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American National Standard

Evaluation of Subsurface Radionuclide Transport at Commercial Nuclear Power Production Facilities

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American National Standard

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Foreword

(This Foreword is not a part of American National Standard "Evaluation of Subsurface Radionuclide Transport at Commercial Nuclear Power Production Facilities", ANSI/ANS-2.17-201X.)

This standard constitutes a major revision of the original standard, ANSI/ANS-2.17-1980, which was adopted on April 9, 1980, reaffirmed on October 3, 1989, and withdrawn on July 28, 2000.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-2.17 of ANS-25 Subcommittee (Siting: Environmental & Emergency Preparedness) of the American Nuclear Standards Committee, was constituted November 2005 to revise the original standard.

This standard might reference documents and other standards that have been superseded or withdrawn at the time the standard is applied. A statement has been included in the references section that provides guidance on the use of references.

This standard mentions, but does not exhaustively describe, the concepts of generating risk-informed insights, performance-based requirements, and a graded approach to quality assurance. The user is advised that one or more of these techniques could enhance the application of this standard.

Two appendices are provided to assist practitioners who would implement the guidance in this standard. Appendix A provides information on relevant U.S. Nuclear Regulatory Commission regulatory criteria and guidance, and its Table A provides a listing of standard documents (e.g., ANS, ASTM, ISO, etc) for conducting subsurface radionuclide transport characterization, monitoring, and modeling programs. Appendix B provides tables that summarize information and parameters identified in the guidance.

The ANS-2.17 Working Group of the Standards Committee of the American Nuclear Society had the following membership:

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This standard was prepared under the guidance of Subcommittee ANS-25, Siting: Environmental & Emergency Preparedness, of the American Nuclear Society. At the time of the ballot, Subcommittee ANS-25 was composed of the following members:

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[1] The working group would like to gratefully acknowledge the contributions by G.S. "Bo" Bodvarsson, who died prior to the completion of this standard.

The standard was processed and approved for submittal to ANSI by the Nuclear Facilities Standards Committee (NFSC) of the American Nuclear Society. Committee approval of the standard does not necessarily imply that all members voted for approval. At the time it approved this standard the NFSC had the following membership:

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Contents

Evaluation of Subsurface Radionuclide Transport at Commercial Nuclear Power Production Facilities

1.0 Scope

This national standard establishes the requirements for evaluating the occurrence and movement of radionuclides in the subsurface resulting from abnormal radionuclide releases at commercial nuclear power production facilities.

This standard applies to abnormal radionuclide releases that affect groundwater, water supplies derived from groundwater, and surface waters affected by subsurface transport, including exposure pathways across the groundwater-surface water transition zone.

This standard does not apply to:

- Subsurface occurrence and movement of non-radioactive materials, other than as indicators of subsurface radionuclide occurrence and movement in soil and groundwater;
- Surface occurrence and movement of radionuclides, except to the extent that surface radionuclide occurrence and movement may affect, or be affected by, onsite subsurface radionuclide occurrence and movement (e.g., a surface release that subsequently infiltrates and affects groundwater, a subsurface release that affects surface water, including exposure pathways across the groundwater-surface water transition zone);
- Corrective action, which may be required as the result of a subsurface radionuclide release; and
- Dose calculations to demonstrate compliance with any regulatory requirement.

2.0 Definitions

2.1 Acronyms and Initialisms

ALARA: As Low As Is Reasonably Achievable

ANS: American Nuclear Society

ANSI: American National Standards Institute

ASTM: ASTM International, previously known as the American Society for Testing and Materials

CFR: Code of Federal Regulations

CRWMS: Civilian Radioactive Waste Management System Management and Operating Contractor

CSM: Conceptual Site Model

DQOs: Data Quality Objectives

EIS: Environmental Impact Statement

EPRI: Electric Power Research Institute

FEPs: Features, Events, and Processes

IAEA: International Atomic Energy Association

NEI: Nuclear Energy Institute

NGWA: National Ground Water Association

NRC: National Research Council

REMP: Radiological Environmental Monitoring Programs

RETS: Radioactive Effluent Technical Specifications

TEDE: Total Effective Dose Equivalent

U.S.: United States

USEPA: U.S. Environmental Protection Agency

USNRC: U.S. Nuclear Regulatory Commission

2.2 Definition of Terms

Abnormal radionuclide release: An unplanned or uncontrolled release of licensed radioactive material, including leaks and spills to the site environs (e.g., locations outside of nuclear power plant systems, structures, and components), which may be undetected at the time of the original release.

As low as is reasonably achievable (ALARA): Every reasonable effort is made to maintain exposures to radiation as far below the dose limits as is practical consistent with the purpose for which the licensed activity is undertaken, taking into account the state of technology, the economics of improvements in relation to state of technology, the economics of improvements in relation to benefits to the public health and safety, and other societal and socioeconomic considerations, and in relation to utilization of nuclear energy and licensed materials in the public interest.

Ambient flow: Natural horizontal or vertical groundwater movement through the subsurface; or resulting from natural hydraulic gradients in an open borehole, well or piezometer.

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, seeps, and wells.

Aquifer, confined: An aquifer bounded above by an aquitard.

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

Aquitard: A geologic formation that restricts, but does not prevent, groundwater movement into or between aquifers.

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

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

Biogeochemical processes: The chemical interactions that exist between the atmosphere, hydrosphere, lithosphere, and biosphere.

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.

Conceptual site model (CSM): An abstract, qualitative representation of the relevant flow and transport FEPs that affect subsurface radionuclide transport at the site. The CSM is best presented as a set of two-dimensional graphics (plan and profile) or a three-dimensional graphic (isometric), which qualitatively present the interrelationships between the FEPs, along with supporting text.

Confining layer: A geologic unit within the saturated or unsaturated zones that has a distinctly lower hydraulic conductivity than the underlying and overlying geologic units; also called an aquitard when in the saturated zone.

Contamination: Occurrence of material in a location where it is not considered indigenous to its surroundings.

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

Critical outcome: A long-term, strategic goal, stated in terms of the expected results, that captures the essence of the desired end state to be achieved.

Data quality objectives (DQOs): Qualitative and quantitative statements derived from the DQO process that clarify the study objectives, define the most appropriate type of data to collect, determine the most appropriate conditions from which to collect the data, and specify tolerable limits on decision error rates. Because DQOs will be used to establish the quality and quantity of data needed to support decisions, they should encompass the total uncertainty resulting from all data collection activities, including analytical and sampling activities.

Data quality objective process: A systematic, strategic-planning tool based on the scientific method that identifies and defines the type, quality, and quantity of data needed to satisfy a specified use. DQOs are the qualitative and quantitative outputs from the DQO process.

Dual porosity model: A flow and transport model applied to a porous medium composed of two porosity fractions or domains. One fraction stores and transmits solute (mobile flow domain), while the second fraction only stores solute (immobile domain). Fluid and solute exchange between the mobile and immobile domains occur as functions of the hydraulic head and concentration gradient between the two, respectively.

Effluent concentration limit: The concentration values (given in Columns 1 and 2 of Table 2 in 10 CFR Part 20, Appendix B) equivalent to the radionuclide concentrations which, if inhaled or ingested continuously over the course of a year, would produce a total effective dose equivalent of 0.05 rem (50 millirem or 0.5 millisieverts).

Effluent discharge (radioactive): Any outflow in which plant-related, licensed radioactive material is released from a system, structure, or component and enters the unrestricted area.

Engineered barrier: A man-made cover, wall, or device used to prevent fluid flow or contaminant migration.

Exposure pathway: A mechanism by which radioactive material is transferred from the (local) environment to humans. There are three commonly recognized exposure pathways; inhalation, ingestion, and direct radiation. For example, ingestion is an exposure pathway, and it may include dose contributions from one or more routes of exposure. For example, one route of exposure that may contribute to the ingestion exposure pathway is often referred to as grass-cow-milk-infant-thyroid route of exposure.

Features, events, and processes (FEP): An assessment of the relevant: 1) Features, which are identified physical characteristics of the total system, and how they behave over time; 2) Events, which are occurrences of abnormal radionuclide releases; and 3) Processes, which include physical, chemical, and biological processes that govern radionuclide transport.

Flux: The volumetric or mass discharge per unit cross-sectional area of medium (solids plus pores); called the Darcian flux when applied to water movement.

Groundwater: All water contained in pores, fractures or voids at or below the water table (also called the phreatic surface); also identifies water in the phreatic zone.[2]

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

Hydraulic gradient: The change in hydraulic head with distance.

Hydraulic head: One of several measures of the energy content of water (in this case, energy per unit weight), expressed as a height of freshwater above a datum. In fresh groundwater, the hydraulic head is commonly found using the water surface elevation in an open borehole, well, or piezometer.

Hydrostratigraphy: A conceptual framework that classifies geologic materials of considerable lateral extent into reasonably distinct hydrologic systems.

Infiltration: The movement of water from above the ground surface into the vadose zone.

Intermediate point of compliance: A location used as a reference point for the purpose of protecting the groundwater resource, where there are no immediate existing receptors but where contamination is regarded as undesirable.

Mathematical model: A quantitative representation of the relevant flow and transport FEPs that affect

[2] Regulatory agencies and industry may consider groundwater to include all subsurface water, so that all contaminants in the subsurface are evaluated, and not only those in the phreatic zone.

subsurface radionuclide transport at the site. The mathematical model can be an algebraic equation for simple, homogeneous systems, or it can be a computer model in more complicated systems.

Normal radionuclide release: The known, planned, or approved release of radionuclides to the environment, including controlled releases of low-level radioactive materials.

Perched water: Subsurface water collecting on low-permeability geologic materials that are separated from an underlying main body of groundwater by an unsaturated zone. Water located above the water table whose water gage pressure is greater than zero.

Performance assessment: A systematic analysis that addresses the types and likelihood of abnormal radionuclide releases, their resulting impacts, and how these impacts compare to regulatory standards.

Performance-based regulation: Regulations that are outcome-oriented rather than procedure-oriented. An approach to regulatory practice that establishes performance and results as the primary bases for decision making. Performance-based regulations have the following attributes: (1) measurable, calculable or objectively observable parameters exist or can be developed to monitor performance; (2) objective criteria exist or can be developed to assess performance; (3) licensees have flexibility to determine how to meet the established performance criteria in ways that will encourage and reward improved outcomes; and (4) a framework exists or can be developed in which the failure to meet a performance criterion, while undesirable, will not in and of itself constitute or result in an immediate safety concern.

Performance indicator: An observable hydrologic (e.g., water content, water flux, water quality parameter) or radiologic (e.g., tritium) parameter, the value (or change in value) of which is used to determine whether a performance objective is achieved.

Performance objective: A targeted outcome or goal desired to achieve a successful end result (e.g., a goal to meet a defined level of environmental quality).

Performance threshold: A quantitative criterion for each performance indicator that defines when performance objectives are, or are not being, met.

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

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

Receptor: An individual located outside of the controlled area (e.g., offsite) that may receive a radionuclide exposure via subsurface transport.

Restricted area: An area, access to which is limited by the licensee for the purpose of protecting individuals against undue risks from exposure to radiation and radioactive materials. Restricted area does not include areas used as residential quarters, but separate rooms in a residential building may be set apart as a restricted area.

Risk-informed approach: An approach to regulatory decision-making represents a philosophy whereby risk insights are considered together with other factors to establish requirements that better focus licensee and regulatory attention on design and operational issues commensurate with their importance to health and safety. This approach enhances the traditional approach by: (a) allowing explicit consideration of a broader set of potential challenges to safety, (b) providing a logical means for prioritizing these challenges based on risk significance, operating experience, and/or engineering judgment, (c) facilitating consideration of a broader set of resources to defend against these challenges, (d) explicitly identifying and quantifying sources of uncertainty in the analysis, and (e) leading to better decision-making by providing a means to test the sensitivity of the results to key assumptions. Where appropriate, a risk-informed regulatory approach can also be used to reduce unnecessary conservatism in deterministic approaches, or can be used to identify areas with insufficient conservatism and provide the bases for additional requirements or regulatory actions.

Risk factors: Parameters related to a radiological risk assessment; e.g., proximity of a member of a public to a facility with subsurface contamination, interconnection between an aquifer and the facility's subsurface contamination, groundwater transport rates, direction of flow, dilution factors from local surface water bodies and/or groundwater flow, etc.

Route of exposure: A specific scenario by which radioactive material may be transferred from the environment to an individual or human receptor causing an exposure. For the ingestion exposure pathway, the routes of exposure could include the ingestion of leafy vegetables, milk, water, fish, etc.

Saturated zone: The zone in the subsurface where the pores are filled with water (phreatic zone plus capillary zone).

Shall, should, and may: The word "shall" is used to denote a requirement; the word "should" is used to denote a recommendation; and the word "may" is used to denote permission, neither a requirement nor a recommendation.

Soil water potential: A measure of the energy content of water in unsaturated materials, the spatial gradient of which causes soil water movement. The energy content is the sum of gravitational, pressure, osmotic, and other forces.

Spatially explicit data: Attributes that can be geo-referenced to a specific location.

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

Subsurface water: Water contained in pores and voids within geologic media below the ground surface.

Sum-of-the-fractions rule: Calculated by dividing each nuclide's concentration by the appropriate limit and adding the resulting values. The appropriate limits must all be taken from the same column of the same table in 10 CFR part 61.55. The sum of the fractions for the column must be less than one if the waste class is to be determined by that column.

System: In the context of this standard, the system consists of: 1) all facilities from which a release to the groundwater could occur; 2) all facility policies or procedures that may impact or cause a release; 3) the man-machine interface of a facility that may cause or contribute to a release; 4) all engineered barriers and leak detection systems; 5) the local and regional hydrogeology; and 6) all monitoring well networks and procedures for gathering and analyzing soil and groundwater samples.

Unity rule: Used to determine whether the sum of the ratios of the quantity of each isotope to the applicable value in 10 CFR part 20, Appendix B, is greater than one.

Unrestricted area: An area, access to which is neither limited nor controlled by the licensee.

Unsaturated zone: 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.

Vadose zone: A subsurface region where the water gage pressure is negative; most commonly, the zone between the ground surface and the water table.

Water table: The water surface in an unconfined aquifer corresponding to where the water gage pressure is zero, also called the phreatic surface.

3.0 Performance Assessment Methodology

A graded, risk-informed, performance-assessment methodology shall be used for evaluating the effects of subsurface radionuclide transport. The graded risk-informed approach allows risk, derived from accident probability and consequences, to be used to optimize the use of resources while achieving a high level of safety[3]. The performance assessment shall be based on 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 and natural barriers, and the proximity to surface water and groundwater receptors.[4]

3.1 Performance Assessment Activities

Performance assessment is used in this ANSI standard to prescribe site characterization, mathematical modeling, and performance-confirmation monitoring. The goal is to understand and describe the relevant geologic, hydrologic, physical, biological, and chemical processes that significantly affect subsurface radionuclide transport. Performance assessment is used to develop and evaluate alternative site characterization, monitoring, and modeling strategies, with the objective of providing data and information that is used to demonstrate whether system design or regulatory requirements have been met.

[3] The performance-assessment methodology may be used to demonstrate regulatory compliance where the basis for compliance is a risk level. In this case, probabilities may be determined from statistical data or reasonable estimates based on failure analyses of the facility.

[4] For example, a facility with a less-significant radionuclide source term, minor subsurface contamination, simple or well-understood hydrogeology, or having limited effects on groundwater resources, generally requires less extensive site characterization, mathematical modeling, and performance-confirmation monitoring than a facility with significant subsurface contamination that has the potential to exceed national radiation protection standards.

The following performance assessment activities shall be conducted (illustrated in Figure 1):

1. Identify the appropriate regulatory (e.g., public dose limits and radiological criteria for license termination) and design (e.g., containment) requirements, and use these requirements to specify performance objectives, performance indicators, and performance thresholds (described in Section 3.2).

2. Identify and assess the relative significance of the subsurface radionuclide release scenarios and transport pathways (described in Section 4.0);

3. Conduct site characterization studies focusing on facilities and site hydrogeology, emphasizing the significant release scenarios and transport pathways (described in Sections 4.1 and 4.2);

4. Develop one or more working conceptual site models (CSMs) of radionuclide transport using information from site characterization studies that account for the features, events, and processes (FEPs) identified during site characterization (described in Section 4.1);

5. Develop mathematical model(s) that are used to demonstrate compliance with performance objectives and to better understand system processes (described in Section 5.0); and

6. Implement a performance-compliance monitoring program that is used to improve the conceptual and mathematical models, and to demonstrate compliance with regulatory requirements and performance objectives (described in Section 6.0).

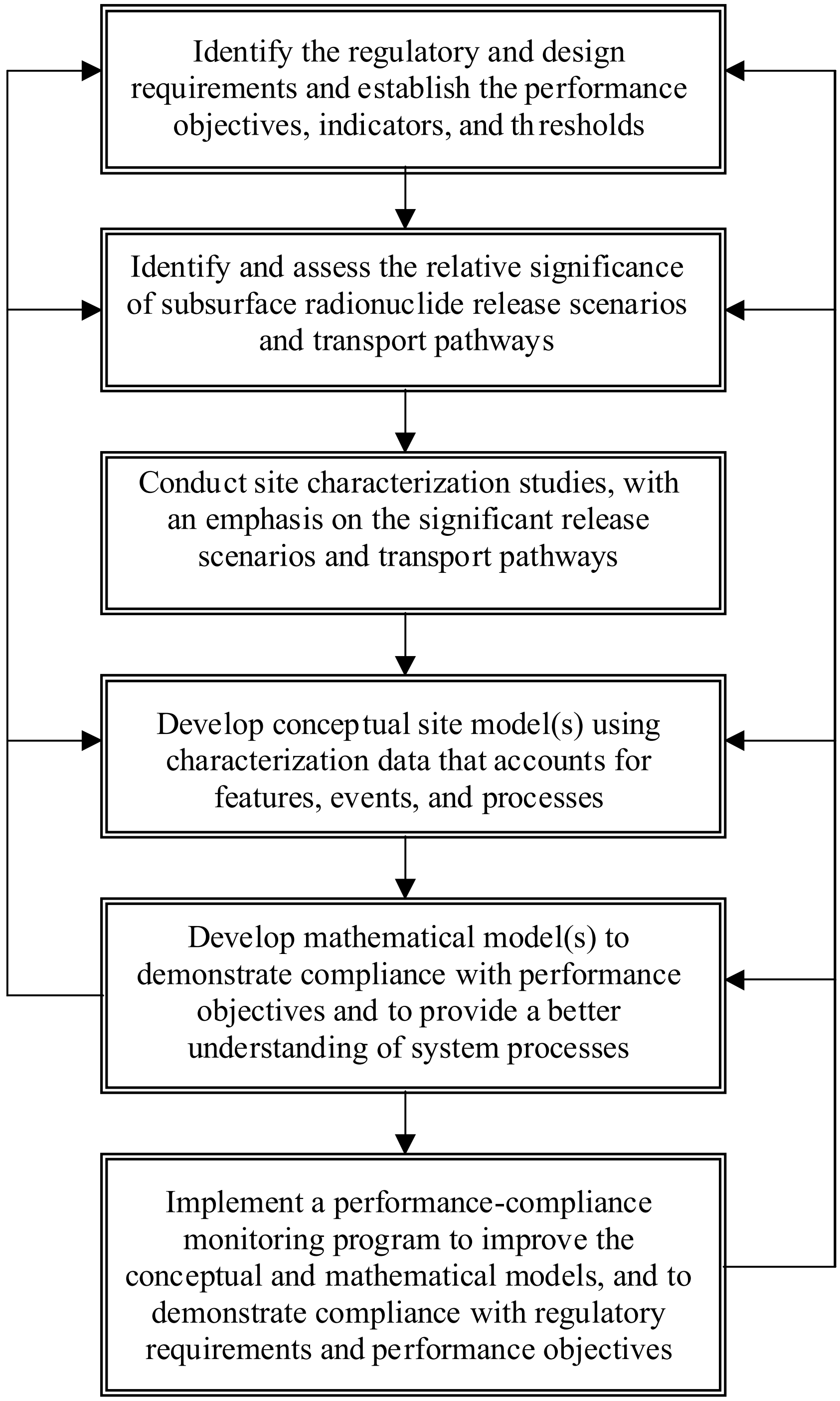

Figure 1. Flow chart describing performance assessmentactivities and the relationships between these activities.

3.2 Performance Assessment Elements

The performance assessment is structured such that the following elements are required:

1. Performance objectives shall be established for all regulatory and design requirements[6]. Separate performance objectives for onsite[7] and offsite[8] areas shall be established. It is acceptable to establish performance objectives that are more stringent than regulatory requirements if greater risk factors are present.

2. Performance indicators shall be defined for the purpose of establishing whether the performance objective has, or has not, been met. An ideal performance indicator is one that unambiguously determines whether a performance objective is being met. If different pathways exhibit different transport and exposure risks, then separate performance indicators (and thresholds) shall be developed for these pathways.[9] Table 1 presents a ranked list of radionuclides at commercial nuclear facilities, and may be appropriate performance indicators, but those selected may differ depending upon site-specific structures, systems and components (e.g., spent-fuel pool, radwaste tank, condensate tank, effluent-transfer pipes, etc.), their associated radionuclide inventories, and transport characteristics. Appropriate consideration shall be given for identifying normal radionuclide concentrations that result from routine operations.

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6 Potentially relevant regulatory requirements are provided in Appendix A.

7 For example, onsite dose limits include the 10 CFR 20.1402 license termination criteria of ≤ 25 mrem/yr (unrestricted use).

8 For example, offsite public dose limits include the USNRC limit of 100 mrem/yr (all pathways), USEPA 40 CFR 141.66 limit of 4 mrem/yr (drinking-water pathway), and 10 CFR 50, Appendix I numerical guides for design objectives and limiting conditions for operation of ≤3 mrem/yr (to a real individual using realistic liquid effluent exposure pathways).

9 For example, tritium concentration in groundwater is likely to be selected as a performance indicator because of its prevalence within nuclear facilities, its mobility, and operational experiences where tritium leaks and spills have occurred. Other mobile radionuclides may also be selected if they are likely to be present.

Table 1. Ranked list of radionuclides at commercial nuclear power facilities (typical pressurized water reactor) based on their relative abundance, activity, and transport characteristics (after Scott, 2008).

Relative Rank	Radionuclide	Half-Life* (years)
1	Strontium-90	28.90
2	Cesium-137	30.08
3	Cobalt-60	5.27
4	Hydrogen-3†	12.32
5	Cesium-134	2.07
6	Iodine-129	1.57×10^7
7	Nickel-63	100.1
8	Carbon-14	5,700
9	Plutonium-238	87.7
10	Americium-241	432.6

* From the National Nuclear Data Center, Brookhaven National Laboratory

† Hydrogen-3 is an alternative name for tritium.

3. Performance thresholds for radioactivity concentrations in environmental samples shall be specified for each performance indicator, and this threshold shall be used to determine whether each performance objective has been met. Suitable methods for specifying a performance threshold include using a derived concentration directly associated with the performance objective[10], statistically significant deviations from local baseline concentrations, an alternative radiological threshold as defined by performance objectives, or expected changes in water quality parameters or hydrologic conditions resulting from an abnormal release.

These criteria also include radionuclide concentrations (either volume- or flux-averaged), travel times, mass fluxes, or predicted doses. Demonstrating that a performance objective has been, or can be, met during operations or at the time of decommissioning requires knowledge of radioactivity levels in the environment (including subsurface) and the exposure pathways to individual members of

[10] For example, a performance threshold of 20,000 pCi/L of tritium in drinking water may be derived based on the USEPA performance objective of 4 mrem/yr. Performance thresholds for the offsite public dose performance objective could be established that correspond to 1%, 10%, and 100% of the 4 mrem USEPA drinking water performance objective. Performance thresholds for onsite areas could be established based on a 1%, 10%, or 100% of the license termination criteria of 10 CFR 20.1402.

the public[11].

4. The performance assessment shall define actions to be taken in the event that an abnormal release has been detected, such as additional environmental evaluations or corrective action[12]. Acceptable methods for determining whether an abnormal release may have occurred includes exceeding the performance threshold, as well as exceedance of indirect or diagnostic indicators (e.g., increased seepage rates, ancillary water quality parameters[13]) that are likely to be affected by an abnormal release. While indirect indicators are not sufficient for confirming a release, they may be used as the basis for initiating additional investigations. Acceptable types of follow-up actions include additional sampling locations and analysis, increased monitoring (frequency and spatial density), additional assessment (e.g., well integrity, analytic integrity) or monitoring facilities (e.g., wells, piezometers), operational or procedural changes, design changes, or other corrective actions.

5. Performance assessments shall be an ongoing, iterative, and interdependent process using site characterization, mathematical modeling, and performance monitoring. The performance assessment shall be updated and revised as significant new information demonstrates that the current CSM or FEPs no longer adequately characterize subsurface transport at the site.

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[11] For example, considering a site-specific performance objective in the presence of an abnormal radionuclide release to groundwater, the associated performance indicator could be the tritium concentration in groundwater in monitoring wells, and a specified tritium concentration could be the performance threshold.

[12] For example, if REMP reporting levels are exceeded (e.g., tritium > 20,000 pCi/L), the licensee shall prepare and submit a report to the USNRC that identifies the problem and defines corrective actions.

[13] Examples include specific conductance, pH, and boron and nitrate concentrations, which may be diagnostic of a radionuclide release. Additional indirect indicators include increased seepage rates, increased soil-water content, water-level changes in the surficial aquifer, increased ponding in low spots or sumps, and anomalies in groundwater temperature.

4.0 Site Characterization

The purpose of site characterization is to obtain site-specific data and information needed to develop a conceptual site model, which is then used in an iterative manner to further characterize the site. The degree of effort required for characterization depends on 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**.**

4.1 Conceptual Site Model

A conceptual site model (CSM) defines the fundamental knowledge and characteristics about the physical, hydrologic, biologic, and geochemical processes that affect the near- and long-term exposure pathways associated with subsurface radionuclide releases. The CSM provides the framework for understanding and predicting subsurface flow and transport, and for identifying and designing site-characterization activities (USNRC, 2003a, 2007b). The CSM is needed to resolve both near-term (e.g., new contamination or impending off-site migration) and long-term (e.g., those affected by natural attenuation and long-term migration) events and consequences.

It is important to recognize that the specification of the CSM is an iterative process that is central to thorough characterization of a site. Because the relevant flow and transport processes at each site may be poorly understood, the CSM includes an ensemble of plausible scenarios and models that is revised as new information or understanding warrant. The CSM relies on site characterization data to better specify and quantify the appropriate Features, Events, and Processes (FEPs) that control subsurface occurrence and movement of radionuclides. Defining the *features* requires an understanding of the physical characteristics of the total system and how they behave over time, including site conditions and inventories along with the effects of radionuclide release scenarios. 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 process of specifying the CSM consists of:

1. Using regional and local hydrogeologic studies to define the *CSM*, which identifies the hydrogeologic environment relevant to subsurface radionuclide transport.

2. Identifying the *FEPs* that may contribute to or affect the release of radionuclides. Priority is given to those radionuclide sources, pathways, travel times, concentrations, and radiological exposures associated with abnormal releases; and

3. Providing quantitative data and information about *processes and parameters* that allows for the development of a mathematical (parametric) model to help understand and manage the geologic, hydrologic, and geochemical environment at the facility.

The CSM shall define the geographic region of concern, which includes the topography, watershed area (i.e., the surface-water drainage basin where the facility is located), and watershed boundaries. Within the specified region, the CSM shall include those hydrographic (e.g., rivers, streams, lakes, ponds, wetlands, estuaries, coastal sea levels), geologic (hydrostratigraphy, faults, hydrogeologic unit interfaces, fracture zones), and hydrogeologic (e.g., phreatic and confined aquifers, confining layers, unsaturated zone, perched systems, springs) features that are likely to affect subsurface radionuclide transport.

The CSM shall also include additional features at sites with greater complexity that may be part of, or have direct influence on, transport pathways. These include preferential flowpaths (e.g., buried stream channels, lineaments, fracture connectivity, voids, conduits), adjacent aquifers or watersheds with subsurface flow interactions (e.g., leakage) or pathways, and groundwater-surface-water interactions (e.g., coastal zones, recharge and discharge zones, groundwater-surface-water transition zones (USEPA, 2008)). The interaction with these systems is important, in that pathways with limited transport capacity are not as important from a risk and characterization perspective as those that may be affected by an abnormal event.

The CSM shall specify the likely radionuclides of concern at the facility, along with the likely pathways for radionuclide movement. This requires a conceptualization of the source term, including type (e.g., liquid waste management system tank, residual radioactivity in soil), location, volume, mass, concentrations, release mechanisms, etc. In addition, the receptor locations, regulatory boundaries, and target aquifers shall be identified. While the water-table aquifer is likely to be the primary pathway, complex hydrogeologic conditions may warrant the identification of pathways through other hydrogeologic units (e.g., vadose zone, underlying confined and semi-confined aquifers). The CSM shall also specify the biological and geochemical processes that are likely to affect radionuclide occurrence and transport characteristics.

Alternative CSMs shall be proposed as suitable hypotheses (i.e., hypotheses that can be tested using characterization or monitoring data) during early stages of site investigations at complex sites (e.g., where fractures or heterogeneities may substantially affect transport behavior). Because reducing uncertainties associated with alternative CSMs is an important component of site characterization, alternative interpretations regarding the major lateral, upper, and lower hydrologic boundaries of the unconfined aquifer and other physical boundaries (e.g., surface-water bodies, surface outcrops, recharge boundaries) shall be provided whenever these alternative interpretations are likely to affect subsurface radionuclide transport.

Periodic evaluation and updating of the CSM shall be performed every five years (or more frequently to coincide with facility alterations) to assure that observed monitoring data are consistent with the CSM. When updating the CSM, the most current values of hydrogeologic parameters, as well as additional hydrogeologic characterization, mathematical modeling, and monitoring data, shall be included. The effects of seasonal fluctuations, significant recharge events, and droughts shall be used to the extent practicable to improve the CSM.

Visualization tools are useful for integration of data and information into figures, graphs, stylized visual diagrams (i.e., cartoons) in both plan and profile views, and shall be used to clearly depict the CSM and alternative CSMs. Relevant site information shall include, but is not limited to, hydrostratigraphy, facility location, boring and well locations, heads in each aquifer, arrows depicting flow direction, and interaction at groundwater-surface water transition zones.

4.2 Facilities Characterization

Facilities shall be characterized in terms of their specific components, procedures, and processes for which an abnormal radionuclide release may occur, with the goal being to identify the potential release modes along with the likelihood of these releases. Guidance for the evaluation of failure modes can be obtained from USNRC (1990a).[14]

Facilities. Specific facility information includes the locations and characteristics (e.g., dimensions, construction materials, hydraulic properties, radionuclide inventories) of the relevant:

- Surface facilities (e.g., spent-fuel pools, holding ponds, condensate tanks, pipelines);
- Liquid waste management systems (e.g., for newer facilities, a failure of a liquid waste management system tank shall be postulated and evaluated against the effluent concentration limits given in 10 CRF Part 20. These tanks should be explicitly identified in the list of facilities);
- Subsurface facilities (e.g., spent-fuel pools, drains, pipes, conduits, artificial fill, backfill, pads, foundations, and the associated vadose zone);
- Engineered barriers (e.g., liners, caps, cutoff walls, leak detection systems, and interceptor wells);
- Well construction data (e.g., grouted and screened intervals, screen and casing type, depth, diameter, perforation, surface seals, aquifers penetrated, location, elevation, use, owner, discharge rates, static hydraulic heads, and drawdown); and
- Abandoned wells and piezometers, along with the method of abandonment.

[14] Licensing of new power reactor sites 10 CFR 100.20(c)(3) requires that: "Factors important to hydrological radionuclide transport (such as soil, sediment, and rock characteristics, adsorption and retention coefficients, groundwater velocity, and distances to the nearest surface body of water) must be obtained from on-site measurement."

Modifications. Because the hydrogeologic regime, as well as biogeochemical processes, may be altered by construction and ongoing facility modifications, important surface and subsurface modifications shall be catalogued and updated to reflect actual site conditions. Changes in subsurface flow conditions resulting from new and previous facility construction and operation shall be documented. These changes can be due to groundwater control or foundation improvement activities, such as installation of slurry trenches and rock grouting, or the construction of buildings with deep foundations that act as barriers to groundwater flow, and may include changes in hydraulic heads within pertinent aquifers, changes in hydraulic conductivity, placement of engineered fill, altered surface topography, and changes in the direction or quantity of groundwater flow. 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 assessed and recorded. These construction and facility changes shall be identified and incorporated within the CSM during periodic updates, or whenever performance thresholds are exceeded.

Abnormal releases. Facility operational practices and procedures that are likely to affect the potential release and subsequent subsurface movement of radionuclides to the environment shall be identified. Data relevant to past abnormal radionuclide releases include corrective actions implemented, radionuclide inventories, release locations and magnitudes, travel paths, and travel times to both potential receptors and regulatory boundaries.

4.3 Hydrogeologic Characterization

Hydrogeologic properties from previous regional studies shall be used to plan the detailed site studies, if available. Because regional properties are not an acceptable substitute for locally derived information, site hydrogeologic properties shall be acquired to either confirm regional estimates, or to provide unique estimates of local conditions. Hydrogeologic information from previous characterization activities that may have been performed for other purposes at the site shall also be used, if available. Technical documents that provide information about or can assist with the development and implementation of hydrogeologic characterization programs include Bennett (1976), Driscoll (1986), USNRC (1988, 2007b), USEPA (1994), Stephens (1996), Faybishenko et al. (2000), Evans et al. (2001), Boulding and Ginn (2003), and Nielson et al. (2006).

Baseline conditions. Ambient subsurface flow conditions shall be defined to establish a baseline against which future conditions are compared. Sufficient data shall be collected to characterize the hydraulic head, hydraulic gradients (magnitude and direction), and the natural variation and bounds of these estimates in the unconfined aquifer, and those confined aquifers identified in the CSM that contribute to risk-significant pathways. Also, if appropriate to the CSM, sufficient data shall be collected to provide a general description of hydraulic conditions in the vadose zone under extreme conditions (e.g., potential flooding or full saturation). Data collected to establish baseline conditions are also normally used to support groundwater model calibration and validation. The baseline data collection program shall therefore consider modeling needs and ensure that the data needed to support modeling are obtained.

Baseline conditions shall be monitored with sufficient frequency and duration to define the probable range of dynamic hydrologic behaviors, and to provide the capability for identifying unusual hydrologic responses. Subsurface conditions (in particular, groundwater levels) shall be monitored on a monthly basis for at least a year to establish the seasonal variability. More frequent monitoring may be needed in complex fractured rock or karstic systems. Precipitation data shall be used to determine whether the data-collection period is representative of the long-term precipitation and recharge conditions. Available historic local and regional groundwater level measurements should be examined, together with onsite measurements, for determining the annual variation in groundwater levels.

Hydraulic heads shall be measured in those surface waters (e.g., rivers, lakes, wetlands, springs, estuaries, bays, oceans, groundwater-surface water transition zones) identified as relevant to radionuclide transport in the CSM. 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. In addition to hydraulic head measurements to determine groundwater flow conditions, concurrent estimates of groundwater flow (using, for example, Darcy's Law) shall also be made to assist in characterizing the water budget and to calibrate groundwater flow models. Flow estimates may also be needed in order to determine dilution factors when contaminated groundwater discharges to perennial stream prior to leaving the restricted area. For sites where the CSM indicates that changes in surface loading (e.g., precipitation, barometric pressure, streamflow, tidal fluctuations, cooling water intake and discharge canals) affect aquifer hydraulic heads, the observation well water-level responses to these processes shall be quantified. Similarly, for facilities in coastal areas, the hydrologic behavior of offshore discharges and tidal influences shall be included if identified in the CSM. For example, the baseline variation in surface and subsurface salinity shall be monitored if they are included in the CSM.

Regional and local water-quality data shall be used to resolve ambiguities in the CSM, such as to identify modes of recharge to the aquifers, or flow within complex hydrogeologic environments, and to assess the interaction of groundwater between geologic formations. Tracer tests are an acceptable method for site characterization at complex sites where existing water-quality data fail to resolve ambiguities in the CSM.

Baseline concentrations of performance indicators (e.g., tritium) shall be collected in pathways identified in the CSM (e.g., precipitation, surface water, coastal waters, groundwater) to determine their spatial and temporal variability, as well as to aid in the specification of performance thresholds.

Water budget. The CSM shall include a water budget analysis for the site showing the precipitation, evapotranspiration, runoff, recharge, and groundwater discharge. Groundwater flow models (e.g., numerical or algebraic) are useful tools for quantifying the water budget and reconciling field observations. Published information may be used to estimate infiltration as a percentage of precipitation to evaluate evapotranspiration-runoff-recharge relationships. The CSM shall include recharge-discharge relationships between surface water and groundwater (and between aquifers, if appropriate), including induced recharge from past and current site operations, and natural recharge from direct infiltration of precipitation, surface water, and site runoff. An important consideration is the variation of short-term (daily to monthly) and long-term (seasonal to decadal) interactions in the water budget, or at time scales defined by the CSM (e.g., shorter intervals may be needed to evaluate tidal and/or streambank exchanges). Other important considerations include the long-term variation in regional recharge and discharge rates, as well as local changes in groundwater flow direction, especially those that may affect radionuclide transport over the facility lifetime. These variations may be assumed constant over appropriately discrete periods (e.g., five-year increments) and evaluated for a suitable range of aquifer recharge and discharge conditions. In addition to using precipitation data to assess whether the data-collection period is representative of long-term conditions, drought indices (e.g., Palmer Drought Severity Index) may also be helpful in determining the representativeness of the data as they typically consider the cumulative effects of above- or below-average precipitation.

Transport pathways. Sufficient data shall be collected to evaluate transport in pathways identified by the CSM. This requires, at a minimum, the identification of regional groundwater and surface water uses and potential receptors, and the calculation of travel times and flow paths. Calculation using simple mathematical models is appropriate at sites with limited hydrogeologic complexity and exposure risks. For complex conditions or with greater risks, additional site-specific data on transport, such as the effective porosity and dispersivity, may be needed, along with more complex numerical flow and transport models. Core-sample analyses and field tracer tests are acceptable methods for determining site-specific transport properties.

Physical properties. Site-specific physical properties of the hydrogeologic units shall be collected to understand and predict radionuclide transport at the site. Of primary interest are the physical properties that affect flow and transport characteristics, including the bulk density, total and effective porosity, grain-size distribution, and mineralogical composition. Physical properties that might affect radionuclide transport, such as preferential flowpaths (e.g., faults, lineaments, fractures, voids, conduits), shall be characterized, 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, as appropriate to the complexity of the site.

Hydraulic properties. The hydraulic properties of hydrogeologic units that have been specified in the CSM as providing pathways to potential receptors or to compliance locations shall be characterized. To be conservative, all aquifers that provide pathways of concern shall be characterized, plus the next underlying hydrostratigraphic unit. This characterization includes test borings in these units, at least one of which at complex sites would be used to collect a continuous set of samples spanning the length of the borehole. Borehole geophysical logging shall be performed in selected test borings. Borings shall be conducted in a manner that they do not create subsurface radionuclide pathways. In-hole horizontal and vertical flow measurements shall be conducted in selected test borings, if appropriate, to identify zones with higher flow rates for both ambient-flow and stressed (e.g., pumping) conditions. Acceptable methods for conducting surface and subsurface geophysical studies to characterize preferential flow paths include hydraulic tomography, tracer tests, seismic arrays, and electromagnetic techniques.

Quantitative estimates of hydraulic parameters identified as relevant by the CSM (e.g., hydraulic conductivity, transmissivity, specific storage, specific yield, specific capacity, storativity, leakance) shall be obtained using aquifer tests (e.g., single and multiple borehole pumping tests, slug tests, specific capacity tests, falling/rising head tests, borehole flowmeter or dilution tests). For anisotropic media, the directional components of hydraulic properties are also important and shall be obtained with appropriate tests. Again, special interest is placed on the hydraulic properties of features identified in the CSM that may affect radionuclide transport, such as preferential flowpaths (e.g., faults, lineaments, fractures, voids, conduits).

Transport through the vadose zone may be assumed to be instantaneous for purposes of obtaining conservative estimates of travel times (thus eliminating the need for defining vadose zone hydraulic properties). Yet, the interpretation of monitoring well responses might require detailed vadose zone characterization. If vadose zone characteristics are relevant, the moisture characteristic curves and unsaturated hydraulic conductivity functions shall be determined[15].

Estimates of ambient flow magnitudes and directions for a range of hydrologic conditions shall be determined. These estimates shall be confirmed using tracer or borehole methods at complex sites. The use of

[15] A practical way to accomplish this is to use, for example, pedotransfer functions based on particle-size distributions, such as described by Schaap et al. (2001), although laboratory-derived functions may be needed, depending upon the extent to which the vadose zone affects facility performance.

in situ borehole flowmeters is acceptable for evaluating the vertical flow direction within and between hydrogeologic units.

Chemical properties. In cases where an abnormal release has occurred or is suspected, sufficient data shall be collected to define the fluid chemistry and potential reactions of formation fluids and solids from the release. Appropriate transport characterization parameters (e.g., total ion-exchange capacity, distribution coefficients, pH, redox potential) shall be determined for performance indicators that are affected by geochemical processes. Laboratory measurements of the distribution coefficient for individual nuclides shall be obtained if conservative values[16] produce estimates of contaminant transport that do not satisfy performance objectives. These measurements shall be made using samples of the materials found along critical groundwater pathways and groundwater from the site. Column tests with undisturbed core samples are preferred. In the event that undisturbed core samples are not available, they may be replaced by batch tests with grab samples. However, it should be noted that the latter tends to result in distribution coefficients that are larger than in-situ values. The effects of chelating agents and other chemicals that might be present in a liquid effluent release and are known to enhance the mobility of radionuclides in groundwater shall be determined. The influence of biological processes (e.g., plant water uptake) on hydrogeologic and geochemical processes shall be included, if appropriate.

[16] Either zero for new power plants (10 CFR 100.20(c)(3)) or determined from published literature otherwise.

5.0 Mathematical Modeling

The modeling goal is to assist in the risk-informed understanding and prediction of groundwater flow and transport. Mathematical modeling shall be used to support performance assessment by demonstrating that design and regulatory-compliance goals are met during the design and permitting stages, as well as during the operation and decommissioning stages. During the design and permitting stages, mathematical models assist in demonstrating facility safety (with characterization and monitoring data being used to establish model accuracy), for planning, designing, and evaluating monitoring strategies, for performing radiological exposure assessments, for evaluating the effects of facilities (including normal radionuclide releases, if necessary) on the hydrologic system, and as an integration tool for documenting and analyzing hydrogeologic processes and assumptions. During the operation stage, models assist in interpreting monitoring data, determining the source, direction, and rate of movement of abnormal releases, and estimating the zone of contamination, if present. Because model predictions are compared with monitoring data at regular intervals, models assist in updating the CSM as new information and insight of system behavior is gained. A robust modeling program also provides valuable assistance during the decommissioning stage by anticipating the likely occurrence and movement of radionuclides in the subsurface.

While recognizing that monitoring data are key to demonstrating the continuing safety of the facility during the operational stage, it is important to note that mathematical models provide additional utility by integrating hydrologic parameters and processes, testing CSM interpretations when monitoring data are ambiguous, counter-intuitive, or do not provide sufficient confidence in system performance. Models are also important for reconciling monitoring and characterization data with the CSM, to estimate the potential movement of contaminants on the site, and to develop mitigation plans for the purpose of preventing offsite migration of contaminations. As such, modeling is a tool that supports the groundwater-monitoring program and performance testing of CSM hypotheses. Models are especially helpful for determining flow directions and magnitudes, as well as for determining the rate of groundwater and radionuclide movement in response to natural and anthropogenic stresses.

5.1 Model Scope

The mathematical model shall incorporate the physical and chemical processes and parameters relevant to describing the flow and transport of radionuclides at the site. Model scope shall incorporate the appropriate FEPs, and provide documentation to support the proposed level of model complexity, including, as required, the spatial extent, heterogeneities, scale effects, transient perturbations, etc. The model calibration accuracy shall be determined using a documented process of model testing and field confirmation. The analytic or numeric methods for model implementation shall be defined for both fluid flow and radionuclide transport. The model selection process shall demonstrate that model capabilities are consistent with the appropriate processes, parameters, site conditions, and data availability.

The level of effort associated with mathematical modeling shall be consistent with the degree of complexity and uncertainty in the underlying CSM, hydrogeologic conditions, the inventories and types of radionuclides that may be released to the subsurface, the proximity to potential receptors, and exposure pathway mechanisms. The appropriate level of model complexity balances model accuracy against modeling effort, with the ultimate goal being the risk-informed understanding and prediction of subsurface transport of radionuclides. An acceptable model at sites where the hydrogeologic setting is simple and the potential for risk to receptors is remote is an algebraic equation using Darcy's Law that is solved manually. Coupled, partial-differential equations that are solved numerically are acceptable for: i) heterogeneous and active groundwater systems, ii) liquid, vapor, and gas fluxes in the unsaturated zone, iii) dual porosity flow and transport through heterogeneous media (Freehley et al., 2000), iv) regional flow and transport through confined aquifers and confining layers below the unconfined aquifer (Aral, 1990); v) sites with complex hydrogeologic conditions in close proximity to potential receptors; and vi) sites where an abnormal release has occurred.

For a simple flow regime, it is acceptable in an initial transport analysis to account for advection and radioactive decay only. If the estimated concentrations meet the performance objectives, no further analysis is needed.[17] If not, then analysis shall consider additional processes as defined by the CSM, including e.g., radionuclide fluxes in aqueous, sorbed, vapor, and gaseous phases, and associated hydrologic processes and mass-transport phenomena including e.g., advection, diffusion, volatilization, hydrodynamic dispersion (longitudinal and transverse), adsorption, and radioactive chain decay.

Additional useful modeling guidance can be found in Yeh (1981), Aral (1990), NRC (1990), Anderson and Woessner (1992), Mercer and Faust (1992), Wang and Anderson (1995), Chien et al. (2003), USNRC (2003a), and Fetter (2008). Additional guidance for modeling contaminant transport is available in Codell and Duguid (1983), Wexler (1992), and Zheng and Bennett (2002).

Spatial scale of analysis. The model shall include potential onsite and near-boundary receptor locations, as defined by the CSM. The model shall resolve features that affect flow and radionuclide transport for normal releases, as well as for abnormal releases, as defined by the CSM. To the extent feasible, the model shall incorporate natural hydrological boundaries such as rivers or basin margins, rather than terminat-

[17] Tritium is a useful radionuclide for modeling because it can be assumed to move at the same rate as water, unaffected by chemical processes such as sorption.

ing the model area at arbitrary locations unrelated to hydrologic conditions, such as property boundaries.

Temporal scale of analysis. The model shall simulate flow over a representative time period because flow conditions may change due to changing site operations, stresses (e.g., recharge, discharge), boundary conditions (e.g., lateral inflows and outflows, heads), and land use. Historical data shall be used for initial model calibration while model predictions shall be compared against monitoring data for model evaluation.

Model geometry. The model geometry shall be consistent with the CSM. Use of a simplified geometry[18] is acceptable as long as it is consistent with the CSM. It is acceptable for the flow and transport model dimensionalities to differ.[19]

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

Hydrologic boundaries. Appropriate time-dependent and spatially varying Dirichlet (head), Neumann (fluid flux), or Cauchy (mixed) boundary conditions, and appropriate time- and space-dependent sources and sinks of fluids shall be used, as defined by the CSM. Combinatory (composite) modeling techniques are acceptable for establishing interfaces between vadose-zone and surface-water model(s).

Radionuclide retardation. If identified in the CSM, the model shall simulate geochemical retardation on a radionuclide-specific basis. Using a linear-equilibrium adsorption model meets the intent of this model component; however, the user should be prepared to justify use of linear or non-linear isotherms for specific radionuclides. The capability to allow adsorption to vary not only by radionuclide, but also spatially (i.e., to be a function also of the hydrogeologic unit in which transport occurs), shall be included if identified in the CSM.

Dispersion and molecular diffusion. If identified in the CSM, the model shall simulate dispersion and molecular diffusion on a radionuclide-specific basis. Using a constant dispersivity meets the intent of this model component; however, the user should be prepared to justify approaches for spatially uniform or variable dispersivity.

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[18] For example, one-dimensional flow tube, horizontal, two-dimensional flow through confined aquifers, and vertical one-dimensional fluid flow through confining layers and the unsaturated zone.

[19] For example, a multi-dimensional flow model may be needed to define the flow path from a release point, but a one-dimensional transport analysis along this path may be adequate.

Radioactive decay. If identified in the CSM, the model shall simulate the effect of first-order radioactive decay. The capability to simulate first-order radioactive decay can be important for radionuclides whose half-life is sufficiently short, and travel times are sufficiently long, to affect observed concentrations. 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. While chain decay is not usually significant for most of the mobile radioactive constituents, there may be instances where the capability to calculate the effect of chain decay in transport simulations is a desirable feature, particularly in cases where the decay products are mobile, have greater toxicity than the parent, or are detected as part of the monitoring program.

Flowpath modeling. If identified in the CSM, the model shall provide streamline (for steady-state conditions) and pathline (for transient conditions) analyses in two and three dimensions. Predicting radionuclide migration rates and directions requires additional information about the effective porosity and sorption capabilities of the aquifer. One method for evaluating predictive model accuracy is to compare model-calculated radionuclide flow behavior with field measurements and observations of natural or artificial tracers.

Reactive transport or transport with chemical transformation. If defined in the CSM, the model shall perform transport calculations of reactive radionuclides (e.g., Sr-85). Reactive transport models have the capability to simulate complex radionuclide-transport behavior in the vicinity of certain facility and radionuclide release locations (Brusseau, 1994; Goldberg et al., 2007). In analyzing the behavior of reactive radionuclides, consideration should be given to the presence of organic or inorganic complexants in the released liquids during the accident. Also, consideration should be given to the effect of chelates on adsorption. The use of reactive transport models, however, is not presently viewed as practical because of substantial geochemical data and computational requirements, but should be used in appropriate circumstances when such models become practicable or if particularly simple, but important, chemical reactions are involved.

5.2 Calibration, Prediction, and Updating

Model calibration. The primary goal of model calibration is to establish that the CSM adequately represents site conditions, as evidenced by the ability to minimize discrepancies between observed and predicted behavior. Characterization data from literature sources may not provide sufficient spatial detail to resolve predictions at the local scale, and may require additional, site-specific characterization data. Monitoring data from the site shall be used to evaluate model predictions, and these data shall be obtained with sufficient spatial and temporal resolution to allow appropriate comparisons. Hydrologic and water-quality observations shall be compared with model predictions using natural (hydrometeorological) and anthropogenic (pumping, recharge, tracer) events.

Where appropriate observed data exist, model calibration shall compare observed with simulated conditions for hydraulic heads, hydraulic gradients, groundwater flow directions, water mass balances, and radionuclide concentrations, migration rates, and directions. These comparisons shall be presented as maps, tables, or graphs. The objective of calibration is to minimize the statistical difference between observed and simulated conditions. Typically, the mean absolute residual error (mean absolute difference between observed and simulated groundwater flow conditions) should be less than ten percent of the variability in the field data across the model domain. In the event that radionuclide concentration(s) span over several orders of magnitude, uncertainties associated with groundwater transport conditions (typically measured by the mean absolute residual of the logarithmic concentration error) should be less than an order of magnitude (i.e., less than one on a logarithmic scale), and shall include a conservative bias. . A description of model-calibration procedures shall be provided, along with calibration data sets and assumptions. Differences between model predictions and field observations shall be discussed.

Periodic model calibration shall be performed in conjunction with updating of the CSM, as noted in Section 4.1. During calibration, it is important to focus on circumstances when predictions are inconsistent with field observations, because inconsistencies could indicate a fundamental error in the CSM, mathematical representation, or field measurement; or that an abnormal event has taken place. Regardless of the cause, efforts should be taken to evaluate what led to the inconsistency so that either the errors are resolved and avoided in the future, or the abnormal event is further evaluated. Model results that indicate significant deviations from the CSM should be used to revise or update the CSM, or to further evaluate the monitoring strategy.

Additional information about model calibration can be found in model-calibration literature that includes Hill and Tiedeman (2007).

Model predictions. Models shall be used to make predictive estimates of radionuclide concentrations at appropriate compliance points. The model shall represent future conditions consistent with source terms, boundary conditions, and material properties (using either best estimate or bounding values) as defined in the CSM (and alternative CSMs, where present) to assure that the predictive model is bounding and protective of the public.

Model updating. The conceptual and mathematical models need to provide a flexible and evolving platform for analyzing flow and radionuclide transport at the site. As more data are collected, it is likely that predictive capabilities of the associated model will be enhanced. Thus, an iterative, interdependent, ongoing effort toward reconciling monitoring data with the CSM is an important part of model updating. Model forecasts are compared with monitoring data, and vice versa. In essence, one can view the iterative and interdependent process as computer-aided thinking and evaluation (modeling) that is continuously refined by measurements (monitoring). Additional monitoring locations, characterization activities, or model complexity may be required to assist with this analysis, especially if source terms have changed. The adopted model framework is one in which new concepts shall be tested by incorporating additional data.

5.3 Uncertainty Assessment

Model uncertainties can be traced back to three basic sources: natural heterogeneity, measurement errors, and structural differences between the CSM and the real world system (USNRC, 1990). Model uncertainties shall be explicitly identified and estimated with respect to various assumptions in the CSM (e.g., unanticipated features, events, processes), hydrogeologic data and parameters (e.g., measurement and statistical variation in hydrogeologic properties, baseline, and boundary conditions, over space and time), and mathematical codes (e.g., mathematical approximation of processes, numerical errors). Acceptable and widely used methods for accounting for model uncertainties include using explicit or implicit margins of safety, bounding or best-estimate (expected value) approaches, stochastic (Monte Carlo) methods, and probabilistic risk assessments.[20]

In circumstances where model uncertainties indicate a significant risk of failure in achieving performance objectives, acceptable and widely used methods for reducing model uncertainties include a) improved characterization, monitoring, and sampling methods (e.g., alternative monitoring network design, more frequent or accurate measurements), b) alternative CSM definition (e.g., consideration of alternative features, events, and processes), and c) improved model calibration (e.g., statistically based parameter optimization techniques, sensitivity analyses, and Monte Carlo simulations). Also acceptable and widely used is a sequential, multi-stage (i.e., each stage planned and executed based on information from previous stages) site characterization, monitoring, and modeling strategy that take full advantage of these three methods. Because transport models are sensitive to local heterogeneity of aquifer properties, the scope of data collection and modeling is likely to be related to the complexity of the model and the geologic. The sequential, multi-stage strategy where site characterization, data collection, and model calibration are performed iteratively provides an opportunity to efficiently reduce uncertainties to acceptable levels.

[20] Use of probabilistic methods requires a result commensurate with the performance objective. For example, when comparing the results of a probabilistic analysis to a deterministic compliance criterion, the mean result should be used unless otherwise specified in regulations or guidance (USNRC 2009a; USNRC 2000b).

Additional information about uncertainty assessment can be found in Saltelli et al. (2000), Helton et al (2006), and USNRC (2000b, 2003a, 2009a).

6.0 Performance-Confirmation Monitoring

Monitoring shall be used to support performance assessment. The primary purpose of monitoring is to provide an evaluation process that assures that an abnormal release will be detected, and that facility components comply with performance objectives and meet necessary state and federal regulatory standards. Another purpose is to confirm the accuracy of the CSM. This implies that the monitoring program provides ongoing confirmation of the understanding of radionuclide concentrations in groundwater. Monitoring is also important for guiding actions if an abnormal release is detected. The monitoring program provides information about the source, magnitude, migration rate, and potential exposures associated with the release.

The monitoring strategy considers site risk factors (e.g., geologic complexity, distance to potential receptors, depth to groundwater), so that extensive monitoring may not be appropriate at all sites. Additional information regarding monitoring data can be found in Freeze and Cherry (1979), USNRC (1990b, 2007b, 2008), USEPA (1994), Stephens (1996), Colin and Quevauviller (1998), Fetter (2000), Ward et al. (2004), Nielsen (2006), NEI (2007), Rosenberry and LaBaugh (2008), and EPRI (2008).

6.1 Types of Monitoring Data

Hydrology. The hydraulic head shall be monitored because its spatial and temporal variation controls (along with the hydraulic conductivity and specific storage or water content) the rate and direction of water movement, and the change in fluid storage. Water-level measurements are adequate at low-risk sites, while more detailed (e.g., water flux,flow, multi-level contaminant) monitoring shall be conducted at complex sites.

Water flow (e.g., from leak detection systems, drains, vertical flow within boreholes, and into lysimeters placed within the unsaturated zone) shall be monitored at complex sites because it directly indicates subsurface flow. The water content, or saturation, within the unsaturated zone shall be monitored when the depth to the water table is significant because it responds to changes in flow at the surface or from subsurface releases. The soil water potential shall be monitored where unsaturated flow is important because it is needed to calculate the hydraulic gradient and the water flux.

Additional ancillary hydrologic data that influence subsurface conditions (e.g., precipitation, streamflow, barometric pressure, tidal stages) may also be monitored, especially if these data assist in discriminating between natural variability and a hydraulic response resulting from an abnormal release. Yet, the hydraulic change caused by an abnormal release may fall below detection levels, even when these external influences are removed from the data.

Water quality. Subsurface water quality shall be monitored, as defined by the performance indicators. Tritium concentration is a likely performance indicator because of its ubiquity at nuclear facilities and its conservative transport nature (i.e., it is not sorbed and does not decay over short time periods). Monitoring for other radionuclides depends 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) may also be used as an indicator of radionuclide presence. Additional parameters (e.g., temperature, specific conductance, pH, dissolved oxygen, redox potential, boron) may be used as additional indicators of abnormal releases, depending upon site conditions and possible release scenarios.

6.2 Monitoring Methods

Sites with low risk for groundwater contamination, with greater distances to receptors, or with simple flow geometries, need not be monitored as comprehensively as those where increased risks or complexities are present.

Hydrology. Acceptable methods for monitoring the hydraulic head in the saturated zone include manual measurement of depth-to-water in piezometers at low-risk sites. Water-level recorders (e.g., pressure transducers, capacitance probes) placed in nested piezometers (i.e., wells installed at multiple depths) shall be used at sites with complex hydrology. Where appropriate to the CSM, ambient and induced fluid flows within a well shall be monitored using borehole flowmeters to determine vertical flow components. Where appropriate to the CSM, the hydraulic head in the unsaturated zone shall be determined using tensiometer probes or other sensors with an operational range appropriate for the soil conditions, or inferred from the soil-moisture content using time-domain reflectometry in conjunction with moisture characteristic curves. Where appropriate to the CSM, flux through the unsaturated zone shall be estimated using capture-type lysimeters, or using the hydraulic gradient (from soil water potential measurements) and the unsaturated hydraulic conductivity function, as described above. Where appropriate to the CSM, water exchange across the groundwater-surface water transition zone shall be determined or inferred using an appropriate technique. Exchange may be determined using water-level measurements in nested piezometers installed at multiple depths combined with vertical hydraulic conductivity estimates. Alternatively, exchange may be determined from seepage runs (measurement of streamflow gain or loss in selected reaches), or by the use of seepage meters

Water quality. Water quality samples shall be collected to demonstrate compliance with performance objectives. A wide array of sampling devices (e.g., portable pumps, dedicated pumps, bailers in oxic conditions) and sampling techniques (purging multiple well volumes, low flow sampling, no purge sampling) are available. Where appropriate to the CSM, water quality data may be collected *in situ* using dedicated probes (e.g., temperature, specific conductance, pH, dissolved oxygen, redox potential, gross alpha, gross beta, gamma), allowing for the early detection of water quality changes. Where appropriate to the CSM, gas-phase sampling shall be used to determine the presence of volatile radionuclides (e.g., tritium, carbon-14, iodine-129) and daughter products (e.g., helium-3) in the unsaturated zone. Surface and subsurface resistivity arrays are suitable methods for detecting subsurface changes in soil moisture content or electrical conductivity.

6.3 Monitoring Locations and Frequencies

The number and location of monitoring wells needed to evaluate performance objectives depends upon site conditions, as defined in the CSM. The monitoring system shall be capable of measuring performance indicators that demonstrate compliance with applicable state and federal criteria, especially near the compliance boundary and intermediate points of compliance.

Flow and transport models developed for the site provide important guidance for finding optimal monitoring locations. These monitoring locations shall be close enough to the locations where a release to the subsurface may occur to ensure that the source of the detected contamination is identified. However, monitoring well locations are often constrained by proximity to subsurface structures, systems and components - their presence shall not interfere with normal operations. Likewise, wells should not be placed in areas where the surrounding infrastructure interferes with sampling and maintenance.

Monitoring locations include preferential flowpaths identified in the CSM because an important monitoring goal is to assure that plumes do not escape detection. Also, the farther the wells are from the facility, the more important it will be to consider the likely vertical trajectory of possible radionuclide plumes. Both the unconfined and confined aquifers (potentially at multiple depths in a deep, unconfined aquifer) shall be sampled if downward flow conditions are present. The unsaturated zone shall be monitored if the depth to water is substantial and is identified in the CSM as being a critical pathway.

While water levels and water-quality samples have traditionally been collected from permanent, long-screen monitoring wells or piezometers, vertical ambient flow in such wells may compromise these measurements (Elci et al., 2001, 2003). To avoid these problems, samples should be taken over short, vertical intervals whenever possible to provide higher resolution information about hydraulic-head and water-quality variation with depth. In place of long-screen wells, various types of multi-level sampling wells are available, along with methods for converting long-screen wells into multi-level samplers.

At least one sampling well shall be placed upgradient of the facility to provide local baseline water quality data. The possibility that abnormal releases may alter local hydraulic gradients, inducing flow in unanticipated directions shall be considered. Monitoring wells placed near topographic lows may be useful for detecting releases to surface water that accumulate in these areas. Examination or control of surface elevations aids in the design of the well monitoring infrastructure.

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 shall be sufficient to detect significant water-quality changes due to radionuclide releases from those facilities.

Because hydrologic conditions tend to vary over time, a key aspect of monitoring data management is the routine statistical characterization of monitoring data, especially performance indicators. Identification of trends and anomalous hydrologic behavior provide important information about system performance.

Short-duration releases may not be detected if transport is rapid and sampling is not sufficiently frequent. The sampling frequency shall be sufficiently often such that sampling is able todetect intermittent or brief releases. Also, the hydrologic effects (e.g., water-level fluctuations) due to precipitation, barometric, and tidal fluctuations shall be monitored at sub-hourly frequencies (e.g., 15 minutes) if these effects have been identified as important in the CSM. Automated data-logging capabilities are available for collecting water-level, water-quality, and gas-phase data at these frequencies and with acceptable precision. In some cases, these instruments may be connected wirelessly to provide real-time monitoring data capability.

Engineered barriers may improve the likelihood of detecting an abnormal release. The establishment of a cone of depression under potential release sites (e.g., a capture zone created by a pumping well that intercepts and removes radionuclides that reach the water table) may provide a method for containing and detecting releases. Data from appropriately designed and installed extraction wells or vapor-capture systems with ancillary monitoring equipment could provide an early warning for both tritiated water in the saturated zone and tritium vapor in the unsaturated zone, respectively. These systems could also be used for corrective action by maintaining positive control during a release. If used, the capture zone shall be designed in conjunction with other engineered-barrier and leak-detection systems.

7.0 Information Management

Important components of performance assessment are the documentation of data, the demonstration of the integrity of its analysis, and maintenance of the supporting databases throughout the life cycle of the monitoring program. These components are important because the ability to access site information is fundamental to supporting the CSM and increases the confidence in meeting performance objectives. Documentation shall contain the hydrogeologic data and information that provides the basis for the CSM, as well as the key interpretations of geologic and hydrologic data and information, including descriptions of methods and approaches used to make these interpretations. Documentation is updated as new data on both the local and regional scale become available.

This section provides guidelines for managing information about the CSM, site characterization and monitoring data, the accuracy of—and the procedures used to procure—these data, and the mathematical models used to analyze these data and to evaluate and revise the CSM.

7.1 Characterization and Monitoring Data Management

Conceptual site model management. The current state of and revisions to the CSM shall be documented to clarify the dynamic understanding of the FEPs at the site. The CSM shall be updated whenever additional characterization and monitoring data indicate the need to do so. Documentation consists of maintaining an archive of the various CSMs, along with the changes and the justification or reason for these changes. The CSM(s) are best documented as a set of two-dimensional (plan and profile) or three-dimensional (isometric) graphics which qualitatively present the interrelationships between the FEPs, along with supporting text (Shah, 2004).

Sampling methods and equipment. Field monitoring equipment installation and sampling methods shall adhere to those defined by ASTM International (previously known as the American Society for Testing and Materials) (ASTM, 1996; ASTM, 1999) and National Ground Water Association guidelines (NGWA, 1998) whenever practicable. 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.

Data quality. Data-quality objectives (DQOs) are used to specify sampling and analytical protocols, specifically with respect to sampling frequencies, precision, and accuracy. A DQO process shall be established to define the type, quality, and quantity of data needed to satisfy performance objectives. A robust data quality-assurance/quality-control program ensures that collected data meet these DQOs. Examples of acceptable methods for assessing data precision include field duplicates and laboratory replicates. Examples of acceptable methods for assessing data accuracy include the use of calibration standards, matrix spikes, and blanks. Example methods for assessing data completeness include the comparison of the number of valid measurements with the planned number of analyses. Multivariate statistical analysis of the data is an acceptable method for identifying Type I and Type II errors and for correcting measurement bias.

Data limitations. Minimizing data limitations assists in CSM development and mathematical model implementation. The sources of field and laboratory uncertainty shall be quantified and minimized. Sources of uncertainty include, but are not limited to, well construction (e.g., casing integrity, screen locations, inadvertent pathways, grout contamination, insufficient well productivity) and sampling protocols (e.g., low-flow sampling, pumping vs. static monitoring, sample representativeness).

Parameter databases. Databases provide a resource for routine electronic storage of, and access to, data and information about the site hydrogeology, which are used for modeling and data interpretations, site operations, support of decision making, and communication with stakeholders. Methods and approaches used to develop the parameter estimates are included as metadata. Databases also provide sufficient information to define parameter distributions (e.g., mean, variance) for hydrogeologic data (e.g., geometry of the main hydrogeologic units, hydraulic properties, boundary conditions, initial conditions, locations and volumes of sources and sinks, artificial and natural recharge estimates). Structured correctly, a relational database assures data consistency by allowing comparative analyses throughout the life of the data collection effort.

Spatially explicit information shall be stored in a standardized geo-referenced coordinate system to facilitate presentation using a geographic visualization platform (Shah, 2004). Time-series data, particularly performance indicators, shall be presented as time-series plots, with statistical characterization including trend analyses. The data and associated plots and statistical characterization shall be updated routinely.

Databases shall be preserved using an industry-standard, computer-readable format so that a third party can use the information to reasonably reproduce temporal or spatial analyses. Databases using proprietary formats should be avoided, because of uncertainties in the ability to access them over time. Instead, consider developing the database in open (free) format with adequate consideration for metadata storage.

7.2 Mathematical Model Management

Verification. Evidence of verification of the numerical implementation of the mathematical model (whether equation or computer code) shall be maintained. Verification provides evidence that the solution methods used in the model are correct and demonstrates the effect of the assumptions and potential errors arising from model limitations. Verification evidence includes comparison of model results for a variety of known or accepted solutions. Previous applications of the selected model, or other evidence that the model is well regarded by the regulatory community, shall be used to establish model credibility.

Configuration control. Models shall be maintained under configuration control, i.e., computer code version numbers or equation forms shall be documented. This includes the databases supporting the CSM and its mathematical implementation, whether equations or computer code. Multiple computer codes may be required to address all significant migration pathways as identified in the CSM. If multiple codes are used, then the relationships between these codes shall be provided.

Documentation. Model documentation (e.g., user manuals, computer source and executable code, basic model data) shall be preserved as formal documents or in standardized documentation packages that are not affected by the vagaries of computer technology (rapid advances in computer and modeling technology may render stored versions irretrievable). Documentation shall be sufficiently complete and detailed (e.g., objectives, processes, parameter values, boundary and initial conditions, individual simulations using variable parameters or conditions, results, and interpretation of the results) so that the model can be accurately re-created for future modeling programs. Documentation also includes model calibration results and statistics, details of successive model revisions, and model limitations.

Availability. Because of the need for transparency and verification of modeling results, the mathematical model (whether equation or computer code, along with model inputs, user manuals, etc.) shall be available to regulatory agencies. Models whose source code is publicly available are preferred over proprietary codes because rapid changes in computer technology may render proprietary codes unusable or obsolete over the lifespan of the facility.

8.0 References

The user is advised to review each of the following references to determine whether it, a more recent version, or a replacement document is the most pertinent for each application. When alternate documents are used, the user is advised to document this decision and its basis.

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Appendix A. Consultation and Coordination

It is recommended that regulatory agencies with jurisdictional authority be consulted prior to the preparation of the scope of work for evaluation of subsurface radionuclide occurrence and movement. The regulatory entities may assist in the identification of specific regulatory programs and objectives related to groundwater protection. Guidance from the U.S. Nuclear Regulatory Commission should be obtained and used to determine the scope of a subsurface radionuclide transport evaluation program.

USNRC regulations are issued under the authority of the Atomic Energy Act of 1954, as amended, and the Energy Reorganization Act of 1974, as amended. The regulations establish reasonable assurance for adequate protection to the health and safety of the public and environment. Regulatory requirements are established for facility design, operation, and decommissioning phases of plant life. The requirements for nuclear power plant facility design are specified in 10 CFR 50, Appendix A, “General design criteria for nuclear power plants”. Specifically, Criterion 60, “Control of releases of radioactive materials to the environment”, specifies the criteria for controlling the release of radioactive materials in gaseous and liquid effluents, including anticipated operational occurrences. Criterion 64, “Monitoring radioactivity releases”, establishes the criteria for monitoring radioactivity in releases, including effluent discharge paths in the plant environs from normal operations, including anticipated operational occurrences. ICRP (1983) and USNRC (2003b; 2007c; 2007d) provide additional technical information.

Standards for protection against radiation are established in 10 CFR 20 for plant operation and decommissioning. The specific dose limits established in 10 CFR 20.1301 for offsite individual members of the public (i.e., total effective dose equivalent, TEDE) are limits not to exceed 100 mrem per year, exclusive of background radiation and medical applications. In addition, USEPA 40 CFR 190 Part 190, “Environmental radiation protection standards for nuclear power operations” establishes dose limits of 25 mrem per year whole body, 75 mrem per year thyroid, and 25 mrem for any other organ for members of the public in the general environment from radioactive materials introduced into the general environment as the result of operations which are part of a nuclear fuel cycle.

For decommissioning purposes, 10 CFR 20 Subpart E, “Radiological criteria for license termination” establishes the radiation protection standard that following decommissioning, a site will be considered acceptable for unrestricted use if the residual radioactivity results in individual dose that does not exceed a TEDE of 25 mrem per year, including that from groundwater sources of drinking water, and that the residual radioactivity has been reduced to levels that are as low as is reasonably achievable (ALARA).

Radiation dose to individual members of the public occurs through various radiation exposure pathways (i.e., inhalation, ingestion, and direct radiation). Individual routes of exposure must be identified based on their exposure pathway.[21] The levels of radioactivity in media from these pathways must be monitored to ensure that the overall system is in compliance with regulatory and design requirements.

It is important to know the on-site concentrations and radionuclide transport pathways in order to estimate whether off-site contamination will exceed the USEPA dose limits (per 40 CFR Part 190) for members of the public in the general environment (i.e., off-site). References that may assist in design include those provided by USNRC (1977, 1988, 1990a, 1991, 2000a, 2007a) as well as ALARA, EIS, and REMP publications (e.g., IAEA, 1999; CRWMS, 2000; NEI, 2007). Specifically, REMP requires sampling of various environmental pathways related to normal (permitted) releases including waterborne pathways at required intervals, which are analyzed for the presence of specified radiological constituents. Additional USNRC guidance related to accidental radionuclide releases is provided by USNRC (2009b, 2010).

Substantial pre-construction and post-construction data and information relevant to subsurface radionuclide transport may already be available at existing facilities (although these may not be in suitable digital format). Additional data and information can be solicited from federal, 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. Consultation with the Federal Interagency Advisory Committee on Water Information (ACWI), specifically the Subcommittee on Groundwater (acwi.gov/sogw), may also provide additional data and information. Existing standards and guidelines for conducting subsurface radionuclide characterization and monitoring programs are also available, including those listed in Table A.

[21] For example, 50% of the dose could arise from the drinking water exposure pathway, and another 50% for other routes of exposure pathways combined. Hence, for subsurface radionuclides, a performance objective for the drinking water pathway can be established to limit the dose to members of the public to meet a fraction of the USNRC decommissioning criteria of 25 mrem per year TEDE for unrestricted site use (per 10 CFR 20.1402), or a fraction of the USEPA 40 CFR 190 criteria of 25 mrem per year whole body, or 75 mrem per year thyroid, or 25 mrem per year for all other organs.

Table A: List of potentially relevant resources for conducting subsurface radionuclide transport characterization, monitoring, and modeling programs.

Document #	Title
ANS-10.2	Portability of scientific and engineering software
ANS-10.3	Documentation of computer software
ANS-10.4	Verification and validation of scientific and engineering computer programs for the nuclear industry
ANS-10.4	Verification and validation of scientific and engineering computer programs for the nuclear industry
ANS-10.5	Accommodating user needs in scientific and engineering computer software development
ANS-10.5	Accommodating user needs in scientific and engineering computer software development
ANS-10.7	Non-real time, high integrity software for the nuclear industry
ASTM D4646-03	Standard test method for 24-h batch-type measurement of contaminant sorption by soils and sediments
ASTM D4700-91(1998)e1	Standard guide for soil sampling from the vadose zone
ASTM D5126-90(1998)e1	Standard guide for comparison of field methods for determining hydraulic conductivity in the vadose zone
ASTM D5126-90(1998)e1	Standard guide for comparison of field methods for determining hydraulic conductivity in the vadose zone
ASTM D5903-96(2006)	Standard guide for planning and preparing for a groundwater sampling event
ASTM D6312-98(2005)	Standard guide for developing appropriate statistical approaches for groundwater detection monitoring programs
ASTM D6538-00(2005)e1	Standard guide for sampling wastewater with automatic samplers
ASTM D6724-04	Standard guide for installation of direct push groundwater monitoring wells
ASTM D7045-04	Standard guide for optimization of groundwater monitoring constituents for detection monitoring programs for RCRA waste disposal facilities
ASTM D7128-05	Standard guide for using the seismic-reflection method for shallow subsurface investigation
ASTM D7128-05	Standard guide for using the seismic-reflection method for shallow subsurface investigation
ASTM E2435-05	Standard guide for application of engineering controls to facilitate use or redevelopment of chemical-affected properties
DIN 18130-2	Soil, investigation and testing - Determination of the coefficient of water permeability - Part 2: Field tests
DIN 18305:2000	Construction contract procedures (VOB) - Part C: General technical specifications in construction contracts (ATV); Groundwater lowering
DIN 19683-9:1998	Soil testing in agricultural hydrology - Physical laboratory tests - Determining the water permeability of saturated core samples
DIN 19683-9:1998	Soil testing in agricultural hydrology - Physical laboratory tests - Determining the water permeability of saturated core samples
DIN 19732	Soil quality - Determination of the site specific potential for translocation of non-sorbable substances
DIN 4944	Closures for groundwater measuring stations
DIN ISO 19258:2005	Soil quality - Guidance on the determination of background values
EN 14968	Semantics for groundwater data interchange
ISO 10381-2:2002	Soil quality - Sampling - Part 2: Guidance on sampling techniques
ISO 14686:2003	Hydrometric determinations - Pumping tests for water wells - Considerations and guidelines for design, performance and use

Document #	Title
ISO 15175:2004	Soil quality - Characterization of soil related to groundwater protection
ISO 15800:2003	Soil quality - Characterization of soil with respect to human exposure
ISO 21413:2005	Manual methods for the measurement of a groundwater level in a well
ISO 22475-1:2006	Geotechnical investigation and testing - Sampling methods and groundwater measurements - Part 1: Technical principles for execution
ISO 22475-1:2006	Geotechnical investigation and testing - Sampling methods and groundwater measurements - Part 1: Technical principles for execution
ISO 5667-11:1993	Water quality - Sampling - Part 11: Guidance on sampling of groundwaters
ISO 5667-11:1993	Water quality - Sampling - Part 11: Guidance on sampling of groundwaters
ISO 5667-18/Cor1:2008	Water quality - Sampling - Part 18: Guidance on sampling of groundwater at contaminated sites - Corrigendum
ISO 5667-18/Cor1:2008	Water quality - Sampling - Part 18: Guidance on sampling of groundwater at contaminated sites - Corrigendum
ISO 5667-18:2001	Water quality - Sampling - Part 18: Guidance on sampling of groundwater at contaminated sites
ISO 5667-18:2001	Water quality - Sampling - Part 18: Guidance on sampling of groundwater at contaminated sites
ISO/CD 5667-22	Water quality - Sampling - Part 22: Guidance on design and installation of groundwater sample points
ISO/TS 17892-11:2004	Geotechnical investigation and testing - Laboratory testing of soil - Part 11: Determination of permeability by constant and falling head
ISO/TS 22475-2:2006	Geotechnical investigation and testing - Sampling methods and groundwater measurements - Part 2: Qualification criteria for enterprises and personnel
ISO/TS 22475-2:2006	Geotechnical investigation and testing - Sampling methods and groundwater measurements - Part 2: Qualification criteria for enterprises and personnel
ISO/TS 22475-3:2007	Geotechnical investigation and testing - Sampling methods and groundwater measurements - Part 3: Conformity assessment of enterprises and personnel by third party
ISO/TS 22475-3:2007	Geotechnical investigation and testing - Sampling methods and groundwater measurements - Part 3: Conformity assessment of enterprises and personnel by third party
LC 91-15752	Groundwater residue sampling design

Appendix B. Summary of Information and Parameters

The following tables summarize information and parameters cited in the guidance. This information is all-encompassing. For an individual site, the information and parameters needed may be a subset of the listing due to the environmental setting and plant conditions.

Table B.1: Summary of information for defining, updating, and visualizing the Conceptual Site Model (CSM).

1) Geographic region of concern (e.g., topography, watershed area and boundaries)
2) Surface water (hydrographic) features (e.g., rivers, streams, lakes, ponds, wetlands, estuaries, coastal sea levels)
3) Geologic features (e.g., hydrostratigraphy, faults, hydrogeologic unit interfaces, fracture zones)
4) Hydrogeologic units and features (e.g., phreatic and confined aquifers, confining layers, unsaturated zone, perched systems, springs)
5) Additional features at complex sites which may be part of, or have direct influence on, transport pathways, such as
   a) Preferential flowpaths (e.g., buried stream channels, lineaments, fracture connectivity, voids, conduits),
   b) Adjacent aquifers or watersheds with subsurface flow interactions
   c) Surface-water and ground-water interactions (e.g., coastal zones, recharge and discharge zones, groundwater-surface water transition zones)
6) Conceptualization of radionuclide occurrence and transport with:
   a) A conceptualization of the radionuclide source terms, including type (e.g., liquid waste management system tank, residual radioactivity in soil), location, volume, mass, concentrations, release mechanisms, etc.
   b) A conceptualization of the receptor locations, regulatory boundaries, and target aquifers
   c) A conceptualization of the radionuclide pathways along with the biological and geochemical processes that are likely to affect radionuclide occurrence and transport characteristics
7) Alternative conceptual site models
8) Periodic updating (e.g., every five years or whenever facilities are significantly altered)
9) Visualization (e.g., figures of cross-sections, block diagrams, graphs, stylized cartoons)

Table B.2: Summary of information and parameters required for characterizing site facility characterization

1) Facilities
   a) Surface facilities (e.g., spent-fuel pools, holding ponds, condensate tanks, radwaste tanks, pipelines conveying steam or liquids containing radionuclides)
   b) Liquid waste management systems (e.g., for newer facilities, a failure of a liquid waste management system tank shall be postulated and evaluated against the effluent concentration limits given in 10 CRF Part 20. These tanks should be explicitly identified in the list of facilities)
   c) Subsurface facilities (e.g., spent-fuel pools, drains, sumps, pipes conveying steam or liquids containing radionuclides, conduits, artificial fill, backfill, pads, foundations, and the associated vadose zone)
   d) Engineered barriers (e.g., liners, caps, cutoff walls, leak detection systems, and interceptor wells)
   e) Hydraulic properties of anthropogenic materials (e.g., permeable foundation backfill, permeable and impermeable pipe trench backfill, impermeable foundations, foundation drains, production wells, etc).
   f) Well construction data (e.g., drilling methods, grouted and screened intervals, screen and casing type, depth, diameter, perforation, surface seals, aquifers penetrated, location, elevation, use, owner, discharge rates, static hydraulic heads, and drawdown)
   g) Abandoned wells and piezometers along with the method of abandonment and confirmation
2) Modifications to plant structures, systems and components affecting ground-water flow and transport
3) History and identification of prior abnormal releases

Table B.3: Summary of information and parameters for hydrogeologic characterization

1) Baseline conditions
   a) Hydraulic head and gradients
      i) Surface water (e.g., rivers, lakes, wetlands, springs, estuaries, bays, oceans, groundwater-surface-water transition zones)
      ii) Subsurface water (e.g., unsaturated zone, unconfined and confined aquifers)
   b) Surface loading (e.g., precipitation, barometric pressure, streamflow, tidal fluctuations, cooling water intake and discharge canals)
   c) Offshore discharges and tidal influences as affected by coastal processes
   d) Water quality data (e.g., tritium, salinity, tracer data)
2) Water Budget
   a) Precipitation, evapotranspiration, and streamflow
   b) Infiltration, recharge, and discharge rates
   c) Surface-water body elevations (including variability, e.g., tidal)
3) Transport Pathways
   a) Regional and local water users as potential receptors
   b) Travel times and flow paths
   c) Additional information at complex sites (e.g., effective porosity and dispersivity, alternative complex models, core samples)
4) Physical Properties
   a) Aquifer, aquitard, and unsaturated zone properties
      i) Thickness and depth
      ii) Composition (total and effective porosity; type and degree of fracture connectivity in rock; and bulk density, grain-size distribution, and sorting in soil)
5) Hydraulic Properties
   a) Hydraulic head, areal and with depth (water potential and water content in unsaturated zone if defined in CSM)
   b) Hydraulic gradient; horizontal and vertical
   c) Hydraulic conductivity and/or transmissivity for confined units
   d) Storage coefficient (confined) or specific yield (unconfined)
   e) Boundary conditions (constant head, general head, no-flow, recharge, etc.)
   f) Ground-water velocity and flux (computed)
6) Transport Properties
   a) Geochemical indicators (e.g., pH, temperature, specific conductance, redox, dissolved oxygen, turbidity)
   b) Major cations and anions present (e.g., sodium, calcium, magnesium, potassium, chloride, bicarbonate, sulfate)
   c) Distribution (adsorption) coefficients (site and contaminant specific)
   d) Dispersivity coefficients (longitudinal and transverse)

Table B.4: Summary of information and parameters for hydrogeologic modeling

1) Model Scope
    a) Relevant physical and chemical processes and parameters
        i) Consistent with identified significant Features, Events, and Processes (FEPs)
        ii) Specification of acceptable model accuracy
        iii) Specification of analytic or numeric methods for flow and transport.
    b) Hydrologic properties and conditions
        i) Spatial scale
        ii) Temporal scale
        iii) Model geometry
        iv) Flow parameters
        v) Hydrologic boundaries
        vi) Parameter estimation
    c) Transport conditions
        i) Radionuclide retardation
        ii) Radionuclide decay
        iii) Dispersion and molecular diffusion
        iv) Flowpath modeling
        v) Reactive transport and transformations
2) Calibration, Prediction, and Updating
    a) Model calibration using monitoring data
        i) Hydraulic heads and gradients
        ii) Groundwater flow directions
        iii) Water mass balances
        iv) Radionuclide concentrations, migration rates, directions
    b) Model predictions
        i) Future conditions and source terms
        ii) Future boundary conditions and material properties
    c) Model updating
3) Uncertainty Assessment
    a) CSM alternatives
    b) Geologic variability
    c) Parameter uncertainty
    d) Measurement error
    e) Unanticipated events
    f) Scenario uncertainty
    g) Mathematical approximations
    h) Numerical errors

Table B.5: Summary of information and parameters for performance-confirmation monitoring

1) Types of Monitoring Data
    a) Hydrology
        i) Hydraulic head
        ii) Additional data at complex sites:
            (1) Water flow (leak detection systems, drains, vertical borehole flow, lysimeters)
            (2) Unsaturated zone water content, saturation, soil water potential
            (3) Ancillary hydrologic data (precipitation, streamflow, barometric pressure, tidal stages)
    b) Water quality
        i) Establish baseline conditions for specific radionuclides
        ii) Water sampling to determine compliance
    c) Geophysical survey data to confirm CSM
2) Monitoring Methods
    a) Hydrology
        i) Depth-to-water sensors
        ii) Methods at complex sites
            (1) Water-level recorders
            (2) Nested piezometers
            (3) Borehole flowmeters
            (4) Tensiometers, time-domain reflectometry
            (5) Capture-type lysimeters
            (6) Seepage runs, meters, or other appropriate techniques
    b) Water quality
        i) Portable or dedicated pumps, bailers
        ii) Methods at complex sites
            (1) In situ probes
            (2) Gas-phase sampling
            (3) Resistivity arrays
3) Monitoring Locations and Frequencies
    a) Capable of measuring performance indicators
    b) Ability to detect and identify subsurface release
    c) Avoid infrastructure
    d) At complex sites:
        i) Located along preferential pathways
        ii) Multiple depths
        iii) Unsaturated zone
    e) Upgradient and downgradient of source terms
    f) Sufficiently often to capture intermittent or brief releases

Table B.6: Summary of information management.

1) Characterization and Monitoring Data Management
    a) Conceptual Site Model (CSM) management
        i) Documentation of current and previous CSMs
            (1) Archive of CSMs data with changes and assumptions
            (2) Graphics showing significant FEPs with supporting text
    b) Sampling methods and equipment
    c) Data quality
    d) Data limitations
    e) Parameter databases
2) Mathematical Model Management
    a) Verification
    b) Configuration control
    c) Documentation
    d) Availability