \exp(-\exp(-( (X_p - 3.16) / 0.19 ))) \]

\[ F(X_p) = \exp(-((X_p / 23.48)^{-5.37})) \]

\[ X_p = X_{Op} \]

\[ X_p = X_{FP} \]
<table>
<thead>
<tr>
<th>Probability level</th>
<th>Return period</th>
<th>Reduced variate</th>
<th>Predicted event</th>
<th>Confidence bands</th>
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<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
<td>.682 Upper</td>
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<td>.5000000</td>
<td>2</td>
<td>.367</td>
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<tr>
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<td>1.500</td>
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<td>32.85</td>
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<tr>
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<td>10</td>
<td>2.250</td>
<td>35.69</td>
<td>38.46</td>
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<tr>
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<td>2.970</td>
<td>40.81</td>
<td>44.78</td>
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<tr>
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<td>63.31</td>
</tr>
<tr>
<td>.9950000</td>
<td>200</td>
<td>5.296</td>
<td>62.92</td>
<td>73.42</td>
</tr>
<tr>
<td>.9980000</td>
<td>500</td>
<td>6.214</td>
<td>74.65</td>
<td>89.28</td>
</tr>
<tr>
<td>.9990000</td>
<td>1000</td>
<td>6.907</td>
<td>84.93</td>
<td>103.51</td>
</tr>
</tbody>
</table>
Figure I.3 Extreme maximum one-minute wind speed - example
ANNEX II

NORMALIZATION OF MAXIMUM WIND-SPEED DATA TO ALLOW FOR AVERAGING PERIOD, REFERENCE HEIGHTS AND TERRAIN CHARACTERISTICS

The reference averaging period and the height above ground-level for gust speeds to be used in design calculations depend on the size and height of the structure. Methods of normalizing over different time periods are discussed by various authors (e.g. Durst, 1960; Hollister, 1970; and Shellard, 1965). Data are often presented in terms of an hourly or short-term (e.g. three or five seconds) averaging time. The ratios between gusts of different averaging periods are related to terrain roughness for which standard categories have been specified (Newberry and Eaton, 1975). Maximum gust values may need to be adjusted to take account of topographical factors such as sheltering within valleys or winds on exposed hill-tops.

Variation of wind speed with height may be expressed in the form of a power law of the form:

\[ V_h = V_z \left( \frac{h}{z} \right)^{\alpha} \]  \hspace{1cm} (II.1)

where: \( h \) = reference height;
\( z \) = measurement height;
\( V \) = wind speed.

The exponent \( \alpha \) can vary with averaging period, surface roughness and whether the profile relates to average or extreme winds (Hellman, 1916; Hardman et al., 1973).

Factors of the above type are usually combined in various ways for the purposes of building codes. See, for example, BSI (1972) and ANSI (1972). In the situation where a long-term record is being analysed but the characteristics of the measuring system have changed (e.g. exposure height, instrument response time) it will be necessary to adjust the data and an understanding of the basic relationships outlined above will be required.

It is deemed inappropriate to specify a default set of values when building codes of numerous countries exist. An appropriate set of factors should be selected to reflect the setting in which the data-base values were measured. Additionally, adjustments to the estimates may need to be made to reflect the differences between the measurement and site locations.
ANNEX III

PRECIPITATION ADJUSTMENT FROM FIXED-INTERVAL DATA

Data collected in the form of precipitation totals for fixed, sequential intervals may be used to estimate the maximum for a given interval. The relationship is given graphically in Figure III.1. Using this method, a maximum 24-hour precipitation would, for example, be 1.01 times the sum of the 24 consecutive one-hour totals which yield the maximum value or 1.13 times the maximum precipitation measured over consecutive 24-hour periods.

![Graph showing adjustment of fixed interval precipitation amounts for number of observational units within the interval]

Figure III.1 - Adjustment of fixed interval precipitation amounts for number of observational units within the interval (after Weiss, 1964, in WMO, 1973)

The above curve was obtained by combining results for a wide variety of locations; no allowance is made for the magnitude of discrete events nor for the variance in the statistics. It may be possible to acquire sufficient data to generate a similar curve for the area of interest or multiple curves for various precipitation ranges.

In all cases, however, this method amounts to the introduction of a bias, obtained by statistical analysis, into observed data. This fundamental limitation of the procedure should not be overlooked.
ANNEX IV

CHARACTERISTICS OF TORNADOES

1. General description

The tornado is visible as a condensation funnel that extends downwards from a cloud base or as a rotating dust cloud rising from the ground. The ground-based phenomenon, dust devil, is a result of differential surface heating and should not be confused with the elevated base tornado. As the storm moves, one or more tornadoes may form at intervals along the path, travel a few kilometres, lift and then reappear further along the track.

A tornado vortex may be described in terms of its tangential, radial and vertical airflow and associated atmospheric pressure drop. In this annex, the three wind components are assumed to be axisymmetrical.

Tornadoes can be characterized by a mutually consistent set of parameters including maximum horizontal wind speed, radius of maximum horizontal wind speed, vertical wind speed, radial wind speed, translation speed of the tornado as a whole and atmospheric pressure change.

Dimensions of visible portions of tornadoes vary considerably: the vertical extent is generally dependent on the altitude of the base of the cloud and may be 300 – 3 000 m or greater, extending somewhat into the cloud. The width of the path of destruction produced by a tornado touching the ground can vary from several metres to more than five kilometres. The length of the path of destruction can vary from several metres to several hundreds of kilometres. Tornado wind speeds have been estimated from 30 to more than 140 m s⁻¹.

Waterspouts are similar to tornadoes but generally form under more homogeneous atmospheric conditions: they form over water bodies and, on occasion, cross the coastline and penetrate several kilometres inland. Characteristically, they are similar to tornadoes, having a high-speed air vortex and a structure descending from the cloud base; occasionally they are destructive. Waterspouts tend to be less intense than tornadoes and smaller in dimension (Golden, 1971, 1973, 1974). Information regarding frequencies and characteristics of waterspouts is sparse.

2. Fujita-Pearson classification scheme

2.1 Maximum wind speed

The Fujita intensity scale number F(V), V = 0 to 5⁺, is based on the most destructive characteristics of particular tornadoes and is also related to maximum wind speed. The following relationship yields the minimum wind speeds, \( F_V \), in metres per second, associated with a given Fujita scale, \( V \):

\[
F_V = 6.30 (V + 2)^{1.5} \quad \text{for } V = 0, 1, \ldots, 5
\]  (IV.1)
Such a relationship yields an increasing increment as class number increases. A characterization of F-scale ranges as well as a description of potential damage is given in Table IV.1; photographs of characteristic damage of the more common classes (F1 to F5) are given in Figure IV.1.

The wind-speed increments between F-scale classes were designed to be sufficiently large so as to allow the estimation of damage to within a possible error of one class. The maximum damage characteristics in terms of F-class occurring within a portion of the path of a particular tornado should be taken as the overall rating for that tornado.

2.2 Path length

The Pearson path-length scale number $P(L)$, $L = 0$ to 5, is based on the actual path length of each tornado. Path length is defined as that along-axis distance of the tornado's path during which the tornado was in contact with the ground. The following relationship yields the minimum path length, $PP_L$, in kilometres, associated with a given Pearson-scale, $L$:

$$PP_L = 1.6 \times 10^{0.5(L - 1)} \quad L = 0, 1, \ldots, 5 \quad (IV.2)$$

2.3 Path width

The Pearson path-width scale number $P(W)$, $W = 0$ to 5 is based on the average width of the tornado. The path width is defined as the average cross-axis distance of the damage area measured in the direction perpendicular to the path. The lifted portions are thus excluded from the averaging. The following relationship yields the minimum path width, $PP_W$, in metres, associated with a given Pearson-scale, $W$:

$$PP_W = 1.609 \times 10^{0.5(W - 5)} \quad W = 0, 1, \ldots, 5 \quad (IV.3)$$

2.4 FPP tornado scale

The FPP tornado scale combines the three characteristics discussed above. The values of wind speed, path length, and path width are given for each scale increment in Table IV.2 based on equations IV.1 to IV.3. Most tornadoes can be expressed by the FPP scale ranging from 0, 0, 0 to 5, 5, 5. Higher values may be used when necessary.
<table>
<thead>
<tr>
<th>Classification</th>
<th>Speed (m s(^{-1}))</th>
<th>Damage Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(F0)</td>
<td>&lt; 33 m s(^{-1}) - LIGHT DAMAGE</td>
<td>Some damage to chimneys and TV antennae; twigs broken off trees; shallow-rooted trees pushed over</td>
</tr>
<tr>
<td>(F1)</td>
<td>33 - 49 m s(^{-1}) - MODERATE DAMAGE</td>
<td>Surfaces peeled off roofs; windows broken; light trailer-houses pushed or overturned; some trees uprooted or snapped off; automobiles moved, some pushed off the road; 32.6 m s(^{-1}) is the beginning of hurricane-wind speed.</td>
</tr>
<tr>
<td>(F2)</td>
<td>50 - 69 m s(^{-1}) - CONSIDERABLE DAMAGE</td>
<td>Roofs torn off frame-houses leaving strong upright walls; weak buildings in rural areas demolished; trailer-houses destroyed; large trees snapped off or uprooted; railroad boxcars pushed over; light object missiles generated; cars blown off roads</td>
</tr>
<tr>
<td>(F3)</td>
<td>70 - 92 m s(^{-1}) - SEVERE DAMAGE</td>
<td>Roofs and some walls torn off frame-houses; some rural buildings completely demolished; trains overturned; steel-framed hangar warehouse-type structures torn; cars lifted off the ground; most trees in a forest uprooted, snapped off, or levelled</td>
</tr>
<tr>
<td>(F4)</td>
<td>93 - 116 m s(^{-1}) - DEVASTATING DAMAGE</td>
<td>Whole frame-houses levelled, leaving piles of debris; steel structures badly damaged; trees debarked by small pieces of flying debris; cars and trains thrown some distance or rolled considerable distances; large missiles generated</td>
</tr>
<tr>
<td>(F5)</td>
<td>117 - 140 m s(^{-1}) - INCREDIBLE DAMAGE</td>
<td>Whole frame-houses tossed off foundations; steel-reinforced concrete structures badly damaged; automobile-sized missiles generated; incredible phenomena can occur</td>
</tr>
<tr>
<td>(F6-F12)</td>
<td>141 m s(^{-1}) to sonic speed (330 m s(^{-1})) - INCONCEIVABLE DAMAGE</td>
<td>Should a tornado with the maximum wind speed in excess of F6 occur, the extent and types of damage are not to be conceived. A number of missiles, such as ice-boxes, water-heaters, storage tanks, and automobiles, would create serious secondary damage on structures.</td>
</tr>
</tbody>
</table>
Figure IV.1 - F-scale damage chart applicable to relatively new suburban structures. Damage scenes were selected from colour pictures of Lubbock tornado, 11 May 1970, taken by Fujita from about 150 m altitude (Fujita, 1971)
TABLE IV.2
FPP tornado scale
*(based on Fujita and Pearson, 1973)*

<table>
<thead>
<tr>
<th>Maximum wind speed</th>
<th>Path length</th>
<th>Path width</th>
</tr>
</thead>
<tbody>
<tr>
<td>FO less than 33 m s(^{-1})</td>
<td>PO less than 1.6 km</td>
<td>PO less than 16 m</td>
</tr>
<tr>
<td>F1 33 - 49 m s(^{-1})</td>
<td>P1 1.6 - 5.0 km</td>
<td>P1 16 - 50 m</td>
</tr>
<tr>
<td>F2 50 - 69 m s(^{-1})</td>
<td>P2 5.1 - 16.0 km</td>
<td>P2 51 - 160 m</td>
</tr>
<tr>
<td>F3 70 - 92 m s(^{-1})</td>
<td>P3 16.1 - 50.9 km</td>
<td>P3 161 - 508 m</td>
</tr>
<tr>
<td>F4 93 - 116 m s(^{-1})</td>
<td>P4 51 - 160 km</td>
<td>P4 0.5 - 1.5 km</td>
</tr>
<tr>
<td>F5 117 - 140 m s(^{-1})</td>
<td>P5 161 - 507 km</td>
<td>P5 1.6 - 5.0 km</td>
</tr>
</tbody>
</table>
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