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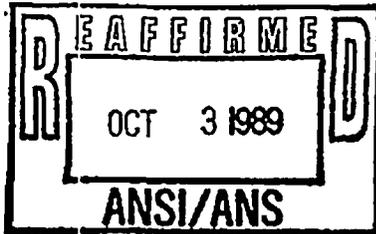
Don, I am sure that you have this, but wanted to make sure...John

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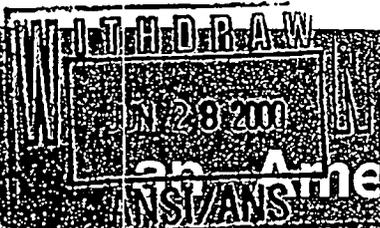
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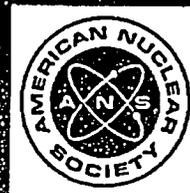
American Nuclear Society



**evaluation of radionuclide transport
in ground water for nuclear power sites**



An American National Standard



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**American National Standard
for Evaluation of Radionuclide Transport
in Ground Water for Nuclear Power Sites**

**Secretariat
American Nuclear Society**

**Prepared by the
American Nuclear Society
Standards Committee
Working Group ANS-2.17**

**Published by the
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Foreword

(This Foreword is not a part of American National Standard for Evaluation of Radionuclide Transport in Ground Water for Nuclear Power Sites, ANSI/ANS-2.17-1980.)

The purpose of this document is to specify standards for determining the concentrations of radionuclides in the ground water resulting from both potential accidental and routine releases from nuclear power plants. This standard was prepared by Working Group ANS-2.17 of ANS-2 Subcommittee, Site Evaluation, of the American Nuclear Society Standards Committee.

The initial meeting of the working group was held in October, 1974. At that meeting, the working group was designated as ANS-2.9, Standards for Evaluating Water Supply and Waterborne Radionuclide Transport for Nuclear Power Sites. This working group was subdivided into surface water and ground water subgroups, and the working group was formally subdivided at the March, 1975 meeting of the ANS-2 subcommittee into ANS-2.9, Standards for Evaluating Water Supply and Waterborne Radionuclide Transport for Power Reactor Sites: Ground Water, and ANS-2.13, Standards for Evaluating Water Supply and Waterborne Radionuclide Transport for Power Reactor Sites: Surface Water.

The draft standard, ANS-2.9, was balloted on May 31, 1977, by the ANS-2 Subcommittee with 12 approved, 10 approved with comments, 2 disapproved, 1 not voting, and 2 unreturned ballots. As a result of comments received during this balloting, the draft standard was further sub-divided into ANS-2.9, American National Standard for Evaluation of Ground Water Supply for Nuclear Power Sites, and ANS-2.17, American National Standard for Evaluation of Radionuclide Transport in Ground Water for Nuclear Power Sites. These draft standards, dated January, 1978, were transmitted to the ANS-2 Subcommittee in June, 1978, for information and informal comments. The draft standards were revised to incorporate these informal comments. As a result of these revisions, the two disapproved ballots were changed to approved with comments.

This standard covers parts of the material that meet the requirements of Section 2.4, Hydrologic Engineering, and Section 11.2, Liquid Waste Management Systems, of the "Standard Format and Content of Safety Analysis Reports for Nuclear Power Plants," Regulatory Guide 1.70, issued by the Nuclear Regulatory Commission (NRC).

Before preparing the Safety Analysis Report (SAR) Sections 2.4 and 11.2, for the licensing of nuclear power plants, the applicant should be aware of hydrologic work which has been done by others in the area of interest. Almost invariably, much work can be saved by utilizing all or parts of studies of local, state, and federal agencies. Such information as historical ground water levels, pumping tests, well logs, withdrawal and recharge rates, geologic data, hydraulic parameters of underlying formations, location and extent of aquifers, and water quality can be obtained from such sources.

Federal agencies which have useful data are the U.S. Geological Survey, Corps of Engineers, Bureau of Reclamation, Soil Conservation Service, Forest Service, Tennessee Valley Authority, Environmental Protection Agency, and the Nuclear Regulatory Commission. Most states have one or more agencies which are concerned with various aspects of water resources. Various local and interstate agencies, including soil and water conservation districts, irrigation districts, and river basin commissions, can be sources of information. SAR's for other nuclear facilities in the region can provide data.

It is also profitable to discuss the specific site in detail with the hydrology staff of the NRC prior to starting preparation of Section 2.4. In such discussions the scope of work can often be reduced, and methodologies and procedures can be agreed upon, which will save many man-hours and dollars, both for the applicant and for the NRC staff.

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

David L. Siefken, Chairman, *Sargent & Lundy*
Y. C. Chang, *Stone & Webster Engineering Corporation*
Stanley N. Davis, *University of Arizona*
James O. Duguid, *Battelle Memorial Institute*

I. Wendell Marine, *E. I. DuPont de Nemours & Company*
John A. McLaughlin, *Pacific Gas and Electric Company*
William M. McMaster, *Tennessee Valley Authority*
Thomas Nicholson, *Nuclear Regulatory Commission*

The chairman of the working group prior to the preparation of Draft 4, dated December, 1978 was Patrick J. Ryan, Bechtel, Inc. Prior to his retirement, Donald L. Milliken represented the Nuclear Regulatory Commission.

Subcommittee ANS-2, Site Evaluation, of the American Nuclear Society Standards Committee had the following members at the time of its approval of this standard:

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Luis E. Escalante, *Los Angeles Department of Water and Power*
J. A. Fischer, *Dames & Moore*
Walter W. Hays, *U.S. Geological Survey*
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N. R. Wallace, *Bechtel, Inc.*
Donald A. Wesley, *General Atomic Company*
Earl Ivan White, *General Atomic Company*
Karl Wiedner, *Bechtel Power Corporation*

The members of American Nuclear Society's Nuclear Power Plant Standards Committee (NUPPSCO) at the time it balloted this standard in July 1979 were:

J. F. Mallay, Chairman
M. D. Weber, Secretary

Name of Representative	Organizations
G. A. Arlotto	U.S. Nuclear Regulatory Commission
R. E. Basso	Catalytic, Inc.
R. G. Benham	General Atomic Company (for the Institute of Electrical and Electronics Engineers)
R. V. Bettinger.....	Pacific Gas & Electric Company
P. Bradbury	Westinghouse Advanced Reactor Division
D. A. Campbell.....	Westinghouse Electric Corporation
C. O. Coffey	Kaiser Engineers
L. J. Cooper	Nebraska Public Power District
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D. M. Leppke	Fluor Power Services, Inc.
J. F. Mallay.....	Babcock & Wilcox Company (for the American Nuclear Society)
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J. E. Ward.....	Sargent & Lundy
G. L. Wessman	General Atomic Company
J. E. Windhorst	Southern Company Services (for the American Society of Mechanical Engineers)
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Evaluation of Radionuclide Transport in Ground Water for Nuclear Power Sites

1. Scope and Purpose

This standard presents guidelines [for the determination of the concentration of radionuclides in the ground water resulting from both postulated accidental and routine releases from nuclear power plants.]

1.1 Coverage. This standard presents the methods to evaluate potential radionuclide transport in ground water for use in evaluation of nuclear power plant sites. This standard contains mandatory requirements as designated by the use of the word "shall".

1.2 Exclusions. This standard does not discuss the release of non-radioactive waste to ground water, nor the radioactive source terms for the ground water evaluation studies.

2. Definitions

In general, ground water terms are used in accordance with definitions as described by Lohman and others.[1]¹ Definitions are given below for terms which can have more than one meaning to ground water hydrologists.

anisotropic. The properties at any point within a medium are different in different directions.
dispersion coefficient (L^2T^{-1}) A measure of the spreading of a flowing substance due to the nature of the porous medium, with its interconnected channels distributed at random in all directions.

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

distribution coefficient ($M^{-1}L^3$). The quantity of the radionuclide sorbed by the solid per unit weight of solid divided by the quantity of radionuclide dissolved in the water per unit volume of water.

exchange capacity (ion exchange capacity). The amount of exchangeable ions measured in milligram equivalents per gram of solid material at a given pH.

flux (specific discharge, darcy velocity) (LT^{-1}). The volume of discharge from a given cross-sectional area per unit time divided by the area of the cross section.

heterogeneity. The properties or conditions of isotropy or anisotropy vary from point to point in the medium.

homogeneity. The properties or conditions of isotropy or anisotropy are constant from point to point in the medium.

hydraulic conductivity (LT^{-1}). "A medium has a hydraulic conductivity of unit length per unit time if it will transmit in unit time a unit volume of ground water at the prevailing viscosity through a cross section of unit area, measured at right angles to the direction of flow, under a hydraulic gradient of unit change in head through unit length of flow." [2] The term "hydraulic conductivity" has been called permeability, coefficient of permeability, field coefficient of permeability, and conductivity.

hydrogeologic unit. Any soil or rock unit or zone which by virtue of its porosity or permeability, or lack thereof, has a distinct influence on the storage or movement of ground water.
infiltration. The process of downward movement of water from the surface into underlying materials.

intrinsic permeability (L^2). The measure of the ability of a rock or soil to transmit fluid under a fluid potential gradient (see definition of hydraulic conductivity).

isotropic. The properties at any point within a medium are the same in all directions.

pore velocity, seepage velocity (LT^{-1}). The average rate of flow in the pores of a given medium. This is approximated by dividing the flux by the effective porosity.

porosity. The property of containing interstices. Total porosity is expressed as the ratio of the volume of interstices to total volume. Effective porosity refers to the porosity through which flow occurs.[2]

¹Numbers in brackets refer to corresponding numbers in Section 7, References.

recharge. The process of water addition to the saturated zone or the volume of water added by this process.

release, accidental. A release of radioactivity that is uncontrolled and unplanned.

release, routine. A release of radioactivity that is either continuous, e.g., leakage from a cooling pond containing trace quantities of radioactivity, or a periodic controlled release of low-level radioactive liquids.

safety class. Applies to structures, systems, or components that have a safety function.

safety function. Any function that is necessary to assure the integrity of the reactor coolant pressure boundary or primary coolant boundary, the capability to shut down the reactor and maintain it in a safe shutdown condition, or the capability to prevent or mitigate the consequences of conditions of design which could result in potential off-site exposures that are a significant fraction of Title 10, Code of Federal Regulations, Part 100, Reactor Site Criteria guideline exposures.[3]

safety related. Of significance or importance because it applies to:

(1) Structures, systems, or components assigned to a safety class.

(2) Drawings, specifications, procedures, analyses, and other documents used to determine or describe parameters affecting safety class structures, systems, or components.

(3) Services to design, purchase, fabricate, handle, ship, store, clean, erect, install, test, operate, maintain, repair, refuel, and modify safety class structures, systems, or components. **shall, should, may.** The word "shall" is used to denote a requirement; the word "should" to denote a recommendation; and the word "may" to denote permission, neither a requirement nor a recommendation.

sorption. All mechanisms, including ion exchange, that remove ions from the fluid phase and concentrate them on the solid phase of the medium.

storage coefficient. The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

test, aquifer. The effect of pumping a well as measured in the pumped well and in one or more observation wells, for the purpose of determining aquifer properties.

test, packer. A method of isolating a section of a borehole by inserting one or more expandable glands (packers) in order to measure hydraulic conductivity or water quality in the section.

yield, specific. The ratio of the volume of water which the rock or soil, after being saturated, will yield by gravity to the volume of the rock or soil.

3. Evaluation Criteria

The purpose of this section is to set criteria for evaluating routine and postulated accidental releases of liquid radioactive effluents to the ground water system. The definition of source terms is not covered by this standard.

3.1 Routine Releases. During normal operation of plants, routine releases of radioactive materials potentially can be made to ground water systems. These routine releases are generally as low as reasonably achievable (ALARA) and satisfy the limits of 10 CFR 20, Appendix B, Concentrations in Air and Water Above Natural Background, Table II, at the discharge point.[4] For these reasons, the calculation of potential concentrations of radionuclides from routine releases to ground water systems need not be performed.

3.2 Postulated Accidental Releases. The effects of a postulated accidental release of radionuclides in the site ground water systems shall be evaluated. In cases of postulated accidental releases to surface water bodies which recharge ground water systems, potential concentrations shall be calculated and these shall be used in the ground water analysis².

Initial calculations may be made assuming instantaneous release to the ground water of the entire source term under the maximum hydraulic gradient in the direction of ground water flow. These calculations may be made assuming the nearest potential user or discharge

²Guidance on performing this calculation for the surface water body can be found in U.S. NRC Regulatory Guide (R.G.) 1.113, Estimating Aquatic Dispersion of Effluents from Accidental and Routine Reactor Releases for the Purpose of Implementing Appendix I.

area is located at the site restricted area boundary. Further, these calculations may be made using conservative values of the hydraulic conductivity and effective porosity. Conservative values of hydraulic conductivity and effective porosity are those which lead to higher concentrations at the point of interest than would be expected to occur.

Alternatively, more realistic calculations may be made of the rate of entry of the radioactive effluent to the ground water. The more realistic calculations may take credit for the actual distances to the nearest user or discharge area, the rate of release through the plant foundations, plant features which may minimize the release of radionuclides, and site characteristics which can reduce the concentrations of radionuclides, e.g., initial inflow into the building.

Only under rare conditions is it necessary to perform a detailed analysis of the postulated accidental release.

4. Description of Ground Water System

The regional and local hydrologic systems of a plant site must be understood to assess possible pathways, travel times, dilutions and concentrations of radionuclides in ground water.

4.1 Regional Hydrogeologic Systems. The regional hydrogeologic system can encompass several thousand square kilometers and is distinguished from the local system which generally encompasses a few hundred square kilometers. The local system is a segment of the regional system. A complete understanding of the local system, which is most vital to the objectives of the study, is usually impossible without regional information. Therefore, regional information shall be included as a necessary prelude to the detailed study of the local system in order to identify those hydrogeologic systems which can be affected by plant releases. For many regions, existing ground water studies will provide most of the required information for this section.

4.1.1 Major Hydrogeologic Units. Major hydrogeologic units of the region shall be defined with respect to accepted stratigraphic

nomenclature and lithologic descriptions. Aquifers and less permeable units shall be included.

4.1.2 Relationship Among Hydrogeologic Units. The distribution and interrelationship of water-bearing, confining, and non-saturated units, shall be defined using maps, geologic cross sections, and fence diagrams.

4.1.3 Water-bearing Characteristics. The water-bearing characteristics of each hydrogeologic unit of regional importance shall be given. Information concerning total and effective porosities, specific yields, storage coefficients, hydraulic conductivities, geophysical-log responses, thicknesses, drilling characteristics, and water chemistry should be given. Where possible, the expected variations of the various critical parameters should be presented.

4.1.4 Recharge-discharge Relationships. The recharge-discharge relationships of the aquifers shall be estimated. Information used in the estimation should be described and summarized in the form of graphs, tables, maps and cross sections. This information includes:

(1) Representative existing water levels in, and head relationships between, individual aquifers shall be presented. The reliability of the data should be evaluated and limitations on the reliability of the data should be noted. These limitations are generally the result of using existing wells and historic data, and, the limitations consist of several types such as where holes tap several aquifers of differing heads, where unreliable techniques such as leaky air lines have been used to measure water levels, or where water levels are measured only during or shortly after pumping of wells. If data are available, water-level change maps should be presented which show the influence of natural or artificial variations of recharge and discharge. If available, representative water-level data should be presented in the form of well hydrographs. The seasonal variations of water levels and correlation of water levels with precipitation and river flows should be presented where applicable.

(2) Long-term changes in regional ground water levels which can affect the transport of radionuclides shall be projected. This projection should be for several periods over the plant life (e.g., at 10-year intervals) and for various conditions of recharge and discharge of the aquifers.

4.1.5 Ground Water Flow Paths. Paths of regional ground water flow shall be inferred for each aquifer of regional importance. As a first approximation, ground water flow directions may be taken as orthogonal to regional water level contours. However, some aquifers are strongly anisotropic and flow directions can be almost parallel to the regional water-level contours. Such flow characteristics may be found in carbonates, basalts, and other rocks with highly developed secondary permeability. Aquifers having anisotropic flow conditions shall be characterized.

4.2 Local Hydrogeologic Systems Near the Plant Site. This section deals with the hydrogeology of the plant site and its immediate surrounding area. Data used to complete this part of the study normally are obtained from studies and field work undertaken specifically for site investigations. Although previously published material and data from existing wells can be useful, information from other studies is sufficient only for a preliminary orientation and shall not be relied upon for all basic data. Information from the regional study, however, should be used to place the study of the local hydrogeologic system in its proper perspective. For example, depths of test holes needed to study aquifers which will be potentially affected by site development or plant operation can be estimated from results of the regional study.

4.2.1 Description. Hydrogeologic units that can be significantly affected by the postulated release of radioactive effluents shall be described in detail. This description should include information with the methods used to obtain the information:

- (1) Lithologic description of the units.
- (2) Stratigraphic and structural relationships of the units. Besides word descriptions, information should be presented in maps, cross sections, and fence diagrams.
- (3) Lateral extent and thickness of the units. This information may be combined with information on thickness and presented in the form of maps with lines of equal unit thickness (isopach maps).
- (4) Hydrochemistry of the units. Sufficient ground water quality data should be provided to determine the physical, chemical, and bacteriological characteristics of ground water, and

to determine the behavior of postulated accidentally-released radioactive liquid in the aquifers. In addition, ground water quality data can be used to identify modes of recharge to the aquifers, and to assess the interaction of ground water with geologic formations. Total ion-exchange capacity of these hydrogeologic units should be given.

(5) Water-bearing characteristics of units. Effective and total porosity, specific yield, field capacity, hydraulic conductivity (both vertical and horizontal), leakance, transmissivity, storage coefficient, and dispersion coefficient should be given. Any significant development of secondary permeability should be described.

(6) Well data. Available data should be tabulated and include aquifers penetrated, location, elevation, use, owner, discharge rates, static water levels, and drawdown. Data should also include details of well construction including grouting, screens, casing type, depth, diameter, performance, and surface seals.

(7) Well abandonment. Existing wells and piezometers used for site investigations, which lie within construction areas, should be identified and described and the method of abandonment should be specified and documented.

4.2.2 Documentation of Ground Water Regimen. For all site hydrogeologic units that can be significantly affected by the postulated release of radioactive effluents, the pre-construction ground water regimen shall be documented. This documentation should include:

- (1) Contours of ground water levels in all pertinent water bearing units.
- (2) Direction of water flow, taking into consideration aquifer anisotropy.
- (3) Existing recharge and discharge areas including ground water and surface water interrelationships.
- (4) Quantities and pore velocities of ground water flow in and between the various hydrogeologic units.
- (5) Short-term changes of ground water levels measured over a minimum period of one year and correlated with precipitation, river flows, and soil-moisture data as appropriate in order to help estimate the frequency and amount of recharge in local aquifers.
- (6) Historical long-term records of ground

water levels, if available.

(7) Seasonal changes in quality and radioactivity of the water in the aquifers that may be significantly affected by postulated releases of radioactive effluents, measured over a minimum period of one year.

4.2.3 Changes in Ground Water Regimen. Changes in the ground water regimen which are anticipated from construction and operation of the plant and can affect the transport of radionuclides shall be presented. These can include:

(1) Changes in hydraulic conductivity due to ground water control or foundation improvement activities such as installation of slurry trenches and rock grouting.

(2) Changes in direction of water flow.

(3) Changes in quantities of water flow.

(4) Changes in water levels within all pertinent aquifers.

(5) Changes in water quality including intrusion of saline water and movement of return-irrigation water, domestic and municipal wastewater, and poor quality water within or between aquifers.

4.2.4 Methods. Methods of study will vary widely according to geologic and hydrologic conditions of the site. Data from regional studies shall be used, therefore, to plan the detailed site studies which will utilize various combinations of the methods mentioned below. The following list gives some of the more common methods presently used. Many of these methods are included in the investigation of site geology.

(1) Detailed geologic mapping of site.

(2) Mapping of ground water levels for all pertinent aquifers.

(3) Construction of hydrographs of observation wells.

(4) Surface geophysical studies.

(5) Remote sensing. Normally of limited use, except in some regional applications.

(6) Test drilling.

(7) Packer tests.

(8) Percolation tests.

(9) Laboratory study of samples including cores.

(10) Downhole logging.

(11) Aquifer tests.

(12) Tracers tests using more than one well, giving concentration as a function of time.

4.3 Ground Water-Surface Water Interrelationship. The ground water and surface water regimens comprise one system that must be considered as an interdependent unit. A constant interchange of water takes place between the surface and subsurface. The nature and amount of this interchange in the vicinity of the site should be documented to the level required by the analysis used.

5. Radionuclide Transport

In general the direction of ground water movement and radionuclide transport is approximately orthogonal to water-level contours.³ However, some aquifers are so strongly anisotropic that movement can be nearly parallel to regional water-level contours. For example, special attention should be given to sites underlain by carbonate rocks, basalts, and various types of dense fractured rocks where most analytical methods are invalid. In these formations, water flux and radionuclide movement may be estimated using tracer studies; however, even these methods are often inadequate because tracer flow paths do not necessarily intersect observation wells. Nevertheless, the general geometry of the aquifer and hydraulic gradients will provide information concerning the probable direction and total distance of travel.

A conservative estimate of radionuclide transport in a fractured rock formation may be obtained by assuming the movement to occur in a single fracture in which dispersion and sorption are neglected. The fracture may be assumed to extend from the nearest point of critical concern in a straight line, or the direction and the dimensions of the fracture and the hydraulic gradient within the fracture may be estimated from data collected during the site investigation.

Some fractured aquifers can be considered as quasi-isotropic, and described by analytical methods, if fracture spacing is small as compared to the distance between point under investigation.⁴

³Where this relationship between movement and gradient exists the analytical methods discussed in the Appendix can be applied.

⁴References relevant to this section are listed in the Appendix.

5.1 Ground Water Flow Paths. With the exception of strongly anisotropic aquifers, the direction of ground water movement from the plant site can be determined using potentiometric surface maps for the site and vicinity. The flow path will be in the direction of the hydraulic gradient, i.e., perpendicular to the equipotential lines. This method or tracer tests can be used to determine the existing flow path from the site; however, future use of ground water by the plant or other users can alter the existing flow path. Estimates of future withdrawals of ground water may be used to approximate future potentiometric surface maps, which in turn may be used to determine future flow paths and hydraulic gradients.

5.2 Travel Time of Ground Water and Radionuclides. The pore velocity of ground water can be determined by either experimental or theoretical methods. The experimental methods consist of in-situ tracer studies using tracers which have been demonstrated as not being sorbed by the solid medium. Theoretical methods consist of solution of the governing ground water flow equations using the appropriate boundary conditions and aquifer coefficients. These determinations range from application of Darcy's law to obtain the approximately steady-state flux, to detailed modeling of the transient flow using sophisticated numerical models. In the simplified approach, Darcy's law⁵ in one dimension is:

$$V_x = -K \frac{dH}{dx}$$

where

V_x is the flux or specific discharge

K is the hydraulic conductivity

H is the total head

$\frac{dH}{dx}$ is the hydraulic gradient in the direction of flow.

The travel time of ground water between the plant site and the nearest user can be calculated using the average pore velocity. If radioactive decay is neglected, this time will also be the travel time of the center of mass of the tritium

⁵The application of more sophisticated models and the approximations made by using Darcy's law are discussed in the Appendix.

which is not sorbed in most cases. Travel times of other radionuclides can be longer than for tritium because of sorption by solids. In regions of slow migration of ground water, as shown by travel-time calculations, only the long-lived radionuclides such as ³H, ⁹⁰Sr, ⁹⁹Tc, ¹³⁷Cs, and the transuranic elements (if present) should be considered when the distance to the nearest user is large. However, where rapid ground water flow occurs, shorter-lived radionuclides should be considered, i.e., those with half-lives approximately equal to or greater than the ground water travel time.

In determinations of radionuclide transport by ground water, additional parameters may be required. These parameters consist of the distribution coefficient, the decay rate, and the coefficient of dispersion (or alternatively, dispersivity).

The distribution coefficient, K_d , is a function of the particular radionuclide, the pH of both the solids and the water, and the chemistry of both the solids and the water. Therefore, if K_d is used, it shall be determined for radionuclides of consequence using solids and water samples taken from the aquifer in which the transport is expected to occur. Sorption (retention) of radionuclides by the solids along the flow path increases the travel time of the radionuclides to the point of use or discharge, or both. Thus, when the distribution coefficient is zero, the radioactivity moves with the pore velocity of the water, and as the distribution coefficient increases, the travel time of the radioactivity becomes greater than the travel time of the water. The retardation of movement by sorption provides time in which radioactive decay reduces the concentration of radionuclides. The concentration of radionuclides is also reduced by the sorption process in which the radioactive material is removed from the water and attached to solids. Sorption coefficients, however, can be lowered dramatically by formation of organic or inorganic complexes.

5.3 Dispersion and Dilution. The amount of dilution that occurs is a function of dispersion within the aquifer. For calculation of radionuclide concentrations in the ground water, the coefficient of dispersion is required.

This coefficient can be approximated using empirical relationships, laboratory tests or tracer studies in the hydrogeologic unit.[5,6] The scale of the tests, the homogeneity of the medium, and the concentration of the tracer can significantly affect the results of the laboratory and tracer tests. Well spacing for field measurements should be selected carefully, otherwise the time involved and the cost can be excessive. Transverse dispersivity may be determined under natural flow conditions. These studies will provide both longitudinal and transverse components of the dispersivity from which the dispersion coefficient can be calculated. The required travel time of the tracer between wells can be decreased by using a combination of injection and pumping wells. Injection pressures should be low enough so as not to affect significantly the hydrogeologic properties of the aquifer.[7]

5.4 Models Used in Computations. The computations of radionuclide transport may begin by use of a simplified one-dimensional dispersion equation or more rigorous models may be employed.⁶ The movement of ground water and radioactive constituents is described by a set of partial differential equations. These equations in their most general form can be solved only by numerical methods. However, the equations can be simplified by assuming ideal physical properties of the aquifer, and the solution can be obtained using simplified boundary conditions. These simplifying assumptions must be well understood if the investigator is to demonstrate that the results obtained from a given model are conservative, i.e., the model does not predict lower concentrations than will be expected to occur. Thus, the implementation of the most sophisticated model is not required when a simplified conservative model predicts acceptable concentrations at the nearest point of potential ground water use or discharge.

5.5 Potential Effects of Postulated Release. The potential effects of a postulated radioactive release to ground water are a function of the concentration, volume, and chemical and physical form of radioactive liquids released, the mechanism of transport to the ground water, the

⁶Examples of simple calculations and discussion of more complex models are given in the Appendix.

rate and direction of ground water transport of the radioactivity, the characteristics and the areal extent of the aquifer, the proximity of water users to the plant site, and the total population of water users. Resulting concentrations of individual radionuclides at the point of nearest potential potable water supply should not exceed the limits stated in 10 CFR 20, Appendix B, Table II, Column 2.[4] Combinations of radionuclides should be within limits stated in 10 CFR 20, Appendix B, Note 1.[4] Alternatively, resulting concentrations may exceed those stated in 10 CFR 20, Appendix B, Table II, Column 2 for a short duration if they do not exceed those concentrations when averaged over a period of up to one year.[4]

6. Monitoring Program

6.1 Monitoring Objectives. The purpose of the ground water monitoring program is to detect the presence of any accidental release of radioactive liquid. The ground water monitoring program may also be designed to encompass monitoring requirements for other purposes. The design of the monitoring program should be based on the analyses of the regional and local ground water systems and radionuclide transport. Most of the monitoring program should be designed in accordance with the postulated ground water system, as described in previous sections. The monitoring program should also be designed to include the varying needs of the pre-construction, construction, operation, and post-operation periods.

Monitoring for radionuclides in ground water is required for routine releases into aquifers providing drinking or irrigation water supplies. For routine releases into aquifers not providing drinking or irrigation water supplies, monitoring for radionuclides in ground water is not required since the routine releases are within acceptable limits at the point of release.

Monitoring may not be required for postulated accidental releases if it is demonstrated that such monitoring is unnecessary because of specific design and site characteristics. However, monitoring is required when local ground water sources used for drinking or irrigation can be

significantly affected by postulated accidental releases.

6.2 Monitoring Methods.

6.2.1 Well Construction. Ground water systems are ordinarily monitored by test holes and wells, although in some circumstances springs, ditches or drains are used. The wells should be designed to last longer than the rest of the plant equipment in the event that monitoring is required for post-operation periods. In this manner, there will be no changes in the data base due to changing data points or disturbance of the aquifer by drilling activities. Wells should be designed and constructed to avoid contamination from the surface and contamination moving from one aquifer to another through the well bore. This is especially critical where the well intersects two or more aquifers which are under different heads.

A single well should be designed to monitor no more than one hydrogeologic unit. If more than one hydrogeologic unit is to be monitored at a specific point, the monitoring system should consist of a cluster of wells, one to each unit. Water levels for more than one hydrogeologic unit may be measured within one borehole only if an effective seal between units has been demonstrated. Vertical movement within one hydrogeologic unit can be monitored by placing piezometers at different depths in the same unit.

In general, monitoring wells should be downgradient of the facilities with potential for accidental release to the ground water. This may not be in the same lateral direction for all hydrogeologic units that are monitored. Areal and vertical spacing of monitoring wells should be consistent with the geohydrologic characteristics of the area. More homogeneous formations would generally require fewer wells than heterogeneous formations.

Observation wells should be periodically tested to ensure their proper functioning. Routine maintenance is recommended to prevent clogging.

6.2.2 Types of Monitoring Data. Types of monitoring data that shall be collected at the site include the following:

(1) **Monitoring water levels and pumpage.** Water levels shall be monitored to indicate trends in the ground water regimen for the purpose of predicting the migration of potential radionuclide releases. Water level, pumpage, and precipitation records during operation will provide demonstration of the long-term performance of the aquifer system. At least one continuous water level recorder should be installed for those major aquifers under the site that can be significantly affected by the postulated accidental release of radioactive effluents. A variety of water-level recording devices is available for monitoring purposes. Whatever system is selected, it shall provide data that can be plotted on a long-term well hydrograph. The frequency of measurement should assure that changes in the water level in excess of a few centimeters are observed. The ground water system should be so understood that the cause can be identified for any long-term trend in water levels.

(2) **Monitoring for radionuclide content of ground water.**[8,9,10,11] The well system for monitoring potential radionuclides in ground water generally requires a greater concentration of wells in a smaller area than that for monitoring water levels or water quality, because the system is designed to detect a substance that is not aquifer wide in its distribution. The design of this system shall focus on locations where radionuclides can enter the ground water systems.

The frequency of sampling shall be determined on the basis of careful study of the hydrogeologic system and the calculated travel time of radionuclide releases. Monitoring should begin at least one year prior to fuel loading. The most mobile radionuclide in ground water systems is tritium; more frequent analysis should be made for this radionuclide than for others. Analysis for tritium requires that water samples be collected. Ground water should be analyzed for tritium at least quarterly, and for other radionuclides of consequence as appropriate, but at least on an annual basis to establish background concentrations. If the tritium concentration in any of the monitoring wells is found to undergo a statistically significant change with respect to the established background level, or if a trend of increasing

tritium level is apparent, analyses for other radionuclides shall be more frequent and the cause of the increased tritium values shall be determined.

6.3 Methods of Reporting Results of Monitoring, Sampling, and Analyses. For those sites which have a ground water monitoring program, the results of the ground water monitoring program should be maintained by the owner and a yearly summary should be available for review by the NRC. This summary should provide a simplified description of the hydrogeologic system being monitored, a map showing the locations of the monitor wells in relation to plant facilities, and a table giving coordinates, ground elevations, drilled depths, intake depths and elevations, diameters, and specific capacities of the monitor wells. These items will remain the same from year to year unless new wells are installed or new understanding of the hydrogeologic system is obtained. If new monitoring wells are installed, details of the construction should be provided. The owner should maintain the current monitoring information and its relation to the historical data from the monitoring program in both tabular and graphic form. The presentation should consist of a graph of monitoring values versus time from the beginning of the monitoring program to the current year. Separate graphs should be prepared for water levels, chemical quality, and radionuclide content. If anomalous values or an adverse temporal trend are indicated, the NRC shall be notified immediately and an explanation shall be provided as soon as possible.

7. References

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- [2] LOHMAN, S.W., 1972 *Ground Water Hydraulics*: U.S. Geological Survey, Prof. Paper 708, 70 p.
- [3] Title 10 Code of Federal Regulations, Part 100, "Reactor Site Criteria," Government Printing Office, Washington, DC.
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- [5] GASPAR, E., and ONCESAU, M., 1972 *Developments in Hydrology I-Radioactive Tracers in Hydrology*: Elsevier Publishing Company, New York, 342 p.
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- [8] KRIEGER, H.L., 1976 *Interim Radiochemical Methodology for Drinking Water*, Environmental Monitoring and Support Laboratory, EP-500/4-75-008, U.S. EPA, Cincinnati, Ohio.
- [9] THATCHER et al., 1977, *Methods for Determination of Radioactive Substances in Water and Fluvial Sediments*: U.S. Geological Survey, Techniques of Water-Resources Investigations, Book 5, Chapter A5, 95 p.
- [10] American Public Health Association, 1976, *Standard Methods for the Examination of Water and Waste Water*, 14th Edition, 1193 p.
- [11] Office of Water Data Coordination, 1977, *National Handbook of Recommended Methods for Water-Data Acquisition*, Chapter 5, Chemical and Physical Quality of Water and Sediment, U.S. Geological Survey, Reston, Virginia.

When the preceding American National Standards referred to in this document are superseded by a revision approved by the American National Standards Institute, Inc., the revision shall apply.

Appendix

(This Appendix is not a part of the American National Standard for Evaluation of Radionuclide Transport in Ground Water for Nuclear Power Sites, ANSI/ANS-2.17-1980, but is included for information purposes only.)

Methods for Analysis of Radionuclide Transport in Ground Water

A. Introduction

Methods of data collection and reduction are presented in the Appendix of American National Standard for Evaluation of Ground Water Supply for Nuclear Power Sites, ANSI/ANS-2.9-1980.

The movement of radionuclides in ground water can be described by two equations: one for the movement of the carrier fluid (water) and one for the transport of the dissolved constituents (radionuclides). In using these equations, the movement of the carrier in the region under consideration must be known before the transport equation can be solved.

In the following sections the equations for water movement and mass transport are discussed. In each section the discussion will begin with the most general equation and proceed to the simplest expression. When applying these equations it is best to begin with the simplest form of the equation or solution, and if necessary, progress to more complex forms. However, when using the simplified expression, the assumptions that were made in their formulation must be considered (i.e., these expressions are valid under the assumptions made in their formulation, and use of them for calculations where the assumptions do not apply will lead to erroneous results). Note that none of the models is valid for aquifers having widely spaced fractures or solution channels. Here the bulk of the flow occurs in the fractures or channels and cannot be averaged over the medium. Thus, the requirement of continuous media assumed in the formulation of the equation has been violated. In fractured or cavernous aquifers, tracer studies can be used to obtain travel time and fluid flux. Also, none of the models is valid for conditions of varying ground water densities or aquifer thickness, such as those encountered in coastal areas at the fresh-water salt-water interface.

A.1 Ground Water Flow

At any plant site the assumption of instantaneous release of radioactive liquids from tank storage is generally accepted as the most severe input of radionuclides to ground water. However, more realistic releases may be assumed. This more realistic type of release will usually bring the radioactive liquid into contact with soil moisture moving as unsaturated flow above the water table. However, the release can also be directly into the zone of saturation. The predominant direction of the unsaturated flow is downward until the flow reaches the zone of saturation. Within the zone of saturation the flow is predominantly lateral.

The governing equations in the unsaturated zone consist of a set of coupled equations for the movement of gas and water. To date, only computer codes of limited applicability are available for the solution of these coupled gas-water equations. When the assumptions are made that the water moves as a single phase and that no trapped air pockets exist, a single governing equation for saturated-unsaturated flow is obtained.^{(1)⁷}

⁷Numbers in parentheses refer to corresponding numbers in Section A.5 References.

$$\left[\frac{\theta}{n'} \alpha' + \theta \beta' + \frac{d\theta}{dh} \right] \frac{\partial h}{\partial t} = \nabla \cdot [\bar{K}(h) \cdot (\nabla h + \nabla z)] \quad (\text{Eq. 1})$$

where

- θ is the moisture content
- n' is total porosity
- α' is the modified coefficient of compressibility of the medium
- β' is the modified coefficient of compressibility of water
- h is the pressure head
- t is the time
- \bar{K} is the hydraulic conductivity tensor
- z is the elevation head
- ∇ is the Del operator

Equation (1) is nonlinear because for unsaturated flow both conductivity and moisture content are functions of pressure head. These relationships should be determined under existing field conditions to avoid the effects of disturbance of the medium. They are difficult to obtain from field measurements and must be obtained for each soil layer. Because of this difficulty, a reasonable empirical relationship or a known relationship from a similar soil type may be selected. Because of the large computer core requirement, the solution of Equation (1) in three dimensions is impractical. Equation (1) can be solved in two dimensions. (1) For saturated-unsaturated flow, the vertical dimension must be considered along with one horizontal dimension, resulting in a vertical plane. From the solution of Equation (1) the pressure heads are known and can be used in Darcy's law to obtain the components of flux.

$$\bar{V} = -\bar{K}(h) \cdot (\nabla h + \nabla z) \quad (\text{Eq. 2})$$

where

\bar{V} is the flux.

Thus, Equation (2) can be solved to obtain the necessary flux data for the solution of the transport equation. In doing this operation numerically the components of the flux are not continuous. These discontinuities can cause difficulty in the solution of the transport equation and can be eliminated by solving the coupled set of equations in which the flux appears as a variable.

$$\left[\frac{\theta}{n'} \alpha' + \theta \beta' + \frac{d\theta}{dh} \right] \frac{\partial h}{\partial t} = -\nabla \bar{V} \quad (\text{Eq. 3})$$

Equations (2) and (3) are adequate to eliminate the discontinuities in the flux; however, the amount of computer core required for their solution has been increased because of the increased number of variables.

The solution of the saturated-unsaturated flow equation will give the most realistic results because the unsaturated region has been considered in the movement of fluid from the point of release through the unsaturated zone to the water table. Depending on the nature of the problem, analytical or numerical methods like the ones described in References (1, 2, and 3) can be used to analyze saturated-unsaturated flow. When the unsaturated zone is neglected or all of the flow is considered to be in the saturated zone, Equations (2) and (3) become

$$(\alpha' + n' \beta') \frac{\partial h}{\partial t} = \nabla \cdot \bar{V} \quad (\text{Eq. 4})$$

$$\bar{V} = -\bar{K} \cdot (\nabla h + \nabla z)$$

where

the moisture content has reached total porosity and the hydraulic conductivity has reached its saturated value which is no longer a function of pressure head.

The hydraulic conductivity is a tensor which accounts for directional properties (anisotropy) that arise in formation such as layered sediments (i.e., hydraulic conductivity is different in different directions). If the coordinate system is oriented parallel to the principal components of hydraulic conductivity, only the principal components of the tensor are required. If the medium is further assumed to be homogeneous and isotropic, hydraulic conductivity becomes a scalar and equation (4) becomes

$$(\alpha' + n' \beta') \frac{\partial h}{\partial t} = -\nabla \cdot \mathbf{V}$$

$$\mathbf{V} = -\bar{K} (\nabla h + \nabla z) \quad (\text{Eq. 5})$$

The terms α' and β' are defined as

$$\alpha' = \rho g \alpha$$

$$\beta' = \rho g \beta \quad (\text{Eq. 6})$$

where

- ρ is the water density
- g is the acceleration of gravity
- α is the coefficient of compressibility of the medium
- β is the coefficient of compressibility of water.

The specific storage coefficient is defined as

$$S_s = \rho g (\alpha + n' \beta) \quad (\text{Eq. 7})$$

Elimination of the flux terms from Equation (5) and substitution of Equations (6) and (7) into the results yield

$$\nabla^2 H = \frac{S_s}{K} \frac{\partial H}{\partial t} \quad (\text{Eq. 8})$$

where

H is the total head.

This equation is valid for saturated flow in confined aquifers.

For a confined aquifer of thickness b , the storage coefficient and transmissivity are defined as

$$S = S_s b$$

$$T = K b \quad (\text{Eq. 9})$$

and Equation (8) becomes

$$\nabla^2 H = \frac{S}{T} \frac{\partial H}{\partial t} \quad (\text{Eq. 10})$$

In simulations using Equation (10) the boundary conditions of leakage should be used when appropriate. For problems involving leaky aquifers, methods like those described in References (2, 4, 5 and 6) can be used.

For unconfined aquifers where compressibility of the medium and the water is relatively unimportant compared to the vertical movement of the free surface (water table), the continuity equation can be written as:

$$\frac{\partial}{\partial x} (b' \frac{\partial H}{\partial x}) + \frac{\partial}{\partial y} (b' \frac{\partial H}{\partial y}) = \frac{S_y}{K} \frac{\partial H}{\partial t} \quad (\text{Eq. 10A})$$

Introducing Dupuit's approximation, Equation (10A) can be simplified as follows:

$$\nabla^2 H^2 = \frac{2 S_y}{K} \frac{\partial H}{\partial t} \quad (\text{Eq. 10B})$$

where

S_y is the specific yield of the aquifer

b' is the saturated thickness of the aquifer

For steady flow in either confined or unconfined aquifers,

Equations (10) and (10B) reduce respectively to the following equations:

$$\nabla^2 H = 0 \quad (\text{Eq. 11A})$$

$$\nabla^2 H^2 = 0 \quad (\text{Eq. 11B})$$

For simplified cases, analytical solutions of Equations (10), (10B), (11A), and (11B) like those given in References (3, 4, 5, 7, and 8) can be used. For more complex situations, numerical solutions like those described in References (6 and 9) should be used.

An approximation of the flux in the major flow direction can be obtained using Darcy's law.

$$V_x = -K \frac{dH}{dx} \approx -K \frac{\Delta H}{\Delta x} \quad (\text{Eq. 12})$$

where

$\Delta H/\Delta x$ is the hydraulic gradient in the direction of flow. This approximation is crude but in many cases it is acceptable because of the inability to accurately measure spatial variations in the hydraulic conductivity. Use of this equation assumes a homogeneous isotropic medium in which the gradient is constant over the increment Δx . The pore velocity (seepage velocity) may be approximated by dividing the flux, V_x , by the effective porosity. In many cases, use of this equation is inadequate and the analyst should use judgement to select a model that adequately considers variable hydraulic conductivity and transient conditions.

A.2 Mass Transport. The most general form of the mass transport equation is for transport in saturated-unsaturated media. If local equilibrium of mass transfer and first order chemical reactions are assumed, sorption can be represented as a linear relationship and the general mass transport equation can be written(10) as

$$R_d \theta \frac{\partial c}{\partial t} - \nabla \cdot (\theta \bar{D} \cdot \nabla c) + \nabla \cdot (\bar{V}c) + (R_d \frac{\partial \theta}{\partial t} + \lambda \theta R_d)c = 0 \quad (\text{Eq. 13})$$

where

- R_d is the retardation factor
- c is the concentration of dissolved constituent
- \bar{D} is the dispersion tensor
- \bar{V} is the flux
- λ is the radioactive decay constant

The radioactive decay constant, λ , is calculated from handbook values of the half-lives of different isotopes in appropriate units of time by the following relationship:

$$\lambda = \frac{\ln 2}{\text{half life of the isotope}} \quad (\text{Eq. 13A})$$

Equation (13) can be solved numerically.(10) The retardation factor is defined as

$$R_d = 1 + \rho_b \frac{K_d}{n'} \quad (\text{Eq. 14})$$

and the distribution coefficient (11) is

$$K_d = \frac{\text{radioactivity/mass of solids}}{\text{radioactivity/volume of water}} \quad (\text{Eq. 15})$$

where

- ρ_b is the dry bulk density of the medium
- K_d is the equilibrium value of the distribution coefficient.

The distribution coefficient is unique for each chemically different radionuclide.

The dispersion tensor for isotropic media is

$$\theta D_{ij} = a_T V \delta_{ij} + (a_L - a_T) V_i V_j / V$$

$$\delta_{ij} = 1 \quad i = j, \quad \delta_{ij} = 0 \quad i \neq j \quad (\text{Eq. 16})$$

where

- δ_{ij} is the Kronecker delta
- a_T is the transverse dispersivity
- a_L is the longitudinal dispersivity
- V is the magnitude of the flux
- V_i, V_j are the components of the flux

In general, the dispersivity is a fourth-rank tensor which contains 81 components; however, if isotropy is assumed, it can be related to two constants, i.e., longitudinal and transverse.(7)

The transverse and longitudinal components of dispersivity may be obtained from tracer studies conducted in the aquifer. This can be done using the tracer data and an appropriate transport model.

Equation (13) may be used in conjunction with Equations (1) and (2) or Equations (2) and (3) for simulation of radionuclide transport. In using Equations (1) and (2) the problem of discontinuous flux

can arise in the numerical scheme whenever the advective-transport term in equation (13) is comparable to or greater than the dispersion term. Thus, in fine-grained sediments where the coefficient of dispersion is small, Equations (2) and (3) must be used.

The assumptions of local equilibrium and first-order chemical reactions result in sorption being a linear relationship. These assumptions are incorporated in Equation (13).

When the medium is assumed to be fully saturated, Equation (13) becomes

$$R_d \frac{\partial c}{\partial t} - \nabla \cdot (\bar{D} \cdot \nabla c) + \nabla \cdot \left(\frac{\bar{V}c}{n} \right) + \lambda R_d c = 0 \quad (\text{Eq. 17})$$

and

$$n D_{ij} = a_T V \delta_{ij} + (a_L - a_T) V_i V_j / V \quad (\text{Eq. 18})$$

The various forms of the transport equations, presented previously, have been solved by numerical integration. The numerical methods used for solution of these equations in a general flow field are discussed in References (9, 10, 12, 13, 14, and 15).

When the fluid flux is assumed to be uniform and steady, Equation (17) becomes

$$R_d \frac{\partial c}{\partial t} - \nabla \cdot (\bar{D} \cdot \nabla c) + \frac{\bar{V}}{n} \cdot \nabla c + \lambda R_d c = 0 \quad (\text{Eq. 19})$$

If the dispersion tensor is assumed to be homogeneous and anisotropic and the flux is assumed to be parallel to the x-axis, Equation (19) can be written as

$$R_d \frac{\partial c}{\partial t} - D_{xx} \frac{\partial^2 c}{\partial x^2} - D_{yy} \frac{\partial^2 c}{\partial y^2} - D_{zz} \frac{\partial^2 c}{\partial z^2} + \frac{V_x}{n} \frac{\partial c}{\partial x} + \lambda R_d c = 0 \quad (\text{Eq. 20})$$

where the components of the coefficient of dispersion are given from Equation (18) as

$$D_{xx} = a_L \frac{V_x}{n}, \quad D_{yy} = D_{zz} = a_T \frac{V_x}{n} \quad (\text{Eq. 21})$$

Equation (20) can be rewritten in the form

$$\frac{\partial c}{\partial t} - E_x \frac{\partial^2 c}{\partial x^2} - E_y \frac{\partial^2 c}{\partial y^2} - E_z \frac{\partial^2 c}{\partial z^2} + U \frac{\partial c}{\partial x} + \lambda c = 0 \quad (\text{Eq. 22})$$

where

$$E_i = \frac{D_{ii}}{R_d}, \quad U = \frac{V_x}{n R_d} \quad (\text{Eq. 23})$$

where

U is the approximate rate of movement of the radionuclide and may be used to estimate the travel time.

The simplified form of the transport equation, Equation (22), can be solved analytically in an infinite region with simple boundary conditions.

The longitudinal and transverse dispersivities used in the calculation of the components of the dispersion coefficient, Equation (21), should be obtained from tracer studies in the aquifer under consideration. Extrapolated, calculated, or laboratory-derived values of dispersivities should seldom be applied to full-scale field problems. The above equations are strictly valid only for isotropic media, but may be applied to slightly anisotropic formations when the dispersivities are obtained from field studies.

A.3 Solutions to the Mass Transport Equation. (15, 17, 18, 19, 20) The equation of mass transport used in this section was formulated under several assumptions which will be reviewed before discussing its solution. The molecular diffusion was assumed to be many orders of magnitude smaller than the mechanical dispersion, and was neglected. The medium was assumed to be homogeneous and isotropic. The fluid flow was assumed to be uniform steady flow parallel to the x-axis. The sorption of the radionuclide was assumed to be linear. Chemical reactions were assumed to be rapid such that equilibrium exists between the dissolved and sorbed radionuclides. The radioactive liquid was assumed to have the same density as the ground water. These assumptions yield Equation (22). For the solution of this equation, it is further assumed that the region is infinite and that the concentration in the region is zero at time equals zero. For the case of an aquifer of finite thickness, the appropriate models are referenced in Appel and Bredehoeft.(19)

A.3.1 Instantaneous Line Source. For the instantaneous release from a line source passing through the point (x_1, y_1) and parallel to the z-axis, the solution of Equation (22) is

$$C = \frac{m}{4\pi R_d n (E_x E_y)^{1/2}} \exp - \left\{ \frac{[(x - x_1) - Ut]^2}{4E_x t} + \frac{(y - y_1)^2}{4E_y t} + \lambda t \right\} \quad (\text{Eq. 24})$$

where

m is the instantaneous mass per unit length in the z direction.

In using Equation (24) for calculation of radionuclide transport, m is calculated by dividing the total activity of a particular radionuclide contained in the release by the assumed length of the line source.

A.3.2 Instantaneous Rectangular Plane Source. For the instantaneous release from a rectangular plane source of width f, parallel to the y-z plane and centered at the origin, the solution of Equation (22) is

$$C = \frac{m'}{4R_d n (\pi E_x t)^{1/2}} \exp - \left\{ \frac{(x - Ut)^2}{4E_x t} + \lambda t \right\} \left[\text{erf} \frac{y + f/2}{2 (E_y t)^{1/2}} - \text{erf} \frac{y - f/2}{2 (E_y t)^{1/2}} \right] \quad (\text{Eq. 25})$$

where

m' is the mass per unit area of the plane source.

Thus, for calculations using Equation (25), m' is calculated by dividing the total activity of a particular radionuclide contained in the release by the source width times the assumed thickness.

A.3.3 Continuous Line Source. For continuous release from a line source passing through the origin and parallel to the z-axis, the transient solution of Equation (22) is

$$C = \int_0^t \frac{q}{4\pi R_d n (E_x E_y)^{1/2} (t-\tau)} \exp - \left\{ \frac{[x - U(t-\tau)]^2}{4E_x (t-\tau)} + \frac{y^2}{4E_y (t-\tau)} + \lambda(t-\tau) \right\} d\tau \quad (\text{Eq. 26})$$

where

q is the time rate of release per unit length in the z direction.

Equation (26) can be integrated numerically using Legendre-Gauss quadrature. However, as the time becomes large, Gauss-Laguerre quadrature may be required for the integration. Computer programs for performing this integration are available in most subroutine packages.

The steady-state solution of Equation (26) is obtained by letting time approach infinity. This yields a solution in terms of Bessel functions which may be approximated to give the steady-state solution

$$C = \frac{q}{4R_d n (\pi E_x E_y L)} \exp - \left\{ \frac{4L E_x - xU}{2E_x} \right\} \quad (\text{Eq. 27})$$

where

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

A.3.4 Continuous Rectangular Plane Source. For continuous release from a plane source of width f , parallel to the y - z plane and centered at the origin, the transient solution of Equation (26) is

$$C = \int_0^t \frac{q'}{4nR_d (\pi E_x)^{1/2} (t-\tau)^{1/2}} \exp - \left\{ \frac{[(x-U(t-\tau))]^2}{4E_x(t-\tau)} + \lambda(t-\tau) \right\} \left[\operatorname{erf} \frac{y+f/2}{2[E_y(t-\tau)]^{1/2}} - \operatorname{erf} \frac{y-f/2}{2[E_y(t-\tau)]^{1/2}} \right] d\tau \quad (\text{Eq. 28})$$

When using the solution for a rectangular plane source, it should be noted that as the distance from the source becomes large as compared to the source width, the results approach those given by a line source. Therefore, the solution for a rectangular source can be used near a waste tank, and the solution for a line source can be applied farther from the tank. When using any of the solutions given in this section, the effort involved in calculation of concentrations can be minimized by computer evaluation of the solution.

A.3.5 Example Problems. Example problems 1 through 4 are based on the following data and different assumptions have been made regarding dispersion, sorption, decay, and the nature of the release. The basic assumptions are listed separately under each example.

A tank, 1.0 meter in diameter, containing 20.0 curies of ^{90}Sr ruptures, and the radioactive liquid enters an unconsolidated sand aquifer which has an average saturated thickness of 10.0 m. The aquifer has the following properties:

- $V_x = 1.2$ m/day
- $n = 0.35$
- $n' = 0.35$
- $K = 17.3$ m/day
- $a_L = 20.0$ m (see Reference 9)
- $a_T = 4.0$ m (see Reference 9)
- $\rho_b = 1.8$ gm/cm³
- $K_d = 80$ cm³/gm (for ^{90}Sr in this aquifer)

The problem is to calculate the change in the concentration at the point $x = 120$ m, $y = 0$.

Example 1. Assume that the radioactive liquid is distributed uniformly across the entire saturated thickness of the aquifer and that no dispersion, sorption, or decay occurs. Under these assumptions the

radionuclide moves as a slug at a rate equal to the pore velocity in the aquifer. The concentration, pore velocity, and travel time are as follows:

$$C = \frac{20\text{Ci}}{n(\text{Vol. of Aquifer})} = \frac{20 \times 10^6 \mu\text{Ci}}{.35 \times 10 \times \frac{\pi}{4} \times 1 \times 10^6 \text{ cm}^3} = 7.3 \frac{\mu\text{Ci}}{\text{ml}}$$

$$\text{Pore Velocity} = V_x/n = 1.2/.35 = 3.4\text{m/day}$$

$$\text{Travel time} = \text{distance/pore velocity} = 120/3.4 = 35.3 \text{ days}$$

Thus the slug would arrive at the point under consideration after 35.3 days with no reduction of the initial concentration. In this time period there will be no appreciable decay of the 28-year half-life ⁹⁰Sr. The distribution of the ⁹⁰Sr across the entire saturated thickness of the aquifer is not realistic; however, the example is useful for comparison with the following example calculation.

Example 2. This example differs from Example 1 only in that longitudinal dispersion is considered. Assume that the radioactive liquid moves in the aquifer with no sorption, decay or transverse dispersion. Note that $K_d = 0$ and the solution for an instantaneous line source, Eq. (24) is undefined because $E_y = 0$. However, the solution for an instantaneous plane source, Eq. (25), for $y = 0, f = 1, E_y = 0$ becomes

$$C = \frac{m'}{2R_{dn}(\pi E_{xt})^{1/2}} \exp - \left\{ \frac{(x-Ut)^2}{4E_{xt}} + \lambda t \right\}$$

From Equations (14), (21), and (23) the following coefficients are calculated:

$$\begin{aligned} R_{cl} &= 1.0 \\ D_{xx} &= 68.6 \text{ m}^2/\text{day} \\ E_x &= 68.6 \text{ m}^2/\text{day} \\ U &= 3.4 \text{ m/day} \end{aligned}$$

The remaining coefficients are $m' = 2.0 \text{ Ci/m}^2$ and $\lambda = 0$. Substitution of the coefficients into the above solution for various times yields:

TIME (days)	CONCENTRATION ($\mu\text{Ci/ml}$)
0	0
16	1.8×10^{-2}
32	3.4×10^{-2}
40	3.0×10^{-2}

Note that the concentration at the point under consideration increases to a maximum value and then decreases as the radionuclide front passes the point. Also note that the arrival time of the maximum concentration is approximately the same as the previous example, but the maximum concentration is diminished.

Example 3. In this example the effect of sorption is added. Assume that the radioactive liquid moves in the aquifer with no decay or transverse dispersion. The solution used in Example 2 applies. From Equations (14), (21), and (23) the following coefficients are calculated:

$$\begin{aligned}
 R_d &= 412.4 \\
 D_{xx} &= 68.6 \text{ m}^2/\text{day} \\
 E_x &= 0.17 \text{ m}^2/\text{day} \\
 U &= 0.01 \text{ m/day}
 \end{aligned}$$

Substitution of these coefficients, m' , and λ into the solution for various times yields:

TIME (days)	CONCENTRATION ($\mu\text{Ci/ml}$)
0	0
5,000	3.2×10^{-5}
10,000	9.0×10^{-5}
15,000	7.0×10^{-5}

Example 4. In this example the effects of transverse dispersion and decay are added. Assume that the tank rupture produces an instantaneous line source, and locate the origin of the coordinate system at the tank. Thus, in Equation (24), $x_1 = 0$, $y_1 = 0$. From Equations (14), (21), and (23) the following coefficients are calculated.

$$\begin{aligned}
 R_d &= 412.4 \\
 D_{xx} &= 68.6 \text{ m}^2/\text{day} \\
 D_{yy} &= 13.7 \text{ m}^2/\text{day} \\
 E_x &= 0.16 \text{ m}^2/\text{day} \\
 E_y &= 0.03 \text{ m}^2/\text{day} \\
 U &= 0.01 \text{ m/day}
 \end{aligned}$$

The half-life of ^{90}Sr is 28 years, and the release per unit area of aquifer is 2.0 Ci/m^2 . Using the half-life, λ is calculated to be $6.66 \times 10^{-5} \text{ (day}^{-1}\text{)}$. Substitution of the coefficients into Eq. (25) for various times yields:

TIME (days)	CONCENTRATION ($\mu\text{Ci/ml}$)
0	0
5,000	5.3×10^{-7}
10,000	7.5×10^{-7}
15,000	3.4×10^{-7}

Note that the arrival time of the maximum concentration remains approximately the same as in Example 3 and that the maximum concentration has been reduced.

Table 1 summarizes examples 1 through 4 and demonstrates the effect of considering more realistic assumptions.

Table 1
Example Summary

Example Problem	Longitudinal Dispersion	Transverse Dispersion	Sorption	Radioactive Decay	Approximate maximum concentration	
					Arrival Time (days)	Concentration ($\mu\text{Ci/ml}$)
1 (slug flow)	no	no	no	no	35.3	7.3
2	yes	no	no	no	32	3.4×10^{-2}
3	yes	no	yes	no	10,000	9.0×10^{-5}
4	yes	yes	yes	yes	10,000	7.5×10^{-7}

A.4 Notation

a_L	Longitudinal dispersivity (L)
a_T	Transverse dispersivity (L)
b	Thickness of a confined aquifer (L)
b'	Thickness of saturated aquifer (unconfined) (L)
c	Concentration of dissolved constituent (M/L ³)
\bar{D}, D_{ij}	Dispersion tensor (L ² /T)
d	Mean grain diameter (L)
E_i	Coefficient defined by Equation (23) (L ² /T)
f	Source width (L)
g	Acceleration of gravity (L/T ²)
H	Total head (L)
h	Pressure head (L)
K	Hydraulic conductivity (L/T)
\bar{K}	Saturated conductivity tensor (L/T)
$\bar{K}(h)$	Conductivity tensor (L/T)
K_d	Distribution Coefficient (L ³ /M)
m	Instantaneous release per unit length (M/L)
m'	Instantaneous release per unit area (M/L ²)
n	Effective porosity
n'	Total porosity
q	Time rate of release per unit length (M/LT)
q'	Time rate of release per unit area (M/L ² T)
R_d	Retardation factor
S	Storage coefficient
S_s	Specific storage coefficient (1/L)
S_y	Specific yield
T	Transmissivity (L ² /T)
t	Time (T)
U	Coefficient defined by Equation (23) (L/T)
V	Magnitude of the flux (L/T)
\bar{V}, V_i	Flux (L/T)
z	Elevation head (L)
α	Coefficient of compressibility of the medium (LT ² /M)
α'	Modified coefficient of compressibility of the medium (1/L)
β	Coefficient of compressibility of water (LT ² /M)
β'	Modified coefficient of compressibility of water (1/L)
δ_{ij}	Kronecker delta
θ	Moisture content
λ	Radioactive decay constant (1/T)
ρ	Density of water (M/L ³)
ρ_b	Bulk density of the medium (M/L ³)
τ	Dummy variable (T)
∇	Del operator (1/L)

A.5 References

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