Nuclear Power Plant Siting: Hydrogeologic Aspects

A Safety Guide
CATEGORIES OF IAEA SAFETY SERIES

From Safety Series No. 46 onwards the various publications in the series are divided into four categories, as follows:

1. IAEA Safety Standards. Publications in this category comprise the Agency’s safety standards as defined in “The Agency’s Safety Standards and Measures”, approved by the Agency’s Board of Governors on 25 February 1976 and set forth in IAEA document INFCIRC/18/Rev. 1. They are issued under the authority of the Board of Governors, and are mandatory for the Agency’s own operations and for Agency-assisted operations. Such standards comprise the Agency’s basic safety standards, the Agency’s specialized regulations and the Agency’s codes of practice. The covers are distinguished by the wide red band on the lower half.

2. IAEA Safety Guides. As stated in IAEA document INFCIRC/18/Rev. 1, referred to above, IAEA Safety Guides supplement IAEA Safety Standards and recommend a procedure or procedures that might be followed in implementing them. They are issued under the authority of the Director General of the Agency. The covers are distinguished by the wide green band on the lower half.

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Note: The covers of publications brought out within the framework of the NUSS (Nuclear Safety Standards) Programme are distinguished by the wide yellow band on the upper half.
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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

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NUCLEAR POWER PLANT SITING:
HYDROGEOLOGIC ASPECTS

A Safety Guide
commissioning, operation or decommissioning of a nuclear power plant will be required to follow those parts of the Codes of Practice and Safety Guides that pertain to the activities covered by the agreement. However, it is recognized that the final decisions and legal responsibilities in any licensing procedures always rest with the Member State.

The NUSS publications presuppose a single national framework within which the various parties, such as the regulatory body, the applicant/licensee and the supplier or manufacturer, perform their tasks. Where more than one Member State is involved, however, it is understood that certain modifications to the procedures described may be necessary in accordance with national practice and with the relevant agreements concluded between the States and between the various organizations concerned.

The Codes and Guides are written in such a form as would enable a Member State, should it so decide, to make the contents of such documents directly applicable to activities under its jurisdiction. Therefore, consistent with accepted practice for codes and guides, and in accordance with a proposal of the Senior Advisory Group, “shall” and “should” are used to distinguish for the potential user between a firm requirement and a desirable option.

The task of ensuring an adequate and safe supply of energy for coming generations, and thereby contributing to their well-being and standard of life, is a matter of concern to us all. It is hoped that the publication presented here, together with the others being produced under the aegis of the NUSS programme, will be of use in this task.

STATEMENT

by the Senior Advisory Group

The Agency’s plans for establishing Codes of Practice and Safety Guides for nuclear power plants have been set out in IAEA document GC(XVIII)/526/Mod.1. The programme, referred to as the NUSS programme, deals with radiological safety and is at present limited to land-based stationary plants with thermal neutron reactors designed for the production of power. The present publication is brought out within this framework.

A Senior Advisory Group (SAG), set up by the Director General in September 1974 to implement the programme, selected five topics to be covered by Codes of Practice and drew up a provisional list of subjects for Safety Guides supporting the five Codes. The SAG was entrusted with the task of supervising, reviewing and advising on the project at all stages and approving draft documents for onward transmission to the Director General. One Technical Review Committee (TRC), composed of experts from Member States, was created for each of the topics covered by the Codes of Practice.
In accordance with the procedure outlined in the above-mentioned IAEA document, the Codes of Practice and Safety Guides, which are based on documentation and experience from various national systems and practices, are first drafted by expert working groups consisting of two or three experts from Member States together with Agency staff members. They are then reviewed and revised by the appropriate TRC. In this undertaking use is made of both published and unpublished material, such as answers to questionnaires, submitted by Member States.

The draft documents, as revised by the TRCs, are placed before the SAG. After acceptance by the SAG, English, French, Russian and Spanish versions are sent to Member States for comments. When changes and additions have been made by the TRCs in the light of these comments, and after further review by the SAG, the drafts are transmitted to the Director General, who submits them, as and when appropriate, to the Board of Governors for approval before final publication.

The five Codes of Practice cover the following topics:

- Governmental organization for the regulation of nuclear power plants
- Safety in nuclear power plant siting
- Design for safety of nuclear power plants
- Safety in nuclear power plant operation
- Quality assurance for safety in nuclear power plants.

These five Codes establish the objectives and minimum requirements that should be fulfilled to provide adequate safety in the operation of nuclear power plants.

The Safety Guides are issued to describe and make available to Member States acceptable methods of implementing specific parts of the relevant Codes of Practice. Methods and solutions varying from those set out in these Guides may be acceptable, if they provide at least comparable assurance that nuclear power plants can be operated without undue risk to the health and safety of the general public and site personnel. Although these Codes of Practice and Safety Guides establish an essential basis for safety, they may not be sufficient or entirely applicable. Other safety documents published by the Agency should be consulted as necessary.

In some cases, in response to particular circumstances, additional requirements may need to be met. Moreover, there will be special aspects which have to be assessed by experts on a case-by-case basis.

Physical security of fissile and radioactive materials and of a nuclear power plant as a whole is mentioned where appropriate but is not treated in detail. Non-radiological aspects of industrial safety and environmental protection are not explicitly considered.
When an appendix is included it is considered to be an integral part of the document and to have the same status as that assigned to the main text of the document.

On the other hand annexes, footnotes, lists of participants and bibliographies are only included to provide information or practical examples that might be helpful to the user. Lists of additional bibliographical material may in some cases be available at the Agency.

A list of relevant definitions appears in each book.

These publications are intended for use, as appropriate, by regulatory bodies and others concerned in Member States. To fully comprehend their contents, it is essential that the other relevant Codes of Practice and Safety Guides be taken into account.

NOTE

The following publications of the NUSS programme are referred to in the text of the present Safety Guide:

Safety Series No. 50-SG-S6
Safety Series No. 50-SG-S8
Safety Series No. 50-SG-S9

The titles are given in the List of NUSS Programme Titles printed at the end of this Guide, together with information about their publication date. Instructions on how to order them will be found on the last page of this Guide.
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Please see http://www-ns.iaea.org/standards/
1. INTRODUCTION

1.1. General considerations

Accidental release of radioactive material into the ground may result in the direct contamination of groundwater. Groundwater can also be contaminated indirectly by accidental release of radioactive material into the atmosphere or into the surface water, from either of which it can enter the groundwater. In any of these cases the contamination may reach points where water is extracted for use, and so result in exposure of the public.

1.2. Scope

This Safety Guide gives guidelines and methods for determining the groundwater concentration of radionuclides that could result from postulated releases from nuclear power plants.

The main emphasis in the Guide is on the behaviour of radioactive materials in groundwater and the methods for assessing radionuclide movement in hydrogeologic units of various types.

The movement of radionuclides in the ground is controlled by the bulk motion of the groundwater (transport), by the spreading of the contaminant front (hydrodynamic dispersion) and by the retention and release of radionuclides from the solid phase (interphase distribution).

In any evaluation of the consequences of a radioactive release from a nuclear power plant into the groundwater, the concentration of the radioactive material at the nearest point in the region where water is extracted for use and the length of time needed by the radioactive material to reach this point are of major importance. The values of these variables can usually be estimated by physical or mathematical models which describe the behaviour of radioactive material in groundwater.

A general requirement for the evaluation of the hydrogeologic characteristics of a site is that all the relevant parameters shall be studied in such detail that the consequences of a release can be estimated at the points of water use. If the postulated accidental releases present a potential for unacceptable radiological consequences for which adequate engineering solutions cannot be found, the site shall be deemed unsuitable.

This Guide gives recommendations on:

(1) The data to be collected and the investigations to be performed at various stages of nuclear power plant siting in relation to the various aspects of the movement of accidentally released radioactive material through the groundwater;
(2) The selection of an appropriate mathematical or physical model for the hydrodynamic dispersion and two-phase distribution of the radioactive material;
(3) An appropriate monitoring programme.

The validation of the models is briefly discussed.

The derivation of source terms for postulated releases is not dealt with in this Guide since these terms are strongly dependent on the type and design of the nuclear power plant under consideration. For similar reasons, the direct and indirect leakage pathways by which the radioactive material reaches the groundwater are not discussed. Nevertheless, it should be recognized that the level of investigation required will depend on the source term selected and the conditions of the site(s) under consideration.

Some consideration is given in Annex I to the problems of the availability of a supply of groundwater, and guidelines are given on the study and investigation to be performed to assess the suitability of an aquifer as a water supply source for safety-related systems. Hydrogeologic aspects of foundation conditions for the plant are dealt with in the Safety Guide on Safety Aspects of the Foundations of Nuclear Power Plants (IAEA Safety Series No.50-SG-S8).

1.3. Hydrogeologic characteristics

The hydrogeologic characteristics of a site are fundamentally characterized by the hydraulic properties of the hydrological units within the hydrogeologic system and by their dispersion and retention properties. For example, the value of the hydraulic conductivity in different hydrogeologic units may be vastly different from one site to another (values can differ by a factor of as much as $10^{16}$), so that in certain locations any released radioactive material may for long periods of time be retained within a short distance (perhaps a few hundred metres) from the nuclear power plant.

It is not possible to define in general terms the precise and quantitative criteria for site acceptability from the hydrogeologic point of view. In extreme cases acceptability and unacceptability are usually clear. However, intermediate situations may be less clear and will have to be assessed case by case by means of the methodology described in this Guide. The following aspects should be considered:

(1) Source term (mechanism, geometry and other characteristics of the release);
(2) Location of nearest groundwater extraction;
(3) Principal groundwater discharge points to surface water bodies;
(4) Depth to regional and local water tables;
(5) Groundwater flow directions and gradients to determine pathways
and travel times to the accessible environment;
(6) Proximity of site to principal regional aquifers and their recharge areas;
(7) Groundwater-related human activities that could affect the site.

An illustration of the contribution of different hydrogeologic factors to
the suitability of a site from a contaminant transport viewpoint is given by the
following two extreme examples.

The first example has very favourable conditions:

− Water use: no important groundwater extraction near the plant for use.
− Groundwater: the water table is reasonably far below the surface; the
  velocity of groundwater movement is low (a few centimetres per day);
  the water table aquifer is unconnected with any other aquifer for
  considerable distances from the site.
− Subsurface geology: a consolidated, homogeneous, hard formation that
  contains significant amounts of minerals with high sorption properties
  extends underneath the site; the unsaturated zone is of a low porosity
  and has a moderately low permeability.

The second example has very unfavourable conditions which may require
more detailed hydrogeologic investigations and analysis:

− Water use: extensive use of the groundwater extracted from near the
  plant with no alternative source of supply.
− Groundwater: high water table underneath the plant (a few metres from
  surface) with high groundwater flow velocities (a few metres per day).
− Subsurface geology: highly porous and permeable materials underlying
  the site with poor retention capability for radionuclides; significant
  fractures and fissures in the rock beneath the porous, superficial deposits.

Many site characteristics related to hydrogeology may be influenced by
the actual construction and installation of the plant; the possible consequences
of any such change should be evaluated.

Where the radioactive content of the surface water can contaminate the
groundwater, a study should be made of that part of the hydrogeologic system
of the area which lies between the relevant surface body of water and the points
of extraction of groundwater.

1.4. Hydrogeologic investigations

1.4.1. Site survey stage

The hydrogeologic investigation in the early phases of the site survey is
generally a desk study, and involves collecting available information on the
hydrogeology of the region and identifying the major water users. When the sites to be compared are identified and reduced to a small number (candidate sites), rough estimates of their dispersion characteristics may be used for further screening. Section 2 gives details of data collection and analysis during this stage. Methodologies to be used in the site survey are given in the Safety Guide on Site Survey for Nuclear Power Plants (IAEA Safety Series No.50-SG-S9).

1.4.2. Site evaluation stage

The detailed study of the hydrogeologic aspects of the site is performed during the site evaluation stage. The data to be collected and the investigations to be performed are specified in Section 3. In this stage, models for the movement of radioactive material in the groundwater are developed, and radionuclide dispersion is evaluated. The selection of an appropriate model is discussed in Section 4.

1.4.3. Pre-operational stage

After site evaluation, pre-operational studies are conducted. Laboratory and field studies are continued in order to adapt the models developed at the site evaluation stage to specific uses, such as emergency planning. Consideration is given to establishing a programme to monitor hydrogeologic conditions during this stage and during the operation of the nuclear power plant. This is described in Section 5.

2. SITE SURVEY STAGE

2.1. General

It is generally difficult to make a definitive determination at this stage as to the suitability of the hydrogeologic characteristics of an area or a site, since data concerning the major hydrogeologic units and their use may not yet be available in much detail. Therefore, during a site survey, areas or sites are seldom rejected on the basis of hydrogeologic considerations alone. An example of a case where sites or areas may be rejected is where the groundwater resources (aquifers) are important to the region and could be readily contaminated to unacceptable levels. This could happen as a result of an accidental release in a situation where aquifers are at shallow depths in close proximity to the proposed site and the aquifers have highly unfavourable dispersion characteristics.
2.2. Information to be collected

2.2.1. Regional analysis

If the hydrogeologic characteristics are considered at this stage, the data on important uses (present and planned) of groundwater for drinking and irrigation purposes are usually collected from the appropriate agency.

In situations where hydrogeologic maps are not available, the information should encompass as a minimum:

(1) Data on existing and projected major water uses;
(2) Identification of major discharge and extraction points;
(3) An indication of groundwater flow (from the surface topography).

Where hydrogeologic maps are available, the following information may be additionally obtained:

(4) Location, extent and interrelationships of the important hydrogeologic units in the regional system;
(5) Average flow rates and prevailing flow directions of the groundwater in the various major hydrogeologic units;
(6) Information on recharge and discharge of the major hydrogeologic units (precipitation, surface water infiltration, leakage and discharge into other bodies of water);
(7) Information on regional and local water tables and their seasonal fluctuations.

2.2.2. Screening of potential sites

The screening of potential sites is usually based on characteristics other than hydrogeology, because data on subsurface conditions for each of the potential sites are not usually available. However, data from remote sensing techniques may be useful at this stage in identifying underground water occurrences at shallow depths.

2.2.3. Comparison of candidate sites

2.2.3.1. Collection of information

This subsection deals with the type and extent of data to be collected if it is decided to consider the hydrogeologic characteristics in the comparison of candidate sites. In this case the information to be collected includes:
— Characteristics of the major hydrogeologic units (water-bearing, confining and unsaturated units). Interconnection of hydrogeologic units and movement of groundwater in them.
— Data on the type and stratigraphic distribution of various geological formations at each site. Data on the presence of major hydrogeologic units and their position in the geological setting. Existing geological and hydrogeologic maps of the basin where the site is located, and data from previous exploratory work carried out around the site.
— Quantitative data on recharge and depletion of any hydrogeologic unit, preferably expressed as an inventory during the different seasons over several years.
— Present utilization and projection of the future demands on the groundwater potential. Records of seasonal variations of levels of wells and of flow rates of springs, for as long a period as possible. (In regions where groundwater has been used over a long period of time, the extent of its utilization and the seasonal pattern should be known.)
— Characteristics of the surface bodies of water around the site, including flow rates and, if available, base flow components at different flow rates, discharges and levels at different periods of time. (This information is of particular interest for the determination of the discharge and recharge areas of the underlying water-bearing formations and for the identification of the major water users around the site.)
— Topographic maps of an appropriate scale for the basin containing the sites. (From the shape of the land surface the direction of groundwater movement can be inferred if the hydrogeologic unit is isotropic, and a rough estimate of the flow rate can be made. The size and density of the drainage network may give preliminary information on discharge points of aquifers present in the region.)
— Data on relevant aspects of the climate, such as precipitation, for the basin containing the candidate sites. (The climate is an important factor in determining the recharge properties of the hydrogeologic system in the region, since the hydraulic head and gradient can govern the direction and velocity of the groundwater flow.)
— Geochemical properties of subsurface material at each candidate site.

2.2.3.2. Comparison

On the basis of the information collected and the results of any field investigation (e.g. drilling) that may have been performed on the site for other purposes, it is possible for an expert to make a comparison of the candidate sites taking into account:
For a first-order evaluation in comparing two sites, use may be made of the values of: (a) the hydraulic conductivity; (b) the hydraulic gradient of the hydrogeologic unit of a site; (c) the distribution coefficient $K_d$; and (d) the distance from the postulated release point to the point of extraction for use. With some risk of oversimplification, preference may be given to the site having the lower value of the ratio of (a) $\times$ (b) to (c) $\times$ (d).

3. SITE EVALUATION STAGE

3.1. General

At the site evaluation stage, the hydrogeologic characteristics of the region and of the site shall be investigated in such detail as to permit evaluation of:

(1) The concentration of radioactive material in the groundwater that would result from accidental releases;
(2) The related travel time of the radioactive material and the delineation of transport path.

To obtain these results the data discussed in this section are collected and the investigations described herein are performed. The results are useful in assessing the suitability of the site in terms of possible radiological consequences.

3.2. Source parameters for release of radioactive material

3.2.1. Accidental releases into the groundwater

For postulated direct radioactive releases to the groundwater, data specifying source terms for accidental radioactive release into the hydrogeologic environment shall be estimated and used. These data include:

(1) Radioactivity, including the rate of release of each important radionuclide, and the total quantity released during a specific period;
(2) Chemical properties of the liquid released, including important anion and cation concentrations and their oxidation states, organic content and pH;
(3) Physical properties of the liquids released, including temperature, density and the content of suspended solids;
(4) Geometry and mechanics of release and postulated transport to the groundwater.

3.2.2. Indirect radioactive releases into the groundwater

Any radioactivity deposited on the ground surface or released into a body of surface water may be transmitted to the hydrogeologic system that is connected with that surface or body of water. The potential for contamination of underground water from either the surface or surface water, at points where it may be extracted for use by man, should be assessed. If this potential exists, the dispersion of the radioactive material in the surface water should be studied by the methods presented in the Safety Guide on Hydrological Dispersion of Radioactive Material in Relation to Nuclear Power Plant Siting (IAEA Safety Series No.50-SG-S6) and the concentration field at the interface with the groundwater should be used for evaluating the concentration in the groundwater at points used by man.

3.3. Regional hydrogeologic information

Regional information shall be collected to the extent necessary in order to identify the hydrogeologic systems which can be affected in case of an accidental release either directly or indirectly through surface water.

The information to be collected includes:

(1) Climatological data;
(2) Major hydrogeologic units;
(3) Water-bearing characteristics of the units;
(4) Recharge and discharge relationships;
(5) Data on surface hydrology.

3.3.1. Climatology

In regions where rainfall makes a substantial contribution to groundwater through percolation and infiltration, data on seasonal and annual rainfall (and on evapotranspiration if available) are usually collected for as long a period as they are available.
3.3.2. Major hydrogeologic units

Data on the type and stratigraphic distribution of the various geological formations in the region are collected in order to characterize the regional system and its relationship with the local hydrogeologic units. This information is supplemented by data from previous exploratory work in the region.

3.3.3. Water-bearing characteristics of the hydrogeologic units

Information on the water-bearing characteristics of the main hydrogeologic units is collected, including:

- Moisture content
- Porosity
- Specific yield for unconfined aquifers and storage coefficients for confined aquifers
- Hydraulic conductivity or permeability
- Transmissivity for fully saturated confined aquifers.

Where possible, information on the expected variation of the various critical parameters is also collected.

3.3.4. Recharge and discharge relationships

Information on recharge and discharge (depleting) mechanisms is collected on a quantitative basis if possible in order to estimate the relationship among hydrogeologic units in the different seasons of the year.

This information includes:

- Existing pressure heads (water levels) of individual hydrogeologic units and their gradients, and the relationship among them. (The reliability of the data should be checked.)
- Records of seasonal variations in levels of open wells, and flow rates at the main natural and artificial groundwater discharge points (wells, boreholes, mine shafts, etc.) for as long a period as possible.
- Long-term forecast of change in regional groundwater level, at least for the lifetime of the nuclear power plant.
- Groundwater/surface water interrelationship.
- Infiltration or leakage of water, either expected from reservoirs constructed for the needs of the nuclear power plant, or due to natural recharge by precipitation.
3.3.5. Surface hydrology

Data such as flow rates, discharges, and levels at different times of the bodies of surface water in the region are collected if not already available. This information is of particular importance for determining the discharge and recharge areas of the underlying water-bearing formations in the region and for identifying the major water users. Surface water may represent the means of transport of the radioactive contamination from the plant to the hydrogeologic system and the information is important from this point of view as well.

3.4. Regional studies and investigations

3.4.1. Geological investigations

When a site is in a region where a certain amount of geological survey work has been carried out, information on subsurface conditions is usually available. On the basis of this information and that described in Subsection 3.3, a regional geological map is prepared with horizontal cross-sections which indicate clearly the geological setting of the site and its relation to the wider setting. If insufficient information is available, it will be necessary to carry out field surveys and a drilling programme so that details of hydrogeologic unit thickness, extent, lithology and physical properties can be obtained and a hydrogeologic map prepared.

3.4.2. Hydrogeologic units

3.4.2.1. Dimensions and physical properties

From the geological succession and structure, the hydrogeologic units of regional significance are defined in terms of thickness, extent, degree of homogeneity and physical properties. If it is considered necessary, further hydrogeologic investigations are performed.

3.4.2.2. Regional flows

The paths of the regional groundwater flow are inferred for each hydrogeologic unit of regional importance, and the flow regime may be established from hydrogeologic maps. Water table and piezometric level maps are usually prepared from available information, but if this is insufficient, a programme of water level measurements is undertaken. Data concerning existing wells and the natural seepage level can be used, but for characterizing a complex aquifer, or series of aquifers, observation wells are drilled.
From such water level maps the necessary inputs for the models are prepared, including seasonal and shorter-term variations.

3.4.2.3. Groundwater and hydrogeologic unit chemistry

Samples of groundwater are chemically analysed, and the results are used to obtain information on the groundwater movement in relation to the geological setting. The number of samples taken and the location of the sampling points will depend on the complexity of the regional hydrogeologic system. Both the vertical and horizontal spacing of monitoring locations will depend on the groundwater flow and hydrostratigraphic system, but a minimum number of locations is likely to be three or four from each 20 km². Detailed guidance on the methodology of choosing the number and spacing of such wells can be obtained from the literature (e.g. Ref.[1]). Undisturbed samples of the hydrogeologic unit and contiguous strata are collected to determine the physical and chemical characteristics of the hydrogeologic units. The number of samples is determined by the variation in lithology; the samples are taken principally from the zones of highest flow rates and from aquifer material where radionuclide retardation is expected to be greatest (i.e. where the permeability in the particular hydrogeologic units is high or there is a marked presence of clay minerals).

3.4.3. Surface waters

A regional investigation identifies those surface waters which:

1. Might be directly affected by an accidental discharge from the site;
2. Might provide a pathway for contamination into a body of groundwater; or
3. Might be contaminated by natural discharge from a contaminated hydrogeologic unit.

It is necessary to identify the permanent and intermittent surface stream courses, springs, seepages, lakes and ponds over an area around the site large enough to take account of potential contamination into and out of the surface waters.

3.4.4. Groundwater/surface water interrelationship

The extent and degree of hydraulic connection between bodies of surface water and the groundwater are identified. Study of topographic and geological maps will allow the identification of lines or areas where such hydraulic connection between surface water and groundwater exists. If direct measurements of gains and losses cannot be made, and if the estimated quantities are significant, it may be necessary to measure the water level (in lakes) or water flow (in streams).
TABLE I. HYDROGEOLOGIC PARAMETERS
Dimensions, common symbols and units and methods of measurement

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dimensions</th>
<th>Unit</th>
<th>Test method</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic head</td>
<td>L</td>
<td>m</td>
<td>Piezometer</td>
<td>H</td>
</tr>
<tr>
<td>Hydraulic conductivity</td>
<td>L/T</td>
<td>m/s</td>
<td>Falling head</td>
<td>K</td>
</tr>
<tr>
<td>Intrinsic permeability</td>
<td>L²</td>
<td>m²</td>
<td>Falling head</td>
<td>k</td>
</tr>
<tr>
<td>Transmissivity</td>
<td>L²/T</td>
<td>m²/s</td>
<td>Pumping, packer</td>
<td>T</td>
</tr>
<tr>
<td>Storage coefficient</td>
<td>-</td>
<td>-</td>
<td>Pumping, packer</td>
<td>S</td>
</tr>
<tr>
<td>Compressibility</td>
<td>LT²/M</td>
<td>Pa⁻¹</td>
<td>Laboratory column</td>
<td>n</td>
</tr>
<tr>
<td>Porosity</td>
<td>-</td>
<td>-</td>
<td>Laboratory porosimeter</td>
<td>n</td>
</tr>
<tr>
<td>Mass density</td>
<td>M/L³</td>
<td>kg/m³</td>
<td>Laboratory densitometer/ gamma-gamma logging</td>
<td>n</td>
</tr>
<tr>
<td>Distribution coefficient</td>
<td>L³/M</td>
<td>m³/kg</td>
<td>Laboratory batch/ column/field tracer</td>
<td>K\text{d}</td>
</tr>
<tr>
<td>Diffusivity</td>
<td>L²T⁻¹</td>
<td>m²/s</td>
<td>Laboratory/field tracer</td>
<td>D</td>
</tr>
<tr>
<td>Intrinsic diffusivity</td>
<td>L</td>
<td>m</td>
<td>Laboratory/field tracer</td>
<td>D</td>
</tr>
</tbody>
</table>

3.5. Collection of information and investigation of the relevant hydrogeologic system

3.5.1. General

The hydrogeologic units that can be significantly affected by any postulated release from the nuclear power plant shall be described in detail. These units are usually limited to the site and its surroundings or to those areas which include any body of surface water that might become contaminated. An evaluation of the characteristics of the relevant hydrogeologic units is performed to determine the interrelationships among them, the groundwater regime and any change to this regime that may result from any constructional, mining or other such activities at, or near, the site (see Table I).

3.5.2. Description of the relevant hydrogeologic units

For a detailed study of the local hydrogeologic system, the existence and location of the relevant aquifers and other hydrogeologic units are determined. Geological cross-sections and three-dimensional (fence) diagrams are then used to display the results. Assessment of this information will identify the need...
for and locations of boreholes in addition to those used in exploratory work carried out at the site for other purposes (determination of foundation stability, etc.).

The geology and surface hydrology of the site itself are studied in sufficient detail to indicate potential pathways of contamination into surface or groundwater. Any surface drains or standing bodies of water accessible to potential accident release points are identified. Areas from which direct entry into an aquifer can be made by contaminated surface water are determined. The relevant hydrogeologic information for surface or near-surface releases includes soil moisture properties, infiltration rates, unsaturated zone configurations and chemical retention properties for unsaturated conditions.

3.5.2.1. Lithological information

Lithological information encompassing physical, physico-chemical and chemical properties of geological strata of the relevant aquifer — including petrographic or mineralogical composition, grain size and packing and texture of rocks — is collected. The lithological properties of any formation are determined by laboratory examination of samples taken from boreholes.

3.5.2.2. Chemical and physical properties of the groundwater

The following data on the groundwater are obtained for the relevant hydrogeologic units:
- important cations and anions — their concentrations and oxidation states
- content of organic and biological material
- pH
- Eh
- temperature.

Although most of these data can be obtained by laboratory analysis of samples of groundwater taken from the boreholes or from existing wells, springs or other bodies of surface water, it may be necessary to supplement the information with field sampling and analysis. Detailed guidance on field sampling techniques is available in the literature (e.g. Ref.[2]).

In the case of an aquifer near a coastal area, flow conditions of the groundwater should be determined with sufficient detail to permit prediction of salt-water intrusion caused by any on-site activity (e.g. dewatering, groundwater use, etc.).
3.5.2.3. Water-bearing characteristics

Information on the water-bearing characteristics of the hydrogeologic units is obtained. This information includes data on the media and the relevant parameters characterizing the hydrogeologic units:

(1) **Data on the media.** Data on the basic physical properties of the porous media of the relevant hydrogeologic units are collected in such a way as to ensure that the characteristics selected to describe the media of the unit are statistically representative. Basic data of this nature are widely available in the literature for a variety of hydrogeologic formations.

(a) Porosity and bulk density. The values of porosity and bulk density are usually obtained by laboratory measurements of samples taken from boreholes. Information on porosity of a stratum can also be obtained from field measurements by means of geophysical techniques (such as sonic, neutron, electric resistivity or gamma-gamma logs) used directly in the open hole.

(b) Intrinsic permeability and hydraulic conductivity. Intrinsic permeability is a parameter that is a function of the medium and is independent of the fluid properties governing flow. Hydraulic conductivity, on the other hand, is a function of both the porous medium and the fluid. The terms are interrelated, so that the determination of hydraulic conductivity by laboratory or field testing will yield intrinsic permeability if multiplied by the ratio of the dynamic viscosity of the fluid to the specific weight of the fluid. Generally, it is hydraulic conductivity that is determined by testing [3].

(c) Compressibility. The compressibility is measured by laboratory tests of the media of the relevant aquifer. The important value of compressibility is the one along the vertical direction, since it is in practice the only direction in which large changes in effective stress occur.

(2) **Parameters characterizing the relevant hydrogeologic unit as a whole.**

For the relevant hydrogeologic unit, assessments are made of various parameters which characterize hydraulic properties, e.g. transmissivity, storage coefficient or specific yield. Their values may be obtained from field pumping tests. For an unsaturated zone, moisture content is a necessary parameter. Furthermore, moisture content and hydraulic conductivity in the unsaturated zone are functions of the pressure head, which is less than atmospheric. These relationships, which can be determined in the laboratory, are called the unsaturated characteristic curves.

(a) Transmissivity. The transmissivity can be defined as the rate at which water is transmitted through a unit width of the aquifer under a unit hydraulic gradient. It is expressed as the product of hydraulic conductivity and the thickness of the saturated portion of the aquifer.
(b) Storage coefficient. For a confined aquifer the storage characteristics are usually expressed by the storage coefficient, which represents the volume of water released from storage per unit of horizontal area and per unit decline of hydraulic head.

(c) Specific yield. For an unconfined aquifer the storage is usually characterized by its specific yield, which gives the yield of an aquifer per unit area and unit drop of the water table.

(d) Unsaturated characteristic curves. For the unsaturated zone the characteristic curves relate the moisture content and hydraulic conductivity to the pressure head. These curves are determined primarily in the laboratory. The reader is directed to the soil science literature for details [2, 4].

3.5.2.4. Groundwater regime

The groundwater regime before construction is assessed for the relevant hydrogeologic units.

This assessment includes the evaluation of:

(1) Groundwater level contours. Data are collected on the hydraulic heads and their seasonal variation for the relevant hydrogeologic units. The basic device for the measurement of hydraulic head, and hence for establishing the hydraulic gradient between two points in the field, is the piezometer.

(2) Direction of groundwater flow. To predict the direction towards which a postulated release of radioactive material will move in the groundwater, information on the direction of groundwater flow is collected. This should cover at least the area between the point of postulated release of contamination into the groundwater and the nearest points of water extraction for use. The flow regime of the hydrogeologic unit may be derived from water table levels in the case of an unconfined unit, and from piezometric surface elevations in the case of a confined one. If hydrogeologic maps with water level contours are available, the flow regime could in theory be established from these contours. In practice, however, the direction of the water movement for the relevant hydrogeologic unit is determined from the values of the water levels given by a group of piezometers that specifically monitor the relevant hydrogeologic unit.

(3) Velocity of the groundwater flow. The velocity of the groundwater flow is determined from the hydraulic gradient and hydraulic conductivity by the application of Darcy's Law. However, the velocity so determined has a large degree of uncertainty, and in cases where the value of this variable is critical for safety, it is measured in situ by means of tracer methods [3].

(4) Map of natural and artificial outlets.
3.5.2.5. Hydrodynamic dispersion and sorption characteristics of the hydrogeologic units

The hydrodynamic dispersion and sorption characteristics of the relevant unit are evaluated. They include:

(1) Hydrodynamic dispersion coefficient. This coefficient has the components \( D_x, D_y, D_z \) (see Section A.6 of Appendix A) which could be determined by laboratory experiments using the column technique, and where necessary in the field by a tracer method.

(2) Sorption-desorption. The movement of the radioactive material may be delayed by the sorption-desorption mechanism (including adsorption on the solid surface and ion-exchange reactions and complexing between radionuclides and the mineral matrix). The net result under equilibrium conditions is represented by the distribution coefficient \( K_d \) (\( K_a \) for hard rock units). This describes the distribution of a radionuclide between the solid and liquid phases and it serves as an input for modelling the movement of radioactive material in hydrogeologic units. The distribution coefficients are usually determined in the laboratory under either static or dynamic conditions using native media and fluids taken from the hydrogeologic unit in which transport is postulated to occur. However, field measurements using tracer techniques may be more appropriate in simulating realistic situations (Ref.[3], pp.404-434). These techniques are difficult to use but are under continuous development.

3.6. Water use

On the basis of the preliminary study of possible contamination of the surface waters or groundwater, the area which might be affected by accidental releases from the plant is identified. Because of the large variation in the values of the groundwater dispersion characteristic, the size of this area may vary considerably from case to case. In those areas which could be directly or indirectly affected by the release of radioactive material, information on present and future uses of both surface water and groundwater shall be collected and shall include data on the location, elevation, discharge rates, water levels and the number of people dependent on each outlet.

Available data should be tabulated and should include a list of hydrogeologic units penetrated, wells (including details of the owners and of the uses to which the water is put), location and elevations of well screens, pumping and injection schedules and drawdowns or recharge mound fluctuations.
3.7. Programme of investigations

3.7.1. General

Few sites can be assessed entirely from existing information, and nearly all require further investigation for evaluating the hydrogeologic aspects. The regional investigations described in Subsection 3.4 are supplemented with local investigations. These range from relatively simple and inexpensive surface geophysical surveys to detailed and costly drilling programmes and associated borehole geophysics and tracer studies (see Table II).

The extent of the investigations will depend upon the availability of detailed information for the region, and also on the need for very precise data to develop the input and the parameters for the model of the movement of radionuclides through surface water and groundwater systems. The radionuclides which have to be considered depend on the type of reactor and the type of accident postulated.

3.7.2. Surface geophysical methods

Of the several different types of surface geophysical techniques available, the main ones used for hydrogeologic investigations are the electrical resistivity and seismic refraction methods. These are used to determine the geological structure and the characteristics, depths and spatial extents of the strata. In reasonably homogeneous hydrogeologic units and areas of uncomplicated geology, a combination of drilling and geophysical survey measurements is usually performed.

The electrical resistivity method may be used to identify the position of the water table. The seismic method is used where there is a two-layer or three-layer geological configuration.

Geophysical information obtained by the above-mentioned methods can be of assistance in optimizing the scope of a complete drilling programme, and can give a sound basis for interpolating drilling data taken at individual points over the whole area of interest. Data from these measurements need to be calibrated with test-hole information. More detailed information on surface geophysical methods applied to groundwater exploration is provided in Refs [2, 3].

3.7.3. Subsurface geophysical methods

With subsurface geophysical methods of investigation, a sensing device is lowered into a test hole to make a record (log) from which the characteristics of the geological formations, and of the water they contain, can be determined. Geophysical logs can be used directly to determine bulk density and porosity,
## TABLE II. INVESTIGATIVE TECHNIQUES IN HYDROGEOLOGY

<table>
<thead>
<tr>
<th>Type of investigation</th>
<th>Required at:</th>
<th>Site survey</th>
<th>Site evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surface geological</strong></td>
<td></td>
<td>a</td>
<td>a</td>
</tr>
<tr>
<td>General information on rock formations; topography; type of soil; surface hydrology; general information on extent and nature of hydrogeologic unit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Subsurface geological; test drilling of boreholes and coring</strong></td>
<td></td>
<td>d</td>
<td>a</td>
</tr>
<tr>
<td>Lithology, stratigraphy, structure of formations; water levels; chemistry of soil and groundwater; porosities; field permeabilities, bulk density, etc.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Surface geophysical:</strong></td>
<td></td>
<td>d</td>
<td>b</td>
</tr>
<tr>
<td>(i) Electrical resistivity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Definition of aquifer limits, mapping of areal variation, groundwater salinity; also supplements salinity, moisture content, etc.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(ii) Seismic refraction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth of bedrock; thickness of surficial fracture zones; areal extent of potential aquifers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Subsurface geophysical:</strong></td>
<td></td>
<td>d</td>
<td>c</td>
</tr>
<tr>
<td>(i) Resistivity logging</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lithology; porosity; chemical composition of groundwater</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(ii) Potential logging</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lithology; qualitative indication of permeable zones</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Nuclear techniques</strong></td>
<td></td>
<td>d</td>
<td>c</td>
</tr>
<tr>
<td>Natural gamma logging</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>To distinguish between rock types, density of rocks and moisture content</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gamma-gamma logging</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutron logging</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Legend:**

- **a:** Essential
- **b:** Desirable to optimize extent of drilling
- **c:** Optional for purposes of confirmation
- **d:** Not required
and indirectly to determine the hydraulic conductivity, moisture content and specific yield of hydrogeologic units. These logs can also help to define the source, movement, and chemical and physical characteristics of groundwater [2].

For hydrogeologic applications, electric logs are usually employed. However, in certain circumstances, other borehole methods, such as nuclear logging and caliper logging, may be used.

Commonly used nuclear logs are the natural gamma, gamma-gamma and neutron types. These measure radioactivity in the rocks, gamma-ray scattering and neutron scattering, respectively. An advantage of nuclear logging is that it can be used through a well casing. Natural gamma logs are records of the amount of natural gamma radiation emitted by all rocks. The natural gamma log is used to identify lithology and stratigraphy, as well as depth of occurrence of the various formations.

The neutron log may be used for measuring porosity in situ. Below the water table the probe measures total porosity, while above the water table it measures the moisture content.

The gamma-gamma log may be used to measure porosity and bulk density.

For a high-resolution caliper log, a caliper is used to probe the walls of the borehole to detect cracks or fractures less than 0.5 cm in width. The caliper can be used to locate solution and fracture zones, washouts, and mud squeezes (swelling of clay layers into the borehole).

3.7.4. Borehole and well construction

Most sites require the drilling of some uncased boreholes or wells to verify formation characteristics and to calibrate geophysical logs. Cased boreholes are used to monitor groundwater levels and water quality, and the casing is perforated over the formation of interest, or screened.

The particular construction method depends on the purpose of the borehole, the hydrogeologic environment, the quantity of water desired, the depth and diameter of the hole, and economic considerations. Augered, driven or jetted wells are limited to shallow depths, unconsolidated deposits and small yields. For deeper, higher-yielding bores and for all those made in rock, drilling is the only feasible method.

Tests to determine the hydraulic properties (e.g. transmissivity, storage coefficient) of the water-bearing materials can also be conducted by controlled pumping. These tests require an appropriate and carefully designed field measurement plan (see, for example, Ref.[5]) and data analysis. The field test generally involves one pumping well and several observation wells. The determination of the layout of the well systems, the timing of water level measurement in the observation wells, and the length of time for the test are included in the experimental plan. Data analysis involves the transformation of field data into calculated values for the hydraulic coefficients, generally by
use of standard graphical analyses. The coefficients thus determined can then be used in the groundwater flow models. In order to prevent inadvertent pathways, the boreholes and wells constructed should be abandoned in an appropriate way and precise records kept.

3.7.5. Tracer techniques

Tracer techniques can be used to determine groundwater direction and speed, hydrodynamic diffusivity and effective porosity. The tracers used include chemicals, dyes or short-lived radioactive isotopes.

3.7.5.1. Velocity measurements

Usually the most accurate method of velocity determination is one based on tracer techniques. The groundwater velocity can also be determined by using the Darcy equation and field-determined values of hydraulic conductivity, hydraulic gradient and effective porosity. However, the estimates based upon this approach have large inherent uncertainties, owing to the uncertainties in the Darcy equation parameters.

The most direct method consists of introducing a tracer at one well point and observing its arrival at other points. The groundwater speed can be computed from the tracer’s travel time and distance, after adjustments are made for dispersion effects. Many non-radioactive tracers have been used, including salts (NaCl or CaCl₂), which can be monitored easily by measuring the electrical conductance, fluorescent dyes (fluorescein and rhodamine compounds) and freon. Freon is perhaps the best tracer because it does not react with geological materials and can be used in extremely small concentrations that are non-hazardous in waters used by the public. (Detailed descriptions of tracer techniques can be found in Refs [3] and [6].) However, in using this method it should be noted that:

(1) Very long periods of time are required for tracers to move significant distances through a groundwater flow system;

(2) Numerous observation points are necessary to monitor the passage of a tracer, because of the heterogeneous nature of geological materials.

Another tracer technique frequently used, which avoids these problems, is the borehole dilution method developed in the USSR in the late 1940s [3]. With this method, tests can be performed in relatively short periods of time in a single well, and estimates of the horizontal average velocity near the well screen can be made [3, 7].

These methods are used to measure velocity when the value is relatively high. Confirmation of the calculated velocity is needed, particularly in the case of an anisotropic hydrogeologic unit.
3.7.5.2. Hydrodynamic dispersivity measurements

The coefficient of hydrodynamic dispersion (hydrodynamic dispersivity) is proportional to the pore velocity. The proportionality constant is called the intrinsic hydrodynamic dispersivity. If groundwater velocity has been determined or measured, then the measurement of groundwater dispersion in the field allows an evaluation of the intrinsic hydrodynamic dispersivity to be made. The laboratory-derived values for intrinsic hydrodynamic dispersivity are often not representative of field conditions and their use may produce errors in the calculation of the concentration distribution.

There are four main types of field tests for estimating intrinsic diffusivity. These are:

– Natural-gradient tracer tests;
– Single-well withdrawal-injection tests;
– Two-well recirculating withdrawal-injection tests;
– Two-well pulse tests.

Details can be found in Ref.[3].

3.7.5.3. Distribution coefficient

Laboratory-derived values for the distribution coefficient \( K_d \) are often not representative of the real value of the parameter in the field. It is theoretically possible to make field measurements with tracer techniques, but the techniques are not yet completely developed and the method is not widely used for nuclear power plant siting. At present \( K_d \) is usually determined by laboratory methods.

### 4. MODELLING OF RADIONUCLIDE DISPERSION AND RETENTION IN GROUNDWATER

#### 4.1. General

This section describes the selection of an appropriate model for hydrodynamic dispersion and sorption-desorption of radioactive material in the groundwater, and the validation of the selected model. Details concerning specific models are included in Appendix A. This Guide deals primarily with radionuclide dispersion in porous media (soils). For other types of media (hard rock or certain fractured rock systems), reference should be made to the literature (Ref.[3], for example). In the selection of the model all basic assumptions should be carefully analysed, with due account taken of the specific
features of the area, such as faults, fracture zones and special topographic features. These modelling techniques, while having been in use for quite some time, are still in continuous evolution. Thus, any model needs to be evaluated carefully before its actual application.

There exist in the literature many models, of varying degrees of complexity, for calculating dispersion and retention of radionuclides released into groundwater. Generally, simple analytical models are satisfactory, and the need for complex models is the exception rather than the rule. Some hydrogeologic situations, however, will not satisfy the assumptions inherent in the simpler analytical models; for these, the more complex, two- or three-dimensional numerical models can be applied. However, the more complex the model, the more care must be exercised in the collection of the data.

The selection of appropriate radioactive source terms to be used as input for groundwater evaluation studies is not discussed in this Guide because it is dependent on the accident analysis specific to the plant, and the site-dependent near-field conditions. The source term for evaluation of hydrodynamic dispersion and sorption-desorption is the release from the plant as modified in its movement through the near-field. The approach taken to analyse the near-field movement of radioactive material, especially through the unsaturated zone, will significantly affect the value of this source term.

4.2. Selection of the model

4.2.1. General

The relationship between the postulated accidental release into the groundwater and the radionuclide concentrations at a point of water extraction for use may be represented by a model of the processes involved. The validity of the model used shall be determined so as to ensure that the site evaluation procedure is adequately conservative. This subsection describes some of the modelling approaches that can be used to express the relationship as a time profile of radionuclide concentrations at the point of water extraction. The causes of uncertainty that may affect the validity of these models for specific site evaluation are also described.

A model is appropriate for the site under consideration if it gives reasonable approximations of the processes that are relevant to that site. The selection of an appropriately validated model is necessary for developing a time profile of radionuclide concentration at a point distant from the place of release. The complexity of the model is dependent upon the complexity of the hydrogeologic system at a particular site. Several modelling approaches are presented in Appendix A. The most appropriate (usually the simplest) for a particular situation should be selected on the basis of engineering judgement.
For evaluating the effects of postulated accidental releases of liquids directly to the groundwater, the first step is to perform simplified evaluations with conservative assumptions and data; more refined analysis can then be performed with more realistic assumptions and models. Initially it may be assumed that:

1. The release of the entire source term to the groundwater is instantaneous and subject to the maximum hydraulic gradient;
2. The radioactive material moves with the groundwater (no dispersion, sorption, or decay) to the nearest potential user, who is assumed to be located at the site boundary.

For this evaluation, conservative values of the hydraulic conductivity and the effective porosity are used to calculate groundwater velocity. (In this case conservative parameter values are those that result in shorter radionuclide travel times and in higher concentrations at the point of water extraction.)

In a similar way concentrations of radioactive releases through indirect pathways can be evaluated.

In some cases, such a conservative analysis will yield unacceptable concentrations of radionuclides at the point of interest. More refined calculations can be made in these cases by:

1. Taking into account the actual distances to the nearest existing or planned point of water extraction;
2. Selecting source terms for the release which take into account specific design and site features of the particular nuclear power plant;
3. Applying a more realistic model of the transport, hydrodynamic dispersion, decay and sorption-desorption of the radionuclides as determined by the site characteristics.

The groundwater movement and the transport of the radionuclides is, in general, approximately orthogonal to groundwater level contours. Where this is the case, the simpler analytical methods can be applied. However, some aquifers are strongly anisotropic, and the water and effluents can move over a limited domain through fractures which may be almost parallel to the regional groundwater level contours [8]. It should be determined whether the sites are underlain by either fissured or fractured rocks; in these cases most analytical models are invalid. Movement of water and radionuclides in such formations may be estimated by conducting tracer studies [9]. However, because tracer flow paths may not necessarily intersect observation wells, the results of tracer studies should be carefully interpreted. Nonetheless, the probable direction and total distance of travel can generally be determined from the aquifer geometry and from hydraulic gradients.
Where groundwater movement and flow path lengths are estimated, potential future withdrawals should be accounted for either by use of conservative gradients or by estimating the effects of such withdrawals on the existing water level contours.

If groundwater movement at a site is affected by a severely fractured rock formation, then a conservative estimate of radionuclide transport may be obtained by assuming that the movement will occur in a single fracture, and by neglecting dispersion, sorption and decay. Furthermore, the fracture may be assumed to extend in a straight line from the point of release to the nearest point of concern. Where the fracture spacing is small compared to the groundwater path length, the fractured formations can be considered as quasi-isotropic aquifers.

4.2.2. Summary description of models

If the groundwater velocity and path length are known, the travel time of groundwater and radionuclides from the source of the release to a point of water use can be estimated. The reduction in the radionuclide concentration between the release point and the point of water extraction for use can be determined by solving the equations representing the hydrodynamic dispersion and sorption-desorption processes. Suitable models for these phenomena are discussed in detail in Appendix A.

4.2.2.1. Transport processes and travel time evaluation

The velocity field of groundwater can be determined by either tracer techniques (see Subsection 3.7.5) or by theoretical methods. In situ tests with fluorescent or radioactive tracers can be used to determine experimentally the velocity field of groundwater if a tracer that will not be sorbed by the solid media is used. A mathematical model representing groundwater flow can be employed. By use of appropriate boundary conditions and aquifer coefficients, the groundwater velocity can be determined theoretically. The mathematical models range from a simple expression of Darcy’s Law in one dimension — to obtain the flux in a steady-state approximation — to a detailed representation of the transient flow, using complex numerical methods. The expressions and approximations for Darcy’s Law in one, two and three dimensions are discussed in detail in Appendix A.

The groundwater velocity can be used in certain cases to estimate the travel time of radionuclides between the plant site and the nearest point of water extraction for use. For example, since tritium is not usually sorbed by the solid media, the travel time of groundwater will be the same as the travel time of the centre of mass of a tritium release. Because other radionuclides are retained by the solid media (as discussed in Subsection 4.2.2.3), their travel
times can be longer than for tritium. If groundwater movement is slow, and the
distance to the nearest point of water extraction is large, it may be possible
to show that the concentration of certain radionuclides with shorter half-lives
will be negligible at the point of extraction. For small releases any radio-
nuclide having a half-life less than one-tenth of the groundwater travel time
(reduction factor of 10^3) is usually neglected, but caution should be exercised
to ensure that the underlying assumption is valid.

4.2.2.2. Hydrodynamic dispersion

The amount of dilution that occurs within an aquifer is fundamentally a
function of the hydrodynamic dispersion. The dominant parameter for calculating
radionuclide concentrations in groundwater is the coefficient of hydrodynamic
dispersion. Empirical relationships, laboratory tests, or field tracer studies can
be used to estimate this coefficient (see Subsection 3.7.5). However, the results
of laboratory and field tracer tests can be significantly affected by the scale of
the tests, the homogeneity of the medium and the concentration of the tracer.
The coefficient of hydrodynamic dispersion can be found from field tracer
tests designed to determine the transverse and longitudinal components of
intrinsic diffusivity. Such field tests may be time consuming, but they can be
speeded up by using a combination of injection and pumping from wells to
reduce the tracer travel time. Care must be taken, however, to maintain injection
pressures low enough that the properties of the hydrogeologic unit are not
significantly affected. Because the diffusivity determined from a tracer test
might be affected by the scale of the test, it must be used with caution when
extrapolating to a different (e.g. larger) scale.

4.2.2.3. Sorption-desorption

Various sorption phenomena affect the radionuclide concentrations resulting
from the transport and hydrodynamic dispersion processes.
The effect on transport is an apparent retardation. For the hydrodynamic
dispersion process, the effect is an apparent reduction in the values of diffusivity
(see Appendix A).

Retardation of radionuclide movement by sorption-desorption processes
results in modification of concentrations of radionuclides in the solid phase
(soil or rock media) and in the liquid phase. Furthermore, because of the
radioactive decay, this retardation also results in a greater reduction in con-
centrations [10, 11].

For the determination of radionuclide travel time in equilibrium conditions,
the equilibrium distribution coefficient K_d (in the case of hard rock materials,
K_a is used) is an important parameter. Its value depends on the particular
radionuclide and on many other factors such as the pH and the chemistry of
both the solid media and the water. Therefore, if $K_d$ is used, it shall be determined for the significant radionuclides by using samples of the hydrogeologic unit and of water taken from the unit in which migration of the radionuclide is expected to occur [12]. Since large variations have been observed from comparisons of laboratory results with field observations, care should be taken to account for the inherent uncertainties. Methods for determining values for $K_d$ are discussed in the technical literature (see, for example, Ref.[3], pp. 432–434).

The apparent effect of sorption on hydrodynamic dispersion is represented by modifications of the radionuclide concentration in the hydrogeologic unit (solid phase) and in the groundwater (liquid phase — see Eq.(18) of Appendix A).

4.2.2.4. Computation procedures

If hydrogeologic conditions are not too complex, computations of radionuclide transport may be performed with relatively simple one-dimensional models. The more rigorous, complex models can be used if the hydrogeologic conditions are anisotropic and non-homogeneous. Pertinent models are described in Appendix A.

A set of partial differential equations describes the movement of groundwater. In their most general form, these equations can only be solved by numerical integration. However, if ideal physical properties and simplified boundary conditions are assumed, the equations become less complex and a solution can be obtained; but the effects of all the simplifying assumptions must be assessed in order to demonstrate that the results obtained from the particular model are conservative. It should be emphasized that the use of sophisticated models is not required when a simplified model conservatively represents the situation and predicts acceptable concentrations at the nearest point of potential water extraction for use. The following procedure may be adopted for small releases where the hydrogeologic situation is such that the hypothesis of homogeneity and isotropy is reasonable.

1. The groundwater travel time from the plant to the point in question can be determined by using effective porosity and Darcy's Law in one dimension. (For the isotropic homogeneous case, see Eq.(10) of Appendix A.)
2. Any radionuclide having a half-life less than one tenth of the groundwater travel time (reduction factor of $10^3$) should be evaluated to determine whether it can be neglected. In particular, the magnitude of the release should be taken into consideration.
3. An appropriate analytical dispersion model can be used for each radionuclide by assuming no sorption ($K_d = 0$) to obtain concentrations at the point of interest (Eq.(32) of Appendix A).
(4) If the peak concentration of a particular radionuclide is sufficiently low\(^1\) at the point of interest, then that nuclide may be eliminated from further consideration.

(5) For the remaining radionuclides, steps 2 and 3 can be repeated with conservative site-specific distribution coefficients (Eq.(33) of Appendix A) and the decay of radionuclides taken into account as appropriate.

If the concentrations at the point of interest are found to be unacceptable, it may be necessary to re-examine the design of the nuclear power plant or the suitability of the site.

This procedure has proved useful, when used with appropriately conservative coefficients, for routine licensing evaluations, as well as for generic studies of the migration of radionuclides through the groundwater pathway.

4.3. Model validation

The application of models to the analysis of radionuclide transport in groundwater is subject to several sources of uncertainty. These include uncertainties associated with the release source term; the realism or representativeness of the model itself; and the validity, accuracy and precision of the measured characteristics of the site. Development of the source term is outside the scope of this Guide, but note should be taken that the early, near-field geochemical processes must be accounted for when the results of postulated accident analysis are translated into a transport source term. The source term can be associated with a large uncertainty in the near-field estimates performed for site evaluation.

The models for groundwater transport and hydrodynamic dispersion have been validated for many circumstances. They can be applied directly to sites where fracture flow is not a significant factor. The model can be validated for the particular application by showing that the site characteristics are similar to those for which it has been validated or that any differences in the site characteristics will result in conservative results. In exceptional cases it can be validated by showing that appropriate field tests at the site confirm the results of the model.

A sensitivity analysis can be helpful in assessing the potential uncertainties resulting from the use of the model. There are large uncertainties associated with the application of sorption-desorption models. While it is believed that most of these result from uncertainties in the site data, the nature of the geophysical and geochemical mechanisms involved in the sorption-desorption processes are not completely understood. The effect of these uncertainties on

\(^1\) In some Member States, reference is made to concentration limits for drinking water.
the radionuclide concentrations estimated by using the models is an important factor in determining the degree of conservatism required.

Information on the validation for general use of the models discussed in this Guide is presented in Appendix A; where possible, the level of expected error is indicated.

5. GROUNDWATER MONITORING PROGRAMME

5.1. Monitoring objectives

There are two main objectives of the monitoring programme: first, to determine whether there have been any changes in the hydrological characteristics in the vicinity of a plant that could affect the outcome of the site evaluation; and second, to detect released radioactivity. The need for including the requirement for monitoring in the programme, and the nature and extent of such a programme, will depend on the hydrogeologic conditions of the site and on the use of the water extracted from near the site. It is usually possible to integrate the measurements with those planned for other purposes and to use the same set of samples. In some cases it may be necessary to review and modify the monitoring programme in order to take into account any changes that have occurred in the hydrogeologic system since the programme was first developed, or any additional information that has been obtained about either the hydrogeologic system or water use.

5.2. Monitoring methods

The basic method used in this programme is to monitor groundwater through boreholes and wells; it may, however, sometimes be possible to monitor the groundwater that reaches the surface through springs or natural depressions. If boreholes are drilled or wells constructed for the purpose of monitoring groundwater in the region, they should be designed to last for the lifetime of the plant.

In regions where more than one hydrogeologic unit may be affected by accidental releases of radioactive material, the monitoring wells are planned in such a way that each well or borehole yields samples from only one hydrogeologic unit. Areal and vertical spacing of monitoring wells should be such that all the hydrogeologic units which may be contaminated are monitored and taken into account. Therefore, the monitoring design will be based upon the local groundwater flow system and should be derived from any available flow and transport analyses (made, for example, on models). Homogeneous formations

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generally require fewer wells than do heterogeneous formations. If the hydrogeologic unit to be monitored is of considerable thickness, samples should be obtained from several different depths. In general, most of the monitoring wells should be down-gradient of the facilities, but not necessarily in the same lateral direction for all hydrogeologic units that are monitored.

In Annex IV, examples of the methods and measurement frequencies that might be appropriate for a monitoring programme are shown.

5.3. Monitoring schedule

The programme of monitoring the hydrogeologic system in the region should be initiated one or two years before the start of construction of the plant, and should be designed to take into account the variations relevant to the site (e.g. seasonal changes). Statistically reliable background data on the groundwater system are normally available by the time the plant goes into operation. Such data collected in the pre-construction and pre-operational periods can serve as a basis for comparison with data obtained later, during the operational phase of the plant.

The sequence and frequency of collection of groundwater samples for the measurement of radioactivity should be related to the decay characteristics of the radionuclides of interest, and to their transport time from the source to the sampling points.
Appendix A

MODELLING OF RADIONUCLIDE MOVEMENT IN GROUNDWATER

A.1. Introduction

Except for the two-phase distribution of the material, radionuclide movement in groundwater can be described by two basic equations: one for the carrier fluid mean movement (advective transport), and one for the hydrodynamic dispersion of the radionuclides within the carrier. In applying these equations, it is necessary first to obtain a solution for the carrier movement or fluid flow system before the hydrodynamic dispersion equation is solved.

In this Appendix, the most complex and general equations representing the process are discussed first, followed by progressively less complex expressions. However, in selecting an equation, the simplest form should be used first (with conservative coefficients) and then, if necessary, the more complex forms. The assumptions and approximations made in applying the simpler models must be carefully considered in order to ensure that their use does not lead to erroneous results. None of the models is applicable to hydrogeologic units containing hard rock, widely spaced fractures or solution channels. For such conditions, tracer studies are used to estimate travel time and fluid flow. Furthermore, the models in this Guide are not designed to be applicable to hydrogeologic conditions that include variable groundwater densities such as those encountered at coastal sites at the interface of fresh water and salt water. When the models are applied to a site where density variations occur, the simplifying assumption of uniform density should not be used, and care should be taken to ensure that the results are conservative.

A.2. Groundwater flow field

A.2.1. Release to the groundwater

Simplifying hypotheses may be made to characterize the mode of release of radionuclides. One conservative assumption is that the release occurs instantaneously and directly to the groundwater table. However, in a more realistic scenario the hypothesis would be made that the radioactive effluent moves through the unsaturated zone (if it exists) above the water table before entering the saturated media. The general balance equation is then:

\[
\frac{\partial \theta}{\partial t} = - \nabla \cdot \mathbf{V}
\]  

(1)
where

\( \theta \) is the moisture content;
\( t \) is the time;
\( \vec{V} \) is the flux of water;
\( \nabla \) is the del operator;

and the moisture content variation depends on the compressibilities, for example,

\[
\frac{\partial \theta}{\partial t} = \left( \frac{\theta \alpha'}{n'} + \theta \beta' + \frac{\partial \theta}{\partial h} \right) \frac{\partial h}{\partial t}
\]  \hspace{1cm} (2)

where

\( n' \) is the total porosity;
\( \alpha' \) is the modified coefficient of compressibility of the medium (= \( \alpha \rho g \));
\( \beta' \) is the modified coefficient of compressibility of water (= \( \beta \rho g \)); and
\( h \) is the pressure head.

A.2.1.1. Movement in the unsaturated zone

In the unsaturated zone, the movement of both gas (air) and water occurs. The physically correct description of the flow in the unsaturated zones consists of a coupled equation for both gas and water movement. However, solutions of this multi-phase flow phenomenon are still in the development stage. If the assumptions are made that no air pockets exist in the hydrogeologic media and that water moves as a single phase for saturated-unsaturated flow, then with \( \partial z/\partial t = 0 \), we can write:

\[
\left[ \left( \frac{\theta}{n'} \right) \alpha' + \beta' \theta + \frac{\partial \theta}{\partial h} \right] \frac{\partial h}{\partial t} = - \nabla \cdot \vec{V}
\]  \hspace{1cm} (3)

This equation has been presented in the general literature [8]. It is a non-linear, three-dimensional, partial differential equation, and it is impractical to solve it numerically because of the extremely large computer code requirement. The two-dimensional saturated-unsaturated flow equation is coupled with the flux (Darcy’s) equation [8]:

\[
\vec{V} = - \vec{K}(h) \cdot (\nabla h + \nabla z)
\]  \hspace{1cm} (4)
where

\[ z \] is the elevation head;
\[ \vec{V} \] is the flux (Darcy's velocity); and
\[ \vec{K}(h) \] is the hydraulic conductivity tensor (permeability or Darcy's coefficient),

to yield the following equation from Eq.(3)

\[
\left( \frac{\theta}{n'} \right) \alpha' + \beta' \theta + \frac{d\theta}{dh} \frac{dh}{dt} = \nabla \cdot (\vec{K}(h) \cdot (\nabla h + \nabla z))
\]  

(5)

The most complete treatment is obtained when the movement of fluid through the unsaturated zone to the water table is considered in the solution of the flow equation. Neglecting the flow through the unsaturated zone will reduce the complexity of the analysis and will usually provide a more conservative result. However, it is necessary to confirm the validity of this assumption for each specific case in which such a simplification is introduced.

### A.2.1.2. Flow in the saturated zone

#### a) Confined aquifer

In the saturated zone, the moisture content is equal to the total porosity \( (\theta = n') \), and the hydraulic conductivity has reached its saturated value and is no longer a function of the pressure head. The resulting equations with \( \partial z/\partial t = 0 \) and

\[
\frac{\partial \theta}{\partial t} = (\alpha' + \alpha' \beta') \frac{\partial h}{\partial t}
\]

are:

\[
\left| \alpha' + n' \beta' \right| \frac{\partial h}{\partial t} = - \nabla \cdot \vec{V}
\]  

(6)

\[
\vec{V} = - \vec{K} \cdot (\nabla h + \nabla z)
\]  

(7)

The hydraulic conductivity \( \vec{K} \) is a tensor parameter that accounts for the directional properties (anisotropy) that arise in a specific hydrogeologic unit. Only the principal components of the tensor are required if the co-ordinate system is oriented parallel to the principal components of hydraulic conductivity.
If the medium can be assumed to be homogeneous and isotropic, the hydraulic conductivity becomes a scalar. For saturated flow in confined aquifers the following equations can be written:

\[ L (\alpha' + n\beta) = S \]
\[ KL = T \]  
\[ \nabla^2 H = \frac{S}{T} \frac{\partial H}{\partial t} \]

where

- \( T \) is the transmissivity;
- \( H \) is the total head;
- \( S \) is the storage coefficient;
- \( t \) is the time;
- \( \nabla \) is the del operator; and
- \( L \) is the confined aquifer thickness.

In Eq.(6), the coefficient \( S/T \) is a function of the water density, gravity, aquifer thickness, and the compressibilities of the medium and of the water. Both \( S \) and \( T \) are determined from field pumping tests.

b) Unconfined aquifer

The compressibilities of the medium and the water are relatively unimportant for unconfined \((\alpha' = \beta' = 0)\) (water table) aquifers. With Dupuit's assumption that the velocity is uniform and essentially horizontal, the equations for the flow in an unconfined aquifer with

\[ \frac{\partial z}{\partial t} \neq 0; \quad \frac{\partial \theta}{\partial t} = 0; \quad H = z; \quad \theta = S_y \]

are

\[ \frac{\partial \theta}{\partial t} = - \nabla \cdot \vec{V} \]

\[ \nabla^2 H^2 = \frac{2S_y}{K} \frac{\partial H}{\partial t} \]

where

- \( S_y \) is the specific yield (effective porosity) in the \( y \) direction, and
- \( K \) is the hydraulic conductivity.
For steady flow, Eqs (8) and (9) simplify to:

\[ \nabla^2 H = 0 \quad \text{for a confined aquifer} \quad (8a) \]

\[ \nabla^2 H^2 = 0 \quad \text{for an unconfined aquifer} \quad (9a) \]

Analytical solutions for the flow field are available for non-complex cases for Eqs (8), (9) and (9a) (see Ref.[1] and Annex II). For more complex situations, numerical solutions such as those described by Reeves and Duguid [13] should be used.

A.2.2. One-dimensional representation

Darcy's Law can be used to obtain a one-dimensional approximation of groundwater flux, neglecting any lateral flow:

\[ V_x = -K_x \frac{\partial H}{\partial x} \quad (10) \]

where

- \( V_x \) is the groundwater flux in the flow direction; and
- \( \frac{\partial H}{\partial x} \) is the hydraulic gradient in the flow direction.

In many cases this simple approximation is acceptable because spatial variations in the hydraulic conductivity cannot be accurately measured in the field. Assumptions inherent in this approximation are that the medium is homogeneous and isotropic, and that the gradient is constant over the increment \( dx \). The average seepage velocity (or pore velocity) of the groundwater can be estimated by dividing the groundwater flux (or Darcy velocity) by the effective porosity:

\[ u = \frac{V_x}{n_e} \quad (11) \]

where

- \( u \) is the average groundwater pore velocity; and
- \( n_e \) is the effective porosity.

Care and engineering judgement should be used when applying Eqs (10) and (11) to ensure that none of the inherent assumptions leads to non-conservative results. In many cases, conservative parameters can be selected to compensate for assumptions that are not completely satisfied.
A.3. Transport and hydrodynamic dispersion

Once the flow field has been solved by the method described in Subsection A.2, the equation for the transport including the effect of hydrodynamic dispersion may be discussed.

Complete analysis of the transport of dissolved constituents in saturated-unsaturated media would require the most general form of the mass transport equation. The following tensor equation describing saturated flow without the sorption process has been presented in the literature:

\[
\frac{\partial c}{\partial t} - \nabla \cdot ( \mathbf{D} \cdot \nabla (\theta c)) + \nabla \cdot \mathbf{V}(c) + \left( \frac{\partial \theta}{\partial t} + \lambda \theta \right) c = 0
\]  

(12)

where

- \( c \) is the concentration of dissolved constituent;
- \( \mathbf{D} \) is the coefficient of hydrodynamic dispersion (hydrodynamic dispersivity);
- \( \mathbf{V} \) is the flux;
- \( \lambda \) is the radioactive decay constant;
- \( \theta \) is the moisture content; and
- \( t \) is time.

As discussed in the literature, e.g. Refs [8] and [12], the coefficient of hydrodynamic dispersion (hydrodynamic dispersivity) may be expressed as a function of intrinsic diffusivity and groundwater velocity. Intrinsic diffusivity is a function of the properties of the hydrogeologic material, including its inhomogeneity. Values determined in the laboratory vary from \( 10^{-2} \) to 1 cm. Values determined in the field may range from about 10 cm in sandy unconfined units to about 200 m in consolidated, confined units [14]. Calculated values are influenced by the scale of testing, particularly by the heterogeneity of the flow stratum and by the spacing of the wells [2].

In general, intrinsic diffusivity is a fourth-rank tensor with 81 components; however, if isotropy can be assumed, the hydrodynamic dispersion coefficient may be described in terms of longitudinal \( \alpha_l \) and transverse \( \alpha_t \) intrinsic diffusivity by means of the following equation [15]:

\[
n_e D_{ij} = \alpha_t \delta_{ij} + (\alpha_l - \alpha_t) \frac{V_i V_j}{V}
\]  

(13)

where

- \( \delta_{ij} \) is the Kronecker delta (equal to 1 for \( i = j \) and to zero for \( i \neq j \));
- \( \alpha_t \) is the transverse intrinsic diffusivity;
- \( \alpha_l \) is the longitudinal intrinsic diffusivity;
- \( V / n_e \) is the magnitude of the groundwater pore velocity.
$V_i/n_e$, $V_j/n_e$ are the velocity components in the co-ordinate directions; $D_{ij}$ is the component of the hydrodynamic dispersion coefficient tensor; and $n_e$ is the effective porosity of the media.

A.4. Two-phase distribution of the material

Many physico-chemical and biochemical processes can alter the concentration of contaminants in groundwater flow systems. Among the processes are adsorption, acid-base reaction, solution/precipitation, oxidation, reduction, complexation, trapping and ion exchange. It is worth noting that some of these processes interact with each other, vary with time and are not necessarily reversible.

If the groundwater flux and convective transport are assumed to be unidirectional in three dimensions, then a mass balance for a saturated flow in a differential volume of a hydrogeologic unit of uniform physico-chemical properties yields the following generalized expression:

$$A + B + D = E + F + G - H - J \quad (14)$$

where

- $A$ is the rate of accumulation (storage) in the liquid phase;
- $B$ is the rate of accumulation (storage) in the solid phase (governed by sorption);
- $D$ is the convective transport in the liquid phase;
- $E$ is the $x$-component of diffusive movement in the liquid phase;
- $F$ is the $y$-component of diffusive movement in the liquid phase;
- $G$ is the $z$-component of diffusive movement in the liquid phase;
- $H$ is the radioactive decay in the liquid phase; and
- $J$ is the radioactive decay in the solid phase.

In terms of the various hydrogeologic, groundwater, and radionuclide parameters, with the $x$ direction assumed to be the direction of the flux, the above expression translates to:

$$n \frac{\partial C}{\partial t} + (1 - n) \frac{\partial q}{\partial t} + nu \frac{\partial C}{\partial x}$$

$$= nD_x \frac{\partial^2 C}{\partial x^2} + nD_y \frac{\partial^2 C}{\partial y^2} + nD_z \frac{\partial^2 C}{\partial z^2} - n\lambda C - (1 - n)\lambda q \quad (15)$$

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where

\( n \) is the fraction of the differential volume occupied by the liquid phase (i.e. the total porosity);

\( C \) is the radionuclide volumetric concentration in the liquid phase;

\( q \) is the radionuclide volumetric concentration in the solid phase;

\( D_x, D_y, D_z \) are the hydrodynamic dispersion coefficient components;

\( t \) is time;

\( u \) is the unidirectional (x) component of groundwater pore velocity; and

\( \lambda \) is the radionuclide decay constant.

The above equation can be reduced to a simpler and more conservative form if it is assumed that the solid and liquid phases are in equilibrium and that their radionuclide concentrations are related by:

\[ q = K_d R_s C \quad (16) \]

in which

\( K_d \) is the equilibrium distribution coefficient (ratio of radioactivity per unit mass of the solid phase to radioactivity per unit volume of the liquid phase); and

\( R_s \) is the density of the solid phase material, i.e. the intrinsic density of the solid phase.

The bulk density of the solid phase, i.e. the mass of solid per unit volume of the hydrogeologic unit, is denoted by \( \rho_b \) and is given by:

\[ \rho_b = R_s (1-n) \quad (17) \]

Substitution of Eqs (16) and (17) into Eq.(15) gives the following after rearrangement of terms:

\[ \frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} = \frac{D_x}{a} \frac{\partial^2 C}{\partial x^2} + \frac{D_y}{a} \frac{\partial^2 C}{\partial y^2} + \frac{D_z}{a} \frac{\partial^2 C}{\partial z^2} - \lambda C \quad (18) \]

where

\[ a = 1 + K_d R_s \left( \frac{1-n}{n} \right) = 1 + \frac{\rho_b}{n} K_d \quad (19) \]

is the retardation factor for porous media.

Particular attention should be given to the \( K_d \), which is normally a complex function of the phenomena related to the two-phase concentration distribution and should not be used in hard rock or fractured rock situations.
A.5. General considerations

Equation (18) can be solved analytically for simple boundary conditions. Appropriate solutions appear in the literature [8] for:

1. An instantaneous release from a point source;
2. An instantaneous release from a rectangular planar source;
3. A continuous release from a line source;
4. A continuous release from a rectangular planar source.

It should be noted that as the distance from a long rectangular planar source becomes large compared to the source width, the results approach those of a line source. The point concentration model of Codell and Schreiber [14] solves Eq.(16) analytically in terms of normalized influence or Green’s function. Solutions are presented in Annex II and include the following cases:

1. An instantaneous release from a point source;
2. An instantaneous release from a vertical line source;
3. An instantaneous release from a horizontal line source;
4. An instantaneous release from a rectangular, vertical planar source.

In addition, Annex II gives the Codell and Schreiber [14] solutions applicable to an infinite region for instantaneous releases from a point source and a horizontal line source. If necessary, Green’s functions could be developed to handle other boundary conditions such as volume sources in finite and infinite aquifers.

With any of the solutions given in Ref. [14] or Ref. [8], the effort involved in calculating concentrations can be significantly reduced by using a computer. However, if a computer is not available, or when it is desirable to provide an independent check without the aid of a computer, the approach developed in Section A.6 may be used.

A.6. Simplified approach

A.6.1. Instantaneous point source — concentration reduction

Most potential releases of radioactivity to the hydrogeologic system at nuclear power plant sites can be adequately described by an instantaneous point source release of radioactivity. The concentration of a contaminant in a uniform, one-dimensional flow for an instantaneous point source release can then be expressed by [16]:

\[
\text{CRF}_{\text{min}} = \frac{C_0}{C} = \frac{(4\pi t)^{3/2} (D_x D_y D_z)^{1/2}}{2v}
\]

(20)
If we consider that

$$D_i = \frac{\sigma_i^2}{2t}$$  \hspace{1cm} (21)

then we get

$$\frac{C_0}{C} = \frac{(2\pi)^{3/2}}{2v} \sigma_x \sigma_y \sigma_z$$  \hspace{1cm} (22)

where

- $\text{CRF}_{\text{min}}$ is the minimum concentration reduction factor at the centre line of the contaminant plume ($x = Vt/a, y = 0, z = 0$);
- $C_0$ is the initial contaminant concentration;
- $C$ is the contaminant concentration at time $t$;
- $t$ is the groundwater travel time to the point of concern;
- $D_x, D_y, D_z$ are the hydrodynamic dispersion coefficient components;
- $v$ is the total volume of released contaminant; and
- $\sigma$ is the standard deviation of spreading.

The hydrodynamic dispersion coefficients $D_x, D_y, D_z$ are defined as:

$$D_x = \alpha_x u$$  \hspace{1cm} (23)
$$D_y = \alpha_y u$$  \hspace{1cm} (24)
$$D_z = \alpha_z u$$  \hspace{1cm} (25)

where

$\alpha_x, \alpha_y$ and $\alpha_z$ are the intrinsic diffusivity components in the $x$, $y$ and $z$ directions.

Applying Eq.(12), we get

$$D_x = \alpha_i u$$  \hspace{1cm} (26)
$$D_y = \alpha_j u$$  \hspace{1cm} (27)
$$D_z = \alpha_k u$$  \hspace{1cm} (28)
For the hydrodynamic dispersion coefficients in Eqs (23)—(25) to be identical to those in Eqs (26)—(28), we must have

\[
\alpha_x = \alpha_i = \alpha_L \tag{29}
\]

\[
\alpha_y = \alpha_j = \alpha_T \tag{30}
\]

\[
\alpha_z = \alpha_k = \alpha_T \tag{31}
\]

Although it is not strictly valid to do so, we can use Eqs (23)—(25) to calculate hydrodynamic dispersion coefficients in an anisotropic medium. This is done for mathematical convenience, because closed-form solutions to Eq.(18) would not be possible if there were off-diagonal components in Eq.(13). In practice, this is not a serious violation because intrinsic diffusivities are determined empirically; thus, errors that would result from imprecise modelling can be minimized. Whenever possible, intrinsic diffusivity coefficients should be obtained from tracer tests in the aquifer being considered. Laboratory-derived values of intrinsic diffusivity are usually too small because of scale effects, and they should not be applied to full-scale field problems.

If Eqs (23)—(25) are substituted into Eq.(20), then after rearrangement of terms the following results:

\[
\text{CRF}_{min} = \frac{(4\pi L)^{3/2} (\alpha_x \alpha_y \alpha_z)^{1/2}}{2v} \tag{32}
\]

where \( L \) is the path length from the source to the point in question. Note that Eqs (20) and (32) do not include the effects of radionuclide sorption and decay. If these effects are included, then Eq.(32) becomes:

\[
\text{CRF} = \frac{(4\pi L)^{3/2} (\alpha_x \alpha_y \alpha_z)^{1/2}}{2v} e^{-\lambda t_i} \tag{33}
\]

where \( t_i = L/(u/a) \) is the radionuclide travel time along the path length.

If Eq.(32) is substituted into Eq.(33), we get

\[
\text{CRF} = \text{CRF}_{min} e^{-\lambda t_i} \tag{34}
\]

The exponential term accounts for the effects of radionuclide sorption and decay. Therefore, the only effect of sorption is to increase travel time, allowing more opportunity for decay. Equations (32) and (33) can be solved readily without the aid of a computer if the number of released radionuclides is not too large.
A.6.2. Instantaneous point source — flux determination

In many hydrogeologic situations, an aquifer is connected to a body of surface water. If such an aquifer becomes contaminated with radioactive material, then it may be desirable to estimate the flux or discharge rate of radionuclides from the aquifer to the surface water. It was to analyse this situation, that the radionuclide flux model was developed by Codell and Schreiber [14]. The same assumptions used to develop the point concentration model were applied to the flux model. Furthermore, it was assumed that all radionuclides entering the aquifer eventually entered the surface water, except for loss through radioactive decay. The flux model provides the rate of radionuclide input to the surface water at an average distance x down-gradient from the source. For the assumed unidirectional flow field, the differential flux, dF (becquerels per second), of a radionuclide crossing a differential area, dA = dy dz, orthogonal to the x-axis is given by:

\[
\frac{dF}{dA} = \left( uC + D_x \frac{\partial C}{\partial x} \right) n_e
\]  \hspace{1cm} (35)

where

C is the radionuclide concentration in the liquid phase; and
n_e is the effective porosity.

Integrating over the entire planar area A, we get the total flux F of the radionuclide across the plane as:

\[
F = n_e \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left( uC + D_x \frac{\partial C}{\partial x} \right) dy dz
\]  \hspace{1cm} (36)

If C_i is the concentration of an instantaneous unit release at x = 0 and t = 0, then the resulting flux F_i at a distance x down-gradient of the source would be:

\[
F_i = \frac{\left( x + \frac{u}{a} t \right)}{4 \left( \frac{D_x}{a \pi t^3} \right)^{1/2}} \exp \left[ -\frac{\left( x - \frac{u}{a} t \right)^2}{4 \frac{D_x}{a t}} - \lambda t \right]
\]  \hspace{1cm} (37)

The analytical models described in Ref.[14] have been applied to a variety of situations since their inception. The models were originally developed to
evaluate potential accidental releases of radioactive liquid to the groundwater at nuclear power plant sites. The models have been applied to the rupture of a radwaste or boron recycle tank and to a hypothetical core-melt accident, as described in the NRC Liquid Pathway Generic Study [17]. A further generic application of the point source concentration model to low-level radioactive waste material is described in Ref.[18]. For circumstances requiring more complex mathematics, numerical solutions, such as the method of characteristics described by Fried and Combarovs [19], may be useful.

A.7. Model validation

High-quality field data on radionuclide dispersion in groundwater are scarce. Furthermore, the collection of necessary field data for a very detailed modelling effort can be extremely costly, since the groundwater in the hydrogeologic unit in which dispersion is taking place can be measured only indirectly at wells. If at all possible, it is desirable to confirm the validity of dispersion models with data that are currently available from measurements of dispersion from actual releases.2

Codell and Schreiber [14] provided a validation, to the extent possible, of their point concentration model on the basis of tritium measurements made at Idaho in October 1961 and July 1966 and reported by Robertson [20]. Agreement between the model results and the field measurements was reasonable and as good as could be expected for a model with non-distributed parameters. This report can be consulted for possible validation procedures for other models.

A.8. Model applications

In applying any of the models described in this Appendix, the most important task is to ensure that the inherent assumptions are valid and that the coefficients and parameters are carefully selected. This selection should be based, as far as possible, on data obtained from the specific site.

Equation (15), which is used as a basis for all the analytical models described in this Appendix, was formulated under a number of assumptions that are summarized here for the sake of emphasis:

1. Molecular diffusion was assumed to be many orders of magnitude smaller than mechanical dispersion (convective dispersion) and was consequently neglected;
2. The hydrogeologic unit was assumed to be homogeneous and isotropic;
3. The fluid flow was assumed to be uniform, steady and unidirectional;

For example, tritium dispersion and migration at the Hanford site and at the Idaho National Engineering Laboratory in the United States of America.
(4) Sorption of radionuclides was assumed to be linear with the concentration;
(5) Chemical reactions were assumed to be so rapid that equilibrium exists between the dissolved and sorbed radionuclides;
(6) The radioactive effluent was assumed to have the same density as the groundwater.
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Annex I

CONSIDERATIONS RELATED TO GROUNDWATER AVAILABILITY

I.1. Introduction

Groundwater offers a potential alternative cooling water source for systems and components important to safety, even though it has not been commonly used for this purpose. Groundwater may also be considered as a supply for many non-safety-related uses, such as condenser cooling water make-up for cooling towers. The equipment and structures associated with the utilization of the groundwater, being design-related, are not within the scope of this Guide. This Annex specifically discusses the factors to be considered in determining the availability of the groundwater for these uses.

I.2. Factors affecting availability

An evaluation of availability of groundwater for both non-safety-related and safety-related uses should include:

(1) Consideration of whether groundwater mining can occur. If so, the effects on piezometric levels, connected surface water bodies and groundwater quality should be estimated.
(2) Determination of potential land subsidence and its effect on foundations, salt-water intrusion, water level and quality changes.
(3) Information on permits required where groundwater withdrawals are regulated by permits or licences. Permit restrictions should be described. The number and duration of groundwater supply interruptions should also be estimated.

In addition, for safety-related uses, the evaluation should include:

(4) Demonstration that the groundwater sources will have adequate availability and capacity for the intended use. This requires determination of the sustained yield of the aquifer.
(5) Consideration of the combined use of surface water and groundwater resources. In this case, demonstration of availability should reflect the combined use rather than that of either component.
(6) Demonstration that the source combination, if a redundant source is required, is capable of withstanding the most severe natural phenomena expected, other site-related events, and reasonable combinations thereof.
(7) Consideration of seismic effects. An engineered system for extracting water from a groundwater source that is intended to be used as a source of supply for a seismically qualified safety system should be qualified to the same seismic level. Some guidance may be obtained from an analysis of the effects of past earthquakes on aquifers.

I.3. Monitoring

The objective of the monitoring programme is to detect any change in the groundwater situation which could affect the use being made of it.

A detailed knowledge of the hydrogeologic system of the area is essential for developing an effective monitoring programme. In some cases it may be necessary to review and modify the monitoring programme on the basis of changes that have occurred in the hydrogeologic system since the programme was initially developed or on the basis of additional information obtained about the system.

I.3.1. Monitoring wells

The basic monitoring of groundwater is performed through boreholes and wells; it may however be possible sometimes to monitor groundwater through springs or natural depressions. If boreholes are drilled or wells constructed for the purpose of monitoring groundwater in the region, they must be designed to last for the lifetime of the plant.

In regions where more than one aquifer exists in the neighbourhood of the plant, it is important to plan the monitoring wells and boreholes in such a way that each well or borehole is used to collect samples from one aquifer only. If the aquifer being monitored is of considerable thickness, plans should be made to obtain samples from different depths.

I.3.2. Data to be collected from monitoring

In order to meet the objectives stated in Subsection 5.1 of this Guide, the monitoring of groundwater should include the following:

(1) Measurement of water table levels and pressures of confined units at suitable intervals to enable the water table contour map of the region to be updated from time to time; and the development of hydrographs for each well.

(2) Systematic collection of information about pumpage and other withdrawal of water from the hydrogeologic unit.

(3) Systematic collection of samples of groundwater to detect any change in its quality or chemistry and its isotopic composition.
Annex II

ANALYTICAL SOLUTIONS OF THE
ADVECTIVE TRANSPORT
AND HYDRODYNAMIC DISPERSION EQUATIONS

This Annex provides typical analytical solutions to the groundwater advective transport and hydrodynamic dispersion equations given in Appendix A. The solutions in this Annex are by no means all that are available in the literature. Furthermore, there are very complex situations which require use of numerical or analog solutions rather than analytical ones. This subject is also mentioned briefly below.

II.1. Typical analytical solutions to the groundwater advective transport equations for evaluating hydrogeologic parameters

For homogeneous and isotropic aquifers, the groundwater advective transport equations are given in Eqs (7) and (8) of Appendix A. Analytical solutions to these equations for evaluating the hydrogeologic parameters are presented in many textbooks dealing with hydrogeology or groundwater hydrology (see, for example, Ref. [1]).

II.2. Groundwater flow field evaluation

In order to predict probable radionuclide movement, the groundwater flow field must be evaluated. This can be done in a preliminary way by using the Darcy flow equations (Appendix A) involving the hydraulic gradients derived from groundwater level measurements and estimates of hydraulic conductivity. This simple analytical approach allows in certain cases an estimate to be made of the general groundwater flow field through specified parts of a hydrogeologic unit. In many cases, however, this is not possible (because of disuniformity, anisotropy, etc.). More reliable predictions can be made, and tested against field data, by the use of digital computer programs that numerically solve the relevant differential equations and analyse the interplay of natural input, groundwater flow, natural and man-induced discharges, and the relation between surface water and groundwater. There is an extensive literature dealing with this topic [21] and numerous field examples [22, 23].

In some instances it is possible to use analog models [1, 22] to provide predictions of groundwater flows, but on the whole these are less versatile and less readily able to take account of additional data or modifications to the inputs than are the digital models.
II.3. Some typical analytical solutions of the hydrodynamic dispersion equations

For homogeneous and isotropic hydrogeologic units with unidirectional groundwater flux and advective transport with hydrodynamic dispersion in three dimensions, the relevant equation is Eq.(18) of Appendix A. Analytical solutions are available in the literature (see, for example, [14]). These solutions are provided in terms of normalized influence or Green's functions [16]:

\[ C_i = \frac{1}{n_e a} X(x,t) Y(y,t) Z(z,t) \] (II.1)

where

- \( a \) is the retardation factor;
- \( n_e \) is the effective porosity;
- \( C_i \) is the concentration in the liquid phase at any point in space for an instantaneous unit release;
- \( X, Y, Z \) are the Green's functions in the x, y, z co-ordinate directions respectively; and
- \( t \) is time.

Equation (II.1) has been developed for several boundary and source configurations.

II.3.1. Instantaneous release from a point source \((0,0,z_1)\) in a hydrogeologic unit of infinite lateral extent \((x,y)\)

II.3.1.1. Hydrogeologic unit of infinite thickness

For an instantaneous release from a point source at \((0,0,z_1)\) in a hydrogeologic unit of infinite thickness, the concentration is given by:

\[ C_i = \frac{1}{n_e a} X_1 Y_1 Z_1 \] (II.2)

\[ X_1 = \frac{1}{\left(4\pi D_x \frac{t}{a}\right)^{1/2}} \exp \left[ -\left(\frac{x-ut}{a}\right)^2 - \lambda \frac{t}{a} \right] \] (II.3)

\[ Y_1 = \frac{1}{\left(4\pi D_y \frac{t}{a}\right)^{1/2}} \exp \left[ -\frac{y^2}{4D_y \frac{t}{a}} \right] \] (II.4)
\[ Z_1 = \frac{1}{\left(4\pi D_z \frac{t}{a}\right)^{1/2}} \left\{ \exp \left[ -\frac{(z - z_1)^2}{4 D_z \frac{t}{a}} \right] + \exp \left[ -\frac{(z + z_1)^2}{4 D_z \frac{t}{a}} \right] \right\} \] (II.5)

Note that the Green’s functions X, Y and Z could alternatively be expressed in terms of Gaussian distribution parameters \( \sigma_x \), \( \sigma_y \) and \( \sigma_z \). This solution is generally applicable for a spot release when the hydrogeologic unit extends laterally over 20 or more kilometres and also has considerable thickness (more than 100 m).

II.3.1.2. Hydrogeologic unit of finite thickness \( h \)

For an instantaneous release from a point source at \((0,0,z_1)\) the solution is:

\[ C_i = \frac{1}{n_e a} X_1 Y_1 Z_2 \] (II.6)

where

\[ Z_2 = \frac{1}{h} \left[ 1 + 2 \sum_{m=1}^{\infty} \exp \left[ -\frac{m^2 \pi^2 D_z t}{h^2 a} \right] \right] \]

\[ \times \cos m\pi \frac{z_1}{h} \cos m\pi \frac{z}{h} \] (II.7)

This solution is a specific case of (II.3.1.1) where the thickness of the unit is finite and small.

II.3.2. Instantaneous release from a vertical line source of length \( h \) at the origin in a hydrogeologic unit of infinite lateral extent \((x,y)\) and thickness \( h \)

The solution is:

\[ C_i = \frac{1}{n_e a} X_1 Y_1 Z_3 \] (II.8)

where

\[ Z_3 = \frac{1}{h} \] (II.9)
This applies to a case where an accidental release passes through a vertical fracture located within the hydrogeologic unit.

II.3.3. Instantaneous release from a horizontal line source of length b centred at \((0, 0, z_1)\) in a hydrogeologic unit of infinite lateral extent \((x, y)\)

II.3.3.1. Hydrogeologic unit of infinite thickness

For an instantaneous release from a horizontal line source of length b centred at \((0,0,z_1)\), the solution is:

\[ Q = \frac{1}{n_e a} X_1 Y_2 Z_1 \quad \text{(II.10)} \]

\[ Y_2 = \frac{1}{2b} \left[ \text{erf} \left( \frac{\left( \frac{b}{2} + y \right)}{\left( \frac{4D_y t}{a} \right)^{1/2}} \right) + \text{erf} \left( \frac{\left( \frac{b}{2} - y \right)}{\left( \frac{4D_y t}{a} \right)^{1/2}} \right) \right] \quad \text{(II.11)} \]

This analytical solution may be applicable to the case of a radioactive leak arising out of cracks in a radwaste building provided that the thickness of the hydrogeologic unit is large.

II.3.3.2. Hydrogeologic unit of finite thickness \(h\)

The solution is:

\[ Q = \frac{1}{n_e a} X_1 Y_2 Z_2 \quad \text{(II.12)} \]

II.3.4. Instantaneous release from a vertical rectangular planar source of width b and thickness h centred at \((0, 0, z_1)\) (hydrogeologic unit of extent \([z_1 < z < z_1 + h]\))

The solution is:

\[ Q = \frac{1}{n_e a} X_1 Y_2 Z_3 \quad \text{(II.13)} \]
This applies generally to a situation where an instantaneous release is through a vertical joint extending horizontally. Other typical solutions have been provided in Ref.[8]; for these, the dispersion tensor is homogeneous and anisotropic: the following notation is used:

\[ D_{xx} = \alpha_L \frac{V_x}{n_e} \quad D_{yy} = D_{zz'} = \alpha_T \frac{V_x}{n_e} \]

\[ E_x = \frac{D_{xx}}{a} \quad E_y = \frac{D_{yy}}{a} \]

\[ U = \frac{V_x}{n_e a} \]

where

- \( V_x \) is the flux parallel to the x-axis;
- \( U \) is the average rate of radionuclide movement; and
- \( a \) is the retardation factor.

II.3.5. *Instantaneous release from a line source passing through the point \((x,y)\) parallel to the z-axis*

The following solutions are provided for a hydrogeologic unit of finite thickness and infinite extent.

For the instantaneous release from a line source passing through the point \((x_1,y_1)\) and parallel to the z-axis, the solution is [8]:

\[ C = \frac{m}{4\pi n_e t (E_x E_y)^{1/2}} \times \exp \left[ -\frac{[(x - x_1) - Ut]^2}{4E_x t} - \frac{(y - y_1)^2}{4E_y t} + \lambda t \right] \]  

(II.14)

where \( m \) is the activity instantaneously released per unit length in the z direction.

To use Eq.(19) in Appendix A for calculating the radionuclide transport, \( m \) is found by dividing the total activity of a particular radionuclide contained in the release by the assumed length of the line source. This applies to a case similar to that described in Subsection II.3.2, except that the release is not at the origin of the x,y co-ordinates.
II.3.6. *Instantaneous release from a rectangular planar source of width $f$, centred at the origin and parallel to the y-z plane, in a hydrogeologic unit of finite thickness and infinite extent*

The solution is [8]:

\[
C = \frac{m'}{4a_{11e}(\pi E_xt)^{1/2}} \exp\left(-\frac{(x-Ut)^2}{4E_xt} + \lambda t\right)
\]

\[
\times \left[ \text{erf}\left(\frac{y + \frac{f}{2}}{2(E_yt)^{1/2}}\right) - \text{erf}\left(\frac{y - \frac{f}{2}}{2(E_yt)^{1/2}}\right) \right] \quad (\text{II.15})
\]

where $m'$ is the activity instantaneously released per unit area of the planar source.

Thus, for calculations using Eq.(20) in Appendix A, $m$ is found by dividing the total activity of a particular radionuclide contained in the release by the source width times the assumed thickness. This equation is applicable to the release of radioactivity through wide joints in a limestone overburden.

II.3.7. *Continuous release from a line source passing through the origin parallel to the z-axis in a hydrogeologic unit of finite thickness and infinite extent*

For continuous release from a line source passing through the origin and parallel to the z-axis, the transient solution is [8]:

\[
C = \int_{0}^{t} \frac{q}{4\pi a_{11e}(E_x E_y)^{1/2} (t-\tau)} \exp\left(-\frac{[x-U(t-\tau)]^2}{4E_x(t-\tau)} + \frac{y^2}{4E_y(t-\tau)} + \lambda(t-\tau)\right) d\tau \quad (\text{II.16})
\]

where

- $q$ is the time rate of release per unit length in the $z$ direction; and
- $\tau$ is a variable introduced for computational convenience.

Equation (18) in Appendix A can be integrated numerically using Legendre-Gauss quadrature. However, as the time becomes large, Gauss-Laguerre quadrature may be required. Computer programs for performing this integration are
available in many subroutine packages. This approach can be used for situations where the release of radioactivity lasts for an extended period of time.

The steady-state solution of Eq. (II.16) is obtained by letting time approach infinity. This yields a solution in terms of Bessel functions which may be approximated to give the steady-state solution:

\[
C = \frac{q}{4 a_0 n e (\pi E_x E_y L)^{1/2}} \exp \left[ \frac{4 LE_x - U_x}{2 E_x} \right]
\] (II.17)

where

\[
L = \frac{[(E_y x^2 + E_x y^2) (U^2 E_y + 4E_x E_y \lambda)]^{1/2}}{4 E_x E_y}
\]

II.3.8. Continuous release from a rectangular planar source of width \( f \), centred at the origin and parallel to the y-z plane in a hydrogeologic unit of finite thickness and infinite extent

The transient solution is [8]:

\[
C = \int_0^t \frac{q'}{4 n e a (\pi E_x)^{1/2} (t - \tau)^{1/2}} \exp \left[ \frac{[x - U(t - \tau)]^2}{4 E_x (t - \tau)} + \lambda (t - \tau) \right]
\]

\[
\times \left[ \text{erf} \left( \frac{y + f/2}{2 [E_y (t - \tau)]^{1/2}} \right) + \text{erf} \left( \frac{y - f/2}{2 [E_y (t - \tau)]^{1/2}} \right) \right] d\tau
\] (II.18)

This equation applies for a release over an extended period of time.
Annex III

ACCURACY AND RELIABILITY OF MEASUREMENTS IN HYDROGEOLOGY*

The accuracy of certain field measurements in hydrogeology is very high, although the derived estimates of values for physical properties fall in a wide range. For instance, the measurement of groundwater levels in wells during a pumping test may be made to an accuracy of ±10 mm, or to 0.1% of the range over which the water level might rise and fall; the derived estimates of hydraulic conductivity may lie within ±10% of the value obtained for this parameter in the part of the hydrogeologic unit affected by an individual pumping test. If the same unit is relatively homogeneous over long distances, then the same value may be assumed to be representative, but greater distance from the test location means a less reliable value for hydraulic conductivity. It is a matter of specialist judgement as to how far apart test locations should be spaced to provide reliable estimates of hydrogeologic properties for use in the predictive model. Similar considerations apply to the derived parameter values needed for modelling; these include transmissivity, storage coefficient, porosity and hydrogeologic unit thickness.

The following specific observations can be made:

(a) Hydrometric measurements. These include data on rainfall, evaporation, river flow, river stage and, if applicable, water levels in lakes and ponds. The uncertainty in the measurement of these variables is well documented in the literature.

(b) Groundwater measurements. These include direct measurements of groundwater levels in wells and of water table elevations in springs, seepage lines and hydraulically related surface water bodies. All of these can be made to accuracies of a few millimetres, which is sufficient for preparing water level contour maps. From these, groundwater or hydraulic gradients are calculated, and at any one spot these may be accurate to only ±10%. Similarly, groundwater flow directions, velocities and volumes can be estimated, the last two only very approximately.

* Since the Guide does not deal specifically with hard or fractured rock, it follows that this Annex likewise may not entirely apply to such units.
Groundwater velocities calculated from hydraulic gradients, utilizing Darcy's Law and values of hydrogeologic properties evaluated in the laboratory (Appendix A), are very likely to be accurate to within a factor of 5; this is acceptable when used in models dealing with flows of a few tens of metres per year, or less. More precise values may be obtained with tracer techniques. These uncertainties of groundwater level contours and of groundwater velocities, however, are related to the velocity of water movement through hydrogeologic units and the half-life of the potential contaminants.

Porosities for materials other than hard or fractured rock can be measured to an accuracy of ±5% in the laboratory, and this is more than adequate for the purpose for which these data are used.

The calculated values of transmissivity, based upon measurements of groundwater level and pumped water flow rate, can vary by an order of magnitude. Although the field measurements are accurate, each test site is unique. As a result of the inhomogeneity of most hydrogeologic units a good deal of judgement has to be exercised in interpreting pumping test analyses. In practice, even these unavoidable uncertainties in the derivation of transmissivity values may result only in minor changes in estimated regional flow patterns and rates. These patterns and rates can be checked against field data in any case. The regional groundwater flow models developed so far predict flows to discharge or withdrawal points which may vary by about 20% for a total transit time of 30 to 40 years. In certain cases, additional values for the parameters may be obtained from simplified tests on single piezometers inserted into the hydrogeologic units. The same considerations apply for the other derived parameters such as hydraulic conductivity and specific storage. The ranges of values of these parameters would, of course, be tested using sensitivity analyses to determine the significance of the extremes of calculated values.

Laboratory measurement of the equilibrium distribution coefficient (Kd) is a specialized technique, carried out under strictly controlled conditions on carefully collected samples of rock material and groundwater. Even so, the results can vary by one or sometimes several orders of magnitude; when used in the relevant models, the conservative, i.e. lower, values have to be chosen.

The range in complexity of field hydrogeologic programmes can be considerable, depending upon the particular region and upon the amount of work already carried out in the area. If it is clear that there is no groundwater present, then investigations would be directed only to confirming the very low permeabilities of the rocks below the site and to determining potential flow paths into surface water bodies. If there is a potential for groundwater contamination, the the field programme will depend upon the amount of information already available. A generalized example is provided below to show the complexity of the studies which may need to be undertaken.

If a site has been selected for a nuclear power plant in a location where no previous detailed hydrogeologic investigations have been made, then a field
programme has to be carried out. A search of available topographic, geologic, hydrologic and meteorological maps will lead to an approximate definition of hydrogeologic units and flow paths. It will also lead to the establishment of the field programme, in particular:

(a) Definition of the location and number of exploratory boreholes required to determine the geological succession and structure in sufficient detail;

(b) Establishment of the groundwater level measurements and of the programme of water sampling in the region in order to prepare maps with dimensions, physical and chemical variations and hydraulic connections of hydrogeologic units with surface waters;

(c) Planning of test wells and associated observation wells, or suitably distributed piezometers, to allow the calculation of hydrogeologic parameters needed for model studies.
## Annex IV

### EXAMPLES OF METHODS AND FREQUENCIES OF MEASUREMENTS WITHIN THE MONITORING PROGRAMME

<table>
<thead>
<tr>
<th>Groundwater</th>
<th>Methods</th>
<th>Frequency(^a)</th>
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<td>Water table level</td>
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<td>Monthly</td>
</tr>
<tr>
<td>Chemistry</td>
<td>Chemical analysis</td>
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</tr>
<tr>
<td>Direction of flow</td>
<td>Tracer tests/calculations from the hydraulic gradient</td>
<td>One initial measurement, and then after any significant changes in water table levels</td>
</tr>
<tr>
<td>Velocity</td>
<td>Tracer tests/calculations from the hydraulic gradient</td>
<td>One initial measurement, and then after any significant changes in water table levels</td>
</tr>
</tbody>
</table>

\(^a\) The sampling frequency will depend on site characteristics; for example, if short-term fluctuations are of large magnitude, more frequent measurements should be made. In some cases, continuous recording may be necessary.
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SPECIAL DEFINITIONS

In general, groundwater terms are used in this Guide in accordance with definitions provided in the International Glossary of Hydrology [24]. Definitions are given below of terms that can have more than one meaning to hydrogeologists. Those marked with an asterisk have been adapted from Ref. [24].

Aquiclude*

Formation which, although porous and capable of absorbing water, does not transmit it at rates sufficient to furnish an appreciable supply for a well or spring.

Aquifer*

Porous water-bearing formation (bed or stratum) of permeable rock, sand or gravel capable of yielding significant quantities of water.

Aquifer, Confined*

Aquifer overlain and underlain by impervious or almost impervious formations.

Aquitard*

Geological formation of a rather impervious and semi-confining nature which transmits water at a very slow rate compared to an aquifer.

Coefficient of Compressibility (of Water)*

Relative decrease in water volume per unit increment of pressure at a given temperature.

Conductivity, Hydraulic (Also called permeability or Darcy’s coefficient.)

Combined property of a porous medium and the fluid moving through it in saturated flow, which determines the relationship, called Darcy’s Law, between the specific discharge and the head gradient causing it.

Density of Soil, Bulk*

Mass of an over-dry soil sample per unit gross volume (include pore space).
Diffusion Coefficient (in Porous Media)* (Also called diffusivity coefficient or dispersion coefficient.)

Amount of solute that passes across a unit cross-section in a porous medium in unit time under the influence of a unit concentration gradient.

Diffusivity, Intrinsic

A geometric property of a porous medium which determines the diffusion characteristics of the medium by relating the components of pore velocity (seepage velocity) to the diffusion coefficient.

Dispersion, Hydrodynamic*

Spreading of a solute through a porous medium resulting from convective transport and diffusion.

Flux (Darcy Velocity or Specific Discharge)†

The volume of groundwater discharge from a given cross-sectional area per unit time, divided by the area of the cross-section.

Hydrogeologic Unit

An aquiclude, aquifer or aquitard.

Permeability, Intrinsic*

Property of a porous medium that allows for the movement of liquids and gases through it under the combined action of gravity and pressure.

Pore Velocity† (Sometimes called seepage velocity.)

The average rate of flow in the pores of a given medium. This is approximated by dividing the flux by the effective porosity.

Porosity†

The ratio of the volume of the interstices in a given sample of a porous medium, e.g. soil, to the gross volume of the medium, inclusive of voids. (In this Guide, the use of the term “porosity” refers to total porosity.)

† From Refs [8, 25].
Porosity, Effective*

Ratio of the volume of water which can be drained from a saturated medium by gravity to the total volume of the medium.

Recharge*

Process, natural or artificial, by which water is added from outside to the zone of saturation of a hydrogeologic unit, either directly into a formation, or indirectly by way of another formation.

Specific Yield (Effective Porosity)

The ratio of the volume of water which rock or soil, after being saturated, will yield by gravity to the volume of the given rock or soil. It is equal to the porosity minus specific retention.

Storage Coefficient (Storativity)*

Volume of water removed from (or added to) an aquifer per unit horizontal area and per unit decline (or rise) of head.

Transmissivity*

Rate at which water is transmitted through a unit width of the hydrogeologic unit under a unit hydraulic gradient. It is expressed as the product of the hydraulic conductivity and the thickness of the saturated portion of the hydrogeologic unit.
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DEFINITIONS

The following definitions are intended for use in the NUSS programme and may not necessarily conform to definitions adopted elsewhere for international use.

Normal Operation

Operation of a Nuclear Power Plant within specified operational limits and conditions including shutdown, power operation, shutting down, starting up, maintenance, testing and refuelling.

Nuclear Power Plant

A thermal neutron reactor or reactors together with all structures, systems and components necessary for Safety and for the production of power, i.e. heat or electricity.

Operation

All activities performed to achieve, in a safe manner, the purpose for which the plant was constructed, including maintenance, refuelling, in-service inspection and other associated activities.

Region

A geographical area, surrounding and including the Site, sufficiently large to contain all the features related to a phenomenon or to the effects of a particular event.

Regulatory Body

A national authority or a system of authorities designated by a Member State, assisted by technical and other advisory bodies, and having the legal authority for conducting the licensing process, for issuing licences and thereby for regulating Nuclear Power Plant siting, construction, commissioning, operation and decommissioning or specific aspects thereof.¹

¹ This national authority could be either the government itself, or one or more departments of the government, or a body or bodies specially vested with appropriate legal authority.
Safety

Protection of all persons from undue radiological hazard.

Site

The area containing the plant, defined by a boundary and under effective control of the plant management.

Siting

The process of selecting a suitable Site for a Nuclear Power Plant, including appropriate assessment and definition of the related design bases.
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Giuliani, P. Scientific Secretary (Siting)
**LIST OF NUSS PROGRAMME TITLES**

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3. Design

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