

IAEA SAFETY STANDARDS

For protecting people and the environment

Status: Step 7

**First review of the draft publication by
the Review Committees**

Investigation of Site Characteristics and Evaluation of Radiation Risks to the Public and the Environment in Site Evaluation for Nuclear Installations

DRAFT SAFETY GUIDE

DS529

Revision of Safety Guide NS-G-3.2

FOREWORD

Later

DRAFT

CONTENTS

1. INTRODUCTION	1
Background	1
Objective	2
Scope	2
Structure	3
2. REQUIREMENTS FOR AND THE GENERAL APPROACH TO INVESTIGATING SITE CHARACTERISTICS AND EVALUATING RADIATION RISKS IN SITE EVALUATION FOR NUCLEAR INSTALLATIONS	3
Requirements for evaluation of the potential effects of the nuclear installations on people and the environment	3
Identification of exposure pathways in site evaluation for nuclear installations	4
Atmospheric releases	6
Releases to surface water	7
Releases to groundwater	7
Releases to ground surface	8
General approach to radiological environmental impact assessment for nuclear installations	8
Site characterization and radiological environmental impact assessment	9
The approach to the assessment of transport of radionuclides in the environment	9
The approach for existing sites	9
Climate change	10
3. BASELINE ENVIRONMENTAL DATA INCLUDING POPULATION DISTRIBUTION	10
Population distribution	12
Uses of land and water in the region of the site	13
Background radioactivity in environmental media	15
Meteorological characteristics of the region	16
Hydrological and hydrogeological characteristics of the catchment of the site	18
Surface water	19
Groundwater	21
4. ANALYSIS OF THE TRANSPORT OF RADIONUCLIDES IN THE ATMOSPHERE	22
Selection of release scenarios for discharges and accidental releases to the atmosphere	23
Selection of source parameters for analysis of the transport of radionuclides in the atmosphere	24
Atmospheric dispersion models	25

Definition and collection of meteorological and other data for modelling atmospheric dispersion	27
Wind speed	28
Wind direction	29
Boundary layer height	29
Atmospheric stability	29
Precipitation	29
Sensitivity study of the analysis of radionuclide transport in the atmosphere	29
Scenario based simulation of atmospheric dispersion	30
Graded approach to assessing the transport of radionuclides in the atmosphere	30
5. ANALYSIS OF TRANSPORT OF RADIONUCLIDES IN SURFACE WATER	31
Selection of release scenarios for discharges and accidental releases to surface water	31
Selection of source parameters for analysis of the transport of radionuclides in surface water	31
Models for radionuclide transport in surface water	32
Radionuclide transport in rivers	33
Radionuclide transport in human-made impoundments and lakes	33
Radionuclide transport in estuaries	34
Radionuclide transport in the open shores of seas and oceans	34
Identification of exposure pathways in surface water	35
Definition and collection of data for modelling radionuclide transport in surface water	35
Modelling in rivers	36
Modelling in human-made impoundments and lakes	36
Modelling in estuaries	36
Modelling in open shores of seas and oceans	36
Calibration of model and sensitivity study of the analysis of radionuclide transport in surface water	37
Scenario based simulation of radionuclide transport in surface water	37
Graded approach to assessing the transport of radionuclides in surface water	38
6. ANALYSIS OF TRANSPORT OF RADIONUCLIDES IN GROUNDWATER	38
Selection of release scenarios from discharges and potential exposure releases in groundwater	40
Selection of source parameters for analysis of the transport of radionuclides in groundwater	40
Construction of a representative conceptual model	41
Definition and collection of data for modelling radionuclide transport in groundwater	42
Models for radionuclide transport in groundwater	44
Identification of exposure pathways in groundwater	45

Calibration of model and sensitivity study of the analysis of radionuclide transport in groundwater	45
Scenario based simulation of radionuclide transport in groundwater	46
Graded approach to assessing the transport of radionuclides in the GROUNDWATER	46
7. ASSESSMENT OF THE OVERALL RADIOLOGICAL IMPACT OF A NUCLEAR INSTALLATION	47
Summary of the nuclear installation site characteristics used for radiological impact assessment	47
Compilation of radiological impact assessment results	47
Identification of the representative person and reference animals and plants	51
Calculation of dose and/or risk to the representative person and dose rates to reference animals and plants	52
Determination of the acceptability of radiological impacts	53
8. MONITORING OF RADIOACTIVITY IN THE ENVIRONMENT AROUND A NUCLEAR INSTALLATION	54
Environmental monitoring programme during the site characterization and pre-operational stages of a nuclear installation	54
Monitoring of radioactivity in the atmosphere	54
Monitoring of radioactivity in the surface water and groundwater	55
Monitoring of radioactivity in the soils and biota	55
Monitoring of population data and other parameters	55
Monitoring programme during the operation of a nuclear installation	56
Environmental monitoring during normal operation	56
Environmental monitoring in an emergency	57
Source monitoring	57
Individual monitoring	57
Other monitoring situations	58
Monitoring following cessation of operations	59
9. CONSIDERATION OF THE FEASIBILITY OF EFFECTIVE EMERGENCY RESPONSE ACTIONS	59
10. APPLICATION OF A GRADED APPROACH TO RADIOLOGICAL ENVIRONMENTAL IMPACT ASSESSMENT FOR NUCLEAR INSTALLATIONS	63
11. APPLICATION OF THE MANAGEMENT SYSTEM TO INVESTIGATION OF SITE CHARACTERISTICS AND EVALUATION OF RADIATION RISKS FROM A NUCLEAR INSTALLATION	65
Project management	65
Engineering uses and output specification	67

Documentation of investigation of site characteristics and evaluation of radiation risks to the public and the environment	67
Independent peer review of investigation of site characteristics and evaluation of radiation risks to the public and the environment	67
REFERENCES	69
APPENDIX	72
APPLICATION OF A GRADED APPROACH TO MODELLING RADIONUCLIDE TRANSPORT IN GROUNDWATER	72
CONTRIBUTORS TO DRAFTING AND REVIEW	80

DRAFT

DRAFT

1. INTRODUCTION

BACKGROUND

1.1. IAEA Safety Standards Series No. SSR-1, Site Evaluation for Nuclear Installations [1] establishes requirements on the potential effects of a nuclear installation on people and the environment to be considered in site evaluation, and requirements on the investigation of site characteristics and assessment of the radiological environmental impact of nuclear installations. IAEA Safety Standard Series Nos SSR-3, Safety of Research Reactors [2], SSR-4, Safety of Nuclear Fuel Cycle Facilities [3], GSR Part 3, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards [4], and GSR Part 7, Preparedness and Response for a Nuclear or Radiological Emergency [5] establish requirements on these topics. This Safety Guide provides recommendations on how to meet these requirements.

1.2. This Safety Guide takes into account progress in the investigation of site characteristics and assessment of the radiological environmental impact of nuclear installations, as well as in regulatory practices in Member States, considering lessons identified from discharges¹ and accidental releases at nuclear installations, feedback from safety review missions and the results of recent research in this area.

1.3. This Safety Guide provides new or updated recommendations that address the following topics:

- (a) Recent updates in investigation of site characteristics and radiological environmental impact assessment for nuclear installations;
- (b) Filling of gaps in guidance and updated methodologies on analysis of dispersion and transport of radionuclides;
- (c) Linking of results of analyses with assessment of overall radiological impact (including dose assessment);
- (d) Full spectrum of potential release scenarios;
- (e) Application of a graded approach for radiological environmental impact assessment of nuclear installations;
- (f) Monitoring of radioactivity in the environment.

1.4. This Safety Guide supersedes IAEA Safety Standards Series No. NS-G-3.2, Dispersion of Radioactive Material in Air and Water and Consideration of Population Distribution in Site Evaluation for Nuclear Power Plants².

¹ As defined in the IAEA Nuclear Safety and Security Glossary [6] a discharge is a planned and controlled release of (usually gaseous or liquid) radioactive substances to the environment.

² INTERNATIONAL ATOMIC ENERGY AGENCY, Dispersion of Radioactive Material in Air and Water and Consideration of Population Distribution in Site Evaluation for Nuclear Power Plants, IAEA Safety Standards Series No. NS-G-3.2, IAEA, Vienna (2002)

OBJECTIVE

1.5. The main objective of this Safety Guide is to provide recommendations on the investigation of site characteristics and the evaluation of radiation risks to the public and the environment in site evaluation for nuclear installations in order to meet the applicable safety requirements established in SSR-1 [1], SSR-3 [2], SSR-4 [3], GSR Part 3 [4] and GSR Part 7 [5]. It provides recommendations on the identification and evaluation of direct and indirect pathways by which a radioactive release from a nuclear installation could potentially affect the public and the environment during operational states and in accident conditions. It also provides specific recommendations on radiological environmental impact assessment for nuclear installations.

1.6. This Safety Guide is intended for use by organizations involved in the investigation of site characteristics and evaluation of radiation risks for nuclear installations, which includes radiological environmental impact assessment (e.g. operating organizations, designers, technical support organizations), as well as by regulatory bodies.

SCOPE

1.7. This Safety Guide provides recommendations on the development of the site evaluation report for a nuclear installation, which is prepared at the end of the site characterization stage. It also provides recommendations on the development of the radiological impact assessment, which is part of the environmental impact assessment report, and relevant sections of the safety analysis report. The recommendations are also applicable to other stages of site evaluation and other assessments performed during the lifetime of a nuclear installation (e.g. periodic safety review) or following a change in the site characteristics.

1.8. This Safety Guide provides recommendations on how to assess the radiological environmental impact of a new or existing nuclear installation on people and the environment during discharges and accidental releases. It covers the investigation of site characteristics, including population distribution, uses of land and water in the region, background levels of radioactivity in the environmental media, and meteorological, hydrological and hydrogeological characteristics of the region. This Safety Guide also covers analysis of the dispersion of radionuclides in the atmosphere, analysis of the transport of radionuclides in surface water and groundwater and assessment of overall radiological impact and dose assessment in the process of site evaluation. The feasibility of effective emergency response actions and the application of a management system for those actions are also addressed.

1.9. Although an environmental impact assessment covers potential radiological and non-radiological impacts, the latter are out of the scope of this Safety Guide.

1.10. In an environmental impact assessment, in addition to analysing the environmental impacts of the proposed actions (in this case, the construction, operation and decommissioning of a nuclear installation at the proposed site) alternative actions are also considered, such as the use of other nuclear technologies or non-nuclear technologies, and the 'do-nothing' scenario³. This publication does not address the conditions that would prevail at the site under the 'do-nothing' scenario. The conditions at the site and in the vicinity could change over time (e.g. population size and

³ Under the 'do-nothing' scenario (sometimes referred to as the 'null' or 'no action' option), it is assumed that the baseline environmental conditions at the proposed site persist with natural progression of other processes and events at and around the site.

distribution); however, this Safety Guide covers existing conditions (e.g. current nuclear facilities on the site) as part of the assessment of environmental impacts from the proposed actions.

1.11. The recommendations provided in this Safety Guide are applicable to all types of nuclear installation as defined in the IAEA Nuclear Safety and Security Glossary [6]. Although they are predominantly written with nuclear power plants in mind, they are also applicable to other nuclear installations through the use of a graded approach.

1.12. The assessment of radiological environmental impacts due to sabotage of nuclear installations are outside the scope of this Safety Guide, although some of the recommendations provided might also be consistent with the needs of nuclear security. Specific guidance on the protection of nuclear power plants against sabotage is provided in IAEA Nuclear Security Series No. 4, Engineering Safety Aspects of the Protection of Nuclear Power Plants against Sabotage [7].

STRUCTURE

1.13. Section 2 summarizes the relevant safety requirements and provides recommendations on the identification of exposure pathways, the general approach to environmental impact assessment, site characterization for such an assessment, the assessment of transport of radionuclides in the environment, the approach for existing sites and addressing climate change. Recommendations on baseline environmental characteristics of site and region, including population distribution, are provided in Section 3. Recommendations on analysis of the transport of radionuclides in the atmosphere are provided in Section 4. Recommendations on analysis of the transport of radionuclides in surface water and groundwater are provided in Sections 5 and 6, respectively. Recommendations on the assessment of overall radiological impact are provided in Section 7. Section 8 provides recommendations on the monitoring of radioactivity in the environment. Recommendations in relation to the feasibility of effective emergency response actions are provided in Section 9. Recommendations on the application of a graded approach to radiological environmental impact assessment for nuclear installations are provided in Section 10. Section 11 provides recommendations on the application of the management system for activities that are performed for the investigation of site characteristics and evaluation of radiation risks to the public and the environment in site evaluation for nuclear installations. The Appendix provides an example of applying a graded approach to the modelling of radionuclide transport in groundwater.

2. REQUIREMENTS FOR AND THE GENERAL APPROACH TO INVESTIGATING SITE CHARACTERISTICS AND EVALUATING RADIATION RISKS IN SITE EVALUATION FOR NUCLEAR INSTALLATIONS

REQUIREMENTS FOR EVALUATION OF THE POTENTIAL EFFECTS OF THE NUCLEAR INSTALLATIONS ON PEOPLE AND THE ENVIRONMENT

2.1. Requirement 5 of SSR-1 [1] states:

“The site and the region shall be investigated with regard to the characteristics that could affect the safety of the nuclear installation and the potential radiological impact of the nuclear installation on people and the environment.”

2.2. Requirement 12 of SSR-1 [1] states:

“In determining the potential radiological impact of the nuclear installation on the region for operational states and accident conditions, including accidents that could warrant emergency response actions, appropriate estimates shall be made of the potential releases of radioactive material, with account taken of the design of the nuclear installation and its safety features.”

2.3. Requirement 25 of SSR-1 [1] states:

“The dispersion in air and water of radioactive material released from the nuclear installation in operational states and in accident conditions shall be assessed.”

2.4. Requirement 29 of SSR-1 [1] states:

“All natural and human induced external hazards and site conditions shall be periodically reviewed by the operating organization as part of the periodic safety review and as appropriate throughout the lifetime of the nuclear installation, with due account taken of operating experience and new safety related information.

2.5. Paragraph 7.5 of SSR-1 [1] states:

“The site-specific external hazards and the site conditions shall be re-evaluated, as necessary, based on the outcome of the periodic review of site-specific hazards or because of new data relevant to the radiological environmental impact assessment or to the safe operation of the nuclear installation.”

IDENTIFICATION OF EXPOSURE PATHWAYS IN SITE EVALUATION FOR NUCLEAR INSTALLATIONS

2.6. Paragraph 4.39 of SSR-1 [1] states:

“The direct and indirect pathways by which radioactive releases from the nuclear installation could potentially affect the public and the environment shall be identified and evaluated. In this evaluation, specific regional and site characteristics, including the population distribution in the region, shall be taken into account, with special attention paid to the transport and accumulation of radionuclides in the biosphere.”

2.7. Exposure pathways are routes by which radiation or radionuclides can reach humans and cause exposure. Possible exposure pathways for radionuclides released to the atmosphere and surface water during normal operation of nuclear installations such as nuclear power plants are listed in para. 5.27 of IAEA Safety Standards Series No. GSG-10, Prospective Radiological Environmental Impact Assessment for Facilities and Activities [8] as follows:

- (a) Inhalation of airborne material in an atmospheric plume (e.g. gases, vapours, aerosols);
- (b) Inhalation of resuspended material;
- (c) Ingestion of crops;
- (d) Ingestion of animal food products (e.g. milk, meat, eggs);
- (e) Ingestion of drinking water;
- (f) Ingestion of aquatic food (e.g. freshwater or seawater fish, crustaceans, molluscs);
- (g) Ingestion of forest food (e.g. wild mushrooms, wild berries, game);
- (h) Ingestion of breast milk or locally prepared food for infants;
- (i) Inadvertent ingestion of soil and sediments;

- (j) External exposure from radionuclides in an atmospheric plume (i.e. cloud shine);
- (k) External exposure from radionuclides deposited on the ground (i.e. ground shine) and on surfaces;
- (l) External exposure from radionuclides in water and sediments (i.e. from activities on shores, swimming and fishing).

2.8. In addition, there may be exposure due to activity directly deposited on skin and direct exposure from activity on the site (i.e. direct exposure to gamma radiation) without any activity having been released. These would also be the expected pathways for accidental releases although their relative importance might differ.

2.9. The first step in evaluating a site for a nuclear installation should be to identify all possible exposure pathways and then determine the most significant ones in terms of the exposure of the public or the environment. The significance of the pathway depends on the quantities and the chemical and physical form of the radionuclides released and other characteristics of the release that might affect the subsequent dispersion of radionuclides and their behaviour in the environment, the location and medium into which the release is made, and the characteristics of the environment and population around the site.

2.10. Although the exposure pathways listed in para 2.7 are usually the most significant, there might be other pathways. It should therefore be confirmed that all significant pathways have been identified, especially if there are specific features about the reactor design, its operation, the site, land use around the site, farming practices or the surrounding location. For example, the presence of desalination plants producing water (either at or close to the discharge outlets) for drinking or irrigation might give rise to exposure pathways.

2.11. Accidental releases may encompass a spectrum of scenarios, from anticipated operational occurrences to severe accidents due to design extension conditions involving different source terms and release locations and releases to different media. Different States may use different criteria to assess the adverse consequences from accidental releases, such as individual dose, individual risk or societal risk. In most cases, atmospheric releases are the dominant contributors to the total risk but there might be other scenarios involving accidental releases to surface water or groundwater. Evaluating the consequences of accidental releases to surface water and groundwater may necessitate detailed analysis. However, if the conditional probability of a consequence being fully realized is assumed to be unity, and it still does not make a significant contribution to the overall risk, then detailed analysis of the consequence may not be needed. If, on the other hand, both the probability of occurrence and the estimated contribution of a potential hazard to the overall risk are significant, then a detailed analysis should be performed. Reference [9] discusses criteria for assessing overall risk.

2.12. Once the significant exposure pathways have been identified, the local environment should be characterized sufficiently to allow exposure from the pathways listed in para. 2.7 to be calculated with an appropriate level of detail. The detail and level of characterization should be commensurate with the importance of the pathway for the particular scenario being modelled. In accordance with para. 4.1 of SSR-1 [1], a graded approach is required to be applied for this purpose (see also Section 10).

2.13. During normal operation, there are usually authorized discharges to the atmosphere and surface water. In accidental releases, there might also be direct releases to groundwater or to the ground surface. The initial release into each of these media and the resulting important exposure pathways are discussed in paras 2.14–2.31.

Atmospheric releases

2.14. The pathways that are significant depends on the nature of the atmospheric release, including the source term, location and medium into which the release is made. Recommendations on the determination of the source term for releases to the environment for anticipated operational occurrences and accident conditions are provided in IAEA Safety Standards No. SSG-2 (Rev. 1), Deterministic Safety Analysis for Nuclear Power Plants [10]. The source term defines the quantities and physical, isotopic and chemical forms of the radionuclides released, the time profile of the release, and other factors that affect its subsequent transport and behaviour in the environment (e.g. physical stack height, energy associated with the atmospheric release).

2.15. For discharges under normal operation, the measures taken to mitigate the atmospheric release, to control the discharge and to ensure that exposures are as low as reasonably achievable (see IAEA Safety Standards Series No. GSG-9, Regulatory Control of Radioactive Discharges to the Environment [11]) tend to focus on nuclides and pathways that are radiologically significant. For this reason, some less obvious radionuclides that might accumulate in the environment during the lifetime of the installation (e.g. radionuclides radiocarbon (^{14}C) and tritium (^3H), which can be difficult to remove) and/or less obvious pathways might become more significant. Direct discharge to groundwater is unlikely to be authorized or permitted. However, radionuclides might enter groundwater indirectly, for example via an atmospheric release and subsequent deposition on the ground.

2.16. The significant exposure pathways from atmospheric releases can also be identified through monitoring of the environment (see Section 8). Ideally, this monitoring should be performed over an extended period of time so that any periodic (e.g. seasonal) or long term trends can be observed.

2.17. Normal discharges from nuclear installations are expected to continue throughout the lifetime of nuclear installations, from construction to decommissioning, and therefore accumulation of activity in the environment over this period should be considered for longer lived nuclides.

2.18. The radionuclides radiocarbon (^{14}C) and tritium (^3H) can be particularly difficult to model in the environment because, whatever chemical form they are released as, they can soon be incorporated into CO_2 or water, respectively, or be incorporated in organic molecules in environmental media and become part of the food chain. 2.18. The radionuclide radiocarbon (^{14}C) has a long half-life (~5000 years): therefore, collective doses should be assessed over large geographical areas and long integration periods.

2.19. For an accidental atmospheric release leading to exposure of the public, the significant pathways depend on the source term and the nature of the release. The most common scenario is an accidental atmospheric release, usually making direct inhalation of the plume the most significant pathway in the short term, because this is a direct route of internal exposure of radionuclides in gas or vapour forms or as suspended particulate. An atmospheric release scenario where inhalation would not be a significant pathway would involve only noble gases (which are not absorbed by the body when inhaled) or where the initial plume does not lead directly to exposure of people.

2.20. Another pathway that can lead to exposure in the very short term is direct radiation (i.e. cloud shine) from the plume. This pathway is usually less significant than direct inhalation.

2.21. Exposure via the other pathways listed in para 2.7 usually involves deposition of radionuclides from the plume. Deposition can be either 'dry' or 'wet'. Dry deposition occurs when contaminants in the plume adsorb to suspended particulates in the air which are then deposited on the ground (for an elevated release this may be some distance from the release point). Wet deposition occurs when precipitation (e.g. rain, snow) washes material from the plume.

2.22. If deposition occurs, the first pathway that should be considered is direct radiation from the deposited activity. The significance of this pathway depends on the rate of deposition, which in turn depends on the chemical and physical form of the nuclide (e.g. elemental iodine as a reactive chemical form has a high deposition velocity) and the radiation emissions of the nuclides. The relative significance of different nuclides also depends on the time frame over which the dose is integrated: nuclides with longer half-lives become increasingly important for longer integration times. For integration times comparable with the duration of the direct inhalation of the plume (a few days), inhalation is usually the dominant pathway; for much longer integration times (years) the deposition pathway can become dominant for longer lived nuclides. External exposure from deposition can be a long term pathway of exposure for long-lived nuclides to members of the public. For long integration times (> 1 year), the weathering and migration of radionuclides through soils — which reduce the dose from this pathway — may also need to be considered.

2.23. The quantities of nuclides deposited by deposition are also important in determining the dose by ingestion. Compared with direct inhalation, the impact is usually less since only a small fraction of the plume will be deposited and incorporated into the food chain and there is some time delay before consumption, during which short lived nuclides can decay. Contamination and consumption of crops is a pathway that can lead to exposure far from the release point as the produce is transported; however, monitoring of commercially produced food and the application of operational intervention levels (see GSR Part 7 [5]) should lead to the control of exposure via this pathway. Ingestion of forest food might be less amenable to control, but its impact is usually limited to areas close to the original contamination. Ingestion can be a significant contributor to the total collective dose, and hence to population risk, but this might be the result of aggregating very low doses over large numbers of people, which is advised against.

2.24. Resuspension of deposited radionuclides which are then inhaled leads to a longer term impact to the public, but given that only a small fraction of the plume is deposited and then resuspended, the impact on any individual is insignificant in comparison with direct inhalation. For those people who do not inhale the plume directly, resuspension should be considered as a possibly significant pathway.

Releases to surface water

2.25. For discharges, the relative impact of aquatic pathways compared with terrestrial pathways depends on the respective quantities discharged and the radiological significance of the nuclides involved. For accidental releases to surface water, the shielding provided by the water, the lower likelihood of anybody being directly exposed in comparison with an atmospheric release, and the greater dispersion (especially for releases to the sea) usually means that aquatic pathways are less significant than terrestrial pathways. These factors should be taken into account in determining the relative significance of surface water pathways.

2.26. Activity might also accumulate in sediments and in the food chain as a result of releases to surface water. This activity should also be considered when determining the relative significance of surface water pathways.

Releases to groundwater

2.27. Discharges to groundwater are unlikely to be permitted or authorized, as explained in para 2.15, although there might be indirect pathways via atmospheric releases and then rainfall. Accidental releases to groundwater could occur, for example as a result of spillage of radioactive waste or core melt through the basemat. Unlike direct releases to the atmosphere, which lead to immediate exposure, activity released to groundwater might be transported through the groundwater for many years before it reaches a location where exposure of the public could occur.

During this time, short lived radionuclides decay, and the shielding of the ground will significantly limit exposure by direct radiation. These accidental releases could, however, lead to long term contamination with few, if any, remediation solutions. These factors should be considered in determining the significance of this pathway.

Releases to ground surface

2.28. As with releases to groundwater (see paras 2.51 and 2.352), planned direct discharges to the ground surface are unlikely to be permitted or authorized. Accidental releases to the ground surface could occur, however, leading to contaminated ground and potentially to resuspension of activity or to activity entering the food chain. The possibility of this should be considered.

GENERAL APPROACH TO RADIOLOGICAL ENVIRONMENTAL IMPACT ASSESSMENT FOR NUCLEAR INSTALLATIONS

2.29. The components of radiological environmental impact assessment for protection of the public and of non-human species in normal operation, and for consideration of potential exposure are shown in Fig. 2 and 3 of GSG-10 [8].

2.30. The first step in conducting the assessment is to select the source term(s). The selection process might be complex, taking into account factors such as reactor design, materials used and additives to the coolant. For nuclear power plants employing technology that is known and used elsewhere, the data from these other operations should be used to select and provide certainty in the source term. For nuclear power plant developments where the reactor technology is yet to be decided, the plant parameter envelope approach could be taken initially, whereby the maximum source term for the options under consideration is used, based on published data from the reactor vendors or from previous projects. For small modular reactors, based on current technology, one option could be to scale the source terms from large reactors. For novel types of reactors (e.g. evolutionary and innovative designs) the only data available might be from the reactor vendors; in this case, the project developers should ensure that the source term estimates are not overly optimistic. For other types of nuclear installation, a similar or simplified approach may be adopted depending on the type and complexity of the installation. Further recommendations on selecting the source term(s) are provided in IAEA Safety Standard Nos SSG-2 (Rev. 1) [10], SSG-3 (Rev. 1), Development and Application of Level 1 Probabilistic Safety Assessment for Nuclear Power Plants [12], and SSG-4, Development and Application of Level 2 Probabilistic Safety Assessment for Nuclear Power Plants [13].

2.31. The next step is to model the dispersion of the radionuclides in the environment (see Sections 4–6). The end points of the radiological environmental impact assessments are generally activity concentrations in the various environmental media (e.g. air, water, ground) that can lead to human exposure. These activity concentrations are then used to calculate the doses to exposed individuals (see Section 7).

2.32. Releases to the atmosphere or water could lead to many people being exposed by several pathways. To assess the risk to the public, a representative person is selected, for whom the individual dose is calculated. Representative persons can be identified by determining the most significant exposure pathways (see para. 2.11); for example, for the inhalation pathway the representative person could be somebody living close to the site in the prevailing wind direction, and for the ingestion pathway it could be a high rate consumer of locally produced food. Further recommendations on selecting the representative person are provided in Section 7, and guidance is also given in Ref. [14]. The doses from all the significant pathways that lead to exposure of the representative person should be added together to give a total dose.

SITE CHARACTERIZATION AND RADIOLOGICAL ENVIRONMENTAL IMPACT ASSESSMENT

2.33. The characterization of the environment should be sufficient to allow the radiation exposure of the public to be modelled for the purposes of the radiological environmental impact assessment. The characterization of the population, including their habits and land use, should be sufficient to allow the identification of a representative person. Further recommendations are provided in Section 3.

THE APPROACH TO THE ASSESSMENT OF TRANSPORT OF RADIONUCLIDES IN THE ENVIRONMENT

2.34. It might not be necessary to model explicitly every single process involving the transfer of radioactivity between different environmental compartments. However, all processes should be considered, and their relative significance assessed, allowing some processes to be discounted if their significance is small, in terms of the impact on the end points being considered. If the effort involved would be disproportionate to the difference in the calculated end points — and considering other uncertainties, such as those in the source term — then few insights would be gained from detailed modelling. For example, for a postulated accidental release to atmosphere, the uncertainties in the source terms might be larger than any differences in the end results. Inevitably in these situations some judgement may be involved, but any simplification made in the analysis should be justified. In making such judgements, the overall objectives of the analysis (e.g. demonstrating regulatory compliance) should be considered.

THE APPROACH FOR EXISTING SITES

2.35. Existing sites have the advantage that the environment should already have been characterized and there may be some data from measured discharges and environmental monitoring that can inform the modelling of proposed discharges. Cumulative impacts from new and existing installations should also be considered.

CLIMATE CHANGE

2.36. Climate changes in terms of the meteorological and hydrological conditions in the region of the nuclear installation site over the lifetime of the installation should be taken into consideration in the radiological environmental impact assessment.

3. BASELINE ENVIRONMENTAL DATA INCLUDING POPULATION DISTRIBUTION

3.1. Requirement 3 of SSR-1 [1] states:

“The scope of the site evaluation shall encompass factors relating to the site and factors relating to the interaction between the site and the installation, for all operational states and accident conditions, including accidents that could warrant emergency response actions.”

3.2. Requirement 4 of SSR-1 [1] states that

“The suitability of the site shall be assessed at an early stage of the site evaluation and shall be confirmed for the lifetime of the planned nuclear installation.”

3.3. Paragraph 4.6 of SSR-1 [1] states (citations omitted):

“In the assessment of the suitability of a site for a nuclear installation, the following aspects shall be addressed at an early stage of the site evaluation:

.....

- (b) The characteristics of the site and its environment that could influence the transfer of radioactive material released from the nuclear installation to people and to the environment;
- (c) The population density, population distribution and other characteristics of the external zone, in so far as these could affect the feasibility of planning effective emergency response actions, and the need to evaluate the risk to individuals and to the population.”

3.4. Requirement 14 of SSR-1 [1] states:

“The data necessary to perform an assessment of natural and human induced external hazards and to assess both the impact of the environment on the safety of the nuclear installation and the impact of the nuclear installation on people and the environment shall be collected.”

3.5. Paragraph 4.46 of SSR-1 [1] states:

“At a minimum, the data collection process shall include the following:

.....

- (d) Information on the potential impact of the nuclear installation on people and the environment for operational states and accident conditions;

- (e) Information required for planning effective emergency response actions on the site and off the site in all environmental conditions and for all states of the nuclear installation”.

3.6. To meet the requirements quoted in paras 3.2 and 3.3, the selected site for a new nuclear installation is expected to go through an extensive characterization process. The investigations for site characterization should begin several years before the application for a licence to construct the proposed nuclear installation is submitted to the regulatory body. The majority of the investigations should be conducted before construction begins. However, the investigations should continue during the construction, operation and decommissioning of the installation to confirm that the public and the environment continue to be protected and that the environmental impacts are as predicted.

3.7. In order to assess the potential effects of the nuclear installation on the region, the site characterization efforts conducted prior to construction in compliance with Requirements 25–27 of SSR-1 [1] serve the following purposes:

- (a) Establishing the baseline environmental conditions at the selected site, which can later be used to measure the incremental environmental impacts of the nuclear installation during construction, operation and decommissioning;
- (b) Using calculational models for prospective radiological dose assessments;
- (c) Ascertaining the feasibility of emergency response capabilities at the site;
- (d) Establishing the beginning of the monitoring programme at and in the vicinity of the site (see Section 8).

3.8. For the purposes of assessing the radiological environmental impact of a nuclear installation, background environmental data on the areas listed below should be compiled:

- (a) Population distribution;
- (b) Uses of land, flora and fauna, and water in the region of the site;
- (c) Background radioactivity in environmental media;
- (d) Meteorological characteristics of the region;
- (e) Hydrological and hydrogeological characteristics of the site catchment for surface water and groundwater.

The background environmental data needed for assessing non-radiological impacts (see para. 1.9), such as socioeconomic impacts and the impact on culturally and historically significant properties at or near the site, should be compiled contemporaneously with the data needed for radiological impact assessments.

3.9. Efforts should be made to collect data that will allow transboundary impacts to be assessed.

3.10. The extent of the geographic area over which these data are compiled should be based on the anticipated effects of the environment on the safety of the proposed nuclear installation and the anticipated effects of the nuclear installation on the environment. The geographic extent of the investigations should be at least wide enough to include both the peak radionuclide concentration and the maximum predicted dose plotted as a function of distance from the installation.

3.11. The spatial and temporal intensity of data collection activities should follow a graded approach, as described in Section 10; consequently, more data should be collected for locations with a higher radiological impact.

POPULATION DISTRIBUTION

3.12. Requirement 26 of SSR-1 [1] states:

“The existing and projected population distribution within the region over the lifetime of the nuclear installation shall be determined and the potential impact of radioactive releases on the public, in both operational states and accident conditions, shall be evaluated and periodically updated.”

3.13. Paragraph 6.8 of SSR-1 [1] states:

“Information on the existing and projected population distribution in the region, including resident populations and (to the extent possible) transient populations, shall be collected and kept up to date over the lifetime of the nuclear installation. Special attention shall be paid to vulnerable populations and residential institutions (e.g. schools, hospitals, nursing homes and prisons) when evaluating the potential impact of radioactive releases and considering the feasibility of implementing protective actions.”

3.14. Paragraph 6.9 of SSR-1 [1] states:

“The most recent census data for the region, or information obtained by extrapolation of the most recent data on resident populations and transient populations, shall be used in obtaining the population distribution. In the absence of reliable data, a special study shall be carried out.”

3.15. Paragraph 6.10 of SSR-1 [1] states:

“The data shall be analysed to obtain the population distribution in terms of the direction and distance from the site. This information shall be used to carry out an evaluation of the potential radiological impact of normal discharges and accidental releases of radioactive material, including reasonable consideration of releases due to severe accidents, with the use of site-specific design parameters and models as appropriate.”

3.16. The operation of a nuclear installation might affect the population in the surrounding area. The distribution and characteristics of the regional population should therefore be studied at the site characterization stage in order to evaluate the radiological impacts of discharges and accidental releases and help demonstrate the feasibility of the emergency plan.

3.17. Data on the present population⁴ in the external zone⁵ should be obtained from census data, local authorities or by means of special field surveys, and those data should be as accurate and as up to date as possible. Similar data should also be collected for the region outside the external zone to distances determined in accordance with national practice and regulatory requirements, and the expected range of the impact of the project. The data should include the number of

⁴ The term ‘present population’ includes both the permanent population and the temporary population.

⁵ The ‘external zone’ includes an area immediately surrounding the site of a nuclear installation in which population distribution, population density, population growth rate, industrial activity, and land and water uses are considered in relation to the feasibility of implementing emergency measures.

people normally present in the area, and the location of houses, hospitals, prisons, schools, other institutions and recreational facilities such as parks and marinas.

3.18. The information collected on the permanent population should relate to the doses that might be received by individuals from direct radiation and from the release of radionuclides from the nuclear installation under normal operation and accident conditions, as well as addressing factors that would affect the feasibility of planning effective emergency response actions. This should include information on major places of work, means of communication, typical living habits such as recreational and work activities and the fraction of time spent indoors versus outdoors, and typical diet of the inhabitants. Typical production rates of food items locally grown, and the fractions locally consumed should be given. If a city or town in the region is associated with a major industrial facility, this should be considered for a number of reasons. For example, the facility may have a large workforce that would need to be evacuated in an emergency, or the facility may be hazardous and need its own emergency arrangements that will need to be coordinated with the emergency plan of the nuclear installation.

3.19. The information collected on the temporary population should cover the short-term temporary population (e.g. tourists, nomads) and the long term temporary population (e.g. seasonal inhabitants, students). The maximum size of the temporary population and its periods of occupancy in the external zone should be estimated. Particular types of institutions such as schools, hospitals, prisons and military bases within the external zone should be identified for the purposes of emergency planning. In the area outside the external zone, estimates of the approximate size of the temporary population together with its periods of occupancy should also be made.

3.20. A projection of the present population in the region should be made both for the expected year of commissioning of the nuclear installation and for selected years (e.g. every tenth year) over the lifetime of the installation. Projections should be made on the basis of population growth rate, migration trends and plans for possible development in the region, including the project itself. The projected figures for permanent population and temporary population should be extrapolated separately if data are available.

3.21. The representative person associated with each nuclear installation should be identified (see Section 7 of this Safety Guide, Section 5 of GSG-10 [8], and Ref. [14]).

3.22. The population data collected should be presented in a suitable format and scale to permit their correspondence with other relevant data, such as data on atmospheric dispersion and on uses of land and water. The data on permanent population and temporary population should be clearly indicated. In general, population data should be presented either in tabular form or graphically, for example using concentric circles and radial segments with the site as the origin. More details should be given for areas closer to the site, especially within the external zone.

USES OF LAND AND WATER IN THE REGION OF THE SITE

3.23. The operation of a nuclear installation might affect the uses of land and water in the surrounding area. The availability of cooling water is an important consideration for the siting of a nuclear power plant. In addition, the characteristics of the land and water utilized in the region should be addressed in demonstrating the feasibility of the emergency plan. Therefore, as part of the site evaluation, the site topography (e.g. flat plains, mountains, hills, creeks,

wetlands, valleys, forests) should be described, and the uses of land and water should be investigated.

3.24. The investigations should cover the following:

- (a) Land devoted to agricultural uses, its extent, the main crops and their yields;
- (b) Land devoted to dairy farming, its extent and its yields;
- (c) Land devoted to industrial, institutional and recreational purposes, its extent and the characteristics of its use;
- (d) Bodies of water used for commercial, individual and recreational fishing, including details of the aquatic species fished, their abundance and their yields;
- (e) Bodies of water used for commercial purposes (e.g. navigation), community water supply, irrigation, and recreational purposes such as bathing and sailing;
- (f) Land and bodies of water supporting wildlife and livestock;
- (g) Direct and indirect pathways for potential radioactive contamination of the food chain;
- (h) Products imported to or exported from the region that may form part of the food chain;
- (i) Foraged foods such as mushrooms, berries and seaweed.

3.25. Present uses of water that could be affected by changes in the water temperature and by radioactive material discharged from a nuclear installation, together with the location, nature and extent of usage, should be identified. Expected changes in uses of water in the region, such as for irrigation, fishing and recreational activities, should also be considered.

3.26. Special consideration should be given to any population centres for which drinking water is obtained from water bodies that might be affected by a nuclear installation. To the extent possible, future water flow and water uses should be projected over the lifetime of the installation. This may lead to a change in the representative person.

3.27. The movement and quality of groundwater should be studied to demonstrate the possibility and extent of groundwater contamination by radioactive releases from the nuclear installation and to indicate if groundwater could be for a significant exposure pathway.

3.28. The data on different water uses should include the following:

- (a) For water used for drinking by humans and animals, and for municipal and industrial purposes:
 - (i) Average and maximum rates of water intake by humans and animals;
 - (ii) Distance of the intake from the potential source of radioactive discharges;
 - (iii) Mode of water consumption;
 - (iv) Number of water users.
- (b) For water used for irrigation:
 - (i) Rate of water use;
 - (ii) Area of irrigated land;
 - (iii) Types and yields of agricultural products, and their usual consumers.
- (c) For water used for fishing:
 - (i) The aquatic species fished, and their abundance and yields in water used for commercial, individual and recreational fishing.
- (d) For water used for recreational purposes:
 - (i) The number of persons engaging in swimming, boating and other recreational uses, and the time spent on these activities.

3.29. These investigations should cover a reasonably large area in the region of the site. The area should be identified according to the hydrological characteristics (relating to the basin or sub-basin) and hydrogeological characteristics (including possible recharge and discharge areas of the groundwater system) of the region where the site is located. The land area should

encompass the region over which the peaks in pathway-specific doses from various exposure routes are encountered. If a nuclear installation is located on a riverbank, users downstream from the site should be identified. If the site is near a lake, all users of the lake should be identified. If a site is on a coast, users of the sea out to a few tens of kilometres in all directions should be identified.

BACKGROUND RADIOACTIVITY IN ENVIRONMENTAL MEDIA

3.30. Paragraph 7.3 of SSR-1 [1] states:

“Before commissioning of the nuclear installation begins, the levels of background radioactivity in the atmosphere, hydrosphere and lithosphere and in biota in the region shall be measured so as to make it possible to determine any additional radioactivity due to the operation of the nuclear installation.”

3.31. Any exposure to radiation from nuclear installations is additional to the exposure from natural background. The calculation of the dose from a nuclear installation should not include the dose due to this natural background.

3.32. The importance of establishing the baseline radiation levels during the pre-operational phase of a nuclear installation is emphasized in GSG-9 [11]. A monitoring programme should be implemented to measure external radiation exposure (dose rates) and activity concentrations in environmental media. To assess the exposure due to the nuclear installation, the monitoring results due to the natural background should be subtracted.

3.33. The natural background of a site area should be measured as early as possible, before the proposed nuclear installation starts operation and any release to the environment from the nuclear installation occurs. Information should be collected and recorded on the levels of background radioactivity and activity concentrations of relevant radionuclides in environmental media within the zone around the installation that is likely to be affected by any planned or potential releases from the installation, in particular in locations where exposure is expected to be higher (e.g. downwind from the proposed stack location, in sediments near outfalls from the proposed aquatic discharges). This zone generally extends up to 20 km from the site (the location or the postulated location of the representative person). However, some of the environmental sampling locations should extend further to serve as control locations that could indicate potential changes in the natural background during the operation of the installation.

3.34. If there are other sources of human-made radioactivity or enhanced natural radioactivity (e.g. another nearby nuclear installation or industrial facility) that contribute to the radioactivity levels in the vicinity of the site, this should also be measured to determine the cumulative exposure of people around the site to human-made radiation.

3.35. If there are any known existing exposure situations at the site or in the vicinity, (e.g. from prior remediation activities or from a nuclear or radiological emergency that has been declared to be ended) those situations and the doses attributable to them should be identified. GSR Part 3 [4] establishes requirements on existing exposure situations.

3.36. The measurement programme set up to assess the background radioactivity in environmental media before the start of operation should guide the development of the long term monitoring programme, as discussed in Section 8, to be followed during operation and decommissioning of the nuclear installation.

METEOROLOGICAL CHARACTERISTICS OF THE REGION

3.37. Investigations should be undertaken in the region of the site to collect specific meteorological information. This information should be compiled in catalogues or databases for analysis and estimation of site-specific values of meteorological parameters. Further recommendations are provided in IAEA Safety Standards Series No. SSG-18, Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations [15]. The general objectives of such investigations should be the collection of meteorological data to derive extreme and rare meteorological hazards for the nuclear installation, and the continuous collection and evaluation of data on site-specific meteorological parameters needed to calculate atmospheric dispersion of radionuclides discharged from a nuclear installation during normal operation and accident conditions (see Section 4).

3.38. Meteorological investigation should be undertaken over an adequate time period (at least one full year to account for seasonal variation), to provide data that are representative of the site before the start of construction of the nuclear installation and should continue for the lifetime of the installation. To obtain one full year of representative data, meteorological data should be collected for several years before construction. In addition, data should continue to be collected throughout construction and operation.

3.39. The meteorological data collected should be compatible — in terms of their nature, scope and precision — with the methods and models in which they are used in evaluating the radiation exposure of the public and the radiological impact on the environment for assessment against each regulatory objective (see Section 4).

3.40. Meteorological measurements are often affected by terrain and local features such as vegetation, ground cover, mountains and hills, and artificial structures, such as cooling towers and masts supporting meteorological sensors. Building wake effects might also influence the representativeness of the data obtained. In collecting meteorological data, care should be taken to prevent local effects from unduly altering the values of the parameters being measured.

3.41. For atmospheric dispersion analysis purposes, data on the following meteorological parameters should be obtained concurrently:

- (a) Wind vectors (i.e. wind directions and speeds);
- (b) Precipitation;
- (c) Air temperatures;
- (d) Humidity;
- (e) Air pressure;
- (f) Specific indicators of atmospheric turbulence.

3.42. The data collected should adequately represent local meteorological conditions, and the extent to which the data represent the long term meteorological characteristics of the site should be indicated. This information may be ascertained by comparing the local data with concurrent and long term data from other meteorological stations in the surrounding area.

3.43. Meteorological investigation activities should be undertaken in accordance with accepted international standards.

3.44. If meteorological equipment is installed, it should be positioned so as to obtain data representing the dispersion conditions at projected or actual release points. The terrain in the range of several kilometres around a nuclear installation site should be examined, paying

particular attention to topographical features such as valleys, principal ridges and coastlines. Equipment should be unobstructed and should be positioned far enough from any obstacles to minimize their effects on measurements. Ground cover and vegetation should be managed for the duration of the investigation programme, so that it does not obstruct the equipment. The positions and settings of the equipment should be selected for maximum exposure to the meteorological conditions.

3.45. The wind speed and direction at a location representative of the site should be measured in order to obtain wind data continuously at the following levels:

- (a) At an elevation of 10 m, for purposes of comparing and correlating wind data from the site with wind data from other meteorological stations in the region;
- (b) At the point representing the height of discharge which is effective stack height (to be evaluated on the basis of preliminary information).

The instruments used should be capable of collecting data that represent the entire profile of the wind at least up to the height of potential releases.

3.46. Measurements should be made at more than one location. For example, where the effect of sea breezes is important, data from an additional meteorological station further inland should be used in order to evaluate characteristics of the diffusion regime for the sea breeze over land.

3.47. Meteorological data should be obtained at least hourly. The averaging time and the sampling time for the data should be in accordance with the regulatory objective. The instruments should provide continuous recording so that the data collected are readily available in situ.

3.48. Fluctuations in meteorological conditions are direct indicators of atmospheric turbulence. To support the computational models used for atmospheric dispersion in determining the atmospheric stability, data relating to the following parameters should be obtained (see also Section 4):

- (a) Fluctuations in wind direction;
- (b) Air temperature and temperature lapse rate;
- (c) Wind speed and solar radiation levels or sky cover during the daytime;
- (d) Sky cover or net radiation levels at night time;
- (e) Wind speed at different heights.

3.49. For some computational models, the height of a mixing or boundary layer may need to be determined (see also Section 4).

3.50. For complex meteorological situations, for example in relation to mountainous regions, measurements of turbulence indicators made at the site alone might not be sufficient. Depending on the particular characteristics of the region, it may be necessary to take additional measurements of wind and turbulence indicators a few kilometres from the site. In certain cases, normal discharges of effluents or experimental discharges of tracers are used for the development of a local diffusion model, which is often a general model with adjustments derived from air concentration values measured at the site and in the region.

3.51. In developing site specific dispersion models, sufficient information should be acquired on the space and time distributions of parameters related to wind direction and speed and atmospheric stability, to be able to understand and determine the trajectory of effluents. Such information could be obtained by way of a programme of field measurements and/or by the method of numerical weather prediction (see para. 3.54).

3.52. Precipitation should be reported at least hourly. Measurements of the intensity of precipitation and total precipitation as well as details of the type of precipitation should be used to evaluate the impact of precipitation on airborne concentrations of contaminants and on ground contamination. Data on humidity may also help to determine any effects of cooling towers (e.g. icing or fogging on roadways and bridges, visibility of cooling tower plumes, effects of salt drift on vegetation). Air humidity can modify the dispersion of aerosols, as it can increase the coalescence of particulates.

3.53. The wind speed and direction at different elevations and temperatures should be averaged at least once per hour, while for other variables such as solar radiation levels and precipitation levels the period of integration should be one hour. Wind direction should be averaged as a vector and wind speed as a scalar over the recommended time period.

3.54. Meteorological data from numerical models supporting local weather forecasts should be collected to complement field measurements. These models would usually be run by the national meteorological organization and involve numerical interpolation of the meteorological data using the existing network of meteorological stations and meteorological data from other sources which may include satellites and observations from commercial aircraft, ships, buoys, radiosondes, light detection and ranging (LIDAR) and radar. Historical data can usually be obtained for any coordinates within the geographical scope of the data, and for as far back in time as data exist, which may be several decades.

HYDROLOGICAL AND HYDROGEOLOGICAL CHARACTERISTICS OF THE CATCHMENT OF THE SITE

3.55. Paragraph 6.7 of SSR-1 [1] states:

“The hydrogeological and hydrological investigations shall determine, to the extent necessary, the dilution and dispersion characteristics of water bodies, the re-concentration ability of sediments and biota, the migration and retention characteristics of radionuclides, the transfer mechanisms for radionuclides in the hydrosphere, as well as the associated exposure pathways.”

3.56. As part of establishing the environmental background and baseline conditions at a site, the hydrological and hydrogeological characteristics of the region around the proposed nuclear installation should be investigated. The emphasis should be placed on investigations related to the surface water and groundwater flows within the catchment area where the nuclear installation is located, keeping in mind the potential effects of water flow on the proposed installation and the potential effects of the proposed installation on the quantity and quality of water in the region. The region for investigations should be extended beyond the catchment area if the discharges to the atmosphere could reach and deposit in significant quantities on the ground and on surface water there.

3.57. The geology and surface hydrology of the site area should be studied in sufficient detail to indicate potential pathways for the transport of radionuclides to surface water or groundwater. Any surface drainage system or standing water body accessible from a potential release point in an accident should be identified. Areas from which contaminated surface water might directly enter an aquifer should be determined. The relevant hydrogeological information for surface or near surface discharges includes information on soil moisture properties, infiltration rates, configuration of unsaturated zones and chemical retention properties under unsaturated conditions, as necessary.

Surface water

3.58. Typical surface water bodies in the vicinity of a nuclear installation range from rivers to inland freshwater lakes (natural or human-made) to marine systems (e.g. estuaries, seas, oceans). Recommendations on the collection of background hydrological data for sites on these types of water bodies are provided in paras 3.60–3.65.

3.59. Recommendations on the parameters needed to analyse the transport of radionuclides in surface water are provided in Section 5.

Rivers

3.60. For sites on rivers, the hydrological and other information should cover the following:

- (a) The channel geometry, defined by the mean width, the mean cross-sectional area and the mean slope over the river reaches of interest (the water level can be computed from the channel geometry and the river flow rate). If there are important irregularities such as dead zones or hydraulic equipment in the stream that could influence the dispersion of the plume, they should be described. Additional downstream measurements of channel geometry should be made as necessary to assess the dispersion process in the river.
- (b) The river flow rate presented as monthly averages of the inverse of daily flows. The inverse rate of flow should be used, since the fully mixed concentration is proportional to the reciprocal of the flow rate if sediment sorption effects are not considered. The flow rates of other relevant and important water bodies (e.g. downstream tributaries of the river) should be measured if they affect dispersion.
- (c) Extremes in the flow rate evaluated from available historical data.
- (d) Seasonal variation of the water level over the reaches of interest.
- (e) Tidal variations in water level and flow rate in the case of a tidal river.
- (f) Data to describe possible interactions between river water and groundwater, and the identification of those reaches of the channel where the river might gain water from or lose water to groundwater.
- (g) River temperature, measured at representative locations (e.g. one location representative of upstream and one representative of downstream in the river) over at least a year and expressed as monthly averages of daily temperatures.
- (h) The thickness of the top layer, if thermal stratification of water in the river occurs.
- (i) Extreme temperatures evaluated from available historical data.
- (j) The concentrations of suspended matter measured:
 - (i) At Locations downstream of sections where the river is slowed, depleted, or fed by tributaries;
 - (ii) In discrete samples at appropriate time intervals (e.g. every two months for at least a year);
 - (iii) Over a sufficient range of flows to establish curves of flow versus sedimentation and/or erosion rate.
- (k) The characteristics of deposited sediments, including mineral and/or organic compositions and size classification.
- (l) The distribution coefficients for sediments and for suspended matter for the various radionuclides that might be discharged.
- (m) The background levels of activity in water, sediment and aquatic food due to natural and artificial sources.
- (n) Seasonal cycles of phytoplankton and zooplankton, with at least the periods of their presence and cyclical evolutions of their biomass.
- (o) Spawning periods and feeding cycles of major fish species.

Natural lakes

3.61. The natural lakes that are used as a source of cooling water for nuclear power plants tend to be large lakes. The information to be collected for such lakes should include the following:

- (a) The general shore and bottom configuration in the region, and unique features of the shoreline in the vicinity of the discharge.
- (b) Data on bathymetry out to a distance of several kilometres, and data on the amount and character of sediments in the shallow shelf waters.
- (c) Speeds, temperatures and directions of any near shore currents that could affect the dispersion of discharged radioactive material. Measurements should be made at appropriate depths and distances, depending on the bottom profile and the location of the point of discharge.
- (d) The duration of stagnation and characteristics of current reversals. After stagnation, a reversal in current usually leads to a large scale mass exchange between inshore and offshore waters that effectively removes pollutants from the shore zone.
- (e) The thermal stratification of water layers and its variation with time, including the position of the thermocline and its seasonal changes.
- (f) The load of suspended matter, sedimentation rates and sediment distribution coefficients, including data on sediment movements characterized by defining at least the areas of high rates of sediment accumulation.
- (g) The background levels of radioactivity in water, sediment and aquatic food due to natural and artificial sources.
- (h) Seasonal cycles of phytoplankton and zooplankton, with at least the periods of their presence and cyclical evolutions of their biomass.
- (i) Spawning periods and feeding cycles of major fish species.

Human-made lakes

3.62. For sites on human-made lakes, the information should include the following:

- (a) Parameters of the lake geometry, including length, width and depth at different locations;
- (b) Rates of inflow and outflow;
- (c) Expected fluctuations in water level on a monthly basis;
- (d) The water quality at inflows, including temperature and suspended solids;
- (e) Data on thermal stratification and its seasonal variations;
- (f) Interaction with groundwater;
- (g) Characteristics of bottom sediments (type and quantity);
- (h) The distribution coefficients for sediments and for suspended matter for the various radionuclides that may be discharged;
- (i) The rate of sediment deposition;
- (j) The background levels of activity in water, sediment and aquatic food due to natural and artificial sources;
- (k) Seasonal cycles of phytoplankton and zooplankton, with at least the periods of their presence and cyclical evolutions of their biomass;
- (l) Spawning periods and feeding cycles of major fish species.

Estuaries

3.63. For sites on estuaries, the following information should be collected:

- (a) The salinity distribution determined along several verticals covering different cross-sections of the salinity intrusion zone. The data should be sufficient to delineate the flow

pattern, which is directed towards the estuary mouth in the upper layer and towards the inner reaches in the lower layer of a fully or partially mixed estuary.

- (b) Evaluations of sediment displacements, the load of suspended matter, the rate of buildup of deposited sediment layers and the movement of these sediments with the tide.
- (c) Channel characteristics sufficiently upstream of the site to model the maximum upstream travel of radioactive effluents, if applicable.
- (d) The distribution coefficients for sediments and for suspended matter for the various radionuclides that may be discharged.
- (e) The background levels of activity in water, sediment and aquatic food due to natural and artificial sources.
- (f) Seasonal cycles of phytoplankton and zooplankton, with at least the periods of their presence and cyclical evolutions of their biomass.
- (g) Spawning periods and feeding cycles of major fish species.

3.64. Measurements of water temperature, salinity and other relevant water quality parameters in estuaries should be made at appropriate depths, distances and times, depending on the river flow, tidal levels and the configuration of the water body in different seasons.

Open shores of seas and oceans

3.65. For sites located on the shores of seas and oceans, the information should include the following:

- (a) The general shore and bottom configuration in the region, and unique features of the shoreline in the vicinity of the discharge.
- (b) Data on bathymetry out to a distance of several kilometres, and data on the amount and character of sediments in the shallow shelf waters.
- (c) Speeds, temperatures and directions of any near shore currents that could affect the dispersion of discharged radioactive material. Measurements should be made at appropriate depths and distances, depending on the bottom profile and the location of the point of discharge.
- (d) The duration of stagnation and characteristics of current reversals. After stagnation, a reversal in current usually leads to a large scale mass exchange between inshore and offshore waters that effectively removes pollutants from the shore zone.
- (e) The thermal stratification, if it exists within a reasonable distance from the shoreline, of water layers and its variation with time, including the position of the thermocline and its seasonal changes.
- (f) The load of suspended matter, sedimentation rates and sediment distribution coefficients, including data on sediment movements characterized by defining at least the areas of high rates of sediment accumulation.
- (g) The background levels of activity in water, sediment and aquatic food due to natural and artificial sources.
- (h) Seasonal cycles of phytoplankton and zooplankton, with at least the periods of their presence and cyclical evolutions of their biomass.
- (i) Spawning periods and feeding cycles of major fish species.

Groundwater

3.66. A conceptual model of the hydrogeological conditions at and around the site where the installation is proposed should be developed. This conceptual model should indicate the following (see also Section 6);

- (a) Hydrostratigraphical description of lithological units;
- (b) Water inflows and outflows;
- (c) Connectivity and interaction between the surface water bodies and groundwater;
- (d) Spatial distribution of potentiometric level and groundwater flow direction.

3.67. The information to be collected, on a local and regional scale, to identify the hydrogeological system should include:

- (a) Climatological and hydrological data;
- (b) Initial concentrations of radionuclides;
- (c) Major hydrogeological units, their hydraulic parameters and the ages or mean turnover times of groundwater;
- (d) Recharge and discharge relationships.

3.68. In terms of climatological data, in regions where rainfall makes a substantial contribution to groundwater, hydrometeorological data on daily and monthly rainfall and the data needed to calculate the potential and actual evapotranspiration that have been systematically collected should be analysed for as long a period as they are available. From the precipitation data, groundwater recharge should be calculated. Alternative methods such as tracers (chemical or isotopic) of the water cycle could be introduced to calculate groundwater recharge.

3.69. Data should be obtained on the various types of geological formations in the region and their stratigraphic distribution in order to characterize the regional groundwater system and its relationship with the local hydrogeological units. These data should include the following:

- (a) Geological data: lithology, thickness, extent and degree of homogeneity of the geological units.
- (b) Hydrogeological data: description of the unsaturated zone, hydraulic conductivities and transmissivities, specific yield and storage coefficients, dispersion parameters, and hydraulic gradients of the saturated zone for the geological units that form a flow domain.
- (c) The chemical composition of groundwater from the respective aquifers.
- (d) Variations of water levels in wells and in the discharges of springs and rivers.
- (e) Morphological features in karstic terrains, locations of closed depressions and active and potential sinkholes in the region.

3.70. For the relevant hydrogeological units, information should be collected on the following chemical and physical properties of the groundwater:

- (a) Physical properties of groundwater (e.g. pH, redox potential, temperature);
- (b) Concentrations of major anions and cations;
- (c) Sorption characteristics, when necessary for the selected grade of modelling.

4. ANALYSIS OF THE TRANSPORT OF RADIONUCLIDES IN THE ATMOSPHERE

4.1. Paragraph 6.1 of SSR-1 [1] states:

“The analysis of the atmospheric dispersion of radioactive material shall take into account the orography, land cover and meteorological features of the region, including parameters such as wind speed and direction, air temperature, precipitation, humidity, atmospheric stability parameters, prolonged atmospheric inversions and any other parameters required for modelling of atmospheric dispersion. If possible, long term meteorological data for nearby locations shall be obtained, evaluated for quality and used.”

4.2. Dispersion of released radionuclides in the atmosphere is a major exposure pathway by which radioactive material that are either routinely discharged under authorization or accidentally released from a nuclear installation could be transported to locations where they expose the public. Exposure can be immediate, by inhalation of material in the plume or by external exposure from radiation in the cloud, or it can occur over an extended period of time from material deposited on the ground which can cause external exposure or be incorporated in the food chain as discussed in Section 2.

4.3. Generally, different dispersion models are used to assess the impacts from planned continuous discharges and accidental short term discharges. However, the meteorological data that need to be acquired for each type of model are usually the same. In both cases, typical rather than extreme data are used and can be collected from the site itself or by numerical weather prediction models if sufficient quality data are available. The meteorological site data should be collected over several years so that it is possible to select a representative year or years from the records. The extreme data used for external hazard analysis need a much longer duration data set that is typically only available on a regional basis. For long range dispersion analysis (which is typically needed for evaluating societal impacts or transboundary impact), time and spatially gridded data for use in Lagrangian modelling (see para. 4.21) may need to be acquired from national or international meteorological organizations.

4.4. The calculations of the dispersion and concentration of radionuclides, coupled with the calculations of dose should show whether the radiological consequences of routine discharges and potential accidental releases of radioactive material into the atmosphere are tolerable. The results of these calculations for normal operations should be used to establish authorized or permitted limits for radioactive discharges from the installation into the atmosphere (see GSG-9 [11]) and those from accident conditions along with their expected frequency and comparison with national requirements for risk and/or dose criteria. In both cases, the results may be used to inform the design process to optimize doses or mitigate risks.

4.5. In summary, the results of the meteorological investigation should be used for the following purposes:

- (a) To confirm the suitability of a site;
- (b) To provide a baseline for site evaluation;
- (c) To determine whether local meteorological characteristics have altered since the site evaluation was made and before operation of the installation commences;
- (d) To select appropriate dispersion models for the site;
- (e) To establish limits for radioactive discharges into the atmosphere;
- (f) To establish limits for design performance (e.g. containment leak rates, control room habitability);
- (g) To assist in demonstrating the feasibility of an emergency plan (based on para. 2.7).

SELECTION OF RELEASE SCENARIOS FOR DISCHARGES AND ACCIDENTAL RELEASES TO THE ATMOSPHERE

4.6. The release scenario for normal operation is the discharge – usually a constant continuous discharge – from a known discharge location. Other scenarios to consider might include maintenance or other events expected to occur during operation that might lead to a shorter term release and a different profile of release in terms of radionuclides and/or their quantities.

4.7. A range of possible accident scenarios should be analysed (depending on the complexity of the installation) spanning high frequency low consequence events to low frequency high consequence events.

4.8. For a nuclear power plant, this analysis might encompass many scenarios to cover the spectrum of events that might occur – from anticipated operational occurrences through design basis accidents, to design extension conditions with core melting. For some advanced reactors, the definition of certain plant states may need to be adapted. Releases resulting from severe accidents might encompass the performance of a full scope level 2 probabilistic safety assessment (see SSG-3 (Rev. 1) [12] and SSG-4 [13]).

4.9. For sites with multiple units and installations with multiple facilities, there might be multiple discharges from several locations which all need to be analysed. Accident conditions might also include scenarios involving releases from multiple units which are either simultaneous or offset in time, which again might need to be analysed if these releases are significant contributors to the overall risk.

4.10. For other types of nuclear installation (e.g. waste storage facilities) analysis of a few or even only one potential exposure pathway might be sufficient.

SELECTION OF SOURCE PARAMETERS FOR ANALYSIS OF THE TRANSPORT OF RADIONUCLIDES IN THE ATMOSPHERE

4.11. For discharges, the calculation of the source terms may necessitate a detailed analysis of fuel performance and the chemical regime for water cooled reactors, for example, generation of corrosion and activation products, performance of waste treatment measures and filter systems.

4.12. Source terms for accident conditions differ from those for normal operation (see SSG-2 (Rev.1) [10] and IAEA Safety Standards Series No. NS-G-1.13, Radiation Protection Aspects of Design for Nuclear Power Plants [16]); for example, they might involve larger quantities, different radionuclides and/or different physical and chemical characteristics.

4.13. When selecting the source parameters, therefore, consideration should be given to the following:

- (a) Physical and chemical processes occurring during the accident sequence;
- (b) Behaviour of any safety features or the effects of any mitigatory measures;
- (c) Behaviour of radionuclides within the installations before they are released to the environment.

4.14. In addition to the quantities of radionuclides released, all the parameters that might affect their subsequent dispersion or behaviour in the environment should be characterized. This characterization should include the following:

- (a) Physical form (e.g. gas, aerosol);
- (b) Chemical form;
- (c) Release point and its height (for an atmospheric release) or depth below surface (for an aquatic release);
- (d) Flow speed and the thermal energy associated with the release may also be necessary to determine the effective height of the radioactive plume;
- (e) Time profile for the release.

4.15. Sources of radioactivity in a nuclear installation such as a nuclear power plant might include the following:

- (a) Corrosion products that remain in coolant during normal operation but that can be released to the environment in loss of coolant accidents (e.g. ^{58}Co , ^{60}Co).
- (b) Fission products and actinides formed by fission or activation of uranium in fuel (e.g. noble gases (^{85}Kr , ^{138}Xe), ^{131}I , ^{137}Cs , ^{90}Sr , ^{238}Pu , ^{239}Np). These are prevented from release in normal operation by many barriers.
- (c) Radionuclides from the fuel matrix, fuel cladding, coolant circuit or containment. Volatile radionuclides can be released into coolant through small pin failures or by tramp uranium and therefore can be released when coolant is released or by off-gassing. This can occur in severe accidents, when the fuel matrix and fuel cladding fail, and the coolant circuit and containment might be breached.
- (d) Activation products formed by the activation of water in water cooled reactors, which can be released when coolant is released or by off-gassing (e.g. radionuclides tritium (^3H), radiocarbon (^{14}C), Argon-41 (^{41}Ar)).

4.16. Radionuclides can also be released through fuel handling faults, radioactive waste handling faults, or accidents involving waste storage.

4.17. In order to determine the source term, the fraction of the initial inventory released to the environment needs to be evaluated; if there are several barriers to the release then the fraction released through each barrier needs to be assessed or modelled as well as the processes that might lead to the mobilization of the source term. For potential exposures from nuclear power plants, numerical codes should be used (see also SSG-2 (Rev. 1) [10] and SSG-3 (Rev. 1) [12]).

4.18. Source term data may be available from reactor vendors or from assessments in other Member States, but they should be supported by well documented numerical modelling and physical assumptions. For small modular reactors, based on current light water reactor designs, a scaling approach may be possible according to the effectiveness and reliability of the safety systems and barriers, whereby the source term from a large reactor is scaled by the relative power and possibly also burnup. For evolutionary and innovative designs, this may not be possible, and a detailed analysis should be performed.

ATMOSPHERIC DISPERSION MODELS

4.19. Different tools are usually used for assessing the impacts of normal operation and accident releases, although they may be based on the same type of atmospheric dispersion model.

4.20. The atmospheric dispersion computer models commonly used fall into two main types: Gaussian and Lagrangian.

4.21. The Gaussian model describes the atmospheric dispersion by the Gaussian equation in both the crosswind and vertical dimensions, whose spread increases with distance from the releases according to the meteorological parameters such as wind speed and those for atmospheric stability. The simple equations can be modified to take account of surface roughness, wet and dry deposition, building wake effects, and plume rise.

4.22. A Lagrangian type model tracks many notional particles (i.e. hypothetical packets of air) transporting each by the wind direction and wind speed and then modelling atmospheric turbulence effects by applying random motion. The atmospheric dispersion parameters used to determine the motion of each particle are interpolated in space and in time from a three

dimensional spatial grid of time series data. The concentration in any grid element of the model is determined by the number of particles in the box representing that grid element. Utilizing these gridded data allows variations in meteorological conditions in location, height and time to be modelled. Effects due to surface topography are implicitly considered, as they are embedded in the meteorological data, provided that a sufficient spatial resolution of the data is considered.

4.23. The advantages of the Gaussian model are as follows:

- (a) It is a simple mathematical expression that is easy to implement;
- (b) It can be modified to take into account, in a simple way, effects such as plume rise, building wake effects, and dry and wet deposition;
- (c) It is fast to execute so there is no need to sample from a meteorological data set; it is quite feasible to perform calculations for every hour of a data set of several years;
- (d) It is considered to be generally conservative with respect to more detailed models;
- (e) It needs a relatively simple meteorological data set of hourly data for the point of release, comprising data such as wind direction, wind speed, atmospheric stability category, mixing layer height and precipitation;
- (f) It can be adapted to model temporal and spatial changes in meteorological conditions during the release (Gaussian puff models);
- (g) There are also 'new generation' Gaussian models that have the ability to take account of more complex terrain and buildings in the vicinity of the release.

4.24. The disadvantages of the Gaussian model are as follows:

- (a) Other than the 'new generation' models mentioned above, it cannot satisfactorily model complex terrain;
- (b) The range of validity is limited to that over which the meteorological conditions remain reasonably constant and consequently it cannot satisfactorily model long range impacts.

4.25. By contrast, the advantages of the Lagrangian model are as follows:

- (a) It can model complex terrain and long-range dispersion if an appropriate meteorological data set is available (i.e. fine enough spatial resolution for the terrain being modelled to be resolved in the meteorological data) and therefore generally gives a more accurate representation of the dispersion for a given set of meteorological conditions;
- (b) It can model changes in meteorological conditions in time and space.

The disadvantages of the Lagrangian model are as follows:

- (a) It has long computer run times;
- (b) It needs a large complex meteorological data set including three dimensional data as a function of time for the area over which the model is being run;
- (c) Compromises may be needed in other areas to reduce the overall computation effect, such as: number of nuclides modelled, geographical resolution, and number of meteorological sequences modelled;
- (d) It is difficult to use for continuous releases over an extended period.

4.26. A Lagrangian model could use single site data rather than a three dimensional grid but in this case – other than being less conservative – it offers few benefits over a simple Gaussian model. To take full advantage of the capabilities of a Lagrangian model, an extensive grid of data is needed, which should be collected from the national meteorological institute or from other international sources of global data.

4.27. The decision on the model to use depends on the type of analysis needed and the characteristics of the site and surrounding area. If only assessment of short-range impacts is

needed, and the surrounding area is reasonably flat, then the Gaussian model approach may be sufficient. If the site has complex topography, long-range results are needed for a transboundary assessment, or an assessment of population risks in a large area is needed, then the Lagrangian model may be more appropriate, if the necessary meteorological data are available. For sites with complex topography and short-range analysis, then the 'new generation' Gaussian model should be used.

4.28. However, use of the new generation Gaussian model might lead to large uncertainties associated with the source term, especially for accidental releases. Consequently, the extra insights gained from performing more sophisticated or more extensive analysis might not be commensurate with the extra effort and should be carefully evaluated.

DEFINITION AND COLLECTION OF METEOROLOGICAL AND OTHER DATA FOR MODELLING ATMOSPHERIC DISPERSION

4.29. Paragraph 6.2 of SSR-1 [1] states:

“A programme for meteorological measurements shall be prepared and carried out at or near the site using instrumentation capable of measuring and recording the main meteorological parameters at appropriate elevations, locations and sampling intervals. Data from at least one representative full year shall be collected and used in the analyses of atmospheric dispersion, together with any other relevant data available from other information sources. The meteorological data shall be expressed in terms of appropriate meteorological parameters.”

4.30. In order to have data for at least one representative full year, at least three years and ideally up to ten years of data need to be collected. The collection of data should continue for the lifetime of the nuclear installation to confirm that conditions have not changed significantly and that updated assessments can be performed using the latest data as necessary.

4.31. To conduct the programme for meteorological measurements, a meteorological tower should be installed at the site. To ensure the measuring of meteorological parameters at appropriate elevations in order to obtain realistic dispersion parameters, data should be collected at least at 10 m above ground (to compare with data from the synoptic network of meteorological stations) and at the heights of the proposed buildings and stack.

4.32. The data collected should adequately represent local meteorological conditions. Meteorological measurements are often affected by terrain, and local features such as vegetation and ground cover, orographic features and plant structures (such as cooling towers and masts supporting meteorological sensors) as well as building wake effects might influence the representativeness of the data obtained. Activities should be undertaken in accordance with accepted international standards, for example Ref. [17].

4.33. The local data collected should be compared with any available concurrent and long term data from synoptic meteorological stations in the surrounding area to determine long term trends for the site or, if the local results seem anomalous, to investigate possible causes.

4.34. Meteorological data should be obtained at least hourly. Instruments should be provided for continuous recording in order to ensure that the data collected can be readily available at the locations where they are used. The raw data should be stored until data qualification and statistical analysis have been performed. Hourly mean values derived from the programme for meteorological investigation should be stored for the lifetime of the installation. Data averaged over shorter periods of time (less than one hour) should be stored continuously for purposes of

emergency response and recovery, as they can be used to assess the plume dispersion in the event of an accidental release.

4.35. The programme for regional meteorological investigation and all information relating to it should be documented for the purposes of site evaluation and design, and for use in emergency plans.

4.36. Local meteorological data can also be derived from dynamic numerical atmospheric prediction models. In this method, data collected (usually by the national meteorological institute) from many sources (e.g. land stations, satellites, aircraft, ships) are processed by the same models used for numerical weather prediction and interpolated for a specified location. In this way, hourly meteorological data can be obtained retrospectively for any location within the region over which the data has been collected and for as far back historically as the data exist.

4.37. By whatever means the data are acquired, the data should be compatible (in terms of their nature, scope and precision) with the methods and atmospheric dispersion models being used (see para 4.18); for example, atmospheric stability can be characterized in different ways with different parameters. The data and models needed also depend on the regulatory objectives for the radiological impact on people on the environment; for example, if the assessment of population risk is an objective, then long range dispersion modelling is needed.

4.38. Generally, the same data collected for normal releases can be used for accidental releases although the latter may also necessitate more long range data if long range dispersion modelling is part of the assessment.

4.39. The typical meteorological data needed for a Gaussian dispersion model include the following:

- (a) Wind speed;
- (b) Wind direction;
- (c) Boundary (or mixing) layer height;
- (d) Parameter(s) determining the atmospheric stability, such as the Pasquill-Gifford stability class or Doury scheme;
- (e) Precipitation.

4.40. In addition, other data that may be used in the model include the following:

- (a) Deposition velocities for aerosol particles or chemical species to model dry deposition;
- (b) Washout coefficients for aerosol particles or chemical species to model wet deposition;
- (c) Release height;
- (d) Energy or momentum of the release;
- (e) Building dimensions to account for building wake effects;
- (f) Surface roughness;
- (g) Surface topography for new generation Gaussian models.

Wind speed

4.41. The wind speed and atmospheric stability are correlated, with higher wind speeds leading to more stable conditions (see para 4.41). Higher wind speeds may also have the effect of inhibiting plume rise effects. Higher wind speeds mean that nuclides reach locations quicker, affording less time for any radioactive decay but this is not usually significant unless very short lived nuclides are involved.

Wind direction

4.42. Wind direction can be very important if there is an uneven population distribution around the site, since the probability of exposure at any given location depends on the probability that the wind blows in that direction.

Boundary layer height

4.43. The boundary (or mixing) layer height is the height at which a temperature inversion occurs, creating an effective boundary for dispersion in the vertical direction. Gaussian dispersion models generally assume that the plume reflects down from the boundary layer with no transfer across the boundary, and up from the ground until fully mixed in the vertical direction. Lagrangian dispersion models, on the other hand, may model transfer across the boundary and subsequent dispersion of material above the layer. The boundary layer height is important since it effectively determines the volume of air that the plume of radioactivity has available to disperse at sufficient distances downwind where the plume is fully mixed vertically; at these distances, the boundary layer height is correlated with the atmospheric stability, with more unstable conditions leading to higher boundary layer heights.

Atmospheric stability

4.44. Atmospheric stability is usually the most important atmospheric dispersion parameter after wind direction and should be considered in modelling. Unstable conditions lead to increased dispersion in both the vertical and crosswind directions and hence lower ground level concentrations. For elevated releases (e.g. from a stack) unstable conditions increase the vertical dispersion which causes the plume to reach ground level at shorter downwind distances than would be the case for more stable conditions. For ground level releases, more stable conditions lead to higher plume centreline concentrations but with lower crosswind spread. For elevated releases, unstable conditions can lead to higher concentration close to the release than would be the case for stable conditions.

Precipitation

4.45. Precipitation enhances the deposition of activity on the ground by washing material out of plume. Precipitation can also transfer activity to surface water and/or groundwater systems and should be carefully modelled.

SENSITIVITY STUDY OF THE ANALYSIS OF RADIONUCLIDE TRANSPORT IN THE ATMOSPHERE

4.46. Since an assessment involves many assumptions and uncertainties, sensitivity studies should be performed to assess the sensitivity of the overall results to assumptions or parameter values. Typical sensitivity studies should include the following:

- (a) Meteorological data used (for practical reasons, only a subset or sample of the meteorological data may have been used, and the effect of different or larger samples could be investigated);
- (b) Source term assumptions, including activity released, possible release heights, energy of release, and time profile of release;
- (c) Representative person assumptions (e.g. age group, location, food consumption);
- (d) Parameter value assumptions (e.g. deposition velocities);
- (e) Assumptions about countermeasures applied.

SCENARIO BASED SIMULATION OF ATMOSPHERIC DISPERSION

4.47. The scenarios simulated for discharges should normally assume that the release continues at a constant rate for the lifetime of the nuclear installation, using every hour of the meteorological data. In addition, short term planned releases, such as those that occur during maintenance, should also be modelled.

4.48. For accidental releases, a Level 3 probabilistic safety assessment may be performed. For this purpose, the results of a Level 2 probabilistic safety assessment (or other accident consequence analysis for accidents not involving core melting) are used in the form of source terms and their corresponding frequencies from a series of accident scenarios⁶. To address the effect of different meteorological conditions on the release, historical meteorological data is sampled to define a set of meteorological sequences for which radiological consequences are calculated for each meteorological sequence; this is repeated for each source term. This set of results can complement deterministic modelling of the individual risk to representative persons, societal risks, or statistical distributions of other economic consequences.

4.49. Such analyses may also be used to inform emergency planning or for transboundary assessments.

GRADED APPROACH TO ASSESSING THE TRANSPORT OF RADIONUCLIDES IN THE ATMOSPHERE

4.50. For simple assessments of low hazard installations, a conservative approach might be possible. In a conservative approach, the following assumptions can be made:

- (a) Conservative source terms are used (e.g. the entire inventory).
- (b) The representative person is directly downwind of the release at a specified distance close to the source (e.g. at the site boundary) or at the point of peak ground-level concentration for elevated releases.
- (c) Either typical or conservative combinations of wind speed and atmospheric stability (and possibly precipitation) are used. A conservative assumption might be stable atmospheric conditions with low wind speed for a ground level release, whereas for an elevated release, unstable conditions might lead to higher ground level concentrations closer to the release point.

4.51. If using such conservative assumptions leads to unacceptable results, then some of the assumptions may need to be refined. This is discussed further in Section 10.

⁶ Scenarios with similar source terms can be grouped together in a bounding case to make the analysis more manageable.

5. ANALYSIS OF TRANSPORT OF RADIONUCLIDES IN SURFACE WATER

5.1. Radionuclides entering surface water are dispersed due to general water movements and sedimentation processes. Liquid radioactive releases may be discharged to freshwater, marine or estuarine environments directly. Radionuclides may also reach surface water bodies through atmospheric release followed by deposition on water, or from the ground surface by surface runoff. The potential exposure scenarios and source terms for each accident scenario should be examined on the basis of the safety assessment, including the quantities and relevant physical and chemical characteristics of the releases to the surface water.

5.2. The hydrological dispersion and transfer of radionuclides should be estimated using relevant models, considering the defined hydrological conditions. The output of atmospheric dispersion models may also be used as input for transport in surface water if considered significant; this is probably necessary for only continuous discharges. As discussed in Section 7, the relevant exposure pathways and the representative person should then be identified. Finally, the estimated dose (and, in some cases, a measure of the risk of health effects based on the estimated doses), should be derived and compared with the applicable established criteria. Possible exposure pathways for a representative person through surface water include consumption of drinking water, fisheries, aquatic food, irrigation and recreation.

SELECTION OF RELEASE SCENARIOS FOR DISCHARGES AND ACCIDENTAL RELEASES TO SURFACE WATER

5.3. In discharges, radionuclides are directly released into the water body as liquid, through atmospheric deposition (mainly aerosol) on the surface water, or through surface runoff and deposition on the ground due to precipitation. The composition and quantity of radionuclides should be determined and the physical properties (e.g. gas, aerosol, liquid) and chemical properties should also be examined to help assess the environmental dispersion of radionuclides.

5.4. In an accidental release, radionuclides may be transferred to surface water bodies either directly or indirectly by atmospheric deposition and deposition; however, the overall radiological impact of the latter is likely to be trivial in comparison with that from a direct atmospheric release. In addition, some of the radionuclides on the ground surface, either due to deposition from atmospheric releases or direct release to the ground might enter surface water through surface runoff due to precipitation. Such surface runoff should be considered after an accidental release to the ground surface.

SELECTION OF SOURCE PARAMETERS FOR ANALYSIS OF THE TRANSPORT OF RADIONUCLIDES IN SURFACE WATER

5.5. The basic source parameters are the same as those for the transport of radionuclides in the atmosphere (see paras 4.10–4.17). Additional parameters should be considered in relation to atmospheric deposition, which may be represented by the scenario-based models described in paras 4.47–4.49.

5.6. In respect of the source term and receiving water, there should be representative values for all the parameters that affect the dispersion of radionuclides in surface water, including the following:

- (a) Radionuclides: the nuclides and the amounts that could be released (e.g. corrosion products, fission products, activation products).
- (b) Chemical properties, which control the behaviour of radionuclides in surface water, such as adsorption affinity, biological uptake and chemical form of radionuclides, whether in dissolved or particulate form:
 - (i) Major anion and cation concentrations, which control adsorption of radionuclides;
 - (ii) Organic content, which is important for biological uptake of radionuclides by aquaculture;
 - (iii) pH, which controls the behaviour of radionuclides in surface water (dissolution affinity of nuclides);
 - (iv) Concentration of dissolved oxygen, conductivity, suspended substance;
 - (v) Salinity, which is important for the marine environment and estuarine area where the fresh water and sea water mix. The water mass characteristics that control the distribution patterns of radionuclides are determined mainly by salinity and temperature.
- (c) Physical properties, which determine the distribution, dispersion pattern and concentration of nuclides in the surface water:
 - (i) Temperature at multiple depths, which could define the thermocline and vertical distribution pattern of radionuclides in the water;
 - (ii) Density is determined by temperature, salinity and water depth, which control the mixture of water parcels with each other; water parcels with different density values never exchange; the distribution of radionuclides in surface water elongate within the zone of equal density (isopycnal water parcel);
 - (iii) Water flow characteristics, which control the dispersion pattern of radionuclides in the surface water;
 - (iv) Sediment load parameters, which control the removal process of radionuclides from surface water to the bottom sediment;
- (d) Sedimentation properties:
 - (i) Distribution coefficient (K_d), which determines the removal of radionuclides from surface water to the bottom sediment;
 - (ii) Particle size distribution of sediment or surface area of sediment, as indices for adsorption of radionuclides.

Most of these parameters are based on the data collected as background hydrological data listed in Section 3. Other parameters can be obtained from literature or more specialized studies in the laboratory or in the field.

MODELS FOR RADIONUCLIDE TRANSPORT IN SURFACE WATER

5.7. There are three basic types of model to estimate radionuclide transport through surface water:

- (a) Numerical models usually transform the basic equations describing radionuclide dispersion into finite difference or finite element forms.
- (b) Box type models treat the entire water body or sections of a water body as homogeneous compartments. These models often include some sediment–radionuclide interactions.

(c) Analytical models solve the basic radionuclide transport equations. Simplifying assumptions are made regarding water body geometry, flow conditions and dispersion processes to obtain analytical solutions to the governing equations.

5.8. Other types of model can be used for assessing radionuclide dispersion in surface water systems (e.g. rivers, human-made impoundments, lakes, estuaries, open shores, oceans). Their selection should be based on the quality of results needed for risk assessment.

Radionuclide transport in rivers

5.9. The modelling approach and level of accuracy of the source data depend on the purpose of the model and the accuracy needed for the river under analysis. Models developed to produce approximate results may be steady or unsteady flow, one or two dimensional models. On the other hand, detailed modelling typically needs more specific data and more detailed knowledge of the river system. One and/or two dimensional models can be developed in steady or unsteady flow mode, using site-specific data. For more detailed studies, one or two dimensional models should be used to obtain a preliminary idea of the behaviour of the hydraulic system and to support a more refined analysis based on three dimensional models.

5.10. The size and length of the river to be modelled dictates the level of modelling. When the length of the river section, for instance, is much larger than the width and depth, a one dimensional model should be developed. If the flow path of the water is unknown for some of the events, or if it changes significantly during the event, then a one dimensional model is not appropriate.

5.11. The analysis objective (expected type and accuracy of results) should dictate the selection of the appropriate model. Consequently, the source and level of accuracy of the data should be compatible with the selected model. The availability, source and level of accuracy of data should not be used as a basis for developing a model; on the contrary, an appropriate model should be selected to achieve the expected results, and the data should be acquired accordingly.

5.12. Mathematical models, either analytical or numerical, need representative values of the relevant parameters and the boundary conditions, which should be collected with appropriate accuracy either from literature or site-specific studies.

Radionuclide transport in human-made impoundments and lakes

5.13. Appropriate models should be selected. The typical models for dispersion in lakes along with their advantages and disadvantages for different situations are discussed below:

- (a) Box model: The water body is divided into multiple boxes in the longitudinal direction and the water quality changes associated with the inflow and outflow within each box are calculated. Hydraulic quantities are only used for inflow and outflow only. The water quality is calculated by taking an average of all the boxes. The advantages of this model are that the calculation time is short, and long term prediction is possible. Its disadvantages are that the model is not suitable for stratified lakes, cannot represent the heterogeneity within a box, and cannot represent the effects of flow changes.
- (b) Vertical one dimensional model: The water body is divided into layers and the vertical distribution of hydrology and water quantity is calculated. The hydrology and water quantity are established using stratigraphic averages. The advantages of this model are that the calculation time is short, and long term prediction is possible. Its disadvantages are that the model cannot represent the distribution within a box, and it is difficult to take into account the effects of flow changes (horizontal variation).

- (c) Horizontal two dimensional model: The horizontal distribution of hydrological and water quantity is calculated by dividing the water body into horizontal meshes. The hydrology and water quality are determined for each mesh, but the vertical distribution is assumed to be uniform. The advantages of this model are that the calculation time is shorter than for three dimensional models, and medium term (1–10 year) prediction is possible. The disadvantage of this model is that it is not suitable for stratified lakes.
- (d) Vertical two dimensional model: The vertical distribution of hydrological and water quality parameters are calculated by dividing the water body into vertical meshes. The hydrology and water quantity are determined for each mesh, but the horizontal distribution is assumed to be uniform. The advantages of this model are that the calculation time is shorter than for three dimensional models, medium term (1–10 year) prediction is possible, and the stratification is represented. A disadvantage is that transverse variation such as horizontal flow is not represented in this model.
- (e) Three dimensional model: The hydrology and water quality is calculated by dividing a water body into meshes in the longitudinal, transverse, and vertical directions. The three dimensional distribution of hydraulic and water quantity is needed. The advantages of this model are that it can describe local hydrology and water quality characteristics, can take into account density flow and drift current, and can reproduce complex phenomena in the lake. A disadvantage of the model is that a long calculation time is needed, so it is not suitable for long term calculations (over 10 years).

Radionuclide transport in estuaries

5.14. Estuarine regions are connected at one end to a river and the other end to the sea. An estuary velocity reverses with the tide, and an estuary can contain fresh or saline water, although estuary water is generally less saline than that of the sea. Any radioactive discharge is assumed to occur from one of the estuary banks. The radionuclide concentration at the banks may be assessed using a methodology that is very similar to that used for rivers, but adjustments should be considered, to take into account tidal effects, salt wedge and estuarine circulation.

Radionuclide transport in the open shores of seas and oceans

5.15. Appropriate models should be selected. There are three main types of ocean general circulation models that could be used to model dispersion of radionuclides in the sea, depending on the vertical coordinate system. These models along with their advantages and disadvantages for different situations are discussed below:

- (a) Z coordinate model, in which the vertical coordinates are perpendicular to gravity. This model is suitable for long term calculations. The z coordinate model utilizes the characteristics of the ocean so that local pressure is expressed as a function of depth by zero-order approximation, which makes implementing the equation of state straightforward. The implementation of bottom topography and drawing of results are also straightforward. This is the most widely used ocean general circulation model because of its versatility. The main disadvantages of this model, however, are that the vertical resolution in shallow seas and near the sea floor tends to be low, and the processes that arise near the coast and the sea floor tend to be poorly reproduced.
- (b) Sigma coordinate model, in which the vertical coordinates are the planes along the sea floor. The number of vertical layers to be calculated in shallow water is the same as for deep water. Since the number of vertical grid points is invariable throughout the model domain, sigma models are widely used for coastal ocean simulations. The main disadvantages of this model are that an accurate representation of the horizontal pressure

gradient is difficult near steeply sloping bottom topography, and the lateral mixing along the same vertical layer near the continental slope region might lead to the mixing of the shoreward light water and the seaward dense water.

- (c) Isopycnal coordinate model, in which the vertical coordinates of the surfaces are along the isopycnal plane. The development of this class of model is based on the fact that seawater moves along isopycnal surfaces in the interior. Thus, the characteristics of a water mass are well maintained in the ocean interior. Since many theoretical studies of physical oceanography use an isopycnal coordinate framework, the isopycnal models have the great advantage of providing good correspondence between theory and numerical models. The main disadvantage of this model is that a surface mixed layer model cannot be incorporated into an isopycnal model.

IDENTIFICATION OF EXPOSURE PATHWAYS IN SURFACE WATER

5.16. According to para 5.27 of GSG-10 [8], possible exposure pathways for releases of radionuclides to surface water in normal operation of nuclear installations such as nuclear power plants include the following:

- (a) Ingestion of drinking water;
- (b) Ingestion of aquatic food (e.g. freshwater or seawater fish, crustaceans, molluscs);
- (c) External exposure from radionuclides in water and sediments (i.e. from activities on shores, swimming and fishing).

5.17. Most accident conditions involve releases to the atmosphere with only indirect releases to surface water. In these situations, assessing only the radiological consequence of the atmospheric release is usually sufficient as these are dominant and any additional impact from indirect releases to surface water is trivial in comparison. Given that the computational effect needed to assess the impact of indirect inputs to surface water is likely to be large, (many hundreds of meteorological sequences may need to be considered, taking account of wet and dry deposition in different locations) and that uncertainties in the atmospheric source term might be far more significant, consideration should be given to whether such calculations are worthwhile in terms of the endpoints being determined. Situations where assessment might be worthwhile include atmospheric deposition on reservoirs used for drinking water.

5.18. Accident conditions involving a direct release to surface water should be considered if their likelihood is such that they could make a significant contribution to the overall risk.

DEFINITION AND COLLECTION OF DATA FOR MODELLING RADIONUCLIDE TRANSPORT IN SURFACE WATER

5.19. The data necessary for the surface hydrological analysis of a nuclear installation site come from different sources. The existing hydrometeorological network usually provides sufficient data. These data, however, should be verified before being used, since their reliability varies depending on the location in which they were collected.

5.20. The data needs presented in this Safety Guide relate to standard calculational methods. For advanced models, the data needs should meet the relevant regulatory requirements. Typical water bodies in the vicinity of a nuclear installation range from rivers, estuaries, open shores of large lakes, seas and oceans to human-made impoundments. The specific parameters necessary

for modelling radionuclide transfer in various aquatic environments are provided in paras 5.22–5.26.

Modelling in rivers

5.21. The following parameters are needed to calculate radionuclide concentrations in a river:

- (a) Average river width and depth;
- (b) Annual average river flow rate;
- (c) Longitudinal distance from the release point to a potential receptor location;
- (d) Radionuclide decay constant and daughter products.

Modelling in human-made impoundments and lakes

5.22. The following parameters are needed to calculate radionuclide concentrations in a human-made impoundment or lake:

- (a) Geology of impoundments and lakes (e.g. the volume-area-elevation curve);
- (b) Seasonal variation of hydrological parameters;
- (c) Longitudinal distance from the release point to a potential receptor location;
- (d) Radionuclide decay constant.

Modelling in estuaries

5.23. The following parameters are needed to calculate radionuclide concentrations in an estuary:

- (a) Estuary width;
- (b) Estuary flow depth;
- (c) River width under a mean annual river flow rate upstream of the tidal flow area;
- (d) Tidal period;
- (e) Longitudinal distance from the release point to a potential receptor location;
- (f) Radionuclide decay constant.

Modelling in open shores of seas and oceans

5.24. All oceanic phenomena affecting dispersion should be considered. The representative physical factors for developing the oceanic models in terms of their space and time scales are given in Table 2.

TABLE 2. THE REPRESENTATIVE PHYSICAL FACTORS FOR DEVELOPING THE OCEANIC MODELS.

Representative physical factor	Time scale	Space scale
Wind waves	1–10 s	1–10 m
Microstructure turbulence	1 s to 1 min	1 cm to 1 m
Boundary layer turbulence	1 min to 1 day	10 cm to 100 m
Swell	1 s to 1 min	100 m
Internal gravity waves	1 hour to 1 day	100 m to 10 km
Sub-mesoscale currents	1 hour to 1 month	100 m to 10 km
Mesoscale eddies	1 day to 1 year	1–100 km
Tides	1 hour to 1 day	1000–10000 km
Wind-driven circulation	1 month to 100 years	100–1000 km
Thermohaline circulation	100–1000 years	1000–10000 km

5.25. The ocean general circulation model should consider wind-driven circulation and thermohaline circulation to represent the global scale. Global models are typically used as a boundary condition for the regional model that represents the target ocean. The regional model should represent the relevant physical oceanographic phenomena, such as tides, mesoscale eddies, swells and wind waves, in order to represent the topography and ocean currents specific to the target area. A high resolution model with a grid size of a few kilometres is often used near the coast, and a low resolution model with a grid size of 10–100 kilometres is used in the open ocean.

CALIBRATION OF MODEL AND SENSITIVITY STUDY OF THE ANALYSIS OF RADIONUCLIDE TRANSPORT IN SURFACE WATER

5.26. The results from a calculational model should be compared with laboratory data or field data for a specific site. Such validation usually has a limited range of applicability, which should be determined with a full understanding of the model. The model should be calibrated by comparing it with the actual environmental monitoring data set. It should be verified, for example, that the errors and uncertainties in the model output values are within the error range of the actual observed values.

5.27. As with the atmospheric dispersion model, the assessment involves many assumptions and uncertainties, so a sensitivity study should be performed to assess the sensitivity of the overall results to the assumptions and parameter values. A sensitivity study should include the following:

- (a) Hydrological data to be used;
- (b) Source term assumptions including radionuclide activity released, potential water depth of release, and surface deposition associated with atmospheric fallout;
- (c) Representative assumptions (e.g. age group, residence, food consumption, water consumption);
- (d) Assumptions about parameter values such as deposition rates;
- (e) Assumptions about the measures to be applied.

SCENARIO BASED SIMULATION OF RADIONUCLIDE TRANSPORT IN SURFACE WATER

5.28. The scenario for a planned release should assume that radionuclides are released to surface water at a constant release rate and that the release continues for the lifetime of the installation. Surface water deposition associated with short term planned releases to the atmosphere, such as those that occur during maintenance, can also be simulated.

5.29. In addition, a series of radiological effects can be simulated by reproducing the diffusion of radionuclides in surface water through calculations based on the release of various types and amounts of radionuclides in multiple accidental releases and the corresponding sample times from hydrological data sets.

GRADED APPROCH TO ASSESSING THE TRANSPORT OF RADIONUCLIDES IN SURFACE WATER

5.30. The level of complexity of a dispersion model for radionuclides in surface water should be chosen primarily according to the magnitude of the installation's hazard category (see para. 10.5) and the complexity of the hydrological environment. In particular, before developing a detailed model, it is useful to simplify the site characteristics and consider conservative transport mechanisms.

5.31. When assessing rivers, the size and length of the river should determine the level of modelling. If the length of the river cross-section is much larger than the width or depth, a one dimensional model may be used. If the water flow path is unknown for certain events, or changes significantly during an event, a one dimensional model is not appropriate and a more sophisticated model should be used.

5.32. The basic flow phenomena in human-made impoundments and lakes are the flow due to the inflow and outflow of rivers, and the wind-driven flow. These flow phenomena can be simplified according to their complexity. The presence or absence of vertical stratification associated with seasonal changes in air and water temperatures is also a criterion for determining whether the model can be simplified. With regard to the spatial scale, a low-dimensional model may be selected when a rough scale such as the average water quality in the lake is sufficient. With regard to the time scale, if the long term variation over a year or more needs to be determined, a low-dimensional model should be considered because a high-dimensional model might not be practical. On the other hand, if a short term phenomenon such as runoff or storm surge needs to be determined, a high-dimensional model would be more appropriate to achieve sufficient accuracy. Section 10 provides further recommendations on the application of a graded approach.

5.33. In the flow field in the ocean, various processes should be considered, such as three dimensional modelling of water mixing associated with temperature, salinity, density, tidal fluctuations, freshwater supply from rivers, the influence of strong currents due to thermohaline circulation in the open ocean, and the presence or absence of eddies. In coastal areas, various processes can be applied to simplify the model depending on the features of the region, such as the presence or absence of large rivers, the seasonal development of vertical stratification, and the influence of tidal currents.

6. ANALYSIS OF TRANSPORT OF RADIONUCLIDES IN GROUNDWATER

6.1. The objectives of conducting a hydrogeological study in a nuclear installation site are to determine the following:

- (a) The estimated concentration of radioactive material in groundwater at the nearest point in the region where groundwater is drawn for human consumption;
- (b) The transport paths and travel times for radioactive material to reach the source of consumption from the point of release;
- (c) The transport capacity of the surface flow, interflow and groundwater recharge;
- (d) The susceptibility to contamination of the aquifers at different levels;

(e) The time and space distributions of the concentrations of radioactive material in the groundwater resulting from discharges and/or accidental releases from the nuclear installation.

6.2. The hydrosphere is a major medium by which radioactive material that are released from a nuclear installation via discharges or accidental releases could be dispersed into the environment and transported to locations where water is used by or for the population. The transport of radionuclides in groundwater is very slow compared to transport in surface waters.

6.3. A detailed investigation of the hydrogeology in the region should be performed. Calculations of transport and concentrations of radionuclides should be made to show whether the radiological consequences of routine discharges and potential accidental releases of radioactive material into the groundwater are acceptable.

6.4. The results of the hydrogeological investigation should be used for the following purposes:

- (a) To confirm the suitability of the site;
- (b) To select and calibrate an appropriate flow and transport model for the site;
- (c) To establish limits for radioactive discharges into pathways that ultimately reach the groundwater;
- (d) To assess the radiological consequences of releases;
- (e) To assist in demonstrating the feasibility of an emergency plan;
- (f) To develop a monitoring programme and a sampling strategy for use in the event of an accidental radioactive release.

6.5. The information necessary to perform dose assessment relating to exposure pathways in the hydrogeological system includes the following (see Section 7 for assessment of doses using the radionuclide concentrations calculated from groundwater transport analyses discussed in this section):

- (a) The source term for the discharge of radioactive material to the groundwater system;
- (b) Hydrological, physical, physicochemical and biological characteristics governing the transport, diffusion and retention of radioactive material;
- (c) Relevant food chains leading to humans;
- (d) Dietary and other relevant habits of the population, including special occupational activities such as fishing and recreational pursuits such as water sports.

6.6. The direction of groundwater movement and of radionuclide transport in isotropic media is orthogonal to the contours at the hydraulic head. In this case, the standard calculational models may be applied. If the aquifers are strongly anisotropic, however, and the water and transported effluents can move over a limited domain through fractures and/or karstic conduits, most calculational models are not valid. In this case, field studies including tracer studies may be necessary and should be considered. The level of complexity of the model should primarily be selected on the basis of the level of risk of the installation and complexity of the hydrogeological configuration.

6.7. The objectives outlined in paras 6.1–6.4 can be achieved primarily by mathematical models that produce groundwater flow velocity vectors in the flow domain. These models should then be coupled with transport models to assess the spatial and temporal variations in the concentrations of radionuclides.

6.8. The calculational model should also be selected on the basis of the objective of the study. Considering the objectives listed in para. 6.1, preference should be given to process-based deterministic models. The models selected should be suitable for simulating the dispersion,

dilution, transfer and accumulation of radionuclides and their decay or other removal mechanisms, as necessary. The mode of the releases expected during normal operation of the installation as well as potential exposures should be taken into account (see also GSG-9 [11]).

6.9. When it is appropriate to use analytical models, a detailed analysis of appropriateness in terms of the boundary conditions and assumptions that satisfy the physical conditions at the study site should be conducted. Consequently, the analytical model used should be validated for each specific application.

6.10. Considering their limitations, analytical models for groundwater flow and radionuclide transport should be applied as an initial prediction because, in most cases, they involve a high level of simplification of the real system. Additionally, the assumptions in these models limit their application to relatively simple systems. Therefore, they should be considered as inappropriate for most practical groundwater problems.

SELECTION OF RELEASE SCENARIOS FROM DISCHARGES AND POTENTIAL EXPOSURE RELEASES IN GROUNDWATER

6.11. A discharge of radioactive material from a nuclear installation might contaminate the groundwater system in the region either directly or indirectly, via soil, the atmosphere or surface water, in the following ways:

- (a) Indirect discharge to the groundwater through seepage and infiltration of surface water that has been contaminated by radioactive material discharged from the nuclear installation;
- (b) Infiltration into the groundwater of radioactive liquids from a storage tank or reservoir;
- (c) Infiltration into the groundwater of any airborne radioactive material deposited on the ground surface or on surface water;
- (d) Direct release from a nuclear installation as a result of an accident.

The potential for indirect contamination in surface water and possible contamination of groundwater from the surface should be assessed.

6.12. The protection of aquifers from accidents should be considered in the safety analysis for postulated accident conditions, and a geological barrier to provide protection should be considered.

SELECTION OF SOURCE PARAMETERS FOR ANALYSIS OF THE TRANSPORT OF RADIONUCLIDES IN GROUNDWATER

6.13. The following properties and parameters should be estimated for radioactive discharges:

- (a) Radioactivity:
 - (i) Rate of discharge of each important nuclide;
 - (ii) Total activity discharged in a specific period and its fixation capacity on soils.
- (b) Chemical properties, including the following:
 - (i) Important anion and cation concentrations, and their oxidation states and complexing states (e.g. Ca^{2+} , K^+ , Mg^{2+} , Na^+ , NH_4^+ , HCO_3^- , Cl^- , SO_4^{2-} , NO_2^- , NO_3^- , PO_4^{3-});
 - (ii) Organic content;
 - (iii) pH;

- (iv) Concentration of dissolved oxygen, and electrical conductivity and concentrations of associated pollutants.
- (c) Physical properties of the liquid effluents discharged, including:
 - (i) Temperature;
 - (ii) Density;
 - (iii) Loads and granulometry of suspended solids.
- (d) Flow rates for continuous discharges, or volume and frequency for batch discharges.
- (e) Variation of the source term over the duration of the discharge.
- (f) Geometry and mechanics of discharges.
- (g) Sorption characteristics of the specific radionuclide onto sediments.
- (h) Distribution coefficient(s) between the liquid phase and solid phase.

CONSTRUCTION OF A REPRESENTATIVE CONCEPTUAL MODEL

6.14. A variety of models and data are necessary to predict the dispersion and transfer of radionuclides through environmental media to the representative person. The processes that are more relevant to dose estimation should be identified and a conceptual model should be elaborated in the form of a representation that captures the key elements or components of a complex system, such as the relationship between the released radionuclides and the environment. The conceptual model should represent the identified relevant dispersion pathways and transfer pathways (see para. 2.8).

6.15. A conceptual model, as a working description of the characteristics and dynamics of the hydrogeological system is essential for any analysis of the flow and transport of radionuclides. It should be regarded as the fundamental step of hydrogeological assessment for a nuclear installation site.

6.16. Conceptualization and characterization of the hydrogeological system is the essential and most important part of the predictive flow and transport modelling. By nature, conceptual models are a simplification of the real system. However, the degree of simplification should be decided according to the type of nuclear installation and the stage of reporting (See Section 10 for more details on graded approach).

6.17. Inadequate conceptualization is one of the main sources of uncertainty and unreliability in the analysis of the transport of radionuclides. A lack of well represented spatial variations of hydrogeological parameters might also adversely affect the results. It should also be considered that simple hydrogeological models might not produce a conservative assessment of the system behaviour.

6.18. It is possible to construct a preliminary hydrogeological conceptual model for a nuclear installation site on the basis of geological and hydrological information available for the site itself and/or its near vicinity. Properties of similar geological materials elsewhere and generic data from similar geographical and geological regions can also be used in preliminary conceptualization. However, each site is unique in its hydrogeological features, properties and behaviour, so it is not possible to represent the hydrogeological setting fully by a generic conceptual model. Therefore, a site specific conceptualization and characterization should be the ultimate objective of the hydrogeological data acquisition.

6.19. To decide on the extent of the study area, first the hydrogeological domain to which the nuclear installation site belongs should be defined. A model area should then be determined for hydrogeological conceptualization and characterization. The conceptual model should extend to natural boundaries (e.g. topography such as topographical divide, geological structure or

lithological contact, or surface water features like streams, rivers or lakes). The model should also consider the extent of the potential impact of stress generated at the site. To reduce the impact of boundary conditions on the model, the extent of the hydrogeological domain to study should be larger than the model domain.

6.20. Alternative conceptual models can be constructed based on the available data, and any reasonable alternative conceptualizations should be evaluated. Further studies should be performed in order to reduce model bias and uncertainty and thus ensure the most appropriate and/or representative conceptual model.

6.21. An iterative approach should be used in the process of construction of a hydrogeological conceptual model. The preliminary conceptual model should be tested by an appropriate mathematical model (defined in paras 6.26–6.34) using the monitored data and refined until minor improvements in the predictive capability of the model are achieved.

DEFINITION AND COLLECTION OF DATA FOR MODELLING RADIONUCLIDE TRANSPORT IN GROUNDWATER

6.22. Hydrogeological investigation in the framework of site evaluation for a nuclear installation involves regional and local investigations using comparatively standard hydrogeological mapping, surface geophysical surveys and borehole drilling programmes for hydrogeological characterization studies such as packer tests, single well tests, pumping tests and geophysical and tracer studies.

6.23. Both local and regional information should be collected to identify the hydrogeological system and the preferential flow paths. The information to be collected should include the following:

- (a) Meteorological data: In regions where precipitation (e.g. rain, snow) makes a substantial contribution to groundwater, long term meteorological data on annual, monthly and, if available, daily precipitation and on corresponding air temperature (to calculate potential evapotranspiration) should be analysed for as long a period as the data are available. The average precipitation should be calculated using appropriate interpolation techniques from precipitation data recorded at meteorological stations in and around the watershed where the installation is situated. The effect of topography may need to be considered where there is a large difference in elevation. Meteorological data analyses should also be performed for the groundwater recharge at an acceptable level of certainty. Alternatively, tracers (chemical or isotopic) of the water cycle as well as satellite technologies could be introduced to calculate groundwater recharge.
- (b) Surface runoff: Another component of the water balance should be either estimated or measured at the outlet of the basin. Long term records of flow of the stream draining the basin may be used to assess the surface runoff. If there is no flow record, empirical relationships or satellite technologies may be used to estimate the surface runoff. The construction of weirs or flumes to measure the flow rate for at least one water year should be considered. This would help with making adjustments of the empirical assessment of the runoff coefficient and the surface runoff. The baseflow component of the measured streamflow may need to be considered and calculated.
- (c) Discharge data of significant springs: Springs with significant discharge should be identified, defined in terms of type, and their discharge measured on at least a monthly basis for a minimum of one water year.
- (d) Surface drainage system or standing water body: Any surface drainage system or standing water body accessible from a potential release point in an accident should be identified.

Areas from which contaminated surface water can directly enter an aquifer (e.g. sinkholes) should be determined. The relevant hydrogeological information for surface or near surface discharges includes information on soil moisture properties, infiltration rates, configuration of unsaturated zones and chemical retention properties under unsaturated conditions. In addition, records of level fluctuation of standing water bodies such as lakes and wetlands are also needed for a complete water balance calculation. Bathymetry should also be mapped for establishing the elevation–area–volume relationship.

- (e) Description and mapping of major hydrogeological units: Data should be obtained on the various types of geological formation in the region and their stratigraphic distribution in order to characterize the regional system. The hydrostratigraphic units should be described on the basis of hydrogeological properties of the lithological units in the region. For consideration of the transport potential of seepage and groundwater in the region of the site data on types of aquifers, aquitards and aquicludes, their interconnections and the flow velocities and mean transit times should be investigated. The extent and thickness of major hydrostratigraphic units, in particular of the aquifer units, should be mapped and depicted on cross-sections. Three dimensional visualization should be provided. Karstic features such as sinkholes, dolines, poljes and alike closed depressions, caves and underground rivers should be mapped.
- (f) Hydraulic head distribution: Potentiometric maps should be prepared for each aquifer (if the flow domain is a multi-aquifer system), for at least one dry and one wet period. The potentiometric map should be produced from the groundwater levels measured in a sufficient number of uniformly distributed piezometers. Heterogeneity should be considered in deciding on the number and locations of the piezometers. Such data permit the regional flow pattern and its relation to the local flow pattern of seepage and groundwater to be characterized. Dye tracing tests should be designed and conducted in karstic aquifers to delineate the groundwater catchment area, and assess the direction and velocity of groundwater flow.
- (g) Description of natural recharge and discharge areas: Potentiometric maps can also be used to delineate recharge and discharge areas, and to define hydraulic boundaries and boundary conditions of the flow domain. Environmental isotopes (stable and radioactive) should be considered as a useful tool in assessment of recharge–discharge relationships. Stable isotope characteristics of local and regional precipitation should be obtained to establish the relationship between elevation and ^{18}O . This relationship can be obtained by analysing seasonal springs issuing at different altitudes.
- (h) Ages, transit time or mean turnover times of groundwater: Artificial or environmental tracers such as tritium, the helium:tritium ratio (where tritium is close to the natural background), or other appropriate tracers should be used to obtain the average apparent age, transit time and turnover time of groundwater. In complex systems, a vertical profile of groundwater age should be determined. Environmental isotopes and hydraulic heads should be used to investigate interconnections between aquifers, and interactions between groundwater and surface waters.
- (i) Hydrochemical data: Water samples from groundwater (e.g. springs, wells) and surface water bodies should be collected properly and analysed for major ion content at least on a seasonal basis. In situ measurements of temperature, electrical conductivity, pH, redox potential and dissolved oxygen should accompany the sampling.
- (j) Hydraulic characteristics and transport parameters: A sufficient number of laboratory and/or field tests should be performed to obtain representative values of the hydraulic characteristics of each aquifer material, such as porosity, hydraulic conductivity, transmissivity, storativity (storage coefficient), specific yield, bulk density of aquifer

material and dispersivity (hydrodynamic dispersion coefficient). Batch, column experiments and/or in situ tracer tests should be performed to determine the sorption characteristics (distribution coefficients) for radionuclides of interest.

MODELS FOR RADIONUCLIDE TRANSPORT IN GROUNDWATER

6.24. Interpretive (also known as informative) and predictive models can be used to model radionuclide transport in groundwater. Interpretive models are used to obtain a thorough understanding of the hydrogeological system dynamics. They help to construct and to test the hydrogeological conceptual model of the site. This type of model does not necessarily need to be calibrated. Predictive models, on the other hand, need to be calibrated.

6.25. Activity concentrations in the subsurface environment resulting from the postulated discharge of radioactive material should be estimated by means of mathematical models. A number of models have been developed to calculate the dispersion and retention of radionuclides released into groundwater. Standard calculational models are generally satisfactory and should be used in most cases. The complexity of the model chosen should reflect the complexity of the hydrogeological system at a particular site. The objective of modelling should also be taken into consideration during selection of the model. See Section 10 for further recommendations on selection of the appropriate level of complexity of the model to be used.

6.26. Two possible approaches can be taken to the use of models and data for the assessment of radionuclide transport in groundwater. A generic and simple methodology can be followed, which takes account of dilution, dispersion and the transfer of radioactive material into the environment with conservative assumptions. Alternatively, a specific, more detailed methodology can be followed, using site specific data to estimate activity concentrations in different environmental media, with more realistic assumptions. In some situations, a combination of generic models with site specific data could also be suitable for the assessment. In all cases, the models selected should be suitable for estimating the spatial distribution and temporal variation of activity concentrations in the environment. The complexity of the model used should be commensurate with the likely level of environmental impact from the installation.

6.27. Models that can be used for nuclear installations are diverse and can be categorized according to the problem being addressed. Deterministic models and stochastic models are the main two categories commonly used by States. The most appropriate approach should be chosen on the basis of the hydrogeological setting (conceptualization and characterization), and the level of accuracy sought at the reporting stage of interest.

6.28. Stochastic models are usually used to consider strong heterogeneity and occurrence of preferential flow paths. Geostatistical methods are useful in producing the spatial variability of parameters that is needed in a stochastic approach. Monte Carlo simulation is the most commonly applied stochastic approach to predict groundwater flow and transport on the basis of geostatistical inputs. This approach can also be used to reduce and quantify the predicted uncertainty.

6.29. Deterministic models can be subcategorized as (a) lumped (or black box, grey box) models and (b) distributed parameter (process-based) models. Mathematical (partial differential) equations simulating groundwater flow and solute (radionuclide) transport are the most used distributed parameter models. These equations are solved either analytically (exact solutions) or numerically (approximate solutions, commonly known as mathematical models).

6.30. Analytical models are solutions that satisfy certain geometry and specific boundary conditions of the flow domain, and generally they do not consider heterogeneity and anisotropy. Significant uncertainties may be associated when the assumptions are not totally satisfied at the site under study. When the hydrogeological conceptual model partly meets the boundary conditions and the assumptions of the selected analytical model, they can be used as a first approximation and the result should be evaluated with caution.

6.31. Numerical flow and transport models can be applied with different levels of simplification. Flow and solute transport phenomena in the subsurface environment might involve various processes. In particular, the transport models are commonly known by the process(es) involved, such as advective, dispersive, sorptive, reactive and radioactive, or a combination of some or all of these processes. The following assumptions determine the level of simplification or complication of the hydrogeological model:

- (a) Ignoring the role of the vadose zone;
- (b) Considering a conservative contaminant;
- (c) Assuming a homogenous and isotropic flow domain.

6.32. Modelling should start with the simplest model — advective — which assumes that the transport is governed only by the mean velocity of groundwater flow. Therefore, it does not need descriptions of transport parameters and variables.

6.33. In order to use more complicated models (e.g. a combination of all processes), more hydraulic and transport parameters need to be determined, such as dispersivity, distribution coefficients, kinetic reaction rates and half-lives. See Section 10 and the Annex for recommendations on the application of a graded approach for different reporting stages.

IDENTIFICATION OF EXPOSURE PATHWAYS IN GROUNDWATER

6.34. Possible exposure pathways for releases of radionuclides to groundwater during normal operation of nuclear installations such as nuclear power plants are as follows:

- (a) Boreholes, wells and galleries used to abstract water for drinking;
- (b) Springs captured for drinking water;
- (c) Ground water used for agriculture;
- (d) Discharge (or emergence) as base flow to streams, rivers, lakes or wetlands (ingestion of drinking water and/or aquatic food such as fish, crustaceans and molluscs);
- (e) Discharge to sea (ingestion of aquatic food, external exposure through activities such as swimming and fishing).

CALIBRATION OF MODEL AND SENSITIVITY STUDY OF THE ANALYSIS OF RADIONUCLIDE TRANSPORT IN GROUNDWATER

6.35. Models always have some limitations because they are simplifications of the complex real world and do not provide a unique representation of reality. However, properly constructed models can provide reliable results within the uncertainty limits. Therefore, the level of uncertainty should be evaluated and reported.

6.36. The calibration of a model provides the means to test and/or compare the selected conceptual models. Calibration involves observation of the actual site conditions and thus monitoring of data sets. To ensure that the model simulates the real system with an acceptable

degree of error and uncertainty, the calibration should be done for steady-state and transient conditions.

6.37. Consideration should be given to uncertainties that might arise from (a) deficiencies in understanding and conceptualization of the hydrogeological system, (b) spatial and temporal variations in variables and parameters, and (c) definition of the boundary conditions of the flow domain.

6.38. A sensitivity study should be conducted to identify the parameters and locations to which the system behaviour is sensitive. Performing additional site characterization to better estimate parameters at these locations reduces model uncertainty. Further monitoring should be performed where the system is most sensitive to model parameters.

SCENARIO BASED SIMULATION OF RADIONUCLIDE TRANSPORT IN GROUNDWATER

6.39. To achieve the objectives described in paras 6.1–6.4, a predictive model should be run to simulate different scenarios. A properly constructed and calibrated model provides a tool to forecast the response of the groundwater system to future conditions.

6.40. Two sources of uncertainty should be considered in scenario-based simulations. The model itself is one source of uncertainty, (see para. 6.36) and the other is associated with the scenario. The accuracy of specification of the future conditions should be considered as a significant source of uncertainty in the forecast.

6.41. Primarily, simulation under normal conditions (discharge) should be run for different scenarios. Scenarios should be based on the expected future changes in natural conditions, and on the design of the installation. Changes in the meteorological and hydrological conditions during the lifetime of the installation and the release of radionuclides during normal operation should be simulated for a period of time covering at least the lifetime of the installation. Changes in meteorological parameters such as precipitation, temperature (evaporation and evapotranspiration) and land use, which affect surface runoff and evapotranspiration should be taken into account. The exposure pathways defined in para. 6.35 should also be considered.

6.42. Similarly, different scenarios defining possible types and locations of an accidental release of radionuclides should also be simulated to forecast the pathways, distribution of concentration, activity and velocity of the radionuclides in the groundwater system. Interactions with surface water bodies should be considered, where applicable.

GRADED APPROACH TO ASSESSING THE TRANSPORT OF RADIONUCLIDES IN THE GROUNDWATER

6.43. Detailed guidelines for determining the most appropriate level of complexity for modelling radionuclide transport in groundwater are provided in Appendix 1.

7. ASSESSMENT OF THE OVERALL RADIOLOGICAL IMPACT OF A NUCLEAR INSTALLATION

SUMMARY OF THE NUCLEAR INSTALLATION SITE CHARACTERISTICS USED FOR RADIOLOGICAL IMPACT ASSESSMENT

7.1. Recommendations on the characteristics of a nuclear installation site that form the basis for radiological impact assessment are provided in Sections 3–6. These characteristics primarily relate to meteorological and hydrological conditions, topography, population distribution and habits, land and water use, natural background radioactivity, and food production and consumption in the vicinity of the site. These site characteristics and where they are used in the radiological impact assessments for a nuclear installation are shown in Table 3 and Fig. 1.

7.2. In addition to the characteristics summarized in Table 3 and Fig. 1, there are other site characteristics considered in site evaluation for a nuclear installation. They relate to natural hazards and include seismicity, slope instability, subsidence, soil liquefaction, volcanism, flooding, and extreme meteorological events (e.g. high winds, tornados, storms, precipitation), as well as to human-induced events such as potential incidents in other nuclear or non-nuclear facilities and in land, water and air transportation corridors in the vicinity of the site. These characteristics are covered in more detail in SSG-18 [15], and IAEA Safety Standards Series Nos SSG-9 (Rev.1), Seismic Hazards in Site Evaluation for Nuclear Installations [18], SSG-21, Volcanic Hazards in Site Evaluation for Nuclear Installations [19], NS-G-3.6, Geotechnical Aspects of Site Evaluation and Foundations for Nuclear Power Plants [20] and SSG-79, Hazards Associated with Human Induced External Events in Site Evaluation for Nuclear Installations [21]. These other characteristics are also considered in the analyses for determining the types of safety features that are incorporated into the design of a nuclear installation, and the frequency of potential accident scenarios during the operation of the installation. Therefore, these design characteristics also affect the radiological impacts of nuclear installations either by altering the source terms (the quantities, physical and chemical form, and timing of radionuclides released to the environment during an accident) or by changing the frequency of potential accident scenarios. Source terms have a strong influence on the doses from individual accident scenarios and the frequency of accidents has a direct effect on the total radiological risk from a nuclear installation (see paras 7.26–7.29).

COMPILATION OF RADIOLOGICAL IMPACT ASSESSMENT RESULTS

7.3. The endpoints for analysis of the atmospheric dispersion and transport in groundwater and/or surface water should be activity concentrations in the environmental media that could lead to radiological exposure of people.

7.4. The inhalation dose for an individual at a particular location should be determined by combining the following:

- (a) The time integrated air concentrations for each radionuclide at that location derived from the atmospheric dispersion modelling;
- (b) The breathing rate of an individual at that location; this could be taken from standard data for a given age group (e.g. Ref. [22]), or determined from habit surveys that record the

- typical daily hours performing various activities (e.g. a farmer working outdoors probably has a higher than average breathing rate for the time of exposure);
- (c) Any location factors applied (e.g. being indoors effectively reduces the activity inhaled);
- (d) Age-dependent inhalation dose coefficients for each radionuclide and its chemical and physical form (see e.g. Ref. [23]).

TABLE 3. OVERVIEW OF SITE CHARACTERISTICS AND THEIR USE IN RADIOLOGICAL IMPACT ASSESSMENTS FOR NUCLEAR INSTALLATIONS.

Site characteristic	Use in radiological impact assessment			
	Atmospheric dispersion	Surface water transport	Groundwater transport	To estimate public dose
Meteorology <ul style="list-style-type: none"> • Wind speed and direction, temperature, humidity and atmospheric stability • Precipitation 	x		x	
Surface water hydrology <ul style="list-style-type: none"> • Physical characteristics • Flow and interconnections • Sedimentation • Interaction with groundwater 		x		
Groundwater hydrology <ul style="list-style-type: none"> • Site hydrogeology (description and mapping of major hydrogeological units) • Groundwater flow, including recharge and discharge • Hydraulic head distribution and hydraulic characteristics (e.g. porosity, conductivity, transmissivity, dispersivity) of aquifers 		x	x	
Surface features, topography	x	x	x	
Population distribution and habits				x
Land use		x	x	x
Water use		x	x	x
Food production and consumption				x

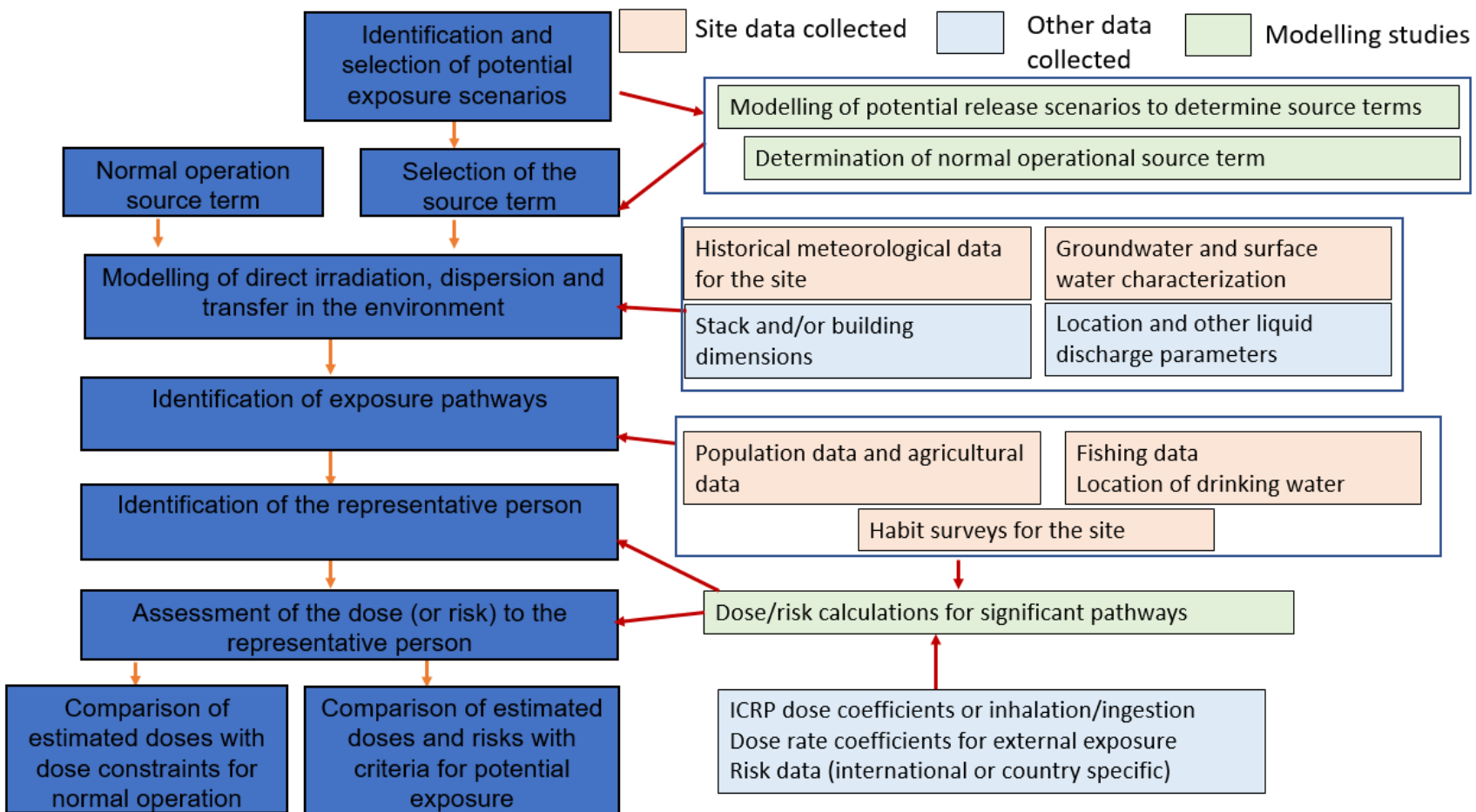


FIG. 1. Data used and modelling performed at the various stages of radiological environmental impact assessment for normal operation and accident conditions.

7.5. The ingestion dose of an individual consumer of a particular food type should be determined by combining the following:

- (a) The activity of each nuclide in that food type (as a function of time if long term exposure is being evaluated) determined by the dispersion and transport modelling and food chain models;
- (b) The ingestion rate for an individual food consumer, usually determined from the habit surveys;
- (c) Age-dependent ingestion dose coefficients for each radionuclide (see e.g. Ref. [23]).

7.6. External exposure should be calculated using the following:

- (a) The activity concentrations in air, on the ground or in water (as a function of time if long term exposure is being evaluated);
- (b) The time an individual is exposed, which is determined from the habit data;
- (c) The geometry of the exposure and distance from any sources of radioactivity (e.g. deposited activity on the ground or a plume in the air);
- (d) Any location factors for shielding applied (e.g. being indoors);
- (e) The dose rate coefficients for each nuclide (see e.g. Ref. [24] which provides values for typical environmental geometries and shielding situations).

7.7. The total dose for any given individual is the sum of all contributions listed in paras 7.3–7.6. If the collective dose is needed, then the dose calculations should be integrated over the necessary geographical scope and temporal scope using the population and habit data.

7.8. To meet any regulatory criteria for individual dose or risk, a representative person should be identified (see paras 7.14–7.19).

7.9. For normal operation of a nuclear installation, the regulatory criterion for a single source or site is usually a dose constraint that is a fraction of the 1 mSv limit for public exposure (see para. III.3. of GSR Part 3 [4]).

7.10. The radiological impact assessment should consider the whole lifetime of the nuclear installation so that the effects of accumulation of longer lived radionuclides in the environment can be assessed.

7.11. The individual doses for the all the accident conditions considered should be considered for comparison with dose constraints and dose limits (see Fig. 2 of GSG-10 [8]). The possible different release routes (i.e. atmosphere, surface water or groundwater) and different pathways for the same release route might result in many different groups of people being exposed to differing extents.

7.12. For accidental releases from nuclear power plants or other types of nuclear installation, for public exposure, it may be sufficient to only consider atmospheric releases since this is likely to be the mode of release for most accident situations unless there are accident scenarios involving a direct release to surface water or groundwater. Compared with an atmospheric release, the impact from a release to surface water or groundwater is less immediate: dilution in large bodies of water can occur, and the water provides some shielding (see Section 2) reducing the exposure of any people in the vicinity. Where there is any uncertainty regarding the proportion of a release to the atmosphere and to water bodies, the conservative assumption would usually be that the entire release is to the atmosphere.

7.13. If multiple release paths for a single accident scenario are considered (which might be necessary if the same groups of people could be significantly affected as a result of each release

path) then the results from each separate modelling study should be combined to determine the dose to the representative person.

IDENTIFICATION OF THE REPRESENTATIVE PERSON AND REFERENCE ANIMALS AND PLANTS

7.14. Reference [14] provides guidance on selecting representative persons and determining their habits (e.g. location, time spent outdoors, breathing rate, food consumption rate) so that their overall radiological exposure can be determined. The selection should be reasonable, sustainable and homogeneous or in other words: not overly conservative by combining a set of extreme habits, not describing one-off events but situations likely to continue over the lifetime of the nuclear installation and applying to more than a single individual.

7.15. The representative person may be different for normal operation and accident conditions at the same site or installation. Possible representative persons for an accidental release from a nuclear installation could be as follows:

- (a) An adult spending most of their time in a location leading to a higher likelihood of exposure, for example in the prevailing wind direction close to the site boundary or close to sediment in surface waters that have accumulated radioactivity;
- (b) An adult high-rate local food consumer living in the nearest population centre (e.g. a village);
- (c) A child or infant consuming supermarket food or non-locally produced food living in the nearest population centre;
- (d) An adult not resident in the nearest population centre, but who spends a significant fraction of the day working outdoors close to the release point (e.g. in an agricultural occupation on an adjacent site).

7.16. Several conservative assumptions should not be combined in selecting the representative person. For example, an infant living in the most exposed location and consuming only local food should not be selected.

7.17. To assess the total risk from a nuclear installation, the risks to the representative person and/or the societal consequences from each accident scenario, and the respective scenario frequency, should be considered.

7.18. For an atmospheric release, the radiological consequences are strongly dependent on the meteorological conditions at the time of the release; for example, the number of people exposed and the level of exposure for individuals are very different for a coastal site if the wind is blowing out to sea or blowing inland at the time of the release. Level 3 probabilistic safety assessment takes into account the consequences of each accident scenario under a range of meteorological conditions combined with the likelihood of these conditions occurring, among other factors. If applying a graded approach to lower risk installations, then it may be acceptable to use a single set of bounding meteorological conditions.

7.19. Level 3 probabilistic safety assessment usually samples from an hourly data set of recent historic data measured or calculated for the site as described in Section 4. Since the accident scenario considered in the assessment might extend over many hours or days, the meteorological data for each hour of the release or for discrete phases should be used; this is termed a meteorological sequence. Sufficient meteorological sequences should be sampled to represent the

range of meteorological conditions that a given site might experience. For random meteorological sampling, the relative likelihoods of each sequence are unity; if other sampling schemes are used to get more examples of particular types of weather (e.g. heavy rainfall) then the relative likelihoods should be adjusted accordingly. This procedure should be repeated for every accident scenario considered, and the conditional risks for each scenario multiplied by their respective frequencies (derived from the Level 1 and/or Level 2 probabilistic safety assessment) to give the risk for each scenario. An analogous procedure could be followed for aquatic releases, if deemed necessary.

7.20. There are software codes available for performing Level 3 probabilistic safety assessment calculations, which combine the atmospheric dispersion modelling and dose and risk calculations using the meteorological data, demographic data, and food production data for the nuclear installation site and surrounding area. If using such codes or specific models developed for different environments, care should be taken to ensure they are applicable to the environment being assessed. For example, such codes might use food chain models developed for agricultural practices in temperate climates which might not be suitable for use in tropical climates.

7.21. Exposure of animals and plants is considered only for normal operation. Care should be taken to protect the more highly exposed population groups of a species rather than individual members of species within those groups.

7.22. Animals and plants might occupy different habitats to those occupied by humans and might be exposed to radioactivity that accumulates over time in those habitats. A region around the discharge locations from the nuclear installation (e.g. with an area of around 100–400 km²) should be considered, in which to identify population groups of animal and plant species that might be exposed. A set of representative animals and plants is defined in Ref. [25]. A generic methodology for assessing exposures of flora and fauna is provided in Annex I of GSG-10 [8].

CALCULATION OF DOSE AND/OR RISK TO THE REPRESENTATIVE PERSON AND DOSE RATES TO REFERENCE ANIMALS AND PLANTS

7.23. The radiological impact to the public from normal operation should be assessed on the basis of the individual effective dose to the representative person. Whether a quantitative assessment of the radiological impact on fauna and flora from normal operation is also required is a matter for individual Member States. With regard to this, para. 1.33 of GSR Part 3 [4] states:

“Trends also indicate the need to be able to demonstrate (rather than to assume) that the environment is being protected against effects of industrial pollutants, including radionuclides, in a wider range of environmental situations, irrespective of any human connection. This is usually accomplished by means of a prospective environmental assessment to identify impacts on the environment, to define the appropriate criteria for protection of the environment, to assess the impacts and to compare the expected results of the available options for protection. Methods and criteria for such assessments are being developed and will continue to evolve.”

7.24. The components of the radiological impact on the public from accidental releases is shown in Fig. 3 of GSG-10 [7].

DETERMINATION OF THE ACCEPTABILITY OF RADIOLOGICAL IMPACTS

7.25. For normal operation, recommendations on setting dose limits and constraints are provided in GSG-9 [11].

7.26. For potential exposures, para. 3.15(e) of GSR Part 3 [4] requires that their likelihood and magnitude of such exposures and the number of individuals who may be affected be considered, while para. 3.120 of GSR Part 3 [4] requires that constraints on dose and constraints on risk be established but does not specify any criteria. It is the responsibility of the government or the national regulatory body to specify these constraints. International guidance on determining the acceptability of impacts is provided in Refs [9, 26].

7.27. Impacts on neighbouring States from both normal operation and accident conditions should be considered. Paragraph 3.124 of GSR Part 3 [4] states:

“When a source within a practice could cause public exposure outside the territory or other area under the jurisdiction or control of the State in which the source is located, the government or the regulatory body:

(a) Shall ensure that the assessment for radiological impacts includes those impacts outside the territory or other area under the jurisdiction or control of the State;

.....

“(c) Shall arrange with the affected State the means for the exchange of information and consultations, as appropriate.”

7.28. For nuclear power plants, since it is difficult to exclude the possibility of any public exposure in neighbouring States, a transboundary assessment should be performed. However, for low hazard installations, such a transboundary assessment might not be necessary.

7.29. When considering transboundary impacts, the criteria used for the assessment of the level of protection for normal operation or for the consideration of potential exposures in other States should be in line with the criteria set out in GSG-10 [8] and should be the same as those used for the State in which the installation is located.

7.30. For impacts on animals and plants, Ref. [25] defines criteria for assessing and managing the radiological impact in the form of ‘derived consideration reference levels’.

7.31. As part of the application for a licence for a new nuclear installation project, the applicant prepares, and the regulatory body reviews, an environmental management plan. The purpose of the environmental management plan is to ensure that potential project interactions with the environment are considered during site preparation, construction, operation, and decommissioning phases of the nuclear installation, to minimize or prevent potential negative impacts, and to enhance the positive impacts. The environmental management plan is a comprehensive document that identifies, among others, the actions to be taken (including any mitigation measures that are included in the environmental impact assessment report and licensing conditions imposed by the regulator), responsibilities, reporting, and processes for implementing corrective actions if needed. Some States may not require such a combined document but instead may require individual plans for specific issues. The environmental monitoring programme, which is discussed in Section 8 of this guide, should be a part of the environmental management plan.

8. MONITORING OF RADIOACTIVITY IN THE ENVIRONMENT AROUND A NUCLEAR INSTALLATION

8.1. Requirement 28 of SSR-1 [1] states:

“All natural and human induced external hazards and site conditions that are relevant to the licensing and safe operation of the nuclear installation shall be monitored over the lifetime of the nuclear installation.”

ENVIRONMENTAL MONITORING PROGRAMME DURING THE SITE CHARACTERIZATION AND PRE-OPERATIONAL STAGES OF A NUCLEAR INSTALLATION

8.2. Recommendations on the measurement of the background radioactivity as part of the establishment of baseline environmental conditions at the site and in the vicinity of the site for a nuclear installation are provided in Section 3. Sampling programmes should be developed for measuring background radiation and other parameters used to estimate radiation doses due to direct radiation from radioactive material inside the installation and from radioactive material released from the installation to the air, surface water, groundwater, and the ground surface during the site characterization and pre-operational stages. These sampling programmes can serve as the basis for the monitoring programmes that will be established during the operation of the proposed nuclear installation. The locations and the media chosen for measuring the radioactivity and other parameters should be those that are likely to be relevant to the exposure of representative persons when the nuclear installation starts to operate.

8.3. The environmental monitoring programme should commence well before the start of construction of the installation and sufficiently before operation to be able to identify any trends in the background levels of radioactivity. For example, if the levels of a particular nuclide are falling prior to the start of operation, then they would be expected to continue to fall in the absence of any new releases from the installation.

8.4. The environmental monitoring programme should continue for the lifetime of the installation.

Monitoring of radioactivity in the atmosphere

8.5. Monitoring stations should be set up at several key locations on the site, on the site perimeter, and away from the site to measure external radiation and the radioactivity in materials suspended in the air. These stations should initially be used to establish the background radiation and meteorological conditions in the area. Their operation should continue after the installation starts operating, to determine changes in radioactivity in the air due to the operation of the installation and to record any changes in the meteorological conditions at the site and in its vicinity.

Monitoring of radioactivity in the surface water and groundwater

8.6. A monitoring programme should be established for both surface water and groundwater. The purposes of such a programme during the site characterization and pre-operational stages are to establish the baseline conditions and to determine whether there are any trends that result in changing the characteristics of the region before the commencement of operation of the nuclear installation. Recommendations on the selection of sampling locations for monitoring of surface water and groundwater are provided in IAEA Safety Standards No. RS-G-1.8, Environmental and Source Monitoring for Purposes of Radiation Protection [27].

8.7. All surface water and groundwater in the region of the site should be sampled regularly. For surface water bodies, sediments should be sampled as well as the water itself.

8.8. Groundwater should be monitored by means of samples taken from boreholes and wells. The samples can also be taken from groundwater reaching the surface in springs or in natural depressions. Boreholes and wells should be kept in an operable state for the same period of time.

8.9. The monitoring programme for groundwater should be initiated at least two years before the start of construction of the installation. The site area should be monitored before the foundation work is begun in order to verify possible changes in the groundwater regime, and monitoring should continue after construction has finished.

Monitoring of radioactivity in the soils and biota

8.10. As recommended in Section 3, soil samples should be taken and analysed to determine the baseline radionuclide concentrations in the soils before the start of operation of the nuclear installation. The sampling locations should include areas on site, in particular those that will not be covered by buildings or paved over by roads and parking lots; as well as areas off site that are residential, industrial, commercial, agricultural, recreational, and for wildlife.

8.11. Samples should also be taken and analysed to determine the baseline concentrations of radionuclides in biota in the vicinity of the nuclear installation. Biota samples should include the following:

- (a) Foodstuffs grown (e.g. vegetables, fruits, grains) and animals reared in the region for human consumption;
- (b) Biota consumed by domesticated and wild animals (e.g. grass, leaves on bushes, shrubs, low tree branches);
- (c) Wild animals in the region (e.g. birds, rabbits).

Guidelines on soil and vegetation sampling for radiological monitoring are given in Ref. [28].

Monitoring of population data and other parameters

8.12. The monitoring programmes started during the pre-operational stages of a nuclear installation and continued during operation should focus on those radionuclides that are important contributors to the total dose of the representative person. In addition, those parameters that are identified as important to this dose calculation through modelling studies and sensitivity analyses should be sampled more frequently and in more locations. The distance of the sampling locations from the nuclear installation should be determined by the results of the pathway analyses. If the results indicate that an individual could receive a substantial dose through a pathway at some

distance, the environmental samples should be extended to that distance. These distances are different for different types of nuclear installation depending on the source terms and site environmental factors. The control locations (see para. 3.26) that are outside the region of influence of the nuclear should continue to be sampled regardless of their distance from the installation.

8.13. As recommended in para. 5.14 of RS-G-1.8 [27], arrangements for emergency preparedness should be considered carefully for any conceivable emergency when implementing the monitoring programmes during the pre-operational stage. The basic intervention levels should be understood by all responsible persons and organizations, and operational intervention levels should be established on a site specific basis. The operational intervention levels should refer to parameters that can be easily measured (e.g. dose rate in air, deposition density of radionuclides) so that an interpretation can be made rapidly if intervention is needed.

MONITORING PROGRAMME DURING THE OPERATION OF A NUCLEAR INSTALLATION

8.14. Requirements for monitoring during operation of a facility are established in Requirements 14, 20 and 32 of GSR Part 3 [4]. RS-G-1.8 [27] provides supporting recommendations, and Ref. [29] provide detailed descriptions of the monitoring programmes employed during the operation of a nuclear installation, including information about the objectives, conduct and use of monitoring both during normal operation and in accident conditions.

8.15. During the operation of a nuclear installation, monitoring programmes should be used to verify compliance with dose constraints and to confirm that levels of radionuclides in the environment are consistent with the discharges reported by the operating organization, to check the predictions of environmental models, and to provide a warning of unusual or unforeseen conditions. In an emergency, additional monitoring activities should be established.

Environmental monitoring during normal operation

8.16. The environmental monitoring programme established during the site characterization and pre-operational stages of a nuclear installation should be continued during the operation of the installation. Samples from the environmental media should be taken and analysed on a schedule that depends on the half-lives of the radionuclides that could potentially be discharged from the installation. However, the frequency and the number of samples taken during the early stages of operation of the installation should be relatively high to confirm the predictions made by modelling conducted during the site characterization and pre-operational stages. As experience is gained, the scale of routine monitoring could be reduced and the locations amended to reflect actual discharge patterns identified during monitoring activities.

8.17. Environmental monitoring in the context of this Safety Guide refers to the measurement of external dose rates in the environment and radionuclide activity concentrations in air, water, soil, bottom sediments, vegetation, the bodies of animals and foodstuffs. A key feature in designing environmental monitoring programmes for major sources is the identification of potentially critical radionuclides, pathways and groups. On the basis of the identification and assessment of these, it is possible to select those radionuclides and pathways that make the biggest contribution to individual doses so that the monitoring programmes can be directed to the more important subjects.

Environmental monitoring in an emergency

8.18. Environmental monitoring takes on special significance during an emergency because it often provides important information about the severity of impacts from the accident. GSR Part 7 [5] requires prompt monitoring and assessment of areas that could be or are known to have been contaminated during a nuclear or radiological emergency.

8.19. In emergency exposure situations, the nature of key data and requirements for the emergency monitoring programme evolve with time from the initiation of the accident, during the pre-release and release phase, the post release or intermediate phase and the recovery or remediation phase. The specific objectives of emergency radiation monitoring in the environment are as follows:

- (a) To provide accurate and timely data on the hazards resulting from a nuclear or radiological emergency;
- (b) To assist decision makers on the need to make interventions and take protective actions;
- (c) To provide information for the protection of emergency workers;
- (d) To provide information to the public on the degree of hazard;
- (e) To provide the information needed to support the medical response to the emergency, in accordance with Requirement 12 of GSR Part 7 [5].

Source monitoring

8.20. In addition to environmental monitoring, there are two other types of monitoring activities that take place during the operation of the installation: source monitoring and individual monitoring.

8.21. Source monitoring is the monitoring of a particular source of radiation or discharges of radionuclides to the environment arising from a nuclear installation. Source monitoring programmes are usually designed to measure dose rates at the source and/or the discharge rates of radionuclides, which may be in the form of gases, aerosols or liquids. The results from source monitoring can be used to verify compliance with the authorized limits on discharges and/or as a basis for estimating environmental radiation levels and activity concentrations in environmental media using predictive modelling. The results of source monitoring can also provide an early warning of any deviations from normal operation.

8.22. As recommended in RS-G-1.8 [27], there should be coordination between the source monitoring programme and the environmental monitoring programme. In the case of discharges, the activity concentrations detected in environmental monitoring are usually very low, and consequently in most cases the dose calculations are based on source monitoring data and appropriate modelling.

8.23. In an emergency, the primary purpose of source monitoring is to determine the magnitude of the releases that might occur, that are occurring or that have occurred. Such data, in combination with meteorological data and the results of predictive dose assessment models, is often the first information available to manage the protective actions taken in response to the emergency.

8.24. Further recommendations on source monitoring are provided in RS-G-1.8 [27].

Individual monitoring

8.25. Individual monitoring relates to measurements taken directly on people. It includes measurements of external doses with personal dosimeters carried by individuals and/or

measurements of the quantities of radioactive substances in the body or in excreta, and the interpretation of such measurements in terms of individual dose. Workers who are exposed to radiation at varying levels in different parts of the nuclear installation site are routinely monitored.⁷ Members of the public who visit the site may also be monitored. However, members of the public off the site are not normally monitored individually. Some emergency workers and some members of the public may be monitored in emergency situations, and RS-G-1.8 [27] indicates that during an emergency, individual monitoring should be conducted together with source and environmental monitoring to determine whether decontamination or medical follow-up of people in the emergency zones is warranted.

Other monitoring situations

8.26. Paragraph 3.137 of GSR Part 3 [4] states:

“Registrants and licensees shall, as appropriate:

(a) Establish and implement monitoring programmes to ensure that public exposure due to sources under their responsibility is adequately assessed and that the assessment is sufficient to verify and demonstrate compliance with the authorization. These programmes shall include monitoring of the following, as appropriate:

- (i) External exposure due to such sources;
- (ii) Discharges;
- (iii) Radioactivity in the environment;
- (iv) Other parameters important for the assessment of public exposure.”

For a nuclear installation, the ‘other parameters’ should include the following:

- (a) Population distribution (permanent and temporary) and characteristics (e.g. age, gender);
- (b) Population habits (e.g. food consumption rates, proportion of time people spend indoors and outdoors);
- (c) Agricultural activity in the region (e.g. types and quantities of food grown);
- (d) Types and numbers of animals raised for food in the region;
- (e) Wildlife in the region;
- (f) The proportion of locally grown food that is consumed in the region compared to that exported to outside the region.

8.27. If the operating organization of the nuclear installation included any mitigation measures in its assessment of the radiological impacts when applying for an authorization, or if the regulatory body granting the authorization imposed any conditions, the parameters needed to verify and document those measures or conditions should also be addressed in the monitoring programme.

8.28. Certain non-radiological impacts of a nuclear installation are usually included in the environmental impact assessment as part of the authorization process. These include the impact on people and the environment from releases of hazardous chemicals and heated water, the impact from the construction of the installation, the impact on places of societal significance (e.g. historical monuments, cultural places), the impact on endangered species, and the impact on the

⁷ Recommendations on the monitoring of workers and the workplace are provided in IAEA Safety Standards Series No. GSG-7, Occupational Radiation Protection [30] and further information is provided in Ref. [31]).

landscape, as well as other societal and economic factors. Such impacts should be considered by the regulatory body, taking into account regulatory requirements. It may be cost-effective and beneficial to coordinate any monitoring activities that are necessary as part of the non-radiological impact assessment with the activities undertaken in the radiological monitoring programme.

Monitoring following cessation of operations

8.29. Paragraph 9.3 of IAEA Safety Standards Series No. GSR Part 6, Decommissioning of Facilities [32] states:

“If the approved decommissioning end state is release from regulatory control with restrictions on the future use of the remaining structures, appropriate controls and programmes for monitoring and surveillance shall be established and maintained for the optimization of protection and safety, and protection of the environment.”

8.30. With regard to nuclear fuel cycle facilities, para. 5.13 of SSR-4 [3] states:

“The operating organization shall establish a programme of monitoring throughout the lifetime of the facility to evaluate natural and human-made changes in the area, including changes in demographics. The programme of monitoring shall be in place no later than the start of construction and shall continue through to decommissioning until termination of the authorization.”

8.31. When a nuclear installation ceases to operate and before the start of decommissioning, and in accordance with the decommissioning plan, the monitoring programme should be re-evaluated and modified as appropriate for the decommissioning phase and for the phase from the end of decommissioning to release from regulatory control. Further recommendations are provided in RS-G-1.8 [27] and IAEA Safety Standards Series No. SSG-47, Decommissioning of Nuclear Power Plants, Research Reactors and Other Nuclear Fuel Cycle Facilities [33], and additional information is provided in Ref. [34].

9. CONSIDERATION OF THE FEASIBILITY OF EFFECTIVE EMERGENCY RESPONSE ACTIONS

9.1. Requirement 13 of SSR-1 [1] states:

“The feasibility of planning effective emergency response actions on the site and in the external zone shall be evaluated, with account taken of the characteristics of the site and the external zone as well as any external events that could hinder the establishment of complete emergency arrangements prior to operation.”

9.2. Any adverse conditions surrounding the site that could hinder off-site emergency response action such as the sheltering or evacuation of the population in the region, or the access of external

services needed to deal with an emergency should be evaluated (e.g. in a transport analysis) and it should be confirmed that effective emergency response actions remain feasible.

9.3. Geographical features of the landscape that might make off-site emergency response actions difficult to implement include physical barriers that would impede evacuation, such as rivers or mountains. Administrative restrictions associated with national parks or other protected environments might also present the same difficulties. There should be at least two evacuation routes in different directions to offer various itinerary options for the implementation of precautionary urgent or urgent protective actions that involve road transportation (especially in case of changing weather conditions) during a nuclear or radiological emergency. If this is not possible owing to geographical features, administrative restrictions or other reasons, the site should be considered unsuitable for a nuclear installation. Examples for an unsuitable site are provided in Fig. 2 and 3. Example for a suitable site are provided in Fig. 4.

9.4. In case of a nuclear or radiological emergency, effective arrangements for sheltering should include the identification in advance of large and closed buildings that can be easily accessed by the public.

9.5. As indicated in Appendix V of IAEA Safety Standards No. GS-G-2.1, Arrangements for Preparedness for a Nuclear or Radiological Emergency [35], stable iodine should be provided to the local population before or shortly after an intake of radioiodine. In case stable iodine tablets have not been predistributed and an ingestion order is issued during a nuclear or radiological emergency, an absence of infrastructure (e.g. insufficient road options to get access to the tablets) might hinder access to stable iodine tablets for the local population. There is normally more time to implement protective actions such as food bans, as any deposited activity takes time to transfer through the food chain.

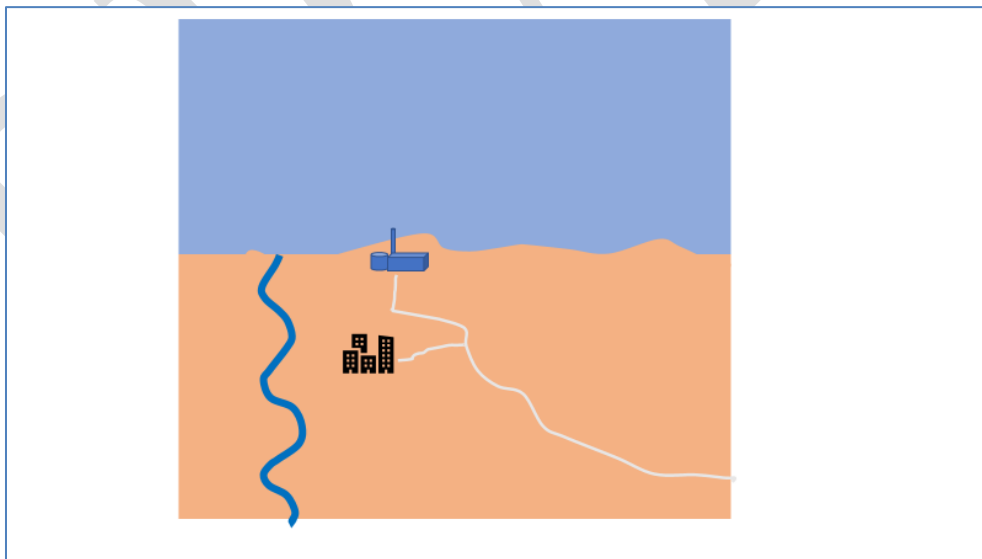


FIG. 2. Example of an unsuitable site — a physical barrier (river) preventing construction of an alternative evacuation route in another direction – site unsuitable if a bridge is not constructed or alternative evacuation route.

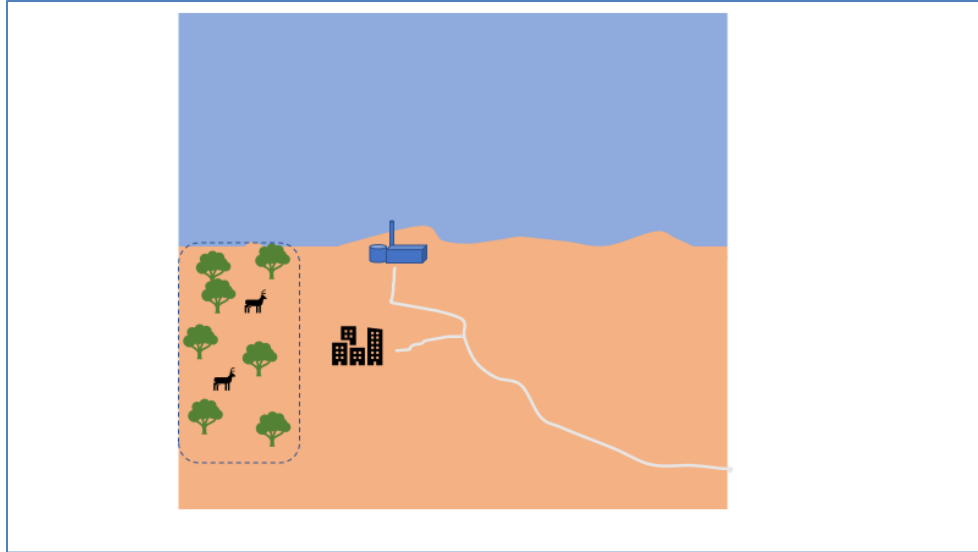


FIG. 3. Example of an unsuitable site — an administrative barrier (national park or special area) preventing construction of an alternative evacuation route in another direction – site unsuitable.

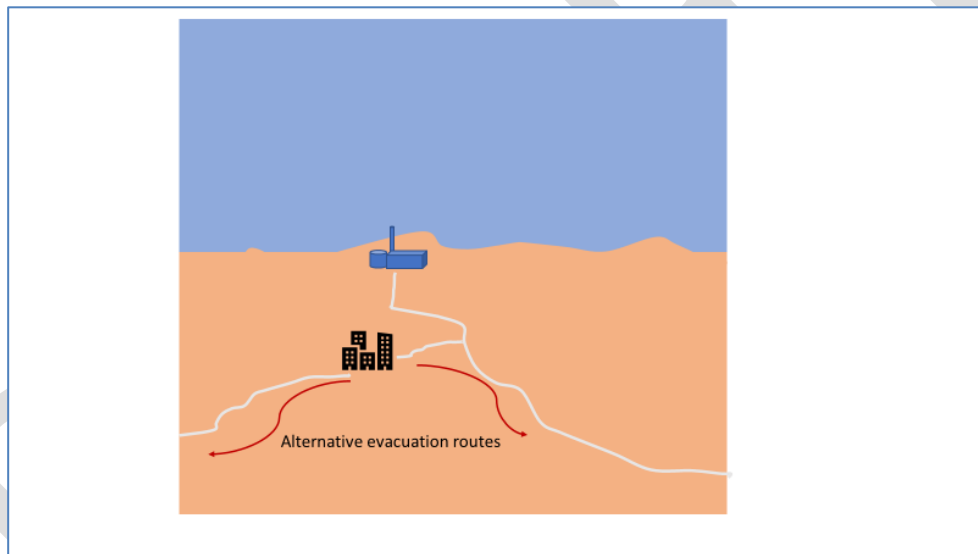


FIG. 4. Example of a suitable site — Alternative two evacuation routes (with sufficient capacity) in different directions exist or can be constructed – site suitable.

9.6. The feasibility of planning effective emergency arrangements off the nuclear installation site should be demonstrated on the basis of the specific natural and infrastructural conditions in the region. In this context, infrastructure means transport and communications networks, industrial activities and anything that might influence the rapid movement of people and vehicles in the region of the site. Other information on the region, such as information on the availability of sheltering, the systems for the collection and distribution of milk and other agricultural products, special population groups (e.g. people in hospitals and prisons, nomadic groups), industrial and critical facilities, and environmental conditions such as the range of weather conditions, should be collected for demonstrating the feasibility of an off-site emergency plan.

9.7. A transport analysis should be performed to demonstrate that the transport infrastructure for multiple evacuation routes is sufficient to evacuate the necessary number of people – taking special

population groups into account – in the necessary amount of time (i.e. within a few hours) to avoid significant exposure. The factors that should be taken into account for the transport analysis of each alternative route include the following:

- (a) Number of people to evacuate;
- (b) Available vehicles;
- (c) Transport needs and arrangements for any special population groups;
- (d) Time to alert people and to prepare to evacuate, taking into consideration any special population groups;
- (e) Time from alert to the start of a radioactive release;
- (f) Typical traffic volumes;
- (g) Traffic bottlenecks such as bridges.

9.8. The transport infrastructure does not need to be present at time of site evaluation, but it should be practicable to improve the infrastructure so that the off-site emergency plan can be made feasible before operation.

9.9. Many site related factors should be taken into account in demonstrating the feasibility of an off-site emergency plan. The most important ones are:

- (a) Population density and distribution in the region;
- (b) Distance of the site from population centres;
- (c) Special population groups;
- (d) Particular geographical features such as islands, mountains and rivers;
- (e) Characteristics of local transport and communications networks;
- (f) Industrial facilities where potentially hazardous activities are conducted;
- (g) Agricultural activities that are sensitive to possible discharges of radionuclides;
- (h) Possible concurrent external events (e.g. earthquake with flooding).

9.10. The presence of large populations in the region or the proximity of a city to the nuclear installation should be carefully taken into account in the hazard assessment to develop effective off-site emergency arrangements. The specific circumstances of any special population groups should be recognized and taken into account. The presence of residents whose evacuation route would pass near the nuclear installation might lead to the rejection of a site if no other emergency measure can overcome this difficulty.

9.11. External events may have consequences that limit the effectiveness of the response to an emergency at a nuclear installation. For example, an external event might result in a problem with the infrastructure or in damage to sheltering facilities. In order to ensure that the population in the region can be sheltered and evacuated effectively, consideration should be given to the provision of backup facilities and alternative routes.

9.12. If it is determined that no effective off-site emergency plan can be established, then the proposed site should be considered unacceptable.

9.13. It is possible that conditions assessed for the purposes of approval of the site and design will change over time. The site characteristics considered in the off-site emergency plan, such as infrastructural developments, should be reviewed periodically during the operational phase of the nuclear installation. Level 3 probabilistic safety assessment may be used in performing such reassessments.

10. APPLICATION OF A GRADED APPROACH TO RADIOLOGICAL ENVIRONMENTAL IMPACT ASSESSMENT FOR NUCLEAR INSTALLATIONS

10.1. A graded approach to radiological environmental impact assessment for nuclear installations should be applied, on the basis of the following:

- (a) The stage of the site evaluation process in the life of the nuclear installation;
- (b) The level of complexity of the site and the radionuclide transport mechanisms;
- (c) The hazard category of the installation (see para. 10.5).

10.2. The advantages of applying a graded approach include the following:

- (a) Allowing conservative calculations to be made, reducing the time and cost of data acquisition;
- (b) Avoiding the construction of models more complicated than are needed to make sufficiently useful and accurate predictions ;
- (c) Providing a guideline for selecting a suitable level of complexity for reporting for the specific stage of site evaluation.

10.3. Radiological environmental impact assessment is required to be performed using site specific data and site specific design parameters (if the technology is known; otherwise a plant parameter envelope can be used in the interim and updated at a later stage) during site characterization (see para. 1.4 of SSR-1 [1]). During further stages of site evaluation over the life of the nuclear installation, it may be necessary to update the assessments depending on the availability of data or results of the monitoring programmes. The radiological environmental impact during construction and operation should be confirmed by the environmental monitoring programme; if the impacts deviate from those expected, a process should be initiated to determine the cause of the discrepancies and implement remedial measures if necessary.

10.4. The level of complexity incorporated in a model should be commensurate with the purpose, hazard category (see para. 10.5) and stage of site evaluation for the installation. Transport mechanisms may need to be used to account for system complexities to achieve the necessary accuracy. The system may be simplified to make a first approximation, or complexities may be incorporated implicitly if their effect on transport is deemed less relevant. Simplifications might decrease the accuracy of the model and do not necessarily mean that the results are conservative. The modelling may be in one, two or three dimensions, assuming steady-state or transient flow conditions. One and two dimensional modelling assuming steady-state conditions is much easier than three dimensional modelling, and should be performed for low hazard installations and for exploratory purposes for high hazard installations to determine the level of complexity that should be applied in the subsequent stages. Analytical models may be used for low to intermediate hazard installations, as long as their use is justified. For intermediate and high hazard installations, a step-wise strategy may be followed. Modelling with some simplifications of the site characteristics and use of the most conservative transport mechanisms may precede more detailed modelling which takes into account site complexities (e.g. stratification in lakes, uniform or non-uniform geometry in rivers, heterogeneity and anisotropy in groundwater systems, complex surface topography for dispersion in the atmosphere) and known mechanisms (e.g. dispersion, sorption and first-order reaction in groundwater systems, sedimentation or resuspension in rivers and lakes).

10.5. The radiological environmental impact assessment for nuclear installations should be commensurate with the radiological hazards and with the hazards due to other materials present on the site. In general, the criteria for categorization should be based on the radiological consequences of the release of radioactivity from the installation, ranging from very low radiological consequences to potentially severe radiological consequences. As an alternative, the categorization may range from radiological consequences within the installation itself, to radiological consequences within the site boundary, to radiological consequences to the public and the environment outside the site. Three or more categories of nuclear installation may be defined on the basis of national practice. The hazard categorization of a nuclear installation for the application of a graded approach can be based on the same characteristics as listed in para. 9.5 of SSG-9 (Rev. 1) [18], as follows:

- (a) The amount, type and status of the radioactive inventory at the site (e.g. whether solid, liquid and/or gaseous; whether the radioactive material is being processed or only stored);
- (b) The intrinsic hazard associated with the physical processes (e.g. nuclear chain reactions) and chemical processes (e.g. for fuel processing purposes) that take place at the installation;
- (c) The thermal power of the nuclear installation, if applicable;
- (d) The configuration of the installation for different kinds of activity (depending on the design of the reactor and accident management, there might be considerable time before a major release of radioactive material is initiated);
- (e) The distribution of radioactive sources in the installation (for research reactors, most of the radioactive inventory is in the reactor core and the fuel storage pool, whereas for fuel processing and storage facilities it might be distributed throughout the installation);
- (f) The changing nature of the configuration and layout of installations designed for experiments (such activities have an associated intrinsic unpredictability);
- (g) The need for active safety systems and/or operator actions for the prevention of accidents and for mitigation of the consequences of accidents, and the characteristics of engineered safety features for the prevention of accidents and for mitigation of the consequences of accidents (e.g. the containment and containment systems);
- (h) The characteristics of the structures of the nuclear installations and the means of confinement of radioactive material;
- (i) The characteristics of the processes or of the engineering features that might show a cliff edge effect in the event of an accident;
- (j) The characteristics of the site that are relevant to the consequences of the dispersion of radioactive material to the atmosphere and the hydrosphere (e.g. size and demographics of the region);
- (k) The potential for on-site and off-site contamination.

10.6. The application of a graded approach may allow certain simplifications and a less detailed approach in the following areas:

- (a) Source term (e.g. radionuclide quantity, activity, mass and/or volume, form, chemical and physical composition, geometry, height of release, potential for release; release start time and time profile of the release; novelty of design or activity);
- (b) Complexity of environmental characteristics of site and its region: characteristics of the site and its region relating to dispersion of radionuclides in the environment (e.g. hydrogeology, hydrology, meteorology, morphology, biophysical characteristics), presence and characteristics of receptors (e.g. demography, population habits and living conditions, flora

- and fauna, exposure pathways), land use and other activities (e.g. agriculture, food processing, other industries) and characteristics of other installations in the vicinity;
- (c) Dimensionality of model (i.e. one, two or three dimensional);
 - (d) Steady-state and transient transport mode;
 - (e) Type of model: analytical, numerical or statistical;
 - (f) Source of information;
 - (g) Transport phenomena.

An example of the application of a graded approach to the analysis of radionuclide transport in groundwater is given in the Annex.

11. APPLICATION OF THE MANAGEMENT SYSTEM TO INVESTIGATION OF SITE CHARACTERISTICS AND EVALUATION OF RADIATION RISKS FROM A NUCLEAR INSTALLATION

11.1. A management system is required to be established, applied and sustained by senior management (see Requirement 3 of IAEA Safety Standards Series No. GSR Part 2, Leadership and Management for Safety [36]). This applies to all facilities and activities and should be implemented for the activities that are performed for the investigation of site characteristics and evaluation of radiation risks to the public and the environment in site evaluation for nuclear installations.

PROJECT MANAGEMENT

11.2. A project work plan for the investigation of site characteristics and evaluation of radiation risks from a nuclear installation should be established that, at a minimum, addresses the following topics:

- (a) The objectives and scope of the project;
- (b) Applicable regulations and standards;
- (c) Organization of the roles and responsibilities for management of the project;
- (d) Work breakdown, processes and tasks, schedule and milestones;
- (e) Interfaces among the different types of tasks (e.g. data collection tasks, analysis tasks) and disciplines involved, especially the various specialists needed for the different aspects of investigation of site characteristics and evaluation of radiation risks to the public and the environment with all necessary inputs and outputs;
- (f) Project deliverables and reporting.

11.3. The project scope should identify all aspects of investigation of site characteristics and evaluation of radiation risks that are relevant for the impact of the nuclear installation on the environment and the public and that are investigated within the framework of the project.

11.4. The project work plan should include a description of all requirements that are relevant for the project, including applicable regulatory requirements in relation to investigation of site characteristics and evaluation of radiation risks to the public and the environment that should be within the project scope. The applicability of the set of regulatory requirements should be reviewed by the regulatory body prior to conducting the project activities.

11.5. All approaches and methodologies that reference lower tier legislation (e.g. regulatory guidance documents, industry codes and standards) should be clearly identified and described. The details of the approaches and methodologies to be used should be clearly stated in the project work plan.

11.6. At a minimum, the following generic processes should be included in the management system to ensure quality of the project:

- (a) Document control;
- (b) Control of products;
- (c) Controls for measuring and testing equipment;
- (d) Control of records;
- (e) Control of analyses;
- (f) Purchasing (procurement);
- (g) Validation and verification of software;
- (h) Audits (self-assessment, independent assessments, and review);
- (i) Control of non-conformances;
- (j) Corrective actions;
- (k) Preventive actions.

Processes covering field investigations, laboratory testing, data collection, and analysis and evaluation of observed data should also be applied, as well as communication processes for interaction among the experts involved in the project.

11.7. The project work plan should ensure that there is adequate provision, in the resources and in the schedule, for collecting and analysing new data that might be important for the conduct of the investigation of site characteristics and evaluation of radiation risks to the public and the environment.

11.8. To make the investigation of site characteristics and evaluation of radiation risks to the public and the environment traceable and transparent to users (e.g. peer reviewers, the operating organization, the regulatory body), the documentation for the analysis should provide a description of all elements of the process and include the following information:

- (a) Description of the study participants and their roles;
- (b) Background material that includes documentation on the data collected and analysed;
- (c) A description of the computer software used, and the input and output files;
- (d) Reference documents;
- (e) All documents supporting the treatment of uncertainties, opinion and related discussions;
- (f) Results of intermediate calculations and sensitivity studies.

This documentation should be maintained in an accessible, usable and auditable form by the operating organization.

11.9. The documentation and references should identify all sources of information used in the investigation of site characteristics and evaluation of radiation risks to the public and the

environment, including information on the sources of important citations that might be difficult to trace.

ENGINEERING USES AND OUTPUT SPECIFICATION

11.10. The investigation of site characteristics and evaluation of radiation risks to the public and the environment should be conducted to develop the site evaluation report and environmental impact assessment report. From the beginning, the work plan for the investigation of site characteristics and evaluation of radiation risks to the public and the environment should identify the intended engineering uses and objectives of the assessment and should incorporate an output specification that describes all the results necessary for the intended engineering uses and objectives of the project.

DOCUMENTATION OF INVESTIGATION OF SITE CHARACTERISTICS AND EVALUATION OF RADIATION RISKS TO THE PUBLIC AND THE ENVIRONMENT

11.11. The project for investigation of site characteristics and evaluation of radiation risks should be well documented, with a clearly defined scope and objectives. The conceptual models used for numerical modelling should be described in detail. The code selected and the reasons for its selection should be described. The steps of model construction should be documented, including grid construction, assignment of parameters, boundary conditions, steady-state and transient calibration and sensitivity analysis, if applicable. Simulation runs should be documented. The scenarios should be well described, and the results should be discussed, taking into consideration the uncertainties. An electronic copy of a ready-to-run model should be provided as an appendix to the documentation. The electronic copy should include the data files and model files of each run.

INDEPENDENT PEER REVIEW OF INVESTIGATION OF SITE CHARACTERISTICS AND EVALUATION OF RADIATION RISKS TO THE PUBLIC AND THE ENVIRONMENT

11.12. An independent peer review should be conducted to provide assurance of the following:

- (a) That a proper process has been duly followed in conducting the investigation of site characteristics and evaluation of radiation risks to the public and the environment;
- (b) That the analysis addresses the uncertainties involved;
- (c) That the documentation is complete and traceable.

11.13. The independent peer review team should possess the multidisciplinary expertise needed to address all technical and process related aspects of the investigation of site characteristics and evaluation of radiation risks to the public and the environment. The team members should not have been involved in other aspects of the project and should not have a vested interest in the outcome.

11.14. Two methods of peer review should be used: participatory peer review and late stage peer review. The participatory peer review should be conducted during the implementation of the project, allowing the reviewer(s) to resolve comments. The late stage (follow-up) peer review should be conducted towards the end of the project. Participatory peer review decreases the

likelihood of the results of the investigation of site characteristics and evaluation of radiation risks from the nuclear installation being found unsuitable at a later stage.

DRAFT

REFERENCES

- [1] INTERNATIONAL ATOMIC ENERGY AGENCY, Site Evaluation for Nuclear Installations, IAEA Safety Standards Series No. SSR-1, IAEA, Vienna (2019).
- [2] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Nuclear Research Reactors, IAEA Safety Standards Series No. SSR-3, IAEA, Vienna (2016).
- [3] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Nuclear Fuel Cycle Facilities, IAEA Safety Standards Series No. SSR-4, IAEA, Vienna (2017).
- [4] EUROPEAN COMMISSION, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS ENVIRONMENT PROGRAMME, WORLD HEALTH ORGANIZATION, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, IAEA Safety Standards Series No. GSR Part 3, IAEA, Vienna (2014).
- [5] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL CIVIL AVIATION ORGANIZATION, INTERNATIONAL LABOUR ORGANIZATION, INTERNATIONAL MARITIME ORGANIZATION, INTERPOL, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, PREPARATORY COMMISSION FOR THE COMPREHENSIVE NUCLEAR-TEST-BAN TREATY ORGANIZATION, UNITED NATIONS ENVIRONMENT PROGRAMME, UNITED NATIONS OFFICE FOR THE COORDINATION OF HUMANITARIAN AFFAIRS, WORLD HEALTH ORGANIZATION, WORLD METEOROLOGICAL ORGANIZATION, Preparedness and Response for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GSR Part 7, IAEA, Vienna (2015).
- [6] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Nuclear Safety and Security Glossary: Terminology Used in Nuclear Safety, Nuclear Security, Radiation Protection and Emergency Preparedness and Response, 2022 (Interim) Edition, IAEA, Vienna (2022).
- [7] INTERNATIONAL ATOMIC ENERGY AGENCY, Engineering Safety Aspects of the Protection of Nuclear Power Plants against Sabotage, IAEA Nuclear Security Series No. 4, IAEA, Vienna (2007).
- [8] INTERNATIONAL ATOMIC ENERGY AGENCY, UNITED NATIONS ENVIRONMENT PROGRAMME, Prospective Radiological Environmental Impact Assessment for Facilities and Activities, IAEA Safety Standards Series No. GSG-10, IAEA, Vienna (2018).
- [9] INTERNATIONAL NUCLEAR SAFETY ADVISORY GROUP, Potential Exposure in Nuclear Safety, INSAG Series No. 9, IAEA, Vienna (1995).
- [10] INTERNATIONAL ATOMIC ENERGY AGENCY, Deterministic Safety Analysis for Nuclear Power Plants, IAEA Safety Standards Series No. SSG-2 (Rev. 1), IAEA, Vienna (2019).

- [11] INTERNATIONAL ATOMIC ENERGY AGENCY, UNITED NATIONS ENVIRONMENT PROGRAMME, Regulatory Control of Radioactive Discharges to the Environment, IAEA Safety Standards Series No. GSG-9, IAEA, Vienna (2018).
- [12] INTERNATIONAL ATOMIC ENERGY AGENCY, Development and Application of Level 1 Probabilistic Safety Assessment for Nuclear Power Plants, IAEA Safety Standards Series No. SSG-3 (Rev. 1), IAEA, Vienna (in preparation)
- [13] INTERNATIONAL ATOMIC ENERGY AGENCY, Development and Application of Level 2 Probabilistic Safety Assessment for Nuclear Power Plants, IAEA Safety Standards Series No. SSG-4, IAEA, Vienna (2010).
- [14] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Assessing Dose of the Representative Person for the Purpose of the Radiation Protection of the Public and The Optimisation of Radiological Protection: Broadening the Process, ICRP Publication 101, Elsevier, Oxford (2006).
- [15] INTERNATIONAL ATOMIC ENERGY AGENCY, WORLD METEOROLOGICAL ORGANIZATION, Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations, IAEA Safety Standards Series No. SSG-18, IAEA, Vienna (2011).
- [16] INTERNATIONAL ATOMIC ENERGY AGENCY, Radiation Protection Aspects of Design for Nuclear Power Plants, IAEA Safety Standards Series No. NS-G-1.13, IAEA, Vienna (2005). (A revision of this publication is in preparation).
- [17] WORLD METEOROLOGICAL ORGANIZATION, Standards and Recommended Practices, available at <https://public.wmo.int/en/resources/standards-technical-regulations>, WMO, Geneva (accessed on August 24, 2020).
- [18] INTERNATIONAL ATOMIC ENERGY AGENCY, Seismic Hazards in Site Evaluation for Nuclear Installations, IAEA Safety Standards Series No. SSG-9 (Rev.1), IAEA, Vienna (2022).
- [19] INTERNATIONAL ATOMIC ENERGY AGENCY, Volcanic Hazards in Site Evaluation for Nuclear Installations, IAEA Safety Standards Series No. SSG-21, IAEA, Vienna (2012).
- [20] INTERNATIONAL ATOMIC ENERGY AGENCY, Geotechnical Aspects of Site Evaluation and Foundations for Nuclear Power Plants, IAEA Safety Standards Series No. NS-G-3.6, IAEA, Vienna (2004). (A revision of this publication is in preparation)
- [21] INTERNATIONAL ATOMIC ENERGY AGENCY, Hazards Associated with Human Induced External Events in Site Evaluation for Nuclear Installations, IAEA Safety Standards Series No. SSG-79, IAEA, Vienna (2023).
- [22] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Human Respiratory Tract Model for Radiological Protection, ICRP Publication 66, Pergamon Press, Oxford (1994).
- [23] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Compendium of Dose Coefficients based on ICRP Publication 60, ICRP Publication 119, Elsevier, Oxford (2012).

- [24] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Environmental Protection: Transfer Parameters for Reference Animals and Plants, ICRP Publication 114, Elsevier, Oxford (2009).
- [25] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Environmental Protection: The Concept and Use of Reference Animals and Plants, ICRP Publication 108, Elsevier, Oxford (2008).
- [26] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Protection from Potential Exposure: A Conceptual Framework, ICRP Publication 64, Pergamon Press, Oxford (1993).
- [27] INTERNATIONAL ATOMIC ENERGY AGENCY, Environmental and Source Monitoring for Purposes of Radiation Protection, IAEA Safety Standards Series No. RS-G-1.8, IAEA, Vienna (2005). (A revision of this publication is in preparation).
- [28] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidelines on Soil and Vegetation Sampling for Radiological Monitoring, Technical Reports Series No. 486, IAEA, Vienna (2019).
- [29] INTERNATIONAL ATOMIC ENERGY AGENCY, Programmes and Systems for Source and Environmental Radiation Monitoring, Safety Reports Series No. 64, IAEA, Vienna (2010).
- [30] INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR OFFICE, Occupational Radiation Protection, IAEA Safety Standards Series No. GSG-7, IAEA, Vienna (2018).
- [31] INTERNATIONAL ATOMIC ENERGY AGENCY, Optimization of Radiation Protection in the Control of Occupational Exposure, Safety Reports Series No. 21, IAEA, Vienna (2002).
- [32] INTERNATIONAL ATOMIC ENERGY AGENCY, Decommissioning of Facilities, IAEA Safety Standards Series No. GSR Part 6, IAEA, Vienna (2014).
- [33] INTERNATIONAL ATOMIC ENERGY AGENCY, Decommissioning of Nuclear Power Plants, Research Reactors and Other Nuclear Fuel Cycle Facilities, IAEA Safety Standards Series No. SSG-47, IAEA, Vienna (2018).
- [34] INTERNATIONAL ATOMIC ENERGY AGENCY, Policies and Strategies for the Decommissioning of Nuclear and Radiological Facilities, IAEA Nuclear Energy Series No. NW-G-2.1, IAEA, Vienna (2011).
- [35] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR OFFICE, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS OFFICE FOR THE COORDINATION OF HUMANITARIAN AFFAIRS, WORLD HEALTH ORGANIZATION, Arrangements for Preparedness for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GS-G-2.1, IAEA, Vienna (2007). (A revision of this publication is in preparation).
- [36] INTERNATIONAL ATOMIC ENERGY AGENCY, Leadership and Management for Safety, IAEA Safety Standards Series No. GSR Part 2, IAEA, Vienna (2016).

Appendix

APPLICATION OF A GRADED APPROACH TO MODELLING RADIONUCLIDE TRANSPORT IN GROUNDWATER

A.1. This Appendix presents guidelines for determining the most appropriate level of complexity for modelling radionuclide transport in groundwater. Since different nuclear installations pose different levels of hazards, the suggested method uses a graded approach based on the level of hazard and the stage of reporting.

A.2. In addition to the level of hazard and the reporting stage, several other factors may need to be taken into account in applying a graded approach. These factors include the complexity of the hydrogeological setting of the site, type of model, the type of solution provided by the mathematical model, the dimensionality of model, modes of flow and transport, type of flow and transport domain, availability, sources, reliability and representativeness of data needed for the selected model, source and reliability of information on boundary conditions, and consideration of processes that affect the transport and fate of radionuclides.

A.3. As described in para. 10.5, three or more levels of hazard categorization for nuclear installations may be defined. In this Appendix, three levels are assumed, based on the type and capacity of the nuclear installation.

A.4. Three reporting stages are also assumed in this Appendix. Reporting Stage 1 relates to the site characterization phase, which involves a detailed study of the hydrogeological domain. Site specific data for hydrogeological conceptualization, characterization and modelling should be collected, evaluated, and reported during this stage. Reporting Stage 2 relates to the construction and operation phases. For the analysis of radionuclide transport in groundwater, this stage should include validation of the predictive model constructed for the site, using well established monitored observations of flow, hydraulic heads and concentrations. Validation is used here to mean a post-audit to assess the predictive accuracy of a site-specific model based on long term monitoring data. Reporting stage 3 relates to the closure of the installation. The validated model should simulate radionuclide dispersion in groundwater from new source terms that might be created or effectuated during the closure of the installation.

A.5. The complexity of the hydrogeological configuration refers to the variety and contact relations of hydrostratigraphical units. Factors such as dual porosity, fracture and/or karst permeability, heterogeneity and anisotropy significantly complicate the hydrogeological setting, and should be considered. The ease of construction of a representative hydrogeological conceptual model without oversimplification should also be considered.

A.6. Depending on the objective defined for the groundwater modelling study, the mathematical model should be selected to simulate different flow domains: saturated or a combination of saturated and unsaturated. In most cases, simulating the flow and transport in the saturated flow domain is sufficient to achieve the objectives. A simulation including the unsaturated flow domain is more complicated and needs data that is more difficult to acquire.

A.7. The groundwater modelling can be achieved by using different techniques to solve the flow and transport equations. Partial differential equations simulating the groundwater flow and solute (radionuclide) transport are solved either analytically or numerically. The pros and cons of the different techniques are discussed in detail in paras 6.23 and 6.34. It should be kept in mind that natural systems do not often exhibit configurations that closely match the geometries defined in specific analytical solutions. Therefore, analytical models should be used when the natural hydrogeological setting can be simplified with certain confidence to fit the assumptions of the analytical solution.

A.8. The objective and the level of hazard category may necessitate groundwater modelling in one, two or three dimensions. One dimensional models simulate flow and transport in the mean flow direction and should be used only for the low hazard category or for the screening stage. Dimensionality should be selected on the basis of the objective, expected impact and level of hazard. The higher the hazard category, the more dimensions the model should have.

A.9. The selected model should then be run and calibrated for steady-state (independent of time) and transient (time dependent) flow and transport modes. Calibration is achieved by reproduction of observed heads and/or concentrations by the model. The model can be run only for steady flow and transport for the screening stage, and/or low hazard category installations. Transient flow and transport need to be simulated to make predictions. Therefore, the selected model (analytical or numerical) should be verified. The term 'verification' is used here in a broad sense to mean checking the model against an independent set of data.

A.10. The application of a graded approach also suggests the collection and use of different levels of data. For low hazard category installations and/or for the screening stage, data from literature, regional studies and information based on expert qualitative observations can be used if site specific data is not available. For higher levels of hazard category and at reporting Stage 1, site specific representative data are needed. These data should include hydraulic parameters that represent all hydrostratigraphic units, the hydraulic head distribution at the flow domain and the hydraulic head, concentration or fluxes at the boundaries of the hydrogeological domain.

A.11. A mathematical model to simulate the flow and transport processes should be selected on the basis of the level of hazard of the installation and the expected impact. The transport and fate of radionuclides in groundwater are primarily affected by advection and radioactive decay, but processes such as dispersion and sorption should also be included if the results of groundwater modelling show that the site is not acceptable for a nuclear installation. In some cases, transport models that include a reactive transport term may be selected.

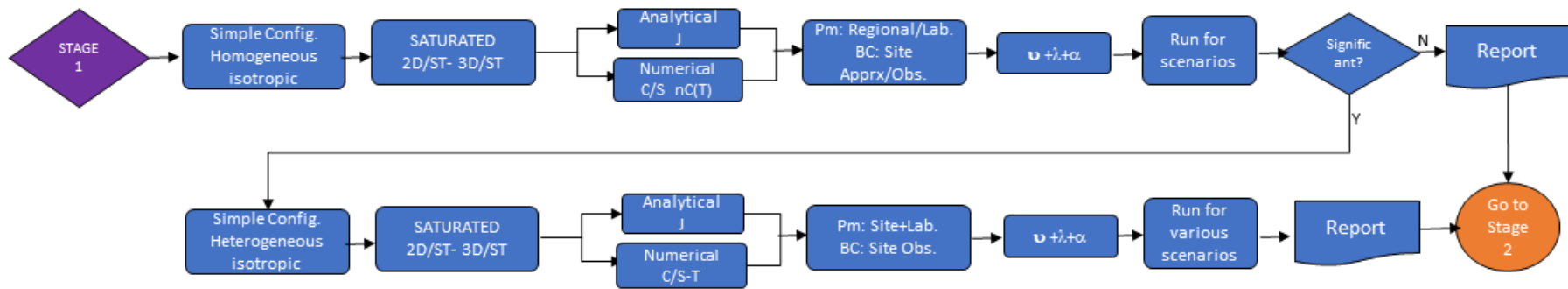
A.12. There are several freeware and commercial computer codes that can be used in modelling studies. The appropriate model should be verified in the sense that its numerical algorithm has

been implemented correctly. In general, this is achieved by comparing the results of a numerical model with an analytical solution.

A.13. The following factors should be considered in selecting the model complexity:

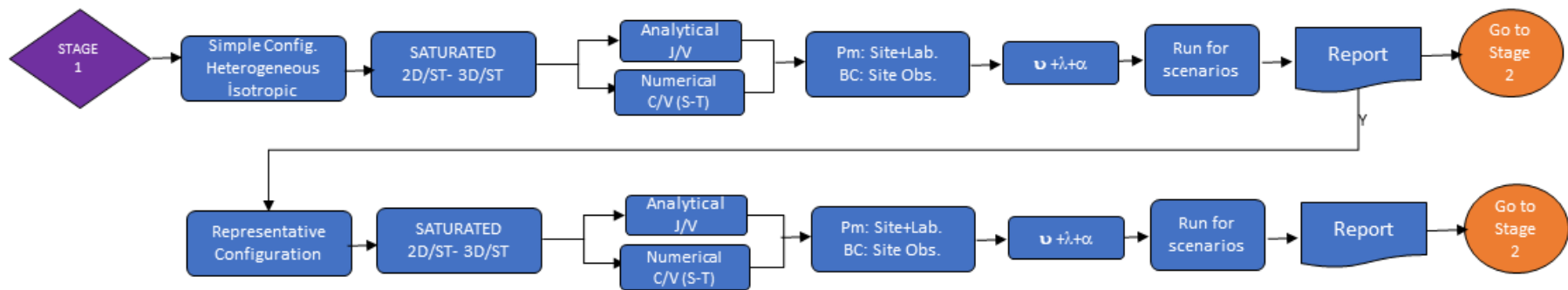
- (a) Level of hazard;
- (b) Reporting stage;
- (c) Complexity of hydrogeological configuration;
- (d) Saturated or unsaturated media;
- (e) Dimensionality of model;
- (f) Steady or transient flow mode;
- (g) Technique for solving equation (i.e. analytical- or numerical);
- (h) Source of data on parameters;
- (i) Source of information on boundary conditions;
- (j) Transport and fate processes.

A.14. The detail of the graded approach to groundwater modelling is illustrated in the flow charts presented in Figs A.1–A.4. The symbols and abbreviations used in these flowcharts are explained in Table A.1.



LOW
HAZARD

FIG. A.1. Flow chart showing a graded approach to modelling radionuclide transport in groundwater in Stage 1 reporting of site evaluation for low hazard category nuclear installations.



INTERMEDIATE HAZARD

FIG. A.2. Flow chart showing a graded approach to modelling radionuclide transport in groundwater in Stage 1 reporting of site evaluation for intermediate hazard category nuclear installations.

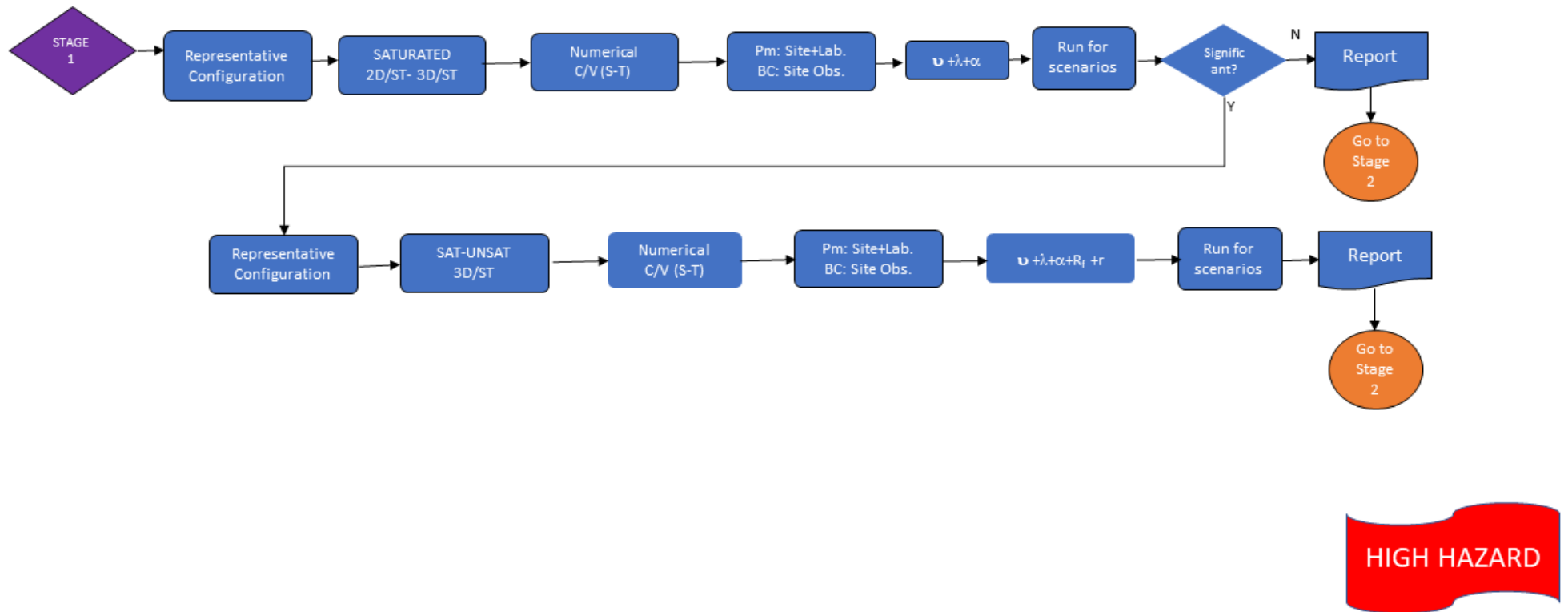


FIG. A.3. Flow chart showing a graded approach to modelling radionuclide transport in groundwater in Stage 1 reporting of site evaluation for high hazard category nuclear installations.

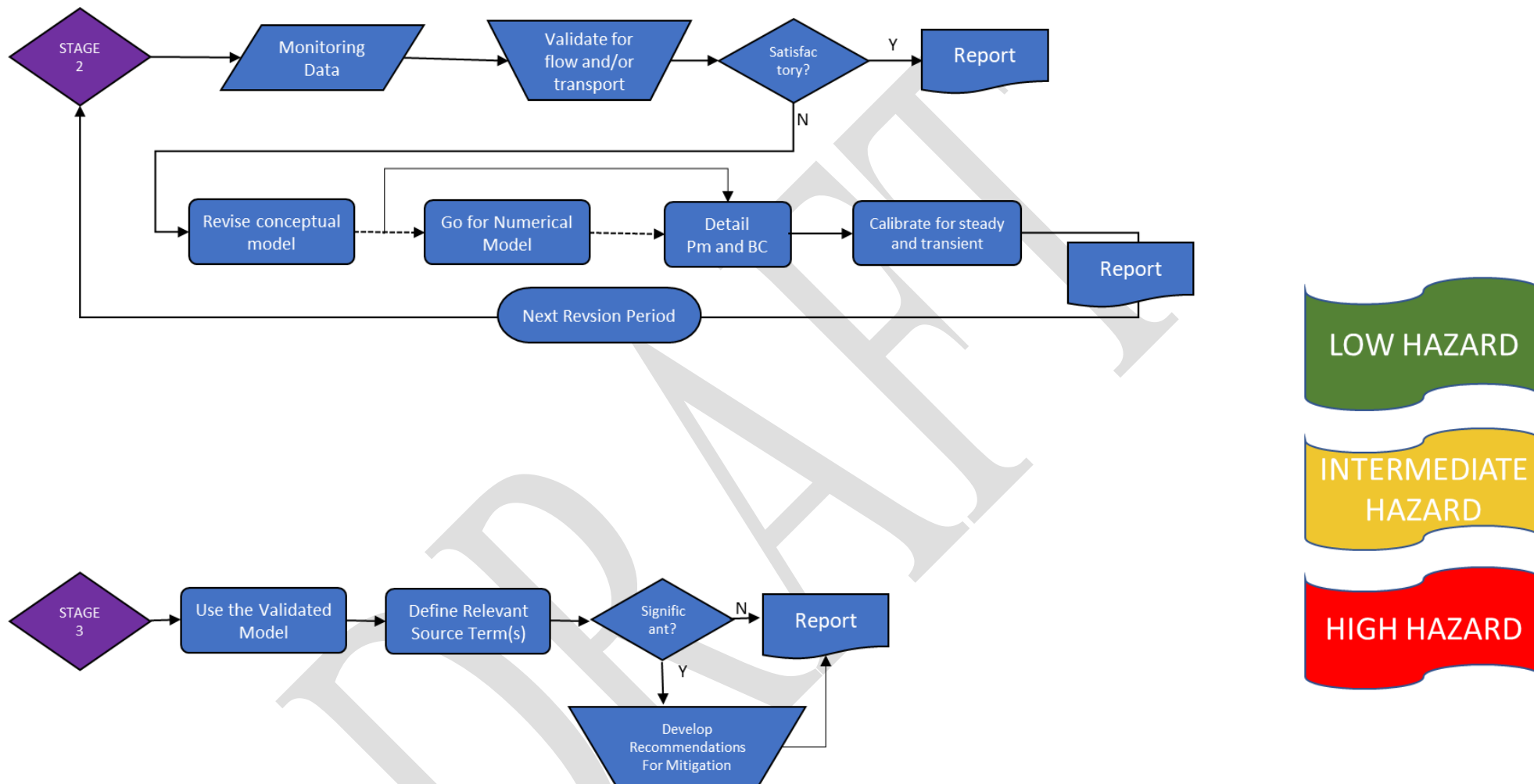


FIG. A.4. Flow chart showing a graded approach to modelling radionuclide transport in groundwater in Stage 2 and 3 reporting of site evaluation for low, intermediate and high hazard category nuclear installations.

TABLE A.1. Symbols and abbreviations used in flowcharts

<i>Hazard category of nuclear installations</i>	
LH	Low hazard category
IH	Intermediate hazard category
HH	High hazard category
<i>Stage of site evaluation</i>	
Stage 1	Site characterization
Stage 2	Construction and operation
Stage 3	Decommissioning
<i>Transport Mechanism</i>	
v	Advective transport
λ	Radioactivity decay
α	Dispersive transport
R_f	Sorption
r	First-order reaction
<i>Dimensionality and flow conditions</i>	
1D/S	One dimensional / Steady
1D/T	One dimensional / Transient
2D/S	Two dimensional / Steady
2D/T	Two dimensional / Transient
3D/S	Three dimensional / Steady
3D/T	Three dimensional / Transient
<i>Source of information</i>	
Pm	Source of parameter value
BC	Source of boundary conditions
Literature	Mean and most conservative values taken from international literature
Region	Data from literature in the close vicinity of the installation site
Appx	Approximation based on site observations
Lab	Data from tests at laboratory
Site	Site specific representative data / field test
<i>Transport domain</i>	
SAT	Saturated
UNSAT	Unsaturated
<i>Model type and status</i>	
J/V	Justified and verified
nV	Not verified
C	Calibrated
nC	Not calibrated
Analy	Analytical model
Num	Numerical model

CONTRIBUTORS TO DRAFTING AND REVIEW

Altinyollar, A.	International Atomic Energy Agency
Avcı, H.	Consultant, United States of America
Contri, P.	International Atomic Energy Agency
Ekmekci, M.	Hacettepe University, Türkiye
Harman, N.	Consultant, United Kingdom
Kaeriyama, H.	Japan Fisheries Research and Education Agency, Japan
Telleria, D.	International Atomic Energy Agency