*Pre-Decisional Draft*

# Evaluation of Subsurface Radionuclide Transport at Commercial Nuclear Power Production Facilities

ANSI/ANS-2.17 (Revised)

December 3, 2007

# Foreword

## Background

This standard constitutes a major revision of the original standard, ANSI/ANS-2.17, which was adopted on April 9, 1980, reaffirmed on October 3, 1989, and withdrawn on July 28, 2000. A new working group, Working Group ANS-2.17R of ANS-2 Subcommittee (Site Evaluation) of the American Nuclear Standards Committee, was constituted November 2005 to revise the original standard.

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# 1. Purpose and Scope

## 1.1 Purpose

This document provides guidance with respect to site characterization, performance confirmation monitoring, and modeling efforts related to evaluating the occurrence and movement of radionuclides within the subsurface at commercial nuclear power production facilities in accordance with appropriate state and federal regulations. This standard is intended for use in facility design and permitting, operation, and closure. This document contains mandatory requirements as designated by the word “shall”.

## 1.2 Coverage

This document addresses radionuclide releases that affect: i) groundwater, ii) surface waters affected by groundwater, and iii) water supplies derived from groundwater. This document addresses subsurface radionuclide transport resulting from normal and abnormal radionuclide releases.

## 1.3 Exclusions

This document does not address the subsurface occurrence and movement of non-radioactive materials, other than as indicators of subsurface radionuclide occurrence and movement in soil and groundwater. This document does not address the surface occurrence and movement of radionuclides, except to the extent that surface radionuclide occurrence and movement may affect onsite subsurface radionuclide occurrence and movement. This document does not address corrective action, which may be required as a result of a radioactive release to groundwater.

## 1.4 Consultation

It is strongly recommended that all regulatory agencies be consulted prior to the preparation of the scope of work for evaluation of subsurface radionuclide transport. It is also advised that relevant data, information, and technical studies be used from all available sources. Substantial pre-construction and post-construction data and information may be available at existing facilities, although these may not be in suitable digital format. Additional data can be solicited from federal sources, such as the U.S. Geological Survey, the U.S. Army Corps of Engineers, the U.S. Bureau of Reclamation, the Natural Resources Conservation Service, the U.S. Forest Service, the Tennessee Valley Authority, the U.S. Environmental Protection Agency, the Nuclear Regulatory Commission, the Agricultural Research Service, the U.S. Fish and Wildlife Service, the Bureau of Land Management, and the U.S. Department of Energy. Additional interstate, state, tribal, regional, and local agencies and authorities, as well as non-governmental organizations, and others with technical information in the area of interest should also be consulted.

**Comment [A1]:** It is stated that all regulatory agencies be consulted prior to preparation of the scope of work. In my opinion, it might be more beneficial if there is a standing committee or an interagency working group that works in close collaboration on a scheduled time frame rather than having a one time effort as needed.

**Comment [A2]:** This is not clear. What are the goals, purposes, expectations, content, and procedures of the consultation?

**Comment [A3]:** We suggest deleting all mention of specific agencies in lines 80-84, or else listing only lead agencies, in particular NRC and EPA.

**Comment [A4]:** Listing of agencies, authorities and organizations to be consulted would benefit from collaborating with the Advisory Committee on Water Information and more specifically the Subcommittee on Groundwater.

## 2. Definitions

*ALARA, As Low As Reasonably Achievable:* To make every reasonable effort to maintain exposures to ionizing radiation as far below the dose limits as practical, consistent with the purpose for which the licensed activity is undertaken and taking into account the state of technology, the cost of improvements in relation to state of technology and benefits to the public health and safety, and other societal and socioeconomic considerations.

*Ambient borehole flow:* Natural vertical flow (up or down) within an open borehole or well due to the surrounding vertical hydraulic gradients.

*Ambient groundwater flow:* Natural horizontal and vertical subsurface flow.

*Aquifer:* A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to springs and wells.

*Aquifer, confined:* An aquifer bounded above by a low-permeability layer.

*Aquifer, unconfined:* An aquifer whose upper surface is a water table.

*Background concentration, natural:* A concentration of a substance in a particular environment that is indicative of minimal influence by human (anthropogenic) sources.

*Background concentration, local:* The concentration or activity of a substance that is indicative of local site conditions prior to the operation of the nuclear facility.

*Background concentration, regional:* The concentration or activity of a substance that is indicative of regional conditions prior to the operation of the nuclear facility.

*Capillary zone:* The region above the water table where pores are saturated, but the water gage pressure is negative; also called the *tension saturated zone*.

**Comment [A5]:** Define this term. Also, this is presumably the same as “fluid gage pressure” (line 158) and “gage fluid pressure” (line 179) – decide on a single term.

*Site conceptual model:* An abstract, qualitative representation of the relevant flow and transport features, events, and processes that affect subsurface radionuclide transport at the site.

*Confining layer:* A geologic unit of distinctly lower hydraulic conductivity than the underlying and overlying geologic units.

*Contamination:* Undesired radioactive material that is deposited on the surface of or inside structures, areas, objects, or people.

*Corrective action:* Activities undertaken to manage or remediate the occurrence or movement of subsurface radionuclides.

*Data quality objectives:* A strategic planning approach based on the Scientific Method to prepare for a data collection activity. It provides a systematic procedure for defining the criteria that a data collection design should satisfy, including when to collect samples, where to collect samples, the tolerable

**Comment [A6]:** Define – or better yet, rewrite to eliminate reference to this broad and ambiguous term.

level of decision error for the study, and how many samples to collect, balancing information needs with costs in an acceptable manner.

*Dual porosity model:* A transport model applied to a porous medium composed of two porosity fractions or domains. One porosity fraction stores and transmits solute (mobile porosity or domain), while the other porosity fraction only stores solute (immobile porosity or domain). Solute exchange between the mobile and immobile porosities occurs.

*Engineered barrier:* A man-made cover, wall, or device used to prevent contaminants from entering or moving through the subsurface, or to retard horizontal subsurface flow.

*Exfiltration:* The movement of water across the ground surface from the subsurface as seepage.

*Features, events, and processes:* A statement of the relevant: i) Features related to site conditions and radionuclide inventories along with the effects of radionuclide releases; ii) Events related to incidents that may result in normal and abnormal radionuclide releases; and iii) Processes related to site liquid and vapor transport pathways, as well as the physical and chemical processes that govern transport along the pathway.

*Fluid velocity, average pore:* The fluid velocity within pores averaged over a representative elementary volume of pores.

*Fluid velocity, classical:* The time rate of displacement of a fluid particle.

*Groundwater:* All water contained in pores at or below the watertable. This term also identifies water in the phreatic zone.

**Comment [A7]:** Two words ("water table") is standard – see line 158.

*Groundwater flux:* The volumetric discharge per unit cross-sectional area of medium (solids plus pores); also called the *Darcy flux*.

*Groundwater, perched:* Unconfined subsurface water collecting on low permeability sediments that are separated from an underlying main body of groundwater by an unsaturated zone.

*Groundwater recharge:* The process involved in the addition of water to the phreatic zone; also, the amount of water added.

*Infiltration:* The movement of water across the ground surface into the subsurface.

*Monitored Natural Attenuation, MNA:* The monitoring of the attenuation of radionuclides, over time and space, due to natural processes (decay, dilution, sorption, hydrodynamic dispersion etc), in a manner that reasonably insures human health and the protection of the environment.

*Percolation:* The movement of water through a porous medium, such as soil or rock.

*Performance assessment:* A systematic analysis of the potential exposures posed by waste management systems to the public and environment, and a comparison of those exposures to established performance objectives.

*Performance-based regulation:* Regulations that are outcome-oriented rather than procedure-oriented.

*Performance objective:* A statement defining compliance with a system design or regulatory requirement.

*Performance indicator:* An observable metric used to determine whether or not a performance objective has been achieved.

**Comment [A8]:** This term is ambiguous. Do you mean a quantitative standard, or an observable quantity that is intended to be compared against such a standard? A little Google-ing shows examples of both senses.

*Performance threshold:* a quantitative criterion for each performance indicator that assures that performance objectives can be, or are being, met

*Phreatic zone:* The region below the water table where fluid gage pressure is greater than or equal to zero.

*Porosity:* The ratio of the volume of pores (or voids) in soil or rock to the total solid plus pore volume.

*Radionuclide release, abnormal:* The non-approved spill, leak, or accidental release of radionuclides to the environment that is not intended and uncontrolled.

*Radionuclide release, normal:* The pre-approved, monitored release of radionuclides to the environment, including permitted releases as well as non-permitted, controlled releases of low-level radioactive materials. Normal radionuclide releases should be as low as reasonably achievable (ALARA).

*Risk-significant:* When used to qualify an object, such as a system, structure, component, accident sequence, or cut set, this term identifies that object as exceeding a predetermined criterion related to its contribution to the risk from the facility being addressed. One that is associated with a level of risk that exceeds a predetermined significance criterion. *Saturated zone:* The zone in the subsurface where the pores are filled with water (phreatic zone plus capillary zone).

**Comment [A9]:** Define or eliminate. This is a really obscure term for a non-specialist.

*Subsurface:* All rock, soil, and fill material below the ground surface.

*Subsurface water:* Water contained within pores below the ground surface.

*System performance:* A quantitative measure of the ability of an engineered or natural system to meet performance objectives.

*Tritium:* A radioactive isotope of hydrogen, primarily found as part of tritiated water, HTO.

*Unsaturated zone:* The zone between the ground surface and the top of the capillary zone in which pores are not completely filled with water.

**Comment [A10]:** Suggested replacement: "A subsurface region where pores are filled partially with water and partially with air, most commonly the zone between the ground surface and the top of the capillary zone.". (An unsaturated zone can occur below perched groundwater.)

*Vadose zone:* The region between the ground surface and the water table where the water gage pressure is negative.

*Water table:* The water surface in an unconfined aquifer corresponding to zero gage fluid pressure.

## 3. Performance Assessment Methodology

This standard uses the performance-assessment methodology, which is an outcome-oriented process for providing credible, objective data and information about potential radiological exposures to the public and environment and for demonstrating whether or not these exposures comply with system design or regulatory requirements. Performance assessment uses site characterization and performance confirmation monitoring, along with conceptual and mathematical models, to understand the different geologic, hydrologic, physical, and chemical processes that affect system performance. This understanding is used to develop and evaluate alternative site designs, monitoring strategies, and closure procedures, with the objective of demonstrating the ability to meet system design or regulatory requirements.

**Comment [A11]:** Define.

System performance is used to assure that an engineered or natural system is able to meet system design or performance objectives. . In the context of this standard, the system is comprised of: (1) all facilities from which a release to the groundwater could occur, (2) all facility policies or procedures which may impact or cause a release, (3) the man-machine interface of a facility which may cause or contribute to a release, (4) all engineered barriers and leak detection systems, (5) a working or conceptual understanding of the local and regional geology and hydrogeology, and (6) all monitoring well networks and procedures for gathering and analyzing groundwater samples. Thus, system performance is a key feature of demonstrating compliance with regulatory requirements. In the context of evaluating subsurface radionuclide transport, a quantitative evaluation of system performance requires an understanding of the hydrogeologic and geochemical system. This understanding is based on characterization of the hydrogeologic system (including geochemistry), monitoring of system behavior, and simulation of flow and transport.

Specifically, a performance assessment establishes:

- The *regulatory requirements* for the facility or activity, including federal, state, tribal, and local rules and regulations;
- The *performance objectives*, which are defined outcomes that demonstrate compliance with system design or regulatory requirements;
- The *performance indicators*, which are observable metrics that are used to determine whether the performance objectives can be, or are being, met; and
- The *performance thresholds*, which are quantitative criteria for each performance indicator that assure that performance objectives can be, or are being, met.

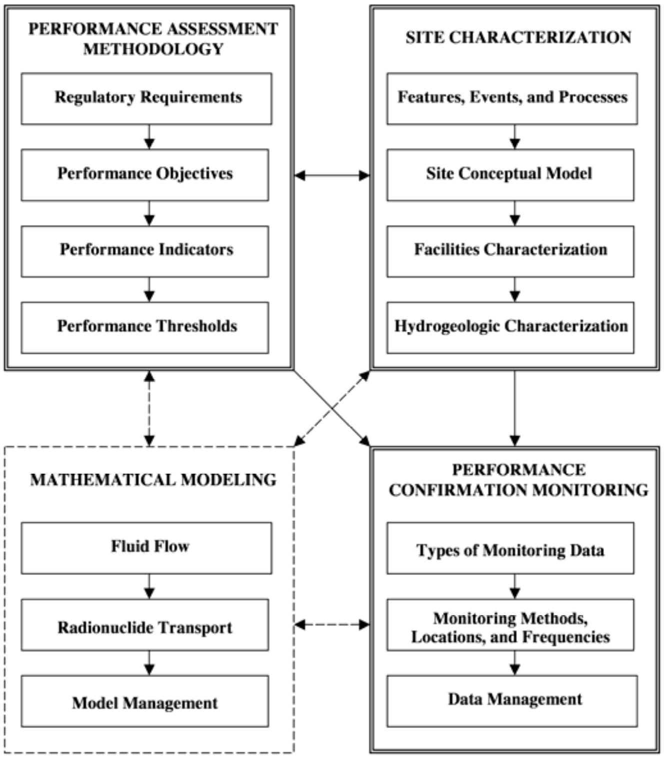

**Figure 1.** Flow chart describing relationships between performance assessment methodology, site characterization, performance confirmation monitoring, and mathematical modeling. Solid lines indicate mandatory activities, while dashed lines indicate where additional modeling efforts can be used when complex site conditions are present.

**Comment [A12]:** This figure should be referenced in the text. Also, it looks like boxes represent activities, and lines represent information flow or feedbacks.

**Comment [A13]:** Lines or boxes?

**Comment [A14]:** Since there is a two way link between the process blocks which is indicative of a repeating information flow, will it be possible to formulate an objective function from the performance objectives and optimize the process?

## 3.1 Regulatory Requirements

Regulatory requirements include those associated with facility design and permitting, operation, and closure. A range of regulatory requirements may exist for a specific site, including maximum or cumulative exposures, maximum concentration, etc., at a variety of different compliance points, including drinking water wells, boundary limits, the water table, etc., and over specific time periods. All relevant regulatory entities shall be consulted and specific regulatory programs and objectives related to groundwater protection shall be determined. It is advisable to discuss the specific site with all appropriate regulatory agencies prior to the preparation of the scope of work for evaluation of subsurface radionuclide transport. Regulatory agencies include the U.S. Nuclear Regulatory Commission, the U.S. Environmental Protection Agency, as well as interstate, state, tribal, regional, and local regulatory agencies and authorities.

## 3.2 Performance Objectives

A range of performance objectives should be used to demonstrate compliance with system design and regulatory requirements. Performance objectives correspond to critical outcomes that rely on site characterization, performance confirmation monitoring, and modeling efforts to demonstrate that system design and regulatory requirements are met. A likely performance objective is the absence of radionuclides in groundwater at concentrations that exceed a performance threshold. Demonstrating that a performance objective is met requires the selection of performance indicators, such as tritium concentrations in monitoring wells, and the specification of performance thresholds for those indicators, such as a radiological activity that statistically exceeds a specified level.

**Comment [A15]:** Much of this section is essentially duplicated in 3.4, below.

**Comment [A16]:** Definition needed.

**Comment [A17]:** The performance objective is described as a set of critical outcomes that rely on a set of factors. In the event a performance objective is not met, it might be necessary to consider regulatory action as mandated by law. In addition to the regulatory action, will the performance objectives prescribe outcome based mitigation guidelines in support of the overall goal?

## 3.3 Performance Indicators

Selection of performance indicators requires an observable metric that can be used to evaluate unambiguously whether a performance objective is being met. Tritium concentration is likely to be selected as a performance indicator because of its prevalence within nuclear facilities, and its high mobility. Other radionuclides can also serve as indicators and should be used if they are likely to be present and are mobile in the environment. Water quality parameters that may indicate a radionuclide release include specific conductance, pH, boron concentration, nitrate concentration, and turbidity. Physical measurements that may indicate a radionuclide release include water-level changes in the surficial aquifer, low spots or sumps, as well as groundwater temperature anomalies, increased seepage rates and increased soil moisture content.

**Comment [A18]:** See note at line 154.

## 3.4 Performance Thresholds

Deciding whether performance objectives have been met requires the specification of a performance threshold for each performance indicator. For example, deciding whether a radionuclide release has occurred might be based on a specific tritium concentration as a performance threshold. An observed concentration that statistically exceeds this threshold would trigger a sequence of responses depending upon the magnitude and extent of the release.

Performance thresholds should be based on the performance objectives and should be developed using knowledge of flow and transport at the site as incorporated in the site conceptual model, as well as the geochemical properties of the indicator. Exceeding the performance threshold should trigger either operational or procedural changes, design changes, increased monitoring (frequency and spatial density), or other corrective actions. Criteria that determine the performance threshold could be based on statistically significant deviations from local background concentrations or an alternative radiological threshold as defined by performance objectives. These criteria can be based on radionuclide concentrations (either volume-averaged or flux-averaged), travel times, mass fluxes, or predicted doses.

Evaluating whether performance thresholds have been exceeded can be based on performance indicators using monitoring data supplemented with modeling results. If monitoring data demonstrate that a performance indicator has exceeded its performance threshold, then a predetermined response should be invoked. Steps in a response include resampling and analysis, additional assessment (well integrity, analytic integrity), and installation of additional monitoring facilities (e.g., additional wells or geoprobes). If these steps are taken, and the performance threshold continues to show exceedance, then corrective action may be undertaken.

**Comment [A19]:** The trade name “Geoprobe” should be capitalized, or better replaced with “direct push samples”.

# 4. Site Characterization

The purpose of site characterization is to support performance assessment by providing data and information about the regional and local hydrogeologic system, as well as information about site facilities, as they may affect subsurface flow and transport. The degree of effort associated with the characterization effort will depend upon the complexity of geologic and hydrologic conditions, the types of radioactive materials and facility components present at the site, the types and effectiveness of engineered barriers, and the proximity to surface water and groundwater receptors. Thus, a multi-tiered strategy is prescribed herein that sets forth a minimum set of characterization activities at all sites, with additional efforts required at sites with greater complexity and receptor proximity.

## 4.1 Features, Events and Processes

Site characterization is intended to assist performance assessment by providing quantitative data and information quantifying the Features, Events, and Processes (FEPs) that control subsurface occurrence and movement of radionuclides. Defining the *features* requires an understanding of the overall system as defined previously, including site conditions and inventories along with the effects of radionuclide releases. Defining the *events* requires the ability to identify and define normal and abnormal radionuclide releases. Defining the *processes* requires the ability to specify the physical and chemical phenomena that determine the movement of water and radionuclides within the subsurface, as well as the pathways between the source and potential receptors.

The characterization effort shall identify features, events, and processes by:

- Identifying the *facilities* that contribute to, or affect the release of, radionuclides, including radionuclide sources, pathways, travel times, concentrations, and radiological exposure;
- Using regional and local hydrogeologic studies to define the *conceptual model*, which provides the framework for identifying and designing site characterization activities related to subsurface flow and radionuclide transport; and
- Providing quantitative data and information about *processes and parameters* that allows for the development of a mathematical (parametric) model that can be used to help understand and manage the geologic, hydrologic, and geochemical environment at the facility.

**Comment [A20]:** Reverse the first two bullet points to match the order of sections 4.2 and 4.3.

**Comment [A21]:** Before contamination, it is possible to identify potential facilities and sources of contaminations at a site, but it is impractical to identify all potential pathways, travel times and concentrations because simply there are too many. Therefore, during the planning stage, we consider the most severe accident only. After identifying a contamination, further detailed characterization will be possible. The standard needs to make clear that more than one stage of characterization may be necessary.

## 4.2 Site Conceptual Model

**Comment [A22]:** Sections 4.2 through 4.5 are specified in the Standard Review Plan (see reference in general comments). Discussions of groundwater and accidental releases are included in Sections 2.4.12 and 2.4.13 in the Final Safety Analysis Report (FSAR) for each site. The FSAR also includes most other site-specific information. Again, after a contamination happens, further detailed site characterization should be done for prediction and remediation of the contamination.

The site conceptual model provides the framework for identifying and designing site characterization activities (USNRC, 2003). As such it contains the fundamental assumptions used for understanding and describing the physical, hydrologic, and geochemical processes that affect the near- and long-term consequences associated with subsurface radionuclide releases.

The conceptual model shall define the geographic region of concern. It is likely that the region will include surface water basins (upstream and downstream), as well as those coastal areas or regional aquifers that are likely to be directly affected by radionuclide releases. Adjacent watersheds shall also be included in the conceptual model for those cases where subsurface flow between watersheds is likely to be present.

**Comment [A23]:** This word should be “cover”, or possibly “describe”.  The area was likely “defined’ (in the sense of being selected) by some prior activity, such as selection of the site.

The conceptual model shall define the significant regional hydrologic features, including relevant rivers and streams, lakes and ponds, wetlands, and estuaries. The local surface hydrologic features shall be identified, including perennial and ephemeral rivers and streams, lakes and ponds, wetlands, and estuaries.

The conceptual model shall define the significant geologic features, including the general stratigraphy and lithology, along with regional faults, fracture systems, conduits, and large voids, if present. The significant hydrogeologic units, including the aquifers and confining units (aquitards) shall be summarized and mapped. In addition, interactions between aquifers (leakage) and between surface- and ground-water systems (recharge and discharge) shall be described. Geochemical processes that may affect radionuclide occurrence and transport shall be described.

The conceptual model shall also be consistent with regulatory requirements, performance objectives, and performance indicators. This will require that the receptor locations, regulatory boundaries, and target aquifers be identified. While the water-table aquifer is likely to be the target aquifer to be protected, hydrogeologic conditions may warrant the identification of other hydrogeologic units, such as underlying confined and semi-confined aquifers, as well as the overlying vadose zone. The performance objectives shall be specified based on system design and regulatory requirements, with the goal being the ability to demonstrate that system design and regulatory requirements are met. Selection of performance indicators shall reflect the likely inventory of radionuclides, in conjunction with the likely scenarios that could result in an abnormal release. At a minimum, tritium shall be the performance indicator, with additional indicators selected based upon site-specific conditions.

Alternative conceptual models shall be proposed at complex sites (e.g., where fractures or heterogeneities may substantially affect transport behavior) as alternative hypotheses that are suitable for testing using additional characterization or monitoring data. Alternative interpretations regarding the major lateral, upper, and lower hydrologic boundaries of the unconfined aquifer and any other physical boundaries (e.g., surface-water bodies, surface outcrops, recharge boundaries) shall be provided if appropriate.

## 4.3 Facilities Characterization

This section focuses on those specific components, procedures, and processes of a nuclear facility for which a failure may occur, with the goal being to identify the failure modes along with the probabilities of failure of those components. This information will be used for specifying subsequent characterization, monitoring, and modeling efforts.

Radionuclide inventories shall be provided for each facility component from which a release to the subsurface could occur (spent fuel pools, holding ponds, condensate tanks, etc.). Locations of potential radionuclide releases shall be identified. The discharges, concentrations, activities, and loads of all radionuclide releases shall be provided. The locations of existing and likely future subsurface radionuclide plumes resulting from radionuclide releases shall be mapped. Regional groundwater and surface water uses and potential receptors shall be provided. Travel paths and travel times to potential receptors shall be provided.

**Comment [A24]:** This must be historical data.

Surface facilities (holding ponds, tanks, pipelines) shall be inventoried and their characteristics shall be provided. Subsurface facilities (including drains, pipes, conduits, backfill, pads, foundations, and the associated vadose zone) shall be inventoried and their characteristics (location, depth, size, etc.) shall be provided. Engineered barriers (cutoff walls, tell-tales, and interceptor wells) shall be inventoried and their characteristics (location, capacity, and monitoring frequency) shall be provided. All fill materials shall be inventoried and their characteristics (location, volume, hydraulic properties) shall be provided.

Well completion data shall be provided, including details of well construction, such as grouted and screen intervals, screens, casing type, depth, diameter, perforation, and surface seals, aquifers penetrated, location, elevation, use, owner, discharge rates, static hydraulic heads, and drawdown. Abandoned wells and piezometers used for site investigations should be identified and described and the method of abandonment shall be provided.

The hydrogeologic regime may be altered due to construction and ongoing facility modifications. Surface and subsurface modifications shall be catalogued and updated to reflect actual site conditions. Changes in groundwater conditions resulting from new and previous facility construction and operation, shall be provided. These changes may be due to groundwater control or foundation improvement activities such as installation of slurry trenches and rock grouting, and may include changes in hydraulic heads within pertinent aquifers, changes in hydraulic conductivity, and changes in the direction or quantity of groundwater flow. In addition, anticipated changes in water quality due to, for example, intrusion of saline water, stormwater or irrigation water infiltration, domestic and municipal wastewater disposal, and induced movement within or between aquifers shall be provided.

All facility policies and procedures that may affect the potential release and subsequent movement of radionuclides to the environment shall be identified.

## 4.4 Hydrogeologic Characterization

**Comment [A25]:** “Hydrogeologic Characterization of Processes and Parameters”

A wide range of site hydrogeologic characterization activities is required to accurately describe the important processes and parameters at a site. These activities will assist in performance assessment, by guiding the specification of performance objectives, indicators, and thresholds. The data and information will also assist in determining the appropriate monitoring frequency and locations, and for providing parameters required for mathematical modeling. Data from regional studies shall be used to plan the detailed site studies. Some characterization activities may duplicate other ANS studies, and can be utilized. Additional technical documents related to groundwater characterization are available, including USNRC (1988) and NEI (2007).

**Baseline Conditions.** Ambient subsurface flow conditions are needed to establish a baseline against which future conditions can be compared. Characterization of hydraulic head, hydraulic head gradients (flow magnitude and direction), and the natural variation and bounds of these estimates shall be provided for the unconfined aquifer, and for the uppermost confined aquifer, if present. A general description of hydraulic conditions in the vadose zone and possible limiting behavior (e.g., potential flooding or full saturation) shall be provided as well.

**Comment [A26]:** Insert following after: "Conditions shall be monitored long enough and frequently enough to define the probable range of variations."

Hydraulic heads in nearby surface waters (e.g., rivers, lakes, wetlands, springs, estuaries, bays, oceans) shall also be provided and compared with subsurface observations. The relationships between observed surface water and subsurface hydraulic heads shall be used to estimate the average and range of hydraulic head response, as well as their effects on the magnitude and direction of subsurface transport at the facility. For sites where aquifer hydraulic heads are affected by changes in surface loading (e.g., precipitation, barometric pressure, streamflow, tidal fluctuations, cooling water intake and discharge canals), then the response to these processes shall also be quantified.

**Comment [A27]:** The baseline data and characterization need to address the unique hydrogeologic setting of coastal aquifers by gathering data and prior modeling results for submarine discharges and tidal influence on the hydraulic head in the aquifer as well as the variable density of flow in the presence of saltwater intrusion.

A water budget for the site shall be prepared showing the precipitation, evapotranspiration, runoff, recharge and discharge. The recharge-discharge relationships between surface water and groundwater (and between aquifers, if appropriate) shall be estimated. Local and regional groundwater recharge and discharge areas shall be identified and mapped. The temporal variation in these areas shall be estimated for both short- and long-term interactions. Interactions include artificial recharge from past and current site operations, as well as natural recharge from direct infiltration of precipitation, surface water, and site runoff. Long-term changes in regional recharge and discharge that affect radionuclide transport shall be projected for several periods over the facility lifetime (e.g., at 10-year intervals) and for various conditions of aquifer recharge and discharge.

**Physical Properties**. The physical properties of hydrogeologic units appropriate for understanding and predicting radionuclide transport at the site shall be provided. Of primary interest are the physical properties that affect flow and transport characteristics, including the total and effective porosity, pore and grain size distributions, and solids surface area. Special interest shall be placed on the physical properties of features that may compromise system performance, such as fractures and large conduits, including their frequency, dimensions, orientation, and interconnectivity. Spatially explicit data shall be collected, using continuous soil or rock samples as well as surface and subsurface (borehole) geophysical methods.

**Hydraulic Properties.** Characterization shall be performed for those hydrogeologic units that significantly affect radionuclide transport. One or more test borings shall be performed, some of which should be used to collect continuous core through the unconfined aquifer, and the underlying confining bed and confined aquifer, if present. Borehole geophysical logs should be collected from selected test borings. In-hole flow tests should be conducted in selected test borings to identify zones with higher flow rates.

**Comment [A28]:** In-hole horizontal and vertical …

**Comment [A29]:** … borings, if appropriate, to identify …

**Comment [A30]:** It isn't clear here whether tests under natural flow conditions or under pumping conditions, or both, are being recommended.

Quantitative estimates of relevant hydraulic parameters (e.g., hydraulic conductivity, transmissivity, specific storage, storativity, leakance) shall be provided using aquifer tests (e.g., single and multiple borehole pumping tests, slug tests, specific capacity tests, falling/rising head tests, borehole flowmeter tests), surface and borehole geophysical and geotechnical investigations along with associated monitoring. For anisotropic media, the directional components of hydraulic properties shall be provided. Special interest shall be placed on the hydraulic properties of features that may compromise system performance, such as fractures and large conduits. Vadose zone characteristics shall be provided, including moisture characteristic curves and the unsaturated hydraulic conductivity functions, if they substantially affect radionuclide transport. A practical way to accomplish this is to use the Van Genuchten functions based on particle size distributions (Schapp et al., 2001).

Estimates of ambient flow magnitudes and directions shall be provided for a range of hydrologic conditions. These estimates should be confirmed using tracer or borehole (e.g., in situ borehole flow-meter) methods.

**Geochemical Properties.** Sufficient data shall be provided to define the fluid chemistry and potential reactions of formation fluids and solids with released fluids. Appropriate transport characterization parameters (e.g., total ion-exchange capacity, distribution coefficients, pH, redox) shall be provided for performance indicators that are affected by geochemical processes.

**Transport Properties.** Sufficient data shall be provided to define the normal and abnormal background concentrations of the performance indicators, likely to be tritium and/or another radionuclide, at and near the facility. Natural background concentrations in both soil and groundwater shall be determined, as well as regional background concentrations that account for anthropogenic activities. Regional trends shall be evaluated with respect to these sources.

The spatial and temporal variability of concentrations of performance indicators in precipitation, surface water, and groundwater shall be provided in a format that allows for the specification of performance thresholds.

Water quality data should also be collected for resolving ambiguities in the conceptual model, such as to identify modes of recharge to the aquifers, flow within complex hydrogeologic environments, and to assess the interaction of groundwater between geologic formations. Tracer tests can also be performed to resolve ambiguities in the conceptual model

# 5. Performance Confirmation Monitoring

The purpose of monitoring is to support performance assessments by providing assurance that the facility complies with performance objectives and meets necessary state and federal regulatory standards. This over-arching purpose can be broken down into specific monitoring objectives, including:

- Determining the source, magnitude, migration rate, and potential exposures associated with a detected release; and
- Providing data useful for conceptual and mathematical modeling, supporting hydrologic parameter estimation, and determining whether a radionuclide release has occurred.

**Comment [A31]:** Insert bullet: "Determining the seasonality of monitored results and the interdependence on release patterns and local hydrometeorology."

Both monitoring efforts are critical – the first is reactive in the sense that data are critical for guiding interdiction when a release has been detected, and the second is proactive in the sense of that data are critical to designing, installing, and maintaining an active monitoring program.

## 5.1 Types of Monitoring Data

Tritium will likely be the key performance indicator that will be used to demonstrate compliance with performance objectives. In addition to tritium, monitoring for other radionuclides will depend upon the anticipated inventory or release scenarios at the site, along with other factors including the solubility, mobility, and volatility of the radionuclide. Screening measurements (e.g., gross alpha, gross beta, total gamma activity) should be used as an indicator of radionuclide presence. Additional water analytes (e.g., temperature, specific conductance, pH, turbidity, dissolved oxygen, redox, boron) should be used as indicators of radionuclide release based on knowledge of the source term.

**Comment [A32]:** These three terms need to be defined in Section 2.

Physical changes in the local hydrology should be used to provide an early indication of radionuclide releases. Changes in the hydraulic head or flow in the absence of corresponding natural hydrologic events could serve as warnings for a radionuclide release.

**Comment [A33]:** Insert paragraph after: "Sampling methods and equipment shall be standardized and documented as early as possible in the monitoring program in order to avoid spurious variation in monitored parameters resulting from inconsistent sampling techniques. The importance of this point cannot be over-emphasized."

## 5.2 Monitoring Methods, Locations, and Frequencies

**Comment [A34]:** This section should address the sampling frequency in time, including relevant scientific bases and regulatory standards for radionuclides. Also needed is a discussion of sampling accuracy and errors.

While water samples have traditionally been collected from permanent, long screen monitoring wells or piezometers, vertical ambient flow in such wells may compromise water samples (Elci et al., 2001, 2003). In place of long-screen wells, various types of multilevel sampling wells are available, along with methods for converting long-screen wells into multi-level samplers. Water samples from these intervals shall be collected using a variety of sampling devices (portable pumps, dedicated pumps, bailers, etc.) and sampling techniques (purging multiple well volumes, low flow sampling, no purge sampling) from wells installed to meet regulatory compliance and performance standards.

**Comment [A35]:** Insert after: "Samples shall be taken over short vertical intervals whenever possible."

**Comment [A36]:** … the most appropriate from among the available …

Gas-phase sampling should be used to determine the presence of volatile radionuclides, such as tritium, carbon-14, helium-3, and iodine-129. Samples are normally taken to laboratories for analysis.

**Comment [A37]:** Delete.

Water quality monitoring should be performed *in situ*, where appropriate, using dedicated water-quality probes (e.g., temperature, specific conductance, pH, turbidity, dissolved oxygen, redox, gross alpha, gross beta, gamma). *In situ* probes allow for the early detection of hydrologic changes resulting from radionuclide releases.

The hydraulic head shall be monitored using pressure transducers or capacitance probes placed in nested piezometers installed at multiple depths in the saturated zone, and by using tensiometer probes in the unsaturated zone. The hydraulic head in the unsaturated zone should be inferred, where appropriate, using soil moisture content (e.g., time-domain reflectometry) in conjunction with moisture characteristic curves. Fluid flow (velocity or flux) in and out of wells in saturated media should be monitored using borehole flow meters. Flux through partially saturated media should be inferred using capture-type lysimeters.

The number and location of monitoring wells needed to evaluate performance objectives depends upon site conditions. At a minimum, monitoring of performance indicators shall be performed within the surficial (unconfined) aquifer. Where appropriate, additional monitoring within underlying confined aquifers and the overlying vadose zone shall also be performed. Additional monitoring in fractured media or where subsurface voids are present shall be performed if these formations affect flow and transport as defined by the FEPs. The monitoring requirements must meet the necessary compliance as per applicable state and federal standards.

At least one multi-level sampling well shall be placed upgradient of the facility to provide local background water quality data. Additional monitoring wells shall be placed downgradient of those components identified in the characterization of operating facilities from which releases may occur. The number and location of the wells should be sufficient to detect significant water-quality changes due to radionuclide releases from those facilities. The design, installation, and maintenance of the monitoring system shall be parsimonious, in that tradeoffs between an increased number of monitoring locations shall be balanced by the need for detailed data collection in each well.

The location of these wells shall also consider the location of the compliance boundary and intermediate compliance points. Wells shall be close enough to the components from which a release to the subsurface may occur to assure that contamination is detected while it is still relatively close to its source and manageable. However, wells should not be located so close to structures that their existence interferes with normal operations. Likewise they should not be placed in areas where the surrounding infrastructure interferes with sampling and maintenance.

Care shall be taken to assure that plumes do not escape detection by traveling along unmonitored flowpaths. The further the wells are from the facility, the more important it will be to consider the likely vertical trajectory of possible contaminant plumes. In many cases it will be necessary to sample more than one vertical horizon at an individual location. This is most commonly done by installing multiple wells. There are various widely accepted methods for installing multiple, vertically discrete sampling points within a single well.

Spatial heterogeneity due to natural geologic conditions (e.g., large voids, fractures, conduits), as well as construction-induced heterogeneities, may introduce substantial uncertainties due to rapid transport in localized regions. Surface and subsurface geophysical techniques are available for characterizing these heterogeneities, including hydraulic, tracer, seismic, and electromagnetic techniques. Monitoring strategies in heterogeneous media shall be justified.

Short-duration releases may not be detected if transport is rapid and sufficient temporal sampling resolution is not provided. Automated data-logging capabilities are available for collecting water-level, water-quality, and gas-phase data at selected frequency and precision. These may be connected wirelessly to provide real-time monitoring data capability.

**Comment [A38]:** … sampling is not sufficiently frequent. Sampling shall be at short enough intervals to detect brief releases.

Engineered barriers may offset the need for additional monitoring locations. The establishment of a no-flow perimeter (i.e., a capture zone) surrounding potential release sites is one method for containing and detecting releases. Appropriately designed and installed extraction wells or vapor-capture systems with ancillary monitoring equipment could provide an early warning system for both water in the saturated zone and tritium vapor in the unsaturated zone, respectively. This system could also be used for corrective action by maintaining positive control if a release is detected. The capture zone should be designed in conjunction with other engineered-barrier and leak-detection systems.

## 5.3 Data Management

A robust quality assurance / data quality assessment process shall be used to assure that data-quality objectives are met. Quality assurance and control programs shall be used for collected data. Estimates of field and laboratory analytic uncertainties shall be provided. Specification of sampling and analysis protocols should be performed in conjunction with the Performance Assessment paradigm. Data analysis and archival should be key elements in defining data quality objectives. Defense in depth using multiple redundant sampling protocols along with independent monitoring systems should be employed.

**Data Quality.** Field monitoring equipment installation and sampling methods should adhere to standard methods as defined by ASTM International (previously known as the American Society for Testing and Materials) and National Ground Water Association guidelines whenever practicable. Data precision can be assessed using field duplicates and laboratory replicates. Data accuracy can be assessed using calibration standards, matrix spikes, and blanks. Data completeness can be assessed by comparing the number of valid measurements with the planned number of analyses. Multivariate statistical analysis of the data can be employed to identify Type I and Type II errors as well as bias corrections.

**Data Limitations.** Minimizing data limitations assists in conceptual model development and computer model implementation. Efforts should be taken to quantify and minimize sources of uncertainty including, but not limited to, well construction (e.g., casing integrity, screen locations, inadvertent pathways, grout contamination, insufficient water, etc.) and sampling protocols (e.g., low flow sampling, pumping vs. static monitoring, sample representativeness, etc.).

**Geographic Information.** All geographic information shall be geo-referenced, stored in a retrievable electronic format, and presented using a geographic visualization platform. Time-series data shall be stored in a retrievable electronic format and plotted. Statistical characterization, including trend analysis, shall be provided for all performance indicators. Data and information updates shall be performed routinely.

**Comment [A39]:** Geographic and Time-Series Information

**Parameter Databases.** Parameter databases shall be based on a consensus interpretation of the available data. Methods and approaches used to develop the parameter estimates should also be described. The database should include all information necessary to develop parameter distributions based on geologic data (e.g., geometry of the main hydrogeologic units), hydraulic property estimates, boundary conditions, initial conditions, locations and volumes of sources and sinks, and natural recharge estimates. Such a database shall contain the basic geologic and hydrologic information that provides the basis for the conceptual model, as well as the key interpretations of geologic and hydrologic data and information, including descriptions of methods and approaches used to make interpretations. The database and data interpretations shall be updated, as new data on both the local and regional scale become available. The database should be stored in a form independent of the method used to obtain the estimate or the assumptions made for the particular study.

# 6. Mathematical Modeling

The purpose of mathematical modeling to assist in assessing the performance of groundwater protection programs, which is particularly important at sites where complex hydrogeologic conditions are present, or where uncertainties in the site conceptual model preclude direct interpretation of field data. The ultimate modeling goal is to develop the capability to understand and predict system behavior.

An important advantage of simulation modeling is the capability to provide a framework for reconciling the conceptual model with characterization and monitoring data, as well as to provide simulations of system behavior in a timely manner that demonstrate compliance with performance objectives.

During the design/permitting stage, model simulations will be an important tool for demonstrating facility safety, with characterization and monitoring data being used to establish model accuracy. During the operational stage, monitoring data will be used to demonstrate the continuing safety of the facility, with model simulations being used to facilitate monitoring data interpretation for circumstances when monitoring data are ambiguous, or do not provide sufficient confidence in system performance.

**Comment [A40]:** Insert after: Operation plans must specify that the model will be updated and compared with monitoring data at regular intervals.

Defining specific model objectives shall be the first step of model development. Possible model objectives include, but are not limited to:

**Comment [A41]:** The statements before and after this point are by and large replicative.

- Providing an integration tool for documenting and analyzing hydrogeologic processes and assumptions,
- Reconciling characterization and monitoring data with site conceptual models,
- Evaluating trends and identifying anomalies or radionuclide releases, and predicting contaminant plume migration,
- Planning, designing, and evaluating monitoring and remediation strategies,
- Estimating the effects of facilities on the hydrologic system,
- Performing radiological exposure assessments.

The mathematical model shall consider the physical and chemical processes and parameters relevant to the flow and transport of radionuclides at the site. The level of effort associated with mathematical modeling shall vary with the degree of uncertainty in the underlying conceptual and mathematical model, and the proximity to receptors. The model may range from a simple analytic equation that can be solved manually, to a complex set of differential equations that must be solved numerically.

Model scope should address the appropriate features, events, and processes, and shall provide documentation to support the relevant level of model complexity, including as required heterogeneities, scale effects, transient perturbations, etc. It shall also specify the level of model accuracy using a documented process of model testing and evaluation. The analytic or numeric methods for model

**Comment [A42]:** Insert after: Model simulations of individual sets of parameter values ("model runs") shall be documented. Documentation shall be in the form of formal documents or standardized documentation packages to ensure its preservation. Documentation of runs shall include their objectives, input values, results, and interpretation of the results.

implementation should be defined for both fluid flow and radionuclide transport. The model selection process shall match relevant processes with code capabilities, data needs with data availability, flow and transport implementations with site conditions.

While monitoring data provide important checks on system performance, mathematical modeling is needed to extrapolate observations and to evaluate the adequacy of characterization efforts. This paradigm is iterative and interdependent, in that monitoring data are used to support conceptual and mathematical modeling assumptions, and models are used to identify the scope of monitoring efforts. Assuring that the appropriate conceptual and mathematical models are being used requires the ability to test the model against characterization and monitoring data.

**Comment [A43]:** "… support and test conceptual …

**Comment [A44]:** "… these models …"

While monitoring is likely to be the primary means for detecting the occurrence and extent of an abnormal release, modeling is another useful tool that can quantify where and how far a release has moved if an abnormal release is suspected. Model predictions are dependent upon the site conceptual model, which may be ambiguous. Thus, an iterative, ongoing effort toward reconciling modeling results with monitoring data is required. Model forecasts should be compared with monitoring data, and vice versa. In essence, one can view the iterative and interdependent process as computer-aided analysis (modeling) that is continuously refined by measurements (monitoring). Additional monitoring locations or characterization activities may be required to distinguish between alternative conceptual models.

## 6.1 Fluid Flow

The mathematical model shall reasonably and conservatively simulate groundwater flow as defined by the conceptual model and performance objectives. At a minimum, the model shall be able to accurately simulate water flow in the unconfined aquifer. For more complex systems, additional capabilities may be required to account for liquid, vapor, and gas fluxes in the unsaturated zone, dual porosity through heterogeneous media, or regional flow through confined aquifers and confining layers below the unconfined aquifer.

**Spatial Scale of Analysis**. The physical domain of the model shall be established by defining the horizontal and vertical extent and boundary conditions for the model. The model extent should be large enough such that potential onsite and near-boundary receptor locations are included within the model. Incorporation of the lateral extent and thicknesses of the major hydrogeologic units identified in the site conceptual model are necessary to accurately simulate past, present, and future behavior of the subsurface flow and contaminant transport. The model shall also have the capability to represent the major sub-units identified in the major hydrogeologic units. The model extent should also be established based on linkages to performance objectives, existing and proposed monitoring locations, as well as zones where remedial actions are proposed, or are likely should the vadose zone or uppermost aquifer(s) receive contaminants. The model shall be sufficiently detailed such that features that may affect flow and radionuclide transport can be resolved.

**Temporal Scale of Analysis**. Flow conditions may change significantly over time due to changing site operations, boundary conditions (recharge, discharge), and land use. The model shall have the capability to effectively simulate flow and contaminant transport on a variety of time scales. The expected simulation period shall be established by defining the historical and predictive simulation periods. The historical simulation periods are used for initial model calibration. Routine predictions are compared against monitoring data. Both the historical and predictive periods shall be consistent with the established model objectives and available data.

**Flow Geometry**. While subsurface flow generally occurs in three spatial dimensions, reasonable approximations of flow can be achieved using fewer dimensions in many cases (e.g., horizontal, two-dimensional flow through confined aquifers and vertical one-dimensional fluid flow through aquitards and the unsaturated zone). A justification shall be provided if lower-dimension geometries are used. In highly heterogeneous environments, a dual porosity model may be necessary.

**Flow Parameters**. The mathematical model shall incorporate those flow parameters relevant to the conceptual model. The model shall represent the spatial variability of these parameters as determined using characterization and monitoring data. In addition, site-specific components (sources, backfill, geotechnical properties) shall be included, along with the characteristics of natural and induced preferential pathways.

**Comment [A45]:** Use “artificial fill”. “Backfill” is material used to refill an excavation, but we may have to deal with fill placed on the natural ground surface as well.

**Hydrologic Boundaries**. If appropriate, the model shall be capable of incorporating time-dependent and spatially varying Dirichlet (constant head or concentration) and Neumann (fluid or mass flux) boundary conditions. Also if appropriate, the model shall be able to simulate time- and space-dependent sources and sinks of water and contaminants. A head-dependent flux boundary condition may be useful to explore local flow conditions. If appropriate, the model should interface with vadose zone and surface water model(s) by assigning appropriate boundary conditions specifying water and contaminant fluxes.

## 6.2 Radionuclide Transport

Tritium transport can be assumed to behave as a conservative tracer. Where the transport of other radionuclides and chemical constituents must also be modeled, then additional transport processes shall be included. Where appropriate, the model shall be capable of simulating contaminant fluxes in aqueous, sorbed, vapor, and gaseous phases as a function of driving hydrologic processes and mass-transport phenomena, including advection, diffusion, volatilization, hydrodynamic dispersion (longitudinal and transverse), adsorption, and radiological decay.

**Comment [A46]:** radioactive

**Contaminant Retardation**. If needed to support transport calculations, the model should be able to support simulation of geochemical retardation on a contaminant-specific basis. Use of the linear equilibrium adsorption model would meet the intent of this requirement, but justification of the linear isotherm approach to represent the process of adsorption for specific contaminants shall be necessary. The capability to allow adsorption to vary not only by contaminant, but also spatially (i.e., to be a function of the contaminant and of the hydrogeologic unit in which transport occurs) is desirable.

**Dispersion and Molecular Diffusion.** If needed to support transport calculation, the model should be able to support simulation of dispersion and molecular diffusion on a contaminant-specific basis. Use of a constant dispersivity would meet the intent of this requirement, but justification of a constant dispersivity shall be necessary.

**Radioactive Decay**. If needed to support transport calculations, the model should be able to simulate the effect of first-order radioactive decay. The capability to simulate first-order radioactive decay is a requirement for the majority of radioactive constituents of concern in predictive contaminant-transport calculations. This capability may also be useful in estimating the effect of chemical degradation if the degradation process can be approximated using this type of decay function. Chain decay is not considered a significant process for most of the mobile radioactive constituents. However, there may be a few instances where the capability to calculate the effect of chain decay in transport simulations would be a desirable feature, particularly in cases where the decay products are more mobile or have greater toxicity than the parent.

**Flowpath Modeling**. If needed to support transport calculations, the model shall be capable of efficiently performing streamline (for steady-state conditions) and pathline (for transient conditions) analyses in two and three dimensions. Prediction of contaminant migration requires additional information about the effective porosity and sorption capabilities. A rigorous evaluation of contaminant concentration modeling capabilities requires the use of tracers that more accurately represent likely radionuclide sources. Comparisons of model predictions with monitored concentrations in piezometers and suction lysimeters can be used for model evaluation.

**Reactive Transport**. If needed to support transport calculations, reactive transport models should be able to simulate complex contaminant-transport behavior in the vicinity of certain facility and contaminant release locations, yet the use of reactive transport models is not presently viewed as practical because of substantial geochemical data and computational requirements.

**Comment [A47]:** Add after: “When such models become practicable, their use should be considered in appropriate circumstances.”

## 6.3 Model Management

Multiple computer codes may be required to address all migration pathways of concern. Each code should be fully documented, along with the relationships between codes.

**Model Calibration.** A description of the model calibration procedures shall be provided. Calibration data sets and assumptions shall be provided. Differences between model predictions and field observations shall be discussed.

**Model Updating**. The conceptual and mathematical model is to be a flexible and evolving platform for analyzing flow and contaminant transport at the site; as more data are collected, it is likely that new predictive capabilities will be desired. The adopted model framework shall be one in which new concepts can be tested and enhancements readily included.

**Model and Data Uncertainty**. Uncertainty accounts for those factors that introduce imprecision in model predictions, including geologic variability, measurement error, conceptual model ambiguity, and numerical errors. Uncertainties in the specification of the appropriate conceptual model determine the required scope of characterization, while the evaluation of alternative conceptual models requires characterization data that provide sufficient information for model specification. Additional characterization data are required where numerical model structure is ambiguous, or where model parameters are uncertain. The scope of characterization data collection is a function of the complexity in the geologic environment, along with uncertainty in background conditions.

**Comment [A48]:** Suggested rewrite: “Model predictions are imprecise because of uncertainty about various factors, …”

**Comment [A49]:** Clarify that “characterization” refers to obtaining enough accurate field data to improve the model to the extent necessary.

**Uncertainty Characterization**. The modeling shall provide for explicit acknowledgement and estimation of uncertainty with respect to the databases, model, and code. Strategies to reduce uncertainties include statistically-based optimization techniques for parameter estimation, sensitivity analyses, and Monte-Carlo simulations. The specification of how uncertainty is incorporated into model development and model-based analyses is also required, especially with regard to how uncertainties will affect monitoring network design, decision criteria, corrective-action strategies, and predictive analyses. Information is needed on how uncertainty is characterized, including its sources and significance, explicit vs. implicit margins of safety, a bounding-approach vs. best-estimate (expected value) approach, use of stochastic (Monte Carlo) methods, etc. Model uncertainties shall be related to model calibration and explicitly linked to decision criteria.

**Comment [A50]:** Identify and analyze sources of both epistemic uncertainty – that is, uncertainty about our actual knowledge - and aleatory uncertainty – uncertainty due to future random events. Also, identify risks associated with uncertainty.

**Configuration Control**. The model, including the databases supporting the conceptual model and its numerical implementation, shall be maintained under configuration control. Because the conceptual model will provide the framework for all modeling performed on the site a common model database shall be maintained containing all the information necessary to establish the pedigree of the most current version of the model.

**Comment [A51]:** computer code?

**Comment [A52]:** Single? Central? Unified? The sense seems to be that one database should be used to track all variants of the model’s computer code and supporting databases, but not including the model input data, which will be tracked separately with appropriate cross-references to the model configuration database.

**Code Verification**. Evidence of code verification shall be available. The verification provides evidence that the solution methods used in the model are correct and shall demonstrate the effect of the assumptions and potential errors arising from limitations of the model. Verification evidence shall include comparison of model results for a variety of known or accepted solutions. A published history of previous model applications shall exist. Prior applications shall demonstrate that the model is well regarded among the user and regulatory community. In particular, the model shall be acceptable to the EPA, NRC, state and other regulatory bodies.

**Model Availability**. The code, along with model inputs and analyses, should be publicly available at a reasonable cost.

**Comment [A53]:** You need to clarify whether you are referring to source code or executable code. Also, where feasible, models whose source code is publicly available should be preferred over proprietary models. This is in part because rapid changes in computer technology are almost certain to make proprietary models unusable within the life of the nuclear power plant.

# References

Aral M, 1990, “Groundwater Modeling in Multilayer Aquifers”, CRC Press.

ASTM, 1996, “Analysis of Hydrologic Parameters and Groundwater Modeling”, ASTM International.

ASTM, 1999, “Determining Subsurface Hydraulic Properties and Groundwater Modeling”, Second Edition, ASTM International.

Boulding JR, JS Ginn, 2003, “Practical Handbook of Soil, Vadose Zone, and Groundwater Contamination: Assessment, Prevention, and Remediation”, Second Edition, CRC Press.

Chien CC, Jr, MA Medina, GF Pinder, DD Reible, B Sleep, C Zheng (eds.), 2003, “Contaminated Groundwater and Sediment: Modeling for Management and Remediation”, Proceedings of a workshop on Modeling and Management of Emerging Environmental Issues: Expert Workshop 2000, Malvern, PA, July 25-27, 2000, CRC Press.

Colin F, Ph Quevauviller, 1998, “Monitoring of Water Quality”, Elsevier Science.

CRWMS M&O (Civilian Radioactive Waste Management System Management and Operating Contractor) 2000. “Total System Performance Assessment for the Site Recommendation”, TDR-WIS-PA-000001 REV 00 ICN 01. Las Vegas NV.

Driscoll FG, 1986, “Groundwater and Wells”, Second Edition, Johnson Filtration Systems, Inc., St. Paul MN.

Elci, A., F.J. Molz and W.R. Waldrop, 2001, “Implications of Observed and Simulated Ambient Flow in Monitoring Wells”, Ground Water, 39, 853-862.

Elci, A., G.P. Flach and F.J. Molz, 2003, “Detrimental Effects of Natural Vertical Head Gradients on Chemical and Water Level Measurements in Observation Wells: Identification and Control”, Journal of Hydrology, 281, 70-81.

Evans DD, TJ Nicholson, TC Rasmussen (eds.), 2001, “Flow and Transport through Unsaturated Fractured Rock”, Second Edition, Geophysical Monograph 42, American Geophysical Union, Washington, DC.

Faybishenko B, PA Witherspoon, SM Benson (eds.), 2000, “Dynamics of Fluids in Fractured Rock”, Geophysical Monograph 122, American Geophysical Union, Washington, DC.

Freehley CE, C Zhen, FJ Molz, 2000, “A Dual-Domain Mass Transfer Approach for Modeling Solute Transport in Heterogeneous Porous Media, Application to the MADE Site”, Water Resources Research, 36:2501-2515.

Gallegos DP, 1991, “A Performance Assessment Methodology for High-Level Radioactive Waste Disposal in Unsaturated, Fractured Tuff”, NUREG/CR-5701, SAND914539, U.S. Nuclear Regulatory Commission, Washington DC.

IAEA (International Atomic Energy Agency), 1999, “Safety Assessment for Near Surface Disposal of Radioactive Waste”, Safety Standards Series WS-G-1.1, Vienna.

Mercer JW, 1992, “Groundwater Modeling”, National Groundwater Association.

NEI (Nuclear Energy Institute), 2007, “Industry Ground Water Protection Initiative – Final Guidance Document”, NE 07-07, Nuclear Energy Institute, Washington DC.

Nielsen DM (ed.), 2006, “Practical Handbook of Environmental Site Characterization and Groundwater Monitoring”, Second Edition, Taylor & Francis Group, CRC Press, Boca Raton.

NRC (National Research Council), 1990, “Groundwater Models: Scientific and Regulatory Applications”, Committee on Groundwater Modeling Assessment, National Academy Press, Washington DC.

Price V, T Temples, J Tauxe, R Hodges, R Falta, 2007, “Integrated Ground-Water Monitoring Strategy for NRC-Licensed Facilities and Sites: Logic, Strategic Approach and Discussion”, NUREG/CR-6948, Volume 1, Division of Fuel, Engineering and Radiological Research, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, Washington DC.

Schaap MG, FJ Leij, MT Van Genuchten, 2001, “ROSETTA: A Computer Program for Estimating Soil Hydraulic Parameters with Hierarchical Pedotransfer Functions”, Journal of Hydrology, 251:163-176.

Shum E., RJ Starmer, MH Young. 1990. Environmental Monitoring at Low- Level Radioactive Waste Disposal Facilities, NUREG-1388, U.S. Nuclear  Regulatory Commission, Washington, DC.

Stephens DB, 1996, “Vadose Zone Hydrology”, CRC Press, Boca Raton, FL.

USEPA (U.S. Environmental Protection Agency), 1994, “RCRA Groundwater Monitoring: Draft Technical Guidance”, U.S. Environmental Protection Agency.

USNRC (U.S. Nuclear Regulatory Commission), 1988. “Standard Format and Content of a License Application for a Low-Level Radioactive Waste Disposal Facility - Safety Analysis Report. Rev. 1”, NUREG-1199, Washington, D.C.

USNRC (U.S. Nuclear Regulaotyr Commission), 1990, “Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants”, NUREG-1150, Volume 1, Washington DC.

USNRC (U.S. Nuclear Regulatory Commission), 2003, A Comprehensive Strategy of Hydrogeologic Modeling and Uncertainty Analysis for Nuclear Facilities and Sites, NUREG/CR-6805

Wang HF, MP Anderson, 1995, "Introduction to Groundwater Modeling: Finite Difference and Finite Element Methods", Academic Press.

Ward RC, GB McBride, JC Loftis, 2004, "Design of Water Quality Monitoring Systems", John Wiley & Sons.