

American Nuclear Society

**evaluation of subsurface
radionuclide transport at commercial
nuclear power plants**

an American National Standard



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**American National Standard
Evaluation of Subsurface
Radionuclide Transport at Commercial
Nuclear Power Plants**

Secretariat
American Nuclear Society

Prepared by the
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Working Group ANS-2.17**

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Foreword

(This Foreword is not a part of American National Standard “Evaluation of Subsurface Radionuclide Transport at Commercial Nuclear Power Plants,” ANSI/ANS-2.17-2010.)

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of the original standard, ANSI/ANS-2.17-1980, which was adopted on April 9, 1980, reaffirmed on October 3, 1989, and withdrawn on July 28, 2000.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This standard might reference documents and other standards that have been superseded or withdrawn at the time the standard is applied.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.

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Evaluation of Subsurface Radionuclide Transport at Commercial Nuclear Power Plants

1 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 plants.

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 the following:

- 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 might affect, or be affected by, on-site 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 might be required as the result of a subsurface radionuclide release;
- dose calculations to demonstrate compliance with any regulatory requirement.

2 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

DQO(s): data quality objective(s)

EIS: Environmental Impact Statement

EPRI: Electric Power Research Institute

FEP(s): feature(s), event(s), and process(es)

IAEA: International Atomic Energy Agency

NEI: Nuclear Energy Institute

NGWA: National Ground Water Association

NRC: National Research Council

REMP: Radiological Environmental Monitoring Program

RETS: Radioactive Effluent Technical Specifications

TEDE: total effective dose equivalent

USEPA: U.S. Environmental Protection Agency

USNRC: U.S. Nuclear Regulatory Commission

2.2 Definition of terms

abnormal radionuclide release: The unplanned or uncontrolled emission of an effluent (i.e., containing plant-related, licensed radioactive material).

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 power plant.

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

biogeochemical processes: The chemical interactions that exist among the atmosphere, hydrosphere, lithosphere, and biosphere.

capillary zone: The region above the water table where pores are saturated but where the water gauge pressure is negative; also called the tension-saturated zone.

commercial nuclear power plant: A commercial electrical generating facility using a nuclear reactor as its heat source to provide steam to a turbine generator.

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 among 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 objective(s) [DQO(s)]: 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 20, Appendix B [1],¹⁾) equivalent to the radionuclide concentrations that, 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 mSv).

effluent discharge (radioactive): The emission of an effluent (i.e., containing plant-related, licensed radioactive material) into 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 might include dose contributions from one or more routes of exposure. One route of exposure that might contribute to the ingestion exposure pathway is often referred to as grass-cow-milk-infant-thyroid route of exposure.

feature(s), event(s), and process(es) [FEP(s)]: An assessment of the relevant (a) features, which are identified physical characteristics of the total system, and how they behave over time; (b) events, which are occurrences of abnormal radionuclide releases; and (c) 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 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 emission of an effluent containing plant-related, licensed radioactive material. The known, planned, or controlled release of radionuclides to the environment, including controlled releases of low-level radioactive materials. The effluent discharge performed in accordance with RETS.

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 gauge 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.

¹⁾Numbers in brackets refer to corresponding numbers in Sec. 8, "References."

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

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 basis for decision making. Performance-based regulations have the following attributes: (a) measurable, calculable, or objectively observable parameters exist or can be developed to monitor performance; (b) objective criteria exist or can be developed to assess performance; (c) licensees have flexibility to determine how to meet the established performance criteria in ways that will encourage and reward improved outcomes; and (d) 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 gauge 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 in an unrestricted area (e.g., off-site) that might 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 might 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 the 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 or pathway by which an individual or human receptor might be exposed to ionizing radiation or radioactive material. For the ingestion exposure pathway, the routes of exposure might 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 move-

ment. 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.

system: In the context of this standard, the system consists of (a) all facilities from which a release to the groundwater might occur, (b) all facility policies or procedures that might impact or cause a release, (c) the man-machine interface of a facility that might cause or contribute to a release, (d) all engineered barriers and leak detection systems, (e) the local and regional hydrogeology, and (f) all monitoring well networks and procedures for gathering and analyzing soil and groundwater samples.

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 gauge 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 gauge pressure is zero, also called the phreatic surface.

3 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. A facility that has a less significant radionuclide source term, minor subsurface contamination, simple or well-understood hydrogeology, or 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.

3.1 Performance assessment activities

Performance assessment is used in this standard to prescribe site characterization, mathematical modeling, and performance-confirmation monitoring. The aim 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 are used to demonstrate whether system design or regulatory requirements have been met.

The following performance assessment activities shall be conducted (illustrated in Fig. 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 Sec. 3.2);
- (2) Identify and assess the relative significance of the subsurface radionuclide release scenarios and transport pathways (described in Sec. 4);

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

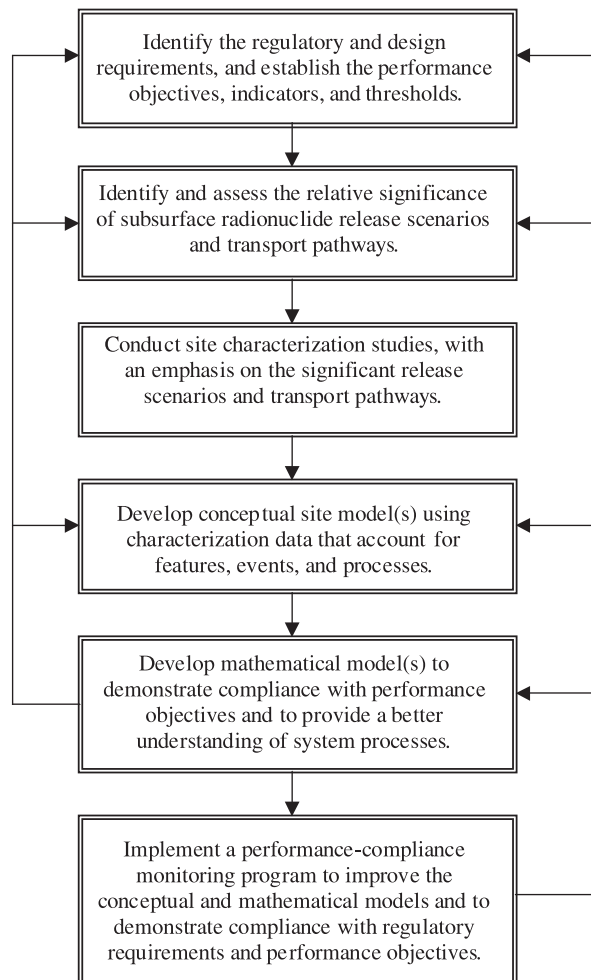


Figure 1 – Flowchart describing performance assessment activities and the relationships among these activities

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

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

(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 Sec. 6).

3.2 Performance assessment elements

The performance assessment contains the following required elements:

(1) Performance objectives shall be established for all regulatory and design requirements.⁴⁾ Separate performance objectives for on-site⁵⁾ and off-site⁶⁾ areas shall be established. Performance objectives more stringent than regulatory requirements may be established 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.⁷⁾ Table 1 presents a ranked list of radionuclides at commercial nuclear power plants, which might be

⁴⁾ Potentially relevant regulatory requirements are provided in Appendix A.

⁵⁾ For example, on-site dose limits include the 10 CFR 20.1402 [2] license termination criteria of ≤ 25 mrem/yr (unrestricted use).

⁶⁾ For example, off-site public dose limits include the U.S. Nuclear Regulatory Commission (USNRC) limit of 100 mrem/yr (all pathways), the U.S. Environmental Protection Agency (USEPA) 40 CFR 141.66 [3] limit of 4 mrem/yr (drinking water pathway), and 10 CFR 50, Appendix I [4] numerical guides for design objectives and limiting conditions for operation of ≤ 3 mrem/yr (to a real individual using realistic liquid effluent exposure pathways).

⁷⁾ 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 might be selected if they are likely to be present.