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OAK RIDGE NATIONAL LABORATORY

MARTIN MARIETTA

Conceptual Model for Radiological Performance Assessment of Low-Level-Radioactive-Waste Disposal Facilities

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OPERATED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
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CONCEPTUAL MODEL FOR RADIOLOGICAL PERFORMANCE ASSESSMENT OF LOW-LEVEL-RADIOACTIVE-WASTE DISPOSAL FACILITIES

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ABBREVIATIONS, ACRONYMS, AND INITIALISMS

DOE	Department of Energy
LLW	low-level waste
ORNL	Oak Ridge National Laboratory
ORO	Oak Ridge Operations
PA	performance assessment
SWSA	solid waste storage area

ABSTRACT

This document describes components of a conceptual model for performance assessment of the low-level-radioactive-waste disposal facilities operated by Martin Marietta Energy Systems, Inc., for the U.S. Department of Energy (DOE)/Oak Ridge Operations. Radiological performance assessments must be conducted for the low-level-waste facilities to demonstrate compliance with the performance objectives established in DOE Order 5820.2A, "Radioactive Waste Management." This report describes the components that must be considered in developing a conceptual model for the assessment of any low-level-waste facility and will serve as a standard and guide in the development of models for specific waste facilities.

1. BACKGROUND

U.S. Department of Energy (DOE) Order 5820.2A, Chapter III, established performance objectives for DOE-owned low-level-radioactive-waste disposal facilities and requires performance assessments of the facilities to demonstrate compliance with the objectives. In accordance with the order, performance assessments will be conducted for low-level-waste disposal sites operated by Martin Marietta Energy Systems, Inc., on three DOE reservations. On the Oak Ridge Reservation, existing or proposed facilities are located at sites known as SWSA 6, West Chestnut Ridge, West Bear Creek Valley, and SWSA 7. Proposals for future facilities at the Paducah Reservation and the Portsmouth Reservation are in preparation.

2. PURPOSE

The purpose of this report is to document the conceptual model that will be used as the basis for all performance assessments conducted by Energy Systems for the disposal facilities operated by Energy Systems for the DOE Oak Ridge Operations (ORO). Radiological performance assessments for disposal facilities are required to demonstrate that the design, construction, operation, and closure of a facility, new or existing, will meet established dose performance objectives. The performance objectives, stated in DOE Order 5820.2A, set standards for dose via all pathways for the public and an inadvertent intruder and include standards for groundwater protection. The standards apply to the facility in different time periods such as normal operation, institutional control after closure, and post-institutional control.

This document presents components of a conceptual model for use as a guide in developing specific models for individual disposal facilities and describes briefly all reasonable possibilities for components of a conceptual model. The definition is used in conjunction with site-specific information to develop a model suitable for use in the assessment of an individual disposal facility.

3. BASIC ELEMENTS OF THE CONCEPTUAL MODEL

For performance assessments, the *conceptual model* is a simplified, but technically credible, verbal and pictorial description of the disposal system. The model describes the ways that radionuclides in the waste can be released from the waste and the disposal unit, can be transported through the environment, and can come into contact with human receptors. The conceptual model covers the time periods of facility operation, institutional control, and post–institutional control. As shown in Fig. 1, it includes submodels for facility performance, transport processes, and exposure modes.

- The *facility model* represents the processes that control the release of radionuclides from the waste and the disposal unit. Release depends on the waste characteristics, the technology used to contain the waste, and the site characteristics.

- *Transport models* describe the transport of radionuclides from the facility through the environment via air, surface water, soil, groundwater, and biota. Using site data, the models estimate changing concentration and rate of transport of the contamination.

- *Exposure models* represent the modes of exposure—external, inhalation, and ingestion—through which human receptors receive a radiation dose. Exposure scenarios combine basic exposure modes and demographic data to postulate human activities that could result in exposure to radionuclides from the waste.

The following sections describe more fully the components of each of the three types of models used in pathways analysis for performance assessments.

3.1 FACILITY MODEL

The waste facility, shown schematically in Fig. 2, includes the waste; the waste package; the disposal unit; and engineered barriers such as a cover, a leachate collection system, and a groundwater suppression system. The purpose of the facility is to isolate the waste from the public and the environment, minimize passage of water to the waste, impede the release of radionuclides from the waste, and retard the movement of released radionuclides into the environment. Over time, direct precipitation, surface water, or groundwater may pass through the barriers, enter the disposal unit, penetrate the waste package, contact the waste, and dissolve some portion of the inventory. The leachate thus generated may then leak out of the package and unit, make its way through the barriers, and enter the environment.

The cover placed over a disposal unit at closure may consist of sloped layers of different materials in different depths. As time passes, the cover is subject to erosion from wind and water, subsidence, animal burrowing, and penetration by root systems. The time of actual infiltration and percolation of water to the disposal unit depends on site meteorological data (e.g., precipitation), permeability of the materials, and local plant and animal communities.

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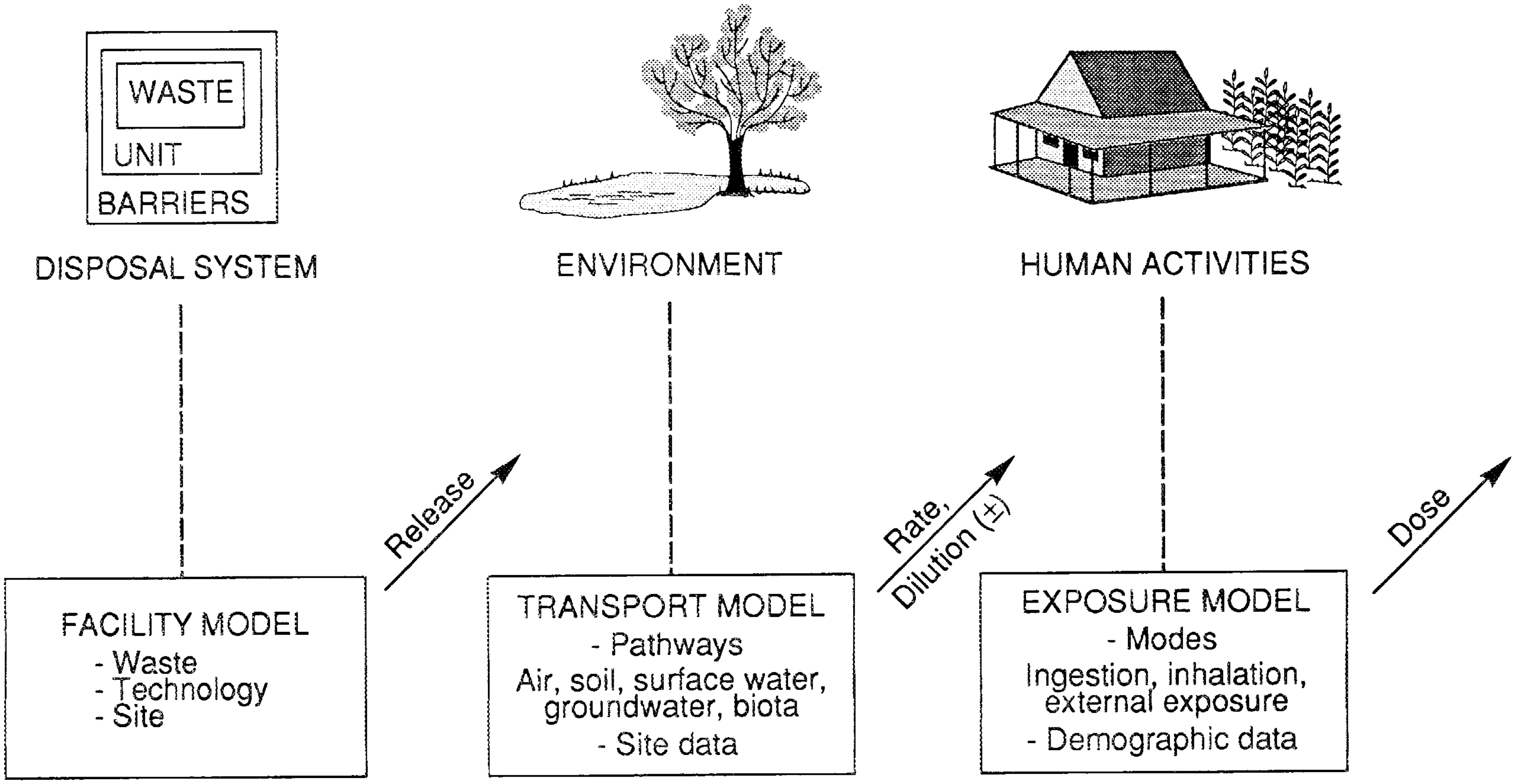

Fig. 1. Components of a conceptual model for performance assessment.

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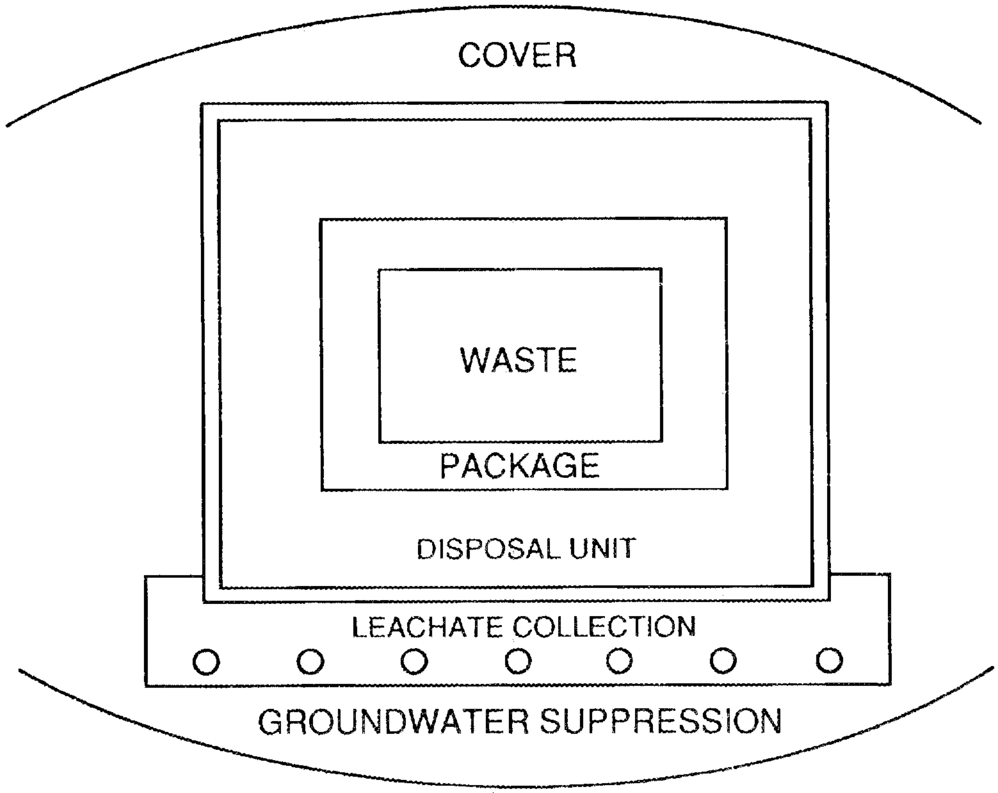

Fig. 2. Schematic of a waste disposal facility.

The disposal unit may exist in any of several forms, including trench, silo, auger hole, and tumulus designs. Its effectiveness at isolating the waste and preventing access of water depends on individual design, materials, structural properties, and the deterioration rates for the materials. Thickness of walls, reinforcement, and stability of the base affect the vulnerability of the unit to cracking and general degradation. Disposal practices at the facility such as backfilling or grouting to fill voids around waste packages in the unit help to stabilize the packages and prevent subsidence.

The waste package can be in various forms, from a plastic sack or metal box to a concrete cask or high-integrity container. The degree of containment provided by the package depends on the susceptibility of the package material to deterioration and to penetration by water. When the package fails, and moisture reaches the waste, the release of radionuclides is inhibited by waste treatment and conditioning, such as compaction and solidification, that stabilize and immobilize the waste.

The characteristics of the waste inventory may vary over time. High-activity wastes with short half-lives decay to lower levels of activity. Some long-lived isotopes decay and generate daughter products, which are new radionuclides that must be considered. Solubility and leaching rates of individual isotopes determine the amount of contamination released from the waste and the amount remaining in the original package.

Engineered barriers such as below-ground liners, leachate collection systems, and groundwater suppression systems are designed to prevent interaction of released radionuclides with the environment. The effectiveness of these barriers depends on the deterioration rates of the materials used and on maintenance activities at the facility.

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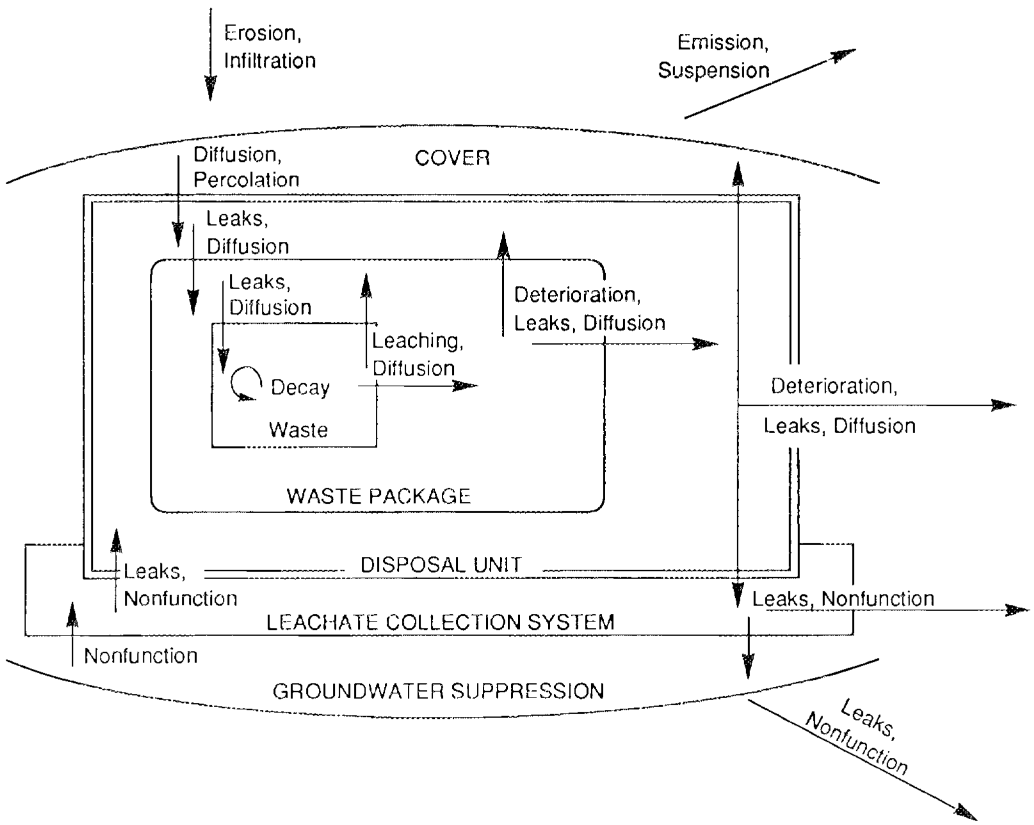

Fig. 3. Processes at a waste disposal facility.

Holes in a below-ground liner allow leaks from the unit to the surrounding soil and entry of moisture from the soil or groundwater into the unit. Failure or nonfunction (when turned off) of collection and suppression systems allows leaks to the soil, interaction between the collection and suppression systems, and entry of moisture to the disposal unit.

The facility model shown in Fig. 3 represents the components and processes that are involved in the release of radionuclides from the waste and disposal units and that must be addressed for a particular facility. The model is based on information about the waste, the facility itself, and the environment surrounding the facility. When quantified in the pathways analysis, using specific waste inventory, waste technology, and meteorological data for the site, the facility model provides the source term.

3.1.1 Waste Description

Release of radionuclides from the waste depends on the original waste components, their form, and the treatment and packaging applied before disposal. A complete description of waste disposed of at a facility includes details about the characteristics of the waste and its treatment and packaging. The description covers the following items:

- Waste inventory—radionuclides, volume, activity, concentration, and location at the disposal facility.
- Waste form (physical and chemical)—heterogeneous or homogeneous, stable or unstable, degradable or inert, uniform or variable composition, and uniform or variable solubility.

- Waste treatment and packaging—loose trash, baled trash, compacted, supercompacted; solidified with grout or bitumen; vitrified; packaged in metal or concrete boxes, drums, vaults, overpacks, or high-integrity containers.
- Radionuclide data—solubility; daughter products.

3.1.2 Disposal Facility Description

Features of the disposal facility isolate the waste and retard the release of radionuclides to the environment. The description of the waste disposal facility includes information about its physical characteristics, expected levels of performance of design features, and the disposal procedures at the facility. Significant topics are given in the following list:

- Facility layout—location and dimensions of the facility, location and dimensions of disposal units at the facility, etc.
- Disposal units—design, materials, and expected levels of performance.
- Engineered barriers—features such as caps, covers, liners, groundwater suppression systems, and leachate collection systems; expected levels of performance.
- Disposal practices—emplacement of waste in a unit, filling voids with dirt or grout, covering waste, monitoring, leachate collection, control of surface water run-on/runoff, maintenance, security (access control, fences, and lights), closure, and postclosure monitoring and maintenance.

3.1.3 Site Characteristics

Site characteristics have a large influence on the effectiveness and longevity of the disposal unit and engineered barriers. The description of the environment surrounding the disposal facility includes information about the geology, soils, hydrology, meteorology, and biology of the area, as listed below:

- Geology—topography, structural features, rock types and formations, and erosion and subsidence features.
- Soils—type, thickness, moisture content, hydraulic conductivity, porosity, and chemical properties.
- Surface water—ephemeral and perennial streams, discharge and direction, springs, sinks, natural bodies of water, run-on/runoff volume, flooding, drainage patterns, recharge areas, water quality, and interaction with groundwater.
- Groundwater—depth to water; gradient and direction; aquifer properties (type, thickness, yield, conductivity, dispersivity, and porosity); water quality; and interaction with other aquifers.
- Meteorology—precipitation, air temperature, humidity, wind speed and direction, storm data, and freeze-thaw cycling.
- Unusual events—flood, earthquake, and tornado occurrence.
- Biology—plant and animal communities that could breach containment, such as burrowing animals and deep-rooted plants.

3.1.4 Processes Involved in Radionuclide Release

Radionuclides are released from the waste packages and disposal units and move through barriers into the environment in a variety of physical and chemical processes, as depicted in Figs. 3 and 4. Specific processes for a particular site will depend on waste and facility characteristics. The amount of contamination released is estimated by quantifying facility components (such as thickness of concrete) and processes (such as diffusion through concrete). Processes involved in the release of radionuclides are given in the following list:

- Package degradation—general deterioration, rusting, and cracking of waste containers such as drums, boxes, and casks of metal or concrete.
- Facility degradation—general deterioration, rusting, cracking, and erosion of facility structures such as concrete pads, metal doors, liners, caps, and covers; failure or closure of leachate collection and groundwater suppression systems.
- Radionuclide release—diffusion through grout or concrete, dissolution, reaction, leaching, leaking, and gaseous emission.
- Release to surface water—direct discharge and surface runoff.
- Release to soils—seepage from surface, leaching, and "bathtubbing."
- Release to groundwater—leaching and seepage through soils.
- Release to atmosphere—gaseous emission and suspension of particulates on the ground or structures by wind.

3.2 TRANSPORT MODELS

Transport models illustrate the movement of radionuclides from the waste facility through the environment via air, soil, surface water, groundwater, and biotic pathways. Transport processes allow for storage, dilution, and concentration of contaminants as they move from the waste to contact with receptors. When quantified using specific waste and site data, the transport models provide an estimate of storage and dilution in the media and a rate of contaminant movement through and between the media.

A schematic diagram of the environmental pathways that must be considered in a performance assessment and the extensive interaction among them is given in Fig. 5. Interactions and processes from the focus of each individual pathway are depicted in succeeding figures. In succeeding sections, significant sources, sinks, processes, and data are listed for each environmental/transport pathway.

3.2.1 Air Transport Model

The air pathway model includes internal and interactive processes with soil, surface water, and biota, as indicated in Fig. 6. Considerable dilution can occur as radionuclides are dispersed in the air. Environmental data and the waste disposed of at a particular site will determine the significance of the air pathway at that site.

- Sources of contamination—gaseous emission from the facility, evaporation, and suspension or resuspension of particulates from surfaces by wind.
- Sinks of contamination—wet deposition (rainout, washout) and dry deposition (gravitational settling, contact with the ground, vegetation, and buildings).

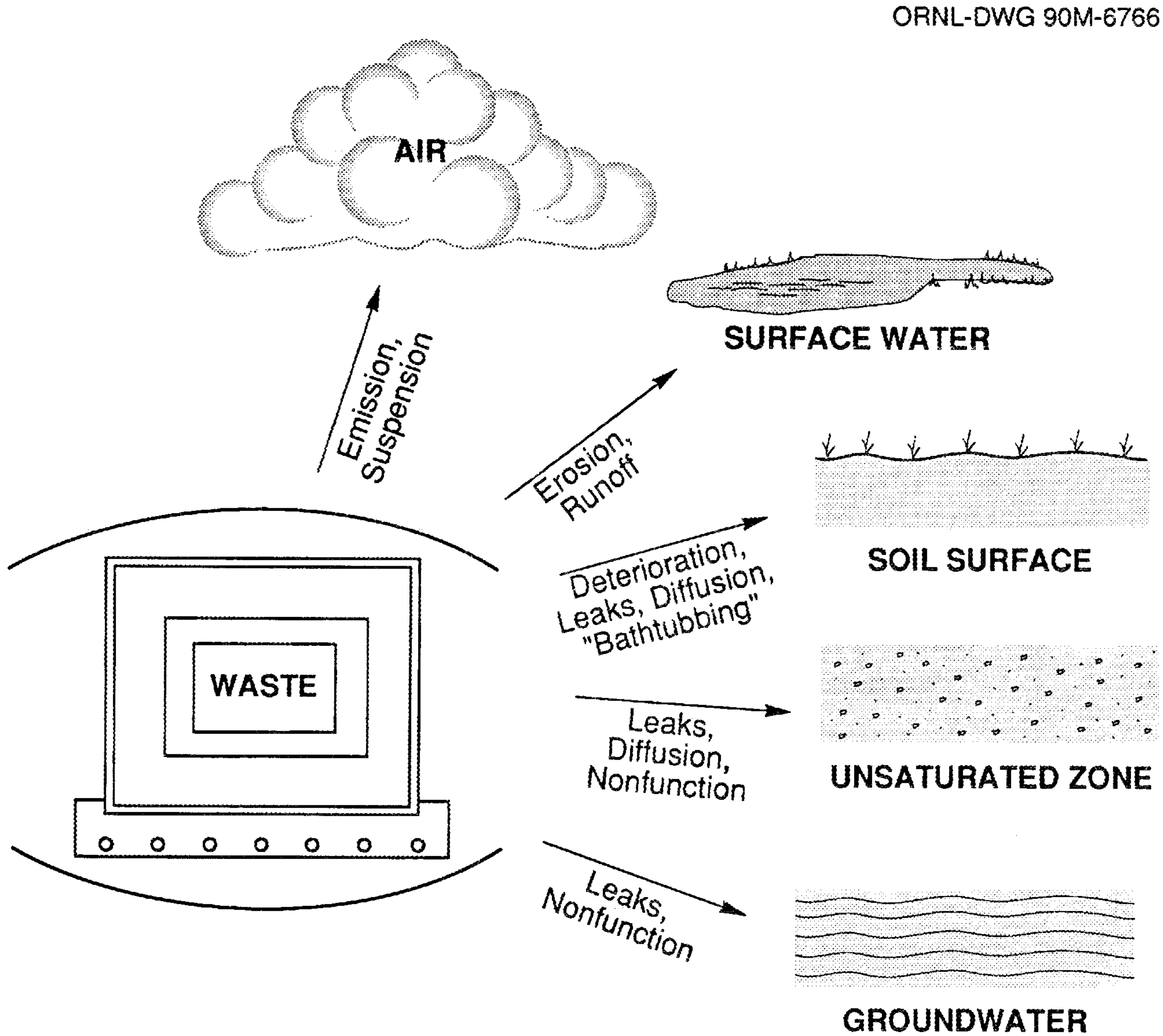

Fig. 4. Release from a waste facility to environmental pathways.

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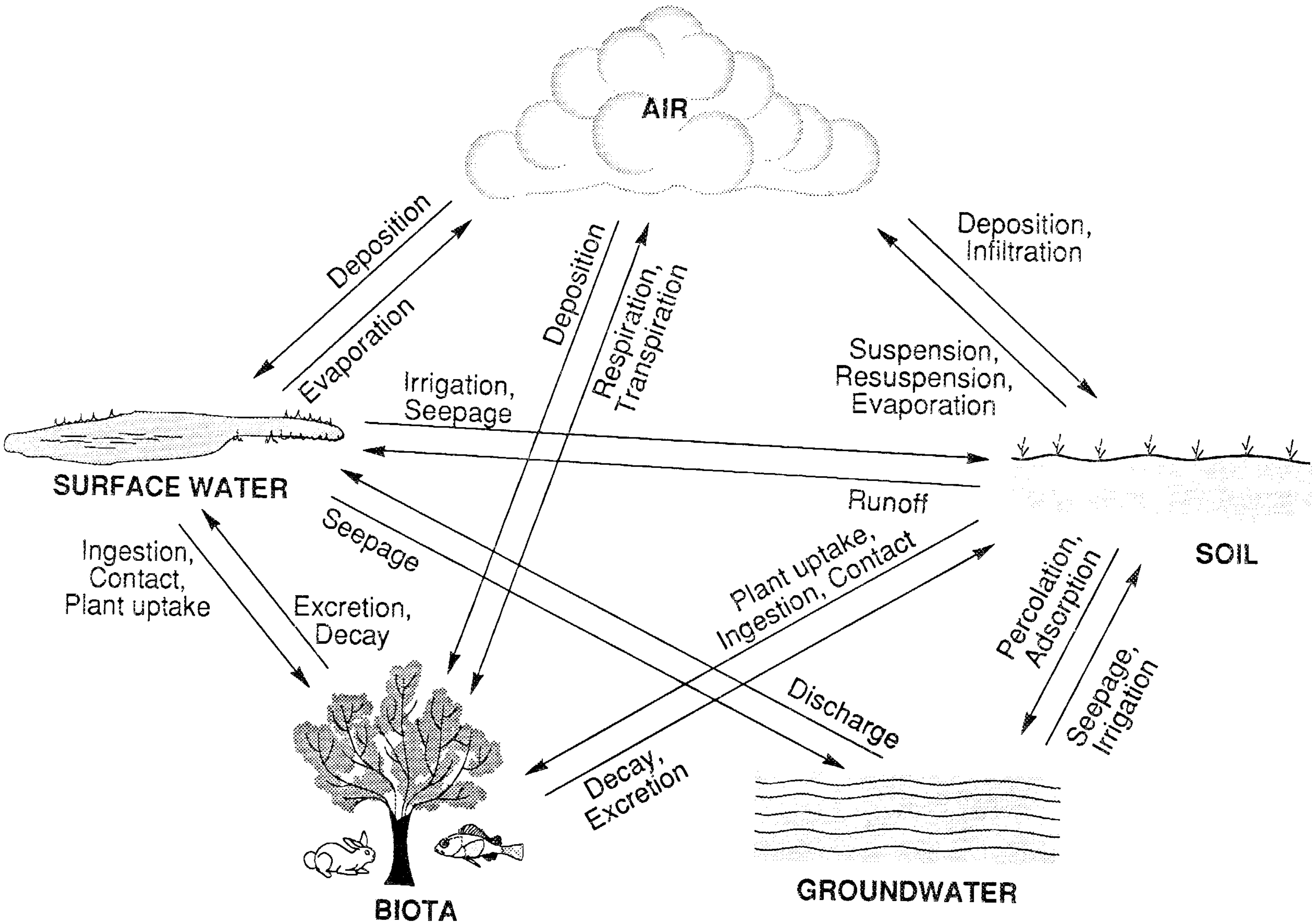

Fig. 5. Environmental pathway interaction.

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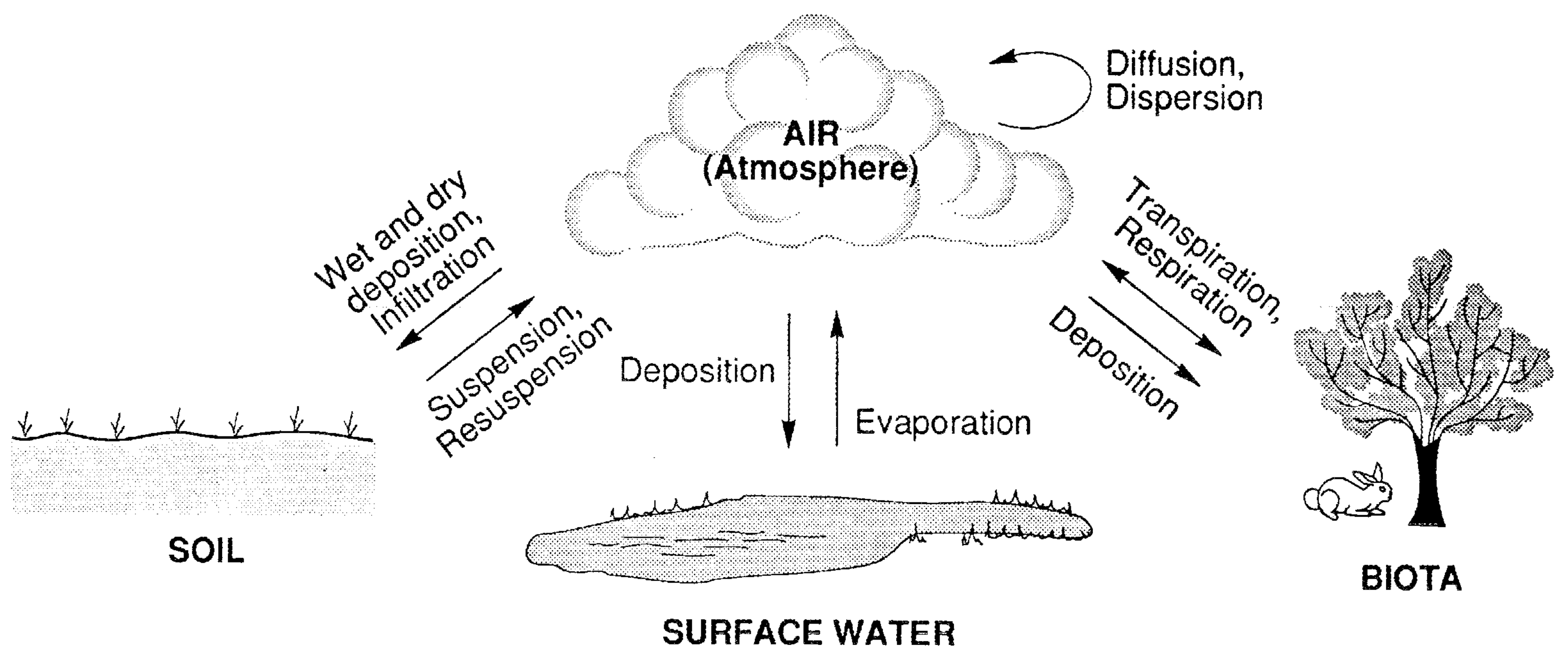

Fig. 6. Air transport processes and interaction.

- Transport processes in the air—diffusion and dispersion.
- Data—wind speed and direction, presence of turbulent eddies, and precipitation.

3.2.2 Surface Water Transport Model

Figure 7 illustrates the processes related to the surface water pathway and shows interactions with air, soil, groundwater, and biota. Drainage paths for rainwater at the facility carry released radionuclides to creeks and streams, which can transport them to lakes and rivers. Dilution of concentration in surface water can be estimated from flow volumes.

- Sources of contamination—direct discharge, surface runoff, seepage from groundwater, discharge from groundwater, and dry and wet deposition from the atmosphere.
- Sinks of contamination—evaporation, seepage to groundwater, irrigation, and adsorption onto soil.
- Transport processes in surface water—advection, diffusion, and dispersion.
- Processes in intermedia transfer—adsorption and desorption, dissolution and precipitation, and volatilization.
- Data—precipitation; evapotranspiration; stream flow (volume, direction, and velocity); water quality; and surface water usage (irrigation and human consumption).

3.2.3 Unsaturated Zone (Soil) Transport Model

Depending on site characteristics, significant storage of radionuclides can occur in the unsaturated zone through adsorption on the soil. However, radionuclides that are not adsorbed may eventually pass through to an underlying aquifer. Contamination in the soil can affect the air, surface water, groundwater, and biota, as shown in Fig. 8.

- Sources of contamination—erosion by wind or water, subsidence, leaching, infiltration, seepage from surface water or groundwater, irrigation with surface water or groundwater, and deposition from the atmosphere.
- Sinks of contamination—runoff of surface water, seepage to groundwater, wicking to surface, plant uptake, and suspension or resuspension in air.
- Processes in the soil—percolation, leaching, dispersion, diffusion, adsorption and desorption, ion exchange, and acid/base reactions.
- Data—soil type, thickness, hydraulic conductivity, porosity, moisture content, soil chemistry, and depth to groundwater.

3.2.4 Groundwater Transport Model

The importance of the groundwater pathway at a particular facility depends on site characteristics and human water-usage patterns. Dilution of concentration of released radionuclides occurs in the uncontaminated waters of the aquifer. The processes and interactions associated with the groundwater pathway are shown in Fig. 9.

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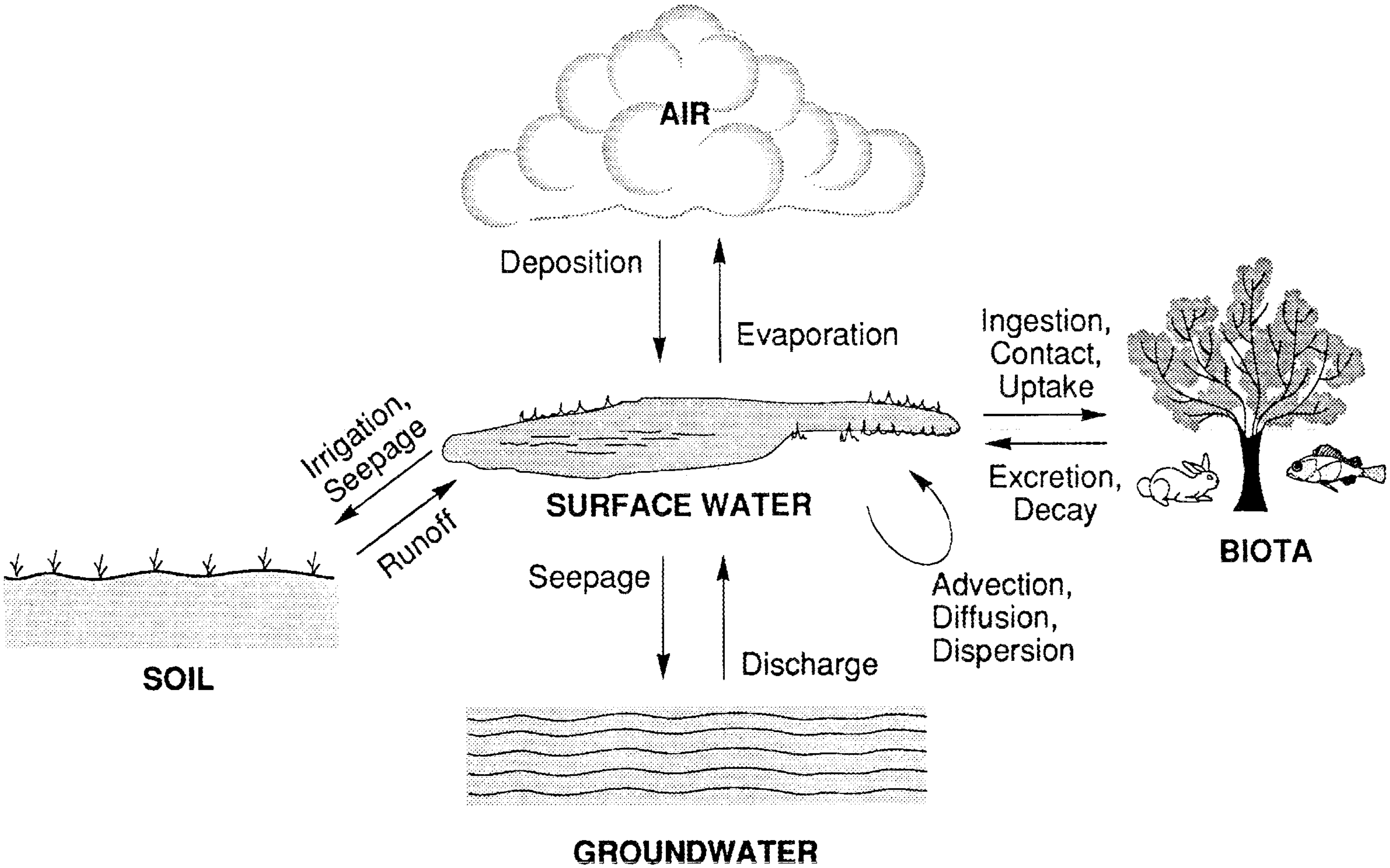

Fig. 7. Surface water transport processes and interaction.

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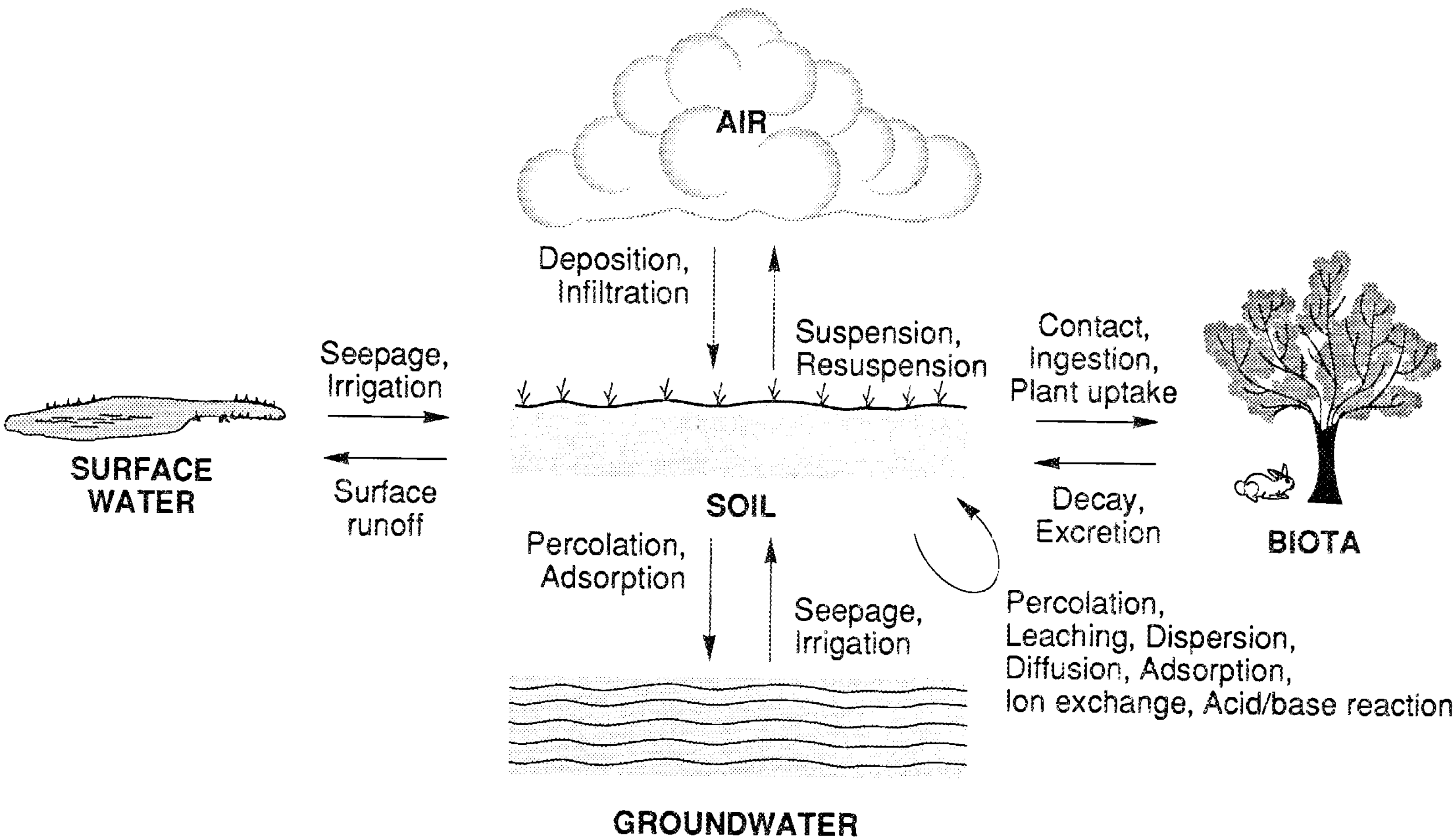

Fig. 8. Unsaturated zone processes and interaction.

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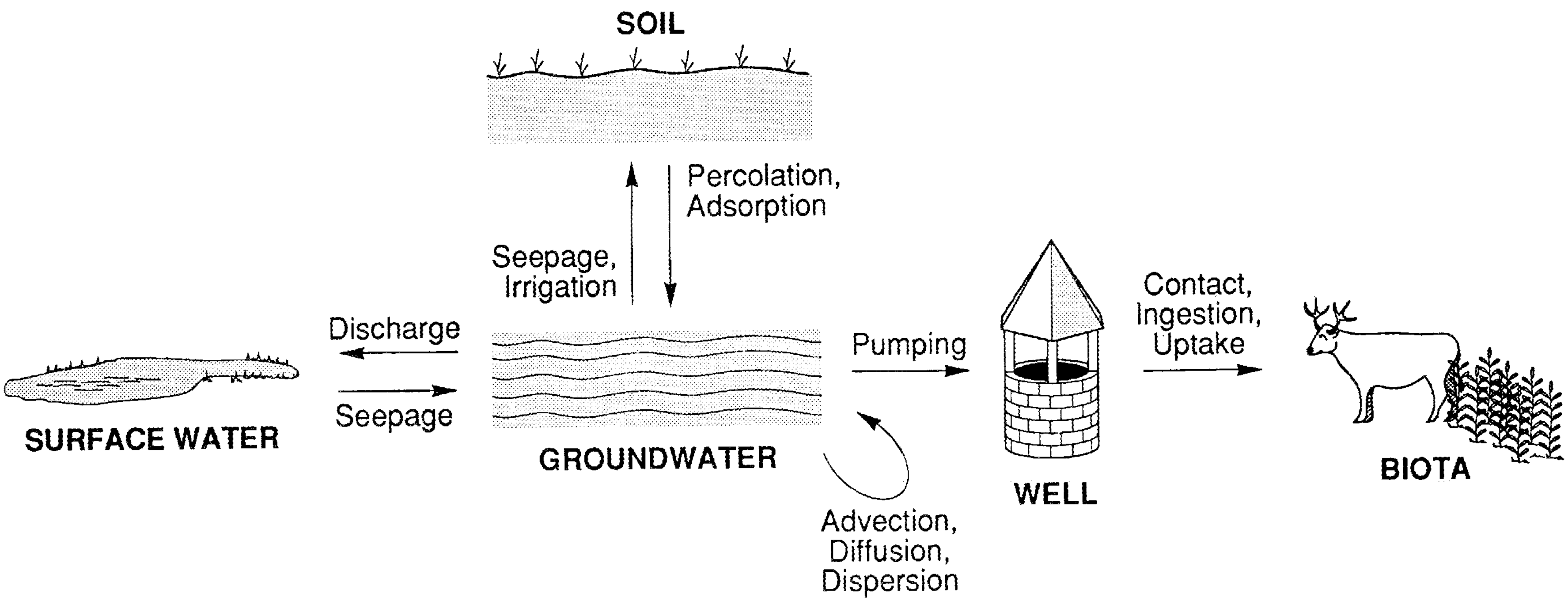

Fig. 9. Groundwater transport processes and interaction.

- Sources of contamination—leaching, seepage from unsaturated zone, and seepage from surface water.
- Sinks of contamination—seepage to surface water, discharge to surface water, pumping, leaching, and wicking to unsaturated zone.
- Processes in groundwater—advection, diffusion, and dispersion.
- Processes in intermedia transfer—adsorption and desorption; dissolution and precipitation.
- Data—flow direction and velocity; water quality; groundwater usage; and aquifer properties (type, thickness, yield, conductivity, dispersivity, and porosity).

3.2.5 Biota Transport Model

In the biotic pathway, the food chain can either dilute or concentrate the contamination. In addition, burrowing animals can breach some barriers and transport waste directly. Figure 10 shows the processes in the biotic pathway and in the pathway's interactions with other media.

- Sources of contamination—contact with waste, soil, and surface water; ingestion and uptake of soil, surface water, and groundwater (pumped); deposition from the atmosphere; and food chain.
- Sinks of contamination—decay and excretion to soil, surface water, and surface water sediment.
- Transport processes—plant uptake, transpiration, plant decay, respiration, animal food chain, animal decay and excretion, animal burrowing, and animal transport (fowl and feral dogs and cats).
- Data—plant and animal communities.

3.3 EXPOSURE MODELS

Exposure models represent the modes of exposure through which human receptors receive a radiation dose. Basic exposure modes are combined with demographic data for the area to develop reasonable scenarios of human behavior that could result in exposure to radionuclides.

3.3.1 Basic Exposure Modes

Basic exposure modes that must be addressed include external contact with radioactive waste or with contaminated soil or water, inhalation of contaminated air, and ingestion of contaminated water or food. Possible sources of radiation exposure for a human receptor are depicted in Fig. 11 and listed below by exposure mode.

- External (direct radiation)
  - waste (at the facility)
  - contaminated surface water or groundwater
  - contaminated soil or other ground surfaces
  - vegetation grown in contact with contaminated soil, surface water, or groundwater

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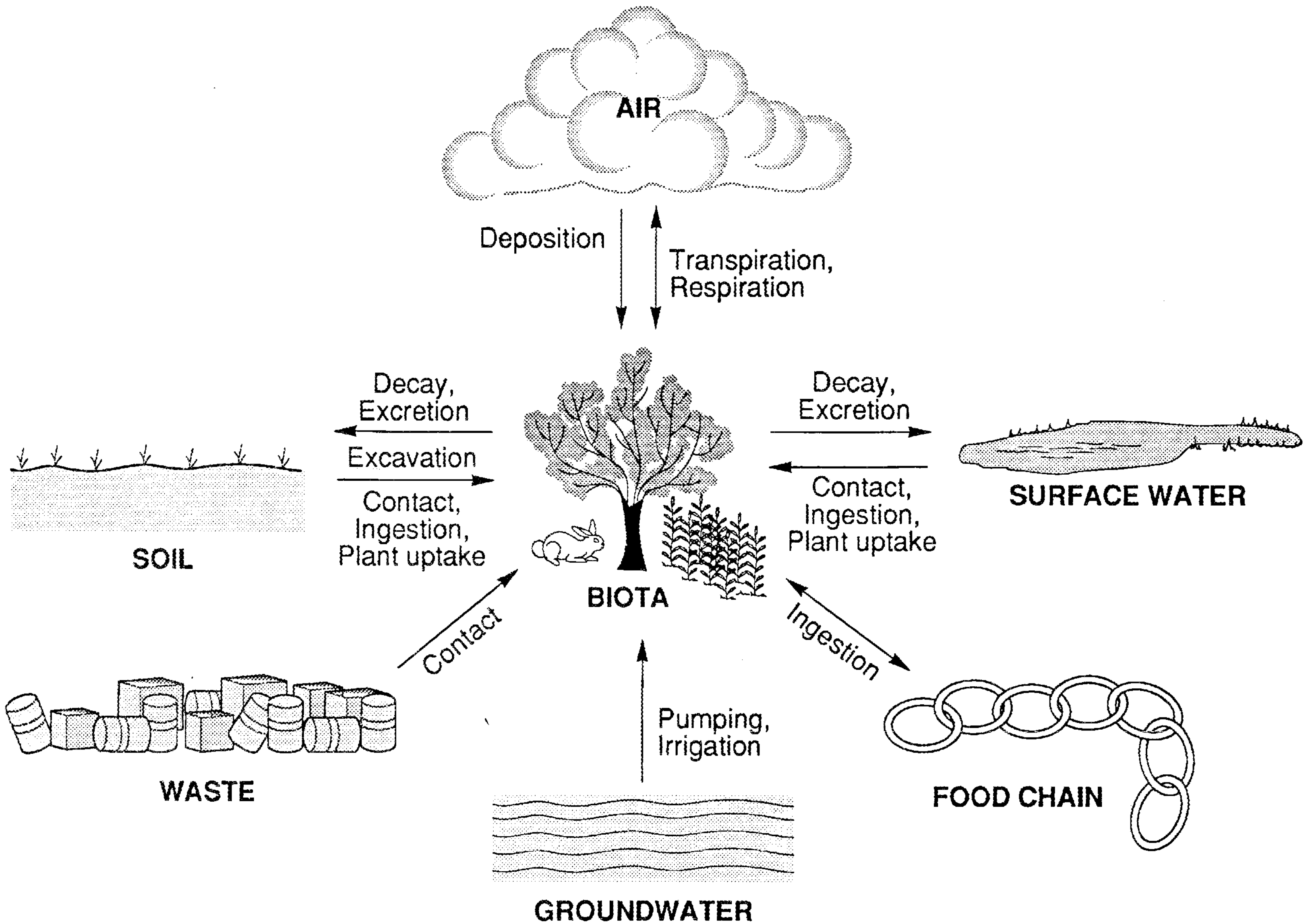

Fig. 10. Biotic transport processes and interaction.

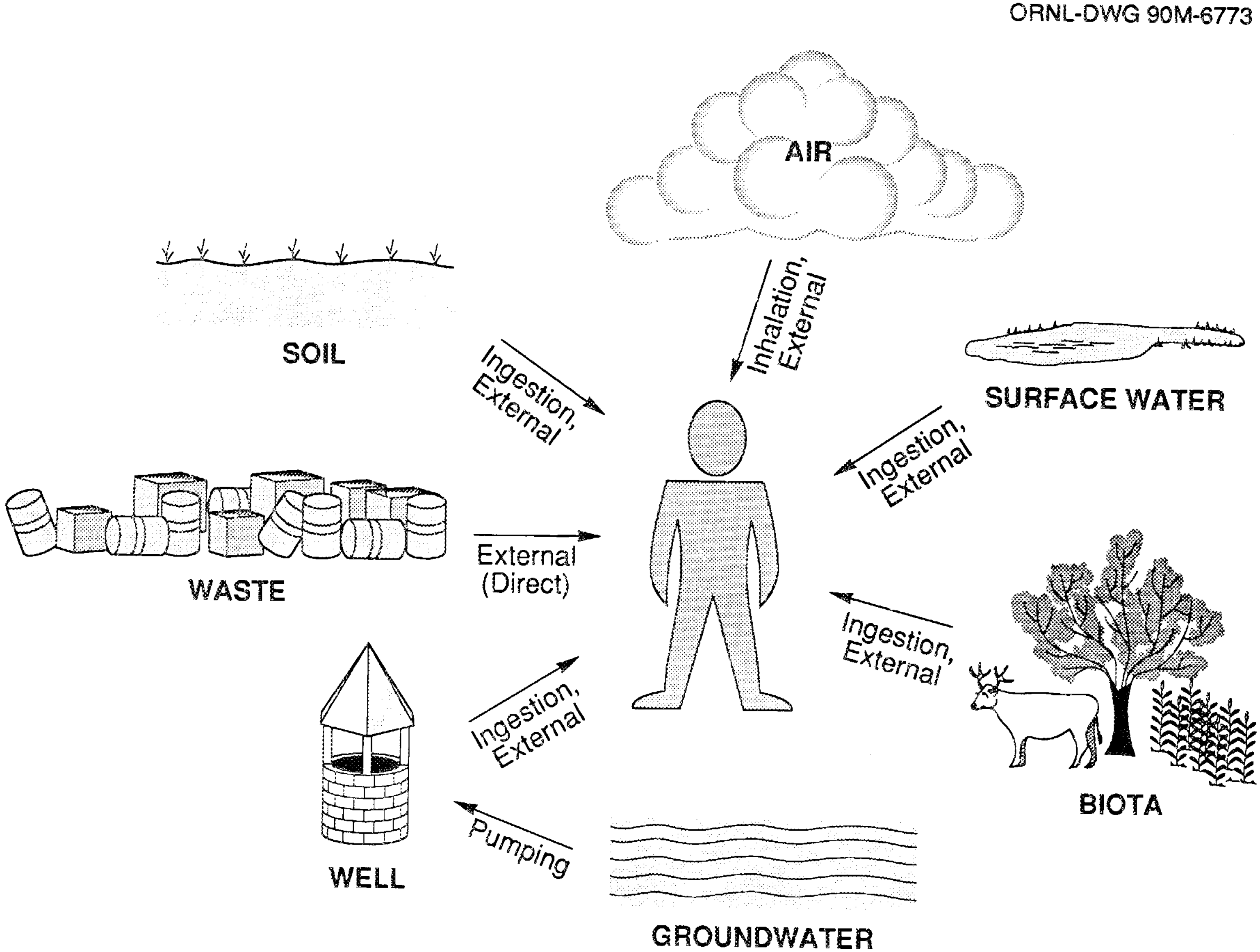

Fig. 11. Human exposure pathways.

- sediment deposited from contaminated surface water
- air contaminated by gases or suspended particulates
- soil contaminated by suspended particulates deposited on the ground

• Inhalation
  - air contaminated by gases
  - air contaminated by suspended particulates
• Ingestion
  - contaminated groundwater or surface water
  - crops grown in contaminated soil and/or irrigated with contaminated surface water or groundwater
  - meat or milk from livestock that ate contaminated pasturage and/or drank contaminated surface water or groundwater
  - fish from contaminated surface water
  - poultry that consumed contaminated dirt
  - foods contaminated by atmospheric deposition
  - dirt on vegetables grown in contaminated soil
  - absorption of radionuclides (tritium) through skin

3.3.2 Demographic Models

Demographic models describe the distribution of the surrounding population and area land-use in space and time. They are used to determine the population density around the disposal facility and to develop scenarios for human intrusion at the facility.

- Population model. The spatial distribution of the population within an 80-km radius of the facility. The model displays the location and approximate size of surrounding communities as they exist now and as they are projected to a future time.
- Land-use model. The spatial distribution of agricultural and other land use (beef cattle, dairy cattle, pasture, cropland, and industry) now and projected to a future time.
- Data. Population figures; dietary habits; water usage; agricultural practices; local crop types and yields; and local production rates for milk, beef, and pasture.

3.3.3 Exposure Scenarios

Scenarios describe plausible occurrences or activities that allow human access to radionuclides at the disposal facility or to radionuclides released from the facility. Exposure scenarios are developed to cover the time periods, locations, and pathways of concern derived from the performance objectives.

The three time periods of concern are the facility operations period, the period of institutional control after facility closure, and the time after institutional control ends. The locations of concern vary with time period. During operational and institutional control periods, exposure is portrayed for the public outside the DOE reservation boundary. In the post–institutional control period, exposure is portrayed both for the public outside the boundary and for an inadvertent intruder at the disposal facility.

Exposure scenarios include both continuing (chronic) exposure and occasional (acute) exposure and are developed by combining individual human activities. Dose to the human receptor is estimated by summing the doses associated with exposures from the individual activities. Possible activities for members of the public and an inadvertent intruder are listed below by time period.

- During the operational and institutional control periods, a member of the public outside the DOE boundary could receive a dose when he

  - drinks contaminated groundwater or surface water
  - contacts contaminated groundwater or surface water
  - contacts soil contaminated by surface water
  - eats fish from contaminated surface water
  - eats crops irrigated with contaminated groundwater or surface water
  - eats meat and dairy products from animals that consume contaminated water
  - breathes contaminated air

- During the post–institutional control period, a member of the public outside the DOE boundary could be exposed to radiation when he

  - drinks contaminated groundwater or surface water
  - contacts contaminated groundwater or surface water
  - contacts soil contaminated by surface water
  - eats fish from contaminated surface water
  - eats crops irrigated with contaminated groundwater or surface water
  - eats meat and dairy products from animals that consume contaminated water
  - breathes contaminated air

- When institutional control has ended, and access to the disposal site is less restricted, an inadvertent intruder could be exposed to radiation when he

  - contacts the waste
  - drinks contaminated groundwater or surface water
  - contacts contaminated groundwater or surface water
  - contacts contaminated soil
  - eats crops grown in contaminated soil
  - eats crops irrigated with contaminated groundwater or surface water
  - drinks milk from cows raised in the contaminated area (the cows ate contaminated pasturage and drank contaminated water)
  - eats meat from cattle raised in the contaminated area
  - eats fish from contaminated surface water
  - breathes contaminated air

3.3.4 Scenarios for Inadvertent Intruder

Some generally accepted scenarios to be considered for inadvertent intruders during the post–institutional control period are described briefly in the following paragraphs. Development of scenarios for a particular facility is based on waste technology and demographic projections for the specific site.

- Intruder drilling. An intruder drills a well for drinking water at a disposal unit. During drilling, waste mingled with soil is brought to the surface. The intruder drinks water from the well, is exposed externally to the contaminated soil and groundwater, and breathes some resuspended particulates.

- Intruder construction. An intruder drills a well for drinking water and constructs a building at the disposal unit. Waste is encountered in excavation activities and mixed with surface soil. This scenario assumes that the waste is indistinguishable from native soil. The intruder drinks water from the well, breathes resuspended particulates, and contacts the contaminated soil and groundwater.

- Intruder discovery. An intruder begins construction at the disposal unit but realizes he is working in something different from native soil and abandons construction. This scenario is used for an acute exposure from contact with the waste and breathing resuspended particulates.

- Intruder residence. An intruder drills a well for drinking water, constructs a house, and lives in the house at the disposal unit. Over an extended time, the intruder drinks water from the well, is exposed externally to contaminated soil and groundwater, and breathes resuspended particulates.

- Intruder agriculture. An intruder drills a well for drinking water, constructs a house, lives in the house, and keeps a vegetable garden at the disposal unit. The intruder drinks water from the well, inhales resuspended particulates, is externally exposed to contaminated soil and groundwater, ingests food grown in the contaminated soil, and ingests meat and milk from cattle fed and watered at the disposal site.

- Intruder artifact. An intruder at the facility digs up a shiny piece of glass (vitrified waste), places it in his home as a household decoration, and is exposed externally over an extended time.

These commonly used scenarios describe possible human activities and associated exposure modes at a disposal facility. They do not represent a complete list but are examples to be considered in choosing or developing exposure models for a particular facility. Scenarios for a specific site are based on measured or measurable physical characteristics of waste and site and on reasonable projections of human activity at the site. Depending on the data available to support the model, scenarios for a particular facility may range from simple and single occasion (intruder discovery) to complex and multistage (intruder agriculture).

4. APPLICATION TO DISPOSAL FACILITIES

Section 3 describes all components that might be included in a conceptual model for performance assessment of a waste facility. It addresses all the processes and pathways involved with release of radionuclides from a facility and their transport through the environment to human receptors. This section discusses components that apply to releases from two general types of waste facilities—those with below-ground units and those with aboveground units. Release processes to specific pathways for above- and below-grade units are considered for the time periods of operations, institutional control, and post-institutional control at the facility.

4.1 BELOW-GROUND WASTE FACILITY

Examples of below-ground waste facilities at sites operated by Energy Systems include trenches, silos, and auger holes. All three methods involve digging or excavation of soil and placement of waste so that the waste resides below normal grade level. Some trenches provide containment through liners and concrete walls. Some silos and auger holes provide isolation and shielding through concrete cylinders or concentric metal pipes. All units are closed with some form of cap or cover of concrete or natural materials. Figure 4 depicts releases to environmental pathways from any disposal unit. Releases from below-ground units are predominantly to the unsaturated zone and to groundwater.

4.1.1 Operations Period at a Below-Ground Facility

During the operations period, estimated at 30 years for Energy Systems sites, waste is actively stored, treated, and disposed of at the facility. Security measures such as fences and patrols restrict public access to the waste. Grading and barriers that control surface water run-on and runoff help limit the contamination of surface soil and water.

During normal operations, below-ground liners, leachate collection systems, and groundwater suppression systems minimize the release of radionuclides to the unsaturated zone and groundwater. If leaks develop in below-grade units without leachate collection capability, release will occur to the soil and groundwater. Monitoring activities provide data on facility performance and indicate areas that need corrective action.

Some contamination of air could occur at open trench units, where dumping of loose trash could cause radioactive particulates to be suspended in the air. Facility practices such as covering the waste with a layer of clean dirt after each disposal help minimize contamination of air. Waste treatment and packaging operations also could contribute some release to air.

The status of facility components during operations is as follows:

- Waste—radioactive decay begins at time of disposal.
- Waste package—mostly intact, except for mishandling and animal disruption; some waste is not containerized.
- Unit and barriers—mostly intact; liners, collection systems, groundwater suppression systems, and other barriers are mostly functional, but failure and disruption by animals is possible.

Release to pathways during operations occurs as follows:

- Air—suspension of particulates from dumping of loose trash and release from waste treatment and packaging operations.
- Surface soil and water—accidental spills and subsequent runoff to surface water; animal transport.
- Unsaturated zone—leaks from units without leachate collection capability; leaks from units with failed collection systems; failure of groundwater suppression system.
- Groundwater—leaks from units without collection and/or groundwater suppression systems; leaks from units with failed collection or suppression systems; seepage from unsaturated zone.

4.1.2 Institutional Control Period at Below-Ground Facility

The institutional control period extends 100 years after the closure of the last disposal unit at the facility. During this time, the facility is fenced and patrolled to restrict public access, and periodic maintenance and monitoring activities are performed. Leachate collection systems are assumed to be nonfunctional at the end of the postclosure care period specified by state or local regulations.

The status of facility components during institutional control is as follows:

- Waste—radioactive decay; some diffusion; some leaching, the amount depends on specific radionuclide, waste form, and treatment.
- Waste package—deterioration and loss of integrity; breaching by burrowing animals; leaks.
- Unit and barriers—some deterioration of structural materials; some erosion of covers; leaks in liners; breaching by burrowing animals; leachate collection closed; leaks in groundwater suppression system.

Release to pathways during institutional control occurs as follows:

- Air—none except possible suspension of particulates from waste brought to surface by burrowing animals.
- Surface soil and water—animal burrowing; spilling onto surface soil and runoff to surface water from "bathtub effect" (assumes no leaks in below-grade portion of unit).
- Unsaturated zone—leaks and diffusion from units; nonfunction of leachate collection system; nonfunction of groundwater suppression.
- Groundwater—leaks and diffusion from units; nonfunction of suppression system; seepage from unsaturated zone.

4.1.3 Post–Institutional Control Period at Below-Ground Facility

For performance assessments, the post–institutional control period begins 100 years after facility closure and extends into the future until the time of maximum impact from the facility. No maintenance and monitoring are conducted, and the facility is assumed to be accessible to the public.

The status of facility components after institutional control is as follows:

- Waste—radioactive decay; diffusion; leaching (amount depends on specific radionuclide, waste form, and treatment).
- Waste package—general deterioration (amount depends on package materials); leaks; breaching by animals and root systems.
- Unit and barriers—general deterioration (amount depends on structural materials); erosion of covers; leaks; breaching by animals and root systems.

Release to pathways after institutional control occurs as follows:

- Air—suspension of particulates from waste brought up by intruder digging or animal burrowing.
- Surface soil—intruder digging; cover erosion; animal burrowing.
- Surface water—surface runoff after intruder or animal activity; runoff after erosion of cover.
- Unsaturated zone—leaks and diffusion from units; seepage from surface soil.
- Groundwater—leaks and diffusion from units; seepage from unsaturated zone.
- Biota—animal burrowing and transport; plant uptake.

Section 3.3 discusses development of exposure scenarios of plausible activities that allow human exposure to radionuclides at a waste facility. For the below-ground facilities, dose from exposures after institutional control will be based on the intruder-agriculture scenario described in Sect. 3.3.4. The intruder may directly encounter the waste 100 years after facility closure. In model quantification, standard values will be used for food and water consumption.

4.2 ABOVEGROUND WASTE FACILITY

At sites operated by Energy Systems, aboveground disposal methods are based on tumulus technology. The tumulus facilities are designed to isolate the waste through multiple engineered barriers. Concrete pads hold numerous concrete vaults containing waste that has been compacted, grouted in containers, and grouted in the vaults. Extensive leachate collection and groundwater suppression systems are installed beneath the pads, and a thick cover of layered materials is placed over the vaults and pads at closure. Releases to environmental pathways from a generic disposal unit are shown in Fig. 4. Releases from an above-grade unit generally enter the air, surface soil, surface water, and the unsaturated zone.

4.2.1 Operations Period at an Aboveground Facility

Active treatment, packaging, and disposal of waste are conducted at a tumulus facility during an estimated 40 years of operations at Energy Systems sites. Fencing, patrols, and other security measures restrict public access to the site.

During normal operations, release to surface soil and water are limited by surface and below-grade runoff collection systems. Leachate collection and groundwater suppression systems minimize release to the unsaturated zone and groundwater. Facility performance is monitored at multiple stations to provide early detection of problems for correction. Waste treatment and packaging operations could release some contamination to the air; otherwise, there is no waste exposure to air.

The status of facility components during operations is as follows:

- Waste—radioactive decay begins at the time of disposal.
- Waste package—intact, except for major failure of grout or concrete.
- Unit and barriers—unit intact, except for major failure of concrete; some deterioration of vaults from exposure to weather possible while the pad is being filled; surface runoff collection, leachate collection, and groundwater suppression systems mostly functional, but failure and disruption by animals could occur.

Release to pathways during operations occurs as follows:

- Air—release or suspension from treatment and packaging operations.
- Surface soil and water—failure of surface runoff collection concurrent with leaks from vaults.
- Unsaturated zone—failure of leachate collection system concurrent with leaks from vaults; failure of groundwater suppression system.
- Groundwater—failure of groundwater suppression system concurrent with leaks from vaults and with failure of leachate collection system; seepage from unsaturated zone.

4.2.2 Institutional Control Period at Aboveground Facility

During the 100 years of active control following facility closure, public access to the facility is restricted through fences and patrolling, and periodic monitoring and maintenance are conducted. Surface runoff collection and leachate collection systems are assumed to be nonfunctional at the end of the required post-closure care period.

The status of facility components during institutional control is as follows:

- Waste—radioactive decay; some diffusion; possible leaching if grout or concrete fails.
- Waste package—mostly intact; deterioration of package possible if grout fails.
- Unit and barriers—mostly intact; some erosion of natural cover; deterioration of vault possible, depending on materials and protection from weather; surface runoff collection and leachate collection closed; leaks possible in groundwater suppression system.

Release to pathways during institutional control occurs as follows:

- Air—none, unless a major event exposes waste.
- Surface soil and water—destruction of cover by major event and leaks or diffusion from concrete vaults; nonfunction of surface runoff collection system.
- Unsaturated zone—leaks or diffusion through concrete pad; nonfunction of leachate collection system; nonfunction of groundwater suppression system.
- Groundwater—leaks or diffusion through concrete pad; nonfunction of groundwater suppression system; seepage from unsaturated zone.

4.2.3 Post–Institutional Control Period at Aboveground Facility

For performance assessments, the post–institutional control period begins 100 years after facility closure and extends into the future until the time of maximum impact from the facility. Some engineered barriers at the facility are designed to isolate the waste well into this period. However, no maintenance and monitoring are conducted, and the facility is assumed to be accessible to the public.

The status of facility components after institutional control is as follows:

- Waste–radioactive decay; diffusion; leaching (amount depends on specific radionuclide and treatment).
- Waste package—general deterioration (extent depends on properties of grout and concrete); leaks.
- Unit and barriers—general deterioration (amount depends on structural materials); erosion of cover; leaks.

Release to pathways after institutional control occurs as follows:

- Air—suspension of particulates from waste brought up by intruder digging or drilling.
- Surface soil—leaks and diffusion from vaults after erosion of cover; intruder digging; animal burrowing.
- Surface water—surface runoff after intruder or animal activity; runoff after erosion of cover.
- Unsaturated zone—leaks and diffusion through concrete pad; seepage from surface soil.
- Groundwater—leaks and diffusion through concrete pad; seepage from unsaturated zone.
- Biota—animal burrowing and transport; plant uptake.

Section 3.3 discusses the development of exposure models, scenarios of reasonable human behavior that lead to a radiation dose. For the aboveground tumulus, human exposure after institutional control will be modeled in two versions of the intruder-agriculture scenario. The exposures used to estimate dose in each model will depend on facility features and time.

In the first version, the intruder arrives 100 years after facility closure and performs the activities associated with the intruder-agriculture scenario. However, the engineered barriers at the tumulus limit direct contact with the waste. The deep multilayered cover

over the concrete vaults of treated waste limits direct intrusion into the waste. The scenario limits external exposure to waste, external exposure to contaminated soil, ingestion of food grown in contaminated soil, and inhalation of resuspended particulates from the soil.

In the second version, occurring at least 300 years after facility closure, the intruder carries out the activities associated with the intruder-agriculture scenario, including direct contact with the waste. The engineered barriers at the facility have deteriorated enough so that they no longer limit the intruder. External and internal exposures from the waste, contaminated soil, food grown in the soil, and breathing the air are considered in the dose estimate.

4.3 APPLICATION TO A PARTICULAR FACILITY

Section 3 of this document presents components of a conceptual model for performance assessment of waste facilities. It describes processes and pathways that might be included in facility, transport, and exposure models for any site, waste, and technology. In Sect. 4, release and transport processes have been addressed for two general types of facilities, aboveground and below-ground.

Development of a conceptual model for a particular waste facility requires consideration of specific site characteristics, waste characteristics, and waste technology. Specific information is used to identify the components that are applicable to the facility and that should be included in the model and to justify the exclusion of those components not applicable. Relevant processes and pathways are then assembled in a model that represents the behavior of the particular disposal facility. The conceptual model thus produced forms the basis for the performance assessment of the facility.

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