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8.3.5.12 Issue resolution strategy for Issue 1.6: Will the site meet the performance objective for pre-waste-emplacement ground-water travel time as required by 10 CFR 60.113?

Regulatory basis for the issue

One of the NRC performance objectives for high-level waste repositories is stated in 10 CFR 60.113(a)(2) as

> The geologic repository shall be located so that pre-waste-emplacement ground-water travel time along the fastest path of likely radionuclide travel from the disturbed zone to the accessible environment shall be at least 1,000 years or such other time as may be approved or specified by the Commission.

The disturbed zone has been defined qualitatively in 10 CFR 60.2 as

> That portion of the controlled area the physical or chemical properties of which have changed as a result of underground facility construction or as result of heat generated by the emplaced radioactive wastes such that the resultant change of properties may have a significant effect on the performance of the geologic repository.

The accessible environment has been defined in 10 CFR 60.2 to mean the atmosphere, the land surface, surface water, oceans, and the portion of the lithosphere that is outside the controlled area. The controlled area, defined in 40 CFR 191.12(g), means

> (1) A surface location, to be identified by passive institutional controls, that encompasses no more than 100 square kilometers and extends horizontally no more than five kilometers in any direction from the outer boundary of the original location of the radioactive wastes in a disposal system, and (2) the subsurface underlying such a surface location.

The current reference locations of the boundaries of the disturbed zone and accessible environment at Yucca Mountain are subject to change and are established now only to provide a planning basis for a site specific approach to resolution of this issue. Solely for the purposes of this discussion, a distance of 50 m below the midplane of the repository is used as the boundary of the disturbed zone (see Section 8.3.5.12.5 for discussion of plans for defining a more formal boundary of the disturbed zone). A preliminary definition of the boundary of the accessible environment, taken from Rautman et al. (1987), is shown in Figure 8.3.5.12-1. The final definition of the boundary of the accessible environment will be determined by Subactivity 1.6.3.1.2 (Section 8.3.5.12.3.1.2).

The fastest path of likely radionuclide travel is not defined in the regulation. For the purpose of resolving this issue, the DOE assumes that it is possible to identify geographically or geometrically distinct pathways for likely radionuclide travel at the Yucca Mountain site. One of these pathways is the generally downward flow of liquid water through unsaturated zone

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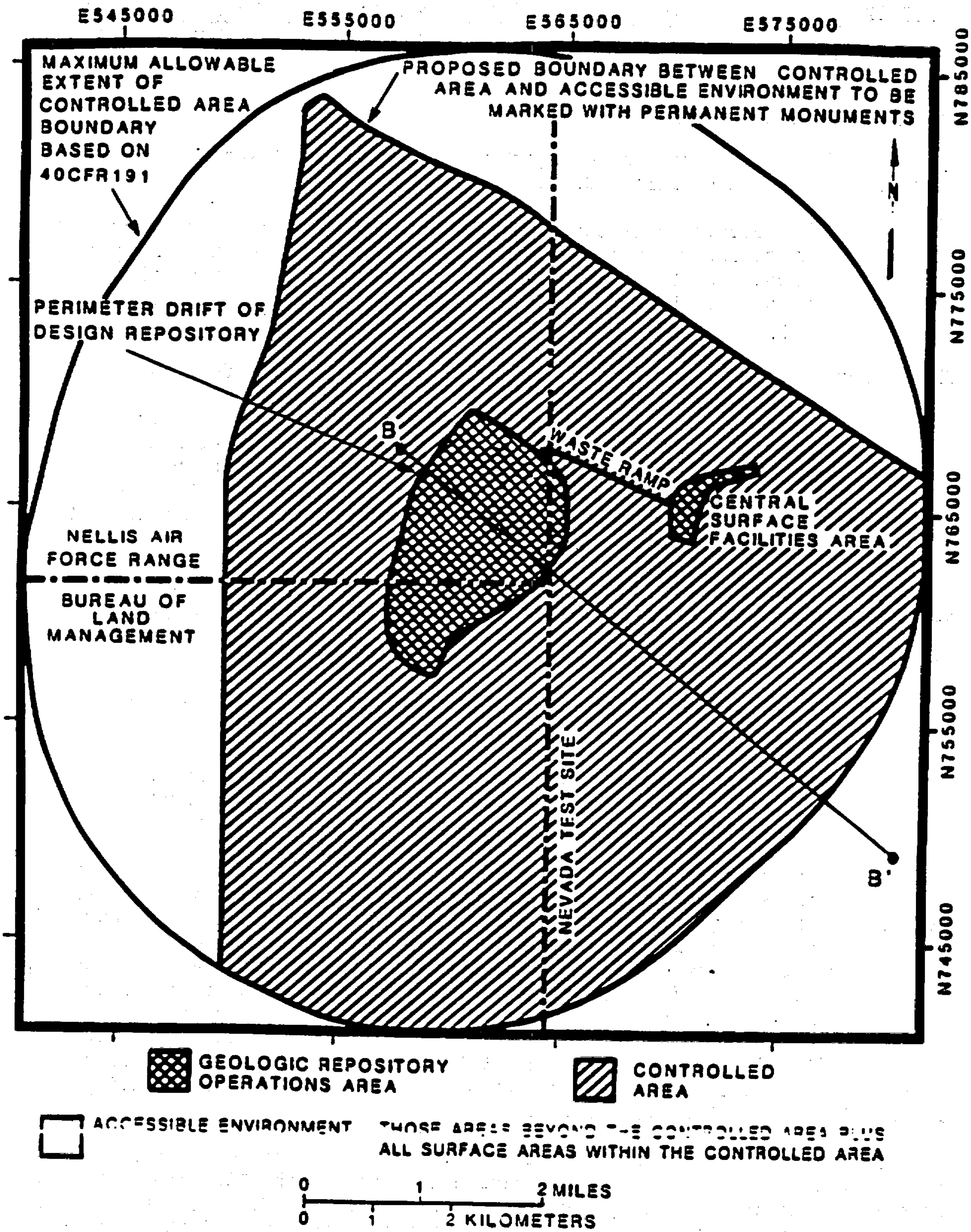

Figure 8.3.5.12-1. Preliminary definition of the boundary of the accessible environment (Rautman et al., 1987) and the location of section B-B'. Figure 8.3.5.12-2

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hydrostratigraphic units underlying the repository level to the water table and then to the accessible environment. The flow in this pathway could be through pores in the rock matrix and through fractures in these units. Pathways may also be identified with potential fracture zones associated with the Ghost Dance fault or other faults that may significantly affect flow times through the site. In addition, there may be local zones within the heterogeneous system in which the necessary values of hydrologic parameters are sufficiently correlated that a discrete, rapid velocity pathway can be identified. The "fastest path of likely radionuclide travel" will be the path (or set of paths from the total set of possible paths) where radionuclides will move with the least travel time.

The approach described here and the activities within this issue will support a demonstration of compliance with 10 CFR 60.113 requirements by providing for the determination of the distribution of pre-waste-emplacement ground-water travel times along the fastest path of likely radionuclide travel from the disturbed zone to the accessible environment. Though water may move through the unsaturated zone in both liquid and vapor phases, this issue is concerned only with the travel time of liquid water. The direct effects on performance of vapor flux through the unsaturated zone are addressed by Issue 1.1 (Section 8.3.5.13). Vapor flux through the unsaturated zone at Yucca Mountain may significantly influence both the magnitude and direction of liquid water flux and will therefore be considered in determining ground-water (liquid) travel time.

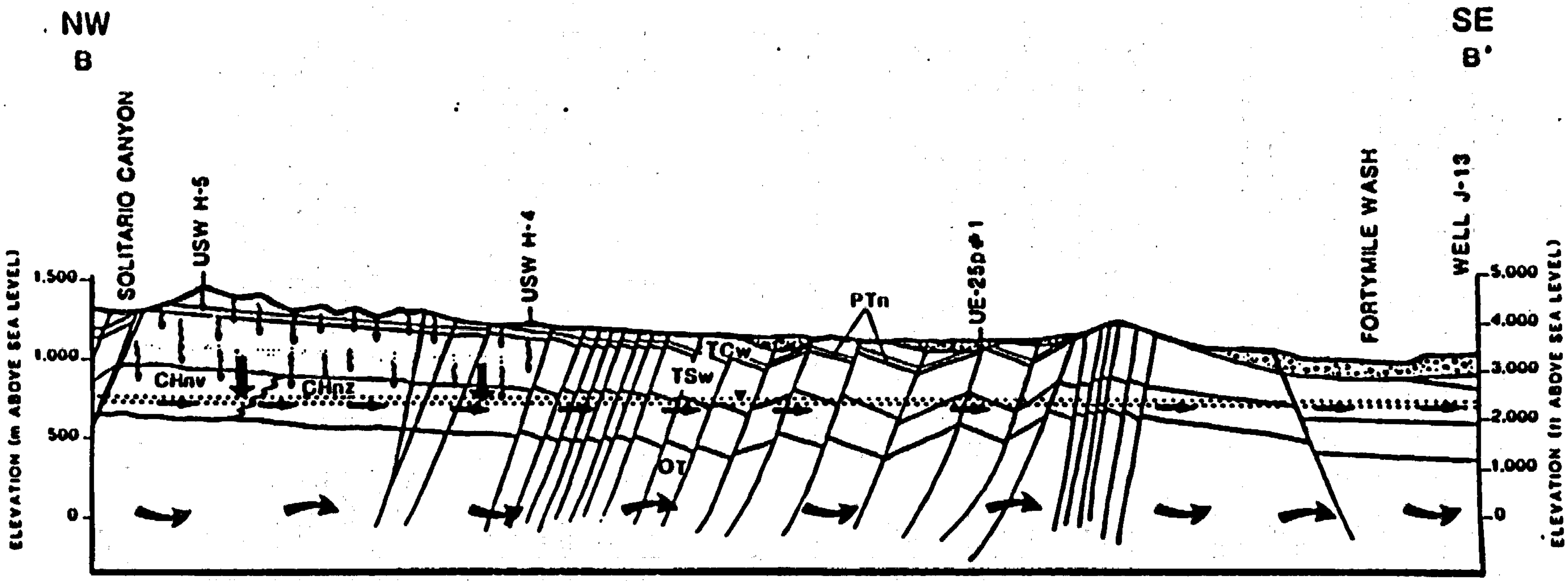
Within the following text of this overview section, the background of this issue is discussed followed by a discussion of the issue resolution strategy, and the relationship between the issue and the information needs.

Background

The present understanding of hydrogeologic conditions at Yucca Mountain is described in Chapter 3. The proposed repository will be located in the unsaturated zone, and liquid-phase releases of radionuclides to the accessible environment will probably occur in the saturated zone after migration downward through the unsaturated zone. This means that the flow paths of concern will have two parts: an approximately vertically downward portion through the unsaturated zone and a generally horizontal portion through the saturated zone (Figure 8.3.5.12-2).

The site parameters that describe the hydrologic characteristics along these general paths, as well as any other paths that may be identified during site characterization, will be measured during the characterization process. The hydrogeologic test plans that support the resolution of Issue 1.6 are addressed in the geohydrology program (Section 8.3.1.2). An additional requirement for resolving Issue 1.6 is the confirmation and refinement of conceptual models for flow through the saturated and unsaturated zones at the site. Plans for development of these models are also described in the geohydrology program.

Current concepts generally distinguish two general modes of ground-water movement through the unsaturated zone.



ALLUVIUM AND TIMBER MOUNTAIN TUFF

REPOSITORY (THICKNESS EXAGGERATED)

WATER TABLE

FLUX THROUGH THE UNSATURATED ZONE

UNSATURATED FLOW PATHS USED FOR TRAVEL TIME CALCULATIONS

SATURATED FLOW PATH USED FOR TRAVEL TIME CALCULATIONS (WATER THAT HAS PASSED THROUGH THE REPOSITORY LEVEL)

DEEP SATURATED FLOW PATHS FOR WATER THAT HAS NOT PASSED THROUGH THE REPOSITORY LEVEL

TCw	TIVA CANYON WELDED UNIT
PTn	PAINTBRUSH NONWELDED UNIT
TSw	TOPOPAH SPRING WELDED UNIT
CHnv	CALICO HILLS VITRIC UNIT
CHnz	CALICO HILLS ZEOLITIC UNIT
OT	OLDER TUFF UNIT

0 0.5 1 MILE

0 0.5 1 KILOMETER

Figure 8.3.5.12-2. Conceptual hydrogeologic section from Solitario Canyon to well J-13. Section location shown in Figure 8 3 5 12-1 (modified from Scott and Bonk, 1984).

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1. Flow predominantly through pores in the rock matrix. In this mode, the time of water movement through a given volume of rock is dominated by flow through the small but abundant matrix pores of the tuffaceous rocks. Current data on site characteristics and likely flux values beneath the repository depths suggest that this is the predominant mode of ground-water movement from the disturbed zone to the water table (Section 3.9.4). Although local regions of fracture flow may exist along significant fractions of any flow path, continuous fracture flow probably does not occur along the entire distance of any given flow path from the disturbed zone to the water table.

2. Continuous flow through fractures or faults. In this mode, the flow rate is relatively rapid because flow along one or more entire paths is constrained to the relatively large but sparse openings constituting a fracture network. Continuous fracture flow from the disturbed zone to the accessible environment may be caused by various sequences of events and may occur in only one general location or be distributed throughout the site. This flow may be caused by episodic or continual lateral diversion of water toward a fault; by an average, sustained percolation rate higher than the values of matrix saturated conductivity; by periodic, high intensity infiltration events at the surface; or by other means (Section 3.9.4). The conditions necessary to induce and sustain fracture flow, if such conditions exist at the Yucca Mountain site, are addressed by the geohydrology program, Sections 8.3.1.2.2 and 8.3.1.2.3. Continuous fracture flow beneath the potential repository is not considered likely at Yucca Mountain (Montazer and Wilson, 1984; Peters et al., 1986; Sinnock et al., 1984a, 1986; Wang and Narasimhan, 1986). However, because implications of such flow include short travel times, this mode of flow will be considered in resolution of this issue.

The strategy for determining ground-water travel times is to account for the current uncertainty about flow mechanisms that may occur at the site, as well as uncertainty about the spatial distribution of rock characteristics along flow paths and about boundary conditions. Therefore, site data are needed to reduce the current uncertainty about whether the likely ground-water flow paths include continuous fracture flow. Flow in both the matrix and fractures in the unsaturated zone will be considered on a probabilistic basis, unless site data unambiguously support a position that continuous fracture flow is not likely enough for serious consideration.

In the saturated zone also, the general pathway for water movement probably includes travel through alternating matrix blocks and fractures. For purposes of conservatively evaluating ground-water travel time, the saturated zone will probably be treated solely as an equivalent porous medium where fracture properties characterize the medium.

Approach to resolving the issue

The general approach to resolving this issue, and others, is discussed in Section 8.2.2. Specifically, the strategy for resolving this issue entails the definition, characterization, and assessment of multiple

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barriers to ground-water flow. By dividing potential flow paths and flow processes into discrete categories, the DOE conceptually can establish multiple, quasi-independent natural barriers to which goals for ground-water travel time can be assigned. For resolving Issue 1.6, the multiple natural barriers are considered to be distinct hydrogeologic units that occur along potential flow paths. For purposes of developing the strategy for resolving Issue 1.6, the distinct hydrogeologic units are defined using thermal and mechanical characteristics. If the listing shows these units to be insufficient for describing hydrogeologic flow paths, the stratigraphy will be revised accordingly. This approach to resolving Issue 1.6 is valid regardless of the stratigraphy that is used to define the distinct hydrogeologic units. Within each unit different types of general flow processes may be distinguished, including advective flow in rock pores, similar flow in fractures, and diffusion between and within the matrix and fractures.

The strategy is based on current understanding of flow behavior in each of the hydrogeologic units and current assessments of the relative contribution of each process in each unit to flow velocities. The strategy will identify any significant discrete pathways for likely radionuclide travel and investigate the flow behavior in these pathways. Separate goals of 1,000 yr of travel time, with varying degrees of confidence, are assigned to the several hydrogeologic units under flow conditions dominated by the several processes. If any combination of a single unit and set of processes can be shown to meet the goal of 1,000 yr, the issue could be considered resolved. However, all units will be characterized and evaluated. If several units and associated processes meet their goals, confidence is significantly enhanced that the repository site, considered in the whole, will meet the 1,000-yr requirement. This defense-in-depth approach is designed to provide reasonable assurance that the site will comply with the NRC performance objective, even given the uncertainty about flow mechanisms and flow path characteristics that will remain after site characterization.

Specifically, resolution of Issue 1.6 requires several steps as shown schematically in Figure 8.3.5.12-3. The process for resolution (the centerline in Figure 8.3.5.12-3) is designed to account for both conceptual and parameter uncertainties (left and right lines, respectively, Figure 8.3.5.12-3). The first general step is performance allocation where relevant characterization needs are established through a five-part process:

1. Identifying all hydrogeologic units along potential flow paths to the accessible environment and identifying all potentially operating processes within each of these units.

2. Classifying hydrogeologic units and flow processes as primary, secondary, and auxiliary "barriers" to establish a defense-in-depth basis for reasonable assurance that flow time to the accessible environment is at least 1,000 yr.

3. Establishing measures of performance (i.e., travel time) that allow comparisons of the flow behavior in each unit to the 1,000-yr flow time requirement.

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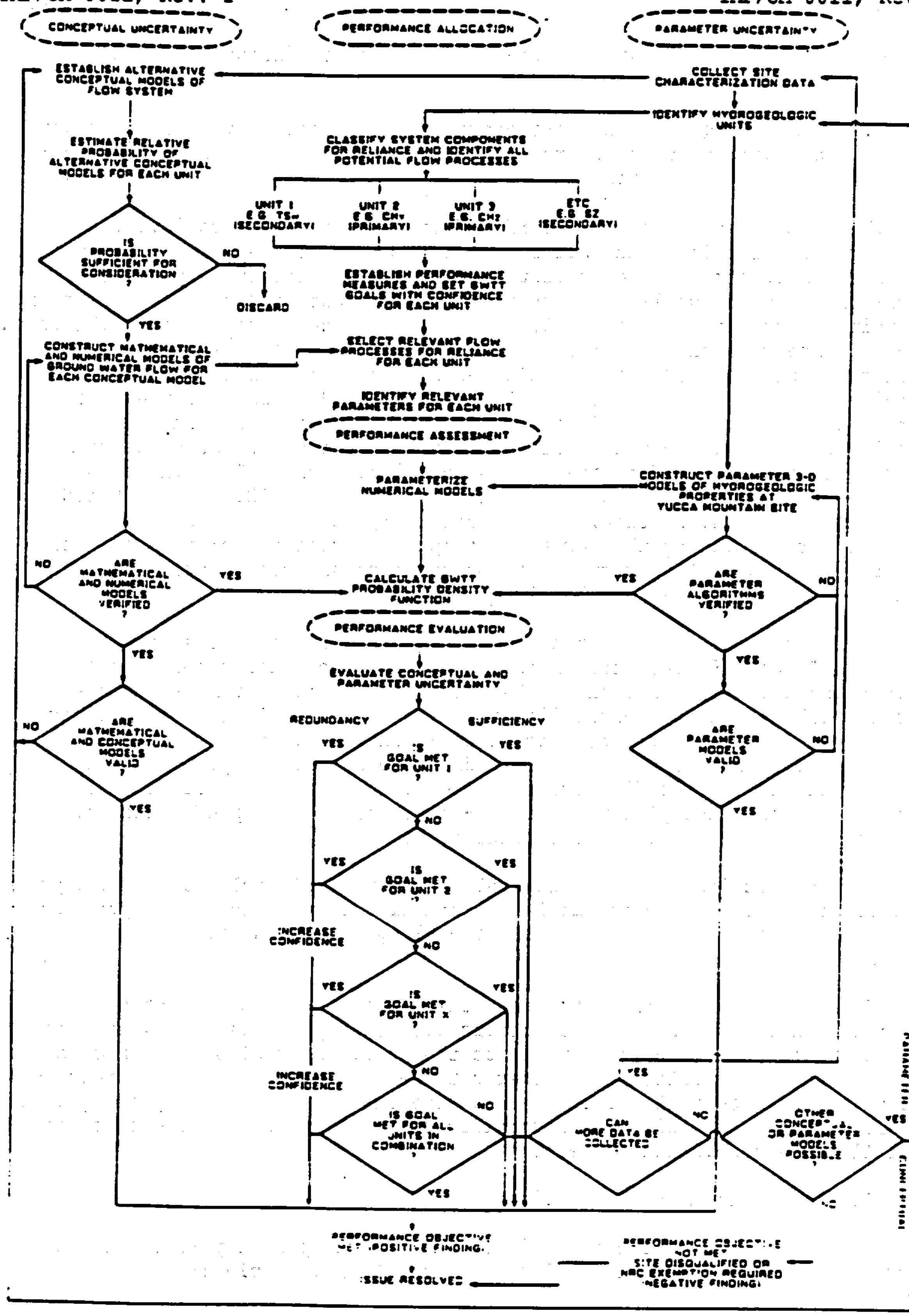

Figure 8.3.5.12-3. Schematic logic for resolution of Issue 1.6 (current alternative models of flow system acknowledge matrix and fracture dominated flow in unsaturated zone, seepage velocity, dispersion and diffusion) (Note: TSw = Topopah Spring welded unit; CHnv = Calico Hills nonwelded vitric unit; CHnz=Calico Hills nonwelded zeolitic unit; SZ=saturated zone; GWTT=ground-water travel time.)

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4. Assigning goals and associated levels of confidence for each performance measure.

5. Identifying relevant parameters and associated levels of confidence that will be used to predict the travel time and associated uncertainty through each unit.

The second general step is performance assessment, which involves defining, constructing, and applying models to make travel-time predictions. The final step, performance evaluation, entails comparison of predicted travel times to the goals for each unit, then comparing the travel times in all units in combination to the 1,000-yr requirement to assess the likelihood of compliance with the 1,000-yr travel-time performance objective. This final step includes some, as yet ill-defined, process for assessing the validity of the predictive models (Section 8.3.5.19). Each of the parts of performance allocation, the first general step, is discussed in the immediately following pages. Current plans for the second step, performance assessment, are outlined in the succeeding discussion of Information Needs 1.6.2 through 1.6.4 (Sections 8.3.5.12.2 through 8.3.5.12.4). The third step, performance evaluation, is not explicitly addressed because the criteria for evaluating the degree of compliance with performance objectives are not yet known. A summary of the performance allocation process for this issue is provided in Table 8.3.5.12-1.

Both technical and institutional uncertainties affect the approach to resolving Issue 1.6 presented in this section. Technical uncertainties surrounding the determination of the ground-water travel time along the fastest path of likely radionuclide travel arise from (1) the uncertainty about the validity of current conceptual models of hydrologic flow and (2) the uncertainty about the spatial distribution of the parameters that describe the hydrologic flow system. Reducing technical uncertainties associated with pre-emplacement ground-water travel time predictions is the goal of the site characterization activities.

The institutional uncertainty relates to the difficulty in defining the concept of "fastest path of likely radionuclide travel" and the approach to determining the ground-water travel time along that path for licensing purposes.

If an approved approach to evaluation of the pre-emplacement ground-water travel times evolves that differs from that presented below evolves, the site data collected in response to the preliminary plan described in this section should be sufficiently generic to be applicable. Periodic reevaluation of the potential for changes in site data needs caused by changes in regulatory interpretations is recognized to be an important aspect of the overall issue resolution process.

Step 1. Flow system identification

The components of the natural setting that compose a portion of the Yucca Mountain geologic disposal system are shown in Table 3-17

Table 8.3.5.12-1. Summary of performance allocation for Issue 1.6 (ground-water travel time) (page 1 of 2)

Hydrogeologic components available[a]	Allocation of reliance[b]	Process[c]	Performance measure	Performance goal (yr)	Needed confidence[d]	Performance parameters
TSw	Secondary	Darcian flow	GWTT[e]	1,000 10,000	Low Very low	See Table 8.3.5.12-2
CHnv	Primary	Darcian flow	GWTT	1,000 10,000	High Low	See Table 8.3.5.12-2
CHnz	Primary	Darcian flow	GWTT	1,000 10,000	High Low	See Table 8.3.5.12-2
PPw	Auxiliary	Darcian flow	GWTT	1,000 10,000	Medium Very low	See Table 8.3.5.12-2
PPn	Auxiliary	Darcian flow	GWTT	1,000 10,000	Medium Low	See Table 8.3.5.12-2
BFw	Auxiliary	Darcian flow	GWTT	1,000 10,000	Medium Very low	See Table 8.3.5.12-2
BFn	Auxiliary	Darcian flow	GWTT	1,000 10,000	Medium Very low	See Table 8.3.5.12-2
SZ	Secondary	Darcian flow	GWTT	1,000 10,000	Low Very Low	See Table 8.3.5.12-2

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Table 8.3.5.12-1. Summary of performance allocation for Issue 1.6 (ground-water travel time) (page 2 of 2)

Hydrogeologic components available[a]	Allocation of reliance[b]	Process[c]	Performance measure	Performance goal (yr)	Needed confidence[d]	Performance parameters
Combination of all units		Darcian flow	GWTT	1,000 10,000	High High	

[a]TSw = Topopah Spring welded; CHnv = Calico Hills nonwelded vitric; CHnz = Calico Hills nonwelded zeolitized; PPn = Prow Pass nonwelded; BFw = Bullfrog welded; BFn = Bullfrog nonwelded; SZ = saturated zone.

[b]If a significant thickness of the unit occurs along the fastest path of likely radionuclide travel.

[c]Darcian flow (advection) with dispersion will be relied upon for matrix dominated flow; Darcian flow with both dispersion and diffusion will be relied upon if substantial continuous fracture flow is identified during characterization.

[d]High, at least two standard deviations below the mean; medium, at least one standard deviation below the mean; low, less than the mean; very low, less than one standard deviation above the mean (see Step 4, performance goals). Goals and confidence levels were established to guide site studies for the hydrology of the entire site to support resolution of Issues 1.1 and 1.6.

[e]GWTT = ground-water travel time along the fastest path of likely radionuclide travel.

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(Section 3.9). These components are defined as hydrogeologic units (system components) that occur along potential ground-water travel paths between the disturbed zone and the accessible environment. There are seven units in the unsaturated zone: (1) Topopah Spring welded unit (TSw), (2) Calico Hills nonwelded vitric unit (CHnv), (3) Calico Hills nonwelded zeolitic unit (CHnz), (4) Prow Pass welded unit (PPw), (5) Prow Pass nonwelded unit (PPn), (6) Bullfrog welded unit (BFw), and (7) Bullfrog nonwelded unit (BFn). The saturated zone (SZ) in its entirety is defined as a separate, eighth unit. As site characterization progresses, it may be determined that the hydrologic units need to be subdivided to characterize more adequately the ground-water flow paths to the accessible environment.

Each of these hydrogeologic units can be subdivided into two types of physical elements that may be considered to define distinct pathways: matrix pores and fractures. Fractures, in turn, are considered to exist as two types: (1) distributed networks and (2) fault zones. This classification, though unit specific, is designed to account for thoroughgoing fracture pathways, distributed throughout the rock mass or along fault zones, that may extend uninterrupted from the disturbed zone to the water table and along the saturated pathways to the accessible environment.

The spatial locations of flow paths from the disturbed zone to the accessible environment are generally through the unsaturated zone to the water table and along a 5-km distance in an approximately down-gradient direction along the upper part of the saturated zone. Although a definition of the boundaries of the disturbed zone is not yet firm (Information Need 1.6.5, Section 8.3.5.12.5), this discussion uses a distance of 50 m below the midplane of the repository as the boundary. The hydrogeologic units that may be relied upon depend to a certain extent on where this boundary lies; however, the ability of the site to meet the 1,000-yr ground-water travel-time criterion probably is not affected much by moderate departures from this definition. The thickness of each unsaturated hydrogeologic unit between the assumed boundary of the disturbed zone and water table is shown in Figure 8.3.5.12-4.

Each of the two physical elements (fractures and matrix) of each hydrogeologic unit is considered a potential pathway for water flow. Several processes may be used to describe flow along each pathway. Darcian flow with dispersion in fractured porous media is the process that will be used as a baseline case to describe water movement through the unsaturated and saturated hydrogeologic units. Dispersion is a mixing and spreading process that should be considered to account for the times of first arrivals in a travel-time distribution. Dispersion is believed to be caused by small- to large-scale heterogeneities along a flow path. The dispersive effects of medium- to large-scale heterogeneities will be addressed by accounting for macroscopic property variations along flow paths, and small scale effects may be addressed, if they are shown to accelerate significantly first arrivals, by assigning a dispersivity factor to each unit.

If diffusion of inert tracers between matrix pores and fracture openings is relied upon, the characteristics and limitations of the diffusive process

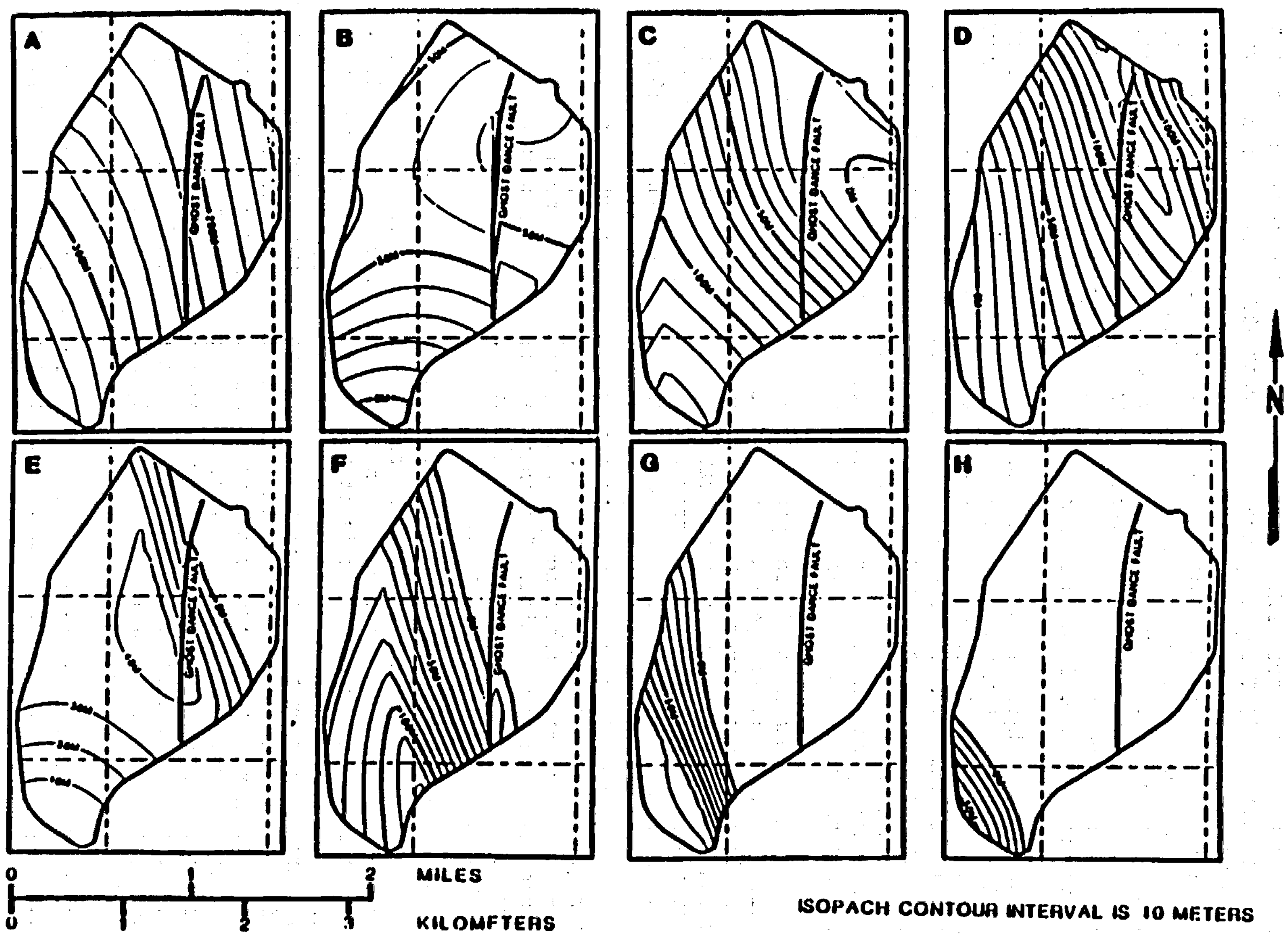

Figure 8.3.5.12-4. Isopach contour maps of hydrogeologic units used for performance allocation: (A) total thickness from disturbed zone to the water table; (B) thickness of undisturbed Topopah Spring welded unit, TSw; (C) thickness of the Calico Hills nonwelded vitric unit, CHnv; (D) thickness of the Calico Hills nonwelded zeolitic unit, CHnz; (E) thickness of the Prow Pass welded unit, PPw; (F) thickness of the Prow Pass nonwelded unit, PPn, (G) ickness of the Bullfrog welded unit, BFw; and (H) thickness of the 'rog nonwelded unit, BFn. Modified from Sinnock et al. (1986).

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must be adequately characterized. Because radionuclide travel may occur by particles larger than inert tracers (such as colloids), characterization of colloid formation and behavior is also planned. The diffusive characteristics of radionuclides and colloids will be investigated under the geochemistry program (Section 8.3.1.3). Section 8.3.5.13 (Issue 1.1) provides more discussion on the transfer of particles between the matrix and the fractures by a diffusive process.

Step 2. Selection by hydrogeologic units and flow process

If the current conceptual model for the unsaturated zone is valid, each of the hydrogeologic units listed previously is a barrier that, in and of itself, is likely to have travel times of at least 1,000 yr along some path of likely radionuclide travel (Figure 8.3.5.12-5, top). Current analyses (Sinnock et al., 1986) indicate that the fastest path of likely radionuclide travel from the disturbed zone to the water table will probably occur beneath the east-northeast region of the proposed repository (Figure 8.3.5.12-5, bottom). Only two unsaturated units occur in this area; the Topopah Spring welded and Calico Hills zeolitic units (Figure 8.3.5.12-6). All potential paths of liquid water flow from the disturbed zone to the accessible environment include segments of flow in the saturated and unsaturated zones. Accordingly, a level of performance has been allocated to the Topopah Spring welded, Calico Hills nonwelded zeolitic, and saturated-zone hydrogeologic units (Table 8.3.5.12-1).

Sinnock et al. (1986) assumed one-dimensional steady-state, vertical flow through matrix and fractures of the unsaturated zone and concluded that the Calico Hills nonwelded zeolitic unit has travel times along the fastest paths much greater than 1,000 yr. Based on these analyses, this unit is allocated a high level of performance and is referred to as a primary barrier. The Topopah Spring welded unit and the saturated zone are considered secondary barriers, and are allocated lower levels of performance. The Calico Hills vitric unit, where present, is also thought to provide relatively long travel times, comparable to or greater than those in a similar thickness of the zeolitic facies of the Calico Hills tuffs, though this unit probably is very thin or absent below the northeast portion of the current facility design where the fastest flow paths to the water table are likely to occur.

Because of uncertainty regarding how to determine the fastest path of radionuclide travel, flow from the entire disturbed zone boundary over the entire site will be included in the distribution of travel times from which the fastest path will be identified. For the entire site, the vitric portion of the Calico Hills unit would also serve as a primary barrier, as indicated in Table 8.3.5.12-1. The Calico Hills vitric unit has a higher saturated hydraulic conductivity than the Calico Hills zeolitic unit and is therefore more likely to have drained to lower saturation and higher suction, particularly in view of its greater distance above the water table. Therefore, matrix-dominated flow can be assumed with more confidence in the vitric unit than in the more nearly saturated zeolitic unit. If the regulatory basis for defining the fastest path is, as expected, restricted to geographical regions of least flow time, it might be prudent to modify the

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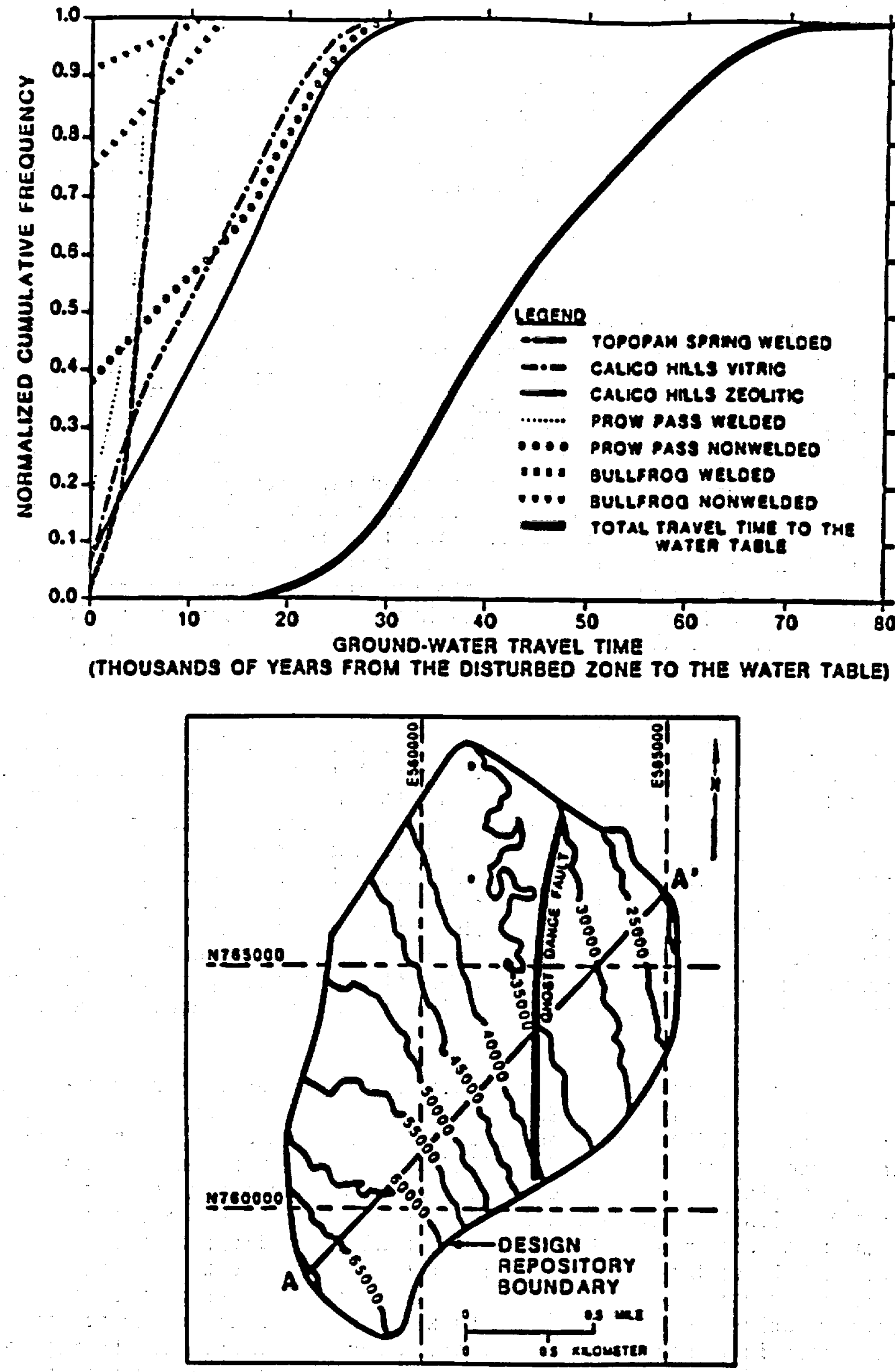

Figure 8.3.5.12-5. Travel-time plots: Top - cumulative frequency plots of current travel-time estimates through each hydrogeologic unit and through the total thickness of the undistrubed unsaturated zone: Bottom - isochron maps of mean total travel times in years. Cross-section A A is shown in Figure 8.3.5.12-6. Modified from Sinnock et al. (1986).

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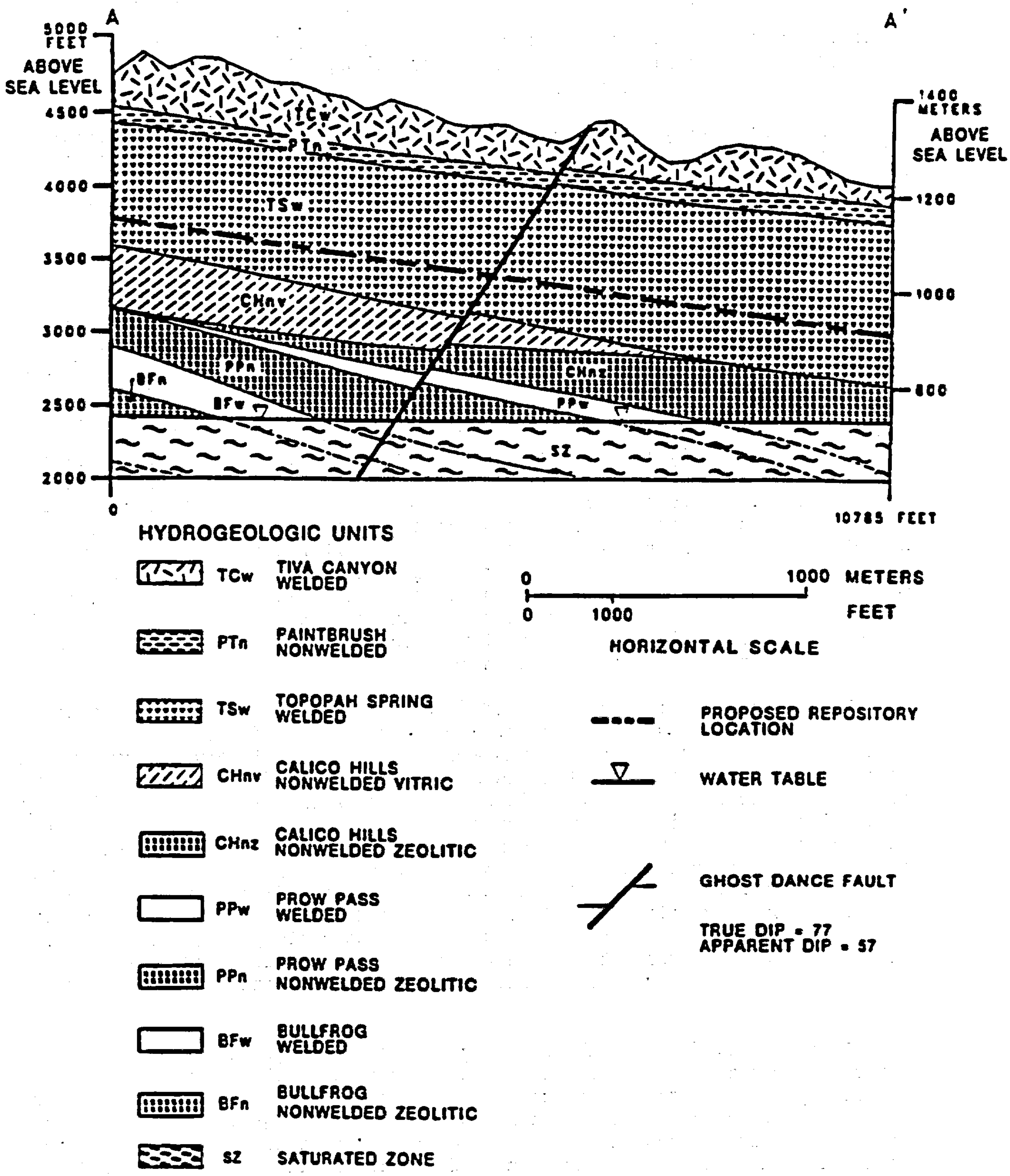

Figure 8.3.5.12-6. Cross section at Yucca Mountain showing pinch-outs of unsaturated hydrogeologic units. Location of section line shown in Figure 8.3.5.12-5. (2 times vertical exaggeration)

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proposed location of the repository to ensure that at least a minimal thickness of vitric Calico Hills tuff occurs along all flow paths from the disturbed zone to the water table.

Other units (e.g., BFw) will also contribute to a longer ground-water travel time; however, the different, sometimes zero, thicknesses of these units (Figure 8.3.5.12-4) for different flow paths requires that their role in resolving the issue be considered somewhat differently. For the purpose of this allocation, these units are termed auxiliary. This allocation strategy may change as additional data and understanding are obtained.

Flow through the unsaturated units of Yucca Mountain includes the possibility of localized sustained flow in fractures (Montazer and Wilson, 1984). Under the current conceptual model, if substantial, continuous fracture flow exists at the site, it probably will not occur throughout broad regions. Sustained flow in fractures is most likely to occur only along a major geologic structural feature such as the Ghost Dance fault or faults bounding the site to the east. This may occur if a sufficient flux of water is diverted laterally to the structural features where the water could then drain quickly through fractures along the fault to the water table (Rulon et al., 1986). Temporary or steady-state ponding of perched water near the structural features is presently considered possible within and above the nonwelded units. Therefore, if water moves as continuous flow in fractures to the water table, it probably occurs in down-dip areas along the eastern portion of the site, where the Calico Hills vitric unit is thin or absent and the zeolitic unit is nearly saturated. Portions of the previously discussed pathways, particularly those at shallow depths, may experience fracture flow following episodic, high infiltration events.

Under the present conceptual model, liquid flow in the unsaturated zone is predominately downward. However, lateral diversion of water at some unit contacts is possible. If such paths are established as likely during site characterization, they would then be used as the basis for determining travel time. There is a credible possibility that, below the repository level, very little liquid water is moving in any direction (e.g., if flux $<< 0.5$ mm/yr) and that a nearly static condition prevails (Roseboom, 1983). A significant possibility also exists that, in terms of quantities of water, downward flux of liquid water is less than the upward flux of vapor (Montazer and Wilson, 1984). These possibilities will be investigated during further development of the hydrologic model, as described in the geohydrology program. In lieu of more definitive information, the assumption of net, downward movement of liquid flux probably is a conservative basis for calculating ground-water travel times.

An auxiliary facet of the strategy for assessing ground-water travel times involves the estimation of ground-water ages at different points along the flow paths. Geochronology using carbon, chlorine, and hydrogen isotopes in the ground water can provide a basis for estimating ground-water residence times. Results of such studies are generally subject to significant uncertainty regarding the identification of flow paths, mixing of waters of different ages, etc. However, data on residence times (ages) of water along the potential pathways are expected to be very useful for helping to interpret

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ground-water travel times calculated with numerical models. Standard hydrochemical data may also be used to help determine whether computed travel times are consistent with the isotopically determined ages (Section 8.3.1.2.2).

Step 3. Performance measure

The probability or frequency distribution of calculated ground-water travel times is the performance measure for each hydrogeologic unit. Ground-water travel time is an obvious choice because of its direct relationship to 10 CFR Part 60.113(a)(2) and because time is a fundamental quantity. The measure of performance for each hydrogeologic unit will be expressed as a cumulative distribution curve.

Uncertainties associated with parameter values will be addressed by randomly sampling the properties from an empirical probability distribution function that describes natural variability within each hydrogeologic unit, as well as uncertainty associated with that variability. The effects of diffusion (between the fractures and the matrix) will be considered. Finally, the uncertainty in the travel time caused by alternative conceptual models will be incorporated in the cumulative distribution curves, perhaps by subjective weighting of the alternatives based on peer review.

The cumulative distribution curve of travel times for each hydrogeologic unit is intended to encompass all relevant sources of uncertainty. This implies neither that all uncertainty will be objectively quantified nor that the cumulative distribution curve will be a measure of the true travel-time distribution. Rather, the curves will represent the uncertainty associated with parameter measurements as well as the uncertainty associated with many professional judgments about the likely effects of the various sources of parameter and conceptual uncertainty on flow mechanisms. Thus, in combination, the cumulative distribution curves will provide a performance measure that allows informed judgments about the likely range and uncertainty in the travel time from the disturbed zone to the accessible environment.

Step 4. Performance goals

The overall performance goal desired for the ground-water travel-time measure for the combination of all hydrogeologic units between the disturbed zone and the accessible environment is 1,000 yr at a high level of confidence (Table 8.3.5.12-1). This goal has been established to guide studies that support the resolution of Issue 1.6 and is considered to be extremely conservative. To achieve the desired confidence in the total site, performance goals of 1,000 yr are set for several individual hydrogeologic units to establish multiple barriers and implement a strategy of defense-in-depth (Table 8.3.5.12-1). Figure 8.3.5.12-7 shows examples of a histogram and an associated cumulative distribution curve for the overall performance measure of ground-water travel time from the disturbed zone through all the units that make up the unsaturated zone. These examples from Sinnock et al., (1986) are based on the net effects of matrix flow, with no diffusion.

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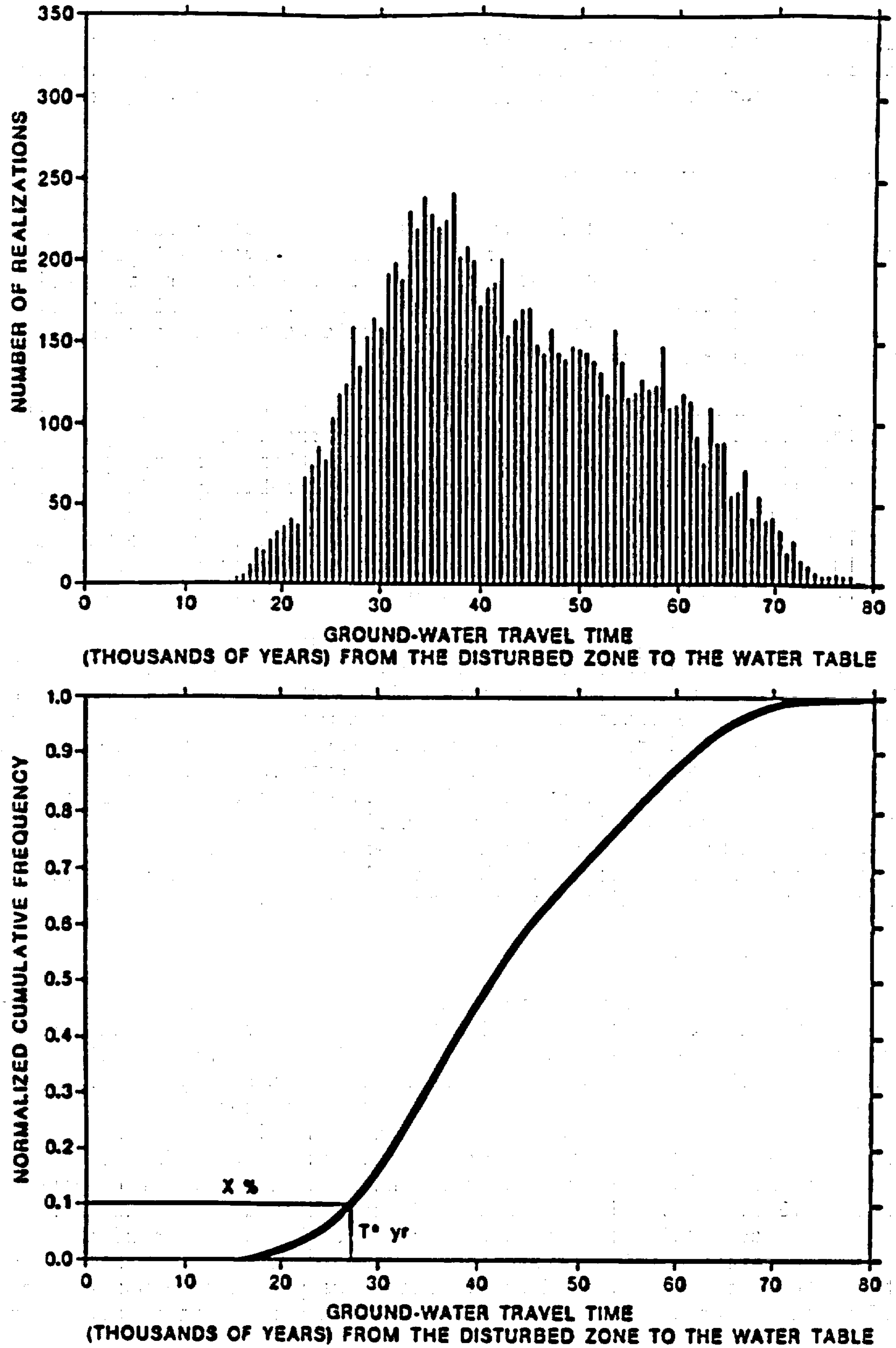

Figure 8.3.5.12-7. Examples of ground-water travel-time distributions: top—histogram; bottom—cumulative distribution function showing x percentile of flow having travel times less than some specified value, T*. Modified from Sinnock et al. (1986).

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Performance goals of 1,000 yr are set to establish a direct basis for assessing compliance with the performance objective. Goals for 10,000 yr are included to provide a second point on the cumulative distribution curve, thereby lending a degree of assurance that minor shifts in the whole curve (e.g., due to conceptual or parameter uncertainties) will not lead to significant differences in the likelihood of travel times less than 1,000 yr. Also, 10,000 yr goals, if met, provide a basis for a defense-in-depth strategy for resolving Issue 1.1, which addresses releases of radionuclides over a 10,000-yr period. The confidence goals set for each unit for both 1,000-yr and 10,000-yr travel times are based on results of preliminary evaluations by Sinnock et al. (1986), exemplified in Figures 8.3.5.12-5 and 8.3.5.12-7.

The confidences indicated for the two travel-time goals for each individual unit range from very low to very high (Table 8.3.5.12-1). Five levels of confidence are assigned; very high, high, medium, low, and very low. Very high indicates that the goal lies at least three standard deviations below the mean of the ground-water travel time distribution; high indicates that the goal lies at least two standard deviations below the mean; medium, at least one standard deviation below the mean; low, less than the mean; and very low, less than one standard deviation above the mean. The differences in assigned confidences depend on such factors as saturation in each unit, frequency and apertures of fractures, thickness of each unit, and percentage of the repository area underlain by each unit. Confidence for the required travel time to the accessible environment would be high if the goal is met for various individual units, or (because of the redundancy among individual units) very high if goals are met for several of the various individual units.

The confidence desired for travel time through both Calico Hills units, CHnv and CHnz, is highest of all units, consistent with their designation as primary barriers. A confidence level of low was set for the TSw unit because only a short path length may exist below some portions of the disturbed zone and because of the greater likelihood of fracture flow through significant portions of this densely fractured and welded unit than through the CHn units. Confidence levels for the auxiliary Prow Pass and Bullfrog units (PPw, PPn, BFw, and BFn) are lower because they occur only beneath part of the repository area (Figures 8.3.5.12-4 and 8.3.5.12-6). The goal for the saturated zone, a secondary barrier, is assigned relatively low confidence based on current, conservative estimates of saturated zone flow times (DOE, 1986b).

Comparisons of calculated ground-water travel-time distributions (Figure 8.3.5.12-5) with the performance goals (Table 8.3.5.12-1) provide the basis for determining if each hydrogeologic unit meets its goal. This performance evaluation will be done after more data are available and new curves are calculated by determining from the cumulative distribution curves the likelihood that travel time is greater than the performance goal (e.g., 1,000 yr).

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Step 5. Parameter needs

The parameters required to satisfy this issue are those that can establish a basis for reasonable assurance that the performance goals are met. This assurance can be achieved, in large part, if it can be demonstrated that water flows predominantly through the matrix rather than the fractures. This would occur if the water flows through a sufficient volume of matrix pores for at least some minimal portion of each unit to which a goal has been assigned. For each unit, the sufficient volume of pore space may be expressed as effective porosity, n_e. The minimum portion of each unit may be expressed for a given flux, q, as distance, d, along a flow path (generally equivalent to thickness of units in the unsaturated zone, assuming vertical flow). The condition of flow through the matrix may be expressed by a ratio of percolation flux to the saturated hydraulic conductivity of the matrix, q/K_s. If this ratio is less than some threshold value, generally taken to be somewhat less than one, a potential (expressed as suction pressure) for additional moisture retention will exist in the matrix materials and the entire flow volume will tend to move through the matrix. This, in effect, means that if flux exceeds matrix saturated conductivity, fracture flow is expected to occur. However, where flux is less than the conductivity, the resulting potential will tend to draw water from adjacent fractures into the matrix pores until pressure equilibrium is established between the matrix and fractures. The water that remains in fractures at this equilibrium pressure will occur in apertures generally equal in diameter to the largest saturated matrix pores or cling to asperities equal in radius to even larger unsaturated matrix pores holding water in menisci. Because an air-gap constrictivity generally occurs along fractures with apertures larger than the radius of partially saturated matrix pores (Wang and Narisimhan, 1985; Montazer, 1982), flow along fractures under suction pressures tends not to occur and flow across fractures may be considered an extension of matrix flow. As the ratio q/K_s decreases, the potential for moisture absorption by the matrix increases, assuming the matrix pores can drain (i.e., assuming they are not bounded downstream by a region where flux exceeds conductivity).

Because local heterogeneities in saturated conductivity can result in a chaotic distribution of regions where some have q/K_s values less than one and others have q/K_s values greater than one, particularly where flux is about equal to the mean of the probability distribution of conductivity, transitions may occur from fracture to matrix flow along any given path. Therefore, a sufficient portion of every flow path in each unit is sought where q/K_s is less than one in freely drained conditions. Given satisfaction of this inequality, seepage velocity can be assumed to equal the flux divided by the effective porosity of matrix materials, and travel time to equal the flow path distance divided by the seepage velocity. By allocating a required travel time (or times) to each unit, a combination of desired flux, effective porosity, and flow distance can be specified that cause the travel-time goal to be met. Further, if current conservatively estimated values for effective porosity and flux are defined as the desired conditions, then a minimum desired thickness of matrix flow can be defined for each unit. This process of quantifying desired parameter values was followed to define the values shown in the performance parameter goal column of Table 8.3.5.12-2, completing the performance allocation process for Issue 1.6.

Table 8.3.5.12-2. Performance parameters for resolving Issue 1.6 (page 1 of 2)

Hydrogeologic unit[a]	Performance parameter[b]	Current estimated range[c]	Performance parameter goal[d,e]	Current confidence	Desired confidence
TSw	q	<0.5 mm/yr	<0.5 mm/yr	Low	Low
	q/K_s	0.005 to 50	<0.85	Low	Low
	n_e	0.01 to 0.2	>0.05	Low	Low
	d	0 to 60 m	>10 m (100%)	Medium	Low
CHnv	q	< 0.5 mm/yr	<0.5 mm/yr	Low	High
	q/K_s	0.00005 to 5	<0.95	Medium	High
	n_e	0.15 to 0.45	>0.2	Medium	High
	d	0 to 160 m	>2.5 m (100%)	Low[f]	High
			>25 m (80%)	Low[f]	Medium
CHnz	q	<0.5 mm/yr	<0.5 mm/yr	Medium	High
	q/K_s	0.005 to 50	<0.9	Medium	High
	n_e	0.2 to 0.4	>0.2	Medium	High
	d	0 to 140 m	>2.5 m (100%)	Low[f]	High
			>25 m (80%)	Low[f]	Medium
PPw	q	<0.5 mm/yr	<0.5 mm/yr	Low	Medium
	q/K_s	0.0005 to 0.5	<0.85	Low	Medium
	n_e	0.015 to 0.35	>0.1	Low	Medium
	d	0 to 40 m	>5 m (80%)	Medium	Medium
PPn	q	< 0.5 mm/yr	<0.5 mm/yr	Low	Medium
	q/K_s	0.005 to 0.5	<0.95	Low	Medium
	n_e	0.1 to 0.45	>0.2	Low	Medium
	d	0 to 140 m	>2.5 m (50%)	Low	Medium
BFw	q	<0.5 mm/yr	<0.5 mm/yr	Low	Medium
	q/K_s	0.0005 to 0.05	<0.85	Low	Medium
	n_e	0.05 to 0.4	>0.1	Low	Medium
	d	0 to 70 m	>5 m (20%)	Low	Medium

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Table 8.3.5.12-2. Performance parameters for resolving Issue 1.6 (page 2 of 2)

Hydrogeologic unit[a]	Performance parameter[b]	Current estimated range[c]	Performance parameter goal[d,e]	Current confidence	Desired confidence
BFn	q	<0.5 mm/yr	<0.5 mm/yr	Low	Medium
	q/K_s	0.0005 to 0.5	<0.95	Low	Medium
	n_e	0.1 to 0.4	>0.2	Low	Medium
	d	0 to 50 m	>2.5 m (10%)	Low	Medium
SZ	dh/dl	0.005	<0.001	Low	Low
	K_s	0.1 to 1000 m/yr	<10 m/yr	Low	Low
	n_e	0.0001 to 0.01	>0.01	Low	Low
	d	0 to 5000 m	1000 m	Low	Medium

[a]TSw = Topopah Spring welded unit; CHnv = Calico Hills nonwelded vitric unit; CHnz = Calico Hills nonwelded zeolitized unit; PPw = Prow Pass welded unit; PPn = Prow Pass nonwelded unit; BFw = Bullfrog welded unit; BFn = Bullfrog nonwelded unit; SZ = saturated zone.

[b]q = flux; K_s = hydraulic conductivity of saturated matrix pores; n_e = effective porosity; d = distance along flow paths.

[c]Based on Section 3.9, Figure 8.3.5.12-4., and Sinnock et al. (1986).

[d]Parenthetical values for d indicate the desired percentage of the repository area underlain by the indicated thickness.

[e]A thickness of greater than 10 m for 100 percent of the area below the repository is based on a disturbed zone thickness less than 50 m.

[f]Low current confidence in meeting the goal is based on a moderate to high confidence that the goal will not be met because of the absence of the units below portions of the current repository area (see Figure 8.3.5.12-4); additional site data are unlikely to increase current confidence, relocation of the repository facilities is probably required to achieve the desired confidence, therefore achievement of these goals must be considered in the context of trade offs with goals for design issues (Sections 8.3.2.2 and 8.3.2.5) relating to facility siting.

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The values set as goals for the performance parameters, if realized, would establish a bounding basis for concluding with reasonable confidence that travel time in each unit would exceed 1,000 yr. However, knowing these goals were met would not be sufficient to calculate a cumulative distribution of travel time, especially if portions of some paths include fracture flow or if travel time, as expected, is influenced by variability of the parameters within ranges that are only bounded by the goals. Therefore, a set of supporting performance parameters based on the elements of the general flow equations is identified in the next section, which describes Information Need 1.6.1. (Section 8.3.5.12.1). For these supporting parameters, no quantitative goals are set; rather, goals are defined in terms of relative confidence desired in the properties of the probability distributions of the parameters. As a result, the total parameter needs for resolving this issue are separated into two categories: those identified here (Table 8.3.5.12-1) for establishing bounds on the travel time for comparison to goals, and those identified in the following section (Section 8.3.5.12.1) for developing a probabilistic performance measure expressed as a cumulative distribution function of travel time.

Interrelationships of information needs

The question raised by Issue 1.6 addresses whether the regulation for ground-water travel time, 10 CFR 60.113(a)(2), can be satisfied at the Yucca Mountain site. There are several distinct parts to the issue that must be resolved to answer the question. The distinct parts, expressed as questions, are as follows:

1. What site information, design concepts, and auxiliary information are needed to (a) identify the fastest path of likely radionuclide travel from the disturbed zone to the accessible environment, and (b) determine the pre-waste-emplacement ground-water travel time along this path?

2. What calculational models of the hydrologic system will be used to identify the fastest flow path(s) and predict ground-water travel-time distributions along this path?

3. Based on the selected models, where is the fastest path(s) from the disturbed zone to the accessible environment, and what are the flow characteristics along this path?

4. What is the cumulative distribution of pre-waste-emplacement ground-water travel times along this path(s) based upon results of simulations using the calculational models and any other information resulting from answering the preceding questions?

5. Where are the boundaries of the disturbed zone?

Each of these questions has been designated as an information need. Questions 1, 2, 3, 4, and 5 are Information Needs 1.6.1, 1.6.2, 1.6.3, 1.6.4, and 1.6.5 (Sections 8.3.5.12.1 through 8.3.5.12.5), respectively. Information Need 1.6.1 summarizes the mathematical basis for calculating ground-water travel time and the associated set of site parameters needed to resolve this issue. Included in Information Need 1.6.1 is an indication of the

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confidence desired for each parameter. Note that the required parameters and associated confidence levels apply to statistical moments of particular properties and not just to a single value for each property. Such statistical information will allow better quantification of uncertainty for a given conceptual model than will data limited to expressions of confidence in a single, target value for a given property.

Information Need 1.6.2 (Section 8.3.5.12.2) describes the planning basis for selecting calculational models that will help identify flow paths and analyze ground-water travel times along these paths. Direct measurements of ground-water travel time for demonstration of compliance with regulatory rules are not feasible. Therefore, resolution of this issue requires calculational models that can simulate ground-water flow at the site and predict flow paths and travel times from the disturbed zone to the accessible environment. These models also enable sensitivity analyses to be performed; such analyses indicate the relative importance of different parameters to travel-time distributions (values, moments, and spatial location), so that data acquisition plans can be focused in an iterative process on parameters that allow the greatest reductions in quantifiable uncertainty about ground-water travel time. The calculational models will be used to identify likely paths of radionuclide travel (Information Need 1.6.3) and to assess pre-waste-emplacement ground-water travel time along these paths (Information Need 1.6.4). Thus, the models selected under Information Need 1.6.2 are based on mathematical concepts addressed in Information Need 1.6.1 that establish the parameters needed to predict ground-water travel time. On the other hand, the confidence desired for each parameter is established by interpreting analyses done to satisfy Information Needs 1.6.3 and 1.6.4.

Information Need 1.6.3 (Section 8.3.5.12.3) addresses a basis for determining the fastest paths of likely radionuclide travel for both matrix- and fracture-dominated modes of water movement. As site characterization proceeds, new data will be analyzed to identify the likely flow paths. Ultimate selection of flow processes and paths used for analysis of travel time may be based, in part, on data or theories that are inadequate for unambiguous estimation of a probability or likelihood of occurrence and will require the judicial use of expert judgment and peer review.

Activities under Information Need 1.6.4 (Section 8.3.5.12.4) focus on determining pre-waste-emplacement ground-water travel times along the fastest path of radionuclide travel. Sensitivity and uncertainty analyses are also performed under Information Need 1.6.4 to establish the effects of uncertainty in parameter values and conceptual approaches on the ultimate confidence that may be placed in the predictions of travel time. Results of these prelicensing studies will be used to evaluate the sufficiency of the data base on which predictions are made, thereby identifying the proper focus of further site characterization to reduce most effectively the remaining sources of uncertainty in predictions of travel time.

Information Need 1.6.5 (Section 8.3.5.12.5) establishes a planning basis for determining the boundary of the disturbed zone. The current plans are based in part on the general guidance given by the NRC (Gordon et al., 1986). Thermal, mechanical, geochemical, and hydrologic analyses will be used to define the extent of disturbances expected from repository construction and heat generated by the waste. Because Information Need 1.6.5 is fundamentally

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different from the previous information needs in this issue (in that the information required for Information Need 1.6.5 will address the postemplacement environment and will not be used directly to assess ground-water travel time), it is treated separately. Information Need 1.6.5 develops its own performance measures and goals, as well as the parameters required to assess the extent of repository-induced disturbances.

8.3.5.12.1 Information Need 1.6.1: Site information and design concepts needed to identify the fastest path of likely radionuclide travel and to calculate the ground-water travel time along that path

This information need summarizes the parameter needs required for analyses to be performed for assessing ground-water travel time. The information and data required for Information Needs 1.6.2 through 1.6.4 (Sections 8.3.5.12.2 through 8.3.5.12.4) are described here. Because defining the disturbed zone is distinct from calculating ground-water travel time, the parameters required for the disturbed-zone definition are addressed in Information Need 1.6.5 (Section 8.3.5.12.5). The parameter needs identified here apply only to pre-waste-emplacement conditions.

The specific parameters requested by Issue 1.6 are discussed later in the logic portion of this section and will provide information in the following four categories (Figure 8.3.5.12-8):

1. System geometry.
2. Material property values.
3. Initial and boundary conditions.
4. Model validation.

Information is required from each of these categories to calculate ground-water travel-time values in Information Need 1.6.4.

The specific parameters requested here (inner circle, Figure 8.3.5.12-8) rarely correspond to parameters directly measured in the field or laboratory (outer circle, Figure 8.3.5.12-8). A set of site characterization modeling activities (middle circle, Figure 8.3.5.12-8) is required to reduce the measured data to the parameters amenable for direct use in ground-water travel-time calculations. The logic that establishes how the actual measurements are used to produce the requested parameters is provided in Sections 8.3.1.2 (geohydrology) and 8.3.1.4 (rock characteristics).

Crucial information required by this issue are descriptions of the conceptual models and associated uncertainties for the unsaturated-zone and saturated-zone flow systems at the site. Though no specific parameter needs are delineated here with regard to the validation of flow models, the means by which the flow models will be developed, as well as the plans that described how the requested specific parameter values will be obtained, are described within the geohydrology program (Section 8.3.1.2) and rock characteristics program (Section 8.3.1.4).

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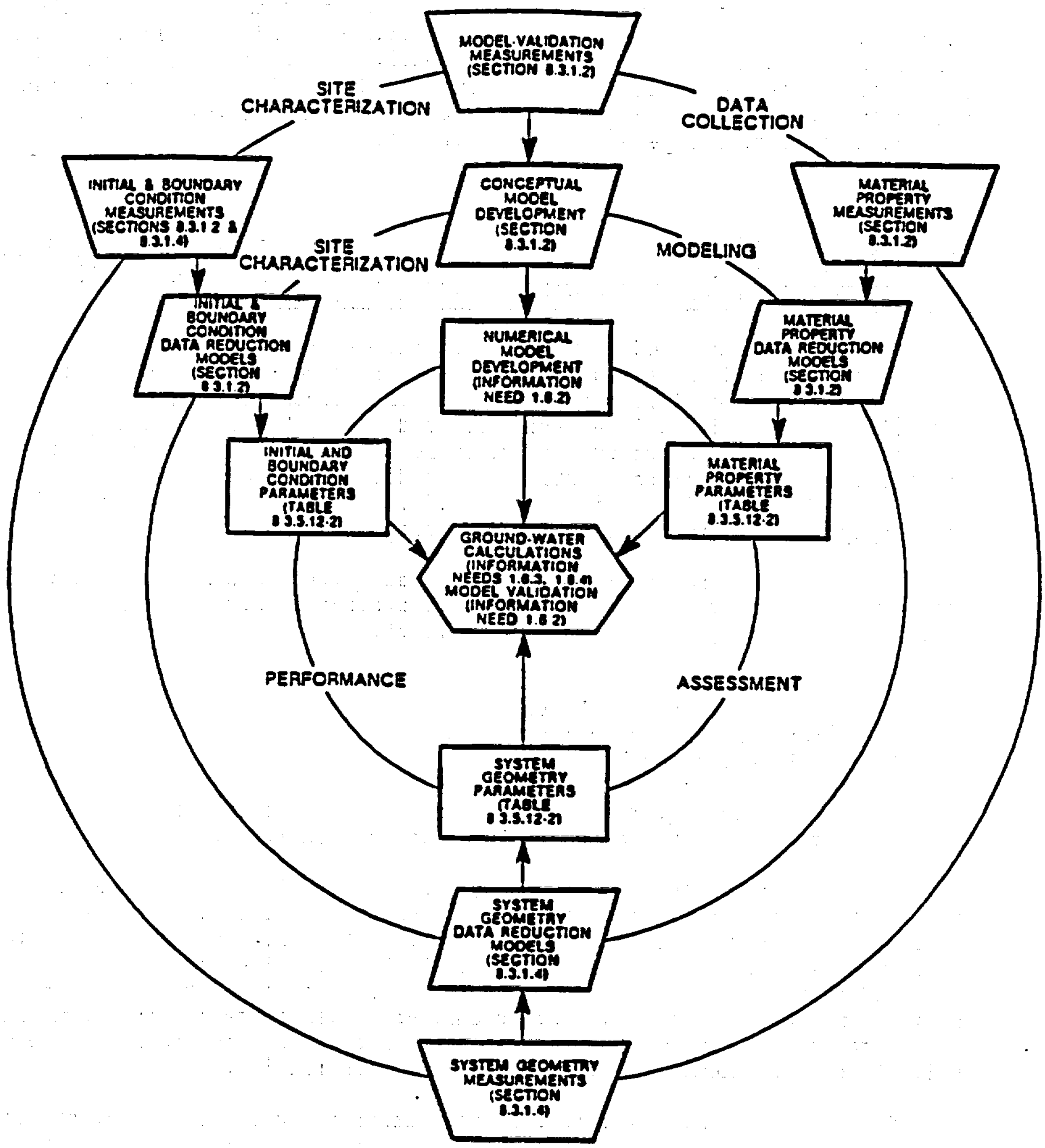

Figure 8.3.5.12-8. Schematic flow of site information on system geometry, material properties, initial and boundary conditions, and model validation through data reduction modeling (Programs 8.3.1.2 and 8.3.1.4) to definition of performance assessment parameters (Table 8.3.5.12-2) for use in ground-water travel time calculations and model validation (Information Needs 1.6.2, 1.6.3, and 1.6.4).

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Detailed plans for the validation of the conceptual and mathematical models that describe the unsaturated-zone flow systems at Yucca Mountain are currently under development. The general approach to validation of these models and the other models to be used for performance assessment is presented in Section 8.3.5.20.2 (plans for verification and validation). Section 8.3.5.12.2.2 (verification and validation) briefly describes the current status of the validation process to be used for the conceptual and mathematical models to be used in the resolution of this issue (1.6) and Issue 1.1 (total system performance).

Technical basis for addressing the information need

Link to the technical data chapters and applicable support documents

Chapter 3 summarizes the current understanding of conceptual models of ground-water flow addressed by the general equations of flow discussed here. Chapters 1 and 2 provide the current data on the geologic and rock characteristics represented by parameters in the equations. Data on the thicknesses and extents of stratigraphic units also are contained in Chapters 1 and 2. Structural information about fracture and fault characteristics is provided in Chapter 1. Data on porosity are in Chapters 2 and 3, and data on permeability, saturation, pressure, and water table elevations are in Chapter 3.

Parameters

The parameter needs established for this information need are identified in Table 8.3.5.12-3. In general these parameters will be obtained from activities discussed in Section 8.3.1.2.

Logic

Parameter requirements cannot be made without using some conceptual model(s) as the basis. The phenomena relevant to predicting ground-water travel times at the site have been indicated in the issue resolution strategy of this issue and are more fully described in Section 3.9. The general concept for flow in the saturated zone postulates Darcian flow in a saturated, equivalent porous medium. The concept for flow in the unsaturated zone postulates near steady-state Darcian flow, with the possibility of flow in both the matrix and fractures. The mathematical equations that are formulated to describe the conceptual flow models are used to determine what parameter information is required. A significant aspect of site characterization is testing the validity of these models. The models will be periodically reevaluated and modified, if necessary, in light of the results of this testing.

Ground-water models generally are based on one or more governing equations. These equations generally are based on mathematical statements for the conservation of mass and momentum.

Table 8.3.5.12-3. Supporting performance parameters used by Issue 1.6 (ground-water travel time)[a] (page 1 of 6)

Performance parameter	Material type	Spatial location	Stratigraphic unit	Statistical measures desired[b]	Needed confidence[c]	SCP Section where current estimate is discussed	Current confidence[d]
			MODEL TYPE: CALCULATION OF GROUND-WATER TRAVEL TIME IN THE UNSATURATED ZONE				
Inital and Boundary Conditions							
Flux, percolation rate	Fault zones	R-area	UZ, TSw2, repository level	Mean	Medium	NA[d]	NA
	Fault zones	R-area	UZ, TSw2, repository level	SCor	Low	NA	NA
	Fault zones	R-area	UZ, TSw2, repository level	SDev	Low	NA	Low
	Fractures	R-area	UZ, TSw2, repository level	Mean	Medium	3.9.3	NA
	Fractures	R-area	UZ, TSw2, repository level	SCor	Low	NA	NA
	Fractures	R-area	UZ, TSw2, repository level	SDev	Low	NA	Medium
	Rock matrix	R-area	UZ, TSw2, repository level	Mean	High	3.9.3	NA
	Rock matrix	R-area	UZ, TSw2, repository level	SCor	Medium	NA	NA
	Rock matrix	R-area	UZ, TSw2, repository level	SDev	Medium	NA	NA
Moisture content (volumetric)	Fault zones	R-area	UZ, each hydro unit below repository	Mean	Medium	NA	NA
	Fault zones	R-area	UZ, each hydro unit below repository	SCor	Low	NA	NA
	Fault zones	R-area	UZ, each hydro unit below repository	SDev	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	Mean	Medium	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	SCor	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	SDev	Low	NA	NA
	Rock matrix	R-area	UZ, each hydro unit below repository	Mean	High	3.9.2.1	Low
	Rock matrix	R-area	UZ, each hydro unit below repository	SCor	High	NA	NA
	Rock matrix	R-area	UZ, each hydro unit below repository	SDev	High	NA	NA
Pressure head (matric potential)	Fault zones	R-area	UZ, each hydro unit below repository	Mean	Medium	NA	NA
	Fault zones	R-area	UZ, each hydro unit below repository	SCor	Low	NA	NA
	Fault zones	R-area	UZ, each hydro unit below repository	SDev	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	Mean	Medium	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	SCor	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	SDev	Low	NA	NA
	Rock matrix	R-area	UZ, each hydro unit below repository	Mean	Medium	3.9.1.2	Low
	Rock matrix	R-area	UZ, each hydro unit below repository	SCor	Low	NA	NA
	Rock matrix	R-area	UZ, each hydro unit below repository	SDev	Medium	NA	NA
Saturation	Fault zones	R-area	UZ, each hydro unit below repository	Mean	Medium	NA	NA
	Fault zones	R-area	UZ, each hydro unit below repository	SCor	Low	NA	NA
	Fault zones	R-area	UZ, each hydro unit below repository	SDev	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	Mean	Medium	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	SCor	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	SDev	Low	NA	NA
	Rock matrix	R-area	UZ, each hydro unit below repository	Mean	High	3.9.2.1	Low
	Rock matrix	R-area	UZ, each hydro unit below repository	SCor	Medium	NA	NA
	Rock matrix	R-area	UZ, each hydro unit below repository	SDev	Medium	NA	NA
Temperature, in situ	Rock mass	R-area	UZ, below repository	Mean	Medium	1.6.2.2.4	Medium

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Table 8.3.5.12-3. Supporting performance parameters used by Issue 1.6 (ground-water travel time)[a] (page 2 of 6)

Performance parameter	Material type	Spatial location	Stratigraphic unit	Statistical measures desired[b]	Needed confidence[c]	SCP Section where current estimate is discussed	Current confidence[d]
<u>Material Properties</u>							
Density, bulk	Fault zones	R-area	UZ, each hydro unit below repository	Mean	Medium	NA	NA
	Fault zones	R-area	UZ, each hydro unit below repository	SDev	Low	NA	NA
	Rock matrix	R-area	UZ, each hydro unit below repository	Mean	Medium	2.4.2, 1.6.2	Medium
	Rock matrix	R-area	UZ, each hydro unit below repository	SCor	Medium	NA	NA
	Rock matrix	R-area	UZ, each hydro unit below repository	SDev	Medium	NA	NA
Moisture retention curve	Fault zones	R-area	UZ, each hydro unit below repository	Mean	Low	NA	NA
	Fault zones	R-area	UZ, each hydro unit below repository	SDev	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	Mean	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	SCor	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	SDev	Low	NA	NA
	Rock mass	R-area	UZ, each hydro unit below repository	Mean	Medium	NA	NA
	Rock mass	R-area	UZ, each hydro unit below repository	SCor	Low	NA	NA
	Rock mass	R-area	UZ, each hydro unit below repository	SDev	Medium	NA	NA
	Rock matrix	R-area	UZ, each hydro unit below repository	Mean	Medium	3.9.2.1	Low
	Rock matrix	R-area	UZ, each hydro unit below repository	SCor	Low	NA	NA
	Rock matrix	R-area	UZ, each hydro unit below repository	SDev	Medium	NA	NA
Permeability, relative	Fault zones	R-area	UZ, each hydro unit below repository	Mean	Low	NA	NA
	Fault zones	R-area	UZ, each hydro unit below repository	SDev	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	Mean	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	SCor	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	SDev	Low	NA	NA
	Rock mass	R-area	UZ, each hydro unit below repository	Mean	Medium	NA	NA
	Rock mass	R-area	UZ, each hydro unit below repository	SCor	Low	NA	NA
	Rock mass	R-area	UZ, each hydro unit below repository	SDev	Low	NA	NA
	Rock matrix	R-area	UZ, each hydro unit below repository	Mean	Medium	NA	NA
	Rock matrix	R-area	UZ, each hydro unit below repository	SCor	Low	NA	NA
	Rock matrix	R-area	UZ, each hydro unit below repository	SDev	Low	NA	NA
Permeability, relative pneumatic	Fault zones	R-area	UZ, each hydrologic unit	Mean	Medium	NA	NA
	Fractures	R-area	UZ, each hydrologic unit	Mean	Medium	NA	NA
	Fractures	R-area	UZ, each hydrologic unit	SDev	Low	NA	NA
	Rock matrix	R-area	UZ, each hydrologic unit	Mean	Medium	NA	NA
	Rock matrix	R-area	UZ, each hydrologic unit	SDev	Low	NA	NA
Permeability, saturated	Fault zones	R-area	UZ, each hydro unit below repository	Mean	Medium	NA	NA
	Fault zones	R-area	UZ, each hydro unit below repository	SDev	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	Mean	Medium	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	SCor	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	SDev	Medium	NA	NA

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Table 8.3.5.12-3. Supporting performance parameters used by Issue 1.6 (ground-water travel time)[a] (page 3 of 6)

Performance parameter	Material type	Spatial location	Stratigraphic unit	Statistical measures desired[b]	Needed confidence[c]	SCP Section where current estimate is discussed	Current confidence[d]
	Rock mass	R-area	UZ, each hydro unit below repository	Mean	High	NA	NA
	Rock mass	R-area	UZ, each hydro unit below repository	SCor	Low	NA	NA
	Rock mass	R-area	UZ, each hydro unit below repository	SDev	Medium	NA	NA
	Rock matrix	R-area	UZ, each hydro unit below repository	Mean	High	3.9.2.1	Low
	Rock matrix	R-area	UZ, each hydro unit below repository	SCor	High	NA	NA
	Rock matrix	R-area	UZ, each hydro unit below repository	SDev	High	NA	NA
Porosity, effective	Fault zones	R-area	UZ, each hydro unit below repository	Mean	Low	NA	NA
	Fault zones	R-area	UZ, each hydro unit below repository	SDev	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	Mean	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	SCor	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	SDev	Low	NA	NA
	Rock mass	R-area	UZ, each hydro unit below repository	Mean	High	NA	NA
	Rock mass	R-area	UZ, each hydro unit below repository	SCor	Medium	NA	NA
	Rock mass	R-area	UZ, each hydro unit below repository	SDev	Medium	NA	NA
	Rock matrix	R-area	UZ, each hydro unit below repository	Mean	High	3.9.2.1	NA
	Rock matrix	R-area	UZ, each hydro unit below repository	SCor	Medium	NA	NA
	Rock matrix	R-area	UZ, each hydro unit below repository	SDev	Medium	NA	NA
<u>System Geometry</u>							
Contact altitude, hydrologic units	Rock mass	R-area	UZ, each hydro unit below repository	Mean	High	8.3.5.12	Medium
	Rock mass	R-area	UZ, each hydro unit below repository	SCor	Low	NA	NA
	Rock mass	R-area	UZ, each hydro unit below repository	SDev	Medium	NA	NA
Fault displacement	Fault zones	R-area	UZ, each hydro unit below repository	Mean	Medium	1.3.2.2	Low
	Fault zones	R-area	UZ, each hydro unit below repository	SCor	Low	NA	NA
	Fault zones	R-area	UZ, each hydro unit below repository	SDev	Medium	NA	NA
Fault locations	Fault zones	R-area	UZ, each hydro unit below repository	Mean	High	1.3.2.2	Low
	Fault zones	R-area	UZ, each hydro unit below repository	SCor	Low	NA	NA
	Fault zones	R-area	UZ, each hydro unit below repository	SDev	Medium	NA	NA
<u>Validation of Model Concepts</u>							
Isotopic ratios, ground-water residence time	Fault zone	R-area	UZ, each hydro unit below repository	Mean	Medium	NA	NA
	Fault zone	R-area	UZ, each hydro unit below repository	SDev	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	Mean	Medium	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	SDev	Low	NA	NA
	Rock matrix	R-area	UZ, each hydro unit below repository	SCor	Low	NA	NA
	Rock matrix	R-area	UZ, each hydro unit below repository	SDev	Low	NA	NA
	Rock matrix	R-area	UZ, each hydro unit below repository	Mean	Medium	NA	NA

Table 8.3.5.12-3. Supporting performance parameters used by Issue 1.6 (ground-water travel time)[a] (page 4 of 6)

Performance parameter	Material type	Spatial location	Stratigraphic unit	Statistical measures desired[b]	Needed confidence[c]	SCP Section where current estimate is discussed	Current confidence[d]
MODEL TYPE: CALCULATION OF GROUND-WATER TRAVEL TIME IN THE SATURATED ZONE							
Inital and Boundary Conditions							
Flux, flow rate	Rock mass	C-area	SZ, upper 100 m	Mean	Medium	3.9.4	Low
Pressure head function of depth	Ground water	C-area	SZ, upper 100 m	Mean	Medium	3.6.3	Low
Temperature, in situ	Rock mass	C-area	SZ, upper 100 m	Mean	Medium	1.6.2	Medium
Material Properties							
Density, bulk	Fault zones	C-area	SZ, each litho unit in upper 100 m	Mean	Low	NA	NA
	Fault zones	C-area	SZ, each litho unit in upper 100 m	SDev	Low	NA	NA
	Rock matrix	C-area	SZ, each litho unit in upper 100 m	Mean	Medium	2.4.2, 1.6.2	Medium
	Rock matrix	C-area	SZ, each litho unit in upper 100 m	SCor	Medium	NA	NA
	Rock matrix	C-area	SZ, each litho unit in upper 100 m	SDev	Medium	NA	NA
Permeability, saturated	Fault zones	C-area	SZ, each litho unit in upper 100 m	Mean	Medium	NA	NA
	Fault zones	C-area	SZ, each litho unit in upper 100 m	SDev	Low	NA	NA
	Fractures	C-area	SZ, each litho unit in upper 100 m	Mean	Medium	3.6.4, 3.9.2.2	Low
	Fractures	C-area	SZ, each litho unit in upper 100 m	SCor	Low	NA	NA
	Fractures	C-area	SZ, each litho unit in upper 100 m	SDev	Medium	NA	NA
	Rock mass	C-area	SZ, each litho unit in upper 100 m	Mean	Medium	3.6.4, 3.9.2.2	Low
	Rock mass	C-area	SZ, each litho unit in upper 100 m	SCor	Low	NA	NA
	Rock mass	C-area	SZ, each litho unit in upper 100 m	SDev	Medium	NA	NA
	Rock matrix	C-area	SZ, each litho unit in upper 100 m	Mean	Medium	3.6.4, 3.9.2.2	Medium
	Rock matrix	C-area	SZ, each litho unit in upper 100 m	SDev	Low	NA	NA
Porosity, effective	Fault zones	C-area	SZ, each litho unit in upper 100 m	Mean	Medium	NA	NA
	Fault zones	C-area	SZ, each litho unit in upper 100 m	SDev	Low	NA	NA
	Fractures	C-area	SZ, each litho unit in upper 100 m	Mean	Medium	3.6.4	Low
	Fractures	C-area	SZ, each litho unit in upper 100 m	SCor	Low	NA	NA
	Fractures	C-area	SZ, each litho unit in upper 100 m	SDev	Medium	NA	NA
	Rock mass	C-area	SZ, each litho unit in upper 100 m	Mean	Medium	3.9.2.2, 3.6.4	Low
	Rock mass	C-area	SZ, each litho unit in upper 100 m	SCor	Low	NA	NA
	Rock mass	C-area	SZ, each litho unit in upper 100 m	SDev	Medium	NA	NA
	Rock matrix	C-area	SZ, each litho unit in upper 100 m	Mean	Low	3.6.4, 3.9.2.2	Low
	Rock matrix	C-area	SZ, each litho unit in upper 100 m	SDev	Low	NA	NA

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Table 8.3.5.12-3. Supporting performance parameters used by Issue 1.6 (ground-water travel time)[a] (page 5 of 6)

Performance parameter	Material type	Spatial location	Stratigraphic unit	Statistical measures desired[b]	Needed confidence[c]	SCP Section where current estimate is discussed	Current confidence[d]
System Geometry							
Aquifer geometry	Rock mass	C-area	SZ, upper 100 m	Mean	Medium	3.6.1, 3.6.2, 3.9.3	Low
Contact altitude, lithologic units	Rock mass	C-area	SZ, each litho unit in upper 100 m	Mean	Medium	3.6.1, 3.6.2, 3.9.3	Low
Fault displacement	Fault zones	C-area	SZ, upper 100 m	Mean	Medium	NA	NA
Fault locations	Fault zones	C-area	SZ, upper 100 m	Mean	Medium	NA	NA
Validation of Model Concepts							
Water table altitude	Ground water	C-area	SZ, water table level	Mean	High	3.9.1.2	Medium
	Ground water	C-area	SZ, water table level	SDev	Low	NA	NA
			MODEL TYPE: CALCULATION OF SPATIAL CORRELATION STRUCTURE				
Material Properties							
Porosity, total	Fault zones	C-area	SZ, each litho unit in upper 100 m	Mean	Medium	NA	NA
	Fault zones	C-area	SZ, each litho unit in upper 100 m	SDev	Low	NA	NA
	Fault zones	R-area	UZ, each hydro unit below repository	Mean	Medium	NA	NA
	Fault zones	R-area	UZ, each hydro unit below repository	SCor	Low	NA	NA
	Fault zones	R-area	UZ, each hydro unit below repository	SDev	Medium	NA	NA
	Fractures	C-area	SZ, each litho unit in upper 100 m	Mean	Medium	NA	NA
	Fractures	C-area	SZ, each litho unit in upper 100 m	SCor	Low	NA	NA
	Fractures	C-area	SZ, each litho unit in upper 100 m	SDev	Medium	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	Mean	Medium	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	SCor	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	SDev	Medium	NA	NA
	Rock mass	C-area	SZ, each litho unit in upper 100 m	Mean	Medium	3.9.2.2	Low
	Rock mass	C-area	SZ, each litho unit in upper 100 m	SCor	Low	NA	NA
	Rock mass	C-area	SZ, each litho unit in upper 100 m	SDev	Medium	NA	NA
	Rock matrix	C-area	SZ, each litho unit in upper 100 m	Mean	Medium	2.4.2, 2.5	Medium
	Rock matrix	C-area	SZ, each litho unit in upper 100 m	SCor	Medium	NA	NA
	Rock matrix	C-area	SZ, each litho unit in upper 100 m	SDev	Medium	3.9.2, 2.4.2, 2.5	Medium
	Rock matrix	R-area	UZ, each hydro unit below repository	Mean	High	NA	NA
	Rock matrix	R-area	UZ, each hydro unit below repository	SCor	High	NA	NA
			MODEL TYPE: CALCULATION OF FRACTURE HYDROLOGIC CHARACTERISTICS				
Material Properties							
Fracture aperture	Fault zones	C-area	SZ, each litho unit in upper 100 m	Mean	Medium	NA	NA
	Fault zones	C-area	SZ, each litho unit in upper 100 m	SDev	Low	NA	NA

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Table 8.3.5.12-3. Supporting performance parameters used by Issue 1.6 (ground-water travel time)[a] (page 6 of 6)

Performance parameter	Material type	Spatial location	Stratigraphic unit	Statistical measures desired[b]	Needed confidence[c]	SCP Section where current estimate is discussed	Current confidence[d]
	Fault zones	R-area	UZ, each hydro unit below repository	Mean	Low	NA	NA
	Fault zones	R-area	UZ, each hydro unit below repository	SDev	Low	NA	NA
	Fractures	C-area	SZ, each litho unit in upper 100 m	Mean	Medium	NA	NA
	Fractures	C-area	SZ, each litho unit in upper 100 m	SDev	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	Mean	Medium	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	SCor	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	SDev	Low	NA	NA
Fracture frequency	Fault zones	C-area	SZ, each litho unit in upper 100 m	Mean	Low	NA	NA
	Fault zones	C-area	SZ, each litho unit in upper 100 m	SDev	Low	NA	NA
	Fault zones	R-area	UZ, each hydro unit below repository	Mean	Low	NA	NA
	Fault zones	R-area	UZ, each hydro unit below repository	SDev	Low	NA	NA
	Fractures	C-area	SZ, each litho unit in upper 100 m	Mean	Medium	NA	NA
	Fractures	C-area	SZ, each litho unit in upper 100 m	SCor	Low	NA	NA
	Fractures	C-area	SZ, each litho unit in upper 100 m	SDev	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	Mean	Medium	3.9.2.1	Low
	Fractures	R-area	UZ, each hydro unit below repository	SCor	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	SDev	Low	NA	NA
Fracture length	Fault zones	C-area	SZ, each litho unit in upper 100 m	Mean	Low	NA	NA
	Fault zones	R-area	UZ, each hydro unit below repository	Mean	Low	NA	NA
	Fault zones	R-area	UZ, each hydro unit below repository	SDev	Low	NA	NA
	Fractures	C-area	SZ, each litho unit in upper 100 m	Mean	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	Mean	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	SCor	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	SDev	Low	NA	NA
<u>System Geometry</u>							
Fracture orientation	Fault zones	C-area	SZ, each litho unit in upper 100 m	Mean	Low	NA	NA
	Fault zones	R-area	UZ, each hydro unit below repository	Mean	Low	NA	NA
	Fault zones	R-area	UZ, each hydro unit below repository	SDev	Low	NA	NA
	Fractures	C-area	SZ, each litho unit in upper 100 m	Mean	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	Mean	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	SCor	Low	NA	NA
	Fractures	R-area	UZ, each hydro unit below repository	SDev	Low	NA	NA

[a]SZ = saturated zone; UZ = unsaturated zone; GWTT = ground-water travel time; C-area = controlled area; R-area = repository area; litho = lithological; hydro = hydrological.
[b]Mean = spatially dependent mean value; SDev = spatially dependent standard deviation; SCor = spatial correlation coefficient.
[c]High = high confidence, highest priority; Medium = medium confidence, medium priority; Low = low confidence, low priority.
[d]NA = not available.

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The governing equation of three-dimensional flow in saturated porous media is generally expressed as follows:

$$S_s \frac{\partial h}{\partial t} - \nabla \bullet (\overline{\overline{K}} \nabla h) + Q = 0 \qquad (8.3.5.12\text{-}1)$$

where

S_s = specific storage

h = piezometric head

$\overline{\overline{K}}$ = hydraulic conductivity

Q = volumetric discharge

t = time

∇ = differential operator $\left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right)$

For steady or nearly steady flow, the storage term can be neglected.

Flow in unsaturated porous media is generally expressed by variants of Richards' equation. The model for liquid water flow in unsaturated fractured porous media, as described in Section 3.9, can be formulated by an equation derived from a version of Richards' equation written for both the matrix and fracture systems and by assuming that, in a near-equilibrium condition, the pressure head in the fractures and the matrix is locally in equilibrium. This can be written in the form

$$\nabla \bullet [(\overline{\overline{K}}_m(\psi) + \overline{\overline{K}}_f(\psi)) \nabla(\psi + z)] = F\left(\frac{\partial \psi}{\partial t}\right) + Q \qquad (8.3.5.12\text{-}2)$$

where

$\overline{\overline{K}}_m(\psi)$ = the relative hydraulic conductivity for the unsaturated matrix system

$\overline{\overline{K}}_f(\psi)$ = the relative hydraulic conductivity for the unsaturated fracture system

ψ = pressure head

z = elevation head

Q = sink/source term

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and F involves the specific moisture capacity of matrix and fractures and the compressibility of water, the bulk rock, and the fracture system (Klavetter and Peters, 1986).

Once the pressure head distribution is established, seepage velocities (v) can be determined by

$$v = -\left(\frac{K(\psi)}{n_e}\right)\left(\frac{\partial h}{\partial l}\right) \qquad (8.3.5.12\text{-}3)$$

and ground-water travel time (GWTT) by

$$\mathrm{GWTT} = \frac{D}{v} \qquad (8.3.5.12\text{-}4)$$

where h is total head defined by an elevation head component, z, and a pressure head component, ψ, l is length along the head gradient, D is the flowpath length, and n_e is effective porosity.

K or $K(\psi)$, hydraulic conductivity is an empirical parameter that depends on properties of both the moving fluid and transmitting medium (i.e., on both water and rock properties). K may be more fundamentally expressed as

$$K = \frac{\rho g k}{\mu} \qquad (8.3.5.12\text{-}5)$$

where k, permeability, is a property of the rock (and moisture content in unsaturated material); g is the acceleration due to gravity; and μ, viscosity, and ρ, density, are properties of the fluid that depend on temperature and on chemical species present. Assuming little effect of chemistry on ρ and μ, in situ temperatures and intrinsic permeability are the parameters needed to derive K. In unsaturated materials, the value of $K(\psi)$ depends on moisture content and may differ (for transient behavior) depending on whether the material is becoming wetter (ψ increasing) or drier (ψ decreasing). This moisture dependency will be accounted for in modeling of the unsaturated zone (8.3.1.2.2).

Effective porosity is used here as a measure of the volume of space through which flow occurs. In the unsaturated zone, this property is taken to be the in situ moisture content less the residual moisture content. As understanding of unsaturated flow evolves, this definition may need to be modified to account for porous channeling or other phenomena.

Equations 8.3.5.12-1 through 8.3.5.12-5 are judged, based on the current understanding of the conceptual models of flow at the site (as described in Chapter 3), to be a suitable basis for generally describing the flow phenomena present in the saturated and unsaturated zones. These equations define the basic set of material-property parameters that must be available to calculate ground-water travel time and therefore resolve this issue. Additional information required to solve Equations 8.3.5.12-1 through 8.3.5.12-5 include the description of the system geometry (for both the

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saturated and unsaturated zones within the controlled area) and initial and boundary conditions for the models.

Parameters requested in Table 8.3.5.12-: are divided into the four categories previously discussed: (1) system geometry, (2) material property values, (3) initial and boundary conditions, and (4) model validation. As described earlier, information is required from the first three categories to provide specific input for the solution of the general equations for ground-water travel time. To determine if those mathematical equations provide an adequate formulation for the calculation of ground-water travel time, information relevant to the fourth category, model validation, is also required.

Under each of the four categories in Table 8.3.5.12-3, specific parameters are requested for several distinct types of models. The parameters may be used primarily in direct calculations of the ground-water travel times in the unsaturated zone or the saturated zone; they may be used primarily in models to derive hydrologic properties of fractures, or they may be used primarily in models to define the basic spatial correlation structure of the rock mass. Table 8.3.5.12-3 is subdivided to show which parameters are used in each of these broad types of models.

The second column in the table, material type, indicates whether information on the requested parameter is required about their distributions in the rock matrix, in distributed fracture networks, as characteristics of a sufficiently large volume of rock (rock mass), or in fault zones. The third column, spatial location, indicates whether information is needed for the requested parameter in the repository area or the entire controlled area. The fourth column in the table, stratigraphic unit, indicates where in the vertical dimension that information is needed. In the unsaturated zone, because this issue is concerned primarily with downward water movement, most of the information is requested only for those units at the repository level or below. However, it is recognized that similar information may be required for units above the repository level (Investigation 8.3.1.2.2) in order to infer some of the parameters requested in Table 8.3.5.12-3, such as percolation flux.

The fifth and sixth columns indicate, respectively, the statistical measures desired and confidence level set for each requested parameter. The measure desired is either one of the first two statistical moments (mean and standard deviation) for the parameter or the spatial correlation coefficient. The confidence level (low, medium, or high) indicates the relative confidence required in the parameter of interest, with a confidence level of high also indicating that the parameter value is of high priority, medium indicating a medium priority item, and low indicating a low priority item. These confidence levels are based on professional judgments about the relative importance of the various parameters and are not meant to imply any quantitative definition. The confidence levels indicate the desired confidence for the location-dependent mean, standard deviation, and spatial correlation. For example, if the "true" standard deviation is large and the desired confidence in the standard deviation is high, sufficient samples must be measured to show high confidence that the standard deviation of the sample population is a good approximation of the "real" variance of the parameter of interest. Also, the location-dependent requirements indicate a desire to define any

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spatial drift in population statistics for each parameter and implies an analysis and removal of drift during data reduction.

Generally, for the unsaturated zone, higher confidence is requested for matrix properties than for properties of fractures, faults, or the rock mass. This reflects current judgments that matrix flow dominates in the unsaturated zone. The relative confidence levels are also based, in part, on the estimated feasibility of obtaining reliable information for each of the parameters.

The seventh and eighth columns in Table 8.3.5.12-3 identify the section in the SCP where current values for each of the identified parameters are discussed and the current confidence that the Yucca Mountain Project has for each parameter.

Table 8.3.5.12-3 lists those site parameters considered necessary to support resolution of this issue. In general, values for parameters listed in the table under the categories of material properties and initial and boundary conditions will provide the direct input necessary to calculate ground-water travel times from the mathematical formulations represented by Equations 8.3.5.12-1 through 8.3.5.12-5. However, some parameters in those equations are not requested by Table 8.3.5.12-3. For example, the viscosity and density of water and the value of the acceleration due to gravity were not requested because they can be readily obtained from scientific handbooks. The specific storage parameter in the first term on the left-hand side of Equation 8.3.5.12-1, which represents responses to transient, stressed conditions, is not requested because pre-waste-emplacement travel times will be calculated under steady or near steady conditions. Also, the parameter in Equation 8.3.5.12-2, representing the specific moisture capacity of the rock and compressibilities of fluid and rock, is not requested because it can be derived from values from a combination of the requested moisture retention curves and from values from literature sources.

The parameters in Table 8.3.5.12-3 related to fracture geometry in the unsaturated zone will be required if evaluation of flow in fractures is required. Values of these parameters for unsaturated units will be used to infer the hydrologic properties of fractures including relative permeability and associated effective porosity, perhaps in the manner of Wang and Narasimhan (1986), only if fracture flow below the disturbed zone is sufficiently widespread or probable to warrant analysis. Similarly, bulk density is listed as a contingency for preserving the option to consider diffusion of nonsorbing tracers in the event of significant fracture flow. The term involving diffusion of tracer particles between the matrix and the fractures is not shown in Equations 8.3.5.12-1 and 8.3.5.12-2 because these equations are ground-water flow rather than transport equations. If diffusion is to be considered then the transport equations developed in Issue 1.1 would apply (Section 8.3.5.13).

For both the unsaturated and saturated zones, the confidence levels set for individual parameters reflect current judgments of their relative importance to ground-water travel time. If the mean values currently available (Chapters 1 through 3) for the parameters listed in Table 8.3.5.12-3 are good estimates of the true values, then those values are probably adequate to show

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compliance with the performance goals set for this issue. In no instance is the current level of confidence high for any of the parameters listed.

The actual parameters requested are the first two statistical moments (mean and standard deviation) and the spatial correlation coefficients of each of the properties for each of the hydrogeologic units. Thus, the confidence levels assume nonstationarity and apply to confidence that the three-dimensional location-dependent mean, standard deviation, and spatial correlation within each unit are known to the indicated level of confidence. Generally, more samples are required to obtain higher confidence levels for, respectively, means, standard deviations, and spatial correlations of individual properties. This is particularly true for geologic materials where properties are commonly treated as regionalized variables (Matheron, 1971). Drift or trend surface analysis techniques will be applied to allow the assessment of spatial change in the statistical moments. This strategy of assigning confidence goals to statistical parameters of distinct properties varies somewhat from the general approach for issue resolution discussed in Section 8.2.2 wherein target goals are requested for the value of a property with specified confidence or within specified intervals. Given the nonunique combination of property values that will satisfy the performance goal and the potentially large contribution of spatial and statistical variability of properties to uncertainty in travel-time predictions (Codell, 1986; Sinnock et al., 1986), definition of the statistical characteristics of property distribution will more effectively and efficiently reduce uncertainties, at least for this issue, than specification of target values for the properties. Because spatial variability is a major source of uncertainty in predictions of ground-water travel time, it is prudent to characterize the spatially dependent statistical structure of the variables.

A large number of samples may need to be tested to obtain high confidence in some parameters over the entire repository site, particularly the spatial correlation. This is because the porous tuff formations are probably heterogeneous, with hydrogeologic properties varying in an irregular manner in space both horizontally and vertically. The heterogeneity can be characterized by the autocorrelation of the properties of interest as a function of spatial separation and by analysis in nonstationary populations. The autocorrelation superposed on the drift is referred to in the remainder of this section as spatial correlation. Different scales (sample separation differences) should be sampled reliably to assess the vertical and horizontal spatial structure of parameter statistics within each hydrogeologic unit. The scale over which a measurement averages flow parameters should be evaluated to estimate the proper hydraulic properties of the medium to use in modeling exercises. The laboratory and even field scales of property measurements are usually relatively small compared with the rock mass represented in numerical simulations. Modeling-scale properties of the fractured porous rock mass need to be developed, accounting for the uncertainty in both the fracture and matrix variability, by calibrating the modeling data with the actual measurements obtained from cores, in situ tests, and subsurface observations in the exploratory shaft. The effect of different scales on hydrologic property values will be investigated in Sections 8.3.1.2.2 and 8.3.1.4.3. Definition of the scale-dependency and spatial variability may require systematic, relatively dense sampling of the properties of interest (or their correlated surrogates).

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To indicate the level of detail at which the information is required for resolution of this issue, a desired level of confidence, for example high, medium, or low, is indicated in Table 8.3.5.12-3. Because of the paucity of current information on hydrologic properties and characteristics, the requested levels of confidence are only qualitative. These qualitative levels relate to the width of the confidence interval for means and variances, with high indicating that the desired confidence interval for the value is smaller than the interval for a medium level of confidence. For spatial correlation, increasing confidence is taken to mean extending the spatial correlation coefficient (variogram) over a greater distance range, at a given level of confidence. Quantitative levels may be set as the hydrologic models are more completely defined and knowledge is improved about the effects of parameter distributions, interrelationships, and characteristics on uncertainty in ground-water travel time.

Confidence in means, standard deviations, and spatial correlations for less densely sampled parameters can be enhanced by defining the covariance coefficients between them and densely sampled parameters, within and between individual hydrogeologic units, and using the spatial distribution of the more densely sampled parameter to constrain the distribution of the other. To be most effective, this approach should rely on measurements of correlated parameters on a single physical sample. Therefore, design of a sampling and testing program should, to the extent practical, sequence measurements of different parameters on single samples.

Although little specific information is called out within Table 8.3.5.12-3 to define the conceptual hydrologic models, it is evident that definition of alternative conceptual hydrologic models and assessment of their relative likelihood for the unsaturated and saturated zones is an important requirement for evaluating ground-water travel times. Chapter 3 more explicitly addresses some of the sources of uncertainty about unsaturated-zone conceptual models, and these uncertainties are shared by this issue, including questions about coupling processes between matrix and fracture flow and about scaling laboratory and field measurements to a sufficiently large volume of rock for numerical modeling.

Hydrologic concepts and data needed to calculate ground-water travel times are provided by the site characterization programs 8.3.1.2 and 8.3.1.4. Calculation of the ground-water travel-time distribution will probably be made with versions of different calculational models. Calculational models are subject to refinement as conceptual understanding of flow in unsaturated and saturated, fractured porous tuff increases and as additional data are acquired from site characterization. The hydrologic parameters and confidence levels listed in this information need will probably be revised as the current versions of calculational models are refined.

No specific activities are defined for this information need. However, as more information about site data and geostatistical modeling becomes available, the data needs defined in this section will be continually reevaluated (Section 8.3.5.12.4.1.1).

8.3.5.12.2 Information Need 1.6.2: Calculational models to predict ground-water travel times between the disturbed zone and the accessible environment

Issue 1.6 addresses the performance objective that pre-waste-emplacement ground-water travel time along the fastest path of likely radionuclide travel from the disturbed zone to the accessible environment shall be at least 1,000 yr. Direct measurements of ground-water travel time are not feasible because the time and distance scales are too great for direct observation. Resolution of the issue will be demonstrated primarily by using numerical models to make quantitative estimates of the distribution of ground-water travel time and by comparing these estimates to the performance goals. Models that describe the appropriate physical processes are needed for estimating the ground-water travel times. Several types of calculational models are required to provide tools for determining the pre-waste-emplacement ground-water travel time.

Technical basis for addressing the information need

Link to the technical data chapters and applicable support documents

Currently available calculational models for ground-water travel time are alluded to in Section 3.9, and more comprehensively listed in Section 8.3.5.19. The conceptual basis for the current models and those that may be developed in the future is described in Section 3.9, and the basic mathematical formulations of current models is given in Information Need 1.6.1, Section 8.3.5.12.1.

Parameters

The following information must be available to select a set of calculational models for establishing ground-water travel time:

1. Site parameters described in Information Need 1.6.1 (Section 8.3.5.12.1) and listed in Table 8.3.5.12-3.

2. Conceptual models of water flow through the unsaturated and the saturated zones at the Yucca Mountain site. The conceptual models should consist of a description of the physical processes, including a definition of the limits of the processes, a listing of parameters believed to be relevant to the process, and a statement of the parameters that the model will predict.

3. A three-dimensional geometric model of the site parameters alluded to in item 1. This geometric model should be capable of associating single values, multiple values, or variations of values for the hydrological and geochemical parameters with specific three-dimensional locations at the Yucca Mountain site.

Logic

The types of calculational models required depend upon the approaches used to resolve the ground-water travel-time performance objective, reflected in the technical basis described for resolving Information Needs

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1.6.3 and 1.6.4 (Sections 8.3.5.12.3 and 8.3.5.12.4). A sufficient understanding of the flow behavior at Yucca Mountain, as well as interpretations of the available data, are needed to select an appropriate suite of models for resolving this issue. Once the physical processes of the flow system have been hypothesized (the issue resolution strategy, Section 8.3.5.12 and the geohydrology testing strategy, Section 8.3.1.2) and a proper set of variables (or data) has been identified (Section 8.3.5.12.1), mathematical and numerical models of the flow behavior can be formulated. Many alternative considerations are examined: What dimensionality and scale of modeling should be used? Can simplifying approximations to the physical processes be used? Should a homogeneous-parameter or heterogeneous-parameter model be used to quantify physical properties of discrete hydrogeologic units? What are the proper mathematical forms of the processes embodied by the models? What are the proper geometric and mathematical forms of boundary and initial conditions?

Ground water at the Yucca Mountain site flows through fractured porous tuff in both saturated and unsaturated conditions. Current conceptual models of Yucca Mountain postulate that flow takes place in matrix pores or in matrix pores in combination with fractures. The matrix porosity is made up of interconnected microscopic pores within tuff blocks bounded by fractures. The fracture porosity is made up of joints and fault zones. Indeed, the many fractures can be envisioned as homogeneous within the framework of continuum models at an appropriately large scale. Faults may serve as specific discontinuities, boundaries, zones of high permeability, etc., but they may be too few and too influential to justify a continuum approach. The different types of calculational models that may be used to simulate the flow through fractured, porous systems are discussed in the following paragraphs.

The equivalent porous medium type of model (Bear, 1972) is based on representative elemental volume concepts and on the assumption that any flow through fractures is Darcian. The equation of flow is described by the conservation of mass, including terms for advection, storage, dispersion, diffusion, and sinks and sources. The underlying assumption is that physical quantities such as porosity, conductivity, and pressure can be averaged over large blocks of rock containing a large number of fractures. There is no well-defined method for computing the equivalent porous medium parameters even if the fractures are completely described, although several models are being constructed to generate unsaturated porous-media properties from detailed structural and physical concepts. When available, these methods may be applied to the unsaturated zone. Equivalent porous medium models are generally taken to be the most realistic way of calculating regional scale and local scale (repository area) saturated ground-water flow. Thus, this type of model will be used for saturated flow simulations used to calculate travel times. The parameters needed for this model are hydraulic conductivity, effective porosity, specific storage, the flux and head at the model boundary, and initial head conditions within the model area.

The double porosity type of model (Barenblatt et al., 1960) lumps all the matrix blocks into one continuum and all the fractures into another continuum and develops a coupling term between the two continua. The rock matrix continuum is commonly characterized by low permeability and high storage, while the fractured continuum is usually characterized by high permeability and low storage. Therefore, the rock matrix often controls the late time response of the system to pressure or stress transients, while the fractured continuum controls the early time response of the system. This system can be described by two mass conservation equations, one for each continuum. If flow is highly dominated by either matrix or fractures, the need for two continua is questionable and reasonable approximations can be obtained by a single equivalent porous medium approach. The parameters needed are the effective porosity, hydraulic conductivity, and the pressure for both matrix and fractured continua; the flux of water; and a coupling function representing the transfer of fluid between rock matrix and fractures, including, as appropriate, hysteric behavior of relative hydraulic conductivity and effects of mineral coatings on fracture-to-matrix conductivity. Physical parameters, such as porosity and permeability, associated with the fracture continuum are obtained from fracture properties such as aperture width, spacing, and orientation. This approach probably will not be used in the studies currently planned because of the current beliefs that flow in the unsaturated zone is predominantly constrained to the matrix pores and in the saturated zone to the fractures.

A special case of the double porosity model, called a composite medium model (Klavetter and Peters, 1986), can be derived by adding the two continuum equations, assuming the potential fields for the two systems (matrix and fractures) are in equilibrium. The validity of this fundamental assumption will be tested by the site characterization program for geohydrology (Program 8.3.1.2). Such superposition is practical in the representative elementary volume approach for saturated flow but has not been demonstrated to be applicable to unsaturated flow. As for the double porosity model, the composite medium model is only applicable under the steady or nonsteady conditions where both matrix pores and fractures are involved in the flow. This model will be provisionally accepted to describe unsaturated flow under transients that cause fracture flow. The parameters required for unsaturated conditions are the relative permeability and saturation as a function of pressure head, effective porosity, and initial conditions; all these parameters are required for both the matrix and fractures (Table 8.3.5.12-3). This type of model will be used primarily to investigate local behavior of fracture and matrix flow within and between units under variable flux conditions to help generate representative concepts, parameters, and flow paths for use in site scale models.

Another approach to investigating the relations between matrix and fracture flow involves discrete fracture models that treat fractures and discontinuities individually rather than as a continuum. The drawback to a discrete fracture model for site scale applications is the amount of detail that is required as input for a large number of fractures and the accompanying difficulties in modeling the discrete fractures throughout a large volume. For small scales, an efficient approach can be applied by using statistical descriptions of fracture characteristics to generate synthetic fractures sets, then simulating the flow through the fractures and between the matrix blocks and the fractures (Long et al., 1982; Wang and Narasimhan, 1985, 1986). Microfractures, which are too numerous to simulate discretely, may be included within the hydraulic properties of the fracture or matrix continuum, as is true for any modeling approach accounting for dual porosity effects. This type of model will be used to augment a composite medium model to establish proper generalized parameters for use in simpler site-scale

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models. Of particular interest are the potential for channeling of fracture flow and other complications that may result in generalizing the characterization of the fractures.

The phenomena of flow in fractured porous tuff are complicated, especially in the unsaturated zone. In particular, the mathematically nonlinear description of permeability changes caused by saturation changes (flux transients) in the differential equations of flow become very difficult to solve, especially where material property contrasts occur between matrix blocks and fractures or across unit contacts. If the spatial variability of properties within units is considered, the difficulties of numerical convergence are increased many fold. To attempt to overcome some of these numerical difficulties, development of simplified models that avoid iterative, convergent solutions of the mass-balance differential equations will be pursued. Current ideas point toward direct kinematic or direct simulation models that calculate velocity, simply, as flux divided by moisture content, where flux is treated as an independent boundary condition. For example, the velocity of ground water in unsaturated flow may be approximated in one-dimensional analysis by dividing percolation flux by the moisture content in the matrix pores. If the flux is greater than the saturated hydraulic conductivity, the travel time is calculated from the velocity of flow through fractures (Sinnock et al., 1986). This, or similar simplified models, will be used to the extent it can be demonstrated as reliable or conservative for site-scale calculations of travel-time distributions. Currently, it is believed that there is a possibility of lateral diversion at some unit contacts or within single units. In this case, one-dimensional vertical flow may be an oversimplification and horizontal components might need to be accounted for in defining a set of one-dimensional flow lines. The computing efficiency associated with such one-dimensional kinematic models allows available computing power to be focused on resolution of the effects of spatial heterogeneity.

As currently planned, a stochastic type of model that generalizes flow processes while enhancing spatial resolution of property variations will serve as the primary site-scale model. Using this approach, ground-water travel time can be treated as a random variable rather than as a fixed quantity through any given distance (Codell, 1986). One source of the variability of ground-water travel time is caused by spatial heterogeneity of the parameters. Irreducible uncertainty about site characteristics with regard to spatial and temporal variabilities will always lead to uncertainty in ground-water travel time. To account for the spatial variability and uncertainty of parameters (e.g., hydraulic conductivity and effective porosity for both the matrix and fractures, and for initial and boundary conditions), many random realizations of the parameter sets will be used to estimate a travel-time probability distribution that reflects parameter uncertainties that are themselves expressed as probability distributions. Such a procedure is known as a Monte Carlo simulation and will be applied to estimate the ground-water travel-time distributions for comparison with the travel-time goals set in Section 8.3.5.12. A preliminary application of this approach was used to generate the cumulative distribution functions for travel time (Sinnock et al., 1986) in Sections 3.9.4 and 8.3.5.12. A more direct stochastic method is to treat numerically the parameters and dependent variables of the governing equations as random processes rather than as deterministic quantities. The partial differential or kinematic equations

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describing flow are solved in terms of means and variances of the dependent variables. The direct stochastic method of modeling has been rapidly developing in recent years (Mantoglu and Gelhar, 1985; Yeh et al., 1985). A good estimate of input covariances of the hydrogeologic parameters is required for such stochastic modeling. If feasible, this direct stochastic approach may be used to supplement or supplant reliance on Monte Carlo simulations.

The proper application of each type of model is determined by its role in building confidence that the flow time can be adequately simulated and that uncertainty can be adequately accounted for. The level of complexity of the phenomena included in the model depends on the purpose for which the model is intended. A flow-system model will be developed to incorporate spatial variability, temporal variability, and uncertainty. Once a modeling concept has been developed to some level of sophistication, a period of evolution begins, wherein the important features of the model are retained and inconsequential features are eliminated. This occurs by comparing the results of simulations using various approaches, modifying the models to test the assumptions, calibrating and validating the models, performing sensitivity analyses and uncertainty analyses, and incorporating new data into the analyses. The correctness of results predicted by the model will be tested against analytical solutions of a similar model and against laboratory and field data. When discrepancies appear, the models may undergo modification and further modeling tests may be performed until a self-consistent model of the flow system is built.

In summary, the calculational models required to estimate ground-water travel times from the disturbed zone to the accessible environment include (1) local (small-scale) models for both the unsaturated zone and saturated ground-water flow to establish the proper processes to consider in the flow description at the site, (2) a travel-time model to determine ground-water travel time based on simplifications of the flow processes established by the local scale models, and (3) a statistical model to incorporate the uncertainty in the input information into the travel-time model and to provide a probabilistic estimate of ground-water travel time.

8.3.5.12.2.1 Activity 1.6.2.1: Model development

The objective of this activity is to develop calculational models for predicting pre-waste-emplacement ground-water travel time. Two subactivities are involved in this activity.

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8.3.5.12.2.1.1 Subactivity 1.6.2.1.1: Development of a theoretical framework for calculational models

Objectives

The objective of this subactivity is to assess conceptual and mathematical representations of unsaturated flow phenomena in fractured porous media and adopt a set or sets of equations for use in calculating ground-water travel time.

Description

This subactivity will assess the concepts and hydrologic mechanisms governing fluid flow in partially saturated fractured porous tuff at Yucca Mountain. Section 8.3.1.2.2, under the geohydrology program, will describe the unsaturated zone hydrologic system at Yucca Mountain. This activity will work in conjunction with plans described in Section 8.3.1.2.2 to develop one or more mathematical representations of the hydrology at the site that are suitable for use in the calculation of ground-water travel time.

8.3.5.12.2.1.2 Subactivity 1.6.2.1.2: Development of calculational models

Objectives

The objective of this subactivity is to develop computer algorithms for calculational (numerical) models to estimate ground-water travel time.

Description

This subactivity will refine existing computer algorithms or develop new ones that embody (1) local flow models for investigating the mechanisms of flow in the unsaturated and saturated zones, (2) travel-time models for estimating ground-water travel time, and (3) statistical models for incorporating the uncertainty in a probabilistic manner. This subactivity will modify present calculational models by comparing them with other models incorporating different levels of sophistication, field test results from the geohydrology program about the conceptual assumptions within the models, and the results of sensitivity analyses. These calculational models will be developed in cooperation with related efforts in Section 8.3.1.2.2.

8.3.5.12.2.2 Activity 1.6.2.2: Verification and validation

The objective of this activity is code verification and model validation. Two subactivities are involved in this activity.

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8.3.5.12.2.2.1 Subactivity 1.6.2.2.1: Verification of codes

Objectives

This subactivity will ensure that the computer algorithms making up the codes correctly perform the intended numerical operations.

Description

The numerical accuracy of the calculational models used in analysis of flow will be verified by tests including comparison to analytical solutions and benchmarking against other codes. Currently, the Yucca Mountain Project is participating in HYDROCOIN, an international effort to verify and support validation of computer codes to be used in assessments of environments related to nuclear waste disposal. The Yucca Mountain Project has also instituted a formal code verification activity, COVE, for all performance assessment codes used by the project. For more information, refer to Sections 8.3.5.19 and 8.3.5.20.

8.3.5.12.2.2.2 Subactivity 1.6.2.2.2: Validation of models

Objectives

The objective of this subactivity is to ensure that the conceptual models and their mathematical and numerical representations correctly account for the physical processes relevant to determining ground-water travel time.

Description

The correctness of theoretical and mathematical models in the simulation of flow phenomena relevant for assessing travel time will be addressed by model validation. The validation tests will involve, to the extent possible, comparisons of model predictions with laboratory experiments and field data or comparisons with other models already validated. The correctness of results predicted by a model will be tested against similar models (verification) and against appropriate laboratory and field data (validation). If discrepancies occur, the models may undergo modification and further verification and validation until the code predicts observed behavior with acceptable accuracy.

This subactivity will perform laboratory experiments that will provide direct observations of flow behavior in unsaturated media that can be compared with code predictions and used to support validation of mathematical models describing unsaturated fluid flow. Integrated sets of laboratory data will be obtained, and the hydrologic properties of the samples used in the validation experiments will be measured. This subactivity is divided into two separate parts. The first is responsible for designing and performing the validation experiments. The second is responsible for ensuring that the hydrologic property values required by the mathematical flow models have been determined for the samples used in the validation experiments.

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Under the first part of this subactivity, laboratory hydrologic experiments will be designed and performed to support comparison of unsaturated flow models to laboratory observations. The computer codes in which those models are embodied and the factors involved in the general validation process are summarized in Section 8.3.5.19.

A primary effort within this subactivity will be to design hydrologic experiments that can be sufficiently controlled to produce integrated sets of data such that every relevant component of the model is addressed. Some experiments may address single components of the model, and others may address the composite response of the entire model. Although the time frame of the experiments generally will not be comparable to the time period desired for the application of the model, the loads imposed in the experiments will be as comparable to those expected in situ as possible, perhaps accounting for time and distance scaling factors. In general, the experiments will be designed to monitor water movement (either wetting or drying processes) in laboratory-scale samples under tightly controlled boundary conditions. Materials may range from tuff samples of various kinds to synthetic or natural materials such as sand. The main parameters to be measured will include pressure, saturation, boundary conditions of pressure, saturation, and temperature profiles, and time.

Two experiments have been designed at this time: One is an imbibition (wetting) experiment and the other is a drying experiment. Laboratory scoping experiments of both imbibition and drying processes have already been performed on a welded tuff sample of cylindrical geometry to develop the necessary instrumentation. In the imbibition experiment, a dry sample of cylindrical geometry will be placed within a core holder and pressure vessel. Pressure conditions will be monitored. One-dimensional water movement will be induced by initiating a constant water flux at one end. The transient saturation profile along the sample will be monitored using a (nonintrusive) gamma-beam attenuation technique. The experiment will be terminated after full saturation is reached. The sample will be tested initially under isothermal conditions.

The drying experiment will use the same sample and experimental apparatus used in the imbibition experiment. A dry gas stream will be passed over one or both ends of the saturated sample. The saturation along the sample will be monitored as a function of time as the sample dries out.

The purpose of the second part of this subactivity is to characterize the hydrologic properties of the samples used in the model validation experiments. The parameters determined will be those required by the unsaturated flow model to be validated. The general unsaturated flow model (e.g., Section 8.3.5.12.1, Equation 8.3.5.12-2) requires the following input parameters: hydraulic conductivity as a function of pressure head, saturation as a function of pressure head, and porosity. The first two parameters are often referred to as characteristic curves of the material. The curves should be determined under the same water movement process (either wetting or drying) as took place in the validation experiment.

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This subactivity will cooperate with the work performed under Investigation 8.3.1.2.2 to characterize the hydrologic properties of the tested samples. The results will be documented and supplied to the scientific and engineering property data base for use in the validation process.

Although no validation of models will occur under this subactivity, the experimental efforts will be closely coordinated with work described in Sections 8.3.5.13, 8.3.1.2, and 8.3.5.19 to ensure that appropriate and sufficient laboratory hydrologic experiments are performed to support model validation.

8.3.5.12.3 Information Need 1.6.3: Identification of the paths of likely radionuclide travel from the disturbed zone to the accessible environment and identification of the fastest path

Descriptions of flow paths in both the unsaturated and saturated zones are required to determine the pathways to be used in compliance with the 10 CFR 60.113(a)(2) requirement for assessing pre-waste-emplacement ground-water travel time along the fastest path of likely radionuclide travel from the disturbed zone to the accessible environment. This information is used in Information Need 1.6.4 (Section 8.3.5.12.4). In addition, the flow paths, velocities, fluxes, boundary conditions, and initial conditions throughout the site will be developed as input to predict the cumulative curies transported to the accessible environment under normal conditions for Information Needs 1.1.4 and 1.1.5 (Sections 8.3.5.13.4 and 8.3.5.13.5).

Technical basis for addressing the information need

Link to the technical data chapters and applicable support documents

Current information on flow paths at the Yucca Mountain site is discussed in Chapter 3 and Section 8.3.1.2.

Parameters

The results obtained from Information Need 1.6.2 (calculational models) together with a hydrogeologic model of the Yucca Mountain ground-water flow system are needed to satisfy this information need.

Logic

Compliance with the 10 CFR 60.113(a)(2) ground-water travel-time performance objective requires (1) characterizing the pre-waste-emplacement environment and its potential spatial and short-term temporal variabilities, (2) determining flow paths in the flow domain, and (3) identifying the fastest path of likely radionuclide travel.

Paths of likely radionuclide travel will be identified in two ways. First, the information regarding the site will be evaluated directly. This evaluation will involve examination of what is known about the features of the site. The properties and behavior of these features will be evaluated

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with regard to the likelihood of radionuclide travel. For example, transport and flow characteristics of the fractures near the Ghost Dance fault will be evaluated. Similarly, the likelihood for lateral diversion of the flow and the transport of radionuclides at contacts of the hydrogeologic units will be evaluated.

Secondly, pathways for likely radionuclide travel will be identified by numerical modeling of the ground-water flow. A distribution of ground-water travel times will be determined for the entire site taking into account the uncertainties in hydrologic properties, the reasonable models of water movement (i.e., matrix versus fracture flow) and ranges of boundary and initial conditions that are plausible. The pre-waste-emplacement ground-water travel time will be determined for each of the paths of likely radionuclide travel. In each case, the variation and uncertainty in values of hydraulic properties will be taken into account in evaluating the ground-water travel time. These analyses will result in probability distributions of travel times for each of the various pathways. These distributions, or their means, can be compared to determine which one or ones are the fastest path of likely radionuclide travel.

Currently, travel-time distributions have been estimated only by simplified one-dimensional modeling (Sinnock et al., 1986). The simplifying one-dimensional assumptions will be modified to account for the dependence between outflow locations, travel times, and quantities. Such dependence and interaction are likely to occur in the actual multidimensional flow system. Therefore, analyses that either directly or indirectly account for two-dimensional or three-dimensional flow will be used to incorporate the uncertainty in identifying flow path correlations in the predicted travel times with such features of the site as fault zones, or area of similar thicknesses of hydrogeologic units, or strong spatial correlation of properties in localized regions of the site. For example, the probability distribution for the site may display multimodality that can be identified with geometrically and geographically distinct site features. Even without obvious modality in the probability distribution associated with distinct site features, geometric and geographic characteristics and locations of the most rapid flow time can be identified using standard statistical techniques.

A general conceptual model of flow in the unsaturated zone was presented in Section 3.9. This general conceptual model is flexible enough to accommodate various alternative hypotheses that are based on current understanding of the hydrogeologic characteristics at the site. Each of the alternative hypotheses may produce different likely paths for radionuclide travel.

Data collected under the geohydrology program (Section 8.3.1.2) will be used to quantify ground-water flow characteristics and uncertainties along the possible flow paths. As additional data are collected, the number of alternative conceptual models necessary to consider will decrease. Numerical modeling based on alternative conceptual models will provide quantitative predictions of flow fields and pathways. These models will evolve as new data become available during the characterization process. Using one or more models of the hydrology of the unsaturated and saturated zones at Yucca Mountain, the range of likely flow paths will be determined. Because current concepts include the possibility of lateral diversion of flow in the unsatu-

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rated zone, determination of flow paths in the unsaturated zone will entail two-dimensional calculations. The definition of flow paths will be coordinated with activities under the geohydrology program (Section 8.3.1.2).

If the accepted definition of a fastest path of likely radionuclide travel incorporates flow from the entire disturbed zone boundary, then the fastest paths will be identified as those originating at that boundary, and the vitric Calico Hills unit will be a primary barrier. If the geometric location of the fastest path can be defined, the facility location could be changed, if necessary, to ensure adequate thickness of specific hydrogeologic units to provide high confidence of 1,000-yr travel times.

8.3.5.12.3.1 Activity 1.6.3.1: Analysis of unsaturated flow system

The objective of this activity is to determine which flow paths or sets of flow paths of likely radionuclide travel in the unsaturated zone will be used in ground-water travel time calculations.

8.3.5.12.3.1.1 Subactivity 1.6.3.1.1: Unsaturated zone flow analysis

Objectives

The objective of this subactivity is to determine pre-waste-emplacement unsaturated flow paths from the disturbed zone to the water table. This description of flow paths will be performed in conjunction with Activity 8.3.1.2.2.9.5. The fastest path of likely radionuclide travel through the unsaturated zone will be identified.

Description

Concepts of the behavior of fluid flow in fractured, unsaturated tuff media will be used in conjunction with Study 8.3.1.2.2.9 to develop and apply two-dimensional numerical models of unsaturated flow. Flow paths in the unsaturated zone will be simulated. Likely paths of radionuclide travel will be identified.

8.3.5.12.3.1.2 Subactivity 1.6.3.1.2: Saturated zone flow analysis

Objectives

The objective of this subactivity is to determine which flow paths or set of paths of likely radionuclide travel in the saturated zone will be used in ground-water travel time calculations.

Description

The local region around Yucca Mountain will be modeled in conjunction with studies described in Section 8.3.1.2.3 by two-dimensional finite-element analysis to support the ground-water travel-time calculations. The two-dimensional models will be evaluated for applicability to the travel-time determination. If necessary to reach the necessary confidence in travel-time predictions, a two-dimensional model of a single layer will be developed. A three-dimensional or quasi-three-dimensional modeling approach would be developed only if two-dimension models are shown to be inadequate. The head field will be predicted based on a set of conductivity values, and boundary head values will be interpreted from the regional model developed under Section 8.3.1.2.3.3. The finite-element mesh will be drawn to follow known or suspected geologic features that may influence fluid flow. Flow paths will be simulated in the saturated zone. This activity will be coordinated with the saturated zone modeling performed in Section 8.3.1.2.3.3.3. Part of this activity will entail defining the boundary of the accessible environment based on the direction of ground-water flow in the saturated zone.

8.3.5.12.4 Information Need 1.6.4: Determination of the pre-waste-emplacement ground-water travel time along the fastest path of likely radionuclide travel from the disturbed zone to the accessible environment

Technical basis for addressing the information need

Link to the technical data chapters and applicable support documents

Chapter 3 provides information on current estimates of ground-water travel time.

Parameters

This information need is a rollup of the previous information needs under this issue. Therefore, the output from these information needs will be used as the basis for determining the pre-waste-emplacement ground-water travel time.

Logic

The determination of the pre-waste-emplacement ground-water travel time should account for spatial and temporal variabilities and uncertainties in the data and models. The difficulty of quantifying uncertainty in the performance measure for the ground-water travel-time objective is recognized by the NRC (Codell, 1986). As yet, the NRC has not indicated the specific basis under which a ground-water travel-time modeling approach would be judged adequate in accounting for such uncertainty.

The uncertainty in ground-water travel time is associated with uncertainties in both conceptual models and measurement of hydrologic properties. Ground-water travel time is considered a function of several spatially distributed hydrologic properties such as effective porosity and permeability. These properties are spatially distributed in a heterogeneous fashion. The heterogeneity is characterized by a length scale that approximately expresses the spatial correlation of hydrologic properties.

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Uncertainty will always exist about the representative values for effective porosities, hydraulic conductivities, and moisture contents of the various rock units at Yucca Mountain, particularly in unsampled regions. Conservative assumptions will be adopted to compensate for the inherent uncertainty in the data and models. Means and variances of the parameter values can be estimated and used with a Monte Carlo approach to account for the uncertainty caused by heterogeneity. If spatially varying parameters (represented by a covariance matrix) can be estimated, then stochastic models or conditional simulations will be applied. Statistical estimates of parameter values from results of well-designed drilling, sampling, and testing programs in conjunction with defensible conceptual models based on appropriate field tests will provide a quantified ground-water travel-time distribution function that incorporates most, if not all, sources of uncertainty.

Ground-water travel-time values are, of course, highly dependent upon the conceptual hydrologic models (to be determined within Section 8.3.1.2) for both the unsaturated and saturated zones. The conceptual hydrologic models are the bases for the formulation of the mathematical models to be used in predicting future hydrologic behavior of the site. In the calculation of the ground-water travel-time distribution function required for resolution of this issue, uncertainties in the conceptual model will be addressed. The uncertainties to be addressed include variations in the possible modes of water movement (i.e., matrix versus fracture flow), the hydrologic initial and boundary conditions, and the hydrologic property values and their intercorrelation. These uncertainties will be investigated within this issue and the geohydrology program (Section 8.3.1.2).

8.3.5.12.4.1 Activity 1.6.4.1: Calculation of pre-waste-emplacement ground-water travel time

The objective of this activity is to define performance measures and perform related analyses of pre-waste-emplacement ground-water travel time. This activity includes two subactivities.

8.3.5.12.4.1.1 Subactivity 1.6.4.1.1: Performance allocation for Issue 1.6

Objectives

The objective of this subactivity is to continually evaluate and, if necessary, update performance allocation for Issue 1.6.

Description

Analyses will be conducted to calculate quantitative estimates of ground-water travel time. The predicted values can be compared directly with the performance goals defined for issue resolution. The strategy for issue resolution outlined in Section 8.3.5.12 will be updated if necessary.

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8.3.5.12.4.1.2 Subactivity 1.6.4.1.2: Sensitivity and uncertainty analyses of ground-water travel time

Objectives

The objective of this subactivity is to determine the sensitivity and uncertainty of ground-water travel time.

Description

Sensitivity analyses will be performed to determine how the ground-water travel time changes as a function of changes in input parameters and conceptual models. Complementary uncertainty analyses will be done to determine how much confidence may be placed in a predicted output parameter based on uncertainties in input parameters.

8.3.5.12.4.1.3 Subactivity 1.6.4.1.3: Determination of the pre-waste-emplacement ground-water travel time

Objectives

The objective of this subactivity is to determine pre-waste-emplacement ground-water travel time at the Yucca Mountain site for comparison with the performance objective in 10 CFR 60.113(a)(2).

Description

Pre-waste-emplacement ground-water travel time will be calculated along the fastest path of likely radionuclide travel. The present planning basis is to calculate ground-water travel times in accordance with the description given in the logic section for this information need, and within the context of the uncertainties that result from the absence of an approved definition and approach for determining the "fastest path of likely radionuclide travel."

8.3.5.12.5 Information Need 1.6.5: Boundary of the disturbed zone

Technical basis for addressing the information need

Link to the technical data chapters and applicable support documents

Chapters 6 and 7 provide design data for current estimates of the disturbed zone. Chapters 1, 2, 3, and 4 provide information on site characteristics that might change after repository development.

Logic

This information need deals with determining the boundary of the disturbed zone. Because the location of the boundary of the disturbed zone depends on repository-induced changes in physical or chemical properties that

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may have a significant effect on the performance of the geologic repository, it is different from the remainder of the information needs under this issue which deal only with pre-waste-emplacement conditions.

In 10 CFR Part 60.2, the NRC defines the disturbed zone as "the portion of the controlled area the physical or chemical properties of which have changed as a result of underground facility construction or as a result of heat generated by the emplaced radioactive wastes such that the resultant change of properties may have a significant effect on the performance of the geologic repository." The definition poses two questions:

1. What physical or chemical changes can have a significant effect on the repository's performance?

2. What constitutes a significant effect on the repository's performance?

The NRC staff addressed these questions in a draft generic technical position (GTP): "Interpretation and Identification of the Disturbed Zone in the High Level Waste Rule; 10 CFR Part 60" (NRC, 1986b). The NRC staff proposed that the disturbed zone be defined "by the zone of significant changes in intrinsic permeability and effective porosity caused by construction of the facility or by the thermal effects of the emplaced waste." This position presumes that permeability and porosity changes are appropriate surrogates for changes in performance. The NRC staff further considers "that the pre-waste-emplacement ground-water travel time will still be an appropriate measure of the overall geologic setting performance for the purpose of licensing." In an earlier version of the draft GTP (April 1985, page 8), the NRC staff explained what constitutes a significant change in intrinsic permeability and effective porosity; "the meaning of 'significant' in this context is considered to be about a factor of two change in effective porosity, which would generally correspond to about an order of magnitude change in intrinsic permeability." Coupling the NRC definition with the NRC staff's guidance, the Yucca Mountain Project will determine the size of the disturbed zone in the following manner:

1. The likely paths of ground-water travel in the pre-waste-emplacement environment will be identified (Information Need 1.6.3, Section 8.3.5.12.3).

2. Ground-water travel time along these paths will be taken as a primary indicator of performance, as related to the definition of the boundary of the disturbed zone. Because of the general importance of effective porosity and intrinsic permeability in calculating travel times, changes in these two properties along the paths (probably confined to the matrix, not the fractures) will be taken as measures used to define the boundary of the disturbed zone.

3. Repository-induced changes to effective porosity and intrinsic permeability will be determined along the identified likely paths of ground-water travel. Because the likely paths are presently expected to be matrix-dominated and vertically downward in the unsaturated zone, only the matrix properties will be considered at this time. The disturbed zone is presumed to be contained entirely

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> within the unsaturated zone. The point(s) along the paths where effective matrix porosity would decrease more than two times relative to the pre-waste-emplacement conditions or matrix permeability would decrease by a factor of 10 times will mark the outer boundary of the disturbed zone.

As more information becomes available regarding possibilities of fracture flow, lateral ground-water flow and paths of likely ground-water travel (Sections 8.3.1.2.2 and 8.3.1.2.3), the present basis for defining the boundary of the disturbed zone will be reevaluated. If site information indicates that the likely path is one of fracture-dominated flow, changes in intrinsic fracture properties rather than intrinsic matrix hydrologic properties will be used to determine the boundary of the disturbed zone.

Several of the hydrogeologic units within the unsaturated zone may be considered in calculations that investigate how the repository changes the ground-water flow field. Properties and conditions in some of these units, particularly those more than 50 to 100 m from the waste, will probably be needed only to provide accurate boundary conditions for analyses. Only the unsaturated Topopah Spring, the unsaturated Calico Hills vitric, and the unsaturated Calico Hills zeolitic units have performance measures and goals associated with delineation of the disturbed zone boundary. The present concepts of ground-water flow and design of the repository suggest that the boundary of the disturbed zone probably will be contained within the Topopah Spring welded unit. The unsaturated Calico Hills vitric unit and Calico Hills zeolitic unit are assigned goals because future design changes could increase the areal power density of the repository enough to cause significant property changes in them, particularly temperature-induced mineral alterations. In determining an approach to fulfilling this information need, the following guidance from the most recent NRC draft technical position paper (NRC, 1986b) was considered:

> A disturbed zone of five diameters for circular openings, 5 opening heights for noncircular openings, or 50 meters, whichever is largest, from any underground opening, excluding surface shafts and boreholes, may be the minimum appropriate distance for use in calculations of compliance with the pre-waste-emplacement ground-water travel-time criterion.

The reference design for the Yucca Mountain repository calls for underground openings approximately 25 ft (8 m) wide and 22 ft (7 m) high (Chapter 6). Five times the maximum dimension is 40 m and is less than 50 m, therefore, by the NRC staff guidance, the disturbed zone should have a minimum value of 50 m.

Using this guidance and the expectation that significant effects on the performance of the repository will be caused by changes in the hydrologic properties within the Topopah Spring welded unit, site-specific information will determine the extent of the disturbed zone. For convenience in determining what this information should be, the following discussion uses the performance allocation terms (performance measures and goals) developed for the issue resolution strategy (Section 8.2). The performance goals assigned in this discussion, if met, will ensure that the disturbed zone is less than, and perhaps much less than, 50 m in extent.

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Some differences exist between the Yucca Mountain Project and the NRC draft GTP in the approach used to define the boundary of the disturbed zone. The GTP states that the disturbed zone is "the zone of significant changes in intrinsic permeability and effective porosity" where "significant changes" was suggested to be about a factor of two change in effective porosity or an order of magnitude change in permeability. 10 CFR 60.2 states that the disturbed zone is "that portion of the controlled area the physical or chemical properties of which have changed...such that the resultant change of properties may have a significant effect on the performance of the geologic repository." The Yucca Mountain Project believes 10 CFR Part 60 offers the opportunity for a more realistic and flexible approach to defining the disturbed zone. The guidance in the GTP infers that changes in the intrinsic permeability of the rock mass are appropriate surrogates for one quantity, ground-water travel time, which itself is an appropriate surrogate for total repository performance. In the unsaturated zone, there will probably not be such a direct correspondence between the intrinsic permeability of the rock mass and ground-water travel time. An order-of-magnitude change in permeability or a factor-of-two change in porosity of either the matrix or fractures will probably cause less than an order-of-magnitude change in the ground-water travel time. The definition for a significant change in intrinsic hydrologic properties may be different for the Yucca Mountain site.

The GTP suggests a minimum distance of 50 m for the disturbed zone boundary based largely upon considerations of stress redistribution around openings. The GTP states that the no-stress-change contour (at which presumably changes in permeability will be eliminated) could be conservatively estimated to be about five times the opening height for noncircular openings or five times the diameter for circular openings. Using 10 m as the appropriate length, a value of 50 m was obtained. However, the Yucca Mountain Project believes that the distance to a contour of minimal changes in permeability is more likely to be two to three diameters (Rautman et al., 1987). This could place the boundary of the disturbed zone at much less than 50 m.

Because the Yucca Mountain Project considers the boundary of the disturbed zone to be at a distance dictated by effects on the performance of the repository, that boundary may be significantly less than the 50-m boundary suggested by the NRC GTP. Ground-water travel time is acknowledged by the DOE as strongly associated with the overall performance of the repository. Effective porosity and permeability are tentatively accepted as reasonable surrogates for ground-water travel time. For this reason, all performance measures for this information need are related to induced changes in matrix permeability and effective porosity. The changes in matrix properties are of primary concern because the movement of water is currently thought to be primarily through the tuff matrix.

Table 8.3.5.12-4 lists the processes of concern in defining the boundary of the disturbed zone; they are processes that could, in principle, change the intrinsic hydrologic properties of the rock. The processes listed in the table are based on the NRC draft technical position paper, which suggested the following processes be considered in determining the boundary of the disturbed zone: (1) stress redistribution, (2) construction and excavation, (3) thermomechanical processes, and (4) thermochemical processes. The first three of these processes could change the permeability of the matrix.

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Because ground-water flow is expected to be dominantly through the matrix, stress redistribution, which primarily affects fracture hydrologic properties, is not expected to affect the location of the disturbed zone boundary. "Fracture activation caused by mining and heating," is listed in Table 8.3.5.12-4 to represent the first three processes. The fourth process, thermochemical processes, is addressed by the remaining four entries in the table, one for each of the hydrogeological units that are within about 100 m of the repository horizon.

Matrix porosity and permeability are listed explicitly as performance measures only for the Topopah Spring welded unit because it is the only unit along the expected path of ground-water flow from the repository to the water table in which it is thought there could be significant changes in hydrologic properties. Until "significant change" in matrix porosity and permeability is defined for the Yucca Mountain site, the disturbed zone will be approximated by the extent of (1) increases in matrix permeability of more than an order of magnitude and (2) decreases in matrix porosity of more than a factor of 2.

A temperature limit is used as a performance measure for the remainder of the units. The associated performance goal of 115°C was set to limit mineral alteration and dehydration. This goal is indirectly related to changes in intrinsic porosity and permeability. At this time, this goal is also expected to limit the changes in intrinsic hydrologic properties to values no greater than those used as a performance goal for the Topopah Spring welded unit. This assumption will be tested as part of the geochemistry program described in Section 8.3.1.3.

Because the definition of the disturbed zone is not governed by any direct numerical regulatory criteria, and because it is expected that the ability to show compliance with the 1,000-yr ground-water travel-time performance criterion will not be very sensitive to the quantitative definition of the disturbed zone boundary (Issue 1.6), the confidence level for each performance goal in Table 8.3.5.12-4 is set qualitatively as "medium."

Parameters

The information required to address Information Need 1.6.5 is listed in Table 8.3.5.12-5. These information items are required under the assumption of matrix-dominated flow. If this assumption is shown to be invalid, the current strategy will be modified and additional fracture flow characteristics may be required. However, those additional parameters are already called for by Information Need 1.6.1 (Section 8.3.5.12.1) and it is believed that no testing would be required by this information need.

The following steps will be used to define and provide supporting evidence for the boundary of the disturbed zone:

Step 1. Obtain information on the likely ground-water flow path and mode of travel from the repository to the water table environment before waste emplacement. Determine the values of intrinsic matrix permeability and effective matrix porosity along this path. If continuous fracture flow becomes the likely ground-water flow path, reevaluate the

Table 8.3.5.12-4. Summary of performance allocation for defining the boundary of the disturbed zone

Hydrologic unit	Process concern	Performance measure	Performance goal	Needed confidence[a]	Approach
Topopah Spring welded unit	Thermomechanical processes: fracture activation caused by mining and heating	Boundary of repository induced changes in effective fracture porosity	Less than a factor of 2 increase in fracture aperture along flow path 50 m from the underground facilities boundary if predominately fracture flow	Medium	Studies are not presently planned because flow is expected to be predominately in the matrix
	Thermochemical processes: alteration within the portion of the Topopah Spring that is considered to be the repository horizon	Boundary of repository induced changes in effective matrix porosity and matrix permeability	Less than a factor of 2 decrease in effective porosity or less than an order of magnitude increase in permeability along the flow path to the accessible environment	Medium	Studies will be completed to determine if mineral alteration can cause factor of 2 decreases in effective porosity or order of magnitudes increases in permeability
Calico Hills nonwelded zeolitic unit	Zeolite alteration below the repository horizon	Temperature	<115°C	Medium	At the temperatures listed as goals, minimal property changes as a result of mineral alteration are expected. Studies will be completed at these temperatures to test the position that there will be minimal changes in rock properties
Calico Hills nonwelded vitric unit	Glass alteration below the repository horizon	Temperature	<115°C	Medium	
Altered vitrophyre below the Topopah Spring welded unit	Clay alteration below the repository horizon	Temperature	<115°C	Medium	

[a]Medium equals a value corresponding to one standard deviation on the most deleterious side of a probability distribution function of the performance measure.

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present strategy used to determine the boundary of the disturbed zone. The locations of the likely ground-water flow paths and modes of flow from the repository to the water table are needed to make this decision.

Step 2. Obtain predictions of matrix hydrologic-porosity changes (porosity and permeability) under expected repository conditions. Matrix porosity and permeability changes as a result of geochemical alteration are needed to complete this step.

Step 3. Evaluate the extent and duration of repository-induced changes along the flow path of interest by performing thermohydrologic analyses using data that bound the expected site characteristics (i.e., include the repository-induced changes in site characteristics).

Table 8.3.5.12-5. Parameter needs for defining the disturbed zone

Item number	Information item description
1	Location of the likely ground-water flow path and mode of flow from the repository to the water table
2	Predicted average travel time and bounds on the travel time along the fastest unperturbed path from the repository location to the accessible environment
3	Reference underground facility designs (including borehole spacing and spacing waste canisters within the emplacement holes)
4	Thermal decay characteristics of the waste package
5	In situ temperature conditions
6	Bulk density
7	Altitude of the hydrogeologic unit contacts
8	Location and displacements of faults within approximately 0.5 km of the outer repository boundary
9	Altitude of the water table
10	Location of any perched-water zones
11	Thermal properties of the rock as a function of saturation (including thermal conductivity and heat capacity) thermal expansion

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Table 8.3.5.12-5. Parameter needs for defining the disturbed zone (continued)

Item number	Information item description
12	Saturation (and moisture content) values as a function of depth and lateral spatial location
13	Pressure head values as a function of depth and lateral spatial location
14	Thermohydrologic response of test under nonisothermal test conditions
15	Fracture and matrix saturated permeability
16	Relative permeability for the fracture network and matrix as a function of temperature
17	Gas relative conductivity for the fracture network and matrix as a function of temperature
18	Moisture retention curves for wetting and draining
19	Effective porosity and porosity of the fracture network, fault zones, rock mass, and matrix
20	Changes in porosity and permeability of matrix due to construction and heat from waste emplacement
21	Ground-water percolation flux at the top of TSw2 (portion of Topopah Spring welded unit proposed for repository unit)

Step 4. Determine quantitatively what would be considered a significant change in the intrinsic hydrologic properties by considering how the ground-water travel time before repository construction and waste emplacement compares with what could be expected after repository construction and waste emplacement in the portion of the rock that has been changed. The original range and mean of the matrix hydrologic properties will also be considered in determining a quantitative value for a significant change in hydrologic properties. The results of step 3 will be needed to complete this step.

Step 5. Review the repository-induced changes in ground-water flow to determine whether there are other repository-induced changes identified in step 3 that could significantly change the

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ground-water travel time from the repository to the accessible environment. Evaluate whether a new strategy for determining the boundary of the disturbed zone should be initiated.

Step 6. If necessary, revise the preliminary estimate of the boundary of the disturbed zone using the new predictions of matrix hydrologic property changes and the quantitative definition of significant property changes determined in Step 4.

8.3.5.12.5.1 Activity 1.6.5.1: Ground-water travel time after repository construction and waste emplacement

Objectives

The objective of this activity is to predict the ground-water travel time to the water table using the hydrologic properties changed as a result of repository construction and waste emplacement for comparing pre- and postemplacement travel times to establish the extent of the disturbed zone.

Description

Using a combination of (1) a two-phase, nonisothermal flow code with the region of significant temperature changes and (2) an unsaturated isothermal code outside that region with boundary conditions determined from a thermal-conduction calculation, the movement of gas and liquid along with the temperature distribution in the near-field region as a function of time will be predicted. The following information will be used to help determine the geometry and boundary conditions for the problem: (1) reference underground facility designs, (2) distribution of rock properties, (3) temperature at the water table and the surface, (4) geothermal gradient, (5) location of the water table, and (6) initial pressure head and saturation conditions. The following information will be used as input for the calculations: (1) initial pressure head and saturation conditions, (2) hydrologic properties of the rock units before and after repository construction and waste emplacement (items 16 through 21 from the parameter list), (3) thermal properties of the rock units (the Topopah Spring as well as surrounding rock units), (4) bulk density, (5) hydrologic and thermomechanical unit contacts, and (6) location of perched-water zones.

8.3.5.12.5.2 Activity 1.6.5.2: Definition of the disturbed zone

Objectives

The objective of the activity is to reevaluate the definition of the disturbed zone.

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Description

This activity will reevaluate and, if necessary, refine the boundary of the disturbed zone using the following information: (1) preliminary definition of the boundary of the disturbed zone, (2) the NRC guidance, (3) the average and fastest likely path of a nonsorbing radionuclide, (4) predicted bounds on the travel time along the average and fastest unperturbed path from the repository location to the accessible environment, and (5) changes in hydrologic rock characteristics that are significant. Although this activity is identified only once, it may be a recurring one. The possibility of recurrence depends on changes in NRC guidance and the understanding of the changes in properties caused by the repository.

8.3.5.13 Issue resolution strategy for Issue 1.1: Will the mined geologic disposal system meet the system performance objective for limiting radionuclide releases to the accessible environment as required by 10 CFR 60.112 and 40 CFR 191.13?

Regulatory basis for the issue

The regulation that governs this issue is given in Section 60.112 of 10 CFR Part 60. This regulation implements the containment requirements of 40 CFR 191.13(a):

> Disposal systems for spent nuclear fuel or high-level or transuranic wastes shall be designed to provide a reasonable expectation, based upon performance assessments, that the cumulative releases of radionuclides to the accessible environment for 10,000 years after disposal from all significant processes and events that may affect the disposal system shall:
>
> (1) Have a likelihood of less than one chance in 10 of exceeding the quantities calculated according to Table 1 (Appendix A); and
>
> (2) Have a likelihood of less than one chance in 1,000 of exceeding ten times the quantities calculated according to Table 1 (Appendix A).

Appendix A of 40 CFR Part 191 gives, in table form, the radionuclide release limits that will be used to make the calculations referred to above. These limits, expressed as curies (Ci) per 1,000 MTHM, are the release limits for each radionuclide to be used in calculating the normalized release to the accessible environment per Appendix A, 40 CFR Part 191 and are as follows:

Americium-241 or 243	100
Carbon-14	100
Cesium-135 or 137	1,000
Iodine-129	100
Neptunium-237	100
Plutonium-238, 239, 240, or 242	100
Radium-226	100
Strontium-90	1,000
Technetium-99	10,000
Thorium-230 or 232	10
Tin-126	1,000
Uranium-233, 234, 235, 236, or 238	100
Any other alpha-emitting radionuclide with a half-life greater than 20 years	100
Any other radionuclide with a half-life greater than 20 years that does not emit alpha particles	1,000

Note that these limits do not represent the maximum allowable cumulative release of these radionuclides when more than one radionuclide is released

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during the performance period. Adjustments for fuel burnups are also needed (see Appendix A, 40 CFR Part 191).

The U.S. Department of Energy (DOE) understands the term "accessible environment" to mean (1) the atmosphere, (2) land surfaces, (3) surface waters, (4) oceans, and (5) all the lithosphere that is beyond the controlled area. Likewise, the DOE understands the term "controlled area" to mean (1) a surface location, to be identified by passive institutional controls, that encompasses no more than 100 km^2 and extends horizontally no more than 5 km in any direction from the outer boundary of the underground facility, and (2) the subsurface underlying such a surface location.

The phrase "significant processes and events that may affect the geologic repository" is interpreted as meaning likely natural events and such other processes and events that could affect a geologic repository and are sufficiently credible to warrant consideration. Significant processes and events that may affect a geologic repository may either be natural processes and events or processes and events initiated by human activities other than those licensed under 10 CFR Part 60. Processes and events initiated by human activities may only be found to be sufficiently credible to warrant consideration if it is assumed that: (1) the monuments provided for by this part are sufficiently permanent to serve their intended purpose; (2) the value to future generations of potential resources within the site can be assessed adequately under the applicable provisions of this part; (3) an understanding of the nature of radioactivity, and an appreciation of its hazards, has been retained in some functioning institutions; (4) institutions are able to assess risk and to take remedial action sufficient to prevent persistent or systematic releases resulting from human-induced disruptions of a repository; and (5) relevant records are preserved, and remain accessible, for several hundred years after permanent closure.

Overview of the performance assessments for this issue

The DOE plans to demonstrate compliance with the total system performance objective by conducting performance assessments. These performance assessments will (1) identify all significant processes and events that may affect the geologic repository, (2) evaluate the effects of these processes and events on the release of radionuclides to the accessible environment, (3) combine estimates of these effects to the extent practicable into a complementary cumulative distribution function (CCDF) displaying the likelihood that the amount of radioactive material released to the accessible environment will not exceed the specified values, and (4) compare the numerical predictions with the performance objective, evaluating the importance of any uncertainties on conclusions from this comparison.

The significant processes and events to be taken into account in these performance assessments will be identified by developing scenarios that specify a sequence of processes and events potentially resulting in significant impacts on the variables of the systems important to waste isolation. Scenarios will be developed for undisturbed conditions (those conditions caused by likely natural events) and for disturbed conditions that are sufficiently credible to warrant consideration. In addition to providing an approach to organizing the information regarding significant processes and events for this issue, these scenarios provide a vehicle for the evaluation

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of the favorable and potentially adverse conditions of 10 CFR 60.122 for the resolution of Issue 1.8 (Section 8.3.5.17).

The remainder of this section discusses a methodology for the performance assessments and for defining suitable information needs for the resolution of this issue. The methodology that will actually be used in preparing the license application may differ from the methodology proposed here. For example, information developed during the site characterization may suggest a different approach that may be more efficient in conveying the assessment of the repository. However, it is the judgment of the DOE, based upon the available information, that the proposed approach will lead to the information needed for the DOE to present its case for the Yucca Mountain site, whichever methodology is chosen.

The following discussion addresses five topics:

1. Methods for constructing a CCDF.
2. A preliminary selection of events, processes, and scenario classes for the Yucca Mountain repository site.
3. Models for evaluating radionuclide releases in the scenario classes.
4. A preliminary performance allocation for Issue 1.1.
5. Summary of licensing and issue resolution strategy for Issue 1.1.

1. Methods for constructing a complementary consulative distribution function

Definitions

With noted exceptions, the following definitions of terms are used throughout the remainder of this section. The term "period of performance" means the 10,000-yr period that follows closure of the repository. An "event" means a natural or anthropogenic phenomenon that takes place during an interval of time that is very short compared with the period of performance; for all practical purposes, events are regarded as discrete occurrences. Conversely, a "process" means a natural or anthropogenic phenomenon that exhibits continuous change over the entire period of performance. A "feature" (usually modified by the adjectives "undetected" or "undiscovered") means an object, structure, or condition that may exist at the repository site at the time of closure. A "scenario" means a sequence of definite types of events and processes that act or occur during the period of performance with prescribed intensities, at prescribed epochs or for prescribed durations, in a prescribed order of occurrence. A "scenario class" (or class of scenarios) is defined as the collection of all scenarios involving definite types of events or processes, but with intensities, epochs of occurrence or durations, and orders of occurrence allowed to range freely over the physically possible numerical values. The word "consequence" means the magnitude of the normalized, cumulative release of radioactivity that would occur should a given scenario be realized ("normalized release" is defined later). The term "containment" as applied in the EPA standard, is the same as the term "isolation," as applied by the NRC and in this document.

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Terms and concepts of probability theory are also frequently used in the following pages e.g., random variable, mean, or expectation, distribution function, and density function. Readers who are unfamiliar with these terms are urged to consult textbooks on the subject for their precise meanings. The texts by Feller (1960, 1966) and Ross (1985) are used as primary references in this section. Other terms are defined as needed throughout the remainder of this section.

Conceptual and mathematical background

Quantitative predictions of the behavior of a geologic waste disposal system over periods of thousand of years are necessarily theoretical and mathematical. Like other mathematical assessments of complex systems, an assessment of the future performance of a geologic waste disposal system must eventually be expressed in terms of a finite number of "performance measures," which are usually numerical. Calculated values of these performance measures can be compared with predetermined numerical criteria that presumably define an acceptable range of system behavior and then judgments concerning the relative worth of the system can be made on the basis of these comparisons.

The performance criterion in this case is specified in the containment requirements of the EPA standard, 40 CFR 191.13, which is to be implemented by the NRC performance objective for overall system performance. This criterion implicitly defines a performance measure of the form

$$M = \sum_i \frac{Q_i}{L_i} \qquad (8.3.5.13\text{-}1)$$

where

M = normalized release from the total system,

Q_i = cumulative radioactivity of the i^{th} radionuclide released to the accessible environment in the 10,000-yr period following closure from significant processes and events that may affect the disposal system (Ci),

L_i = release limit for the i^{th} radionuclide as specified in the regulations (Ci). (See 40 CFR Part 191, Appendix A, for the calculation of these limits.)

The values of the performance measure (M) are not to be simply estimated and compared with a range of acceptable standard values, as might be done for a different kind of system. In the guidance and discussion sections of 40 CFR Part 191 relating to the EPA containment standard, 40 CFR 191.13(a), it is explicitly recognized that considerable uncertainty will attach to estimates of M because of the length of the period of performance and the difficulties inherent in predicting far-future system behavior. Therefore, the regulations imply that M must be treated not as a single number or range of numbers, but as a random variable.

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The random variable M may be described by a cumulative distribution function (CDF); the EPA containment standard places conditions on the form taken by the CDF by specifying limits on its complementary cumulative distribution function (CCDF). In terms of the CCDF, the containment standard reads

$$\Pr\{M > 1.0\} < 0.1$$

$$\Pr\{M > 10.0\} < 0.001 \qquad (8.3.5.13\text{-}2)$$

where $\Pr\{\epsilon\}$ stands for the probability that the statement "ϵ" is true.

A CCDF is always a nonincreasing function of a variable, say m, which in the problem of present interest ranges from zero to the normalized inventory of the repository closure. (A hypothetical CCDF is shown as the solid curve in Figure 8.3.5.13-1a.) To show this dependence, the CCDF will hereinafter be denoted by

$$G(m) = \Pr\{M > m\}$$

How would one experimentally construct $G(m)$? In principle, one might imagine the following experiment (which will be called a "thought experiment" for convenience in cross referencing): Construct a large number of replicas of the system, begin operation of each replica at some common time, and at the end of the period of performance observe the number of replicas for which M exceeds any one of a set of predetermined values, say 10^{-1}, 1, 10^{1}, 10^{2}, 10^{3}. If the replicas were real systems, there would always be some uncertainty in the initial state of each replica and the physical conditions under which each replica evolved during the period of performance; consequently, the outcomes of the experiment would very likely be different for each replica. Because the replicas are all prepared in the same way, each is equally likely to correspond to the "real" system. By plotting a histogram of the relative frequency of the number of replicas that are observed to exceed each predetermined value (i.e., the number of replicas exceeding that value divided by the number of replicas in the experiment), one would end up with a step-like approximation to a continuous curve very much like the one shown in Figure 8.3.5.13-1b. Such a curve is called an empirical CCDF. By increasing the fineness of the grid of predetermined exceedance values and the number of replicas in the "thought" experiment, the empirical CCDF could be made to approach a continuous curve such as the one shown in Figure 8.3.5.13-1a.

In practice, such an experimental construction of the CCDF for a waste disposal system is impossible. Nevertheless, the experiment may be mimicked with mathematical models of the system which are capable of generating sample values of M when given a numerical specification of the physical states of the system during the period of performance. The mathematical models, invariably implemented by computer code, are used to generate a large number of sample M's; this action replaces the simultaneous observation of the outcomes for the large number of system replicas in the "thought" experiment. To correspond to the identically prepared system replicas, the states of the system during the period of performance must be specified in a way that

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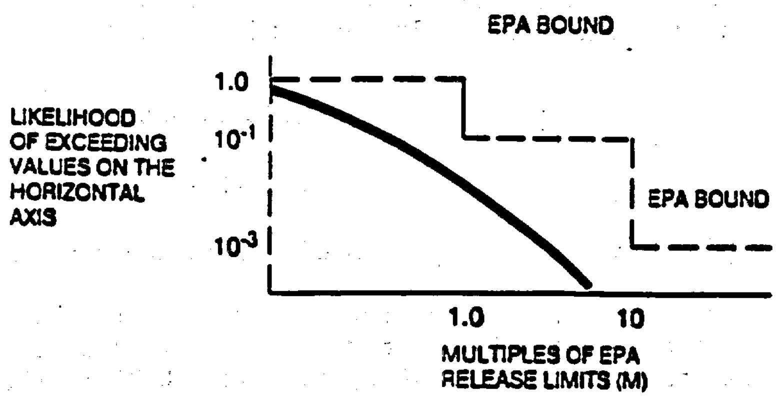

Figure 8.3.5.13-1a. Graphic representation of Environmental Protection Agency (EPA) containment requirements. Modified from NRC (1968)

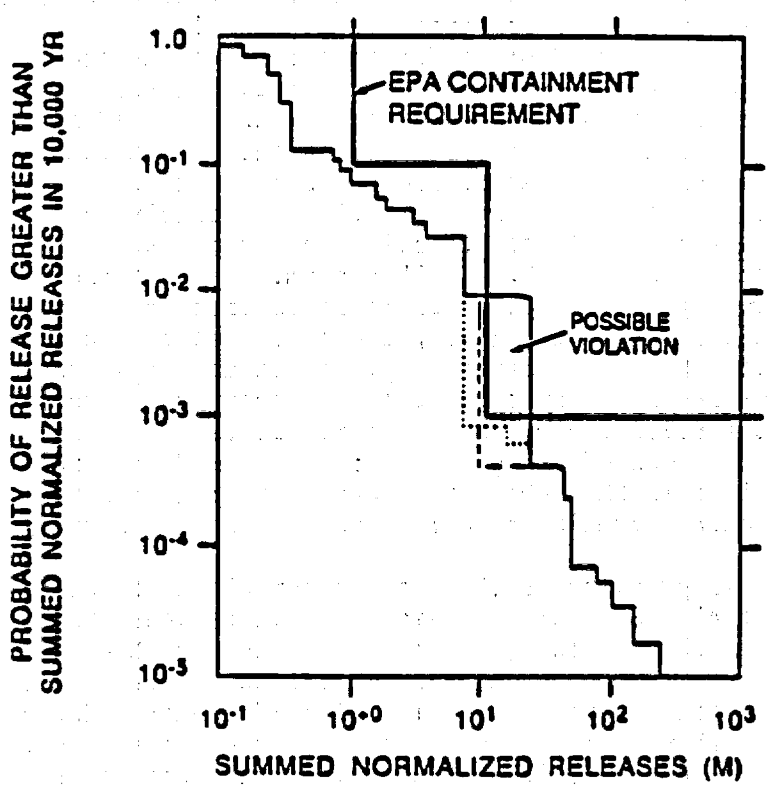

Figure 8.3.5.13-1b. Example of an empirical complementary cumulative distribution function. EPA = Environmental Protection Agency. Modified from Figure 18, Hunter et al. (1986).

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properly reflects their probabilities. The sample M's so generated may then be plotted as a histogram to give an empirical CCDF. Roughly speaking, this is the way the step-like curve in Figure 8.3.5.13-1b (taken from Hunter et al., 1986) was actually constructed.

Formulating, testing, and validating the mathematical models to be used in mimicking the replicas of the "thought" experiment are by far the major tasks of performance assessment. An extended discussion of mathematical modeling of phenomena relevant to geologic waste disposal is beyond the scope of this section (although there will be some description of systems-level models later in the section entitled "models for evaluating radionuclide releases in the scenario classes." Here, it will simply be assumed that there exists a collection of formulae and algorithms which, when implemented on a high-speed digital computer, are capable of transforming any scenario into a value of the performance measure M.

An idealized geologic repository system must be described ultimately by a finite number if dependent variables (here called performance measures). In turn, the performance measures are functionally dependent upon a finite number of independent variables, which are called state variables. The number and nature of the state variable depend upon the level of detail at which the system is modeled and upon the kinds of scenarios to be included in the modeling efforts. In general, state variables can be arranged in a hierarchy, with certain directly measured physical properties of the system (i.e., the data to be obtained during site characterization) forming the base of the hierarchy. Above the base a graded series of aggregations of quantities, each derived from measured properties and theory or from theory alone form the next lower aggregation in the series.

Some concrete examples of highly aggregated state variables for the Yucca Mountain system are

1. Mass of the i^{th} radionuclide in the repository at closure time.

2. Average percolation flux at repository level.

3. The liquid-phase transport time of the i^{th} radionuclide from the repository level to the accessible environment.

4. The times of occurrence of displacement of the Ghost Dance Fault greater than 1 m.

5. The depth of penetration of a future episode of exploratory drilling.

6. The annual rate of erosion of the washes at Yucca Mountain.

7. The effective weights assigned by professional judgment to alternative conceptual models of some site phenomenon or the response of the system to a known site phenomenon.

In any case, there will exist a level in the hierarchy of state variables at which the aggregations of quantities are judged to be sufficient to describe the occurrence, intensity, and perhaps even the subjective

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likelihood of all processes, events, and features making up the scenario classes for release of radioactivity to the accessible environment. In other words, there is a level in the hierarchy of variables that is adequate to describe and model the consequences of all scenarios that have been judged to play a significant role in determining the values of the performance measure.

As described later, the number of state variables necessary in the modeling of sequences is in principle unbounded, but for purposes of discussion, it is assumed that there are N such independent state variables. These variables are conveniently represented as components of a vector

$$\vec{V} = (v_1, v_2, v_3, ..., v_N)$$

and the performance measure is seen to be a function of the state variables that will hereinafter be denoted by $M(\vec{V})$. Note that $\vec{V}$ is to be regarded as the logical union of the sets of all state variables required in the modeling of the consequences.

A degree of uncertainty is usually attached to a state variable, owing to various causes such as measurement error in physical quantities, the spatial and temporal inhomogeneities intrinsic to geologic processes and events, and imprecision in the theories relating the variables in different levels of the state-variable hierarchy. That is, most state variables may be regarded as random variables in that they may take on values in ranges of numbers rather than always taking on a single value. Whether any given variable needs to be treated as a random variable depends upon the size of the ratio of the variable's standard deviation to its mean. If that ratio is very small (as is the case for standard physical constants and the dimensions of most engineered features), the variable need not be regarded as a random variable. If the ratio is nearly one or larger, and if the results of a calculation are particularly sensitive to changes in that variable, it may be necessary to treat it as a random variable in order to capture all uncertainty in system behavior.

The previous examples of state variables support this claim. Example 1 cites quantities that in principle could be measured but in practice will probably be known to within at least 20 percent about their estimated mean value. Examples 4, 5, and 7 are scalar random variables with predictable ranges but presently unknown distributions. Examples 2 and 6 are processes that must be described as random functions of time because both processes depend upon climatic variables whose future behavior is presently unknown. Because of hydrodynamic and geochemical dispersion, which arise from unpredictable inhomogeneities in rock properties, the transport time in example 3, under steady-state conditions, must be regarded as a scalar random variable. Finally, all state variables may not be mutually independent: a good example of correlated state variables are examples 2, 3, and 6; all of these quantities ultimately depend on climatic conditions at the site.

Because some of the components of the state-variable vector are random variables, the performance measure, $M(\vec{V})$, taken as a function of the state variables, must also be a random variable whose properties (mean, variance, and distribution) are determined by the joint distribution of the state variables. The joint CDF for the state variables is denoted by $F(\vec{V})$; and the joint density function associated with $F(\vec{V})$ is simply symbolized by $F(d\vec{V})$

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using notation from Feller (1966). The mean (or expectation) of the performance measure, $\bar{M}$, can be obtained by applying to $M(\vec{V})$ the expectation operator, an operation formally defined here as

$$E[\bullet] \equiv \int_{v_1}\int_{v_2}\cdots\int_{v_N}[\bullet]F(d\vec{V}) \qquad (8.3.5.13\text{-}3)$$

that is

$$\bar{M} = E[M(\vec{V})]$$

Other moments of the CDF for the performance measure can be obtained by applying the expectation operator. For instance, the variance of M (denoted by $\mathrm{Var}[M]$) is

$$\mathrm{Var}[M] = E[(M - \bar{M})^2]$$

The CCDF for the performance measure can be formally represented by

$$G(m) = E[u(M - m)] \qquad (8.3.5.13\text{-}4)$$

where $u(x)$ is the unit step function ($u(x) = 0$ if $x < 0$ and $u(x) = 1$ if $x \geq 0$).

If the joint distribution function $F(\vec{V})$ is continuously differentiable for all the components of $\vec{V}$, then the joint density $F(d\vec{V})$ can be represented in a more familiar form as

$$F(d\vec{V}) = f(v_1, v_2, v_3, \ldots, v_N)dv_1dv_2dv_3\ldots dv_N$$

and the formal expectation operation (Equation 8.3.5.13-3) would be identical with ordinary integration of the quantity $[\bullet]f$ over the ranges of the N state variables. Although $F(\vec{V})$ generally is not differentiable in all variables, the equivalence between evaluation of multiple integrals of large dimension and Monte Carlo simulation (see Hammersley and Handscomb (1964) or Chapter 11 of Ross (1985) suggests that one may evaluate expressions like Equation 8.3.5.13-4 in a manner nearly identical to the scheme for the "thought experiment" outlined earlier. For example, one draws S (>> 1) "samples" from the joint CDF for $\vec{V}$ (say $\vec{V}^1$, $\vec{V}^2$, $\vec{V}^3$, ..., $\vec{V}^S$) and uses each sample value to calculate sample values of the performance measure, for example, $M(\vec{V}^1)$, $M(\vec{V}^2)$, $M(\vec{V}^3)$, ..., $M(\vec{V}^S)$. The sample values of the performance measure may then be arithmetically averaged to give an estimate of $\bar{M}$, or their relative frequency of occurrence may be tabulated and plotted as a histogram to give an empirical distribution function for the performance measure. It follows that the two essential ingredients for construction of an empirical CCDF are (1) a set of consequence models, that is, models that calculate the $M(\vec{V})$ attached to a specific $\vec{V}$s, and (2) a joint distribution function for all uncertain state variables.

In practice, a crude Monte Carlo simulation of the kind just outlined is seldom used, because it is inefficient in the use of random numbers and

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therefore, expensive in computing time. Instead, various "modified" Monte Carlo methods such as Latin hypercube sampling (Iman and Conover, 1982) are used to reduce the variance in the estimate for a given sample size (*). But even if variance-reducing schemes are used, the sample size required for adequate resolution of the empirical CCDF may be large, and so, depending upon the time needed to calculate a sample value, the proposed calculation would still be expensive. Iman and Helton (1985) suggest that "good results are obtained" when

$$S \geq (4/3)N$$

This empirical rule illustrates the impracticability of using highly detailed, two- and three-dimensional computer models of the system in attempts to calculate the CCDF by Monte Carlo simulation. Even a modestly detailed, one-dimensional finite-difference model of liquid-phase flow and solute transport at the site, such as the TOSPAC model (Dudley et al., 1988), could involve on the order of 10,000 uncertain state variables and could require at least several minutes to generate its output on even the fastest digital computer. (In addition, note that the output of the code would only be part of the numerical manipulations needed to calculate a sample value of the performance-measure function associated with a scenario involving many kinds of processes and events.) Although such elaborate and detailed models may be necessary for gaining insight into the behavior of site phenomena, their use in simulations of the total system could result in months of continuous computing time being required to construct an empirical CCDF. The DOE realizes these limitations and will attempt to overcome them by developing relatively simple systems-level models of system behavior and system response for use in calculating the empirical CCDF.

As a final background note: The DOE has noticed that there is a <u>single sufficient</u> condition for satisfaction of the inequalities in Equation 8.3.5.13-2. That condition is derived here since it will be used later in developing an approximate criterion for screening events and processes according to the contributions they may make to the CCDF. The condition follows from Markov's Inequality (Loeve, 1960), which states that, for any nonnegative random variable X and any positive number x,

$$\Pr\{X \geq x\} \leq E[X]/x$$

In other words, a CCDF must be bounded above by the positive branch of the hyperbola defined by $y = E[X]/x$. If this result is applied to Equation 8.3.5.13-2, it can be seen that if the inequality

$$E[M] < 0.01 \qquad (8.3.5.13\text{-}5)$$

is satisfied, then both inequalities in Equation 8.3.5.13-2 are satisfied. As stated, Equation 8.3.5.13-5 is only a <u>sufficient</u> condition; the inequalities in Equation 8.3.5.13-2 may be satisfied even if $E[M] \geq 0.01$, and in such a case, the entire CCDF would have to be constructed to see whether Equation 8.3.5.13-2 is satisfied.

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The Cranwell methodology for constructing a complementary cumulative distribution function

Cranwell et al. (1982) and Hunter et al. (1986) present extended summaries and further references to supporting documents for a methodology for constructing a CCDF that shows compliance with 10 CFR 191.3(a). This methodology is hereinafter called the Cranwell methodology.

The methodology represents the CCDF as a weighted sum of conditional CCDFs. Using the mathematical notation developed in the background material, equation (2) of Hunter et al. (1986) reads

$$G(m) = \sum_j G(m|S_j)P(S_j) \qquad (8.3.5.13\text{-}6)$$

where

S_j = a designator for the j^{th} "scenario"

$P(S_j)$ = probability that S_j is realized

$G(m\,S_j)$ = a conditional CCDF: probability that $M > m$, given that only members of the j^{th} "scenario" are realized.

Scenario is placed in quotation marks in the above definitions because the Cranwell methodology definition of the term apparently includes objects that are more general than the objects defined by this section's definition of scenario; the intended meaning of Hunter et al. (1986) appears to be closer to the term "scenario class".

Any CDF or CCDF may be expanded in the manner indicated by Equation 8.3.5.13-6, provided that the S_j are statistically independent entities (i.e., are mutually exclusive events in the probabilistic sense of the term "event") and that the set of all S_j is exhaustive (that is, the S_js represent all possible outcomes of an experiment, again in the probabilistic sense of the term "experiment"). In other words, $P(S_j) > 0$ for all j and $\sum_j P(S_j) = 1$. The conditional CCDFs, $G(m|S_j)$, are to be calculated in the same way as the unconditional CCDF, $G(m)$, (e.g., by Monte Carlo simulation), using the marginal joint distribution function for those state variables, $\vec{V}j$, that appear in the specification of the j^{th} "scenario." These state variables will, in general, be a subset of the components of $\vec{V}$ and will be denoted in vector form by $\vec{V}j$. The reader should note that construction of each conditional CCDF will generally be easier than construction of the unconditional CCDF. This is because some of the events or features that appear in the specification of the j^{th} "scenario" are, by definition, forced to occur during the period of performance, and therefore fewer random numbers are needed.

That the two representations of a CCDF, Equations 8.3.5.13-4 and 8.3.5.13-6, are formed by the same principle. That is, the expansion of a distribution as a sum of conditional distributions, can be seen by making the following correspondences: the integration operation in Equation 8.3.5.13-3 with the summation in Equation 8.3.5.13-6; the $F(d\vec{V})$ in Equation 8.3.5.13-3 with the $P(S_j)$ in Equation 8.3.5.13-6; and the unit step function $u(M - m)$ in Equation 8.3.5.13-4 with the $G(m|S_j)$ in Equation 8.3.5.13-6.

In the first representation (Equation 8.3.5.13-4), the CCDF is expanded in terms of each scenario in the nondenumerably infinite set of scenarios. The "probability" of a scenario is the infinitesimal quantity $F(d\vec{V})$, and the conditional probability that $M > m$ given that the scenario is realized is the unit step function $u(M - m)$. (Note that the unit step function is a perfectly good CCDF for a quantity that takes a single value, say $M = m^*$, with certainty at some point on the line of real numbers.) It is seen that the requirements of mutual independence and exhaustivity are automatically met by Equations 8.3.5.13-3 and 8.3.5.13-4. The function $G(m)$ defined by these equations will always have the properties of a CCDF (that is, $G(0) = 0$ and $G(m) \geq 0$ for $m > 0$, and $G(m)$ nonincreasing for $m > 0$) provided only that $F(\vec{V})$ is a joint CDF for the state variables $\vec{V}$.

In the second representation (Equation 8.3.5.13-6), the CCDF is expanded in terms of a finite number of mutually independent and exhaustive scenario classes; the probability of each scenario class is the finite quantity $P(S_j)$, and the conditional probability that $M > m$, given that only members of scenario class S_j occur, is $G(m|S_j)$.

The remarks in the preceding paragraphs may help in understanding why it has not been clear how the the requirements of mutual exclusivity and exhaustivity could be met for the kinds of "scenarios" proposed in the Cranwell methodology. The Cranwell methodology (Hunter et al., 1986) bypassed certain logical problems by first assigning values to the $P(S_j)$ (usually, on a subjective basis) and then, if the sum of the $P(S_j)$ was not one, renormalizing to obtain new probabilities:

$$\hat{P}(S_j) = P(S_j)/\sum_j P(S_j)$$

Although this procedure might be justified on the pragmatic grounds that all $P(S_j)$ are very small numbers whose assignments are ultimately based on subjective judgment, it nevertheless violates the logic of probability theory and provides no definite logical pathway for inferring the $P(S_j)$ from the more-fundamental probabilities of the occurrence of events and processes. The preceding discussion is a preliminary comparison of two approaches represented by Equations 8.3.5.13-4 and 8.3.5.13-6.

The U.S Department of Energy approach to choosing scenario classes

The approach used by the DOE to solve the problem of exclusivity and exhaustivity inherent in Equation 8.3.5.13-6 has been to interpret the S_j as scenario classes instead of "scenarios," and to attempt to partition the set of all scenarios into mutually exclusive classes of scenarios. There are many ways in which such a partition might be accomplished, and each way seems to have its own logical problems. The partitioning scheme adopted by the DOE for the purpose of identifying the significant processes and events for inclusion in the CCDF is illustrated below with the help of some examples.

Consider a waste-disposal system in which any number of processes may be operating, but in which only two independent kinds of disruptive events, E_1

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and E_2, may occur. For example, E_1 might be motion along an existing fault, and E_2 might represent exploratory drilling. The probability that event E_k ($k = 1, 2$) occurs at least once during the period of performance is denoted by p_k. The partitioning into four mutually exclusive scenario classes for this hypothetical example is illustrated in the form of an "event tree" in Figure 8.3.5.13-2. This figure requires further explanation. First, note that the sum of the four probabilities $P(S_j)$, $j = 1, 2, 3, 4$, is 1. Next, let S_1 denote the class in which no disruptive events have occurred. This class is often and variously called the expected case, the anticipated case, or the nominal case; all these terms may be misleading because there is no reason to believe that $P(S_1)$ will always be larger than the other three probabilities or the probability used in administratively defining the term anticipated process and events. (The DOE will, however, continue the use of these terms because of their significance in the interpretation of other parts of 10 CFR Part 60.) Finally, note that processes are shown to play no explicit role in this kind of expansion of a CCDF in independent scenario classes; a calculation of the conditional CCDFs, $G(m|S_j)$, that appear in Equation 8.3.5.13-6 would have to be accomplished by Monte Carlo simulation and would require that a common set of sample processes be used consistently for the simulation of each of the conditional CCDFs. In other words, all processes are automatically expected or anticipated in this partitioning scheme.

The formalism of Figure 8.3.5.13-2 can be used to show how undetected features may be included in the definition of independent scenario classes. Suppose that, in addition to the possible occurrence of two kinds of events E_1 and E_2, the possibility of the presence of a feature that could influence releases to the accessible environment is admitted. The feature, F_1, is present at the beginning of the period of performance with probability p_3 and absent with probability $(1 - p_3)$. Figure 8.3.5.13-3 illustrates the way the possibility of an undetected feature will lead to a doubling of the number of independent scenario classes. This figure also applies to situations in which there are two alternatives for the conceptual or mathematical model of some process, event, or condition believed to be important in the determination of releases to the accessible environment. A concrete example of this situation is the conceptual model of recharge under Yucca Mountain (Montazer and Wilson, 1984): is recharge concentrated in highly fractured, structural features lying to the southeast of the mountain, or is it nearly uniform throughout the mountain? Such a two-state alternative model is, for all practical purposes, the same as an undetected feature, because it leads to a doubling of the number of independent scenario classes (but note that there may also be n-state alternative models, where $n > 2$, leading to a multiple of n branches). A simple example of a diagram arising from a two-state alternative model can be found in Figure 9 of Hunter et al. (1986).

All the examples just cited involve only a few independent types of events, undetected features, or two-state alternative models. The formalism for expanding the CCDF in independent scenario classes is nevertheless capable of being generalized to any number of such objects, provided that they are statistically independent entities (i.e., having information about the occurrence of one of them does not change the probability that any of the others will occur). If there are K independent types of objects (events or undetected features or two-state alternative models), there will be $J = 2^K$

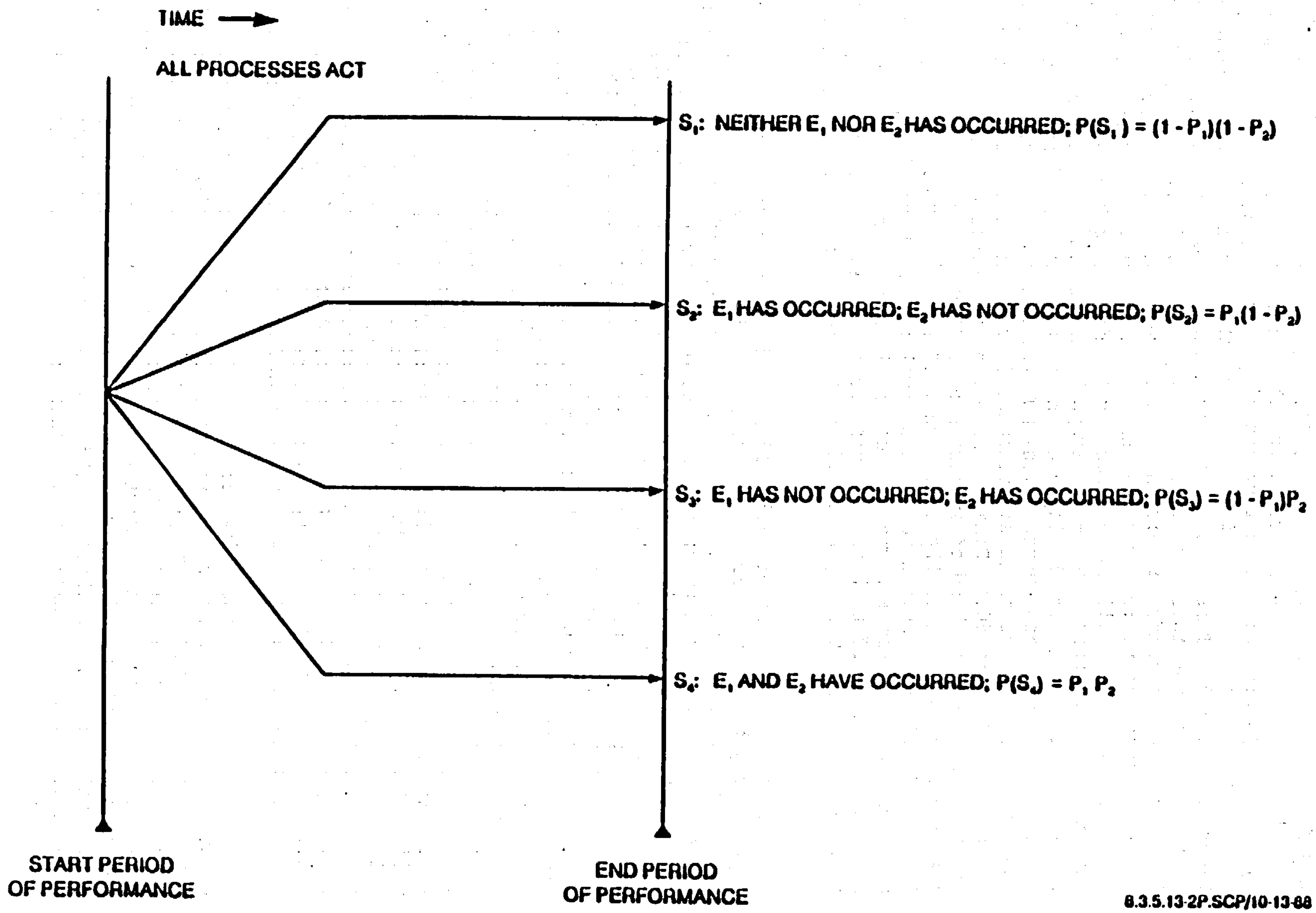

Figure 8.3.5.13 2. An illustration of the expansion of a complementary cumulative distribution function in independent scenario classes Two types of events are assumed (See the text for a further explanation of this figure)

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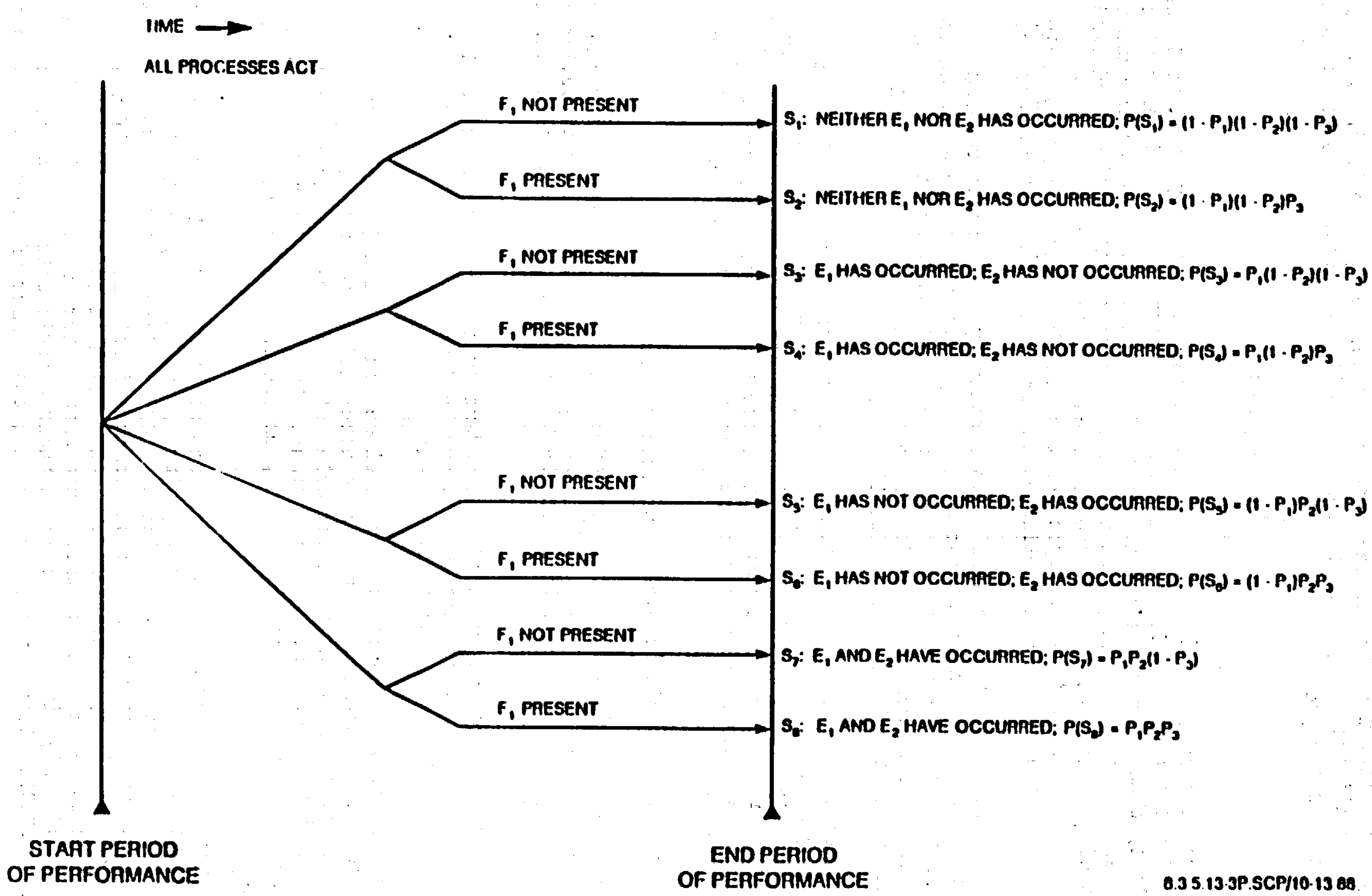

Figure 8.3.5.13-3. An illustration of the expansion of a complementary cumulative distribution function in independent scenario classes. Two types of events and one undetected feature are assumed. (See the text for a further explanation of this figure.)

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independent scenario classes denoted, as before, by S_j, $j = 1, 2, 3, \ldots, J$). The probabilities assigned to each class, $P(S_j)$, are then the J terms in the expansion of the product

$$\prod_{k=1}^{K} [(1 - p_k) + p_k]$$

as a sum of terms. (Note that this product is automatically equal to 1 since each of its terms equal 1; hence the representation as a sum of terms also equals 1, thus providing exhaustivity.) The p_k appearing in the product are here called the "elementary probabilities of occurrence" of the K independent types of objects. As shown in the previous examples, the p_ks may have different meanings, depending upon the type of object to which they apply. A discussion of elementary probabilities is provided later in this section.

Incorporation of uncertainties in repository performance related to undetected features in the manner discussed previously is one approach to this problem. Other approaches (e.g., sensitivity analyses and bounding analyses) will be considered before selecting the approach that will be used in the compliance demonstration for licensing.

A generalization of this scheme has been adopted by the DOE for the screening that identifies significant processes and events for inclusion in the CCDF; the next part of this section describes that screening. However, this partitioning scheme is adopted here for the purpose of deriving guidance for the site characterization program. It will not necessarily be the basis adopted in licensing.

Screening for significant events, processes, and features

In the Cranwell methodology, the CCDF for the performance measure M is represented as a weighted sum of 2^K conditional CCDFs (Equation 8.3.5.13-6). The weights are the probabilities of the 2^K exclusive and exhaustive scenario classes, and K is

K = (number of types of independent events) + (number of distinct types of undetected features) + (number of independent, two-state alternative models)

Distinct types of processes are not included in the sum (unless they are the distinguishing features of a two-state alternative model) because, in the Cranwell methodology, the state variables of all processes are included in the specification of every scenario class. In the next few paragraphs, a CCDF depending upon K events, features, or alternative models is denoted by $G_K(m)$.

Thus, the number of scenario classes to be considered in the performance assessments increases exponentially with K; for example, if $K = 10$, there are already 1,024 classes. Calculation of 1,024 empirical CCDFs by Monte Carlo simulation would require an enormous computational effort, even if the increased efficiency inherent in the calculation of conditional CCDFs by simulation is taken into account. Note that Hunter et al. (1986) understandably include only five "scenarios" in their example calculations of an empirical CCDF. Some methods for reducing the number of scenario classes to

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be included in a CCDF calculation to a manageable size are needed. At the same time, these methods should preserve exclusivity and exhaustivity, be applicable in advance of a CCDF calculation, and lead to the identification of those scenario classes that play essential roles in determining the shape of an empirical CCDF. Such methods, which might be called screening methods, are mentioned in this descriptions of the Cranwell methodology: "Scenario probabilities offer a means of screening the scenarios to determine which ones should be modeled" and "A preliminary estimate of consequences can also be used to screen scenarios before full-scale consequence modeling" (Hunter et al., 1986). The EPA also mentions the possibility of eliminating events and processes on the basis of their probabilities of occurrence: Guidance for 40 CFR Part 191 states that "performance assessments need not consider categories of events or processes that are estimated to have less than one chance in 10,000 of occurring over 10,000 years." (Appendix B of EPA (1985)).

Certain disruptive events, features, or alternative models (hereinafter collectively called agents) may be eliminated as ingredients of scenarios, provided that their elementary probabilities are sufficiently small. It can be shown that the absolute error in the calculated CCDF caused by dropping those scenario classes in which a single, to-be-eliminated agent occurs is bounded by that agent's elementary probability of occurrence. For example, if event k_1 is to be eliminated, then the absolute error obeys the following inequality:

$$|G_K(m) - G_{K-1}(m)| \leq p_{k_1}$$

If a total of L ($\leq K$) agents is to be eliminated, then

$$G_K(m) - G_{K-L}(m)| \leq p_{k_1} - p_{k_2} + p_{k_3} - \cdots - p_{k_L}$$

This bound on absolute error incurred by eliminating L out of K agents suggests a way of setting a criterion for screening events, features, or alternative models before constructing a CCDF. If the elementary probability of each agent considered for elimination is such that

$$p_k \leq 0.0001/K \qquad (8.3.5.13\text{-}7)$$

then up to K of the agents may be eliminated without causing more than 10-percent error in the CCDF at the more restrictive of the two inequalities shown in Equation 8.3.5.13-2, that is, the inequality $G(10) < 0.001$. (Note that other kinds of errors, i.e., those arising from a finite sample size, are inherent in the construction of the empirical CCDF and are not counted in the 10-percent relative error.)

The DOE does not intend to screen scenarios by consequences alone. The methodology will retain an analysis of low-consequence, high-probability events in order to provide a complete estimate of the CCDF and a thorough characterization of repository performance.

A crude but probably adequate measure of the relative importance of the consequences of different disruptive agents can be derived using the CCDF representation in the Cranwell methodology (Equations 8.3.5.13-6 and

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8.3.5.13-5). Taking the formal derivative of Equation 8.3.5.13-6 to obtain a probability density function for M, multiplying that probability density function by m, and applying the expectation operator (Equation 8.3.5.13-3) to the resulting product gives

$$E[M] = \sum_{j=1}^{2^K} E[M|S_j]P(S_j) \qquad (8.3.5.13\text{-}8)$$

The quantities $E[M|S_j]$ are the conditional expectations of the performance measure M, given the occurrence of scenario class S_j. Each term in Equation 8.3.5.13-8 (i.e., the product $E[M|S_j]P(S_j)$) is called the expected partial performance measure (EPPM) for scenario class S_j). Using the inequality in Equation 8.3.5.13-5, a sufficient condition for meeting the regulatory requirements of Equation 8.3.5.13-2 is

$$\sum_j (\text{EPPM for scenario class } S_j) \leq 0.01 \qquad (8.3.5.13\text{-}9)$$

It intuitively follows from Equation 8.3.5.13-9 that the significant scenario classes are those that have the largest EPPMs. In particular, scenario classes with EPPMs having values near 0.01 are significant, although the occurrence of an EPPM > 0.01 does not automatically imply a violation of the regulatory requirements. The connection between EPPMs and screening of potentially disruptive agents according to their consequences can be made by two observations: First, the EPPM for a scenario class in which a given disruptive agent, say the k^{th} one, is assumed to occur will be bounded above by the product, $p_k\, E[M|S_j]$. Second, an upper bound for the conditional expectation $E[M|S_j]$, say B_j, may often be estimated by simple, deterministic calculations. It follows that the EPPMs for scenario classes involving the k^{th} disruptive agent are bounded above by $p_k B_j$ (or B_j when p_k is unknown), and that the latter quantities can be used as surrogates of the EPPMs in a preliminary screening of potentially disruptive agents. This procedure is particularly useful in the performance allocation process. Several examples of its use are provided later in the section entitled "A preliminary performance allocation for Issue 1.1."

Probabilities of events, processes, and features

The foregoing discussions in this section have established that, in order to calculate an empirical CCDF for the performance measure, various measures of probability (i.e., CDFs for Monte Carlo simulation and elementary probabilities for calculating scenario class probabilities) must be associated with those events, processes, features, and alternative conceptual models that determine the classes of release scenarios. The present discussion briefly addresses two topics regarding probability: (1) the measures of probability needed for each kind of agent or process in order to include their uncertainties in the CCDF and (2) whether and to what extent the DOE believes that those measures of probability can be objectively derived from physical observations and data.

Probability measures for events (and some kinds of undetected features) are usually derived from probability models. A "probability model" is a

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mathematical model that is capable of relating measurable quantities associated with past occurrences of the event to CDFs for certain state variables. For example, the state variables of interest for events are usually

1. The number of events that occur in a prescribed interval of time.

2. The times of occurrence of each event.

3. One variable (at least) describing the magnitude or intensity of each event.

For events whose occurrence in time is uncertain, all these variables of interest must be treated as correlated random variables. The elementary probability of the k^{th} kind of event, p_k is the probability that the k^{th} kind of event will occur at least once in the period of performance. The elementary probability for events can always be derived from the CDF (or probability density function) for state variable 1, that is, the number of events that occur in a prescribed interval of time.

Probability models for geologic events can be exemplified by the so-called Poisson process (Ross, 1985). The Poisson process is characterized by the assumption that the waiting times, Δt_k between the occurrence of any two events of type k are independent, exponentially distributed random variables, that is

$$Pr\{\Delta t_k \leq t\} = 1 - \exp(-\lambda_k t),\ 0 \leq t < \infty$$

where λ_k depends upon the type of event and the associated magnitudes of intensities of the event. The quantity λ_k is sometimes called the probability per unit time since it has units of reciprocal time. The reciprocal of λ_k is the mean time between any two events. The probability that exactly n events of type k will occur in a time interval t is given by the Poisson distribution

$$\frac{(\lambda_k t)^n}{n!} \exp(-\lambda_k t),\ n = 0, 1, 2 \ldots$$

If t is taken to be 10,000 years, it follows that the elementary probability of the occurrence of an event of type k is

$$p_k = 1 - \exp(-\lambda_k t)$$

And when $(\lambda_k t) << 1$, the series expansion of the exponential function is used to justify the approximation, $p_k \approx \lambda_k t$.

In their investigations of the likelihood that the Yucca Mountain repository could be intercepted by extrusive basaltic volcanism, Crowe et al. (1982) combine available data on remnants of volcanic activity with Poisson-process assumptions to arrive at a maximum probability per unit time for volcanic disruption of 4×10^{-8}/yr. Donath and Cranwell (1981) use Poisson-process assumptions combined with geometrical probabilities to estimate the probability that faulting will disrupt a repository.

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Poisson-process assumptions are convenient for the treatment of rare, geologic events because there are usually only enough data on past occurrences of the event to fit one parameter (λ_b). The mean time between events, $1/\lambda_b$, can be simply estimated by three steps.

1. Dating physical evidence that marks the past occurrence of an event.

2. Counting the number of events that have occurred in some prescribed time interval.

3. Calculating a mean time between events, by dividing the number of events by the time interval.

This was essentially the method of Crowe et al. (1982). Crowe et al., however, also assumed that episodes of basaltic volcanism in the Yucca Mountain region would be Poisson distributed in space as well as time. In some investigations, there exist sufficient data to conclude that the occurrences of some geologic event actually fit the Poisson distribution. Algermissen and Perkins (1976) assert that "large shocks [from earthquakes] closely approximate a Poisson process, while small shocks may depart significantly from a Poisson process."

Poisson-process assumptions are used to exemplify probability measures for geologic events throughout the remainder of this section. Nevertheless, the DOE recognizes the possibility that data obtained during site characterization may justify the use of different kinds of probability models in performance assessment calculations. For example, if strong evidence is developed that shows that the time intervals between the occurrences of a critical type of geologic event, say during the Quaternary Period, are increasing (or decreasing) instead of remaining approximately constant (as required by Poisson-process assumptions), then a probability model for that type of event based on the so-called nonhomogeneous Poisson process (Ross, 1985) would be used in performance assessment calculations involving that event. The probability per unit time in a nonhomogeneous Poisson process can be any nonnegative function of time, say $\lambda(t)$, that can be fitted with the data.

The DOE also recognizes that the use of a finite data set to fit the parameters of a probability model imposes uncertainty on those parameters themselves. For example, the procedure indicated above for fitting the mean time between events in a homogeneous Poisson-process gives what is called a maximum-likelihood estimate of the true meantime. Such estimates are themselves normally distributed about the true mean with a variance that decreases with increasing sample size (i.e., the number of data points used in calculating the estimator). There is no practical way of minimizing this kind of uncertainty because the number of data points obtainable is always limited by other practical considerations such as limited time, funds, or simply the difficulties in finding and recording the evidence of a past event or process. The only reasonable way to address the fact that the parameters in a probability model may take on a range of values is to first attempt to minimize the spread of those ranges as much as possible and then use those values within the indicated ranges that lead to conservative elementary probabilities (i.e., probabilities that will to some degree overestimate the likelihood of the occurrence of an event). This scheme is used in interpreting the results of Crowe et al. (1982), and the DOE will apply it generally to arrive at an assignment of the parameters of any probability model that appears in the calculation of an empirical CCDF.

In contrast with geologic events, the assignment of probability measures to anthropogenic events that may occur in the far future must be based entirely on expert judgment. That judgment could be expressed in terms of a probability model or, more likely, by an assignment of a maximum credible rate of occurrence of the event. The EPA has already assigned a maximum credible rate of future exploratory drilling on a waste-disposal site: "...the Agency assumes that the likelihood of such inadvertent and intermittent drilling need not be taken to be greater than 30 boreholes per square kilometer of repository area per 10,000 years for geologic repositories in proximity to sedimentary rock formations, or more than 3 boreholes per square kilometer per 10,000 years for repositories in other geologic formations." (EPA, 1985). Given a maximum credible value on the rate of occurrence of an anthropogenic event, requiring a conservative estimate of the elementary probability forces the use of a Poisson probability model. Placing a maximum credible value on the rate of occurrence of that event automatically forces the use of a Poisson probability model, because such an assignment places a constant upper bound on the failure-rate function (Ross, 1985) uniquely associated with the CDF for the interval of time between occurrences of the event.

The elementary probabilities of the occurrence of natural undetected features, such as fault zones, magmatic intrusions, and perched water, would ideally be derived from probability models similar to the ones used in estimating the occurrence of mineral commodities (see John W. Harbaugh's treatment of this topic in Chapter 2 of Hunter and Mann, 1988). But, because of the quantity and specialized nature of the field measurements required to fit the parameters in these kinds of models (i.e., special boreholes and remote-sensing experiments), it may not be possible to realize the ideal for all but the most credible and potentially important kinds of natural undetected features.

As previously remarked, the numerical specification of a process is the same for all scenario classes unless the process is the distinguishing feature of an alternative model, or unless the process is changed by the occurrence of an event. Hence, processes will generally not play a direct role in the definition of scenario classes in the representation of the CCDF in the Cranwell methodology. Accordingly, processes cannot be screened using the methods associated with the Cranwell methodology and need not be assigned elementary probabilities. There may nevertheless be considerable uncertainty inherent in the description of a process. Important examples are the uncertainty in percolation flux and water-table level because these quantities may be affected by future climatic changes. Such process-related uncertainties can be incorporated into Monte Carlo simulations in at least two ways, whichever way proves to be the most efficient or justifiable in terms of available data:

1. The time-dependent function representing the process may be represented by a piecewise-linear function, as shown in Figure 8.3.5.13-4, or by a piecewise-constant function.

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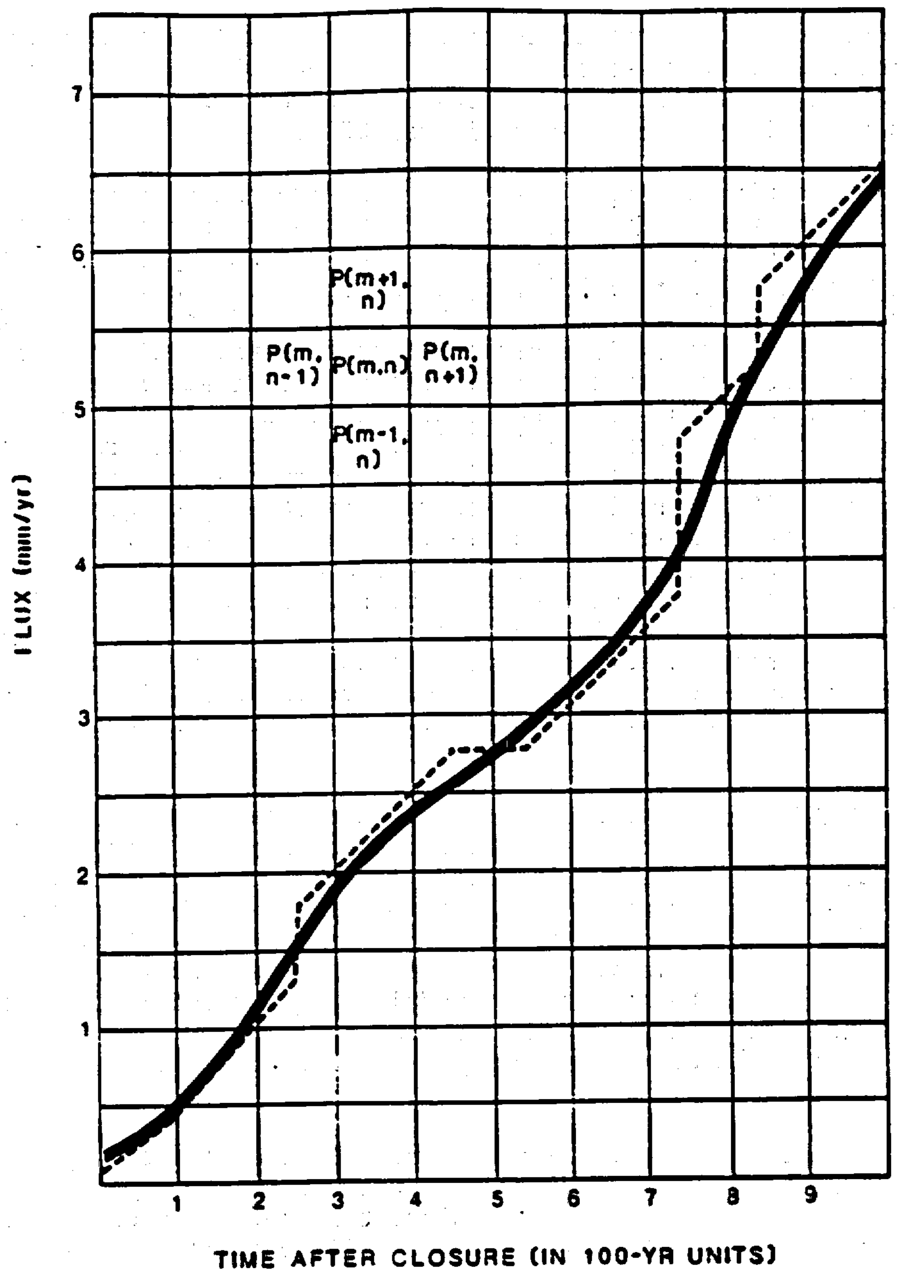

Figure 8.3.5.13-4. Representation of a time-dependent state variable. The hypothetical case shown is of percolation flux in the Topopah Spring welded unit as a function of time. The solid curve is the predicted flux history: the dotted curve is a discrete approximation to solid curve. Subdivisions of the ordinate show possible exceedance intervals for the percolation flux. The cells defined by the subdivisions of the ordinate and abcissa form an M by N matrix for the definition of exceedance probabilities. the notation P(m.n) stands for the probability that percolation flux in the m^{th} interval is exceeded in the n^{th} time interval

2. The time-dependent function representing the process may be approximated by an analytical expression involving a few deterministic functions of time and a few scalar random variables.

For example, the spatially averaged percolation flux at the level of the repository might be most simply approximated by

$$q(t) = q_o + \delta t, \ 0 \leq t \leq 10{,}000 \text{ yr}$$

where q_o is a random variable representing the spatially averaged percolation flux at closure time ($t = 0$), and δ is a random variable representing the rate of change of the spatially averaged flux owing to future climatic changes. Other approximations might be justified, depending upon expert judgments in the areas of future climatology and unsaturated-zone hydrology.

The U.S. Department of Energy approach to constructing the complementary cumulative distribution function

In calculating the CCDF, the DOE intends to take into account all those natural processes and events that are sufficiently credible to warrant consideration. Generally, categories of natural processes and events that can be shown to have a likelihood of less than one chance in 10,000 of occurring in the first 10,000 yr after permanent closure would not be taken into account in CCDF. Furthermore, categories of natural processes and events whose contribution to the overall probability distribution can otherwise be shown to be insignificant would not be included in the detailed assessments. Likewise, any particular combinations of categories of natural processes and events that meet either of these two criteria would not be incorporated into the CCDF. That is, particular scenario classes involving a sequence of categories of events or processes that, in combination, can be shown to have a probability of occurrence in the 10,000-yr period following permanent closure of less than one chance in 10,000 or that otherwise can be shown to make a negligible contribution to the overall probability distribution would not be evaluated in detail.

Impacts of processes and events initiated by human activities will also be considered in the system performance assessments with regard to this issue. Repository construction and waste emplacement, as they affect the conditions in the geologic repository, will be taken into account in the evaluating of the CCDF for normalized releases. The treatment of such events and processes will follow an approach similar to that used for the natural processes and events. To address the effects of human activities (such as direct intrusion), the DOE will (1) evaluate the effects of potentially adverse human activities, such as those identified in the examination of the potentially adverse conditions of 10 CFR 60.122; (2) develop scenario classes of categories of processes and events that are initiated by human activities and that result in potentially significant impacts on normalized releases; and (3) estimate relative probabilities and consequences for these scenarios, taking into account the factors and the assumptions given previously in the regulatory basis for this issue. The scenarios and scenario classes associated with human activities are often highly speculative and often do not involve significant impacts on the variables important to waste isolation.

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Therefore, the specification of highly speculative, low-impact human-activity-related scenarios and scenario classes, the development of the methods to analyze these classes, and the identification of data to support these analyses will not be allowed to dominate the testing program.

A scenario class will be developed for undisturbed performance of the geologic repository; it will take into account the legitimate, distinguishable alternative conceptual models that are supported by the available information. (As explained previously, this class is called the nominal class; it is associated with anticipated or expected conditions.) By undisturbed performance, the DOE means the predicted behavior of a geologic repository, taking into account the uncertainties in predicted behavior, and considering only likely natural events. In this instance, "natural events" refers to those natural processes and events that are reasonably likely to occur in the 10,000-yr period following permanent closure. The judgments of which natural processes and events are likely to occur during this period will be based on the assumption that those processes operating in the geologic setting during the Quaternary will continue to operate, but that with construction of the repository or the presence of emplaced radioactive waste, some perturbation will occur.

Disruptive scenario classes will also be developed for the analysis. Such scenario classes will be those that involve processes and events that are sufficiently credible to warrant consideration, but which are outside the range of those considered for the nominal case. For example, these scenarios may involve disruptive natural processes such as significant fault displacement, climate change, or volcanic activity that have a low probability of occurrence in the next 10,000 yr. These scenario classes would also include those developed for human interference activities discussed earlier.

As the preceding discussion points out, to describe the system ideally, the set of scenario classes should be exhaustive and the classes should be mutually exclusive. That is, the set of scenario classes should provide a partitioning of all the physically realizable futures for the repository system, and the set should be constructed so that the consequences of some effect are not counted more than once. In practice it will be difficult to provide such an ideal representation of the significant processes and events. For example, it will be difficult to distinguish between the low probability, extreme site characteristics taken into account in the undisturbed-performance scenario classes and the site characteristics resulting from unlikely processes and events that are taken into account in the disturbed-performance scenario classes. Care will be necessary to ensure that the scenario classes are as representative as possible.

It will also be difficult to ensure that every physically realizable future is represented in the set of scenario classes, particularly those that may be associated with unlikely processes and events. One of the undisturbed scenario classes is assumed to account not only for the likely processes and events explicitly specified in the description of the scenarios, but also for all unlikely processes and events that have no impact on repository performance. This scenario class is termed the "nominal" performance scenario class. Again, effort is needed to ensure that the nominal case scenario class provides a reasonable representation for these conditions.

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Within each scenario class it will be possible to specify one or more release modes. For example, release of radionuclides may occur by way of water pathways, in which dissolved radionuclides are transported by water; by way of gas pathways, in which the radionuclides are transported in gaseous form and not with the moving water; and by direct pathways, in which the radionuclides are transported directly to the accessible environment by mechanical means, such as by magmatic extrusion or human recovery. In some instances, the scenario class will be defined with a particular release mode in mind; for example, for some scenario classes, such as drilling scenarios, the direct-pathways mode may be considered to dominate.

2. A preliminary selection of events, processes, and scenario classes for the Yucca Mountain repository site

The identification of scenario classes for any system is ultimately a matter of professional judgment. Methods that have been used to identify scenarios were recently reviewed with the following conclusion: "Three different approaches have been proposed to identify scenarios for performance assessments of high-level waste repositories: simulation, event trees, and judgment. Simulation models require large amounts of hard-to-obtain input data. Event trees tend to produce extremely large numbers of scenarios. Most published performance assessments rely on judgmental methods. . ." (Ross, 1986). To this fair appraisal might be added the observation that construction of meaningful simulation models or event trees also requires judgment. Observational and experimental evidence should be used to screen out insignificant effects before attempting to construct simulation models; similarly, efficient construction of event trees can proceed only after there has been a thorough examination and interpretation of the evidence concerning phenomena that might affect the system. The DOE will use professional judgment to guide the program for identifying scenario classes that have significance. At this point, it is appropriate to summarize specific efforts to identify scenarios for a repository system at the Yucca Mountain site.

In addition to the studies summarized below, the DOE has correlated the selection of scenarios with the results of evaluations of alternative conceptual models of site behavior. As Section 8.3.1.1 explains, various alternative models may, on the basis of currently available evidence, be used to describe the behavior of the site. Tables that display these models (called hypothesis-testing tables in Section 8.3.1) have been linked to Issue 1.1 by identifying the performance measures (from the performance allocation tables throughout Section 8.3.5) whose values are sensitive to those processes and then estimating qualitatively the effect that variations on those measures could have on the performance of the repository system.

The list of scenarios derived from the studies summarized below has been expanded as part of the ongoing evaluations of alternative conceptual models described in the tables. The preliminary set of scenario classes derived in this section is intended to incorporate the consequences of all the significant processes that, according to current evidence, could reasonably be expected to affect the performance of the site. The decisions regarding which alternative models will be the bases for the selection of scenarios used in licensing will be reevaluated throughout site characterization as additional information becomes available.

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The decision-aiding methodology study

A panel of experts assembled by the DOE (1986a) proposed 15 generic, potentially significant scenarios (Table 8.3.5.13-1) and assessed the significance of these generic scenarios for a repository at Yucca Mountain, Nevada, using professional judgment and information from the Yucca Mountain environmental assessment (DOE, 1986b). The panel judged that scenarios 3, 4, and 12 of Table 8.3.5.13-1 are not sufficiently credible to warrant consideration*** and that realization of scenarios 5 through 9, 13, and 14 would not entail consequences more severe than the nominal case (scenario 1). Scenario 1 (the nominal case), scenario 2 (unexpected features), and scenarios 10a through 11 were regarded by the panel as being potentially significant at Yucca Mountain.

The unexpected-features scenario (scenario 2) was divided into six categories of features: (1) repository-induced subsidence or uplift, (2) undetected fault zones, (3) undetected significant lateral variations, (4) undetected dikes or sills, (5) undetected vertical heterogeneity (perching of water), and (6) other--a category of unspecified features. The panel stated that "The impacts of extreme conditions that result from unexpected features could lead to releases that could be as much as 10 times greater than those for the nominal case" (DOE, 1986a). After making evaluations, the panel concluded that the most important releases would be by ground water; consequently no scenarios were developed for gas-phase releases (i.e., carbon-14 as carbon dioxide).

The Ross study

Ross (1987) surveyed the events, processes, and features that might play a role in disruptions of the performance of the Yucca Mountain repository site. He examined the 56 processes, events, and features listed in the International Atomic Energy Agency (IAEA) list of phenomena potentially relevant to disruptions of a radioactive-waste repository (IAEA, 1983a) and, on the basis of information associated with the Yucca Mountain statutory environmental assessment (DOE 1986b), concluded that about 25 distinct events, processes, or features are credible for the Yucca Mountain situation. He also identified 84 sequences formed from the 25 events, processes, and features that, if realized, could influence the performance of one or more of the engineered or natural barriers.

These 84 sequences are summarized in the following series of in-text tables. Each table groups sequences by the event, process, or feature believed to initiate the sequence or substantially guide its progress. The tables identify the sequence number arbitrarily assigned by Ross (1987), as well as an abbreviated description of the sequence.

Following each table is a discussion of the sequences associated with the event, process, or feature that were excluded from consideration. Also given are page numbers from Ross (1987) where the reasons for exclusion can be found.

The sequences associated with climate change identified by Ross (1987) are given in the following table:

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Table 8.3.5.13-1. Potentially significant scenarios[a]

Scenario	Description
1	Nominal case (expected conditions)
2	Unexpected features
3	Repository induced dissolution of the host rock
4	Advance of a dissolution front
5	Movement on a large fault inside the controlled area but outside the repository
6	Movement on a large fault within the repository
7	Movement on a small fault inside the controlled area but outside the repository
8	Movement on a small fault within the repository
9	Movement on a large fault outside the controlled area
10a	Extrusive magmatic event that occurs during the first 500 yr after closure
10b	Extrusive magmatic event that occurs 500 to 10,000 yr after closure
11	Intrusive magmatic event
12	Large-scale exploratory drilling
13	Small-scale exploratory drilling
14	Incomplete sealing of the shafts and the repository

[a]Source: Table 3.2 in DOE (1986a).

Ross sequence number	Sequence for climate change
1	An increase in infiltration due to climate change at the repository site increases the unsaturated water flux through the repository.
2	An increase in recharge due to climate change raises the water table beneath the repository above the top of the Calico Hills nonwelded tuff unit.
3	A higher water table short-circuits a flow barrier in the saturated zone, changing the pattern of flow.
4	Regionally higher water tables create discharge points closer to the repository, reducing the distance to the accessible environment. The rise in the regional water table floods the repository.
5	Perched water develops above the repository, diverting downward flow through the repository into localized zones.
6	Perched water develops at the base of the Topopah Spring welded unit. Flow through the Calico Hills unit is diverted into fracture zones draining the perched water table.

The sequences associated with climate change dismissed by Ross (1987) and the pages in his report giving the reasons for exclusion are as follows: increased recharge due to "greenhouse effect" warming that exceeds 50 percent (p. 16), recharge exceeding maximum level attained during the past 100,000 yr (p. 16), new points of discharge of ground water from the water-table aquifer closer than 10 km from the repository if the repository does not flood (p. 18), release of radioactivity from discharge of perched water closer than 10 km from the repository (p. 18), and flooding of the repository by perched water (p. 19).

The sequences associated with stream erosion identified by Ross (1987) are given in the following table:

Ross sequence number	Sequence for stream erosion
7	Entrenchment of the Amargosa River at Alkali Flat lowers base levels and increases regional gradients. Regional hydraulic relations are such that water-table lowering at Yucca Mountain is insignificant, but increases in ground-water velocity are significant.

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Ross sequence number	Sequence for stream erosion (continued)
8	Beds of intermittent streams now resting on the Tiva Canyon welded tuff unit erode through to the underlying nonwelded unit. These washes form a barrier to lateral flow in the Tiva Canyon and divert flow downward. Regions of high flux are formed below them.

The sequences associated with stream erosion dismissed by Ross (1987) and the pages in his report giving the reasons for exclusion are as follows: major changes of course of the washes on Yucca Mountain (pp. 22-23), stream erosion rates in Yucca Mountain washes exceeding 50 m over the next 10,000 yr (p. 23), stream erosion that exposes the repository (p. 23), and substantial change in saturated-zone hydraulic gradient due to erosion upgradient or near the repository (p. 23).

The sequences associated with flooding identified by Ross (1987) are given in the following table:

Ross sequence number	Sequence for flooding
9	Flooding of the washes on Yucca Mountain is a major source of infiltration, and zones of higher moisture flux exist permanently or seasonally below washes. One or more of these zones is not detected during the site characterization.
10	Occasional major floods provide sufficient infiltration to overcome the capillary barrier that usually diverts flow laterally, creating temporary wetter zones beneath the washes.
11	Most percolation through the deeper unsaturated portions of Yucca Mountain occurs following the major precipitation events whose recurrence interval is tens, hundreds, or thousands of years. After future events, there are periods of tens to hundreds of years during which percolation through the unsaturated zone is increased over the present relatively dry conditions. Fracture flow then occurs in the Topopah Spring unit and perhaps other hydrogeologic units between the repository and the water table.

The sequences associated with faulting and seismicity identified by Ross (1987) are given in the following table.

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Ross sequence number	Sequence for faulting and seismicity
12	Movement of a new or existing fault shears canisters along the line of the fault. The same fault also creates a "trap" for moisture moving laterally through the Tiva Canyon welded unit, and so the sheared canisters are placed in a region of enhanced downward moisture flux.
13	Fracture dilation along a new or existing fault creates zones of enhanced permeability in the Calico Hills and Paintbrush nonwelded units. Erosion of an arroyo at the surface and increased hydraulic conductivity of the Paintbrush unit create a zone of increased percolation along the fault. Moisture moves through fractures along the fault.
14	The downdip side of a new or existing fault moves up. The fault thus forms a "trap" for laterally moving moisture in the Tiva Canyon welded unit. A new region of enhanced flux through the Topopah Spring unit is created.
15	Fracturing along a newly mobilized fault creates a permeable pathway through the flow barrier north of the repository block. The magnitude of the resulting change in the flow system is sufficient to raise the water table under the repository to the top of the Calico Hills nonwelded unit.
16	As in sequence number 15, fault-caused fracturing breaches the flow barrier north of the repository block. Flow is blocked by another barrier, not apparent from the current head distribution, and the resulting rise in water table floods the repository. The water passing through the repository discharges through springs in Fortymile Wash.

The sequences associated with faulting and seismicity dismissed by Ross (1987) and the pages in his report giving the reasons for exclusion are as follows: seismic acceleration due to earthquakes centered outside the site (p. 28); formation of new faults in areas where an existing fault of the same nature might not be discovered during site characterization (p. 29), fault uplift bringing waste canister to the surface (p. 29), and fault movement sufficient to place nonadjacent tuff units in contact (p. 30).

The sequences associated with geochemical changes identified by Ross (1987) are given in the following table:

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Ross sequence number	Sequence for geochemical changes
17	Precipitation of zeolites or other minerals in the saturated zone reduces effective porosity without significantly improving the sorptive properties of the rocks.
18	Fracture flow occurs in the unsaturated zone at current percolation rates. Precipitation or alteration of minerals blocks the small-aperture fractures and diverts the flow into larger fractures, increasing the water velocity.

The sequences associated with undetected faults and shear zones identified by Ross (1987) are given in the following table:

Ross sequence number	Sequence for undetected faults and shear zones
19	A wet zone below a minor fault through the Tiva Canyon lower contact escapes detection during repository construction, and waste is emplaced in it.
20	An undetected major fault dips below the repository. The fault has greater permeability than surrounding unfaulted rock, and enhanced moisture flow along it passes through the Calico Hills nonwelded unit in fractures.
21	An undetected major fault dips below the repository. Because of the formation of fault gouge, matrix hydraulic conductivity in the fault is less than the moisture flux, and so moisture flows through the Calico Hills nonwelded unit along fractures in or just above the fault.
22	An undetected fault provides a path for water movement from the tuff aquifer beneath the western portion of the repository to an underlying carbonate aquifer.

The sequences associated with undetected faults and shear zones dismissed by Ross (1987) and the pages in his report giving the reasons for exclusion are as follows: existence of undiscovered major through-going faults in tuff at the repository site (p. 34), undiscovered faults in underlying Paleozoic sedimentary or igneous intrusive rocks (p. 35), existence of a major fault that intersects the repository workings but is not discovered during the construction phase (p. 35), fault passing above the repository but not intersecting it (p. 35), water movement from tuff to carbonate aquifers in the eastern portion of the repository site (p. 36), and undetected faults affecting only the saturated tuff aquifer (p. 37).

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The sequences associated with undetected dikes identified by Ross (1987) are given in the following table:

Ross sequence number	Sequence for undetected dikes
23	An undetected dike passing through the Calico Hills nonwelded unit beneath the repository has very low matrix permeability but fairly high fracture permeability. Moisture infiltrating along the dike moves through fractures.

The sequence associated with undetected dikes dismissed by Ross (1987) and the pages in his report giving the reasons for exclusion are undetected intrusive sills (p. 38).

The sequence associated with extrusive magmatic activity identified by Ross (1987) is given in the following table:

Ross sequence number	Sequence for extrusive magmatic activity
24	A basaltic volcano erupts through the repository. The volcano is fed through a dike; waste canisters within the dike mix with the magma, and their contents are erupted.

The sequences associated with extrusive magmatic activity dismissed by Ross (1987) and the pages in his report giving the reasons for exclusion are as follows: direct release by volcanic eruption of waste that does not lie within a feeder dike or vent (p. 41), and indirect releases due to volcanic eruption (p. 42).

The sequences associated with faulty waste emplacement identified by Ross (1987) are given in the following table:

Ross sequence number	Sequence for faulty waste emplacement
25	Canisters are placed by mistake in wet zones.
26	Drains installed to divert water around canisters are improperly built or omitted altogether over some canisters.

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Ross sequence number	Sequence for faulty waste emplacement (continued)
27	Canisters are left lying on the floor of repository drifts. These canisters have poorer heat removal than those properly emplaced, and their increased horizontal cross-section raises the amount of water they intercept. Water drips on the canisters and corrodes them even while their temperatures are well above 95 degrees centigrade.
28	Canisters are placed closer together than planned. As a result, temperatures inside the packages are higher than anticipated and corrosion of fuel cladding is accelerated.
29	Some waste canisters are manufactured so improperly that they fail early.
30	Some waste canisters are punctured or abraded during emplacement.

The sequence associated with irrigation identified by Ross (1987) is given in the following table:

Ross sequence number	Sequence for irrigation
31	Irrigation in Midway Valley increases the moisture flux through the repository.

The sequences associated with irrigation dismissed by Ross (1987) and the pages in his report giving the reasons for exclusion are as follows: irrigation directly over the repository (p. 45), significant increase in hydraulic gradient caused by irrigation elsewhere in the ground-water basin (p. 46), and construction of water reservoirs above the repository (p. 47).

The sequences associated with intentional ground-water recharge or withdrawal identified by Ross (1987) are given in the following table.

Ross sequence number	Sequence for ground-water recharge or withdrawal
32	Water is collected in covered cisterns above the repository to enhance ground-water recharge.
33	Irrigation wells are drilled in Midway Valley.
34	Irrigation wells are drilled in Crater Flat or Jackass Flats.

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Ross sequence number	Sequence for ground-water recharge or withdrawal (continued)
35	Pumping rates increase in the presently irrigated areas around the town of Amargosa Valley. The water table is significantly drawn down, and the hydraulic gradient increases.
36	Mine dewatering is carried out directly below the repository. The saturated zone is eliminated as a barrier.

The sequence associated with intentional ground-water recharge or withdrawal discussed by Ross (1987) and the page in his report giving the reasons for exclusion are artificial recharge using water imported from outside the vicinity of the repository (p. 47).

The sequence associated with large-scale alterations of hydrology identified by Ross (1987) is given in the following table:

Ross sequence number	Sequence for large-scale alterations of hydrology
37	An active management scheme is introduced for the Alkali Flat-Furnace Creek Ranch ground-water basin, by which hydraulic gradients in the saturated zone beneath the repository are increased.

The sequence associated with large-scale alterations of hydrology dismissed by Ross (1987) and the page in his report given the reasons for inclusion is damming of the Colorado River (p. 50).

The sequence associated with undiscovered boreholes identified by Ross (1987) is given in the following table.

Ross sequence number	Sequence for undiscovered boreholes
38	A horizontally emplaced waste canister lies in the trace of an old undiscovered borehole. Moisture conditions are wetter than now thought, and water flows in fractures in the old borehole.

The sequences associated with undiscovered boreholes dismissed by Ross (1987) and the page in his report giving the reasons for exclusion are as follows: undiscovered boreholes in which waste canisters are not placed (p. 51), and emplacement of wastes in tunnel floors in the trace of an undiscovered borehole (p. 51).

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The sequence associated with undiscovered mine shafts identified by Ross (1987) is given in the following table:

Ross sequence number	Sequence for undiscovered mine shafts
39	An old prospect in a wash retains water after floods and therefore is a source of enhanced infiltration. The wet zone beneath it is not detected during repository construction, and waste is emplaced in it.

The sequences associated with undiscovered mine shafts dismissed by Ross (1987), and the pages in his report giving the reasons for exclusion are as follows: undiscovered deep mine shafts (p. 52), and undiscovered shallow prospector shafts outside washes (p. 52).

The sequences associated with exploratory drilling identified by Ross (1987) are given in the following table:

Ross sequence number	Sequence for exploratory drilling
40	Exploratory drillers intercept a waste canister and bring waste up with the cuttings.
41	Water introduced into the unsaturated zone as drilling fluid by exploratory drillers drains downward, through the repository.
42	An exploratory borehole creates a pathway for preferential flow through the upper nonwelded unit, and a wetter zone develops beneath in the Topopah Spring welded unit.
43	Surfactants introduced into unsaturated rock by drilling fluids shift its characteristic curve, draining smaller pores around the borehole. Water introduced by subsequent infiltration events acts as though air were the wetting phase and flows through large pores and fractures.

The sequence associated with exploratory drilling dismissed by Ross (1987) and the page in his report giving the reasons for exclusion are exploratory drilling to prepare for recovery of HLW from the repository (p. 53).

The sequences associated with resource mining identified by Ross (1987) are given in the following table:

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Ross sequence number	Sequence for resource mining
44	Builders of a mine shaft intercept a waste canister and bring radioactive waste up with the mine waste.
45	Water introduced into the unsaturated zone for mining above the repository drains downward through the repository.
46	A mine shaft crates a pathway for preferential flow through the upper nonwelded unit, and a wetter zone develops beneath in the Topopah Spring welded unit.
47	Surfactants introduced into unsaturated rock by drilling fluids shift its characteristic curve, draining smaller pores around the mine. Water introduced by subsequent infiltration events acts as though air were the wetting phase and flows through large pores and fractures.

The sequences associated with resource mining dismissed by Ross (1987) and the pages in his report giving the reasons for exclusion are as follows: lowering of water table due to "mining" of ground water (p. 55); and mining of the repository level for minerals other than the waste itself (p. 56).

The sequences associated with climate control identified by Ross (1987) are given in the following table.

Ross sequence number	Sequence for climate control
48	An increase in recharge at the repository site due to artificial climate change increases the unsaturated water flux through the repository.
49	An increase in recharge due to climate modification raises the water table beneath the repository above the top of the Calico Hills nonwelded tuff unit and induces fracture flow in the welded Topopah Spring unit.
50	Recharge induced by large-scale climate modification raises the regional water table sufficiently to flood the repository.
51	A higher water table due to climate modification short-circuits a flow barrier in the saturated zone, changing the pattern of flow.

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Ross sequence number	Sequence for climate control (continued)
52	Perched water develops above the repository because of climate-modification-induced recharge, diverting downward flow through the repository into localized zones.
53	An increase in recharge due to climate control causes perched water to develop at the base of the Topopah Spring welded unit. Flow through the Calico Hills nonwelded unit is diverted into fracture zones draining the perched water table.

The sequences associated with differential elastic response to heating identified by Ross (1987) are given in the following table:

Ross sequence number	Sequence for differential elastic response to heating
54	Thermal expansion closes most fractures near the repository. Pre-existing fracture percolation is diverted into fractures of larger aperture.
55	Differential thermal expansion of surrounding rocks stresses canisters, leading to stress-corrosion cracking.
56	Differential thermal expansion of surrounding rocks creates stresses that shear canisters.
57	Rock movements driven by thermal expansion of underlying units open fractures through the Paintbrush nonwelded unit. This creates local zones of increased flux through the unsaturated units below.

The sequence associated with differential elastic response to heating dismissed by Ross (1987) and the page in his report giving the reasons for exclusion are opening or closing of fractures due to thermal expansion under natural flux conditions (p. 60).

The sequence associated with nonelastic response to heating identified by Ross (1987) is given in the following table:

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Ross sequence number	Sequence for nonelastic response to heating
58	Thermally induced fracturing of rocks immediately surrounding waste canisters creates capillary barriers to movement of moisture between blocks of the rock matrix. The matrix is locally saturated, forcing flow out into the fractures and resulting in film flow or droplet impact on waste packages. The result is accelerated localized corrosion and waste dissolution.

The sequences associated with nonelastic response to heating dismissed by Ross (1987) and the page in his report giving the reasons for exclusion are as follows: fracturing of rock due to thermal expansion more than 10 cm from waste canisters (p. 62), and changes in ground-water travel time due to fracturing of rock near canisters (p. 62).

The sequences associated with temperature-driven fluid migration identified by Ross (1987) are given in the following table:

Ross sequence number	Sequence for temperature-driven fluid migration
59	Water accumulates above a repository during the thermal period because of evaporation and condensation. When gravity-driven flow resumes, a large volume of water contacts canisters, and flow goes through fractures.
60	Emplacement of waste in the floor of repository drifts creates a large thermal gradient across the drifts. Moisture condenses on the roof and drips onto canisters, accelerating corrosion.
61	Temperature inhomogeneities in the repository lead to localized accumulation of moisture above it. Wet zones form below the areas of moisture accumulation.
62	A thermal convection cell arises in the saturated zone beneath the repository. The thermally driven outward water flow in the upper portion of the tuff aquifer increases ground-water velocities.

The sequences associated with temperature-driven fluid migration dismissed by Ross (1987) and the pages in his report giving the reasons for exclusion are as follows: temperature dependence of water pressure, density, viscosity and rock relative permeability (p. 63), formation of artificial geysers by steam pressure of repository (p. 65), transport of radioactive aerosols to surface through drained fractures (p. 66), Soret effect (p. 67), and thermal osmosis (p. 67).

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The sequence associated with local mechanical fracturing identified by (Ross 1987) is given in the following table:

Ross sequence number	Sequence for local mechanical fracturing
63	Rock bursts propel rocks into waste packages and puncture the canisters.

The sequences associated with local mechanical fracturing dismissed by Ross (1987) and the pages in his report giving the reasons for exclusion are as follows: subsidence creating open fractures to surface (p. 68), and increases in permeability due to fracturing around repository workings (p. 69).

The sequences associated with corrosion identified by Ross (1987) are given in the following table:

Ross sequence number	Sequence for corrosion
64	Water drips or wicks onto canisters at specific locations, leading to buildup of brine deposits on small previously stressed areas. These areas are focuses of localized attack.
65	Water drips or wicks onto canisters at specific locations, leading to buildup of brine deposits on small areas that happen to have previously been stressed. Stress-corrosion cracking ensues.
66	The canister material is subject to stress-corrosion cracking, but the initiation time is too long to be detected in tests. Canisters fail by this mechanism a few decades after the repository has been sealed.
67	Canisters are sensitized by long-term storage at moderately hot temperatures in the repository. Stress-corrosion cracking (or perhaps intergranular corrosion) ensues in a stressed zone.
68	Zircaloy cladding is subject to stress-corrosion cracking at repository temperatures, but initiation times are too long for detection in in-reactor service or in the repository testing program.
69	After canister breach, colloids of corrosion products sorb normally highly retarded radionuclides and carry them away unretarded.

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The sequences associated with corrosion discussed by Ross (1987) and the pages in his report giving the reasons for exclusion are as follows: erosion corrosion (p. 70), galvanic corrosion (p. 70), selective leaching (p. 70), and hydrogen attack on canisters (p. 71).

The sequences associated with chemical reaction of the waste package with rock identified by Ross (1987) are given in the following table:

Ross sequence number	Sequence for chemical reaction of waste package with rock
70	Water dripping or running over waste contains ions that precipitate uranium. The precipitation reaction removes uranium from solution and increases the rate of fuel dissolution.
71	Waste and rock are placed in close juxtaposition by mechanical failure of emplacement holes or drifts, or by small movements on faults. Reactions between uranium, rock minerals, and water in contact with both precipitate uranium, leading the spent fuel to dissolve more rapidly than if constrained by the equilibrium solubility of uranium.
72	The high dissolved-silica content of natural waters entering the repository causes rapid corrosion of Zircaloy fuel cladding.
73	Colloids are formed from the rock by alteration under thermal, mechanical, and chemical stresses. Normally well-retarded radioelements such as plutonium and americium sorb to the colloids.
74	Waste-contaminated water reacts with rock, and colloid phases of minerals containing radioelements are formed by coprecipitation. The colloids are transported with little or no retardation.

The sequences associated with geochemical alteration identified by Ross (1987) are given in the following table:

Ross sequence number	Sequence for geochemical alteration
75	During the period of heating of rocks around the repository, minerals adjacent to the residual water-bearing pores are altered to clays. These clays clog the pores. When the repository cools, water flows through fractures.

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Ross sequence number	Sequence for geochemical alteration (continued)
76	During the thermal period, zeolite minerals in fracture fillings are altered to less sorptive phases.
77	Waters moving away from the hot region around the repository precipitate minerals derived from dissolved constituents of tuff and cements used in repository construction. These minerals clog pores and divert subsequent flows into fractures.
78	Evaporation of ground water in the hot zone near the repository horizon leaves precipitates that plug pores. As a result, when gravity-driven flow resumes, water near the repository is diverted into fractures. Initially, there is a pulse of corrosive brine.
79	Evaporation of ground water in the hot zone near the repository horizon leaves precipitate. When gravity-driven flow resumes, the precipitates redissolve, and after a short period of fracture flow, the flow returns to the matrix. There is a considerable period of flow of corrosion brines with elevated dissolved solids.
80	There is fracture flow in the Topopah Spring welded unit even under undisturbed conditions. Chemical reactions induced by repository heat plug smaller-aperture fractures. After the thermal pulse ends, percolation is diverted into larger fractures.
81	Water passing through the warm region around the repository is depleted of calcite by temperature-induced precipitation. Below the repository, the calcite-poor water dissolves out calcite veins in the Calico Hills nonwelded unit.

The sequences associated with chemical alteration dismissed by Ross (1987) and the pages in his report giving the reasons for exclusion are as follows: thermal release of moisture from hydrated zeolites (p. 76), and loss of mechanical strength due to thermal dehydration and rehydration of the Topopah Spring welded unit (p. 77).

The sequences associated with microbial activity identified in Ross (1987) are given in the following table:

Ross sequence number	Sequence for geochemical alteration
82	Microbial activity accelerates canister corrosion.

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Ross sequence number	Sequence for geochemical alteration (continued)
83	Microbial activity accelerates cladding corrosion.
84	Radionuclides are incorporated into microorganisms or sorbed on their surfaces. Waste dissolution is accelerated. The nuclides taken up by microorganisms are unaffected by chemical sorption or matrix diffusion.

The sequences associated with microbial activity discussed by Ross (1987) and the pages in his report giving the reasons for exclusion are microbial deterioration of concrete or bentonite (p. 82); transport of radioactivity by motile microorganisms (p. 82); and microbial alteration of ground-water chemistry (p. 83).

Ross (1987) also dismissed, or chose not to identify, any sequences associated with certain events, processes, and features in the IAEA list (IAEA, 1983a); a summary of these dismissed events, processes, and features i given in the following table, along with the page numbers of his report where the reasons for dismissing each item are given.

Event, process, or feature	Sequence description and Ross text page
Hydrology change	Change in hydrologic system not caused by some other event or process (p. 20)
Sea-level change	Change of base level due to flooding of Death Valley caused by seal level change (p. 20).
Denudation	Lowering of the land surface to the level of the repository by denudation (p. 21).
	Denudation that exposes the present water table within the ground-water basin (p. 22).
	Change in unsaturated-zone flow, due to removal of the Paintbrush nonwelded unit above the repository by denudation (p. 22).
Glacial erosion	Glaciation (p. 24).
Sedimentation	Sedimentation that affects the repository (p. 27).
Diagenesis	Sedimentary diagenesis (p. 28).
Diapirism	No salt or shale formation (p. 28).
Dissolution	Not a concern at Yucca Mountain (p. 33).

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Event, process, or feature	Sequence description and Ross text page (continued)
Brine pockets	Not a concern at Yucca Mountain (p. 33).
Orogeny	Cessation or reversal of current Great Basin orogeny (p. 33).
Epeirogenic uplift and subsidence	Epeirogenic uplift (p. 34).
	Epeirogenic subsidence of repository toward water table (p. 34).
Isostatic uplift and subsidence	No Pleistocene glaciation at Yucca Mountain (p. 34).
Undetected breccia pipes	Not a concern at Yucca Mountain (p. 38).
Undetected lava tubes	Existence of lava tubes unlikely at Yucca Mountain (p. 38).
Undetected gas or brine pockets	Not a concern at Yucca Mountain (p. 39).
Magmatic intrusion	Granitic intrusion (p. 39).
	Intrusion of large bodies of basaltic magma (p. 39).
	Container failure caused by intrusion of dikes or sills (p. 39).
	Intrusion of magma into repository drifts (p. 40).
	Indirect releases of radioactivity due to magmatic intrusion accompanying a volcanic eruption (p. 40).
	Magmatic intrusion below the repository (p. 40).
Meteorite impact	Probability less than 1 in 100 million (p. 42).
Shaft-seal failure	Not a concern in unsaturated zone (p. 43).
Failure of exploration-borehole seals	Not a concern in unsaturated zone (p. 43).

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Event, process, or feature	Sequence description and Ross text page (continued)
Chemical liquid waste disposal	Deep-well injection of chemical wastes (p. 49).
	Construction of surface impoundments for chemical wastes (p. 50).
Archaeological exhumation	Not a proper concern of performance assessment (p. 55).
War	Fracturing of rock by nuclear explosion in a war (p. 57); exhumation of waste by nuclear explosion in a war (p. 57).
Sabotage	Unlikely action at Yucca mountain (p. 57).
Waste recovery	Not a proper concern of performance assessment (p. 57).
Canister movement	Significant canister movement not expected (p. 68).
Gas generation	Not a concern in an unsaturated repository (p. 75).
Radiolysis	Radiolytic pressure buildup (p. 79).
Decay-product gas generation	Not an independent failure mode for canister generation (p. 80).
Nuclear criticality	Criticality in a spent-fuel canister (p. 81).
	Criticality due to precipitation of plutonium in a zone of reducing conditions (p. 81).
	Criticality due to accumulation of plutonium on a sorbing zeolite seam (p. 81).

Finally, Ross (1987) did not explicitly consider disruptive sequences that could involve the release and transport of gas-phase radioelements, such as carbon-14 and iodine, to the accessible environment.

Scenario classes defined in the Ross study

The in-text tables that compose most of the preceding subsection on the Ross study list the 25 agents identified in the Ross study. These agents include eleven natural processes, one anthropogenic process (climate control), three natural events (flooding, faulting, and extrusive magmatic activity), five anthropogenic events, and five undetected features. An estimate can be made of the number of independent, mutually exclusive scenario classes contained in the Ross study. (The reader may wish to review Part 1 (methods of constructing a CCDF), for the rationale of these

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estimates. The eight events and five undetected features are assumed to be mutually statistically independent entities; that is, information about the occurrence of one such entity gives no information about the future occurrence of any of the others. All hypothetical sequences are also assumed to be somehow resolved, so that there are no two-state alternative models in the picture. The number of independent, mutually exclusive scenario classes is then

$$2^{8+5} = 2^{13} - 8,921.$$

This estimate illustrates why the DOE cannot give a detailed description of all the independent, mutually exclusive scenario classes it will consider within the confines of the present document. The estimate also demonstrates the necessity for screening proposed events, processes, features, and alternative models against consequences, in order to reduce the number of scenario classes that will ultimately be included in a licensing assessment. For each event, feature, or two-state alternative model that can be eliminated by screening (that is, by showing that inclusion of such an agent in the analyses leads to insignificant changes in the CCDF). The number of scenario classes can be reduced by one half.

Favorable and potentially adverse conditions of 10 CFR 60.122

The siting criteria of 10 CFR 60.122 specify certain potentially adverse conditions (PACs). The evaluation of the site with regard to these conditions is taken up in the strategy to resolve Issue 1.8, which directly addresses the siting criteria (Section 8.3.5.17). Because these conditions may be important to waste isolation, they should be taken into account in the strategy for the resolution of this issue in particular, in the development of scenarios for the evaluation of release of radionuclides to the accessible environment.

The set of PACs from the regulation is listed in Table 8.3.5.17-2, which numbers them in the same order as 10 CFR 60.122. The 24 PACs listed in that table do not necessarily define 24 disruptive scenarios. For example, the set of PACs was developed on the basis of generic considerations, and a few do not apply to the Yucca Mountain site at all (e.g., PAC 10). Others may be associated with the expected characteristics of the site (e.g., PAC 24) and therefore need to be taken into account in the nominal, or expected-case, scenario class. Others of these PACs, however, should be explicitly considered in developing the classes of disruptive scenarios for the analysis of repository system performance. The association of each such PAC with one or more scenario classes is explained in the next subsection. The approach used in making this association was simply to compare each of the PACs with the scenario classes developed for the potentially significant, site-specific processes and events. This comparison led to an effort to ensure that each PAC considered applicable to the Yucca Mountain site is addressed by the nominal scenario class or by one or more of the disruptive scenario classes. Further, each of the scenario classes was defined to clarify the association with the relevant PACs. This association is explained in the next subsection and is discussed in some detail in Section 8.3.5.17.

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Scenario classes to guide the site-characterization program

The specification of the information needs to resolve this issue is to be framed in terms of a set of scenario classes chosen to address all the processes and events considered potentially significant to release of radionuclides to the accessible environment at the Yucca mountain site. This set includes the nominal class and a sufficient number of additional classes to address all the credible disruptions to this undisturbed class.

As the discussions in the previous subsections suggest, few scenarios have been screened out at this time. In general, the scenarios eliminated by Ross (1987) and those scenarios screened out as part of the DOE decision-aiding methodology (1986a) are assumed to be inapplicable at Yucca Mountain. Such scenarios would include events such as meteorite impact and tornadoes, and processes such as sedimentation and glaciation. The scenarios specified in the compilations of the previous subsections are considered by the DOE to be adequate to guide the testing program.

As explained previously in the discussion entitled "DOE approach to constructing a CCDF, the nominal scenario class is defined by the conditions that the available evidence suggests are expected at the site. These conditions are described in Section 8.3.5.8 and, more generally, in Section 8.0, which discusses the top-level strategy for the site-characterization program. The following three paragraphs are taken from Section 8.0 as a brief summary of the scope of the nominal scenario class.

The currently available information suggests that small amounts of water are available to percolate slowly downward through Yucca mountain. If the Yucca Mountain site is developed for a repository, water that moves through the unsaturated rock above the repository could continue down to the unsaturated rock unit in which underground repository would be constructed. If any of this water could reach penetrate the engineered barrier system and the emplaced waste, it might dissolve radionuclides and carry them in solution through the unsaturated rock below the repository to the saturated rock deep beneath the site. After reaching saturated rock, the water joins the much larger, horizontal flow there; therefore, radionuclides that are carried by the water could be transported by the flow in the saturated zone and move toward the accessible environment.

This sequence of events--downward water movement, water penetration into the engineered-barrier system, and downward transport of radionuclides to saturated rock, and horizontal transport to the accessible environment --defines the expected mode of release in the nominal scenario. According to the available evidence, the percolation flux at and below the repository horizon is very low. Furthermore, it appears that the percolation of water through the unsaturated rock units at this depth is primarily in the rock matrix rather than through fractures. If the water is held tightly within the rock, as it appears to be, it would not be excepted to move from the rock across the air gap to the waste container; the water would therefore not be expected to reach the waste. Furthermore, the results of preliminary studies suggest that the quantity of moving water is so small that any corrosion of the disposal container and the dissolution of radionuclides would be very limited even if the water could cross the air gap. The evidence also suggests that the movement of water in the rock matrix is very slow, and,

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therefore, the transport of any radionuclides dissolved in this water downward through the unsaturated rocks below the repository would be very slow. An additional characteristic of the unsaturated rock is the geochemistry of the water in the rock, which will determine the radionuclide dissolution and the retardation of radionuclide transport.

One further sequence of events might contribute to a release under the conditions expected at Yucca Mountain and is also included in the nominal case. If the waste containers are breached, the radionuclides that exist in the waste in gaseous form might move upward through the air spaces in the unsaturated rock above the repository. They might then reach the accessible environment at the ground surface above the repository. The available information is not complete enough to decide definitively whether this sequence is capable of producing significant releases. It is not clear, for example, that the waste form can release gaseous radionuclides rapidly enough or in sufficient quantities for the release to be important. Nevertheless, in this scenario class it is assumed that this mode could also contribute to release to the accessible environment.

The effects of repository construction and the heat generated by the emplaced waste must be fully taken into account in the nominal scenario class. These effects include changes in the hydrologic properties and in the fluid conditions in the vicinity of the waste packages; they include the effects of temperature increases and thermomechanical stresses on the waste packages themselves. The testing program must provide the information to evaluate these and other effects for the nominal scenario class.

There are clearly large uncertainties in the specification of the nominal scenario class, and the information needs for this issue will have to address the full range of these uncertainties. The investigations of the hydrogeologic, geochemical, and rock characteristics that fully specify this scenario must take into account the full range of tectonic and climatic conditions that are expected at the site. In addition, any expected changes in these conditions that are not sufficient to change the general description that has been given would be taken into account in the nominal class. Therefore, the nominal class can include a wide range of expected tectonic and seismic activity and climatic conditions.

Extreme conditions outside the ranges considered for the nominal class, that is, those that may be possible but have very low probability of occurrence at the site, are considered in the category of disturbed conditions. For example, extreme values of the percolation flux that are sufficiently credible to warrant consideration, but that are not, in fact, expected at the site would be included in this category. The category of disturbed conditions also includes those that would result from disruptive processes or events. For example, tectonic activity that could significantly change ground-water flow conditions would be taken into account in the category of disturbed conditions. Any volcanic activity or extreme climatic changes would also be included in the category of disturbances to the nominal case, as would credible human activities that could interfere with expected repository system performance.

Such disturbances will be explicitly taken into account in the disruptive scenario classes. The three scenario-screening compilations

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described above identify a number of disruptive scenarios and provide the basis for selecting the scenario classes used to develop the information needs for this performance issue. The disruptive scenario classes that are used to guide testing and the correlation of these scenario classes with the scenarios of the three compilations are presented in Table 8.3.5.13-2. This table show that this set of scenario classes is strongly correlated with the set of scenarios of the Ross report. Thus, the issue resolution strategy is in general agreement with the screening and conclusions of this study.

The list of candidate scenario classes in Table 8.3.5.13-2, however, differs from the set of scenarios from the Ross study in two ways. First, several of the scenarios described by Ross are enveloped by the nominal scenario class in this issue-resolution strategy; they do not appear in the table. For example, the particular flooding scenarios (scenarios 9, 10, and 11) and geochemical-change scenarios (scenarios 17 and 18) considered by Ross lead to hydrogeologic and geochemical conditions that are taken into account in the nominal class. That is, investigations of the range of hydrogeologic and geochemical characteristics by the site characterization program should be adequate for understanding the effects described in those scenarios.

All the Ross scenarios associated with undetected features (scenarios 19 through 23, 38, and 39) have also been included in the nominal scenario class. At this stage of the site characterization program, it seems appropriate to plan to detect such features and to investigate the full range of conditions associated with heterogeneity at the site. Note that the categorization of scenarios as nominal or disruptive is merely a matter of convenience since the scenarios will be investigated in either instance. It may be determined that for licensing it would be convenient to categorize scenarios that involve undetected features separately from the nominal class. But for the sake of developing the strategy to test for the features of the site, this separation is not important.

Finally, those Ross scenarios associated with the full ranges of conditions to which the waste package is subjected (for example, the full range of temperatures expected from the heat generated by the waste and the full range of local fluid and chemical conditions expected near the waste packages) are all included in the nominal class. In the Ross study, scenarios 25 through 30 and 53 through 84 were developed to ensure that such conditions would receive explicit consideration. All these conditions will be evaluated in the waste-package program (Section 8.3.4) and are included here as part of the nominal class.

The second difference between the scenario classes of Table 8.3.5.13-2 and those of the Ross study is the addition of several scenario classes. They have been added to the set as part of the development of the SCP and the ongoing evaluations of alternative conceptual models. The scenario classes that have been added are briefly described in the following in-text tables in the format used to describe the scenarios of the Ross study in a previous subsection.

The sequences associated with surface flooding or impoundments are given in the following table.

Table 8.3.5.13-2. Disruptive scenario classes for the site characterization program (page 1 of 2)

Scenario initiating event or process	Number of scenario class	Scenario compilation: Decision-aiding methodology[a]	Ross study[b]	Potentially adverse conditions[c]	Release model[d]	Barriers affected: Seal system	Waste package	Unsaturated zone	Saturated zone	Scenario class category[e]
Extreme climate change	1		1	5,23	I		X	X		C-1
	2		2	5,22	I			X		C-2
	3		3	5	I				X	D-1
	4		4	5,22	I			X	X	C-2,D-1
	5		5	5	I		X	X		C-3
	6		6	5	I		X	X		C-3
Stream erosion	7		7	5,16	I				X	D-2
	8		8	5,16	I		X	X		C-1
Faulting and seismicity	9	6,8	12	5,23	I		X	X		C-1
	10	5,7	13	5,23	I		X	X		C-1
	11	5,7	14	5,23	I		X	X		C-1
	12	9	15	4,5,11,12	I			X	X	C-2
	13	9	16	4,5,7,8, 22	I		X	X	X	C-2,C-3
	14	5,7	89	4,5,7,8, 22	I			X	X	C-2,D-2
					I		X	X		C-1
Intrusive magmatic activity	15	11	90	5	I		X	X		C-1
	16	11	91	5	I		X	X		C-3
	17	11	92	5,7	I		X	X		C-3
	18	11	93	5						
Extrusive magmatic activity	19	10	24	15	D					A-1
Irrigation	20		31	2,5	I		X	X		C-1
Intentional ground-water withdrawal	21		32	2,5	I		X	X		C-1
	22		33	2,5	I		X	X		C-1
	23		34	2,5,22	I			X	X	C-2,D-1
	24		35	2,5	I				X	D-2
	25		36	2,5	I				X	D-1
	26		37	2,5	I				X	D-1

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Table 8.3.5.13-2. Disruptive scenario classes for the site characterization program (page 2 of 2)

Scenario initiating event or process	Number of scenario class	Scenario compilation: Decision-aiding methodology[a]	Scenario compilation: Ross study[b]	Scenario compilation: Potentially adverse conditions[c]	Release model[d]	Barriers affected: Seal system	Barriers affected: Waste package	Barriers affected: Unsaturated zone	Barriers affected: Saturated zone	Scenario class category[e]
Exploratory drilling	27	13	40	2,17	D					A-2
	28		41	2,5,17	I		X	X		C-1,C-3
	29		42	2,5,17	I		X	X		C-1,C-3
	30		43	2,5,17	I		X	X		C-3
Resource mining	31		44	2,17	D					A-2
	32		45	2,5,17	I		X	X		C-1
	33		46	2,5,17	I		X	X		C-1,C-3
	34		47	2,5,17	I		X	X		C-3
Climate control	35		48	2,5	I		X	X		C-1
	36		49	2,5,22	I			X		C-2
	37		50	2,5,22	I			X		C-2
	38		51	2,5	I				X	D-1
	39		52	2,5	I		X	X		C-1
Surface flooding or impoundments	40		1,85	3,5	I	X	X	X		C-1
	41		1,86	3,5	I	X	X	X		C-1
	42		1,87	3,5	I	X	X	X		C-1
	43		1,88	2,5	I	X	X	X		C-1
Regional changes in tectonic regime	44		93	5,11,22	I			X		C-2
	45		94	4,5,11,22	I			X	X	C-2,D-1,D-2
Folding, uplift, and subsidence	46		95	5,11	I		X	X		C-1
	47		96	5,11	I		X	X		C-1
	48		97	5,11,22	I			X		C-2
	49		98	5,11	I		X	X		C-1

[a]These numbers represent the potential significant scenarios as listed in Table 3-2 of DOE (1986a).

[b](Sequence numbers from Ross (1987), supplemented by the scenarios (numbers 85 through 99) constructed during SCP development and the evaluations of alternative conceptual models.

[c]These numbers represent the potentially adverse conditions as listed in 10 CFR 60.122 that are associated with one or more scenario classes (see discussion in the text).

[d]I = indirect; D = direct.

[e]Scenario class categories are defined in Table 8.3.5.1

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Sequence number	Sequence for surface flooding or impoundments
85	Flooding occurs in Drill Hole Wash, and percolation flux is substantially increased below the wash. Some water seeps to sealed shafts and boreholes where there are unexpectedly large flows down through seal material or down through the disturbed rock around these seals.
86	Faulting at the surface leads to a scarp that produces an impoundment during a period of high precipitation. Percolation flux is substantially increased beneath this impoundment. Some water seeps to sealed shafts and boreholes where there are unexceptedly large flows down through seal materials or down through the disturbed rock around the seals.
87	Volcanic activity in the vicinity of the site leads to damming that produces a large surface-water impoundment. Percolation flux is substantially increased beneath this impoundment. Some water seeps to sealed shafts and boreholes where there are unexpectedly large flows down through seal materials or down through the disturbed rock around the seals.
88	A large surface-water impoundment is constructed near the site. Percolation flux is substantially increased beneath this impoundment. Some water seeps to sealed shafts and boreholes where there are unexpectedly large flows down through the seal material or down through the disturbed rock around the seals.

The sequence associated with faulting and seismicity is given in the following table:

Sequence number	Sequence for faulting and seismicity
89	Fault creep incudes minor restructuring of the in situ strain-energy field. This change causes short-term stress-induced fluctuations in the level of the water table.

The sequences associated with magmatic intrusion are given in the following table:

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Sequence number	Sequence for magmatic intrusion
90	Igneous activity leads to a sill that extends over a portion of the underground facility. Water percolating down is diverted at the top surface of the relatively impermeable sill; local percolation flux near the sill is therefore much higher than average flux expected at the site.
91	Igneous intrusion near the underground facility causes extreme changes to rock hydrologic properties.
92	Igneous intrusion near the underground facility causes extreme changes in rock geochemical properties.
93	Igneous intrusion causes a barrier to flow or drastically alters thermal conditions, causing the water table to rise.

The sequences associated with regional changes in the tectonic regime are given in the following table:

Sequence number	Regional changes in the tectonic regime
94	The current tectonic environment at the site is extensional. Fault movement relieves the stresses, causing the fractures in the system to decrease in aperture. The water from the saturated-zone fractures is driven up into the unsaturated-zone fractures, raising the water table.
95	The in situ heat flow at the site changes with time because of large-scale changes in the tectonic environment. The modifications in the temperature gradients at the site lead to convective flow in the saturated zone and modifications to the elevation of the water table.

The sequences associated with folding, uplift, and subsidence are given in the following table:

Sequence number	Sequence for folding, uplift, and subsidence
96	Tectonic folding changes the dip of the tuff beds at the site, thereby changing the local percolation flux to values not currently observed.

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Sequence number	Sequence for folding, uplift, and subsidence (continued)
97	Uplift or subsidence changes the drainage at the site, thereby changing the local percolation flux to values not currently observed.
98	Folding, uplift, or subsidence lowers the underground facility with respect to the water table.
99	Subsidence of the mined underground facility creates impoundments or diverts drainage, thereby increasing the local percolation flux to values not currently observed.

Some of the scenario classes result in direct discharge of radionuclides to the surface. Others result in indirect releases; that is they produce movement of radionuclides through the barriers of the repository system to the accessible environment. The table labels the scenario classes according to these modes of release.

Because site investigations will address the scenario classes in Table 8.3.5.13-2, they will produce information needed to determine probabilities of occurrence. However, in order to develop the CCDF, information will also be needed to evaluate releases of radionuclides, and it is convenient to organize these scenarios according to their effects on waste isolation in order to guide the testing program to obtain this information. Table 8.3.5.13-2 also indicates the barriers of the repository system that are important to waste isolation and can be significantly affected in each scenario class. These barriers are (1) the engineered barrier system, (2) the unsaturated zone, and (3) the saturated zone.

The engineered barriers include the waste container, the waste form for spent fuel, and the spent-fuel cladding. These components would provide barriers to the release of radionuclides to the host rock under the conditions expected at the site.

The unsaturated zone includes the Topopah Spring host rock, the Calico Hills unit in the unsaturated zone, and other unsaturated units that underlie the underground facility. These units are expected to provide barriers to radionuclide migration down to the water table. In addition, the unsaturated units that overlie the underground facility are expected to limit release of gaseous radionuclides to the surface.

The saturated zone includes all rock units beneath the water table. These units will serve as barriers to the transport of radionuclides that reach the water table.

It is convenient to organize the scenario classes according to the barriers that, in principle, would be significantly affected by them. To do this, a reference scenario class is defined. Ideally, this scenario would be for the expected, undisturbed conditions at the site. Because there is substantial uncertainty in the expected condition in many respects at

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present, this scenario class is simply denoted as the nominal scenario class discussed earlier in this section.

Then, scenario categories are defined in which the barriers important to waste isolation are significantly disturbed from the conditions defined in the nominal scenario. These scenario categories are shown in Table 8.3.5.13-3. The first category (A) is for the direct-release scenarios. Two direct-release scenario classes were identified as one listed explicitly in the table.

Category B is for scenario classes in which only the engineered barriers are affected. The classes in this category that are considered relevant to the system performance objective are judged to occur concurrently with the scenarios in categories C or D or to be part of the uncertainty associated with nominal performance of engineered barrier system components (i.e., container and cladding degradation rates or waste-form dissolution rates and solubilities under various likely conditions). Thus, no independent, potentially significant scenario classes associated with category B appear in Table 8.3.5.13-3.

Category C is for the scenario classes in which major aspects of the unsaturated zone are disturbed. In these classes, the engineered barriers may also be affected. These scenario classes appear to be of three types: (1) ones in which the total or local percolation flux through the repository is increased, owing to the appearance of sources above the repository (e.g., those involving climatic change or local flooding from surficial sources); (2) ones in which the thickness of the unsaturated zone is decreased, for example, by a rise in the water-table level under the site; and (3) ones in which there are adverse changes in unsaturated-zone rock hydrologic properties or the geochemistry of the unsaturated zone. The logic of this organization follows from the fact that the appearance of any one of the changes (increased flux, decreased unsaturated-zone thickness, decreased saturated matrix conductivity, or decreased geochemical retardation properties) could lead to an increase in the rate at which dissolved radionuclide-bearing compounds are transported from the repository to the water table. Depending upon the events and processes associated with these changes, each change could appear singly or in combination, i.e., correlated with any or all of the other changes.

Category D is for scenarios in which the saturated zone is affected. The unsaturated zone and the engineered barriers could also be affected. Scenario classes in category D may be organized in a fashion similar to that of category C, but because saturated flow is not dominated by vertical flow like unsaturated-zone flow, the change "increased flux through the saturated zone" would be connected either with rises in the water-table level (considered in C-2) or increased linear water velocity (considered in D-2).

For completeness, the nominal scenario class is also included as category E.

The categories in Table 8.3.5.13-3 serve as the basis for the information needs for this issue. That is scenarios within a category are defined by the category of process or event that initiate the scenario and by the potential effects associated with the category; these factors define the

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Table 8.3.5.13-3. Categories of scenarios delineated according to potential impacts on barriers of the geologic repository (scenario classes)

Disturbed performance of barriers.

(A) Direct Releases:

1) direct release in an extrusive magmatic event;

2) direct release associated with human intrusion

(B) Partial failure of engineered barriers[a]

(C) Partial failure of unsaturated zone barriers:

1) accelerated releases to the water table attending increased flux from sources above the repository;

2) accelerated releases to the water table attending a rise in the water table (foreshortening of unsaturated zone);

3) accelerated releases to the water table attending changes in unsaturated zone rock-hydrologic properties or geochemical properties.

(D) Partial failure of saturated zone barriers:

1) accelerated releases to the accessible environment owing to appearance of discharge points within 5 km downgradient of controlled area (foreshortening of the saturated zone flow path), or changes in flow direction in saturated zone.

2) accelerated releases to the accessible environment owing to increased linear water velocity in the saturated zones, changed rock-hydrologic properties, or changed geochemical properties.

Undisturbed and nominal performance of all barriers.

(E) Undisturbed performance of all natural barriers:
(matrix flow predominates in unsaturated zone barriers, some carbon-14 released in gas phase)

---

[a]No independent, potentially significant classes have been associated with this category.

parameters needed to evaluate and take that scenario class into account in the assessment. For example, a scenario class associated with increased flux in the unsaturated zone (category C-1) may be initiated by climate change. Parameters associated with the effect of the climate change on the flux in the unsaturated zone can be developed to address this scenario class.

3. Models for evaluating radionuclide releases in the scenario classes

To perform the preliminary allocations that guide testing for each scenario class, models for the various release and transport mechanisms must be defined. The models for the release from the engineered barrier system are discussed in Chapter 7 of this SCP. In the following, models for transport of radionuclides by water, for transport of gases and for direct release are discussed in order to identify the parameters to be evaluated in the testing program.

Models for water-pathway releases

A representation of the present hydrologic setting at Yucca Mountain is shown in Figure 8.3.5.13-5, which also shows the abbreviations used for the hydrogeologic units. The proposed location of the repository is in the Topopah Spring welded unit (TSw). The TSw unit includes the TSw1 and TSw2 units shown on Figure 8.3.5.13-5. Conceptual models of present hydrologic conditions are described in Chapter 3 and Section 8.3.5.12 of this document. Briefly, it is believed that, within each unsaturated-zone rock unit, water flows downward and mainly in the matrices of the rock units, with spatially averaged percolation flux not exceeding 0.5 mm/yr. Some lateral diversion of flux may occur at the interfaces between distinct hydrologic rock units (e.g., the interface between units TSw2 and CHnv and CHnz below the repository, and the interface between units PTn and TSw1 above the repository). This diverted water may be directed down dip along the interface (as matrix flow, given the present recharge rates) to the water table or to downward drainage points in the highly faulted zone southeast from the edge of the emplacement zone. Water reaching the water table will then flow in a lateral direction to the accessible environment boundary to the southeast of the controlled area.

Those radionuclide-bearing compounds that might be released in the liquid phase as water percolates through the host rock (TSw2) could be transported along these water pathways, and may eventually reach the accessible environment boundary. The subsurface portion of this boundary may be imagined as a vertical, curved sheet that is everywhere located up to 5 km from the edge of the waste emplacement. The amount of radioactivity released to the accessible environment, expressed in curies, in a 10,000-yr period, in the form of the i^{th} radionuclide, for the j^{th} scenario class involving water pathways, is calculated by the following expression:

$$Q_{ij} = a_i \int_0^{10{,}000\,yr} \left[\int_A \int (\vec{F}_m^i - \vec{F}_j^i) \cdot d\vec{A} \right] dt \qquad (8.3.5.13\text{-}10)$$

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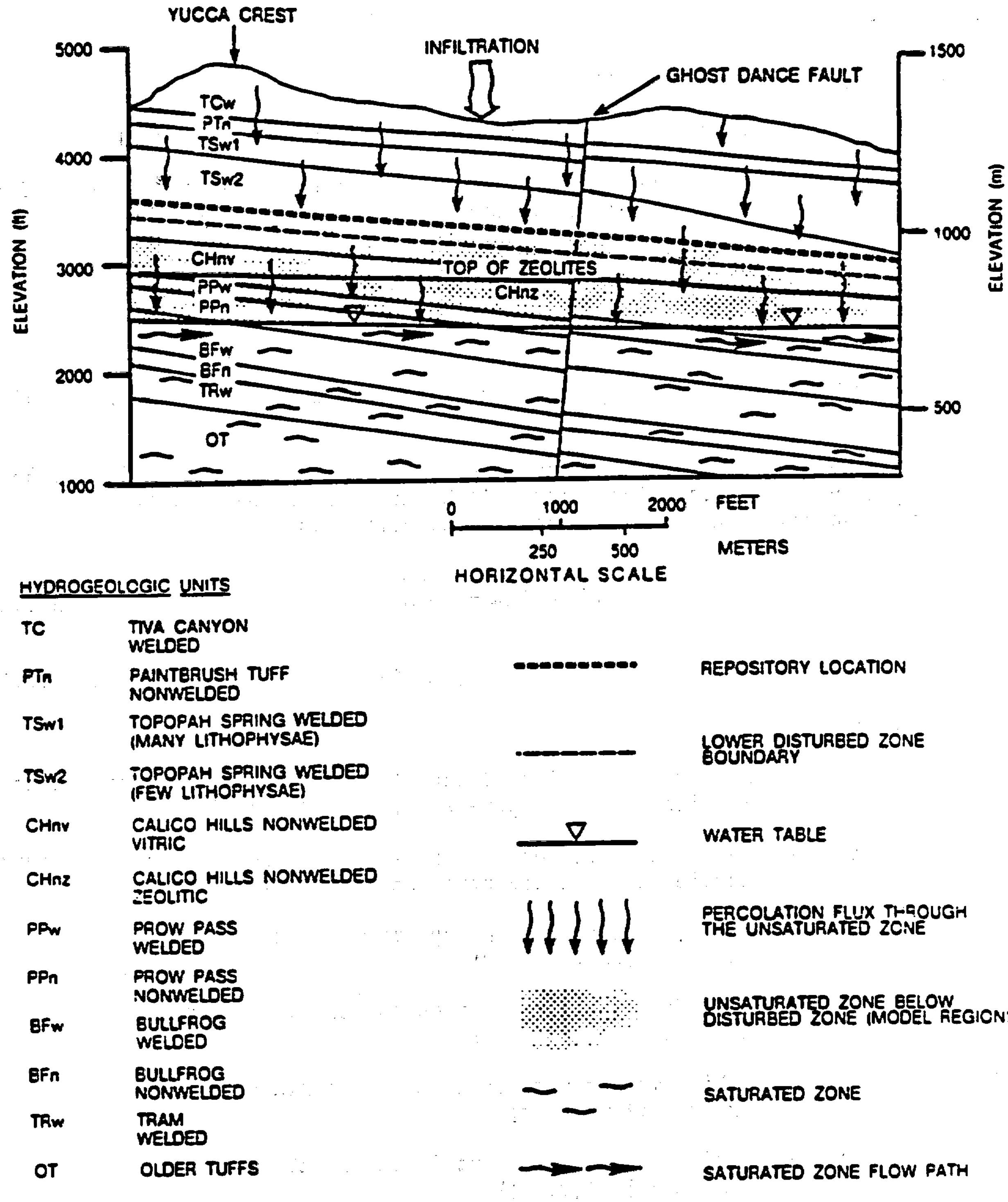

Figure 8.3.5.13-5. General hydrogeologic cross section at Yucca Mountain. The wavy arrows show the flow paths, as assumed in this report, from a potential repository through the unsaturated zone to the water table and along the upper portion of the saturated zone toward the accessible environment (5 km away). Modified from Sinnock et al. (1986).

where

Q_{ij} = radionuclide release (Ci)

a_i = specific activity of the i^{th} radionuclide (Ci/kg)

$\vec{F}^i_m$ = local mass flux of the i^{th} radionuclide in the matrix of the saturated zone (kg/m^2[rock]yr)

$\vec{F}^i_f$ = local mass flux of the i^{th} radionuclide in the fracture system of the saturated zone (kg/m^2[rock]yr)

t = time (yr)

$d\vec{A}$ = an outwardly directed area element on the accessible environment boundary.

Note the j-dependence of quantities on the right of Equation 8.3.5.13-10 has been suppressed for simplicity. Each mass flux is assumed to be the sum of an advective flux and a dispersive-diffusive flux:

$$\vec{F}^i_m = C^i_m \vec{q}_m - \theta_m \overline{\overline{D^i_m}} \bullet \nabla C^i_m \qquad (8.3.5.13\text{-}11A)$$

$$\vec{F}^i_f = C^i_f \vec{q}_f - \theta_f \overline{\overline{D^i_f}} \bullet \nabla C^i_f \qquad (8.3.5.13\text{-}11B)$$

where

C^i_m = mass concentration of the i^{th} radionuclide-bearing chemical species in matrix pore water (kg/m^3[water])

C^i_f = mass concentration of the i^{th} radionuclide-bearing chemical species in fracture pore water (kg/m^3[water])

$\vec{q}_m$ = specific discharge through the matrix system (m^3[water]/m^2[rock]yr)

$\vec{q}_f$ = specific discharge through the fracture system (m^3[water]/m^2[rock]yr)

θ_m = mobile moisture content in the matrix system (m^3[water]/m^3[rock])

θ_f = mobile moisture content in the fracture system (m^3[water]/m^3[rock])

$\overline{\overline{D^i_m}}$ = effective dispersive-diffusive tensor in the matrix system (m^2[rock]/yr)

$\overline{\overline{D^i_f}}$ = effective dispersive-diffusive tensor in the fracture system (m^2[rock]/yr).

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The dispersive-diffusive tensors are the sums of two tensors, one describing molecular diffusion and the other describing hydrodynamic dispersion (Freeze and Cherry, 1979). Note that, in the following development, the contribution of the longitudinal component of molecular diffusion to the dispersive-diffusive fluxes is ignored because the Peclet numbers for the flows that are likely to result in significant releases of radioactivity are about 10 or greater. Furthermore, the dispersive component of mass flux is implicitly included in the specific discharges ($\vec{q}_m$ and $\vec{q}_f$) by assuming the latter are random fields (Sinnock et al., 1986).

To calculate the mass fluxes ($\vec{F}^i_m$ and $\vec{F}^i_f$) one must first solve partial differential equations expressing the transport of dissolved mass from the vicinity of the repository to the accessible environment boundary. A solution of the transport problem gives the mass concentrations (C^i_m and C^i_f) as functions of time and space, and requires the specific discharges ($\vec{q}_m$ and $\vec{q}_f$) and the moisture contents (θ_m and θ_f) as input quantities from a separate calculation of the flow fields in the medium. The mathematical models of flow that have so far been used to predict the hydrologic regime at Yucca Mountain are not reviewed here; Section 8.3.5.12 and Klavetter and Peters (1986) describe the development of a Richards' equation that incorporates composite-porosity concepts for flow through fractured, porous rock. The following partial differential equations for the transport of dissolved mass are consistent with the flow model of Klavetter and Peters and are adopted from Wilson and Dudley (1987):

$$\frac{\partial C^i_m}{\partial t} = -\vec{V}^i_m \bullet \nabla C^i_m - \lambda^i C^i_m - \lambda^{i-1}\left(\frac{R^{i-1}_m}{R^i_m}\right) C^i_m - \frac{1}{\theta_m R^i_m}(A_1 - A^i_2)(C^i_f - C^i_m) \qquad (8.3.5.13\text{-}12A)$$

$$\frac{\partial C^i_f}{\partial t} = -\vec{V}^i_f \bullet \nabla C^i_f - \lambda^i C^i_f - \lambda^{i-1}\left(\frac{R^{i-1}_f}{R^i_f}\right) C^i_f - \frac{1}{\theta_f R^i_f} A^i_2 (C^i_f - C^i_m) \qquad (8.3.5.13\text{-}12B)$$

where

λ_i = decay rate of the i^{th} nuclide species (yr^{-1})

$\vec{V}^i_m$ = effective transport velocity for the i^{th} species in the matrix system (defined below) (m[rock]/yr)

$\vec{V}^i_f$ = effective transport velocity for the i^{th} species in the fracture system (defined below) (m[rock]/yr)

R^i_m = adsorptive retardation factor for the i^{th} species in the matrix system (defined below)

R^i_f = adsorptive retardation factor for the i^{th} species in the fracture system (defined below)

A_1 = advective coupling constant (m^3[water]/m^3[rock]yr)

A^i_2 = diffusive coupling constant (m^3[water]/m^3[rock]yr).

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The numbering of nuclides is such that nuclide $i-1$ decays into nuclide i. The nuclide at the beginning of the chain, nuclide 1, would not have a parent, so λ^0 has a value of zero by definition.

$\vec{V}_m^i$ and $\vec{V}_f^i$, the effective transport velocities for the i^{th} species, are defined by

$$\vec{V}_m^i = \frac{\vec{q}_m}{R_m^i \theta_m} \qquad (8.3.5.13\text{-}13A)$$

$$\vec{V}_f^i = \frac{\vec{q}_f}{R_f^i \theta_f} \qquad (8.3.5.13\text{-}13B)$$

R_m^i and R_f^i, the adsorptive retardation factors for the i^{th} radionuclide species, are defined by

$$R_m^i = 1 - \frac{\rho_b K_d^i}{\theta_m} \qquad (8.3.5.13\text{-}14A)$$

$$R_f^i = 1 - \sigma_f \frac{K_a^i}{\theta_f} \qquad (8.3.5.13\text{-}14B)$$

where

K_d^i = distribution coefficient of the i^{th} species (m^3[water]/kg)

ρ_b = bulk density of rock (kg/m^3[rock])

σ_f = fracture surface area per unit volume of rock (m^{-1}[rock])

K_a^i = distribution coefficient of the i^{th} radionuclide species expressed on a per-unit-surface-area basis (m^3[water]/m^2[rock]).

Some typical values for K_d and estimated values of R_m^i for the various radionuclides in spent fuel are shown in Table 8.3.5.13-4. Because fracture surface areas are usually much smaller than pore surface areas and because chemical equilibrium may not be reached in rapid fracture flows, the adsorptive retardation in fracture flow R_f^i can be regarded as a number of the order of unity (Sinnock et al., 1984b) (i.e., sorption in fractures may be ignored).

Equations 8.3.5.13-12A and 8.3.5.13-12B would be the standard transport equations (Freeze and Cherry, 1979), without dispersive-diffusive terms, except for the presence of the coupling terms proportional to $C_f^i - C_m^i$ on their right-hand sides. In particular, the reciprocal of the quantity Λ_2^i is a measure of the time required for the concentrations in the fracture pore water (C_f^i) to come to equilibrium with its counterpart in the slowly moving matrix pore water (C_m^i). Wilson and Dudley (1987) show that these coupling constants have the forms

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Table 8.3.5.13-4. Typical distribution coefficients and approximate retardation factors for welded and nonwelded Yucca Mountain hydrogeologic units

Element	Distribution coefficient,[a] K_d (ml/g)		Retardation factor,[b] R_m	
	Welded	Nonwelded	Welded	Nonwelded
Americium	1,200	4,600	28,000	24,000
Carbon	0[c]	0[c]	1	1
Curium	1,200	4,600	28,000	24,000
Cesium	290	7,800	6,700	41,000
Iodine	0[c]	0[c]	1	1
Neptunium	7	11	160	58
Protactinium	64	140	1,500	740
Lead	5[d]	5[d]	120	27
Plutonium	64	140	1,500	740
Radium	25,000[e]	25,000[e]	580,000	130,000
Tin	100[d]	100[d]	2,300	530
Strontium	53	3,900	1,200	21,000
Technetium	0.3	0[c]	8	1
Thorium	500[d]	500[d]	12,000	2,600
Uranium	1.8	5.3	27	45
Zirconium	500[d]	500[d]	12,000	2,600

[a]Unless otherwise indicated, distribution coefficients were taken from Table 6-25 (DOE, 1986b) or were inferred from the sorption ratios quoted by Daniels et al. (1982).

[b]Calculated using values of moisture content of 10 and 28 percent and bulk densities of 2.33 and 1.48 g/cm^3 for welded and nonwelded tuff.

[c]No data available; assumed to be zero.

[d]Inferred from the midrange retardation factor for tuffs in compilation in Table 7-1 in National Research Council (1983).

[e]Barium used as a chemical analog.

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$$\Lambda_1 = \frac{\partial \theta_m}{\partial t} - \nabla \bullet q_m \qquad (8.3.5.13\text{-}15)$$

$$\Lambda_2^i \cong \frac{\pi^2 \theta_f \cdot \overline{\overline{D_m^s}} \cdot R_f^i}{R_m^i a^2} \qquad (8.3.5.13\text{-}16)$$

where

a = one-half of the mean spacing between fractures (m[rock])

$|\overline{\overline{D_m^s}}|$ = absolute magnitude of the effective dispersive-diffusive tensor in the matrix (m^2[rock]/yr).

Note that lateral diffusion is accounted for in these coupling terms.

Several of the possible cases of transport of dissolved radionuclides through Yucca Mountain rocks can be qualitatively analyzed by means of Equations 8.3.5.13-12A, 8.3.5.13-12B, and 8.3.5.13-16:

1. Partially saturated flow. In this case, percolation flux does not exceed the saturated matrix hydraulic conductivity so the flow is predominantly through the rock matrix, and only Equation 8.3.5.13-12A applies. This is believed to represent present hydrologic conditions at Yucca Mountain. Under these conditions, the unsaturated-zone rocks act as barriers to the release of liquid-phase contaminants because water flows predominantly in the rock matrix, and matrix flow promotes rather long ground-water travel times (GWTT) to the water table, as shown in Table 8.3.5.13-5. Retardation of many elements is likely to be large under these circumstances (Table 8.3.5.13-4).

2. Fracture flow with weak coupling. In this case, the coupling constants are small compared with the reciprocal of typical transport times in fracture flow ($L \cdot \bar{v}$; where L is the unit thickness), and Equations 8.3.5.13-12A and 8.3.5.13-12B both apply. The radionuclide concentrations spread out through the matrix and fracture systems separately, with the fracture-system concentrations usually "outracing" the matrix-system concentrations. This situation could arise in a discharge through a saturated structural feature (Class C-3, Table 8.3.5.13-3).

3. Fracture flow with strong coupling. In this case, the coupling constants are larger than or comparable to the reciprocal of typical transport times in fracture flow, and the concentrations of radionuclides in both systems come to equilibrium. Wilson and Dudley (1987) show that in this case a single transport equation for the equilibrium concentration applies, and that the effective transport velocity in the advective term of this equation after equilibrium has been reached has the form

$$V'' = \frac{\bar{q}}{\theta_m - \theta_f - \rho_b K_d^i} \qquad (8.3.5.13\text{-}17)$$

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Table 8.3.5.13-5. Estimates[a] of ground-water travel time, predominantly matrix flow[b,c]

Unit	Percentage of total repository area underlain by the unit	Mean (yr)	Standard deviation (yr)
Topopah Spring welded unit	99	4,800	1,900
Calico Hills vitric unit	95	11,000	7,800
Calico Hills zeolitized unit	95	14,000	8,100
Prow Pass welded unit	83	3,900	1,700
Prow Pass unwelded unit	63	15,000	8,000
Bullfrog welded unit	26	6,800	4,100
Bullfrog nonwelded unit	7.5	5,400	3,500
Estimated total[d]		43,000	13,000

[a]Estimates (rounded to 2 significant figures) are for the entire unsaturated zone underlying the disturbed zone. Variability in unit thickness is taken into account.

[b]Percolation flux = 0.5 mm/yr.

[c]Source: Sinnock et al. (1986).

[d]Estimated total is not a sum of the individual columns but represents the quantities for total ground-water travel time through the entire unsaturated zone.

Since θ_m is almost always much greater than θ_f, the effective transport velocity is virtually the same as that for an equivalent porous medium with an effective porosity equal to θ_m and an adsorptive distribution coefficient equal to K_d^i. Thus, models of equivalent-porous-medium transport apply when concentrational equilibrium is reached (or closely approached), and Equation 8.3.5.13-17 approximately applies. Under these circumstances, for percolation flux up to 5 mm/yr, transport times for nonsorbing species through a 50-m section of unsaturated-zone rock would equal or exceed 1,000 yr, and transport times for sorbing species would exceed 10,000 yr.

The third case stated above is likely to apply to those water-pathway scenario classes involving repository-wide failure of the unsaturated-zone barriers: i.e., classes C-1, C-2, and C-3 in Table 8.3.5.13-3. Of most

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interest, though, is whether it would apply in the saturated zone. Because the rocks in the saturated zone are known to be highly fractured and it is known that flow through fractures may be orders of magnitude faster than matrix flow, it has previously been assumed that the saturated zone would not be an effective barrier against releases. In Table 6-19 of the EA (DOE, 1986b), the ground-water travel time along a 5-km path to the accessible environment boundary is estimated to be approximately 170 yr, which is brief compared with the times shown in Table 8.3.5.13-5; the effective porosity used in these estimates was 0.0001, a value of fracture porosity attributed to Sinnock et al. (1984b). But if equivalent-porous-medium transport models are applicable to the saturated zone, the transport times for nonsorbing species would be larger than 170 yr by a factor of 100 to 400 (the estimated ratio of matrix porosity to fracture porosity) (i.e., 17,000 to 68,000 yr) and once coupled, sorbing species would be practically immobile in the saturated zone. Thus, whether the saturated zone is an effective barrier against releases to the accessible environment depends on whether equivalent-porous-medium models apply there (i.e., whether advective-dispersive coupling can be achieved along the flow paths between the repository area and the accessible environment boundary).

According to the Wilson-Dudley model, the saturated zone may provide a good barrier to transport of nonsorbing and some weakly sorbing species, but would not reduce by much the releases of strongly sorbing species which, nevertheless, could be strongly retarded in the unsaturated zone. To see this, note that according to Equations 8.3.5.13-12B and 8.3.5.13-16, an estimate of the time constant governing establishment of concentrational equilibrium between fracture and matrix flows is

$$t_c = \frac{R^i_m a^2}{\pi^2 |\overline{\overline{D}}^s_m|} \qquad (8.3.5.13\text{-}18)$$

Assume that the parameters in this expression take the following values in the saturated zone: fracture spacing (2a) equal to 30 cm (CHnv + CHnz from Table 1 of Klavetter and Peters, 1986), an effective diffusivity ($\overline{\overline{D}}^s_m$) equal to 1.0 x 10^{-2} m/yr and adsorptive retardation factors (R^i_m) equal to the values given in Table 8.3.5.13-4 for nonwelded tuff. Then, using these assumptions, the following are the time-constant (t_c) estimates: (1) for nonsorbing species, 0.23 yr; (2) for uranium, 10.4 yr; (3) for plutonium, 170 yr; and (4) for americium, 5,520 yr. In the Wilson-Dudley model (Wilson and Dudley, 1987), the effect of weak coupling on concentrations of strongly sorbing species in fracture flows is seen from Equations 8.3.5.13-12A and 8.3.5.13-12B. Transport of these species is at the fracture-flow velocity, and weak coupling may at best only increase the effective decay rate for concentrations of strongly sorbing species. Thus, using plutonium-239 as an example, one could assign an effective half-life of 0.693 times 170 yr (118 yr) instead of the usual 24,400-yr half-life against radioactive decay. In the saturated zone, where water travel times in fracture flow are also about 170 yr, the effective "decay" of concentration would only reduce cumulative discharge of plutonium-239 by a factor of about $1/e$, or about 37 percent.

The Wilson-Dudley model (Wilson and Dudley, 1987) may prove to be overly conservative in the sense that it overestimates the time required to couple mass concentrations in fracture flows with mass concentrations in matrix flows, thereby leading to larger discharges of strongly sorbing species at the accessible-environment boundary than would be predicted by equivalent-porous-media transport calculations (i.e., calculations using a single mass concentration that moves with the effective transport velocity in Equation 8.3.5.13-17). Other investigators (Rasmuson and Neretnieks, 1981; Sudicky and Frind, 1982) seem to reach a different conclusion regarding the dependence of the time constant (t_c) governing coupling on the retardation factors (R_m^i). Although it is difficult to see in their analysis, Rasmuson and Neretnieks (1981) appear to predict a time constant of the form

$$t_c = \frac{r^2}{15|\overline{D_m^i}|} \qquad (8.3.5.13\text{-}19)$$

where r is the radius of a matrix block (which is assumed to be spherical and is the same order of magnitude as a in the Wilson-Dudley model (Wilson and Dudley, 1987 (see Equation 8.3.5.13-16). Similarly, the work of Sudicky and Frind (1982) suggests that the time constant should be

$$t_c = \frac{a^2}{3|\overline{D_m^i}|} \qquad (8.3.5.13\text{-}20)$$

where a is now one-half the uniform spacing between fractures, which are assumed to be planar and parallel. Note that each of the last two forms of time constant is independent of the retardation factor and, apart from factors of 2 or 3, is of the same magnitude as the time constant for coupling nonsorbing species in the Wilson-Dudley model (Equation 8.3.5.13-18).

These different estimates of the time required to couple mass concentrations in fracture and matrix flows illustrate the need for validated conceptual and mathematical models of transport of solutes through the actual (i.e., not idealized) fractured, welded and nonwelded tuffs of Yucca Mountain. Investigations to produce such validated models are described in Chapter 4 and in Section 8.3.1.3 (geochemistry program). The Wilson-Dudley model (Wilson and Dudley, 1987) is undoubtedly conservative relative to the models of Rasmuson and Neretnieks (1981) and Sudicky and Frind (1982); but it is not clear that the first or the third of these models is conservative, because each assumes that the permeabilities and constrictivity-tortuosity factors of the surfaces separating fracture void space from matrix void space are the same as the permeability and constrictivity-tortuosity factor of the matrix. Rasmuson and Neretnieks (1981) do postulate an arbitrary mass-transfer coefficient for the interface between matrix and fracture void spaces, but they then assume it is the same as internal mass transfer coefficients for their calculations. Such an assumption could be wrong if relatively impermeable mineral coatings or mineral-grain occlusions occur over a large fraction of the fracture surfaces. In such circumstances, the effective area for entry into the matrix per unit volume of rock could be reduced by several orders of magnitude, with the effect of reducing the effective diffusivity in the formulas for coupling time given above.

A systems-level mathematical model has been developed for predicting releases for those scenario classes involving releases along water pathways

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(e.g., classes in categories E, C, and D in Table 8.3.5.13-3). Discussion of this model serves several purposes in this section:

1. Illustrate the feasibility of and level-of-detail required for the "simplified" models mentioned in the preceding section (Construction of a CCDF) as being necessary for a calculation of the CCDF.

2. Show, in a way that may be clearer than the preceding discussion of radionuclide transport theory, why certain data and information concerning (a) hydrologic and geochemical properties of Yucca Mountain rocks and (b) probabilities and intensities of events or processes initiating a scenario class are needed to resolve this issue.

3. Partially document the basis for the largely nonquantitative reasoning so far used to make preliminary assessments of the relative magnitudes of the EPPMs for scenario classes involving releases along water pathways.

This last purpose should be emphasized: The model to be presented here is preliminary and has at least three serious limitations (the assumptions (1) through (3) given in the next paragraph) that could lead to underestimates of the partial performance measure. These limitations will be remedied by further model development and validation in the future. Most of the detailed development of the following model can be found in Section 3.0 of Sinnock et al. (1986).

Assume that (1) coupling between mass concentrations in matrix and fracture flows is always strong enough to justify the assumption of equivalent-porous-media transport in both the unsaturated and saturated zones, (2) all radionuclides can be treated as single-member decay chains, (3) the process of longitudinal molecular diffusion can be ignored, and (4) mass release rates from the engineered barrier system can be calculated with the formulae given in Section 3.1.1 of Sinnock et al. (1986). Then, making a slight extension of Equation 40 in Sinnock et al. (1986), one can show that the partial performance measure for the j^{th} scenario class involving releases along the water pathway may, in most cases, be approximated by the following expression:

$$M_j = \frac{N}{N_T} \sum_i \frac{a_i}{L_i} \cdot \frac{r_i}{(r_i + \lambda_i)} e^{-\lambda_i t} \cdot e^{\lambda_i \tau_i} \left[1 - e^{-(\lambda_i + r_i)\tau_i}\right] u(\tau_i) \qquad (8.3.5.13\text{-}21)$$

where

N = number of waste packages involved in the release scenario

N_T = total number of waste packages in the repository at closure

a_i = inventory of the i^{th} radionuclide species at time of closure (Ci/MTHM)

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L_i = release limit (per MTHM) for the i^{th} radionuclide as specified in proposed 10 CFR 60.115 and 40 CFR Part 191, Appendix A (Ci)

r_i = fractional mass release rate of the i^{th} radionuclide species from any one of the waste packages involved in the release scenario (yr^{-1})

t = regulatory period of performance (10,000 yr)

λ_i = decay constant for the i^{th} radionuclide species (yr^{-1})

τ_i = a time interval to be described below (yr)

$u(z)$ = unit step function, ($u(z) = 1$ if $z > 0$, and $u(z) = 0$ if $z < 0$).

Table 8.3.5.13-6 provides values for decay constants, radionuclide inventories, release limits, and calculated values for the normalized inventory at risk (a_i/L_i) for the radionuclide species of concern. The following discussion clarifies the meaning of these variables and the equation in general. Note that the subscript j applies to certain variables appearing on the right-hand side, but has been suppressed to simplify the expression. The j-dependence of each variable is noted below.

With the exception of t, N_T, λ_i, and L_i, all the variables appearing on the right-hand side of Equation 8.3.5.13-21 may be regarded as random variables in the sense that uncertainties dictate that they be treated as distributed quantities (examples are mentioned later). Thus, M_j is also a random variable whose statistical properties must usually be evaluated by simulation.

The number of waste packages involved in the release scenario (N) depends on scenario class S_j and on the nature and intensity of the process or event that initiates a realization of the release scenario (e.g., the number of packages intercepted by flow through a fault zone). In every case, $0 < N < N_T$.

The fractional mass release rate (r_i) applies only to release in a liquid phase from bare waste form, and is estimated in Section 3.1.1 of Sinnock et al. (1986) by

$$r_i = \frac{q_w A \hat{S}_i}{M_e} \qquad (8.3.5.13\text{-}22)$$

where

q_w = magnitude of specific discharge of water near a waste package (m^3/m^2 yr)

A = effective water-intercept area of a waste package (m^2)

M_e = mass of waste matrix per package (kg)

$\hat{S}_i$ = effective solubility limit (kg/m^3).

Table 8.3.5.13-6. Reference inventory used in system-level models (page 1 of 2)

Nuclide	Decay constant λ_i (yr^{-1})	Assumed inventory at closure, α_i (Ci/MTHM)[a]	10 CFR 60.115[b] limit, L_i (Ci/MTHM)	Normalized inventory at risk, α_i/L_i
Cm-246	1.26×10^{-4}	3.5×10^{-2}	0.1	3.5×10^{-1}
Cm-245	7.45×10^{-5}	1.8×10^{-1}	0.1	1.8×10^{0}
Am-243	8.72×10^{-5}	1.4×10^{1}	0.1	1.4×10^{2}
Am-242	4.56×10^{-3}	1.0×10^{1}	1.0	1.0×10^{1}
Am-241	1.51×10^{-3}	1.6×10^{3}	0.1	1.6×10^{4}
Pu-242	1.83×10^{-6}	1.6×10^{0}	0.1	1.6×10^{1}
Pu-240	1.05×10^{-4}	4.5×10^{2}	0.1	4.5×10^{3}
Pu-239	2.84×10^{-5}	2.9×10^{2}	0.1	2.9×10^{3}
Pu-238	8.06×10^{-3}	2.0×10^{3}	0.1	2.0×10^{4}
Np-237	3.24×10^{-7}	3.1×10^{-1}	0.1	3.1×10^{0}
U-238	1.54×10^{-10}	3.2×10^{-1}	0.1	3.2×10^{0}
U-236	2.90×10^{-8}	2.2×10^{-1}	0.1	2.2×10^{0}
U-235	9.76×10^{-10}	1.6×10^{-2}	0.1	1.6×10^{-1}
U-234	2.81×10^{-6}	7.4×10^{-2}	0.1	7.4×10^{-1}
U-233	4.28×10^{-6}	3.8×10^{-5}	0.1	3.8×10^{-4}
Pa-231	2.13×10^{-5}	5.3×10^{-6}	0.1	5.3×10^{-5}
Th-232	4.95×10^{-11}	1.1×10^{-10}	0.1	1.1×10^{-9}
Th-230	8.66×10^{-6}	4.1×10^{-6}	0.1	4.1×10^{-5}
Th-229	9.44×10^{-5}	2.8×10^{-8}	0.1	2.8×10^{-7}
Ra-226	4.33×10^{-4}	7.4×10^{-9}	0.1	7.4×10^{-8}
Pb-210	3.11×10^{-2}	7.0×10^{-10}	1.0	7.0×10^{-10}

Table 8.3.5.13-6. Reference inventory used in system-level models (page 2 of 2)

Nuclide	Decay constant λ_i (yr^{-1})	Assumed inventory at closure, a_i (Ci/MTHM)[a]	10 CFR 60.115[b] limit, L_i (Ci/MTHM)	Normalized inventory at risk, a_i/L_i
Cs-137	2.31×10^{-2}	7.5×10^{4}	1.0	7.5×10^{4}
Cs-135	2.31×10^{-7}	2.7×10^{-1}	1.0	2.7×10^{-1}
I-129	4.36×10^{-8}	3.3×10^{-2}	1.0	3.3×10^{-2}
Sn-126	6.93×10^{-6}	4.8×10^{-1}	1.0	4.8×10^{-1}
Tc-99	3.22×10^{-6}	1.3×10^{1}	10.0	1.3×10^{0}
Zr-93	7.29×10^{-7}	1.7×10^{0}	1.0	1.7×10^{0}
Sr-90	2.39×10^{-2}	5.2×10^{4}	1.0	5.2×10^{4}
Ni-59	8.66×10^{-6}	3.0×1.0	1.0	3.0×10^{-2}
C-14	1.21×10^{-4}	1.5×10^{0}	0.1	1.5×10^{1}
			SUM =	1.7×10^{5}

[a]MTHM = metric tons of heavy metal.
[b]From the proposed amendments to 10 CFR Part 60.

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$\hat{S}_i$ is expressed mathematically as

$$\hat{S}_i = \min(S_i, S_m)$$

where

S_i = solubility limit for the chemical species carrying the i^{th} radionuclide (kg/m^3)

S_m = solubility limit for the bulk waste form (kg/m^3).

The fractional mass release rate (r_i) depends on the scenario class and the nature and intensity of initiating events or processes through its dependence on q_w and $\hat{S}_i$ (which are also dependent on the nature and intensity of initiating events and processes). In future formulations of Equation 8.3.5.13-21, r_i may be replaced with empirically determined fractional release rates as a function of time and specific discharge (q_w) near a waste package. Determination of actual release rates from waste packages under different repository hydrologic conditions is part of the investigations associated with Issues 1.4 and 1.5.

The quantity τ_i appearing in Equation 8.3.5.13-21 is defined by

$$\tau_i = t - [\max(T_c, T_d) - T_u^i - T_s^i] \qquad (8.3.5.13\text{-}23)$$

where

t = regulatory period of performance (10,000 yr)

T_c = waste package containment time (yr)

T_d = total delay time (yr)

T_u^i = the unsaturated zone transport time for the i^{th} radionuclide species (yr)

T_s^i = the saturated zone transport time for the i^{th} radionuclide species (yr).

The waste-package containment time (T_c) is actually either the waste-package containment time or the time during which waste package temperature exceeds 95°C, whichever is greater. T_d, the total delay time, measured after closure and before the onset of a release, is defined by

$$T_d = T_w + t_p \qquad (8.3.5.13\text{-}24)$$

where

T_w = waiting time, after closure, before the first occurrence of an initiating event or process that may lead to a release (yr)

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t_p = time interval representing the delay between the occurrence of the initiating event or process and the epoch when releases begin (yr).

Examples of T_e are (1) the epoch at which motion occurs along a fault zone that is sufficient to divert substantial amounts of downdip flow through the repository (t_p would then be the delay between the event, "fault motion," and the event "flow in fault reaches the repository level") and (2) the epoch at which a large surface-water impoundment is formed near the controlled area (t_p would then be the delay between the event, "formation of impoundment," and the event "wetting front from impoundment reaches repository level"). Thus, T_e and t_p depend on the scenario class (j) and the nature and intensity of the initiating events or processes.

The unsaturated zone (UZ) transport time for the i^{th} radionuclide species (T_u^i) is the time required for a molecule of a chemical species carrying the i^{th} radionuclide, which is released from the repository in the liquid phase, to reach the water table. If it is assumed that coupling between mass concentrations in matrix and fracture flows is strong in the UZ, then the effective transport velocity is given by Equation 8.3.5.13-17 and

$$T_u^i = \int_z^y \frac{ds}{|\bar{V}_u^i|} = \int_z^y \frac{1}{q_u}(\theta_m + \theta_f + \rho_b K_d^i)\, ds \qquad (8.3.5.13\text{-}25)$$

where

z = any point in that part of the repository affected by flows associated with the j^{th} scenario class and the event or process initiating the flow

y = a point on the water table connected to z by a flow pathway through the UZ

ds = an element of length along the pathway from z to y.

The saturated zone (SZ) transport time for the i^{th} radionuclide species (T_s^i) is defined in a manner similar to the UZ transport time. Again, if strong coupling in the SZ is assumed, then

$$T_s^i = \int_y^s \frac{ds}{|\bar{V}_s^i|} = \int_y^s \frac{1}{q_s}(n_m - n_f - \rho_b K_d^i)\, ds \qquad (8.3.5.13\text{-}26)$$

where

q_s = specific discharge in the saturated zone (m^3/m^2 yr)

n_m = effective matrix porosity in the saturated zone

n_f = effective fracture porosity in the saturated zone

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z = a point on the accessible environment boundary connected to (defined above) by a flow pathway through the saturated zone.

Finally, the quantity $u(\tau_i)$ appearing in Equation 8.3.5.13-21 is the unit step function: $u(\tau_i) = 1$ if $\tau_i > 0$, and $u(\tau_i) = 0$ if $\tau_i < 0$. Since this function appears as a multiplicative factor in each term of the sum in Equation 8.3.5.13-21, then if any one of the Ts in Equation 8.3.5.13-23 exceeds 10,000 yr, or if the sum of the Ts exceeds 10,000 yr, that term will make no contribution to the sum in Equation 8.3.5.13-21. Thus, the various Ts (T_c, T_e, T_w and T_z), are sensitive quantities in the determination of the magnitude of the partial performance measure (M_i) and warrant special discussion. It is appropriate to reiterate the claim made earlier that, with few exceptions, the variables in Equation 8.3.5.13-21 are distributed variables; it is therefore appropriate to refer to the distribution of the Ts, rather than specific values that the Ts may take.

The distribution of waste-package containment time (T_c) is not known. Estimates in the Yucca Mountain site environmental assessment (DOE, 1986b) suggest that 3,000 yr < T_c < 30,000 yr, but no distribution was attached to this range. Current studies proposed for determining the distribution of T_c are outlined in Section 8.3.5.9.

The waiting times after closure until first occurrence of the process or event that initiates a release (T_e) is distributed differently according to the process or event and scenario class to which it pertains (in this nominal case, $T_e = 0$). In most cases, and particularly for events, waiting times are assumed to be exponentially distributed with a given annual probability of occurrence. For example, consider the scenario class C-1 (Table 8.3.5.13-3) and the initiating event, "episodic offset on faults creates new pathways for drainage of water through the repository"; in this instance T_e may be exponentially distributed with an annual probability less than 10^{-5}/yr (an expected recurrence time of 100,000 yr).

If the waiting time to first occurrence of an event is exponentially distributed with mean annual probability less than 10^{-8}/yr, then the probability that T_e is less than 10,000 yr would be less than one chance in ten thousand. In other words, the event would be expected to occur at most once during a simulation of many tens of thousands of runs and, even on occurrence, the consequences might be zero if other time delays were finite. To make a significant contribution to the CCDF, the consequences (the sample value of M_i) attending the occurrence of such a low-probability event would have to exceed 10,000, with little delay between the event and a release to the accessible environment. Events or processes associated with releases along water pathways fulfilling these conditions are inconceivable, although some events attending direct releases (e.g., scenario class A-1) may come near to fulfilling them.

The time delay (t_b) between the occurrence of an initiating event or process and the epoch when releases from the engineered barrier system attending that event or process begins may in certain contexts be highly sensitive in the determination of the magnitude of the partial performance measure. Generally speaking, $t_b > 0$ for those scenario classes involving hydrologic response to changed boundary conditions on the flows through

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either the UZ or SZ (scenario classes in categories C and D). Though few calculations of the dynamic response of flows to changed boundary conditions have yet been made, the preliminary studies that have been documented indicate that t_r for events affecting flows in the UZ tends to be long (1,000 to 10,000 yr), while t_r for events affecting flows in the SZ tends to be relatively short (tens to hundreds of years). Current tools for investigating hydrodynamic response times are the hydrodynamics module of the Total System Performance Assessment Code (TOSPAC) for the UZ (under development, but refer to Peters et al. (1986) or Klavetter and Peters (1986) for the physical basis of TOSPAC's hydrodynamics), and the ISOQUAD code (Barr and Miller, 1987) for the SZ. The calculation of t_r for different scenario classes and different initiating events or processes will in general require the use of these or similar, phenomenological codes. In those cases where the calculation proves difficult or time consuming, t_r may conservatively be set to zero.

The transport times (T_u^i and T_s^i) are probably the most sensitive quantities determining the performance measure, Equation 8.3.5.13-21. From Equations 8.3.5.13-25 and 8.3.5.13-26, it is seen that the distributions of T_u^i and T_s^i apparently must be inferred by calculating the distributions of space integrals whose arguments contain quantities that are themselves distributed in space (e.g., the product $\rho_b K_d^i$ is expected to be spatially distributed with different mean values, variances and autocovariances pertaining to each rock unit). Such a calculation would be time-consuming in a systems-level model. However, considerable simplification is possible using extensions of the analytic methods proposed in Appendix A of Sinnock et al. (1986). Sinnock et al. (1986) show that distributions of ground-water travel time can be conservatively represented by a normal distribution, and analytic methods are developed therein for calculating the mean and variance of the GWTT distributions; these analytic methods can be applied to the calculation of the mean and variance of the transport times (T_u^i and T_s^i). For example, the mean of the UZ transport times can be estimated by

$$\bar{T}_u^i = \sum_k [\bar{\theta}_m + \bar{\theta}_f + \rho_b K_d^i]_k \cdot l_k \overline{(q_u^{-1})} \qquad (8.3.5.13\text{-}27)$$

where

$\bar{\theta}_m$ = mean mobile moisture content in the matrix system (m^3[water]/m^3[rock])

$\bar{\theta}_f$ = mean mobile moisture content in the fracture system (m^3[water]/m^3[rock])

k = index labeling rock geohydrologic units in the UZ below the repository horizon

l_k = thickness of the k^{th} geohydrologic unit that intervenes between the repository floor and the water table in the repository area (m).

A bar over a quantity denotes the mean value or spatial average for a spatially varying quantity.

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Note that $l_k = 0$ if a water-table rise completely submerges the k^{th} unit.

Similarly, the mean of the SZ transport times can be estimated by

$$\bar{T}_s^i = \sum_s (\bar{n}_m + \bar{n}_f + \rho_b K_{d,s}^i) \cdot d_s \overline{q_s^{-1}} \qquad (8.3.5.13\text{-}28)$$

where

$\bar{n}_m$ = mean effective porosity in matrix

$\bar{n}_f$ = mean effective porosity in fractures

s = index labeling rock geohydrologic units in the SZ

d_s = flow-path length through the s^{th} unit (m).

The sum of the individual d_s is a total flow-path length from a given point on the water table under the repository to any point on the accessible-environment boundary. The formulae for estimating the variances of the transport times (T_u^i and T_s^i) are not quoted here; the evaluation of these formulae requires the same mean values of the quantities that appear on the right-hand sides of Equations 8.3.5.1.3-27 and 8.3.5.13-28, and in addition, the spatial variances and autocovariance lengths for, and correlation coefficients among, all these quantities. In short, given estimates of the statistical parameters associated with the natural distributions of rock hydrologic and geochemical parameters associated with each geohydrologic unit, one can estimate the distribution of the transport times (T_u^i and T_s^i). Estimates of each statistical parameter are intrinsically uncertain because of practical limitations on both the analytical methods used to ascertain values of those parameters, and on the number of the data units (field samples or measurements) that can be obtained for use in those analytical methods. Data that could be used to infer these statistical parameters are presently sparse or nonexistent.

Considerable insight into the sensitivity of the transport times for the determination of the releases can be gained by study of the expressions for the mean value of those times (i.e., Equations 8.3.5.13-27 and 8.3.5.1.3-28). Because fracture porosities are almost always much less than matrix porosities, order-of-magnitude estimates of the mean transport times can be made from

$$\bar{T}_u^i \cong \frac{\bar{n}_m}{\bar{q}_u} \bar{R}_m^i \cdot l \qquad (8.3.5.13\text{-}29A)$$

$$\bar{T}_s^i \cong \frac{\bar{n}_m}{\bar{q}_s} \bar{R}_m^i \cdot d \qquad (8.3.5.13\text{-}29B)$$

where all barred quantities on the right-hand sides now denote spatial averages over the entire UZ or SZ as appropriate. Again, it is emphasized that these estimates apply only if the assumption of strong coupling between mass concentrations in matrix and fracture flows is valid.

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For the UZ, one may take n_m equal to 0.2 (Figure B-1 in Sinnock et al., 1986), values for R^i_m from column 5 of Table 8.3.5.13-4, and l equal to 250 m (Figure 4(A) in Sinnock et al. (1986)). Using these values, one finds that at q_c = 5 mm/yr, the mean UZ transport time for nonsorbing species (where R^i_m = 1) is just about 10,000 yr, and much longer for sorbing species (e.g., uranium's mean transport time through the UZ would be 270,000 to 450,000 yr). The SZ mean transport times can be estimated by taking n_m and R^i_m as in the UZ case, but q_c = 3.2 x 10^{-2} m/yr and l = 5000 m (Table 6-19 in DOE, 1986b). The mean transport time in the SZ for nonsorbing species is about 30,000 yr, and for sorbing species, a term longer by the factor R^i_m.

Estimates such as these show (1) why it may be possible to ignore the contributions of sorbing species to the sum in Equation 8.3.5.13-21, provided that the standard deviations (i.e., the square root of the variances) of the transport times are small compared with the mean and (2) why the variances of the transport times are important in determining the relative contributions of all species to the sum in Equation 8.3.5.13-21. These estimates also show why a solution to the problem of coupling times for the transfer of mass concentrations between fracture and matrix flows is seriously needed, particularly for flows in the SZ. If coupling times are short then, as indicated, transport times for all species in the SZ may exceed 30,000 yr and the SZ becomes the primary barrier to releases through the water pathways (indeed, those scenario classes involving water-pathway releases would make little if any contribution to the complementary cumulative distribution functions in this alternative). On the other hand, if coupling times are long compared with the estimated 170-year ground-water travel time in the SZ, the SZ barrier could only modestly reduce the magnitude of 10,000-yr cumulative releases, and the UZ barrier would become the primary barrier to releases.

Models for gas-phase releases

Release of radionuclides by gas pathways appears in both undisturbed-case and disturbed-case scenario classes. A few of the radionuclides in spent-fuel waste forms, namely tritium, carbon-14, krypton-85, and iodine-129, could be released from waste packages as gases or in compounds that form gases. Of these, the only important one appears to be carbon-14, in the form of carbon dioxide. The half-lives of tritium and krypton-85 (12.3 yr and 10.7 yr, respectively) are short. Current evidence and the extremely reactive nature of elemental iodine suggest that it is likely to be released or quickly transforms in a liquid or solid phase. The source of gas-phase carbon-14 "is thought to be removal of carbon from the oxidized skin of the Zircaloy cladding by reaction of the oxygen in the atmosphere with carbon in the cladding oxidation layer to release carbon dioxide" (Oversby and McCright, 1985). Oversby and McCright believe that as much as 1 percent of the carbon-14 inventory in spent fuel may be available for rapid release from the breached waste packages in the form of carbon dioxide during the first 100 to 1,000 yr following closure (Section 8.3.5.9). After the 1,000-yr containment period, the amount of carbon-14 available for rapid release from the breached waste packages would be very small because of slow oxidation rate of carbon-14 to carbon dioxide due to low temperatures and gamma fluxes (Section 8.3.5.10). Carbon-14 in nongaseous forms will be released slowly, probably in a liquid phase.

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Rapid release of 1 percent of the carbon-14 inventory to the accessible environment would not alone violate the proposed rule (10 CFR 60.115). An upper-bound estimate of the normalized cumulative release under expected conditions is 0.15, assuming a normalized inventory of 15 for carbon-14 (Table 8.3.5.13-6) at closure time and prompt transfer of 1 percent of the carbon-14 to the atmosphere above the repository. Carbon-14 dioxide originating in the waste form would, of course, not be promptly transferred to the atmosphere, but would have finite and possibly long residence times in partially saturated pore spaces of the repository's overburden during which times the carbon-14 could decay. In addition, some of the released carbon-14 dioxide would diffuse downward and presumably become dissolved in water in pore spaces of rock below the repository horizon. The effect of long residence times and downward diffusion would be to reduce the time-integrated flux of carbon-14 to the atmosphere above the repository.

The time-dependent surface flux of carbon-14 originating in the waste form may, in principle, be estimated by first constructing a conceptual model of transport of carbon-14 dioxide through the partially saturated overburden units at Yucca Mountain and, second, solving the system of transport equations rising from the conceptual model. The remainder of this discussion is devoted to a description of one possible conceptual model of transport of carbon-14 dioxide and the site-specific data needed to verify that conceptual model and implement a solution of the associated transport equations.

The conceptual model for the transport of carbon-14 dioxide through the partially saturated overburden has three principal features:

1. Gas-phase carbon-14 dioxide moves upward through air-filled pores and fractures of the unsaturated tuffs by molecular diffusion and by advection in a thermally driven air-convection cell. Analyses to date do not permit either of these processes to be neglected.

2. An isotopic equilibrium exists between carbon dioxide in the gas phase, which is mobile, and dissolved bicarbonate, which is immobile. Advection of dissolved bicarbonate almost certainly may be neglected.

3. Precipitation of calcite, if it occurs, irreversibly removes carbon-14 from the system. The chemical controls on calcite precipitation are not yet understood.

To describe this system, three sets of equations are required:

1. Equations for the movement of carbon-14 and its transfer among phases.

2. Equations that determine the chemical environment, insofar as it is not directly observable.

3. Equations for the velocity of air flow.

The following discussion describes the preliminary model for releases along gas pathways. Thorstenson et al. (1983) point out that each isotopic species of CO_2 within unsaturated-zone gas diffuses according to its own concentration gradient. Advective transfer also will depend on the local concentration of any given species, independent of the presence of other isotopes. Mass transfer among phases can, however, depend on the concentrations of other isotopic species.

With these considerations in mind, a governing equation for the concentration of any gas in the unsaturated zone is needed. This is obtained by adding advection terms to Equation 12 of Thorstenson et al. (1983). The one dimensional equation is as follows:

$$-q_g \frac{\partial C_A}{\partial z} - q_L \frac{\partial C_A^*}{\partial z} + \tau \Theta_D D_A \frac{\partial^2 C_A}{\partial z^2} = \Theta_D \frac{\partial C_A}{\partial t} + (\Theta_T - \Theta_D) \frac{\partial C_A^*}{\partial t} + \frac{\partial \hat{C}_A}{\partial t} - \alpha_A \qquad (8.3.5.13\text{-}30)$$

where

q_g = Darcy velocity of mass flow of the pore gas (cm/s)

q_L = Darcy velocity of liquid water flow (cm/s)

C_A = concentration of gas A (mole/cm^3)

C_A^* = concentration of gas A and its reaction products in the soil water (mole/cm^3 of water) (Thorstenson et al. define this variable as a concentration per unit mass)

$\hat{C}_A$ = concentration of substance A and its reaction products in the solid phase (mole/[cm^3 of medium], where [cm^3 of medium] refers to the space occupied by solids + liquids + gases)

z = dimension increasing with depth; 0 at land surface (cm)

τ = a tortuosity factor accounting for the added resistance to diffusion imposed by the structure of the porous medium (dimensionless)

Θ_D = drained or gas-filled porosity (dimensionless)

D_A = molecular diffusion constant for diffusion of gas A into the pore gas (cm^2/s)

t = time (s)

Θ_T = total porosity (dimensionless)

α_A = a production term for substance A [(mole/cm^3 of medium)/s].

In addition to the measurable parameters τ, Θ_D, D_A, and Θ_T, Equation 8.3.5.13-30 contains five quantities that must be calculated from other models: q_L, q_g, $\partial C_A^*/\partial t$, $\partial \hat{C}_A/\partial t$, and α_A. The production term α_A will, for carbon-14 originating from a repository, be obtained from waste-package models that will not be discussed here. The interphase transfer terms ($\partial C_A^*/\partial t$ and $\partial \hat{C}_A/\partial t$) depend on C_A, and if species A is total carbon dioxide

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the relationship is nonlinear. The chemical models describing this relationship must therefore be incorporated into the transport model.

Since liquid-phase advection is almost certainly negligible for carbon species at Yucca Mountain, the second term on the left-hand side of the equation, involving q_l, can be dropped.

The gas advection velocity q_g at any point depends on the gas density throughout the mountain; the gas density depends on temperature and on the partial pressures of water vapor (which, in turn, depends on temperature because the relative humidity of pore gas is always close to 100 percent) and carbon dioxide. Both of these gases are more concentrated in unsaturated-zone gases than in the atmosphere; water vapor is lighter than air and carbon dioxide is heavier. Temperature differences between the mountain interior and the outside arise from the damping out of daily and annual temperature variations in the subsurface, the geothermal gradient, and the heat source in the repository. The first two of these factors, combined with the topographic relief of the mountain, induce a nonnegligible air flow under existing conditions (Weeks, 1986; Kipp, 1986). Another, steadier component of air flow will be induced by repository heating and continue until the rock temperature throughout the mountain has returned to its initial temperature. The relative magnitude of these flows is unknown.

Steady air flows, such as those due to repository heating or mean humidity differences between pore gas and atmosphere, are incorporated into Equation 8.3.5.13-30 through the q_g term. The best manner of treating oscillating flows due to daily and annual temperature variations is uncertain; rather than calculating a varying q_g, it may be easier to treat these flows as a mixing process and replace the effective molecular diffusion constant (τD_A) with a mixing constant (D^*), which varies from place to place.

Fortunately, it is possible at Yucca Mountain to decouple air-flow and carbon-dioxide-transport models and solve the air-flow problems without reference to CO_2. The advection velocity q_g is essentially independent of CO_2 concentration because humidity and temperature effects are much greater than the density changes associated with variations in CO_2 partial pressures.

Equation 8.3.5.13-30 requires two boundary conditions, one at the water table and the other at or near the surface. Because the production of CO_2 by plant roots is large and difficult to quantify and because seasonal temperature variations result in changes in CO_2 flux that extend for some distance below the surface, it will probably be more convenient to locate the upper boundary at a depth of about 10 m rather than the surface. As for the lower boundary, Thorstenson et al. (1983) found that an assumption of chemical equilibrium between pore gas just above the water table and water just below it frequently is not borne out. Very likely, it will not be possible to develop mechanistic models of CO_2 fluxes at the boundaries, and concentrations there will simply have to be set to measured values.

The quantity that must be calculated to determine regulatory compliance is not the concentration C_A, but the integral of the net flux to the accessible environment over the area of the repository and over a 10,000 yr period following closure. The mass flux of species A, which is denoted q_A, can be computed from solutions to Equation 8.3.5.13-30 as

$$q_A = q_g C_A + q_L C_A^* - \tau \Theta_D \frac{\partial C_A}{\partial z} \qquad (8.3.5.13\text{-}31)$$

In the sign convention used here, the fluxes (q) are positive downward.

Solution of Equation 8.3.5.13-30 requires that formulae be derived for the time derivatives of the quantities C^* and C_A, representing the concentrations of species A in the liquid and solid phases. Because the species of interest are total carbon dioxide and carbon-14, these derivatives will be equal to the rates of carbon-dioxide dissolution and carbonate mineral precipitation. The rates of these reactions will be determined by the carbonate chemistry of the system. Unfortunately, existing data are not adequate to identify a unique chemical model. The model needed for resolving Issue 1.1 will be developed as part of an investigation in the Yucca Mountain Project geochemistry program (Section 8.3.1.3.8).

A model for concentrations of total carbon dioxide is a prerequisite for predicting transport of carbon-14 for two reasons:

1. The equation for carbon-14 transport will contain parameters depending on concentrations of total carbon dioxide and bicarbonate.

2. The success of a model in explaining currently observed carbon dioxide concentrations is a valuable test of its validity.

To apply the transport Equation 8.3.5.13-30 to total carbon dioxide, one needs formulae for the rates of change in the dissolved bicarbonate concentration C^* and the solid calcite concentration $\bar{C}$. These two quantities will be addressed in an investigation in the Yucca Mountain Project geochemistry program (Section 8.3.1.3.8).

Two equations are needed to describe the aqueous and solid carbon-14 concentrations. Here, the concentrations and partial pressures of total carbon dioxide are denoted as C_T and P_T, respectively, and the concentration and partial pressures of carbon-14 dioxide are denoted as C_{14} and P_{14}.

The liquid and gas phases are intimately mixed, and both gas molecules and dissolved ions are very mobile. The chemical reactions are rapid, and isotopic fractionation factors between gas and aqueous-phase species and among aqueous-phase species in the carbonate system are all very close to unity. Consequently, isotopic equilibrium can be expected between gas-phase carbon dioxide and dissolved bicarbonate. This gives the equation

$$\frac{C_{14}^*}{C_T^*} = \frac{P_{14}}{P_T} \qquad (8.3.5.13\text{-}32A)$$

Carbon atoms in solid calcite are much less mobile. At least as a first approximation, they may be thought of as a reservoir of "dead" carbon with no carbon-14 content. In this case, we can write equations not for the solid

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concentration *C*, but for its time derivative. Different equations are obtained for the cases of net precipitation and net dissolution:

$$\frac{\frac{\partial \check{C}_{14}}{\partial t}}{\frac{\partial \check{C}_T}{\partial t}} = \frac{P_{14}}{P_T}\ ,\ \text{for}\ \frac{\partial \check{C}_T}{\partial t} > 0 \qquad (8.3.5.13\text{-}32B)$$

$$\frac{\partial \check{C}_{14}}{\partial t} = 0\ .\ \text{for}\ \frac{\partial \check{C}_T}{\partial t} < 0 \qquad (8.3.5.13\text{-}32C)$$

Equation 8.3.5.13-32C for net dissolution rests on the assumption that there has been no precipitation in the relatively recent past (intervals of a few times the half-life of 5,730 yr). If a period of precipitation followed by dissolution within the next 10,000 yr is predicted, some carbon-14 would be released from the dissolving calcite and a different equation would have to be used instead of Equation 8.3.5.13-32C.

If Equation 8.3.5.13-30 for transport of total carbon can be solved without regard for carbon-14, substitution of that solution along with Equations 8.3.5.13-32 and 8.3.5.13-30 for carbon-14 will yield a linear equation for carbon-14 transport. This will indeed be the case. Natural carbon-14 abundances are on the order of one part in 10^{14}. The carbon-14 in the repository will be considerably more abundant, but still negligible compared with the carbon in impinging water and soil gas. Even a relatively high estimate of the repository carbon-14 inventory at 10^5 Ci (van Konynenburg et al., 1984) only places about 22 kg of carbon-14 in the repository. It should be noted that less than 1 percent of the 22-kg inventory of carbon-14 may become available for gaseous release. By comparison, if the disturbed zone around the repository has a thickness of 100 m, an area of 6 km, a drained porosity of 0.1, and a CO_2 partial pressure of 0.1 percent by volume, it will contain approximately 33,000 kg of carbon in the gas phase, and even more carbon will be present as dissolved bicarbonate.

Discussion of some preliminary scenario classes

Disturbed case (A-1): direct release in basaltic volcanism. The consequences of basaltic volcanism on a waste-disposal site at Yucca Mountain were thoroughly studied (Link et al., 1982) before reference repository host rock and inventories for the presently proposed site at Yucca Mountain were conceived. Many of the insights from this study are still relevant, however, and can be used as background for the discussion of this scenario class.

"The formation of the basic Basin and Range topography of the (Yucca Mountain site) has been punctuated throughout Tertiary and Quaternary time by volcanism. In fact, (the site) is an up-faulted block made up of at least 6,000 feet of tuff, a volcanic rock. Only basaltic volcanism (dike-fed cinder cones) is known to have occurred during Quaternary time in the region surrounding the (site)." (Link et al., 1982)

During eruption, cinder cones like the ones near the Yucca Mountain site are usually characterized by a pulsating columnar eruption of jets of gas and lava fragments. At repository depths, cones are fed by vertical, tabular magma bodies called dikes.

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"Geometric arguments suggest that if a tabular dike intersects the repository, it would most likely intercept about seven spent fuel canisters....Other positions or lengths of penetration of the dike in the repository could result in the interception of as few as zero canisters or as many as 448 spent fuel canisters.... Because there is no information available on the possible interaction between a waste canister and a basaltic dike, all waste in each canister was assumed to be released into the magma.... If waste were entrained by magma, some of it would be released by the eruption column in the form of fine particles." (Link et al., 1982)

Using these insights about basaltic volcanism, an estimate of the normalized cumulative release can be made for this scenario class. It is assumed that (1) the surface projection of the area bounded by the perimeter drift, and extensions, is 5.1 km^2; (2) a tabular feeder dike passes through the center of the area bounded by the perimeter drift, and extensions, and has dimensions 1 m by 3 km (i.e., 3×10^{-3} km^2 area); (3) 18,000 waste packages are uniformly distributed over the area bounded by the perimeter drift, and extensions, with radionuclide inventory given in columns 1 and 3 of Table 8.3.5.13-6; and (4) any waste packages intercepted by the feeder dike are immediately ejected through the cinder cone. The perimeter drift is the boundary of the primary repository area and extensions; the surface projection is the vertical projection of the primary repository area and extensions onto the ground surface.

Geometric argument shows that 11 waste packages are intercepted in this case. One can estimate a bound on the consequences for release to the accessible environment for this case using Equation 8.3.5.13-21, that is,

$$M \leq \frac{N}{N_T} \sum_i \frac{a_i}{L_i} = 104 \qquad (8.3.5.13\text{-}33)$$

where $N = 11$, $N_T = 18{,}000$, and the sum over the index i of a_i/L_i is computed at the bottom of column 5 of Table 8.3.5.13-6. If 4×10^{-8}/yr (Crowe et al, 1982) is taken as the upper-bound estimate of the annual probability of occurrence of basaltic volcanism in the area bounded by the perimeter drift, and extensions, then the probability of such an event occurring once in a 10,000-yr period is 4×10^{-4} and the probability of more than one occurrence is negligible. According to these estimates, the normalized release is less than

$$104 \times 4 \times 10^{-4} = 4.16 \times 10^{-2}.$$

This estimate is not necessarily an upper bound, because the size of the feeder dike was arbitrarily assumed. A more realistic calculation that takes into account the decay of the waste inventory, the distribution in sizes of feeder dikes, and the distribution of waiting times until occurrence of basaltic volcanism can easily be made once the values of performance parameters for the scenario are known.

Disturbed case (A-2): direct release via human intrusion. Many scenarios involving human intrusion at Yucca Mountain can be imagined, but for this document consideration is restricted to the events cited in the list of potentially adverse conditions (PACs) (10 CFR 60.122(c)(2)). This list mentions some of the human activities that could adversely affect ground-water flow systems, namely (1) ground-water withdrawal, (2) extensive irrigation, (3) subsurface injection of fluids, (4) underground pumped storage, (5) military activity, and (6) construction of large-scale surface water impoundments. In considering the potential effects of future activities of these kinds, the DOE has assumed that none could credibly occur within the boundaries of the controlled area (the area to be delimited by long-lasting markers); however, the possibility of some circumspect exploratory drilling within the controlled area is allowed.

Scenarios involving activities (2) and (6) are incorporated in the discussions of scenario classes C and D, which involve local or repository-wide flooding from sources above the repository (C) and effects on the saturated zone (D); neither of these activities could logically lead to direct releases of radionuclides to the accessible environment in the context of Yucca Mountain.

Activity 1, ground-water withdrawal, could lead to either direct or indirect releases. Direct releases would occur through the pumping to the surface of saturated-zone ground water that has become contaminated with radionuclides from the repository. This situation is of concern for the ground-water protection rule addressed by Issue 1.3 (Section 8.3.5.15). Indirect releases could be linked to changes in ground-water velocities in the saturated zone through changes in head gradients caused by water withdrawal. Given the long transport times through the unsaturated zone that are predicted for the nominal case (less than 1 percent of calculated ground-water travel times are less than 10,000 yr (Sinnock et al., 1986)), the consequences of direct release through ground-water withdrawal appear to be minuscule and probably can be ignored. The consequences of indirect release through alterations in the head gradients of the saturated zone probably can also be ignored, but in any case are amenable to quantification using models for failure of the saturated-zone barriers (category D in Table 8.3.5.13-3).

This leaves the essentially underground activities (3, 4, and 5), which, along with other underground activities in the controlled area not mentioned in the potentially adverse condition (PAC) list (e.g., underground exploration for economic and scientific purposes), would logically be preceded by some kind of investigations from the surface. Consistent with the PAC list's context of late 20th-century socioeconomic needs and technology, the most likely method of exploration from the surface would be the drilling of boreholes. It is recognized that, in principle, other human activities could be important. However, the DOE's judgment is that the assumptions specified with regard to human activities in the definition of significant events and processes in the proposed amendments to 10 CFR 60.2 (and given in the regulatory background for this discussion) limit those that should, in fact, be considered. In the remainder of this discussion, an upper-bound estimate of the scenario probability and the normalized cumulative release for such inadvertent exploratory drilling is made. The scenario assumptions are given in the following paragraphs.

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It is assumed that Yucca Mountain could become the site of many episodes of exploratory drilling during the 10,000-yr period following closure. Each episode is presumed to follow a period in which markers for the controlled area (as defined by the NRC in 10 CFR 60.2) have either disappeared or become unreadable, and records and knowledge of previous exploratory efforts are lost. During each episode, there is the possibility that deep drilling on the site will accidentally graze or penetrate a waste package, resulting in radioactive material being brought to the surface along with core. The activity of this material would thus contribute to the cumulative release to the accessible environment. Depending on the time of an episode after closure and the depth of drilling in the unsaturated zone, some radioactivity could be brought to the surface in the pore water of cores from those boreholes that do not graze a waste package. This contribution is not considered in the present analysis, but it could be considered in future analyses, given the same kinds of data as will be required for a complete analysis of the present scenario class (A-1) and the nominal class (E).

It is assumed that 18,000 waste packages, each containing 3.89 MTHM of spent fuel, are uniformly distributed throughout the area bounded by the perimeter drift, and extensions, in the Topopah Spring (TS) unit (Figure 8.3.5.13-5). The bounded area is 1,260 acres (510 ha, or 5.1 km^2). The waste packages are cylindrical with an internal diameter of 68 cm and internal length of 4.3 m; the analysis below treats both vertical and horizontal placement of waste packages. Waste composition of each package is given in Table 6-47 of DOE (1986b). To bound the estimate, it is assumed that a 100-yr-old waste inventory prevails during every exploratory episode and that the rate of penetration over the 10,000-yr period is constant and equal to 0.0003 boreholes per square kilometer per year (this rate of drilling is specified by the EPA in 40 CFR Part 191, Appendix B as a maximum rate of penetration at sites containing nonsedimentary rock). It is also assumed that each penetration passes vertically through the TS unit and that the drill-bit diameter is constant and equal to 6 cm.

Given that the entire thickness of the TS unit under the surface projection of the perimeter drift and extensions is vertically penetrated by the drill-bit, the probability that a waste package is at least grazed by any one drill-bit is

$$p = \begin{cases} .0125 & \text{(horizontal emplacement)} \\ .00152 & \text{(vertical emplacement)} \end{cases}$$

This probability is equal to the ratio of the total effective intercept area of the 18,000 packages to the area bounded by the perimeter drift and extensions. The effective intercept area/package is just the projected area per package plus the area of a 3-cm-thick border around the projected area. At the given upper limit on the rate of penetration of the site 0.0003 boreholes per square kilometers per year, one expects about 15 penetrations in 10,000 yr. Given $N = 15$ tries, the expected value of curies brought to the surface on the n^{th} try ($n = 1, 2, 3, \ldots N$) is $C_i(n)p$, where $C_i(n)$ is the expected curies, in the form of the i^{th} nuclide species, intercepted by the drill bit on the n^{th} try. Note that this quantity would have to be estimated by simulation, taking into account the change in waste-package nuclide

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inventory with time. For purposes of this bounding calculation, we introduce $C_i(\max)$, the maximum curies that could be intercepted by a drill bit in any try; thus, the expected value of curies brought to the surface in N tries is

$$\hat{Q}_i = \sum_{n=1}^{N} C_i(n)p \leq NpC_i(\max) \qquad (8.3.5.13\text{-}34)$$

and the expectation of the performance measure for this scenario class is

$$\hat{M} = \sum_i \frac{\hat{Q}_i}{L_i} \leq Np \sum_i \frac{C_i(\max)}{L_i} \qquad (8.3.5.13\text{-}35)$$

The quantity on the right side of the above inequality is an upper-bound estimate of the expected partial performance measure (EPPM) for this scenario class. The sum on the right side is calculated in Table 8.3.5.13-7. Using the values of N and p given above

$$\hat{M} < \begin{cases} 7.66 \times 10^{-4} & \text{(vertical)} \\ 9.92 \times 10^{-4} & \text{(horizontal)} \end{cases}$$

This upper-bound estimate should be compared with the estimate of the EPPM for nominal-case releases along water pathways, about 2×10^{-7} (Table 4 in Sinnock et al., 1986).

Disturbed case (C-1): increased flux through the unsaturated zone. Some of the initiating events or processes causing an increased percolation flux through the unsaturated zone (UZ) and a consequent decrease in radionuclide transport times through the UZ are the following:

1. Climate change causes increase in infiltration over controlled area (C-area).

2. Offset on faults creates surface-water impoundments, alters drainage, creates perched aquifers, or changes dip of tuff beds.

3. Volcanic eruption causes flows or other changes in topography that result in surface-water impoundments or diversion of drainage.

4. Igneous intrusions, such as a sill, that could result in a change in flux.

5. Tectonic folding changes the dip of tuff beds in C-area, thereby changing flux.

6. Uplift or subsidence changes drainage, thereby changing flux.

7. Subsidence of the mined repository creates surface-water impound ments or diverts drainage.

8. Natural surface-water impoundments are formed over access shafts connecting surface and repository.

Table 8.3.5.13-7. Maximum radioactivity (in curies) released in a single exploratory drilling at the Yucca Mountain site

Species[a]	Inventory[b] (Ci/MTHM)	Maximum radioactivity in 6-cm-diameter core, $C_i(max)$ (Ci): Horizontal emplacement	Maximum radioactivity in 6-cm-diameter core, $C_i(max)$ (Ci): Vertical emplacement	Limit, L_i[c] (Ci)	$C_i(max)/L_i$: Horizontal emplacement	$C_i(max)/L_i$: Vertical emplacement
Am-241	3.5×10^3	16.7	106	7,000	2.39×10^{-3}	1.51×10^{-2}
Pu-241	1.0×10^3	4.78	30.4	7,000	6.83×10^{-4}	4.34×10^{-3}
Pu-240	4.5×10^2	2.15	13.7	7,000	3.07×10^{-4}	1.96×10^{-3}
Pu-239	2.9×10^2	1.39	8.84	7,000	1.99×10^{-4}	1.26×10^{-3}
Pu-238	1.0×10^3	4.78	30.4	7,000	6.83×10^{-4}	4.34×10^{-3}
Cs-137	9.4×10^3	44.9	286	70,000	6.41×10^{-4}	4.09×10^{-3}
Sr-90	5.7×10^3	27.2	173	70,000	3.89×10^{-4}	2.47×10^{-3}
	Subtotal	102	648			
	Contributions from other species	0.42	3			
	Totals	102	651		5.29×10^{-3}	3.36×10^{-2}

[a]The seven radionuclides listed contribute more than 99 percent of maximum radioactivity in core; refer to column 3.
[b]100-yr-old spent fuel. Source: Tables 3.3.8, 3.3.9, and 3.3.10 in DOE (1979). MTHM = metric tons of heavy metal.
[c]EPA limit on 10,000-yr releases for 70,000 MTHM of spent fuel (40 CFR Part 191).

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9. Extensive irrigation is conducted near the C-area.

10. Large-scale surface-water impoundments are constructed near the C-area.

Of these events and processes, climatic change is probably the agent with the most potential for increasing local and repository-wide flux levels. The diversion of drainage from down-dip flow attending an episodic offset along a fault passing through the repository could also substantially increase local flux and, as a consequence, place a limited number of waste packages in pathways to the water table along which the UZ transport times are short relative to the mean transport times of the nominal case. The other initiating events or processes appearing in the above list will probably prove to have consequences that are indistinguishable from nominal-case consequences. In particular, those events or processes leading to floods over the C-area will probably have very long hydraulic-response times, and thus near-zero consequences. This belief stems from preliminary calculations of flooding that show response times of thousands of years. There is also a small number of waste packages that would be intercepted by the "plume" of a flooding event, and a negligible reduction in UZ transport time would be caused by the slight increase in flux that attends a flooding event.

Disturbed case (C-2): foreshortening of the unsaturated zone. Some initiating events and processes that could lead to a decrease in the effective thickness of the unsaturated zone (UZ) and a consequent decrease in radionuclide transport times through the UZ are the following:

1. Climate change causes an increase in altitude of water table.

2. Igneous intrusion causes a flow barrier or thermal effects that alter water-table level.

3. Offset on fault juxtaposes transmissive and nontransmissive units, resulting in either the creation of a perched aquifer or a rise in water table.

4. Episodic changes in strain in the rock mass due to faulting cause changes in water-table level.

5. Folding, uplift, or subsidence lowers repository with respect to water table.

6. Extensive irrigation is conducted near the C-area.

7. Large-scale surface-water impoundments are constructed near the C-area.

8. Extensive surface or subsurface mining occurs near C-area.

9. Extensive ground-water withdrawal occurs near C-area.

Of these events and processes, climate change probably is the agent with the most potential for increasing the elevation of the water table under the C-area; Czarnecki (1985) used a regional hydrologic model (Czarnecki and

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Waddell, 1984) and extremely conservative assumptions about the effects of climatic change on ground-water systems to show that water-table elevations might rise by as much as 130 m in the future. The effect of changed offset along faults on saturated-zone (SZ) transmissivity may also be important in determining water-table elevations. Barr and Miller (1987) have used the ISOQUAD code (Pinder, 1976) to explore the effects of abrupt alterations of (SZ) features presumed to control the distribution of hydraulic heads. For example, they assumed a fault-controlled model with sudden leakage across the Solitario Canyon fault and predicted rises in the water-table altitude under the C-area of 30 m with hydrodynamic response times of about 115 yr. A connection between fault motion and changes in leakage across that fault has not been firmly established. Hence, the calculations of Barr and Miller (1987) should be viewed as a worst-case calculation.

The other initiating events or processes appearing in the list will probably prove to have consequences indistinguishable from nominal-case consequences, or even have positive effects such as the lowering of the water-table level through ground-water withdrawals or mine dewatering. In any case, these beliefs need to be confirmed by quantitatively screening the consequences of realization of each of the initiating events or processes shown in the list.

Disturbed case (C-3): altered unsaturated-zone rock-properties and geochemistry. Some initiating events and processes that could alter rock-hydrologic properties and geochemical conditions in the unsaturated zone (UZ) in such a way as to decrease radionuclide transport times through the UZ are the following:

1. Igneous intrusions cause changes in rock hydrologic properties.

2. Igneous intrusions cause changes in rock geochemical properties.

3. Episodic offset on faults causes local changes in rock hydrologic properties, thereby destroying existing barriers to flow or creating new conduits for drainage.

4. Offset on a fault causes changes in movement of ground water, resulting in mineralogical changes along the fault zone.

5. Offset on a fault changes radionuclide travel pathway to one with different geochemical properties.

6. Changes in stress or strain in the C-area resulting from episodic faulting, folding, or uplift cause changes in the hydrologic properties of the rock mass.

7. Tectonic processes cause changes in ground-water table or movement that results in mineralogic changes in the C-area.

8. Extensive irrigation is conducted near the C-area.

9. Large-scale surface-water impoundments are constructed near the C-area.

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10. Extensive surface or subsurface mining occurs near the C-area.

Acting alone, none of these events or processes are currently believed to be capable of leading to consequences distinguishable from undisturbed-case consequences; nevertheless, this belief needs to be confirmed by a quantitative screening of consequences.

Disturbed case (D-1): foreshortening of flow paths in the saturated zone. Some initiating events and processes that could lead to the appearance of surficial discharge points within the C-area, thereby shortening radionuclide travel times through the saturated zone (SZ) to the accessible environment, are the following:

1. Climate change causes appearance of surficial discharge points within the C-area.

2. Igneous intrusions cause flow barrier or thermal effects that alter water-table level.

3. Offset on fault juxtaposes transmissive and nontransmissive units, resulting in either the creation of a perched aquifer or a rise in the water table.

4. Episodic changes in strain in the rock mass due to faulting causes changes in water-table level.

5. Folding, uplift, or subsidence lowers repository with respect to water table.

Climate change probably is the only credible cause of a water-table rise sufficient to create long-term surficial discharge points. Even so, a consideration of the minimum distances between the current water table and the surface levels apparent within recently proposed boundaries for the C-area (Rautman et al., 1987) shows that water-table rises greater than 160 m would be required to create new discharge points. The appearance of surficial discharge points within the C-area is not the only way by which the SZ could be foreshortened. Changes in the horizontal component of the gradient of the SZ head contours could also lead to decreases in the means and increases in the variances of the radionuclide transport times (changes in the vertical components of the SZ head contours, i.e., changes in the magnitude of the linear water velocity through the SZ, are included in scenario class D-2). This latter effect depends upon the definition of the boundaries of the C-area that is ultimately adopted. The effect has not been considered in the choice of initiating events and processes in the preceding list.

Disturbed case (D-2): altered saturated zone head gradients, rock hydrologic properties, and geochemistry. Some initiating events and processes that could lead to adverse alterations of the saturated zone (SZ) vertical head-gradients, or SZ rock hydrologic properties, or SZ geochemistry are the following:

1. Climate change causes an increase in the hydraulic gradients of the water table within the C-area.

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2. Igneous intrusion causes flow barriers or thermal effects that alter water table (or hydraulic gradients).

3. Offset on faults juxtaposes transmissive and nontransmissive units, resulting in either the creation of a perched aquifer or a rise in the water table (or a change in hydraulic gradients).

4. Extensive irrigation is conducted near the C-area.

5. Large scale surface-water impoundments are constructed near the C-area.

6. Extensive surface or subsurface mining occurs near the C-area.

7. Extensive ground-water withdrawal occurs near the C-area.

"Adverse" alterations means changes that could decrease radionuclide transport times in the SZ. Again, the only potentially important cause of adverse alteration in the vertical head gradient probably is climatic change. In his most recent calculations, Czarnecki (1985) predicts that a four-fold increase in specific discharge in the SZ could accompany the 130-m water-table rise associated with a model of future climatic conditions. Changes in SZ transmissivity associated with fault motion might also have some small effects on radionuclide transport times in the SZ, as shown by Barr and Miller (1987); however, the model effects on transport time of an uncoupled contaminant particle through the SZ observed by Barr and Miller (1987) are probably related more to changes in the horizontal components of the head gradients than in the vertical components. In any case, both climatic change and faulting need to be seriously considered as agents of change in the SZ transport times.

4. <u>A preliminary performance allocation for Issue 1.1</u>

A preliminary performance allocation for this issue is summarized in Table 8.3.5.13-8. Because this allocation deals with the total system and performance measures for the total system, it is appropriate to allocate performance against those perceived events and processes to which the total system must respond. Column 1 of Table 8.3.5.13-8 lists the eight potentially significant categories of scenario classes identified in Table 8.3.5.13-3. Column 2 indicates the mode(s) of the release (or release pathway) corresponding to each scenario class. For reasons mentioned in the background material on gas-phase releases, the gas pathway is considered important only for the nominal case (E). Column 3 shows a preliminary assessment of the barriers on which primary reliance may be placed in meeting the performance goal listed in column 6; possible backup barriers are also indicated. Column 4 shows the component(s) of the primary barrier that are believed to contribute most to the achievement of the performance goal; column 5 gives the reason for the assignment of a primary barrier in the form of the processes or conditions that may ensure the achievement of the performance goal.

Column 6 shows the performance measure for each scenario class, the expected partial performance measure (EPPM). The EPPM is defined earlier in this section, in the discussion entitled "Screening for significant events,

Table 8.3.5.13-8. Preliminary performance allocation for Issue 1.1 (page 1 of 2)

Release scenario class	Pathway	System elements: Primary barriers	System elements: Primary barrier components	Primary processes or conditions	Performance measure (EPPM)[a]	Tentative goal	Needed confidence
			NOMINAL CASE				
E	Water	Unsaturated zone; saturated zone, EBS[b] as backup	Combined facies of Calico Hills; other units as backup	Equivalent-porous-media transport through matrix with adsorptive retardation	EPPM	< 0.01	High
	Gas	EBS; overburden as backup	Container and structural components	Limited rapid release of carbon-14 as carbon dioxide	EPPM	< 0.2	Medium
			DIRECT RELEASES				
A-1	Direct	(No allocation: see text for explanation)			EPPM	< 0.1	High
A-2					EPPM	< 0.1	Medium
			FAILURE OF UNSATURATED ZONE BARRIERS				
C-1	Water	Repository overburden	Paintbrush Tuff unit and Topopah Spring	Flooding-pulse delay times > 10,000 yr	EPPM	< 0.01	High
	Gas	None	None	None			High
C-2	Water	Saturated zone; EBS and residual unsaturated zone as backup	Saturated zone to boundary of AE[c] (or discharge points)	Equivalent-porous-media transport with adsorptive retardation	EPPM	< 0.1	Medium
	Gas	None	None	None			High

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Table 8.3.5.13-8. Preliminary performance allocation for Issue 1.1 (page 2 of 2)

Release scenario class	Pathway	System elements: Primary barriers	System elements: Primary barrier components	Primary processes or conditions	Performance measure (EPPM)[a]	Tentative goal	Needed confidence
		FAILURE OF UNSATURATED ZONE BARRIERS (continued)					
C-3	Water	Saturated zone; EBS and residual unsaturated zone as backup	Saturated zone to boundary of AE (or discharge points)	Equivalent-porous-media transport with adsorptive retardation	EPPM	< 0.01	High
	Gas	None	None	None			High
		FAILURE OF SATURATED ZONE BARRIERS (does not affect gas-phase releases)					
D-1	Water	Residual saturated zone + residual unsaturated zone, EBS as backup		Equivalent-porous-media transport with adsorptive retardation	EPPM	< 0.1	Medium
D-2	Water	Residual saturated zone + residual unsaturated zone, EBS as backup		Equivalent-porous-media transport with adsorptive retardation	EPPM	< 0.1	High

[a]Maximum EPPM for each event/process associated with scenario/class (see subsection on discussion of issue-resolution strategy for Issue 1.1).
[b]EBS = engineered barrier system.
[c]AE = accessible environment.

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processes, and features"; it appears formally in Equation 8.3.5.13-8. Ideally, the value of the entire CCDF could be used as the performance measure. To obtain such a value would, however, require that information for all the scenario classes be available at the same time; for that reason, such a measure would not be useful or practical in guiding the site characterization program toward acquiring the information needed for evaluating a single scenario class. The EPPM is therefore used in the preliminary performance allocation as a surrogate measure suitable for individual scenario classes. The final resolution of this issue will be made in terms of the full CCDF and not the EPPMs.

Column 7 shows a tentative goal for each expected partial performance measure; column 8 gives an indication of the confidence that the DOE expects to need in licensing when it demonstrates that this goal has been met. These measures of confidence are subjective, since models to calculate the EPPMs for all scenario classes are not yet available, and considerable judgment has been used in making assignments in columns 7 and 8. The use of tentative goals and indications of confidence is explained in Section 8.1.2.2.

Except for the gas pathway in the first scenario class of Table 8.3.5.13-8, all entries in column 7 were made using the assumption that fractional release rates of radionuclides from the engineered barrier system (EBS) would not exceed the 10 CFR Part 60 limit of 0.00001 parts per year of the 1,000-yr inventory. This may be an unrealistic assumption for the highly soluble compounds associated with carbon, technetium, and iodine.

It is not possible to allocate performance of the total system for the direct-release scenario classes (A-1 and A-2 in Table 8.3.5.13-3). However, the estimates of the EPPMs for these scenarios that are in column 7 of Table 8.3.5.13-8 are conservative, particularly if the improbability of short delay times before the occurrence of the initiating events is taken into account. The delay-time probabilities have also been factored into the assignments in columns 7 and 8 for some of the water-pathway scenario classes (C-1, C-2, D-1, and D-2).

Tables 8.3.5.13-9 through 8.3.5.13-16 (performance-parameter tables) list the parameters needed to evaluate the EPPM for the scenario classes and the goals associated with these parameters. Table 8.3.5.13-17 lists parameters that support the performance parameters in these tables and are needed to evaluate the overall CCDF. The eight performance-parameter tables give, for each initiating event or process, the associated performance measure, performance parameters, tentative goals, and confidence (current and needed). These phrases are explained in general terms in Section 8.1.2.2. In these tables, the performance measure is the EPPM specified in Table 8.3.5.13-8. The performance parameters are data and information that are required to calculate or assess values of the EPPM for each scenario class. The tentative goals state quantitative or qualitative conditions on the value of a performance parameter. These goals are not criteria that the site repository or other parts of the system must meet; they are merely values which, if met, are likely to lead to achieving the quantitative goal for the EPPM. In the confidence columns, current confidence is a measure of the confidence on a scale of high (H), medium (M), and low (L), that currently available data and information would suffice to show that the goal for the performance parameter could be met; the needed confidence column indicates,

Table 8.3.5.13-9. Performance parameters for scenario class E (the nominal case) (page 1 of 3)

Performance measure[a]	Performance parameter[b]	Tentative parameter goal	SCP section providing expected parameter values	Current confidence	Needed confidence
EPPM for liquid pathway, unsaturated zone (UZ) barrier only	$\bar{q}_u$ - average flux through R-area UZ	< 0.5 mm/yr	None	Medium	High
	$\bar{n}_e$ - average effective matrix porosity, R-area UZ	> 0.1	3.9.2.1	Low	High
	$\bar{R}_i$ - average chemical retardation factor for i^{th} species	≥ 1	4.1.3.3, 8.3.1.3	High	High
	$\bar{d}_u$ - average thickness of R-area UZ between repository and water table	> 100 m	8.3.5.12, 3.9.1.2	Medium	High
	r_i - fractional mass release rate from engineered barrier system (EBS) for i^{th} species	< 10^{-4}/yr, all species[c]	8.3.5.10	Low	Medium
EPPM for liquid pathway, saturated zone (SZ) barrier only[d]	$\bar{q}_s$ - average discharge in SZ under C-area	< 32 mm/yr	None	Low	Medium

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Table 8.3.5.13-9. Performance parameters for scenario class E (the nominal case) (page 2 of 3)

Performance measure[a]	Performance parameter[b]	Tentative parameter goal	SCP section providing expected parameter values	Current confidence	Needed confidence
EPPM for liquid pathway, saturated zone (SZ) barrier only[d] (continued)	$\bar{n}_g$ - average effective matrix porosity, C-area, SZ	> 0.1	3.9.2.1	Low	Medium
	$\bar{R}_i$ - average chemical retardation factor for i^{th} species, C-area, SZ	≥ 1	4.1.3.3, 8.3.1.3	High	Medium
	$\bar{d}_e$ - average length of flow paths through SZ from C-area to accessible environment boundary	> 5,000 m	3.6.4	Low	Medium
	r_i - fractional mass release rate from EBS for i^{th} species	< 10^{-4}/yr, all species[c]	8.3.5.10	Low	Medium
EPPM for gas pathway	Fraction of total carbon-14 inventory that could be released as carbon-14 dioxide	Fraction < 1% of inventory at closure	8.3.5.10	Low	High

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Table 8.3.5.13-9. Performance parameters for scenario class E (the nominal case) (page 3 of 3)

Performance measure[a]	Performance parameter[b]	Tentative parameter goal	SCP section providing expected parameter values	Current confidence	Needed confidence
EPPM for gas pathway (continued)	Mean residence time of released carbon-14 dioxide in UZ units	Show residence time > 10,000 yr	None	Low	High

[a]EPPM = expected partial performance measure; see subsection on discussion of complementary cumulative distribution functions and significant processes and events.

[b]R-area = the projection of primary area and extensions onto the surface; C-area = the controlled area, i.e., the actual area chosen according to the 10 CFR 60.2 definition of controlled area.

[c]The performance allocation for Issue 1.5 (engineered barrier system release rates, Section 8.3.5.10) sets a goal for the fractional mass release rate from the EBS at 10-5 per yr to comply with the performance objective in 10 CFR 60.113.

[d]Performance parameters and goals apply only if equivalent-porous-media transport is valid in the SZ; otherwise, the SZ cannot act as a backup barrier to water-pathway releases.

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Table 8.3.5.13-10. Performance parameters for scenario class A-1 (extrusive magmatic events)

Performance measure	Initiating event or process	Performance parameter	Tentative parameter goal	SCP section providing expected parameter values	Current confidence	Needed confidence	SCP section
EPPM[a]	Volcanic eruption penetrates repository and causes direct releases to the accessible environment	Annual probability of volcanic eruption that penetrates the repository	$<10^{-6}$/yr	1.5.1	Low	High	8.3.1.8.1
		Effects of volcanic eruption penetrating repository, including area of repository disrupted	Given occurrence, show <0.1% of repository area is disrupted with a conditional probability of <0.1 of being exceeded in 10,000 yr	1.5.1	Low	Medium	8.3.1.8.1

[a]EPPM = expected partial performance measure; see subsection on discussion of complementary cumulative distribution function and significant processes and events.

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Table 8.3.5.13-11. Performance parameters for scenario class A-2 (exploratory drilling)

Performance measure	Initiating event or process	Performance parameter[a]	Tentative parameter goal	SCP section providing expected parameter values	Current confidence	Needed confidence	SCP section
EPPM[b]	Exploratory drilling intercepts a waste package and brings waste up with core or cuttings.	Presence and readability of C-area markers over next 10,000 yr.	>50% chance that markers are readable over next 10,000 yr.	None	Low	Medium	8.3.1.9.1
		Expected drilling rate (no. of boreholes per square kilometer per year) R-area over the next 10,000 yr.	Expected drilling rate ≤ 3 x 10^{-4} boreholes per square kilometer per year	None	Low	Low	None
		Distribution of depths of exploratory drillings.	No goal	None	Low	Low	None
		Distribution of diameters of exploratory drill holes.	No goal	None	Low	Low	None

[a]R-area = the projection of primary area and extensions onto the surface; C-area = the controlled area, i.e., the actual area chosen according to the 10 CFR 60.2 definition of controlled area.

[b]EPPM = expected partial performance measure; see subsection on discussion of complementary cumulative distribution function and significant processes and events.

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Table 8.3.5.13-12. Performance parameters for scenario class C-1 (local or extensive increases in percolation flux through unsaturated zone) (page 1 of 2)

Performance measure	Initiating event or process	Intermediate performance measure	Performance parameter[a]	Tentative parameter goal	SCP section providing expected parameter values	Current confidence	Needed confidence	SCP section
EPPM[b]	Climatic change causes increase in infiltration over C-area[d]	Radionuclide transport time through unsaturated zone (UZ), given fixed UZ thickness, rock hydrologic properties, and geochemical properties	Expected magnitude of flux change due to climatic changes over next 10,000 yr; quantitative confidence bounds on expected magnitude of change	Flux change will be < 0.5 mm/yr with 67% confidence or more	3.9.3.3	Low	High	8.3.1.5.2
	Offset on faults creates surface impoundments, alters drainage, creates perched aquifers, or changes dip of tuff beds	Radionuclide transport time through UZ, given fixed UZ thickness, rock hydrologic properties, and geochemical properties	Probability of offset >2 m on a fault in the C-area in 10,000 yr	$<10^{-8}$	1.3.2.2	Low	Medium	8.3.1.8
			Probability of changing dip by >2° in 10,000 yr by faulting	$<10^{-4}$ per 10,000 yr	None	Low	Low	8.3.1.8
			Effect of faulting on flux	Faulting will not affect flux because of low slip rate	None	Low	Medium	8.3.1.8
	Volcanic eruption causes flows or other changes in topography that result in impoundment or diversion of drainage	Radionuclide transport time through UZ, given fixed UZ thickness, rock hydrologic properties and geochemical properties	Annual probability of volcanic events within C-area	$<10^{-8}$/yr	1.5.1	Low	Medium	8.3.1.8
			Effects of a volcanic event on topography and flow rates	Topographic changes are not enough to affect flux	None	Low	Low	8.3.1.8
	Igneous intrusions, such as a sill, that could result in a change in flux	Radionuclide transport time through UZ, given fixed UZ thickness, rock hydrologic properties and geochemical properties	Annual probability of significant igneous intrusions in the C-area	$<10^{-8}$/yr	1.5.1	Low	High	8.3.1.8
			Effects of an igneous intrusion on flux	Igneous intrusion will not affect flux because of depth, location, and extent of intrusion	None	Low	Low	8.3.1.8
	Tectonic folding changes dip of tuff beds in C-area, thereby changing flux	Radionuclide transport time through UZ, given fixed UZ thickness, rock hydrologic properties and geochemical properties	Probability of changing dip by >2° in 10,000 yr by folding	$<10^{-4}$ per 10,000 yr	1.3.2	Low	Low	8.3.1.8

Table 8.3.5.13-12. Performance parameters for scenario class C-1 (local or extensive increases in percolation flux through unsaturated zone) (page 2 of 2)

Performance measure	Initiating event or process	Intermediate performance measure	Performance parameter[a]	Tentative parameter goal	SCP section providing expected parameter values	Current confidence	Needed confidence	SCP section
EPPM[b] (continued)	Uplift or subsidence changes drainage, thereby changing flux	Radionuclide transport time through UZ, given fixed UZ thickness, rock hydrologic properties and geochemical properties	Probability of exceeding 30 m elevation change in 10,000 yr	$<10^{-4}$ per 10,000 yr	1.1.3.3	Low	Low	8.3.1.8
	Subsidence of mined repository creates impoundments or diverts drainage	Radionuclide transport time through UZ, given fixed UZ thickness, rock hydrologic properties, and geochemical properties	Probability that continuously displaced surfaces from subsidence originating at repository will intersect interface of TSw and PTn units in 10,000 yr	$<10^{-4}$	None	Low	Medium	None
	Natural surface-water impoundments are formed over access shafts connecting surface and repository	Radionuclide transport time through UZ, given fixed UZ thickness, rock hydrologic properties, and geochemical properties	Expected magnitude of local flux change, and quantitative bounds on magnitude of flux change, due to flooding through access shafts	Show $<25,000\ m^3/yr$ would pass through access shafts	None	Low	Medium	None
			Expected fraction of waste containers which are subject to changed flux	Show less than 0.01% of containers would be subject to more than a 100% flux change caused by flooding through access shafts.	None	Low	Medium	None
	Extensive irrigation is conducted near the C-area	Radionuclide transport time through UZ, given fixed UZ thickness, rock hydrologic properties, and geochemical properties	Expected magnitude of flux change due to extensive irrigation near C-area over next 10,000 yr	No goal (human activity)	None	Not applicable	Not applicable	8.3.1.9.3
	Large scale surface-water impoundments are constructed near the C-area	Radionuclide transport time through UZ, given fixed UZ thickness, rock hydrologic properties, and geochemical properties	Expected magnitude of flux change due to presence of an artificial lake near the C-area in next 10,000 yr	No goal (human activity)	None	Not applicable	Not applicable	8.3.1.9.3

[a]TSw = Topopah Spring welded unit; PTn = Paintbrush nonwelded unit; C-area = the controlled area, i.e., the actual area chosen according to the 10 CFR 60.2 definition of controlled area.
[b]EPPM = expected partial performance measure; see subsection on discussion of complementary cumulative distribution functions and significant processes and events.

Table 8.3.5.13-13. Performance parameters for scenario class C-2 (foreshortening of the unsaturated zone) (page 1 of 2)

Performance measure	Initiating event or process	Intermediate performance measure	Performance parameter	Tentative parameter goal	SCP section providing expected parameter values	Current confidence	Needed confidence	SCP section
EPPH[a]	Climatic change causes an increase in altitude of water table	Radionuclide transport time through unsaturated zone (UZ), given fixed UZ rock hydrologic and geochemical properties	Expected magnitude of change in water-table level due to climatic changes over the next 10,000 yr	Expected magnitude of change in water-table altitude will not bring water table to within 100 m of repository horizon in 10,000 yr	3.7.4, 3.9.8	Low	High	8.3.1.5.2
	Igneous intrusion causes barrier to flow or thermal effects that alter water-table level	Radionuclide transport time through UZ, given fixed UZ rock hydrologic and geochemical properties	Annual probability of significant igneous intrusion within 0.5 km of C-area[b] boundary	$<10^{-8}$/yr	1.5.1	Low	Medium	8.3.1.8
			Barrier-to-flow effects of igneous intrusions on water-table levels	Expected magnitude of change in water-table altitude will not bring water table to within 100 m of repository horizon in 10,000 yr	None	Low	Low	8.3.1.8
			Thermal effects of igneous intrusions on water-table levels	Expected magnitude of change in water-table altitude will not bring water table to within 100 m of repository horizon in 10,000 yr	None	Low	Low	8.3.1.8
	Offset on fault juxtaposes transmissive and nontransmissive units, resulting in either the creation of a perched aquifer or a rise in water table	Radionuclide transport time through UZ, given fixed UZ rock hydrologic and geochemical properties	Probability of total offsets >2.0 m in 10,000 yr on faults within C-area boundary	$<10^{-1}$	1.3.2.2	Low	Medium	8.3.1.8
			Effects of fault offsets on water-table levels	Expected magnitude of change in water-table altitude will not bring water table to within 100 m of repository horizon in 10,000 yr	None	Low	Low	8.3.1.8

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Table 8.3.5.13-13. Performance parameters for scenario class C-2 (foreshortening of the unsaturated zone) (page 2 of 2)

Performance measure	Initiating event or process	Intermediate performance measure	Performance parameter[a]	Tentative parameter goal	SCP section providing expected parameter values	Current confidence	Needed confidence	SCP section
EPPM (continued)	Episodic changes in strain in the rock mass due to faulting causes changes in water-table level	Radionuclide transport time through UZ, given fixed UZ rock hydrologic and geochemical properties	Probability that strain-induced changes increase potentiometric level to >850 m mean sea level	$<10^{-5}$/yr	1.3.2.3	Low	Low	8.3.1.8
	Folding, uplift or subsidence lowers repository with respect to water table	Radionuclide transport time through UZ, given fixed UZ rock hydrologic and geochemical properties	Probability that repository will be lowered by 100 m through action of folding, uplift, or subsidence in 10,000 yr	$<10^{-4}$ per 10,000 yr	1.1.3	Low	Low	8.3.1.8
	Extensive irrigation is conducted near the C-area	Radionuclide transport time through UZ, given fixed UZ rock hydrologic and geochemical properties	Expected magnitude of change in altitude of water table under C-area due to extensive irrigation near C-area over next 10,000 yr	No goal (human activity)	None	Not applicable	Not applicable	8.3.1.9.3
	Large-scale surface-water impoundments are constructed near the C-area	Radionuclide transport time through UZ, given fixed UZ rock hydrologic and geochemical properties	Expected magnitude of change in water-table level under C-area due to placement of artificial lake near C-area in next 10,000 yr	No goal (human activity)	None	Not applicable	Not applicable	8.3.1.9.3
	Extensive surface or subsurface mining occurs near C-area	Radionuclide transport time through UZ, given fixed UZ rock hydrologic and geochemical properties	Expected magnitude of change in water-table level under C-area due to mine water usage or mine dewatering near C-area in next 10,000 yr	No goal (human activity)	None	Not applicable	Not applicable	8.3.1.9.3
	Extensive ground-water withdrawal occurs near C-area	Radionuclide transport time through UZ, given fixed UZ rock hydrologic and geochemical properties	Expected magnitude of change in water-table level under C-area due to extensive ground-water withdrawal near C-area in next 10,000 yr	No goal (human activity)	3.8.1	Not applicable	Not applicable	8.3.1.9.3

[a]EPPM = expected partial performance measure; see subsection on discussion of complementary cumulative distribution function and significant processes and events.
[b]C-area = the controlled area, i.e., the actual area chosen according to the 10 CFR 60.2 definition of controlled area.

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Table 8.3.5.13-14. Performance parameters for scenario class C-3 (changes in rock, hydrologic, and geochemical properties in the unsaturated zone) (page 1 of 2)

Performance measure	Initiating event or process	Intermediate performance measure	Performance parameter	Tentative parameter goal	SCP section providing expected parameter values	Current confidence	Needed confidence	SCP section
EPPH[a]	Igneous intrusion causes changes in rock hydrologic properties	Radionuclide transport time through unsaturated zone (UZ), given fixed thickness of UZ	Annual probability of significant igneous intrusion within 0.5 km of C-area[b] boundary	$<10^{-5}$/yr	1.5.1	Low	Medium	8.3.1.8
			Effects of igneous intrusion on local permeabilities and effective porosities	No significant changes in rock hydrologic properties	None	Low	Low	8.3.1.8
	Igneous intrusion causes changes in rock geochemical properties	Radionuclide transport time through UZ, given fixed thickness of UZ	Annual probability of significant igneous intrusion within 0.5 km of C-area boundary	$<10^{-5}$/yr	1.5.1	Low	Medium	8.3.1.8
			Effects of igneous intrusions on local rock geochemical properties	Potential changes in mineralogy will not be extensive	None	Low	Low	8.3.1.8
	Episodic offset on faults causes local changes in rock hydrologic properties, thereby destroying existing barriers to flow, or creating new conduits for drainage	Radionuclide transport time through UZ, given fixed thickness of UZ	Annual probability of faulting events on Quaternary faults within 0.5 km of C-area boundary	$<10^{-4}$/yr	1.3.2.2	Low	Medium	8.3.1.8
			Effects of fault motion on local permeabilities and effective porosities	Change in fracture permeability is less than a fac- of 2 and fracture porosity decreases	None	Low	Medium	8.3.1.8
	Offset on a fault causes changes in movement of ground water that result in mineralogical changes along the fault zone	Radionuclide transport time through UZ, given fixed thickness of UZ	Probability of movement within 2 km of surface and location of Quaternary faults in C-area	$<10^{-4}$/yr per fault	1.3.2.2	Low	Medium	8.3.1.8
			Degree of mineralogic change in fault zone in 10,000 yr	Adverse changes in mineralogy will not occur	None	Low	Low	8.3.1.8
	Offset on a fault changes potential radionuclide travel pathway to one with different geochemical properties	Radionuclide transport time through UZ, given fixed thickness of UZ	Probability of total offsets >2.0 m in 10,000 yr on faults within 0.5 km of C-area boundary	$<10^{-1}$	1.3.2.2	Low	Medium	8.3.1.8
			Effects of fault offsets on travel pathway	Significant changes will not occur	None	Low	Low	8.3.1.8

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Table 8.3.5.13-14. Performance parameters for scenario class C-3 (changes in rock, hydrologic, and geochemical properties in the unsaturated zone) (page 2 of 2)

Performance measure	Initiating event or process	Intermediate performance measure	Performance parameter	Tentative parameter goal	SCP section providing expected parameter values	Current confidence	Needed confidence	SCP section
EPPM[a] (continued)	Changes in stress or strain in C-area[b] resulting from episodic faulting, folding or uplift causes changes in the hydrologic properties of the rock mass	Radionuclide transport time through UZ, given fixed thickness of UZ	Effects of changes of stress or strain on hydrologic properties of the rock mass	Changes in conductivity and porosity of rock mass are less than a factor of 2	1.3.2.3	Low	Low	8.3.1.8
	Tectonic processes cause changes in ground water table or movement that results in mineralogic changes in C-area	Radionuclide transport time through UZ, given fixed thickness of UZ	Degree of mineralogic change in the controlled area resulting from changes in water-table level or flow paths in 10,000 yr	Adverse changes in mineralogy will not occur	None	Low	Low	8.3.1.8
	Extensive irrigation is conducted near C-area	Radionuclide transport time through UZ, given fixed thickness of UZ	Expected magnitude of changes in distribution coefficients, solubilities and chemical reactivity of the engineered barrier system and UZ units due to extensive irrigation near C-area in next 10,000 yr	No goal (human activity)	None	Not applicable	Not applicable	8.3.1.9.3, 8.3.1.3.7
	Large-scale surface water impoundments are constructed near the C-area	Radionuclide transport time through UZ, given fixed thickness of UZ	Expected magnitude of changes in distribution coefficients, solubilities and chemical reactivity of the engineered barrier system and UZ units due to presence of an artifical lake near C-area in next 10,000 yr	No goal (human activity)	None	Not applicable	Not applicable	8.3.1.9.3, 8.3.1.3.7
	Extensive surface or subsurface mining occurs near C-area	Radionuclide transport time through UZ, given fixed thickness of UZ	Expected magnitude of changes in distribution coefficients, solubilities and chemical reactivity of the engineered barrier system and UZ units due to mining activities near the C-area in next 10,000 yr	No goal (human activity)	None	Not applicable	Not applicable	8.3.1.9.3, 8.3.1.3.7

[a]EPPM = expected partial performance measure; see subsection on discussion of complementary cumulative distribution functions and significant processes and events.
[b]C-area = the controlled area, i.e., the actual area chosen according to the 10 CFR 60.2 definition of controlled area.

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Table 8.3.5.13-15. Performance parameters for scenario class D-1 (appearance of surficial discharge points within the C-area[a]; foreshortening of the saturated zone) (page 1 of 2)

Performance measure	Initiating event or process	Intermediate performance measure	Performance parameter	Tentative parameter goal	SCP section providing expected parameter values	Current confidence	Needed confidence	SCP section
EPPM[b]	Climate change causes appearance of surficial discharge points within C-area	Radionuclide transport time through UZ, given fixed SZ rock hydrologic and geochemical properties	Expected locations of surficial discharge points within C-area over next 10,000 yr	That no surficial discharge points could appear within C-area given a water table rise <160 m	None	Low	Medium	8.3.1.5.2
	Igneous intrusion causes barrier to flow or thermal effects that alter water-table level	Radionuclide transport time through saturated zone (SZ), given fixed SZ rock hydrologic and geochemical properties	Annual probability of significant igneous intrusion within 0.5 km of C-area boundary	$<10^{-8}$/yr	1.5.1	Low	Medium	8.3.1.8
			Barrier-to-flow effects of igneous intrusions on water-table levels	Show water table will not rise to within 100 m of repository horizon in 10,000 yr	None	Low	Low	8.3.1.8
			Thermal effects of igneous intrusions on water-table levels	Show water table will not rise to within 100 m of repository horizon in 10,000 yr	None	Low	Low	8.3.1.8
	Offset on fault juxtaposes transmissive and nontransmissive units, resulting in either the creation of a perched aquifer or a rise in the water table	Radionuclide transport time through SZ, given fixed SZ rock hydrologic and geochemical properties	Probability of total offsets >1.0 m in 10,000 yr on faults within 0.5 km of C-area boundary	$<10^{-1}$	1.3.2.2	Low	High	8.3.1.8
			Effects of fault offset on water-table levels	Show water table will not rise to within 100 m of repository horizon in 10,000 yr	None	Low	High	8.3.1.8
	Episodic changes in strain in the rock mass due to faulting cause changes in water-table level	Radionuclide transport time through SZ, given fixed SZ rock hydrologic and geochemical properties	Probability that strain-induced changes increase potentiometric level to greater than 850 m mean sea level	$<10^{-8}$/yr	1.3.2.3	Low	Low	8.3.1.8

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Table 8.3.5.13-15. Performance parameters for scenario class D-1 (appearance of surficial discharge points within the C-area[a]; foreshortening of the saturated zone) (page 2 of 2)

Performance measure	Initiating event or process	Intermediate performance measure	Performance parameter	Tentative parameter goal	SCP section providing expected parameter values	Current confidence	Needed confidence	SCP section
EPPM (continued)	Folding, uplift, or subsidence lowers repository with respect to water table	Radionuclide transport time through SZ, given fixed SZ rock hydrologic and geochemical properties	Probability that repository will be lowered by 100 m through action of folding, uplift, or subsidence in 10,000 yr	$<10^{-4}$	1.1.3.3	Low	Low	8.3.1.8

[a]C-area = the controlled area, i.e., the actual area chosen according to the 10 CFR 60.2 definition of controlled area.
[b]EPPM = expected partial performance measure; see subsection on discussion of complementary cumulative distribution functions and significant processes and events.

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Table 8.3.5.13-16. Performance parameters for scenario class D-2 (increased head gradients or changed rock, hydrologic, or geochemical properties in the saturated zone) (page 1 of 2)

Performance measure	Initiating event or process	Intermediate performance measure	Performance parameter	Tentative parameter goal	SCP section providing expected parameter values	Current confidence	Needed confidence	SCP section
EPRW[a]	Climatic change causes an increase in the gradient of the water table within the C-area[b]	Radionuclide transport time through saturated zone (SZ), given fixed distances to accessible environment boundary	Expected magnitude of change in water-table gradient due to climatic change over the next 10,000 yr	Gradients change less than a factor of 4	3.7.1	Low	Medium	8.3.1.5.2
	Igneous intrusion causes barriers to flow or thermal effects that alter water-table (or hydraulic gradients)	Radionuclide transport time through SZ, given fixed distances to accessible environment boundary	Annual probability of a significant igneous intrusion within 0.5 km C-area boundary	$<10^{-8}$/yr	1.5.1	Low	Medium	8.3.1.8
			Barrier-to-flow effects of igneous intrusions on water table level	Show water table will not rise to within 100 m of repository horizon in 10,000 yr	None	Low	Low	8.3.1.8
			Thermal effects of igneous intrusions on hydraulic gradients	Gradients change less than a factor of 4	None	Low	Low	8.3.1.8
	Offset on faults juxtaposes transmissive and nontransmissive units, resulting in either the creation of a perched aquifer or a rise in the water table (or a change in hydraulic gradients)	Radionuclide transport time through SZ, given fixed distances to accessible environment boundary	Probability of total offset > 2.0 m in 10,000 yr on faults within 0.5 km of C-area	$<10^{-1}$	1.3.2.2	Low	Medium	8.3.1.8.3
			Effects of fault offsets on water-table levels	Show water table will not rise to within 100 m of repository horizon in 10,000 yr;	None	Low	Medium	8.3.1.8.3
			Effects of fault offsets on hydraulic gradients	Show gradients change less than a factor of 4				
	Extensive irrigation is conducted near C-area	Radionuclide transport time through SZ, given fixed distances to accessible environment boundary	Expected magnitude of changes in head gradients of SZ in C-area due to extensive irrigation near C-area over next 10,000 yr	No goal (human activity)	None	Not applicable	Not applicable	8.3.1.9.3

Table 8.3.5.13-16. Performance parameters for scenario class D-2 (increased head gradients or changed rock, hydrologic, or geochemical properties in the saturated zone) (page 2 of 2)

Performance measure	Initiating event or process	Intermediate performance measure	Performance parameter	Tentative parameter goal	SCP section providing expected parameter values	Current confidence	Needed confidence	SCP section
EPPM (continued)	Extensive irrigation is conducted near C-area (continued)		Expected magnitude of changes in distribution coefficients of SZ due to extensive irrigation near C-area over the next 10,000 yr	No goal (human activity)	None	Not applicable	Not applicable	8.3.1.9.3, 8.3.1.3.7
	Large-scale surface-water impoundments are constructed near the C-area	Radionuclide transport time through SZ, given fixed distances to accessible environment boundary	Expected magnitude of changes in head gradients of SZ in C-area due to presence of an artificial lake near C-area over the next 10,000 yr	No goal (human activity)	None	Not applicable	Not applicable	8.3.1.9.3
			Expected magnitude of changes in distribution coefficients of SZ units due to presence of an an artificial lake near C-area in next 10,000 yr	No goal (human activity)	None	Not applicable	Not applicable	8.3.1.9.3, 8.3.1.3.7
	Extensive surface or subsurface mining occurs near C-area	Radionuclide transport time through SZ, given fixed distances to accessible environment boundary	Expected magnitude of changes in gradients of water table under C-area due to extensive surface or subsurface mining near C-area in next 10,000 yr	No goal (human activity)	None	Not applicable	Not applicable	8.3.1.9.3
			Expected magnitude of changes in distribution coefficients of SZ units due to extensive surface or subsurface mining near C-area in next 10,000 yr	No goal (human activity)	None	Not applicable	Not applicable	8.3.1.9.3, 8.3.1.3.7
	Extensive ground-water withdrawal occurs near C-area	Radionuclide transport time through SZ, given fixed distances to accessible environment boundary	Expected magnitude of changes in gradients of water table under C-area due to ground-water withdrawal near C-area in next 10,000 yr	No goal (human activity)	None	Not applicable	Not applicable	8.3.1.9.3

[a]EPPM = expected partial performance measure; see subsection on discussion of complementary cumulative distribution functions and significant processes and events.
[b]C-area = the controlled area, i.e., the actual area chosen according to the 10 CFR 60.2 definition of controlled area.

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Table 8.3.5.13-17. Supporting parameters needed to evaluate the nominal case and as baseline data for the disturbed cases (page 1 of 6)

Issue 1.1 calculation using supporting parameter[a]	Supporting parameter: Description	Supporting parameter: Modifier	Lateral spatial location where needed[b]	Unit where needed[c]	SCP section providing expected parameter values	Characterization goal[d]	Current confidence[e]	Needed confidence[e]	SCP section
Specific-discharge field in UZ (Klavetter and Peters, 1986); moisture contents of UZ units; hydrodynamic response times in overburden	Saturated permeability	Rock matrix	R-area	UZ-units, Ovb	3.9.2.1	m,v,a	NA	H,M,L	8.3.1.2.2
		Fracture network	R-area	UZ-units, Ovb	3.9.2.1	m,v,a	NA	H,M,L	8.3.1.2.2
	Relative liquid permeability (wetting and draining)	Rock matrix	R-area	UZ-units, Ovb	None	m,v	NA	H,L	8.3.1.2.2
		Fracture network	R-area	UZ-units, Ovb	None	m,v	NA	L,L	8.3.1.2.2
	Effective porosity[f]	Rock matrix	R-area	UZ-units, Ovb	3.9.2.1	m,v,a	NA	H,M,L	8.3.1.2.2
		Fracture network	R-area	UZ-units, Ovb	None	m,v,a	NA	L,L,L	NA
	Moisture retention curve (wetting and draining)	Rock matrix	R-area	UZ-units, Ovb	3.9.2.1	m,v	M,M	L,L	3.9.2.1
		Fracture network	R-area	UZ-units, Ovb	None	m,v	NA	L,L	NA
	Altitudes of hydrogeologic unit contacts	As a function of lateral spatial location	C-area	UZ-units, Ovb	8.3.5.12	m,v	M,M	H,M	8.3.1.4.2, 8.3.1.4.3, 8.3.1.2.2
	Altitude of water table	Ambient, as a function of lateral spatial location	C-area	NA	3.9.1.2	m,v	M,M	H,M	8.3.1.3.1
Specific-discharge field in fault zones in UZ; moisture content in fault zones; hydrodynamic response times of fault zones	Location, width, and offset of fault zones	As a function of lateral spatial location	C-area	UZ-units, Ovb	1.3.2.2.2	m,v	L	H	8.3.1.4.2, 8.3.1.8.5
	Saturated permeability	Fault-zone rock-mass	C-area	UZ-units, Ovb	None	m,v	NA	H,L	8.3.1.2.2
	Effective porosity	Fault-zone rock-mass	C-area	UZ-units, Ovb	None	m,v	NA	L,L	8.3.1.2.2

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Table 8.3.5.13-17. Supporting parameters needed to evaluate the nominal case and as baseline data for the disturbed cases (page 2 of 6)

Issue 1.1 calculation using supporting parameter[a]	Supporting parameter: Description	Supporting parameter: Modifier	Lateral spatial location where needed[b]	Unit where needed[c]	SCP section providing expected parameter values	Characterization goal[d]	Current confidence[e]	Needed confidence[e]	SCP section
Coupling factors and radionuclide retardation factors in UZ and SZ (Wilson and Dudley, 1987)	Bulk density	Rock matrix	C-area	All units	1.6.2.2 & Chapter 2	m,v	M,L	M,M	8.3.1.15.1, 8.3.1.2.2
	Fracture frequency	Fracture networks	C-area	All units	3.9.2.1, 1.3.2.2.2	m,v,a	L,L,L	M,L,L	8.3.1.2.2
	Fracture frequency	Fault-zone rock-mass	C-area	All units	1.3.2.2.2	m,v,a	L,L,L	M,L,L	8.3.1.4.2
	Liquid constrictivity/tortuosity factor	Rock matrix	C-area	All units	None	m,v	L,L	M,L	8.3.1.2.2, 8.3.1.3
		Fracture networks	C-area	All units	None	m,v	L,L	L,L	8.3.1.2.2, 8.3.1.3
		Fault-zone rock-mass	C-area	All units	None	m,v	L,L	L,L	8.3.1.2.2, 8.3.1.3
	Distribution coefficients (K_ds)	Rock matrix, for the following chemical species: Sr, Cs, Pu, Am, C, U, Np, Tc, Zr, I, Cm	C-area	All units	4.1.3.3, 8.3.1.3	m,v,a	M,L,L	M,M,L	8.3.1.3.4
Specific-discharge field in SZ (ISOQUAD code, Pinder, 1976); also hydrodynamic dispersion in SZ; hydrodynamic response times of SZ times of SZ	Effective thickness of saturated zone	As a function of lateral spatial location	C-area	SZ-units	3.6.4	m	L	L	8.3.1.3.3
	Hydraulic conductivity	Rock matrix	C-area	SZ-units	3.6.4, 3.9.2.2	m,v,a	M	M,L,L	8.3.1.3.3
		Fracture networks	C-area	SZ-units	3.9.2.2, 3.6.4	m,v,a	L	M,L,L	8.3.1.3.3
	Effective porosity	Rock matrix	C-area	SZ-units	3.9.2.2, 3.6.4	m,v,a	L,L,L	M,M,L	8.3.1.3.3
		Fracture networks	C-area	SZ-units	3.6.4	m,v,a	L,L,L	M,M,L	8.3.1.3.3
	Fracture compressibility	Fracture networks	C-area	All units	3.9.2.1	m	L	L	8.3.1.3.3

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Table 8.3.5.13-17. Supporting parameters needed to evaluate the nominal case and as baseline data for the disturbed cases (page 3 of 6)

Issue 1.1 calculation using supporting parameter[a]	Supporting parameter: Description	Supporting parameter: Modifier	Lateral spatial location where needed[b]	Unit where needed[c]	SCP section providing expected parameter values	Characterization goal[d]	Current confidence[e]	Needed confidence[e]	SCP section
Model validation-coupling factors in UZ and SZ	Matrix-fracture interface permeabilities	NA	C-area	All units	4.1.3.5	Not significantly different from matrix values	L	M	8.3.1.3.6
	Matrix-fracture interface constrictivity (MF-CT factors)	NA	C-area	All units	None	Not significantly different from matrix factors	L	M	8.3.1.3.6
Gas-phase carbon-14 transport in overburden of UZ units	Relative pneumatic permeability (wetting and draining)	Rock matrix	R-area	Ovb	None	m,v	L,L	M,L	8.3.1.3.2
		Fracture network	R-area	Ovb	None	m,v	L,L	M,L	8.3.1.3.2
	Effective pneumatic porosity	Rock matrix	R-area	Ovb	None	m,v,a	L,L,L	L,L,L	8.3.1.3.2
		Fracture network	R-area	Ovb	None	m,v,a	L,L,L	M,L,L	8.3.1.3.2
	Profile of partial pressure of CO_2	Ambient, rock mass	R-area	UZ-units, Ovb	None	No goal	L	M	8.3.1.3.2
	Profiles of bicarbonate concentration, calcium ion concentration, pH, in liquid phase	Ambient, rock mass	R-area	UZ-units, Ovb	None	No goal	L	M	8.3.1.3.1, 8.3.1.2.2
	Profile of temperature	As a function of time, including effects of heat from repository	R-area	UZ-units, Ovb	1.6.2.2.4, Chapter 6	Predict profiles where temperature change exceeds 10% of ambient (°C)	L	M	8.3.1.4.2
	Profile of near-field saturation	As a function of time, including effects of heat from repository	R-area	UZ-units, Ovb	2.7.2	Prediction consistent with temperature profile (above)	L	M	8.3.1.2.2

Table 8.3.5.13-17. Supporting parameters needed to evaluate the nominal case and as baseline data for the disturbed cases (page 4 of 6)

Issue 1.1 calculation using supporting parameter[a]	Supporting parameter: Description	Supporting parameter: Modifier	Lateral spatial location where needed[b]	Unit where needed[c]	SCP section providing expected parameter values	Characterization goal[d]	Current confidence[e]	Needed confidence[e]	SCP section
Model calibration and validation, gas-phase carbon-14 transport in overburden of UZ	Profile of carbon-14 concentration	Ambient, rock mass pore spaces	R-area	UZ-units, Ovb	None	TBD	L	M	8.3.1.2.2, 8.3.1.3.8
	Major-ion water chemistry (i.e. composition, Eh, pH)	Ambient, rock mass pore fluids	R-area	UZ-units, Ovb	None	TBD	L	M	8.3.1.3.1, 8.3.1.2.2
	Profiles of abundances of secondary calcite, carbon-14 in calcite	Ambient, rock mass	R-area	UZ-units, Ovb	None	TBD	L	L	8.3.1.3.2
	Profile of Darcy velocity of air flow	Ambient, rock mass pore spaces	R-area	UZ-units, Ovb	None	TBD	L	M	8.3.1.2.2
Source term - liquid and gas-phase releases from waste packages	Geometry of waste package	Diameter, length and proposed orientation with respect to vertical direction	NA	NA	6.2.3	No goal (design parameter)	NA	NA	8.3.2.2.3, 8.3.4.2.2, 8.3.4.2.3
	Radionuclide inventory at closure in waste package	Expressed as kilograms (or curies) per package for radionuclides listed in Table 8.3.5.13-7	NA	NA	7.4.3.2.1, 7.4.3.1.1	m,v	L,L	M,M	8.3.4.2.2
	Areal density of k[th] kind of waste package in repository	As a function of lateral spatial location, and, if more than one level, altitude above mean sea level	NA	NA	None	No goal (design parameter)	NA	NA	8.3.2.2.6, 8.3.4.2.2

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Table 8.3.5.13-17. Supporting parameters needed to evaluate the nominal case and as baseline data for the disturbed cases (page 5 of 6)

Issue 1.1 calculation using supporting parameter[a]	Supporting parameter		Lateral spatial location where needed[b]	Unit where needed[c]	SCP section providing expected parameter values	Characterization goal[d]	Current confidence[e]	Needed confidence[e]	SCP section
	Description	Modifier							
Source term - liquid and gas-phase releases from waste packages (continued)	Containment time of k^{th} kind of waste package i.e., time after closure at which liquids would have free access to waste form	As a function of position in repository, if necessary	R-area	Host rock	None	m,v	L,L	M,M	8.3.5.9.4
	Post-containment mass release rate from k^{th} kind of waste package	Waste form to liquid phase; expected conditions; if necessary, as a function of: time since closure, position in repository, percolation flux at repository level	R-area	Host rock	7.4.3.1.1, 7.4.3.2.1	m,v Also show mean release rates for C, Tc, and I are less than 10^{-5} of 1000-yr inventory	L,L	M,M	8.3.5.10.4
	Mass release rate of carbon-14 in a gas phase from the k^{th} kind of waste package	Waste form to a gas phase; pre- and post-containment periods; if necessary, as a function of: time since closure, position in the repository	R-area	Host rock	7.4.3.1	m,v Also show that fraction of C-14 inventory that could be released in gas phase is less than 1%	L,L	M,M	8.3.5.10.4
	Degradation rates of waste form in the k^{th} kind of waste package	Ambient conditions (i.e., natural water chemistry associated with repository host rock)	R-area	Host rock	7.4.3.1.1, 7.4.3.2.1	m,v	L,L	M,M	8.3.5.10.3

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Table 8.3.5.13-17. Supporting parameters needed to evaluate the nominal case and as baseline data for the disturbed cases (page 6 of 6)

Issue 1.1 calculation using supporting parameter[a]	Supporting parameter: Description	Supporting parameter: Modifier	Lateral spatial location where needed[b]	Unit where needed[c]	SCP section providing expected parameter values	Characterization goal[d]	Current confidence[e]	Needed confidence[e]	SCP section
Source term - liquid and gas-phase releases from waste packages (continued)	Maximum concentration of chemical species associated with the i[th] radionuclide (i.e., solubility limits)	In general, for the radionuclides listed in Table 8.3.5.13-4, ambient conditions	R-area	Host rock	None	m,v	L,L	M,M	8.3.5.10.3

[a]UZ = unsaturated or partially saturated zone; SZ = saturated zone.

[b]Notation for indicating the various areas or zones around the repository: R-area = the vertical projection of primary repository area and extensions; C-area = the controlled area, i.e., the actual area which is chosen according to the 10 CFR Part 60 definition of controlled area.

[c]Ovb = overburden; i.e., all hydrogeologic units above repository floor; UZ-units = all hydrogeologic units below repository floor but above water table; SZ-units = all hydrogeologic units below water table which are included in the effective thickness of the saturated zone.

[d]Notation for statistical descriptors: m = mean value; v = variance; a = autocorrelation length. In general, these descriptors are used for spatially varying quantities, but m and v will also be used to indicate mean and variance of a scalar random variable; the supporting parameter being described should make clear which usage is intended.

[e]L = low, M = medium, H = high, and NA = not applicable.

[f]Effective porosity, sometimes called the kinematic porosity (see pp. 24-25 of DeMarsily, 1986).

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on the same scale, an assessment of the confidence needed to establish in a formal licensing action that the goal for the performance parameter has been met.

5. Summary of licensing and issue-resolution strategy for Issue 1.1

A nine-step program for providing the documented analyses and calculations for resolving Issue 1.1 is outlined in Table 8.3.5.13-18.

Table 8.3.5.13-18. Licensing strategy for resolving Issue 1.1 (total system performance)

Step	Description
1. Identify relevant phenomena leading to releases	Generic lists of phenomena potentially leading to releases from a geologic repository (IAEA, 1983a) are used together with site-specific information to single out those phenomena that are relevant to the waste-disposal system being considered.
2. Identify potentially significant events and processes	Relevant phenomena are examined in the light of being possible initiators or promoters of release scenarios. The implications of the site-specific frequencies and magnitudes, insofar as these are known for the integrity of each of the system's barriers, are explored.
3. Identify release scenarios	Events, processes, and conditions identified in step 2 are chained together to form scenarios. The construction of chains is constrained by physical causality and evidence concerning the likelihood of occurrence of events and processes that form the chain (in other words, screening against probability may occur in this step). The result of this step is usually a large number of potential release scenarios.
4. Identify scenario classes	All release scenarios identified in step 3 are examined and, by judgment, assembled in classes, each class being amenable to formulation as a single mathematical model. The result of this step is usually a moderate number of scenario classes that, after being put in mathematical form in step 5, can be screened against consequences in step 6.

Table 8.3.5.13-18. Licensing strategy for resolving Issue 1.1 (total system performance) (continued)

Step	Description
5. Construct scenario class models	Mathematical models of the scenario classes identified in step 4 are constructed. The independent variables of each model are those state variables needed to determine initial conditions, boundary conditions, and any time-dependent forcing functions that appear in the scenario class; the dependent variable (the output) of each model is the partial performance measure for the scenario class associated with a particular choice of the class's independent variables.
6. Eliminate inconsequential scenarios	Release scenarios or even whole scenario classes may be eliminated from set of exceptional scenarios by screening against relative or absolute consequences. If necessary, the models that survive screening against consequences may be simplified in this step by elimination of insensitive independent variables (sensitivity analyses).
7. Construct total system	Simplified mathematical models resulting from step 6 are implemented by efficient computer codes that can be combined in a single calculational model under the control of a driver routine. The driver routine must provide independent variables for each submodel, direct a simultaneous calculation of the partial performance measure for each submodel, and sum the resulting partial performance measures to obtain a value of the total performance measure, M, for a system; the driver routine must also select independent variables for the submodels by Monte Carlo sampling from the joint probability distribution of state variables for all submodels. The form of the joint probability distribution of state variables, and the ranges of those state variables, will inevitably be determined by judgment. Wherever possible, judgment will be enhanced and supplemented with site specific actuarial data concerning magnitudes and frequencies of the phenomenon that determine the state variables.

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Table 8.3.5.13-18. Licensing strategy for resolving Issue 1.1 (total system performance) (continued)

Step	Description
8. Construct an empirical complementary cumulative distribution function (CCDF)	The computer-implemented simulator assembled in step 7 is used to generate sample values of the total performance measure M. By repeated sampling, a large number of samples can be generated and used to construct an empirical CCDF or as a data set to which standard statistical methods for estimating likelihoods with given confidence bounds may be applied.
9. Document results	The logic and data bases supporting the analyses for steps 1 to 4, the rationales for the models developed in steps 5 to 7, and the results of the CCDF calculations in step 8 are all documented and presented as evidence that the proposed waste disposal system will meet the proposed 10 CFR 60.112 and 60.115 requirements, thereby resolving Issue 1.1 (8.3.5.13).

The logic of issue resolution is diagrammed in considerable detail in Figures 8.3.5.13-6A through 8.3.5.13-6G. The list and logic diagrams complement one another and both are shown in enough detail to be self-explanatory. Most of the elements, processes, and factors that appear in the list and logic diagrams are defined and explained in Part 1 (Methods for constructing a CCDF) and Part 2 (A preliminary selection of events, processes, and scenario classes for the Yucca Mountain repository site) of this overview.

Interrelationships of information needs

Sections 8.3.5.13.2 through 8.3.5.13.5 address the information and tasks needed to complete the nine-step program. Section 8.3.5.13.2 (Information Need 1.1.2) covers the required information and activities for step 5, the construction of scenario-class models. Section 8.3.5.13.4 (Information Need 1.1.4) covers required information and activities for step 6, the screening of scenario classes on the basis of consequences, and for the process of constructing the simplified scenario-class models to be used in completing steps 7 and 8. Finally, Section 8.3.5.13.5 (Information Need 1.1.5) addresses construction of the total-system simulator (step 7) and the empirical CCDF (step 8). The activities and schedules necessary for the preparation of licensing material (step 9) are also addressed in Section 8.3.5.13.5. Section 8.3.5.13.1 (Information Need 1.1.1) is a summary of all data and information called for in Information Needs 1.1.2 (8.3.5.13.2) through 1.1.5 (8.3.5.13.5).

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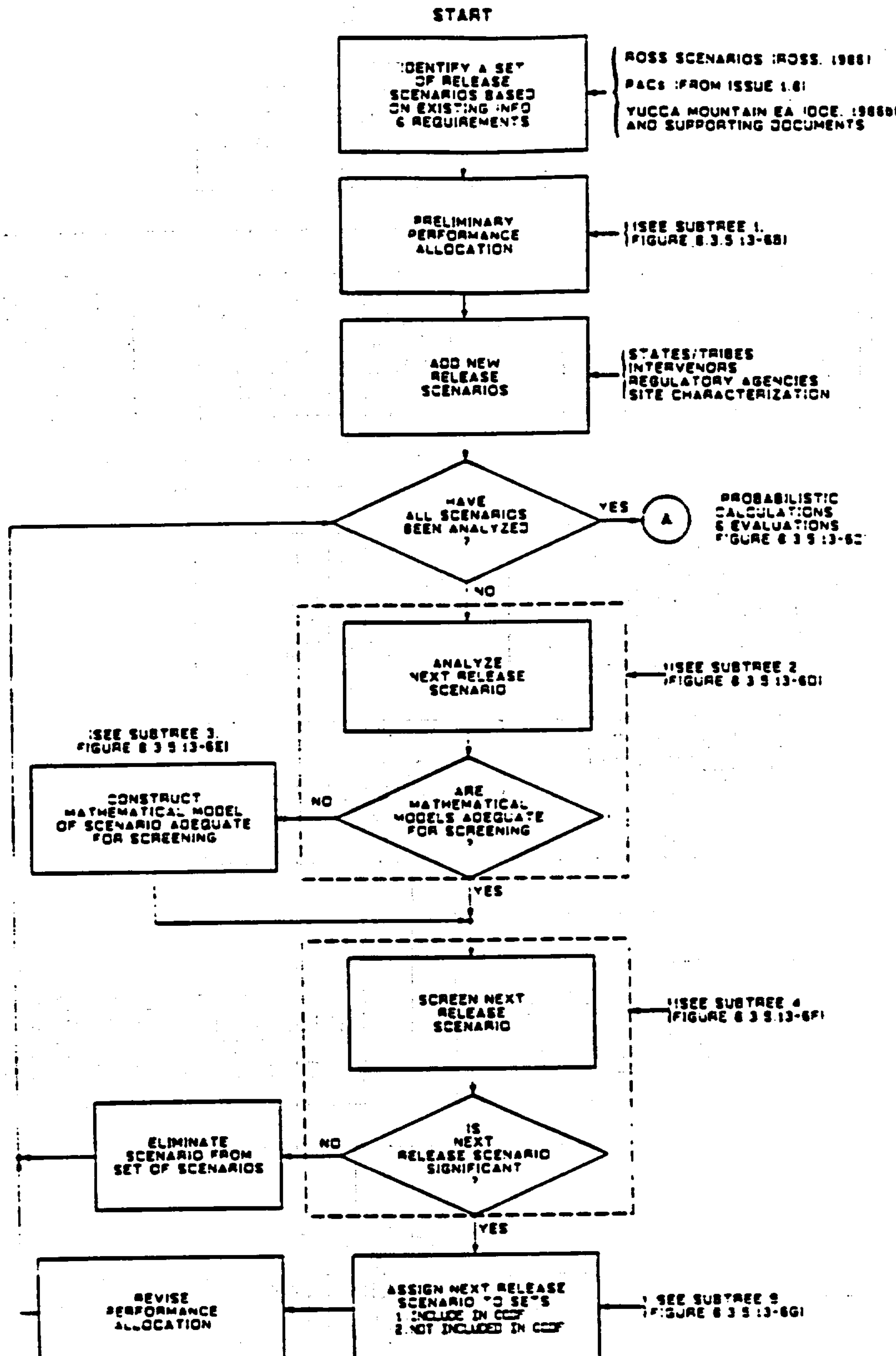


CCDF - COMPLEMENTARY CUMULATIVE DISTRIBUTION FUNCTION
EA - ENVIRONMENTAL ASSESSMENT
PAC - POTENTIALLY ADVERSE CONDITION
INFO - INFORMATION

TBA RELEASE SCENARIOS - THOSE SCENARIOS THAT ARE TO BE ASSIGNED SIGNIFICANCE AND A DETERMINATION MADE AS TO WHETHER THEY COULD BE INCORPORATED IN THE CCDF

Figure 8.3.5.13-6A. Idealized scenario classification and screening (logic diagram for Issue 1.1, total system performance)

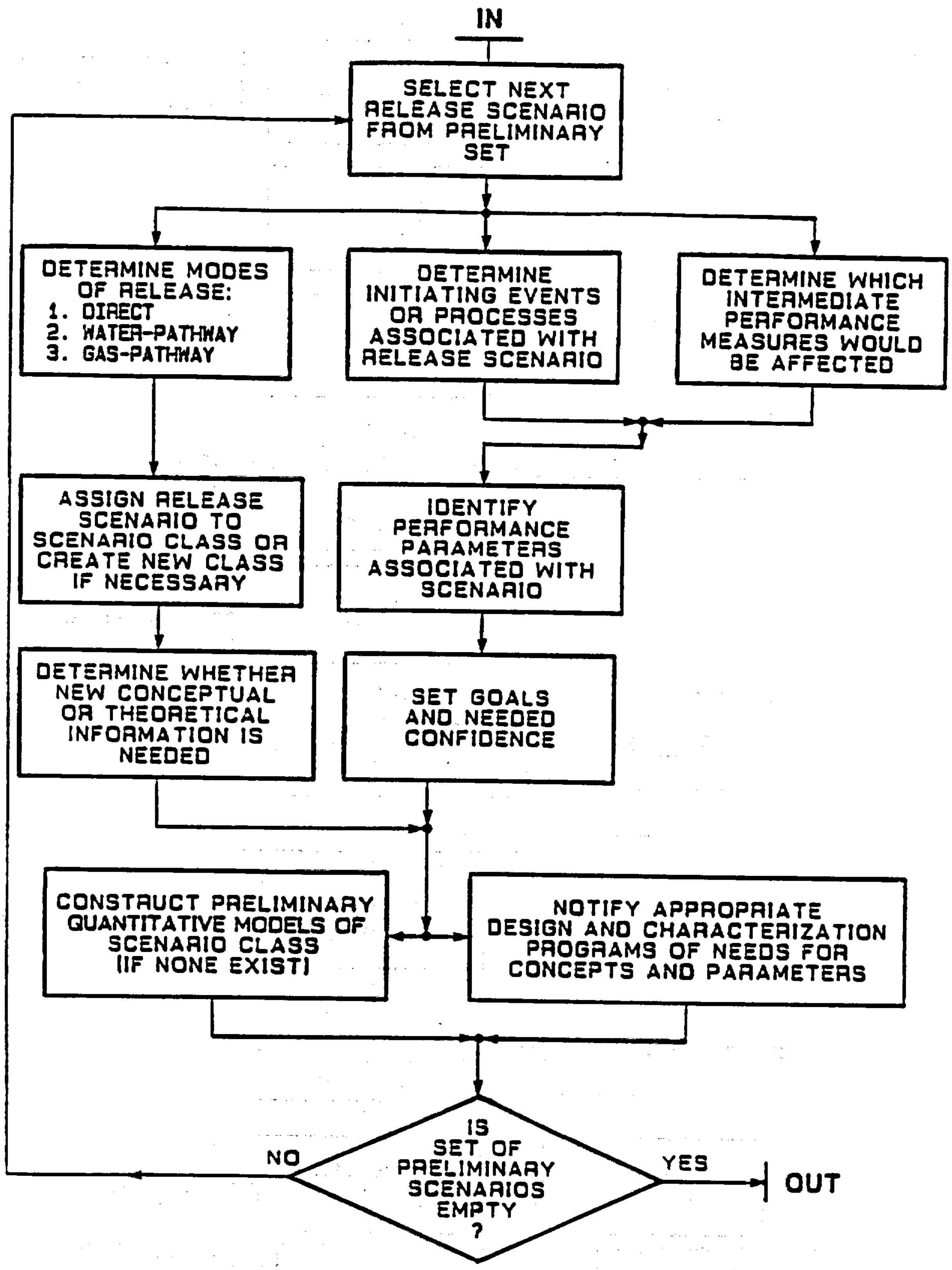
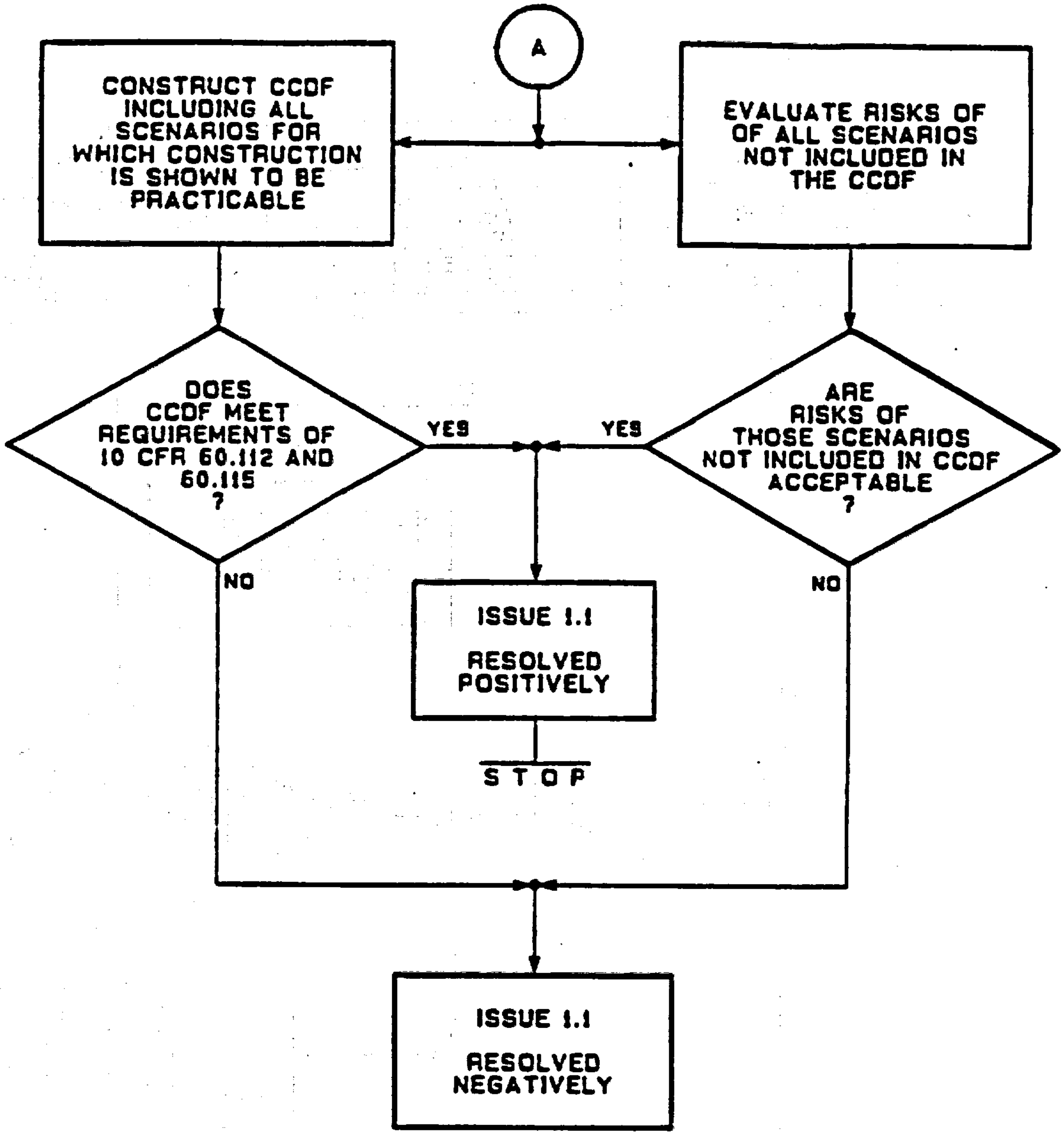


Figure 8.3.5.13-6B. Subtree 1--Idealized preliminary performance allocation (logic diagram for Issue 1.1 total system performance)



CCDF - COMPLEMENTARY CUMULATIVE DISTRIBUTION FUNCTION

Figure 8.3.5.13-6C. Idealized probabilistic calculations and evaluations (logic diagram for Issue 1.1. total system performance)

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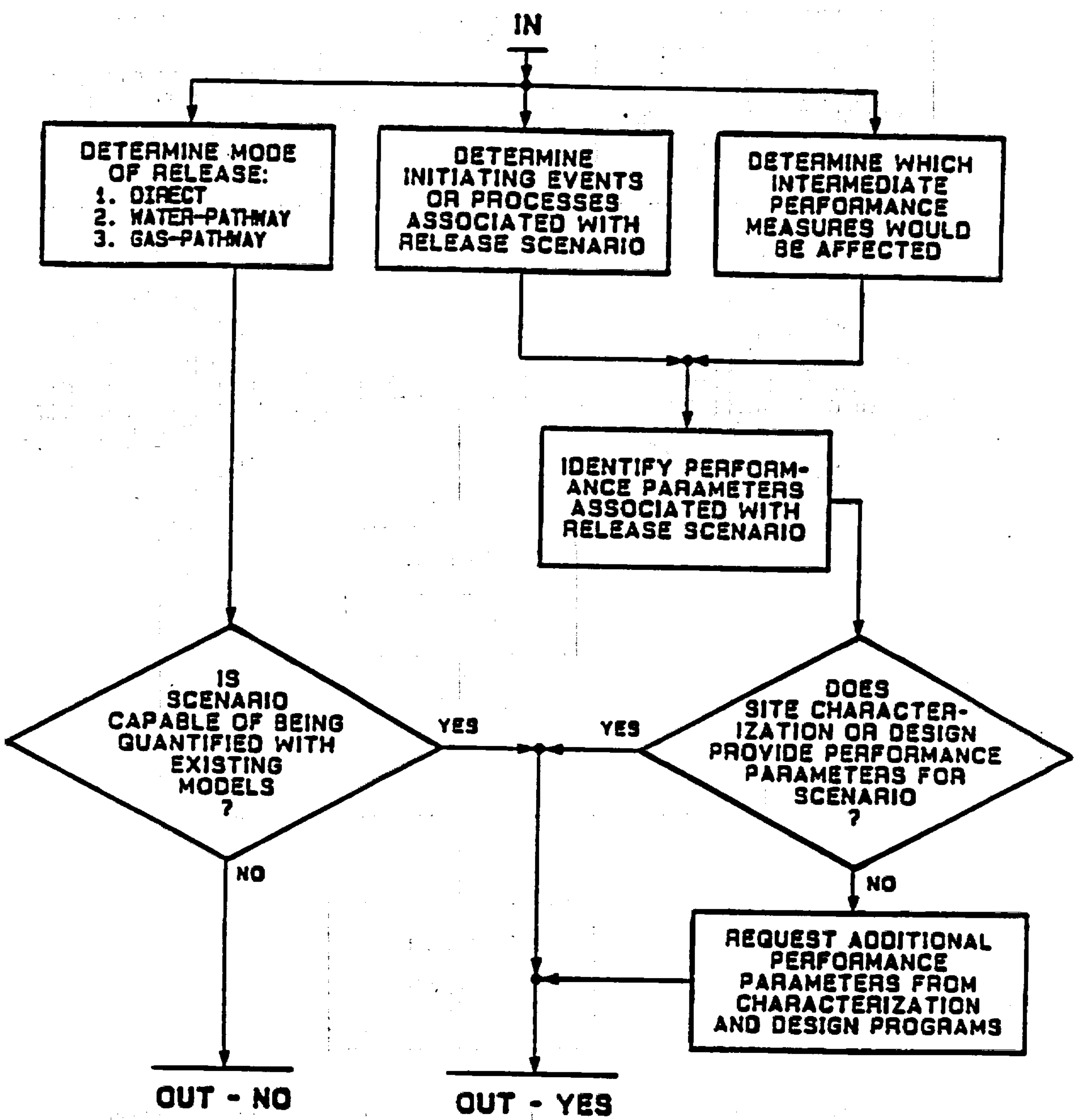

Figure 8.3.5.13-6D. Subtree 2--Idealized scenario classification (logic diagram for Issue 1.1, total system performance).

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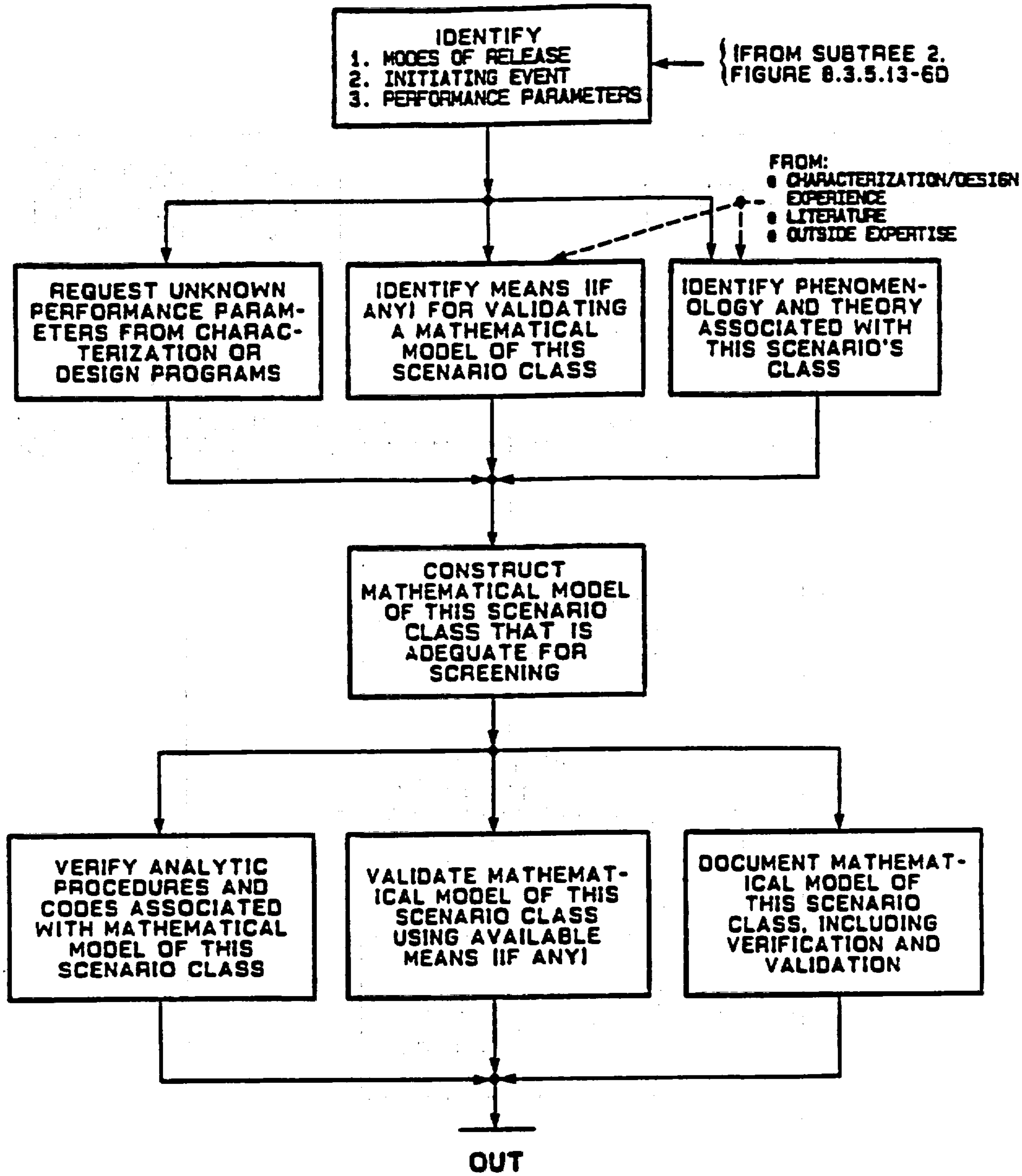

Figure 8.3.5.13-6E. Subtree 3--Idealized sequence for constructing a mathematical model of a scenario class (logic diagram for Issue 1.1, total system performance)

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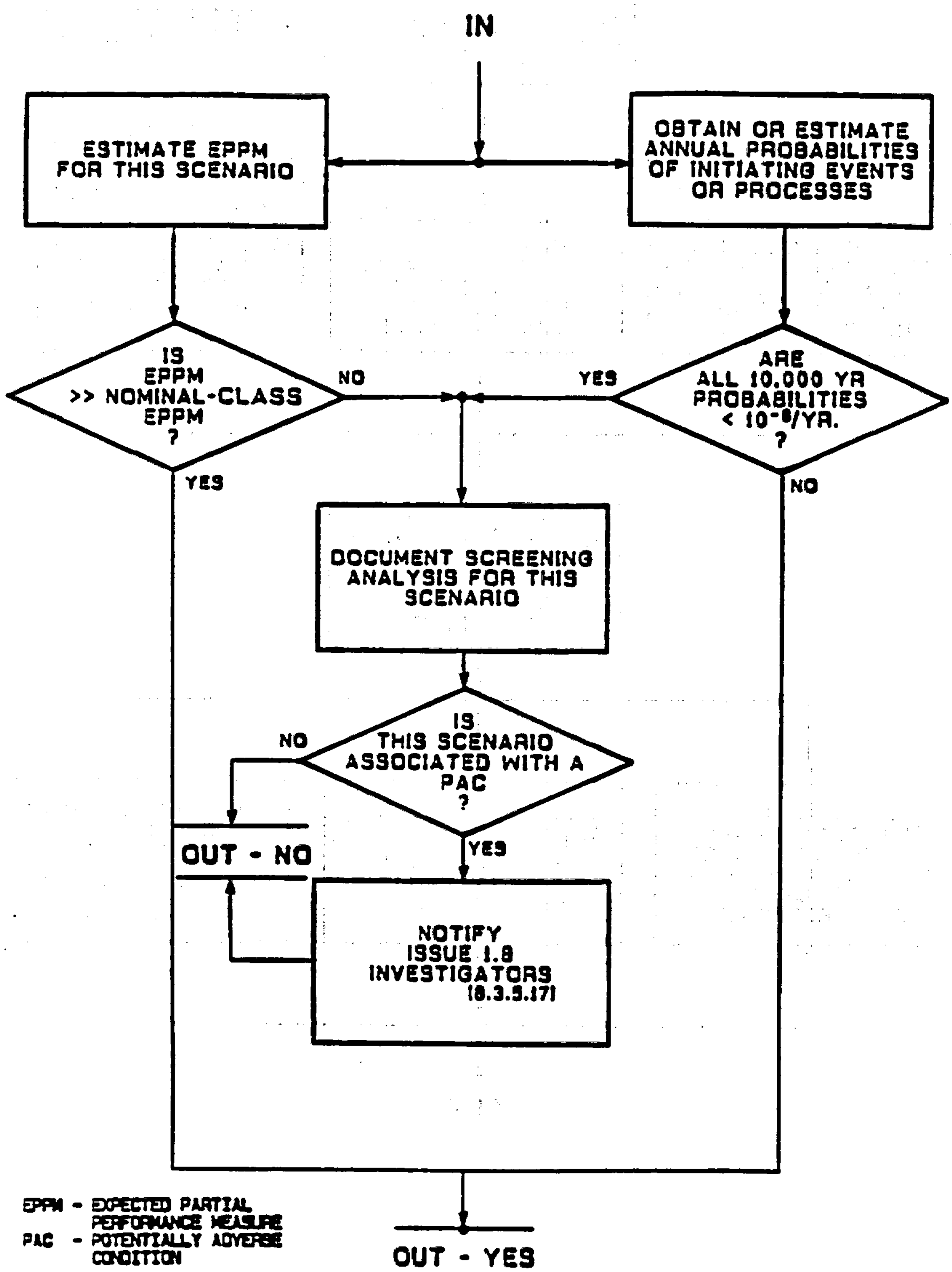

Figure 8.3.5.13-6F. Subtree 4--Idealized scenario screening (logic diagram for Issue 1.1. total system performanc

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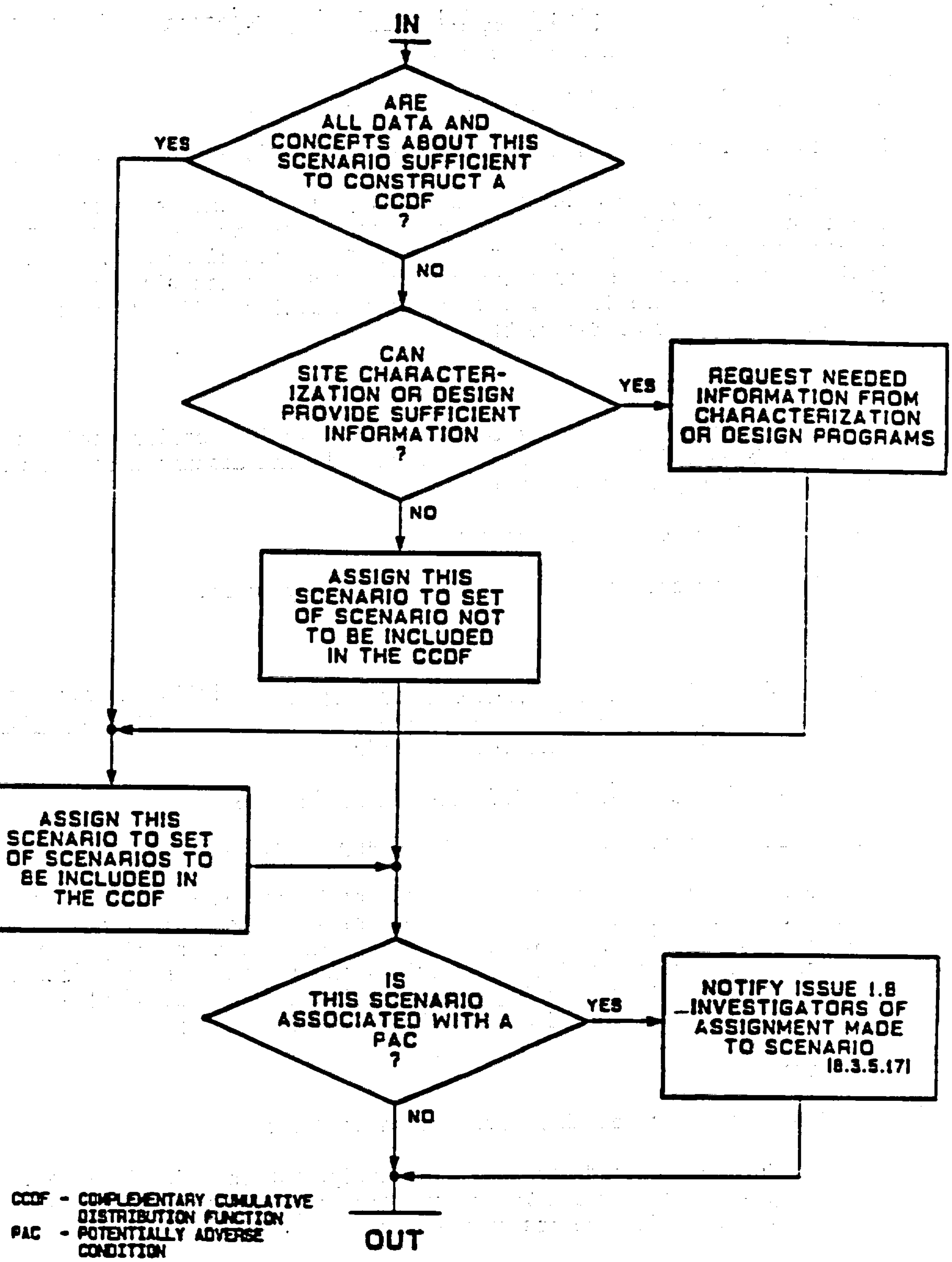

Figure 8.3.5.13-6G. Subtree 5--Decision to include scenario in complementary cumulative distribution function calculation (logic diagram for Issue 1.1, total system performance).

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8.3.5.13.1 Information Need 1.1.1: Site information needed to calculate releases to the accessible environment

Technical basis for addressing the information need

Link to the technical data chapters and applicable support documents

Section 8.3.5.13 discusses the complementary cumulative distribution function (CCDF) and significant processes and events, summarizes the issue resolution strategy, and discusses the performance allocation for Issue 1.1. Applicable support documents include Ross (1986) (scenario selection), Klavetter and Peters (1986), and Wilson and Dudley (1987) (flow and transport through porous, fractured rock).

Parameters

All information and data requested in this information need are specified in Tables 8.3.5.13-8 through 8.3.5.13-17 and discussed in the text of the preliminary performance allocation.

Planned performance assessment activities

No performance assessment activities are planned.

8.3.5.13.2 Information Need 1.1.2: A set of potentially significant release scenario classes that address all events and processes that may affect the geologic repository

Technical basis for addressing the information need

Link to the technical data chapters and applicable support documents

Section 8.3.5.13 discusses the interpretation of significant processes and events and disruptive scenarios for the Yucca Mountain repository site. In Table 8.3.5.13-18, Step 3 describes the identification of potentially disruptive scenarios and Step 4 describes the identification of scenario classes. Applicable supporting documents include DOE (1986a,b) and Ross (1987) (preliminary identification of release scenarios).

Parameters

The parameters for this information need are

1. Information and data on, and interpretations of, site-specific phenomena from the Yucca Mountain Project environmental assessment (DOE, 1986b) and its supporting references and documents.

2. Data and interpretive information to be supplied through the fulfillment of other performance and characterization issues. See Tables 8.3.5.13-9 through 8.3.5.13-17 for performance and supporting parameters.

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Logic

All data and interpretive information arising from the resolution of the Yucca Mountain Project site characterization program are potentially relevant to the identification of release-scenario classes at the Yucca Mountain repository site. But in advance of obtaining these data, and for the purpose of guiding site characterization activities, one must proceed with scenario identification using the data and knowledge bases established during the preparation of the Yucca Mountain Project environmental assessment (DOE, 1986b). On the other hand, once site characterization work is well advanced, the interpretations and decisions originally considered for the purpose of initially guiding site characterization activities must be reexamined in the light of new data and information. Accordingly, there are two phases of work toward fulfilling this information need: (1) a preliminary phase, in which current data and interpretive information are used to construct potentially significant release scenario classes, and (2) a final phase, during which the preliminary scenario classes are modified, supplemented, dropped from consideration, or reconsidered if they had been previously dropped but warrant a second examination on the basis of new evidence. The logic of phase 1 is described in the following paragraph.

In the preliminary phase, the phenomena identified in the environmental assessment as being significant at the Yucca Mountain site are compared with generic lists of world-wide natural processes, events, or conditions that have been thought to influence the long-term performance of geologic waste disposal systems (for examples of such lists see Table 2.3.1 in Campbell et al. (1978); or IAEA (1983a)). Those natural processes or events in the generic lists that are either manifestly irrelevant to the context of the Yucca Mountain site (e.g., sea-level rise and glaciation) or have had demonstrably minor effects on site characteristics during the Quaternary (e.g., meteorites, hurricanes, and root penetration) are eliminated as potential ingredients of disruptive scenarios. In a similar fashion, features of the site and the repository design, and available estimates of the effects of repository excavation and waste emplacement on site characteristics are compared with anthropogenic processes and events in the generic lists and eliminated as being either irrelevant (e.g., brine-bubble migration) or insignificant. This elimination process leaves a set of natural and anthropogenic processes and events that, in the absence of further information, may be considered to play roles in changing the nominal performance of the total system (e.g., climatic change, seismic events, volcanic activity, erosion, dissolution of the host rock, undetected geologic features such as mineral resources near the site, subsidence, and permanent thermal changes in rock hydrologic and geochemical properties).

The processes and events that are determined to play potential roles in release scenarios are then subjectively arranged in series, and an attempt is made to discover the effects of realization of each series on the performance of one or more of the isolation barriers for the total system. This part of the analysis is necessarily subjective because the number of series formed in this way could be astronomical if the intuition and knowledge of the analyst is not applied to reduce the number of possibilities to a manageable size. Two nonsubjective principles may, however, be used at this point to guide the formation of the series: (1) the principle of causality (i.e., certain chains of events and processes are not possible because one or more event or

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process upstream in the chain is logically antecedent to others downstream in the chain), and (2) the fact that long series of events or processes are unlikely to be realized in the 10,000-yr period being considered (e.g., events with even a modest probability--chances of 0.1 or less in a 10,000-yr period--will compose an unlikely series if there are more than four of them in a serial chain). In addition, certain short series of events may be eliminated on the basis of probability at this point if there is sufficient evidence that the initiating event or guiding process is improbable (in the sense of not exceeding the 0.0001 cutoff probability threshold in 10,000 yr). Using the kinds of reasoning and analyses indicated previously, Ross (1987) has identified 84 series of events and processes that could cause or influence releases of radioactivity to the accessible environment that have the potential of adding to nominal-case releases.

As seen from Ross (1987), the results of the kinds of analyses previously indicated is a large but finite number of sequences of events and processes that must be further organized into scenario classes to efficiently begin construction of the mathematical models of those classes. In turn, the mathematical representations of the scenario classes are necessary to determine each class's consequences and also to enable screening of each class against relative consequences. A preliminary organization of scenario classes is shown in Table 8.3.5.13-3.

8.3.5.13.2.1 Performance Assessment Activity 1.1.2.1: Preliminary identification of potentially significant release scenario classes

The objective of this performance assessment activity is to preliminarily identify significant release scenario classes for the purpose of determining data and informational needs that must be supplied by the Yucca Mountain Project site characterization program. This activity includes two subactivities.

8.3.5.13.2.1.1 Subactivity 1.1.2.1.1: Preliminary identification of potentially significant sequences of events and processes at the Yucca Mountain repository site

Objectives

The objective of this subactivity is to identify a set of causally related, apparently probable sequences of events and processes, any member of which, if realized, could cause or influence releases of radioactivity to the accessible environment at the Yucca Mountain site in excess of nominal-case releases.

Parameters

See the general parameters listed previously for Information Need 1.1.2.

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Description

See the general logic discussion given previously for Information Need 1.1.2.

8.3.5.13.2.1.2 Subactivity 1.1.2.1.2: Preliminary identification of potentially significant release scenario classes

Objectives

The objective of this subactivity is to preliminarily identify a set of significant release scenario classes for the purpose of determining data and informational needs that must be supplied by the Yucca Mountain Project site characterization program.

Parameters

The parameters for this subactivity are the sequences of events and processes identified in Subactivity 1.1.2.1.1 plus the information, data, interpretations, and calculational models related to site-specific phenomena from the Yucca Mountain Project EA (DOE, 1986b) and its supporting documents.

Description

This subactivity has been completed, and the results are summarized in the section on approach to resolving this issue.

8.3.5.13.2.2 Performance Assessment Activity 1.1.2.2: Final selection of significant release scenario classes to be used in licensing assessments

Objectives

The objective of this performance assessment activity is to use data and information obtained in the Yucca Mountain Project site characterization program to modify, if necessary, the set of significant release scenario classes developed in Activity 1.1.2.1 and in the preliminary phases of work fulfilling Information Needs 1.1.3 and 1.1.4 (Sections 8.3.5.13.3 and 8.3.5.13.4).

Parameters

All data and information that could arise during the site characterization program are potential parameters. The tables in the introductory material of this section give the requested data and information.

Description

Only examples of possible study topics can be given. Work in fulfillment of Information Need 1.5.4 (Section 8.3.5.10.4) may show that release rates of radionuclides from the engineered barrier system are orders of magnitude less than the regulatory rate under unanticipated conditions in the repository. In such a case, certain scenario classes in Table 8.3.5.13-3 would be screened again and possibly eliminated. Work in fulfillment of Information Need 1.1.3 (Section 8.3.5.13.3) and Investigation 8.3.1.5.2 may indirectly indicate that delay times for climatic infiltration pulses are long compared with 10,000 yr. In such a case, certain scenarios in class C-1 in Table 8.3.5.13-3 could be dropped from consideration. Similarly, two-dimensional calculations of transient flow in faulted zones, when combined with predictions of the effects of tectonic activity on hydrologic characteristics (from Investigation 8.3.1.8.3), may indicate that certain scenarios in class C-3 in Table 8.3.5.13-3 can be dropped. On the other hand, the development of evidence that colloids play a significant role in radionuclide transport (in fulfillment of Investigation 8.3.1.3.5) could force a modification of the transport equations used to screen scenario classes in Information Need 1.1.3 (Section 8.3.5.13.3), and a reassessment of all scenario classes involving releases along the water pathways. Finally, the development of evidence for future, inadvertent human activity on or near the site may lead to the reconsideration or augmentation of the direct-release scenario classes such as Class A-2 in Table 8.3.5.13-3.

8.3.5.13.3 Information Need 1.1.3: Calculational models for predicting releases to the accessible environment attending realizations of the potentially significant release-scenario classes

Technical basis for addressing the information need

Link to the technical data chapters and applicable support documents

The introductory discussion of Section 8.3.5.13 develops disruptive scenarios for the Yucca Mountain repository site and addresses the topics of gas-phase releases and calculation of releases through the water pathways. In Table 8.3.5.13-18, Step 5 discusses the construction of scenario-class models. The supporting documents are DOE (1986b), Sinnock et al. (1986) (calculational models used in Section 6.4.2 of the Yucca Mountain Project environmental assessment), and Wilson and Dudley (1987).

Parameters

The parameters of this information need are

1. The release-scenario classes identified in the preliminary phase of work fulfilling Information Need 1.1.2 (Section 8.3.5.13.2).

2. The same rock hydrologic properties that are needed to resolve the ground-water travel time issue (Information Need 1.6.1, Section 8.3.5.12.1), but extended to include rock hydrologic properties for overburden units. See Tables 8.3.5.13-9 and 8.3.5.13-17 and parameters for Information Need 1.6.1 and Investigations 8.3.1.2.2 and 8.3.1.2.3.

3. Data and interpretive information concerning rock and ground-water geochemical properties, with emphasis on the properties of rock units and ground water below the repository horizon; also, the effective retardation of carbon dioxide by isotopic exchange with ground water in the overburden units of the unsaturated zone. See Tables 8.3.5.13-9 and 8.3.5.13-17 and parameters from Investigations 8.3.1.3.4, 8.3.1.3.5, 8.3.1.3.7, and 8.3.1.3.8.

4. Definition of the boundary of the engineered barrier system, and release rates of radionuclides from the engineered barrier system for nominal and disturbed conditions in the repository. See Tables 8.3.5.13-9 and 8.3.5.13-17 and parameters from Information Need 1.5.4 (Section 8.3.5.10).

5. Preliminary estimates of the kind and nature of human-intrusion and magmatic-intrusion events. See Tables 8.3.5.13-10 and 8.3.5.13-11 and parameters from Investigations 8.3.1.8.3 through 8.3.1.8.5 and 8.3.1.9.3.

6. Calculational models of transient flow in the unsaturated and saturated zones capable of predicting time-dependent specific discharge in at least two dimensions. See the introductory material to this section and parameters from Information Need 1.6.2 (Section 8.3.5.12.2).

7. Calculational models of transport of dissolved species in the unsaturated and saturated zones capable of predicting time-dependent mass-flux fields in at least two dimensions. See the introductory material to this section and parameters from Investigation 8.3.1.3.7.

8. Final conceptual models of the unsaturated and saturated zone hydrologic systems. See the introductory material to this section and parameters from Investigations 8.3.1.2.1, 8.3.1.2.2, and 8.3.1.2.3.

9. Final conceptual models of the unsaturated and saturated zone geochemical systems, including geochemical effects on gas-phase transport. See the introductory material to this section and parameters from Investigations 8.3.1.3.7 and 8.3.1.3.8.

Logic

The release-scenario classes identified in the preliminary phase of work fulfilling Information Need 1.1.2 (item 1 in parameter list) are listed in Table 8.3.5.13-3. Mathematical models of these release-scenario classes are the product of this information need. The models are needed (1) to screen the scenario classes against consequences, and (2) provided that the scenario class survives screening against consequences, to serve as a basis for constructing the simplified mathematical models required for the construction of the complementary cumulative distribution function (CCDF) in fulfillment of Information Need 1.1.5 (Section 8.3.5.13.5). The screening of scenario-class models against relative consequences, and the construction of simplified scenario-class models based on the preliminary models developed in this

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information need, are studies to be conducted in Information Need 1.1.4 (Section 8.3.5.13.4). There are two phases of work toward the construction of scenario-class models: (1) a preliminary phase in which current data and interpretive information are used to build and test the models, and (2) a final phase in which data and interpretive information arising out of the site characterization program are used to justify modifications or replacements of existing models, or the construction of entirely new models. The logic of phase 1 is emphasized in the discussion that follows.

As shown by the grouping of release-scenario classes in Table 8.3.5.13-3, at least four distinct kinds of models are needed to calculate releases to the accessible environment: (1) those that predict radionuclide releases along water pathways, (2) those that predict gas-phase radionuclide releases, (3) those that predict releases associated with intrusive or extrusive magmatic events, and (4) those that predict direct releases associated with inadvertent human intrusion (here, inadvertent exploratory drilling on the site).

Water-pathway models. The Total System Performance Assessment Code (TOSPAC), which is under development (Klavetter and Peters, 1986), is currently the major "workbench" for the development of the phenomenology of water-pathway models that apply to Yucca Mountain conditions. As implied by its name, the TOSPAC is capable of simulating the static and dynamic response of a one-dimensional conceptual model of the total waste-disposal system at Yucca Mountain. This is done by the coupling of three submodels (or modules): (1) a flow module, that can predict time-dependent, specific-discharge fields in the unsaturated zone given surficial infiltration rates; (2) a source term module, that supplies mass flux or concentrations of liquid-phase radionuclides in the host rock near the repository given radionuclide release rates from the engineered barrier system (EBS); and (3) a transport module that solves the transport equations for coupled matrix-fracture flow (see Equations 8.3.5.13-12 to 8.3.5.13-17 in the introductory material to this section) in the unsaturated zone and computes cumulative releases to the water table, given the flow field from the flow module and the boundary concentrations from the source-term module. The TOSPAC currently has no modules for flow or transport through the saturated zone; these phenomena are being investigated with the ISOQUAD code (Pinder, 1976).

In spite of its limitation to one dimension, the TOSPAC can still be used to screen some of the water-pathway release scenarios in Table 8.3.5.13-3 against consequences. The code has already been used to show (1) that transient flooding from surficial sources may have little effect on repository performance and (2) that increases in fracture density will have no effect on repository performance in the absence of extreme climatic changes. Items 1 through 4 in the parameter list will be needed to provide a rock-property data set for these TOSPAC calculations. The screening of some other water-pathway release scenario classes in Table 8.3.5.13-3, namely in C-1, D-1, and D-2, will definitely require two-dimensional models of flow and transport of the kind mentioned in items 6 and 7 of the parameter list. These two-dimensional models will also be used to validate the phenomenology incorporated in TOSPAC's flow and transport modules (i.e., the neglect of horizontal flow paths and transport along those paths).

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It is very likely that the TOSPAC and the phenomenology that it contains will require substantial modification after the "ground truth" of the site characterization program is established. Items 8 and 9 in the parameter list will be required to assess the changes that must be made in the systems-level models.

Models of gas-phase releases. The significance of gas-phase release of carbon-14 has only recently become apparent, and no models for transport of carbon-14 dioxide from the repository through overburden units have so far been developed within the Yucca Mountain Project. An adequate general theory of carbon-14 transport is presented in the introductory material to this section; however, application of that theory to the Yucca Mountain setting would seem to require considerable study of hydrologic, gas-phase hydraulic, and geochemical properties of the overburden units. For that reason, thought should be given to balancing complexity and cost factors associated with site characterization studies with complexity and cost factors associated with engineered barrier system performance and design, because these factors relate to models of gas-phase, carbon-14 releases. The parameters required by systems-level models for gas-phase transport would include both the effective diffusivity of carbon dioxide and the effective retardation factor for carbon-14 dioxide because of isotopic exchange, each as a function of depth within the overburden units. The latter quantity is requested in item 3 of the parameter list. The effective diffusivity of carbon dioxide might be inferred from final results of experiments being conducted in partial fulfillment of Investigation 8.3.1.2.2.

While the general model of carbon-14 transport may predict travel times shorter than might be expected on the basis of experimental measurements, it is judged to be useful for present purposes of identifying parameter needs because it tends to produce conservative results. As an alternative to a full transport calculation, a simpler systems-level model of gas-phase releases might be devised; use of this model would require estimates of the mean and standard deviation of residence time of carbon-14 nuclei in the repository overburden. Either modeling technique requires specification of the release rate of carbon-14 dioxide from the engineered barrier system, a quantity that is called for in item 4 of the parameter list. However, that release of C-14 is limited at the waste container and at the engineered barrier system boundary to satisfy the requirements in 10 CFR 60.113. Depending on the containment strategies, including alternatives adapted for the waste package, the C-14 source term for the total system may be significantly changed. For example, if all the fast fraction of C-14 were released before waste emplacement, no consideration of C-14 transport would be necessary for the total system performance assessment in Issue 1.1.

Models of releases through basaltic volcanism. The mathematical model for predicting the consequences of basaltic volcanism developed by Link et al. (1982) can be modified and used to estimate cumulative releases to the accessible environment attending the realization of such events at Yucca Mountain. The work by Link et al. (1982) was specifically applied to Yucca Mountain, but the conceptual and data bases may be outdated, and a request is made for the most current concepts and data in item 5 of the parameter list.

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Models of releases through human intrusion. A calculation of an upper bound to the consequences of inadvertent exploratory drilling on the Yucca Mountain site during the next 10,000 yr is described in the introductory material to this section, along with a brief discussion of other types of human-intrusion scenarios that might be realized at that location. The model implicit in the calculation is easily put into mathematical terms. The state variables for the model include (1) the mean recurrence time between penetrations (current guidance in Appendix B of 40 CFR Part 191 sets a limit on the penetration rate of 0.0003 penetrations/km^2 per yr), (2) the depth of penetration (and the attending probability distribution), and (3) the diameter of the exploratory drill bit (and its probability distribution). Data required to implement the model, and models of other potential human-intrusion scenario classes, are requested through item 5 in the parameter list.

8.3.5.13.3.1 Performance Assessment Activity 1.1.3.1: Development of mathematical models of the scenario classes

The objective of this performance assessment activity is to construct mathematical models of the scenario classes developed in Information Need 1.1.3 (Section 8.3.5.13.3). Four subactivities are included in this activity. These subactivities describe the models to be developed for this activity.

8.3.5.13.3.1.1 Subactivity 1.1.3.1.1: Development of models for releases along the water pathways

Objectives

The objective of this subactivity is to produce mathematical models whose phenomenology is sufficient (1) to effect a screening of the release scenarios associated with the water pathways with respect to consequences and (2) to form an adequate basis for the simplified models needed to fulfill Information Need 1.1.5 (Section 8.3.5.13.5).

Parameters

The parameters for this subactivity are items 1 to 4 in the general parameter list for Information Need 1.1.3 and preliminary versions of the conceptual models referred to in items 8 and 9 of the same general parameter list.

Description

Several systems-level models of releases along the water pathways have already been constructed: the TOSPAC (see Klavetter and Peters, 1986), RELEASE (Sinnock et al., 1986), and SPARTAN (Lin, 1985). The two- and three-dimensional models of flow and transport that could be used to screen scenario classes on the basis of long delays for certain effects are listed in Section 8.3.5.19. The TOSPAC probably will be sufficient to screen scenario classes E and C-2 through C-3 (Table 8.3.5.13-3) if calculations with the

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multi-dimensional models show that lateral flow paths can be ignored. The screening of scenario class C-1 will require at least a two-dimensional model of transient flow through a faulted zone. Scenario classes D-1 and D-2 can probably be screened with the simple RELEASE code (or modifications of it) if saturated-zone flow fields are provided by the two-dimensional ISOQUAD model. Effective use of any of these models in the screening of water-pathway scenario classes will definitely require better, site-specific conceptual and data bases. Thus, items 2 and 3 are in the general parameter list.

8.3.5.13.3.1.2 Subactivity 1.1.3.1.2: Development of a model for gas-phase releases

Objectives

The objective of this subactivi-- is to produce a mathematical model whose phenomenology is sufficient (1) to effect a screening of the release scenario associated with the anticipated gas-phase releases and (2) to form a basis for the simplified model needed to fulfill Information Need 1.1.5.

Parameters

The parameters for this subactivity are items 3 and 4 in the general parameter list for Information Need 1.1.3.

Description

A systems-level model similar to the one described for water-pathway releases in the introductory material to this section may be sufficient to determine the expected partial performance measure (EPPM) for anticipated gas-phase releases, and at the same time be simple enough to use as a scenario-class model in the construction of the complementary cumulative distribution function (CCDF) (Information Need 1.1.5, Section 8.3.5.13.5). This subactivity will thus involve the calibration of one of the parameters of a system-level model (the reciprocal of the mean residence time) with estimates of the actual time for carbon-14 dioxide to diffuse from the repository level to the surface (from item 4). Other parameters required by the model are supplied through item 3.

8.3.5.13.3.1.3 Subactivity 1.1.3.1.3: Development of a model of releases through basaltic volcanism

Objectives

The objective of this subactivity is to produce a mathematical model whose phenomenology is sufficient (1) to effect a screening of the release scenarios associated with basaltic volcanism and (2) to form an adequate basis for the simplified models needed to fulfill Information Need 1.1.5 (Section 8.3.5.13.5).

Parameters

The parameters for this subactivity are the model of basaltic volcanism proposed by Link et al. (1982) and the updated estimates of the kind and nature of magmatic-intrusion events at Yucca Mountain (item 5 in the general parameter list).

Description

The model proposed by Link et al. (1982) will, if necessary, be modified to reflect most recent estimates of the kind and nature of basaltic volcanism to be expected at Yucca Mountain.

8.3.5.13.3.1.4 Subactivity 1.1.3.1.4: Development of a model of releases through human intrusion

Objectives

The objective of this subactivity is to produce mathematical models whose phenomenology is sufficient (1) to effect a screening of the release scenarios associated with inadvertent human intrusion and (2) to form an adequate basis for the simplified models needed to fulfill Information Need 1.1.5 (Section 8.3.5.13.5).

Parameters

The parameters of this subactivity are the model of releases through inadvertent exploratory drilling presented in Section 8.3.5.13 and the preliminary and final assessments of the nature of future human intrusion events at the Yucca Mountain repository site (item 5 in general parameter list).

Description

The model of releases through exploratory drilling presented in the introductory material to this section will be put into mathematical terms. Depending upon the outcome of the preliminary assessments of potential human-intrusion events, new conceptual models may have to be developed and put into mathematical terms.

8.3.5.13.4 Information Need 1.1.4: Determination of the radionuclide releases to the accessible environment associated with realizations of potentially significant release scenario classes

Technical basis for addressing the information need

Link to the technical data chapters and applicable support documents

The introductory material to this section addresses the interpretation of "significant processes and events." In Table 8.3.5.13-18, Step 6

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discusses the screening of scenario classes on the basis of relative consequences. The supporting documents are DOE (1986b), Sinnock et al. (1986), and Barr and Miller (1987).

Parameters

The parameters of this information need are the mathematical models of the release scenario classes that were developed in Activity 1.1.3.1 (Section 8.3.5.13.3.1) under Information Need 1.1.3 and their supporting data bases.

Logic

The goals of the work fulfilling this information need are twofold: (1) a screening of the release scenario classes in Table 8.3.5.13-3 (and other classes that may be proposed during the site characterization program) against the criterion of relative consequences, and (2) a set of simplified mathematical models of those release-scenario classes that survive the screening process. In simple terms, the release-scenario classes that survive the screening process will be those release-scenario classes that will provide the major contribution to the empirical complementary cumulative distribution function (CCDF) to be constructed during activities fulfilling Information Need 1.1.5 (Section 8.3.5.13.5). As is explained in the logic section of Information Need 1.1.3 (Section 8.3.5.13.3), there are necessarily two phases of work fulfilling the need: a preliminary and a final. There are also at least four distinct kinds of models that need to be considered in the preliminary phase of work.

To meet goal 1 in the preliminary phase, computer-implemented versions of the models developed in fulfillment of Information Need 1.1.3 (Section 8.3.5.13.3) will be used to simulate the general consequences of realizations of members of the scenario classes in Table 8.3.5.13-3, and the results of these simulations will be compared. The comparisons will show which (if any) of the scenario-class members may temporarily be dropped from consideration. The work toward meeting goal 2 in the preliminary phase will then focus upon the models of the scenario classes that survive these comparative studies. Work toward meeting goal 1 in the final phase will proceed in a similar fashion, except that the modified or entirely new models produced in the final phase of work fulfilling Information Need 1.1.3 (if any) and final data bases developed in site characterization work will be used in making the comparisons.

The procedures that may be used to turn a complex mathematical model into a simple one representing the same phenomenology (i.e., one that meets goal 2) are best described in a model-specific context. All such procedures could probably be lumped under the title of "sensitivity studies"; but the reader should recognize that there are at least two kinds of model sensitivity: (1) sensitivity of model output to the kinds and manner of representation of physical phenomena incorporated in the model and (2) the sensitivity of model output to variations in the model's input variables. Model simplification is primarily concerned with the first kind of sensitivity. A mathematical model may initially include kinds and representations of physical phenomenon that later prove inessential. These phenomena can be deleted from the model, thereby effecting a simplification and increasing computational efficiency. In the studies fulfilling this information need, sensitivity of

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the second kind will generally not be investigated; uncertainties in the model input variables will be taken into account by including them in the construction of the joint probability distribution of the model's state variables (i.e., input parameters) an activity conducted in fulfillment of Information Need 1.1.5 (Section 8.3.5.13.5).

8.3.5.13.4.1 Performance Assessment Activity 1.1.4.1: The screening of potentially significant scenario classes against the criterion of relative consequences

The objective of this performance assessment activity is to identify the set of scenario classes representing the significant events and processes mentioned in proposed 10 CFR 60.112 and 60.115. Two subactivities are included in this activity.

8.3.5.13.4.1.1 Subactivity 1.1.4.1.1: The screening of the preliminary scenario classes

<u>Objectives</u>

The objective of this subactivity is to identify those scenario classes among the members of the preliminary set (Table 8.3.5.13-3) whose consequences of realization are not significantly different from nominal-class consequences, and therefore may be temporarily dropped from consideration.

<u>Parameters</u>

See the general parameter list for Information Need 1.1.4.

<u>Description</u>

See the general logic and descriptions of Subactivities 1.1.3.1.1 through 1.1.3.1.4 listed in Section 8.3.5.13.3.1.

8.3.5.13.4.1.2 Subactivity 1.1.4.1.2: A final screening of scenario classes

<u>Objectives</u>

The objective of this subactivity is to identify the final scenario classes to be used in constructing the empirical complementary cumulative distribution function (CCDF) during fulfillment of Information Need 1.1.5 (Section 8.3.5.13.5).

<u>Parameters</u>

The parameters for this subactivity are a modified and an amended set of mathematical models produced in the final phase of Subactivities 1.1.3.1.1 to 1.1.3.1.4, plus amended data bases from site characterization work.

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Description

See the remarks on the final phase in the general logic section for this information need.

8.3.5.13.4.2 Performance Assessment Activity 1.1.4.2: The provision of simplified, computationally efficient models of the final scenario classes representing the significant processes and events mentioned in proposed 10 CFR 60.112 and 60.115

The objective of this performance assessment activity is to provide the simplified, computationally efficient models of the final scenario classes representing the significant processes and events mentioned in proposed 10 CFR 60.112 and 60.115. Two subactivities are included in this activity.

8.3.5.13.4.2.1 Subactivity 1.1.4.2.1: Preliminary development of simplified, computationally efficient scenario-class models

Objectives

The objective of this subactivity is to construct, as necessary, simple computationally efficient versions of the scenario-class models developed during the Subactivities 1.1.3.1.1 to 1.1.3.1.4 listed in Section 8.3.5.13.3.1.

Parameters

The parameters for this subactivity are the mathematical models developed in Activity 1.1.3.1 of Information Need 1.1.3.

Description

The activities to be conducted depend upon which of the scenario classes survive screening in Subactivity 1.1.4.1.1. If classes E, C-2, or C-3 in Table 8.3.5.13-3 survive, the phenomenology of the existing TOSPAC (in development, but see Klavetter and Peters, 1986) may be amenable to simplifications that preserve the code's ability to represent the essential events and processes of any one of these classes that survive. Simplified, exploratory versions of the TOSPAC have already been tried. See, for instance, the RELEASE model in Sinnock et al. (1986) or the systems-level model proposed in Section 8.3.5.13. These exploratory versions of TOSPAC may also be used to represent classes C-2 or C-3 in Table 8.3.5.13-3 if these classes survive a preliminary screening. The models currently proposed for the screening of the expected-case, gas-phase releases (part of scenario class E) and the direct releases (scenario classes A-1 and A-2), are being developed.

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8.3.5.13.4.2.2 Subactivity 1.1.4.2.2: Development of the final, computationally efficient models of the scenario classes that will be used to represent all significant processes and events in the simulation of the total system

Objectives

The objective of this subactivity is to develop the final, computationally efficient models of the scenario classes that will be used to represent the simulation of the total system.

Parameters

The parameters for this subactivity are the scenario classes that survive the final screening of Subactivity 1.1.4.1.1 and the techniques and insight established in Subactivity 1.1.4.2.1.

Description

See the remarks on final phase of work in the general logic section of this information need.

8.3.5.13.5 Information Need 1.1.5: Probabilistic estimates of the radionuclide releases to the accessible environment considering all significant release scenarios

Technical basis for addressing the information need

Link to the technical data chapters and applicable support documents

Section 8.3.5.13 discusses the regulatory basis for the issue and the construction of the complementary cumulative distribution functions (CCDFs). In Table 8.3.5.13-18, Step 7 discusses the construction of a total system simulator and Step 8 discusses the construction of an empirical CCDF.

Parameters

The parameters for this information need are

1. Simplified versions of the mathematical models of the significant scenario classes (from Information Need 1.1.4, Section 8.3.5.13.4).

2. Statistical data and interpretive information sufficient to construct the joint probability distribution for the set of state variables that describes all necessary state variables in the simplified mathematical models of the significant scenario classes. See the introductory material to this section and parameters from Tables 8.3.5.13-9 through 8.3.5.13-17.

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Logic

The simplified mathematical models provided through fulfillment of Information Need 1.1.4 (Section 8.3.5.13.4) will be implemented by efficient computer codes that are then combined in a single calculational model under the control of a driver routine. The driver routine will (1) provide values for state variables for all submodels through Monte Carlo sampling from the joint distribution of the state variables, (2) direct a calculation of the partial performance measure for each submodel, and (3) sum the resulting partial performance measures for each submodel to obtain a sample value of the total system performance measure. By repeatedly sampling in this way, a large number of samples can be generated and used to construct an empirical complementary cumulative distribution function or as a data set to which standard statistical methods for estimating likelihoods with given confidence bounds may be applied.

The joint distribution of state variables will be constructed using judgment guided by the site-specific statistical data and interpretive information mentioned in the foregoing parameter list.

8.3.5.13.5.1 Performance Assessment Activity 1.1.5.1: Calculation of an empirical complementary cumulative distribution function

Objectives

The objective of this performance assessment activity is to construct an efficient, total-system simulator that is capable of providing probabilistic estimates of radionuclide releases to the accessible environment, under both nominal and disturbed conditions, for 10,000 yr after closure. Three sub-activities are included in this activity.

8.3.5.13.5.1.1 Subactivity 1.1.5.1.1: Construction of the total-system simulator

Objectives

The objective of this subactivity is to construct an efficient, total-system simulator.

Parameters

The parameters for this subactivity are efficient, computer-implemented mathematical models of significant scenario classes (see Information Need 1.1.4, Section 8.3.5.13.4) and a synthetic joint probability distribution for the state variables in all submodels sufficient for testing the operation of the total-system simulator.

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Description

A driver routine will be constructed and tested, using submodels and synthetic joint probability distribution. Available variance-reduction techniques will be applied, and the technique most efficient for total-system simulation will be determined.

8.3.5.13.5.1.2 Subactivity 1.1.5.1.2: Construction of the joint probability distribution to be used in the licensing-assessment calculations

Objectives

The objective of this subactivity is to construct a joint probability distribution that incorporates data and interpretive information from the site characterization program.

Parameters

The parameters for this subactivity are given in the parameters list for this information need.

Description

The state variables will be grouped into statistically independent subsets. For each subset of state variables, a multivariate analytical distribution will be chosen, and its parameters fitted by techniques such as maximum-likelihood, using available, site-specific data for the mean annual probabilities and the intensities of the processes and events that determine the state variables.

8.3.5.13.5.1.3 Subactivity 1.1.5.1.3: Construction of an empirical complementary cumulative distribution function for the licensing action

Objectives

The objective of this subactivity is to construct an empirical complementary cumulative distribution function for the licensing application.

Parameters

The parameters for this subactivity are the total-system simulator from Subactivity 1.1.5.1.1 and the joint distribution function from Subactivity 1.1.5.1.2 (Sections 8.3.5.13.5.1.1 and 8.3.5.13.5.1.2).

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Description

By repeated simulation, sample statistics on the total system performance measure, M, will be obtained with a sample size large enough to ensure that proposed 10 CFR 60.112 and 60.115 are (or are not) met with high confidence.

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8.3.5.14 Issue resolution strategy for Issue 1.2: Will the mined geologic disposal system meet the requirements for limiting individual doses in the accessible environment as required by 40 CFR 191.15?

Regulatory basis for the issue

The regulatory basis for limiting individual does from ground water as stated in 40 CFR 191.15 has been vacated by the first district court of appeals (NRDC et al. vs. EPA, 1987) and the EPA has been asked by the court to reevaluate the rule in light of other rules protecting individuals. If and when EPA modifies 40 CFR 191.15, the DOE will reevaluate the plans for resolving Issue 1.2. Until that time, the DOE will proceed with plans to address individual dose limitations as currently covered by the rule now under reevaluation by the EPA.

The relevant parts of 40 CFR 191.15 are quoted in the following:

191.15 Individual protection requirements.

> Disposal systems for spent nuclear fuel or high-level or transuranic radioactive wastes shall be designed to provide a reasonable expectation that, for 1,000 yr after disposal, undisturbed performance of the disposal system shall not cause the annual dose equivalent from the disposal system to any member of the public in the accessible environment to exceed 25 millirems to the whole body or 75 millirems to any critical organ. All potential pathways (associated with undisturbed performance) from the disposal system to people shall be considered, including the assumption that individuals consume 2 L per day of drinking water from any significant source of ground water outside of the controlled area.

In the regulation just given, undisturbed performance means the predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events. The term accessible environment means (1) the atmosphere, (2) land surfaces, (3) surface waters, (4) oceans, and (5) all the lithosphere that is beyond the controlled area, a surface location that encompasses no more than 100 km^2 and extends horizontally no more than 5 km in any direction from the outer boundary of the original location of the radioactive wastes in a disposal system.

In addition, the regulation (40 CFR 191.12) defines the significant source of ground water to mean:

> (1) An aquifer that: (i) Is saturated with water having less than 10,000 milligrams per liter of total dissolved solids; (ii) is within 2,500 feet of the land surface; (iii) has a transmissivity greater than 200 gallons per day per foot, provided that any formation or part of a formation included within the source of ground water has a hydraulic conductivity greater than 2 gallons per day per square foot; and (iv) is capable of continuously yielding at

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least 10,000 gallons per day to a pumped or flowing well for a period of at least a year; or (2) an aquifer that provides the primary source of water for a community water system as of the effective date of this Subpart.

The expected condition of the repository environment is such that no significant amounts of liquid water will be present in and adjacent to the borehole for at least 300 yr after repository closure. For 300 to 1,000 yr after closure, a limited amount of water (i.e., less than 5 liters per package per year for 90 percent of the packages and less than 20 liters per package per year for 10 percent of the packages) may be available to contact some waste containers, although most of the containers are expected to remain in a dry environment for well over 1,000 yr (Section 8.3.4). A limited amount of radionuclides, therefore, may be released from breached containers and transported by ground water to the accessible environment.

Three radionuclides might be able to escape from the breached container as gaseous species under the conditions at Yucca Mountain: carbon-14, tritium, and krypton-85. Of these, only carbon-14 is readily available for rapid release from a breached waste container. The other radionuclides, both of which have short half-lives, are contained within the waste form (Sections 8.3.5.9 and 8.3.5.10). Carbon-14 release is expected to be in the form of carbon-14 dioxide that will percolate up through the pore space in the unsaturated overburden to the accessible environment.

Approach to resolving the issue

There are only two significant pathways for the radionuclides from the waste package to reach humans in the accessible environment (i.e., ground-water transport and gaseous phase transport). These probable flow paths for each transport mechanism lead to quite different and separate exposure sources for any released radionuclides. Therefore, they will be treated separately.

The approach to resolving Issue 1.2 for the ground-water pathway is to determine whether any exposure to the public will result during the 1,000-yr period after disposal (40 CFR 191.15). Because a significant source of ground water might exist at the boundary of the controlled area, the dose calculation will assume that individuals consume 2 liters per day of drinking water at the outside boundary of the controlled area, where the concentration of radionuclides in ground water could be expected to be the highest. For the gaseous pathway, the reference case will examine whether the upper bounding value of the exposure to the public will be less than 25- and 75-mrem/yr dose limits based on the amount of the carbon-14 inventory that can be released in gaseous form. Alternatively, it may be possible to show that the gaseous carbon-14 dioxide may never reach the accessible environment during the 1,000-yr period. The total dose to the individuals will be the sum of the doses through both pathways and it will be compared against the required dose limits. Figure 8.3.5.14-1 illustrates the objective and logic to resolve Issue 1.2.

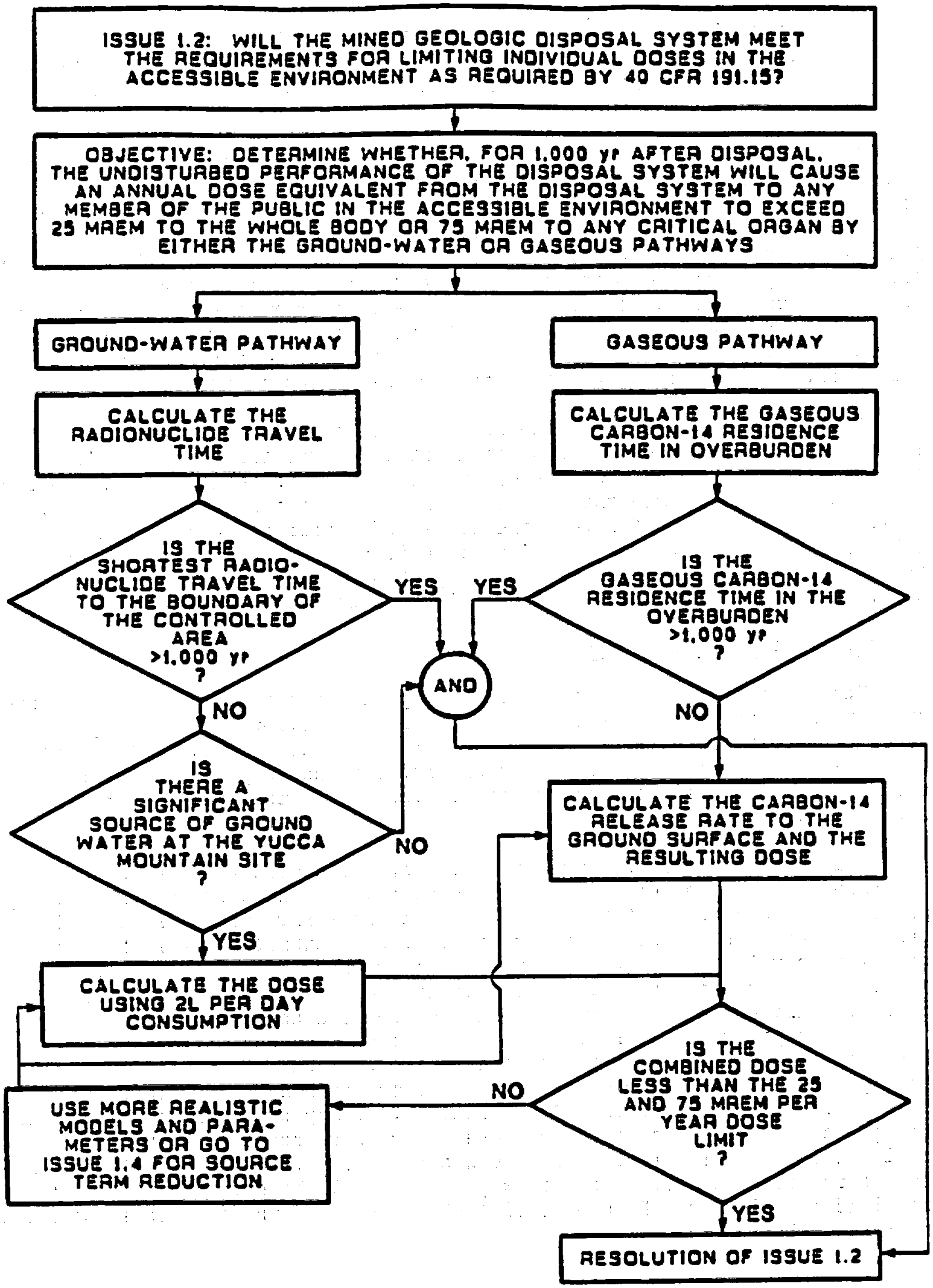

Figure 8.3.5.14-1. Logic diagram for Issue 1.2 (individual protection)

Under the undisturbed conditions of the repository, it is expected that most of the waste packages will remain dry and that the radionuclides will be substantially completely contained in the waste package. Under very conservative assumptions, however (described in Section 8.3.5.9), up to 20 percent of the waste containers may be breached and radionuclides may be released and transported in the ground water through the unsaturated and saturated zones before they reach the accessible environment (Section 8.3.5.13). Sorbing species of the radionuclides would travel slower than the ground-water movement because of retardation, and even the nonsorbing species cannot travel faster than the ground-water movement itself along the path of likely radionuclide travel. For the ground-water pathways, this issue will be resolved if reasonable expectations are established that contaminant transport to the water table exceeds 1,000 yr with high confidence. Current estimates of the ground-water travel time show a mean value of 43,265 yr with a standard deviation of 12,765 yr (Sinnock et al., 1986), thus providing an initial level of confidence that the radionuclide travel time will be longer than 1,000 yr (Section 8.3.5.12).

If the radionuclide transport time is less than 1,000 yr, then the concentration of radionuclides in ground water and its change with time will be calculated using the total system performance model (see Section 8.3.5.13) at the boundary of the controlled area. There may be no significant source of ground water at the outside boundary of the controlled area. However, using the concentration of radionuclides at the boundary of the controlled area and the assumption that individuals consume 2 liters per day of drinking water, the dose to a maximally exposed individual can be calculated. Alternatively, it could be determined that there is no significant source of ground water outside the controlled area but that a source exists within the 1,000-yr radionuclide travel time boundary. If, however, any such source is identified, the same calculation as above can be made for that location. It should be noted that there is another requirement for the site (10 CFR 60.113(a)(2)) that the pre-waste-emplacement ground-water travel time must be at least 1,000 yr. The pre-waste-emplacement ground-water travel time and the radionuclide travel time (post-emplacement) are related but not the same; therefore, a radionuclide travel time that is less than 1,000 yr, although very unlikely, would not necessarily violate the 10 CFR 60.113 requirement (see Section 8.3.5.12).

Both spent fuel and glass waste forms contain carbon-14. The total amount of carbon-14 in the spent fuel is conservatively estimated to be 1.5 Ci/MTHM (metric tons of heavy metal) by actual measurements and analyses (Van Konynenburg et al., 1986). A smaller inventory of carbon-14 is expected for glass waste forms because of the potential for release and transfer to other waste streams during reprocessing. Most of the carbon-14 in the spent fuel is locked inside UO_2 fuel, Zircaloy cladding, and fuel assemblies and will be released slowly after the containment is breached. Only a small fraction of the total carbon-14 inventory in the spent fuel could be rapidly released from the oxidized skin of the Zircaloy cladding by reaction of the oxygen in the atmosphere with the carbon in the cladding oxidation layer (Oversby and McCright, 1985). Oversby and McCright believe that as much as 1 percent of the carbon-14 inventory in spent fuel could be rapidly released in this way during the first 100 to 1,000 yr following closure when high temperature and gamma radiation are expected (Section 8.3.5.9). No rapid release of carbon-14 is known from glass waste forms.

A bounding-case calculation for carbon-14 release can be made as follows: when the repository is completely filled with 70,000 MTHM, the total inventory of carbon-14 will be less than 105,000 Ci; considering that some of the wastes are in glass waste forms, the rapid release fraction of carbon-14 from the entire repository is not likely to exceed 1,000 Ci even if every waste container were breached within 1,000 yr. The goal of the waste-container design limits the container failure to less than 5 percent for the first 300 yr and to less than 20 percent for 1,000 yr after closure. Under a conservative assumption of 20 percent container failure, the total inventory of available carbon-14 for rapid release in gaseous form, therefore, would be less than 200 Ci. The 200 Ci would most likely be released gradually as the containers fail in a time-distributed manner. Even with a total failure of the entire 20 percent of the containers in 1 yr, the maximum release will not exceed 200 Ci in 1 yr, with no further release during the subsequent years, because there will be no more carbon-14 available for rapid release. Evaluation of the inventory and release of carbon-14 from Zircaloy cladding is being investigated in Section 8.3.5.10.

The carbon-14 released from the spent fuel during the initial breach of the container is expected to be in the form of carbon dioxide. Gas-phase carbon-14 dioxide moves upward through air-filled pores in the unsaturated tuffs by molecular diffusion and by advection in a thermally driven air-convection cell. In the course of the upward movement of carbon-14 dioxide, isotopic exchange of carbon-14 with the normal carbon of the carbon dioxide gas in the pore space will occur, thus retarding the movement of the carbon-14 to the atmosphere above the repository. The carbon dioxide gas in the pore space is probably in equilibrium with dissolved bicarbonate in the pore water. Therefore, a large reservoir of normal carbon exists in the unsaturated tuffs and is available for carbon-14 isotopic exchange. In addition, precipitation of calcite, if it occurs, will irreversibly remove carbon-14 from the system. Actual residence times of carbon-14 in the pore spaces of the repository overburden could, in principle, be estimated by solving a transport equation that takes the isotope exchange and chemical models into account. However, site-specific data that would permit realistic estimates of the carbon-14 residence time are lacking.

If the residence time of the carbon-14 in the overburden (the time needed for carbon-14 to travel through the overburden) is established with high confidence to exceed 1,000 yr, this part of Issue 1.2 will be resolved. The mean and standard deviation of the residence time in the overburden of a carbon-14 nucleus that is released at the repository level will be estimated in Section 8.3.1.3.8, and a model for gas-phase releases will be developed in Information Need 1.1.3 (Section 8.3.5.13.3).

A realistic estimate of doses from the gaseous pathway to the public in the accessible environment will have to be based on the gas-phase release estimated from Information Need 1.1.3 (Section 8.3.5.13.3). For the resolution of Issue 1.2, however, a bounding-value calculation will be used. The inventory of carbon-14 available for rapid release, a total of 200 Ci for 1,000 yr, is small compared with (1) an average release of 5 to 10 Ci from each operating nuclear power plant (boiling water and pressurized water reactors) into the atmosphere every year and (2) the design-basis release of approximately 800 Ci/yr from a 1,500-MTHM/yr fuel-reprocessing plant. Because of the very small dose consequences expected from the assumed release

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of carbon-14 through the repository overburden, bounding calculations will be done for a hypothetical maximally exposed individual on the ground surface above the repository assuming a ground-level release of the total 200 Ci in one year. Internal dose from ingestion has not been calculated because of the lack of site-specific data. This dose is, however, expected to be significantly smaller than the inhalation dose because of the lack of vegetation at the Yucca Mountain site.

Unless this issue has been resolved by having both the radionuclide travel time (liquid pathway) and residence time of carbon-14 in the overburden greater than 1,000 yr, doses from the individual pathways will be summed to see if the goal is met. At present, there is a high confidence that the goal can be met with the current design of the waste package and the site geohydrologic conditions. If, however, the goal has not been met, the source term for the radionuclide release can be reduced by a more realistic (less conservative) assessment of the dose pathways to the individuals or by alternative designs of the waste package (Section 8.3.5.9).

A preliminary performance allocation for this issue is summarized in Table 8.3.5.14-1. Because Issue 1.2 concerns only the undisturbed performance of the disposal system with respect to individual protection from radiation, it is appropriate to allocate performance against the expected pathways. A goal is set for the liquid pathways for near-zero release; it calls for the radionuclide travel time to exceed 1,000 yr. More detailed performance measures and their goals are set for the gaseous pathway. No significant external dose is expected from the weak beta radiation from carbon-14 through the skin. The only significant pathways for internal dose are through inhalation of carbon-14 dioxide in breathing air and ingestion of carbon-14-containing food items grown in the area. Specific goals based on the preliminary analysis are established with a high confidence for the internal doses by inhalation and ingestion. A goal is also set for the residence time of gaseous carbon-14 in the overburden.

Table 8.3.5.14-1 also illustrates the relationship between the performance measures and the parameters. Table 8.3.5.14-2 identifies the characterization parameters needed to determine the transport of carbon-14 dioxide on the surface above the repository.

Interrelationships of information needs

Two information needs have been identified for Issue 1.2: Information Need 1.2.1 determines the doses through the ground-water pathway, using the same methodology as that used for Issue 1.1, total system releases. The second information need (1.2.2) determines the internal and external doses to the public in the accessible environment through the gaseous pathway of carbon-14.

8.3.5.14-1. Performance allocation for Issue 1.2 (individual protection)

Release scenario class	Pathway	Primary barriers	Performance measure	Tentative goal	Needed confidence
Nominal (expected)	Significant ground-water source	Unsaturated zone and saturated zone	Individual dose (whole body)	Near zero (dose much less than standards)	High
	Gaseous phase	Waste container and overburden	Individual dose (whole body)		High
			External	Near zero	High
			Internal		
			Inhalation	<5 mrem/yr	High
			Ingestion	<5 mrem/yr	High

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8.3.5.14-2. Performance parameters for Issue 1.2 (individual protection)

System element relied on	Function	Process or conditions	Performance measure	Performance parameter	Tentative parameter goal	Needed confidence	SCP section providing expected parameter values	Current confidence	Investigations supplying parameter
Unsaturated zone and saturated zone below the repository (ground-water transport)	Retardation of radionuclide movement in ground water	Porous-media transport through matrix and adsorptive retardation	Individual dose	Ground-water[a] travel time	>1,000 yr	High	3.9.4	Low	4.3.5.12.4
				Retardation	>1	High	4.1.3.3	Medium	8.3.1.3.4
Overburden (gaseous phase transport)	Retardation of movement of gaseous nuclides	Isotope exchange, chemical equilibrium and pre-cipitation	Individual dose	Residence time of carbon-14 in over-burden	>1,000 yr	High	None	Low	8.3.1.3.4
Waste form (gaseous phase transport)	Containment and controlled release of gaseous nuclides	Distribution of radio-nuclides and con-tainment	Individual dose	Inventory of rapid release fraction of carbon-14	<1,000 Ci	High	7.4.3.1	Low	8.3.5.10.2

[a]Ground-water travel time is used as a measure of the radionuclide transport time to the boundary of the accessible environment.

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8.3.5.14.1 Information Need 1.2.1: Determination of doses to the public in the accessible environment through ground-water transport

Technical basis for addressing the information need

Link to the technical data chapters and applicable support documents

The information needed to satisfy this information need and the methodology to be used are basically the same as that used for Section 8.3.5.13, total system performance.

Parameters

The parameters needed to satisfy this information need are the same as those required for Information Need 1.1.4, Section 8.3.5.13.4. Specifically, these parameters include:

1. Flux through the unsaturated zone (also from Section 8.3.5.12.4).

2. Retardation through the unsaturated zone (also from Section 8.3.1.3.4).

3. Dose conversion factors (standard values).

4. Determination of whether a significant source of ground water is present or absent (information from Section 8.3.5.15.1.1.2 will be used).

Logic

This information need addresses the movement of radionuclides through the ground water to the accessible environment. The parameters needed and the methodology to be used to satisfy this information need are similar to those used to determine the total releases to the accessible environment under expected conditions. The difference between this issue and Issue 1.1 is that the parameters and scenarios to be considered for this issue will cover only the first 1,000 yr after closure under expected conditions, whereas Issue 1.1 (Section 8.3.5.13) will cover releases over 10,000 yr under expected and unexpected conditions. Radionuclide releases will be determined from the engineered barrier system, and contaminant transport will be considered through the unsaturated zone to the water table. Because the ground-water travel time through the unsaturated zone is expected to be much greater than 1,000 yr, this issue will initially examine the transport to the water table. If the ground-water travel time to the water table through the unsaturated zone is less than 1,000 yr, then the ground-water travel time to the boundary of the controlled area and the change in radionuclide concentration in a significant source of ground water at the boundary will be calculated for the dose evaluation.

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8.3.5.14.1.1 Activity 1.2.1.1: Calculation of doses through the ground-water pathway

Objectives

The objective of this activity is to use the methodology applied in Section 8.3.5.13 to calculate the radionuclide transport to the boundary of the controlled area.

Parameters

See the general parameters list for this information need.

Description

This activity will obtain from Information Need 1.1.4 the distribution of radionuclides transported to the boundary of the controlled area during the first 1,000 yr after closure. Only expected conditions will be considered for this analysis. The radionuclide transport model used to make this evaluation will be verified and validated under Issue 1.1. The concentration of radionuclides in the ground water at the boundary of the controlled area and the assumption that individuals consume 2 liters per day of drinking water from a significant source of ground water at the controlled area boundary will be used to calculate the individual dose. The results of this evaluation will be presented in a report.

8.3.5.14.2 Information Need 1.2.2: Determination of doses to the public in the accessible environment through the gaseous pathway

Technical basis for addressing the information need

Link to the technical data chapters and applicable support documents

The following sections of Chapter 8 summarize the information relevant to this information need.

Chapter 8 section	Short title
8.3.1.12	Meteorology
8.3.5.3	Public radiological exposures--normal conditions
8.3.5.13	Total system performance

Sections 8.3.5.9 and 8.3.5.10 will establish that carbon-14 is the only important gaseous radionuclide that can be transported to the accessible environment through the gaseous pathway and also will establish the maximum inventory of carbon-14 for rapid release. Since a bounding-value calculation

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is believed to be sufficient to resolve this issue, time distribution of container failure from Information Need 1.4.4 (Section 8.3.5.9.4) will not be used here.

Parameters

Most of the parameters needed to satisfy this information need are obtained from other information needs as noted in the following list:

1. Important gaseous radionuclides (Section 8.3.5.10.1).
2. Inventory and release of gaseous radionuclides (Section 8.3.5.10.2).
3. Retardation of gaseous flow through the overburden (Section 8.3.5.13.3).
4. Site meteorological data (Section 8.3.1.12.2).
5. Offsite activities for ingestion and inhalation scenarios (Section 8.3.1.13).
6. Dose conversion factors (standard published values).

Logic

Releases of gaseous radionuclides will be determined by using a two-step process. The first step involves examining the retardation of gaseous flow of carbon-14 dioxide through the overburden. This step will use the same parameters and methodology as used to address Issue 1.1, total system performance, with the exception that this issue considers only expected conditions over the first 1,000 yr following disposal. The second step involves examining inhalation and ingestion rates when the carbon-14 dioxide reaches the surface. This step will be performed only if it is determined that the goal for gaseous retardation through the overburden cannot be achieved with a high level of confidence.

For a given radionuclide, when the release rate, wind speed, and dispersion coefficients are known, it is a straightforward calculation to obtain the external and internal inhalation doses with standard dose-conversion factors. Inhalation dose is expected to be the overwhelming component of the potential dose from carbon-14 releases. Uptake by ingestion, however, greatly depends upon local vegetation and agricultural activities and can vary significantly from area to area even for the same amount of release. No significant agricultural activities are currently present at the Yucca Mountain area, and the expected conditions for 1,000 yr in the area can be assumed in order to estimate the ingestion dose. Since the dose rate will be highest at the land surface, only one calculation for a hypothetical maximally exposed person will be required to resolve this information need.

Two activities are planned to calculate doses to the public in the accessible environment through the gaseous pathway. The second activity will be performed only if it is determined that the goal for gaseous retardation through the overburden cannot be achieved with a high level of confidence.

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8.3.5.14.2.1 Activity 1.2.2.1: Calculation of transport of gaseous carbon-14 dioxide through the overburden

Objectives

The objective of this activity is to estimate the transport time for gaseous carbon-14 dioxide from the repository to the land surface during the first 1,000 yr after disposal.

Parameters

Parameters 1, 2, and 3 identified under Information Need 1.2.2 are required for this activity.

Description

This activity will obtain from Information Need 1.1.4 the distribution of gaseous radionuclides transported through the overburden to the land surface during the first 1,000 yr after disposal. Only expected conditions will be considered for this analysis. The results of this evaluation will be presented in a final report on doses to the public in the accessible environment through gaseous phase transport.

8.3.5.14.2.2 Activity 1.2.2.2: Calculation of land-surface dose and dose to the public in the accessible environment through the gaseous pathway of carbon-14

Objectives

The objectives of this activity are to collect the necessary data on carbon-14 inventory and meteorology and to calculate upper bound values for external and internal doses. The latter objective includes doses from both inhalation and ingestion.

Parameters

See the general parameter list for this information need.

Description

This activity will extract the carbon-14 inventory data from Information Need 1.5.2 (Section 8.3.5.10.2) and calculate the dispersion coefficients and wind speed from meteorological data from Section 8.3.1.12.1. This activity will also calculate the expected and upper bound internal and external doses to a hypothetical maximally exposed person on the land surface above the repository. The AIRDOS-EPA program or other appropriate programs will be used for the dose calculation. Model verification and validation are discussed in the Project Radiological Monitoring Plan (Section 8.3.5.3). The results will be presented in a report.

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8.3.5.15 Issue resolution strategy for Issue 1.3: Will the mined geologic disposal system meet the requirements for the protection of special sources of ground water as required by 40 CFR 191.16?

Regulatory basis for the issue

The regulatory basis for protection of special sources of ground water as stated in 40 CFR 191.16 has been vacated by the first district court of appeals (NRDC et al. vs. EPA 1987), and the EPA has been asked by the court to reevaluate the rule in light of other rules protecting ground water. If and when the EPA modifies 40 CFR 191.16, the DOE will reevaluate the plans for resolving Issue 1.3. Until that time, the DOE will proceed with plans to address ground-water protection as currently covered by the rule now under reevaluation by EPA.

The parts of 40 CFR 191.16 relevant to Issue 1.3 are quoted in the following:

191.16 Ground water protection requirements

(a) Disposal systems for spent nuclear fuel or high-level or transuranic radioactive wastes shall be designed to provide a reasonable expectation that, for 1,000 yr after disposal, undisturbed performance of the disposal system shall not cause the radionuclide concentrations averaged over any year in water withdrawn from any portion of a special source of ground water to exceed:

(1) 5 picocuries per liter of radium-226 and radium-228;

(2) 15 picocuries per liter of alpha-emitting radionuclides (including radium-226 and radium-228 but excluding radon); or

(3) The combined concentrations of radionuclides that emit either beta or gamma radiation that would produce an annual dose equivalent to the total body or any internal organ greater than 4 millirems per year if an individual consumed 2 liters per day of drinking water from such a source of ground water.

(b) If any of the average annual radionuclide concentrations existing in a special source of ground water before construction of the disposal system already exceed the limits in 191.16(a), the disposal system shall be designed to provide a reasonable expectation that, for 1,000 years after disposal, undisturbed performance of the disposal system shall not increase the existing average annual radionuclide concentrations in water withdrawn from that special source of ground water by more than the limits established in 191.16(a).

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In the previous regulations, undisturbed performance means the predicted behavior of a disposal system, including consideration of the uncertainties in predicted behavior, if the disposal system is not disrupted by human intrusion or the occurrence of unlikely natural events.

An aquifer must meet several criteria to be designated as a special source. The first step in the evaluation is to establish whether the aquifer is a Class I source as defined by the EPA Ground Water Protection Strategy of 1984 (EPA, 1984). The conditions that must be met for designation as a Class I source are (1) that the source is highly vulnerable to contamination because of the hydrologic characteristics and (2) that the source is irreplaceable in that no reasonable alternative is available to substantial populations or that the source is ecologically vital in that it provides baseflow to a sensitive ecological system.

If an aquifer meets the criteria for a Class I source, the next step is to determine whether it qualifies as a special source of ground water. 40 CFR 191.12 defines a special source of ground water as

> those Class I ground waters identified in accordance with the agency's Ground-Water Protection Strategy . . . that: (1) are within the controlled area encompassing a disposal system or less than 5 km beyond the controlled area [the controlled area is the actual area chosen according to the 40 CFR 191.12 definition of the controlled area]; (2) are supplying drinking water for thousands of persons as of the date that the [DOE] chooses a location within that area for detailed characterization as a potential site for a disposal system (e.g., in accordance with Section 112(b)(1)(B) of the Nuclear Waste Policy Act); and (3) are irreplaceable in that no reasonable alternative source of drinking water is available to that population.

Approach to resolving the issue

The approach to resolving this issue consists of a series of determinations and decision points, any one of which could result in an affirmative resolution. As shown in the logic diagram for this issue (Figure 8.3.5.15-1), the first decision is whether Class I or special sources of ground water exist in the vicinity of Yucca Mountain as determined by comparing the criteria with the hydrogeologic, demographic, and ecologic characteristics of the site and its contiguous vicinity. If Class I or special sources are found not to exist, the issue is resolved affirmatively.

If a Class I source exists, the Yucca Mountain Project will proceed to evaluate whether the Class I ground water is also a special source of ground water. If so, the concentration of waste in special-source ground water must remain below the limits specified in 40 CFR 191.16. The approach is first to determine whether slow ground-water movement alone can ensure meeting the limits. If neither path can provide this assurance, the Yucca Mountain Project will conduct transport modeling to test whether concentrations in special-source ground water will remain below the established limits.

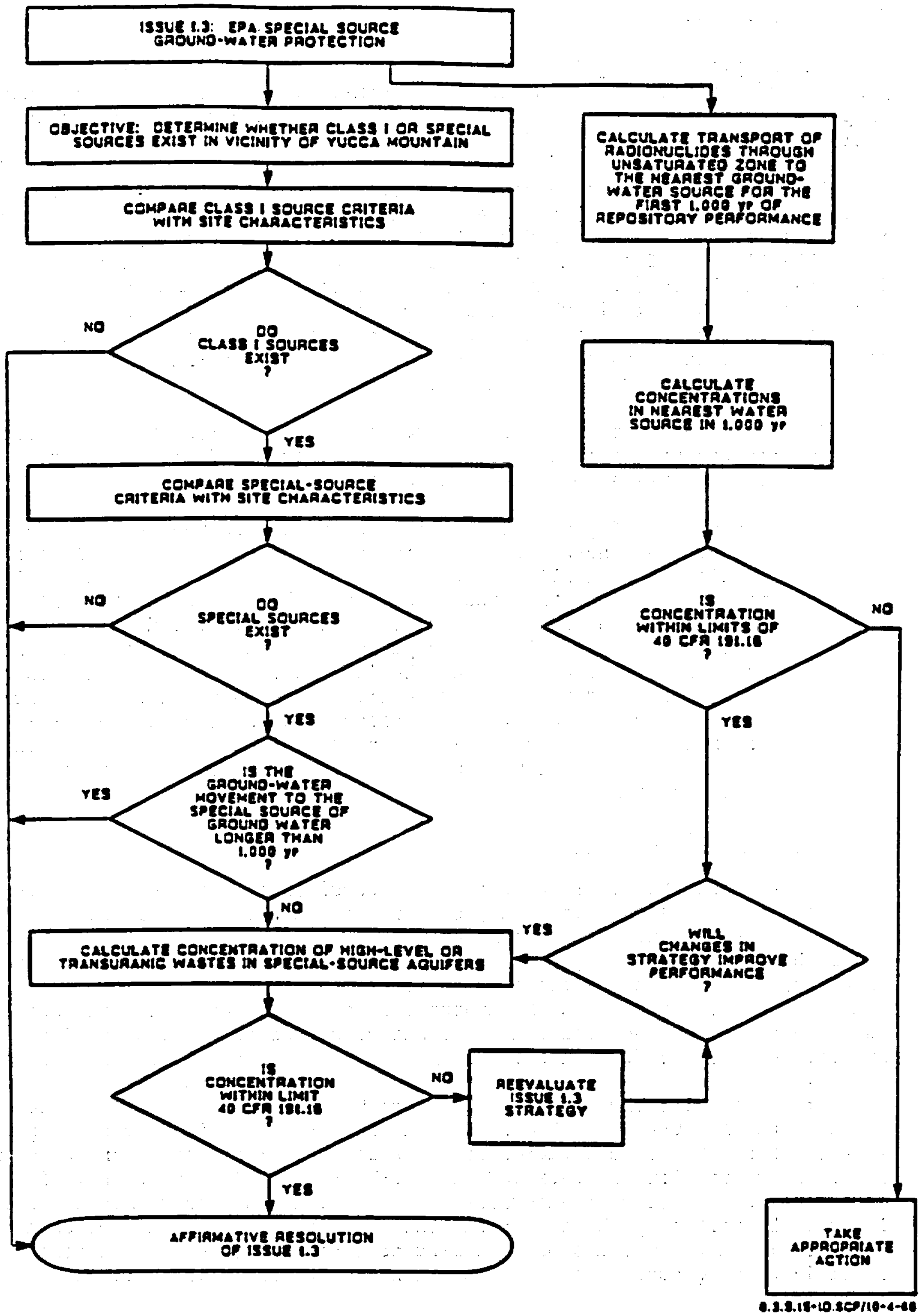

Figure 8.3.5.15-1. Logic diagram for Issue 1.3 (ground-water protection).

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These two fundamental questions (i.e., whether special sources exist, and whether contamination of a special source will be below the 40 CFR 191.16 limits) are the basis for defining two information needs:

1.3.1 Determine whether any Class I or special sources of ground water exist at Yucca Mountain, within the controlled area, or within 5 km of the controlled area boundary.

1.3.2 Determine for all special sources whether concentrations of waste products in the ground water during the first 1,000 yr after disposal will not exceed the limits established in 40 CFR 191.16.

Performance allocation for Issue 1.3

A preliminary performance allocation for this issue (1.3) is summarized in Table 8.3.5.15-1. Because this issue is concerned with the protection of special ground-water sources from contamination, it is appropriate to first establish whether a Class I or special ground-water source exists. If no special sources exist, then the issue is resolved. If a special source is identified at or near the site, this issue could be resolved by establishing that the concentrations of waste products in the special source are likely to be much less than allowed by EPA limits. The relationship between the performance measures and the required parameters is illustrated in Table 8.3.5.15-1.

Interrelationships of information needs

Two information needs have been identified for this issue; the first is the determination whether a Class I or special source of ground water exists at or in the vicinity of the Yucca Mountain site. If a special source aquifer is identified during site characterization, a second information need will be addressed to determine whether concentrations of waste in the ground water could exceed the limits established by 40 CFR 191.16.

8.3.5.15.1 Information Need 1.3.1: Determination whether any Class I or special sources of ground water exist at Yucca Mountain, within the controlled area, or within 5 km of the controlled area boundary

Technical basis for addressing the information need

Link to the SCP technical data chapters and applicable support documents

The following sections of Chapter 3 of the SCP (Hydrology) summarize the data relevant to this information need:

Table 8.3.5.15-1. Performance allocation for Issue 1.3 (ground-water protection)

Performance measure	Goal	Needed confidence	Performance parameters	Goal	Modifier	Current estimate	Current confidence	Needed confidence
Existence of special source of ground water	No special source	High	Existence of aquifers within 5 km of controlled area[b]	NA[a]	Valley fill (VF) Tuff (T) Lower carbonate (LC)	Exists Exists Exists	High High High	High High High
			Aquifer vulnerability to contamination	Not vulnerable within 10,000 yr	VF, T, LC	Not vulnerable within 20,000 yr	Low	Medium
			a. Population served or b. Baseflow to sensitive ecological system	<substantial None	VF T LC VF T LC	>3,000, < 5,000 <1,000 ~500 None None Exists	High Medium Medium Medium Medium Medium	High High High High High High
			Population served	<thousands	VF T LC	>3,000, <5,000 <1,000 ~500	High Medium Medium	High High High
			Existence of reasonable alternative source	Exists	VF T LC	Does not exist Exists Does not exist	Low Medium Low	High High Medium
Waste concentration in special source aquifer within 1,000-yr after disposal	<limits of 40 CFR 191.16 for 1,000 yr	High	Concentration of specified constituents as function of time	<limits specified in 40 CFR 191.16 for 1,000 yr	VF, T, LC	Meets goal	Low	High

[a]NA = not applicable.
[b]Controlled area is the actual area chosen according to the 40 CFR 191.12 definition of controlled area.

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SCP section	Subject
3.6	Regional hydrogeologic reconnaissance of candidate area and site
3.7	Regional ground-water flow system
3.8	Ground-water uses
3.9	Site hydrogeologic system

The information contained in these sections supports a preliminary determination that no potential special sources of ground water are present at the site, below the site, within the boundaries of the controlled area, or within 5 km of the controlled area boundary. The following discussion is a brief compilation of this information from Chapter 3 of the SCP.

All the aquifers meet the criterion for location. The tuff aquifer and the lower carbonate aquifer both underlie the proposed repository location. The valley-fill aquifer is located within 5 km of the controlled area (Chapter 3 of the SCP) and was the only aquifer in the Yucca Mountain area serving a population of thousands of persons at the time that the site was chosen for characterization (Section 3.8 of the SCP). Within the Amargosa Desert where the valley-fill aquifer is used, it is underlain by the Paleozoic rocks of the lower carbonate aquifer.

The lower carbonate aquifer is considered an irreplaceable source because it supplies baseflow to the Ash Meadows region in southern Nye County (Dudley and Larson, 1976), which has been designated a critical habitat for several species of endangered fish. The Ash Meadows area, however, is part of a different ground-water subbasin (Ash Meadows) from the Alkali Flat-Furnace Creek Ranch ground-water subbasin, which contains Yucca Mountain (Section 3.6). Evaluations of the hydrologic feasibility of developing the lower carbonate aquifer must consider the possibility of interbasin diversion of this baseflow (Section 8.3.1.9.2).

It is presently considered, with a medium level of confidence, that none of the three aquifers is vulnerable to contamination within 1,000 yr after emplacing waste at Yucca Mountain, based on the hydraulic and geochemical characteristics of the thick unsaturated zone that would contain the repository. In addition to its protection by the thick unsaturated zone, the lower carbonate aquifer has a higher potentiometric head than does the tuff aquifer in the vicinity of the site, according to data obtained from drillhole UE-25p#1 (Craig and Robison, 1984). Therefore, the potential or tendency for flow is upward from the lower carbonate aquifer rather than downward into it. Both the lower carbonate and tuff aquifers crop out in limited areas of rugged terrain, indicating the potential for contamination directly into these aquifers from future human activities is slight. However, a low level of confidence is assigned (Table 8.3.5.15-1) to this determination for the valley-fill aquifer because (1) the valley-fill materials occur at the surface over broad areas and (2) the designation of a Class I source is not restricted to its vulnerability to contamination from the proposed repository (EPA, 1984).

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Parameters

Most of the cultural parameters (i.e., demographic and water-use data) needed to complete this information need relative to potential special sources have already been obtained from preliminary investigations. Further investigations being carried out as part of the geohydrology test program will provide confirmatory hydrologic data needed to raise the confidence level of the preliminary finding. The main parameters to be confirmed are

1. The degree and location(s) of hydraulic communication between the aquifers of the flow system (Investigation 8.3.1.2.3).

2. The potential for contamination of the aquifers from the mined geologic disposal system (Investigation 8.3.1.2.1).

3. Refined demographic information on local ground-water users (Investigation 8.3.1.9.2).

Logic

There are four criteria that must be met in order to classify an aquifer as a special source. One of the criteria (that the aquifers are located within the controlled area or within 5 km of the controlled area boundary) has been established with a high level of confidence. The three remaining parameters will need to be known with greater certainty to resolve this issue.

One analysis, which consists of two activities, is planned to evaluate the data that will be obtained from the geohydrology and human interference programs. This analysis will be a synthesis of the required information and will present the final evaluation of the three subject aquifers against the regulatory criteria.

8.3.5.15.1.1 Analysis 1.3.1.1: Determine whether any aquifers near the site meet the Class I or special source criteria

This analysis consists of two synthesis activities that will obtain required parameter values from Investigations 8.3.1.2.1 and 8.3.1.2.3, which are part of the postclosure geohydrologic programs. Additional information will be taken from Investigation 8.3.1.9.2, which is a part of the human activities program.

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8.3.5.15.1.1.1 Activity 1.3.1.1.1: Synthesis and evaluation of hydrologic and environmental information needed to determine whether aquifers at the site meet the special source criteria

Objectives

The objectives of this activity are (1) to raise the confidence levels of the previously obtained hydrologic and environmental data and (2) to analyze these data in order to evaluate whether any aquifers at or near Yucca Mountain meet the criteria for designation as a Class I or special source of ground water.

Parameters

The parameters that will be obtained and evaluated are the location(s) and degree of hydraulic communication between the aquifers and the expected susceptibility of the aquifers to contamination from the mined geologic disposal system.

Description

This activity will extract its parameters from Investigations 8.3.1.2.1, 8.3.1.2.3, and 8.3.1.9.2, which are needed to raise the confidence on the determination whether any special source of ground water exists at or near the Yucca Mountain site. The results of the synthesis will be evaluated in conjunction with data obtained from Activity 1.3.1.1.2 (Section 8.3.5.15.1.1.2) and will be presented in a report.

8.3.5.15.1.1.2 Activity 1.3.1.1.2: Synthesis and evaluation of demographic and economic data needed to determine whether Class I or special sources of ground water exist

Objectives

The objectives of this activity are (1) to obtain refined demographic data on water use needed to establish the number of users from each aquifer at the time Yucca Mountain was selected for site characterization and (2) to examine the economic feasibility of development of the lower carbonate aquifer for alternative water supply to local populations.

Parameters

The parameters that will be obtained and evaluated are population data and locations, depths, and completion dates for all wells within the boundaries of the hydrogeologic study area (Chapter 3 of the SCP introduction). Information on short-term water demand, water supply, and projected socioeconomic conditions will be obtained (Section 8.3.1.9.2.2.1) and evaluated to determine the economic feasibility of developing the lower carbonate aquifer.

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Description

This synthesis activity will obtain data from Section 8.3.1.9.2.2.1 (human interference program) in order to evaluate the site aquifers against the criteria for special source status. These criteria are (1) population served at the time Yucca Mountain was selected for site characterization and (2) presence of alternative water supplies.

8.3.5.15.2 Information Need 1.3.2: Determine for all special sources whether concentrations of waste products in the ground water during the first 1,000 yr after disposal could exceed the limits established in 40 CFR 191.16

Technical basis for addressing the information need

Link to the SCP technical data chapters and applicable support documents

Section 8.3.5.13 (Issue 1.1, total system performance) presents the data and methods relevant to this information need. The information contained in this section supports the preliminary determination that concentrations of contaminants in the ground water during the first 1,000 yr after disposal will not exceed the limits established in 40 CFR 191.16.

Parameters

The parameters needed to satisfy this information need will be obtained from other studies, in particular from the geohydrology program (Section 8.3.1.2) and the total system performance issue (Section 8.3.5.13). The main parameters are (1) concentration of existing contaminants in all potential special source aquifers identified by Analysis 1.3.1.1 and (2) total system performance over the next 1,000 yr.

Logic

This information need will be investigated only if it is determined that a special source of ground water exists within 5 km of the controlled area at Yucca Mountain (Figure 8.3.5.15-1).

8.3.5.15.2.1 Analysis 1.3.2.1: Determine the concentrations of waste products in any special source of ground water during the first 1,000 yr after disposal

This analysis consists of one activity that will calculate the concentration of waste products in any special-source aquifers during the first 1,000 yr after disposal.

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8.3.5.15.2.2 Activity 1.3.2.1.1: Synthesis and evaluation of releases of waste products to special sources of ground water during the first 1,000 yr after disposal

Objectives

The objective of this activity is to determine the quantity of waste products that could be released and transported to a special source of ground water during the first 1,000 yr after disposal.

Parameters

The parameters that will be obtained are the releases to the accessible environment under expected conditions over the first 1,000 yr after disposal.

Description

This study will obtain information directly from studies associated with Issue 1.1 (total system performance, Section 8.3.5.13). The difference between this issue and Issue 1.1 is that the parameters and scenarios to be considered in this issue will only cover the first 1,000 yr after disposal under expected conditions, whereas Issue 1.1 examines releases over 10,000 yr under expected and unexpected conditions. No additional information is requested under this activity.

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8.3.5.16 Issue resolution strategy for Issue 1.7: Will the performance-confirmation program meet the requirements of 10 CFR 60.137?

Regulatory basis for the issue

Issue 1.7 addresses the NRC requirements for performance confirmation. 10 CFR 60.137 requires that the repository be designed to permit implementation of a performance confirmation program in accordance with the requirements of Subpart F of 10 CFR Part 60. Subpart F gives both general and specific requirements for a program directed toward confirming that the actual subsurface conditions and changes in those conditions during construction and operations are within the limits specified in the license application (10 CFR 60.140(a)(1)), and that the natural and engineered systems are functioning as intended and anticipated (10 CFR 60.140(a)(2)). The program is to be started during site characterization and continued until permanent closure (10 CFR 60.140(b)). Specific data collection activities are required, and subsurface conditions are to be evaluated and compared with the original (license application) design bases and assumptions to determine if changes are needed in design to accommodate actual field conditions encountered (10 CFR 60.141). Differences and changes must be reported to the NRC (10 CFR 60.141(a)). The program must also test the effectiveness of engineered portions of the repository (10 CFR 60.142), and the waste packages (10 CFR 60.143). The construction authorization from the NRC will incorporate provisions requiring that the DOE provide additional information during construction with respect to (1) differences between actual conditions and the repository design basis (provided in the license application), (2) any deficiencies in the design and construction that could adversely affect safety, and (3) research and development results intended to resolve safety issues (10 CFR 60.32(b)). The performance confirmation program will be designed to address appropriate portions of these information requirements.

As defined in 10 CFR Part 60.2,

> performance confirmation means the program of tests, experiments, and analyses which is conducted to evaluate the accuracy and adequacy of the information used to determine with reasonable assurance that the performance objectives for the period after permanent closure will be met.

The repository must be designed so as to permit the performance confirmation program to be implemented (10 CFR 60.137), and the program must include tests that the NRC deems appropriate (10 CFR 60.74(b)). A performance confirmation plan will be available in the same time frame as the license application to guide the development and implementation of the program.

The DOE considers that the repository conditions and design assumptions integral to demonstrating compliance with the postclosure performance objectives should be the primary subject of the performance confirmation program. In addition, the validity of models and the assumptions and uncertainties associated with their application to demonstrate compliance with these objectives are crucial aspects to be addressed by the performance confirmation program. These aspects are also discussed in Section 8.3.1.1 (overview of the site program) and Section 8.3.5.20 (analytical techniques requiring significant development). The DOE has specified that collection of data and

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performance of analyses to support the license application be adequate to quantify site performance and demonstrate that conceptual model(s) adequately represent relevant processes. This requirement was used to determine which data collection and analysis activities must be completed prior to submittal of the license application and which should be continued, as part of the performance confirmation program, to confirm the assumptions presented in the license application. The portion of the performance confirmation program that succeeds the license application will be designed to confirm that the models chosen from the suite of alternatives continue to be the alternatives most consistent with site data. This is consistent with the requirements of 10 CFR 60.140(a)(1) and (2). The confirmation program implemented following submittal of the license application will be based on tests begun during site characterization and continuing in various forms through permanent closure.

For purposes of implementing 10 CFR 60 Subpart F, the DOE has established a performance confirmation program consisting of two phases (shown schematically in Figure 8.3.5.16-1): (1) a baseline phase ending with the submittal of the license application for construction authorization (10 CFR 60.140(d)(2)), and (2) a confirmation phase that begins with the submittal of the license application and ends with the approval of the license amendment for permanent closure (10 CFR 60.51). The confirmation phase is subdivided into three periods: (1) an interim period, ending with the issuance of the construction authorization, during which performance confirmation activities will be consistent with the requirements of 10 CFR 60.140(d)(2); (2) the construction period, ending with the issuance of the license to accept waste, during which the appropriate requirements of 10 CFR 60.141 and 60.142 will be addressed; and (3) the operation period, ending with the license amendment for permanent closure, during which the confirmation activities under 10 CFR 60.141 and 60.142 will be continued and additional testing and monitoring will be initiated to meet the intent of 10 CFR 60.143. The performance confirmation program ends with the issuance of the license amendments for closure (10 CFR 60.51) and license termination (10 CFR 60.52).

<u>Technical background and licensing strategy</u>

The performance confirmation program is the program of testing, analysis, and monitoring activities required to confirm assumptions regarding the subsurface conditions at the site and the functioning of the engineered and natural systems as predicted by the performance assessment calculations presented in the license application. At the time of license application submittal, sufficient information must be provided to allow the commission to determine, with reasonable assurance, that the geologic repository will not pose unreasonable risk to the health and safety of the public. Understanding of the site and confidence in the ability to predict the performance of the site and engineered barriers will increase as the project progresses. The purpose of the performance confirmation program (which will be continued until permanent closure) is to supply added confidence, beyond that supplied in the license application, that the actual subsurface conditions are within the limits assumed for the geotechnical and design parameters in the license application and that the engineered and natural systems of the repository are functioning as anticipated to meet the long-term performance objectives for containment and isolation.

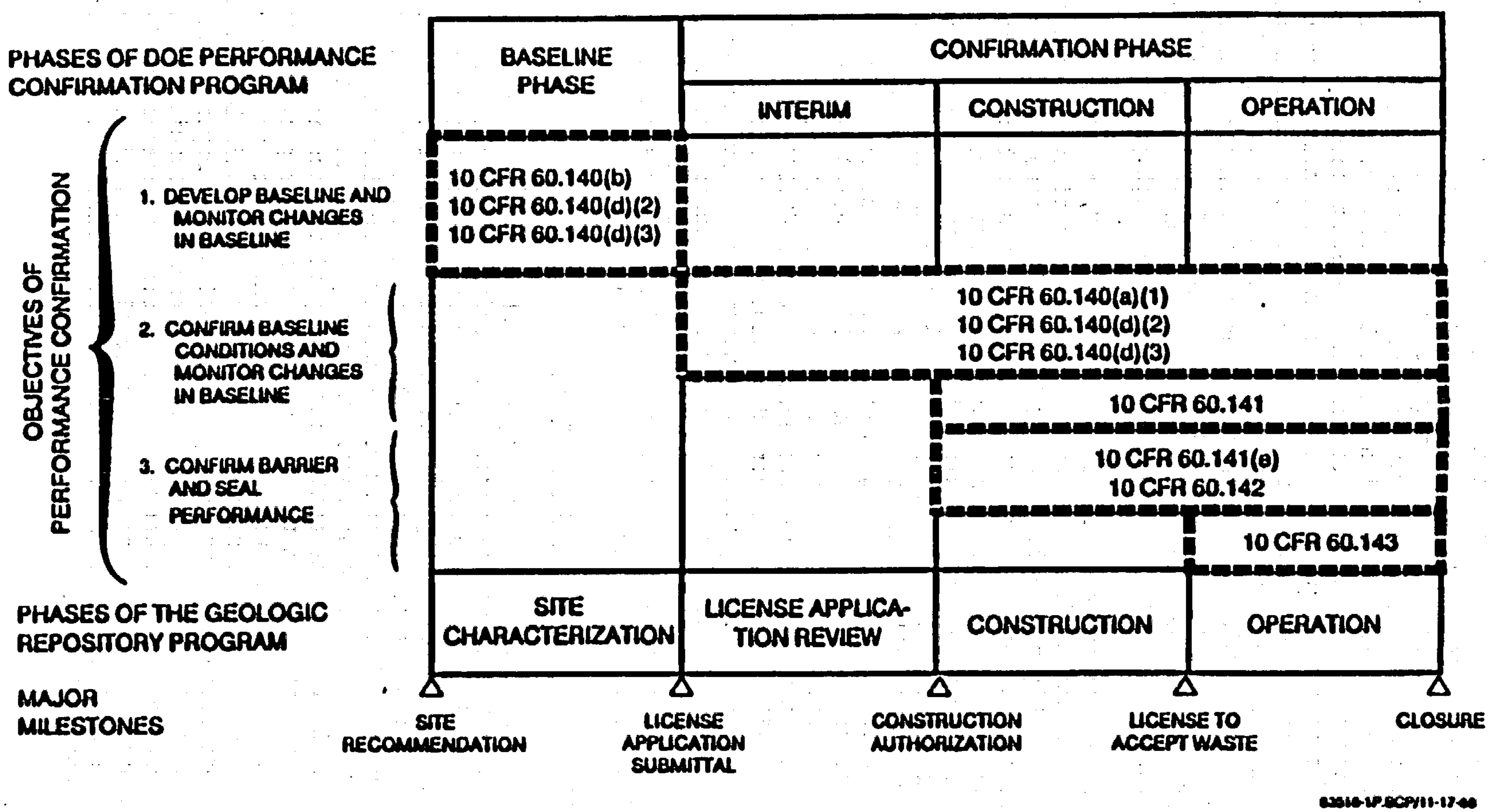

Figure 8.3.5.16-1. Correlation between the phases and objectives of the DOE's performance confirmation program, phases of the repository program, and NRC requirements driving the objectives

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The DOE's performance confirmation program, as discussed later in more detail, consists of a baseline phase that includes collection of data that is a subset of the data collected during site characterization and a subsequent confirmation phase that involves the testing and monitoring needed to add additional confidence to the assumptions and performance assessments provided in the license application. The DOE's position is that the subset of the site characterization activities presently planned to obtain and evaluate baseline information on conditions at the site, and to monitor and analyze changes from these conditions as a result of site characterization, meets the requirements of 10 CFR 60.140(d)(2) and (3) for that part of the performance confirmation program that could reasonably be expected to begin during site characterization. Therefore, no performance confirmation activities for the baseline phase have been specified in addition to the site characterization activities already planned. The information and data needs identified through the performance allocation process represent the baseline information on site parameters and natural processes that will be obtained during site characterization.

During site characterization, information is gathered (1) to evaluate the suitability of the site, (2) to develop a suitable design, and (3) to make defensible performance assessments to establish with reasonable assurance that the performance objectives will be met. Most of the postclosure performance issues have been designed to address the NRC's performance objectives. Through the activities undertaken to support resolution of these issues (Issue 1.1 through 1.6), information will be made available to demonstrate compliance with the related performance objectives. The DOE's issue resolution strategy, as described in Section 8.1, involves an iterative process of testing and analyses. When sufficient information is gathered to prepare defensible performance assessments for the license application, the DOE's issue resolution process for the license application can be considered complete and the results documented. Information supporting the resolution of performance issues (that is, demonstrating compliance with the performance objectives) will be included in the license application. This information will be supplemented, as necessary during the licensing proceedings and at each stage of repository development, by testing and monitoring to be conducted under the confirmation phase of the performance confirmation program designed to satisfy the applicable and appropriate requirements of 10 CFR 60.140-143.

The details of the testing and monitoring activities of the performance confirmation program to be conducted following the submittal of the license application are expected to be developed and the baseline phase conducted in conjunction with the issue resolution process during site characterization. The resolution of Issue 1.7 is linked to the resolution of Issues 1.1 through 1.6 in that the performance assessments, issue resolution strategies, and baseline data developed during site characterization to support issue resolution in the license application will, in large measure, determine the nature of the information to be obtained under the confirmation phase of the performance confirmation program. At the beginning of site characterization, only very general plans for the program can be defined. The plans will mature in parallel with the development of the assessments needed for the license application as the parameters and measurements most significant to the confirmation program are identified. Preliminary design provisions for accommodating performance confirmation testing and monitoring in the repository are given in the SCP Conceptual Design Report (SNL, 1987). As issues are resolved to support the license application, the testing and monitoring activities to be conducted under the performance confirmation program will become better defined. Development of the details for each phase of the performance confirmation program will proceed in accordance with the general schedule indicated in Figure 8.3.5.16-1.

As stated previously, Issue 1.7 focuses on the performance confirmation program responding to Subpart F of 10 CFR Part 60. Based on the content of Subpart F, the objectives to be met by the DOE's performance confirmation program can be described as follows:

1. Develop baseline information: Develop information on subsurface conditions and natural systems important to the performance assessments to be provided in the license application and those aspects of design integral to the assessments (10 CFR 60.140(d)(2)); monitor and analyze changes in this baseline information as a result of site characterization, and predict changes resulting from construction and operation (10 CFR 60.140(d)(3)); begin collection of such information during site characterization (10 CFR 60.140(b)).

2. Confirm baseline information: Confirm, to the extent practicable, that actual subsurface conditions and the changes in those conditions resulting from construction and operation are within the limits assumed in the license application (10 CFR 60.140(a)(1) and (d)(3); 10 CFR 60.141).

3. Confirm barrier and seal performance: Confirm, to the extent practicable, that natural and engineered systems and components that are designated or assumed to operate as barriers after permanent closure are functioning as intended and anticipated within the limits described in the license application (10 CFR 60.140(a)(2); 10 CFR 60.142-143)).

These objectives will be pursued in a manner that does not adversely affect the ability of the natural and engineered barriers to meet the performance objectives, as required by 10 CFR 60.140(d)(1). This concern is addressed specifically in Section 8.4.3, which is applicable to the baseline phase of performance confirmation that will be conducted during site characterization. If, at any time, the monitoring or testing being conducted as part of site characterization (for example, the multipurpose borehole tests) indicates that changes being brought about by characterization activities (e.g., shaft sinking) may adversely affect repository performance, appropriate analyses and mitigation actions will be implemented as required by 10 CFR 60.140(d)(4).

Figure 8.3.5.16-1 shows the phases of the DOE's performance confirmation program relative to the stages of the overall repository program. The DOE's performance confirmation program, as discussed earlier, is divided into baseline and confirmation phases, with the submittal of the license application serving as a convenient demarcation between phases. Before the license application, site characterization testing provides for baseline data on site conditions important to repository design and performance, monitoring of

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changes in those conditions as a result of site characterization, predictions of changes in those conditions as a result of construction and operation, and predictions of repository performance after closure.

With the submittal of the license application, the DOE begins the formal licensing process with the NRC. The license application will present the performance assessments intended to show that repository performance will satisfy the regulatory postclosure performance objectives and will also present the data on site conditions upon which the repository design and performance assessments are based. Further data gathering activities after the application is submitted are intended to be confirmatory or for other purposes, such as design optimization.

A subset of the testing conducted during site characterization to support the resolution of the performance and design issues in the license application will provide the baseline data needed to meet the requirements of 10 CFR 60.140(d)(2),(3). This includes baseline data on the parameters important to design and performance, as well as data on natural processes that may be changed by site characterization, construction, and operational activities. All the activities presently required to obtain this baseline information are included in the site characterization program, and the information needed is identified in the performance allocation tables. If, based on data and other information gathered during site characterization, the need for additional baseline information is identified, the baseline phase of the performance confirmation program will be appropriately expanded or otherwise modified.

Some of the site characterization activities that also meet requirements of 10 CFR 60.140(d)(2) and (3) for performance confirmation during the baseline phase will be continued past the license application submittal date, if continuation of these activities would produce useful data of a confirmatory nature. Such activities fall into two general categories: (1) long-term monitoring of natural processes, events, or site conditions (e.g., seismic monitoring and monitoring of unsaturated zone hydrologic parameters) and (2) long-duration in situ testing to characterize processes and evaluate conceptual models (e.g., in situ testing of flow processes in the unsaturated zone). These activities are also consistent with and would support the requirements of 10 CFR 60.141 for confirmation of geotechnical and design parameters during construction and operation. Data collected from such activities during characterization would be used in licensing assessments.

Tables 8.3.5.16-1 and -2 list the testing and monitoring activities in each of the above categories that have been tentatively identified. Included in the tables are the test titles, locations, purposes, value for performance or design confirmation, approximate dates, and the SCP section that provides the information. The column describing the value of the activity to performance or design confirmation provides a link between the performance confirmation program and the appropriate regulatory requirements or technical concerns relating to repository performance. In addition to these long-duration monitoring and testing activities to be conducted as part of site characterization and continued into the confirmation phase, certain tests may be identified as being necessary for confirmation only. If the time scales for such testing are long, they may be initiated during site characterization. A

Table 8.3.5.16-1. Monitoring activities initiated during site characterization and planned to be continued as performance confirmation

Test title	Location[a]	Purpose	Principal value for performance or design confirmation	Approximate dates	SCP section providing information
MONITORING ACTIVITIES SUPPORTING PERFORMANCE ISSUE RESOLUTION STRATEGIES IN THE LICENSE APPLICATION					
Precipitation and meteorological monitoring	At and around the site	Continue data collection for precipitation, wind speed, direction, etc.	Improve estimates for recharge and infiltration for ground-water travel time and total system performance	Ongoing, continuing beyond 1/95	8.3.1.12.2.1.1 8.3.1.2.1.1.1
Seismic network monitoring	Regional monitoring	Continue expansion of earthquake catalog	Improve estimates of earthquake probabilities and magnitudes for total system performance	Ongoing, continuing beyond 1/95	8.3.1.17.4.1.2
Geodetic leveling - Yucca Mountain base station network) monitoring	Across the site	Measure station elevations over time	Confirm and evaluate rates of tectonic deformation	Ongoing through preclosure period	8.3.1.17.4.10.1
Surface water runoff monitoring	In and around the site	Continue data collection on runoff	Improve calculations for seal performance and ground-water travel time	Ongoing, continuing beyond 1/95	8.3.1.2.1.2.1
Site vertical boreholes/ unsaturated zone boreholes monitoring	Overlying and adjacent to the primary repository boundary	Expand data base for site hydrologic conditions	Increase confidence in calculation of ground-water travel time	Ongoing, continuing beyond 1/95	8.3.1.2.2.3.2
Natural infiltration monitoring	In and around the site	Continue infiltration monitoring	Increase confidence in infiltration values used in developing ground-water flow models	Ongoing, continuing beyond 1/95	8.3.1.2.2.1.2
Site potentiometric-level monitoring	Around the site	Measure water table levels over time	Improve site hydrologic model for total system performance	Ongoing, continuing beyond 1/95	8.3.1.2.3.1.2
MONITORING ACTIVITIES SUPPORTING DESIGN PARAMETERS IN THE LICENSE APPLICATION					
Drift stability monitoring	Exploratory shaft facility (ESF) and underground facility	Expand data base on rock mass deformation around openings	Confirm design assumptions on stability	11/90, continuing beyond 1/95	8.3.1.15.1.8.3
Seismic network monitoring	Regional monitoring (a 150 km radius of Yucca Mountain)	Extend earthquake catalog	Increase confidence in earthquake probabilities and magnitudes	Ongoing, continuing beyond 1/95	8.3.1.17.4.1.2

[a]For more specific details on locations of tests to the conducted, see Section 8.4.2.2.3.

Table 8.3.5.16-2. Testing activities initiated [illegible] characterization planned to be continued as performance c[illegible]

Test title	Location[a]	Purpose	Performance assessment analysis	Approximate dates	SCP section providing information
		TESTING ACTIVITIES SUPPORTING PERFORMANCE ISSUE RESOLUTION STRATEGIES IN THE LICENSE APPLICATION			
Intact fracture test	Laboratory ESF samples	Continue measurements of dispersivity, diffusion, and flow rates in response to changes in stress	Evaluation of discrete fracture flow models for total system calculations	5/92, continuing beyond 1/95	8.3.1.2.2.4.1
Percolation test	ESF	Validation of dual porosity and discrete fracture models	Improve confidence in ground-water travel time and radionuclide transport calculations	5/92, continuing beyond 1/95	8.3.1.2.2.4.2
Bulk permeability test	ESF	Continue measurements of large scale hydrologic parameters, gas permeability	Addresses scale effects important to flow models used for calculations of ground-water travel time and radionuclide transport	5/92, continuing beyond 1/95	8.3.1.2.2.4.3
Near-field thermally perturbed hydrologic properties	Underground facility - repository level and laboratory testing	Improve data base for fluid flow paths and rates in near-field environment	Improve confidence in performance assessments for engineered barrier system (EBS) and waste package	6/92, continuing beyond 1/95	8.3.4.2.4.4.1
Rock/water interaction tests	Underground facility - repository level and laboratory testing	Continue to measure dispersivity, diffusion, perturbation of rock/water chemistry by thermal effects	Improve confidence in EBS and waste package performance assessments	6/92, continuing beyond 1/95	8.3.4.2.4.4.2
		TESTING ACTIVITIES SUPPORTING DESIGN ISSUE RESOLUTION IN THE LICENSE APPLICATION			
Heated room experiment	Repository level ESF drift	Obtain data base on rock mass deformation and stress changes as a function of temperature, rock thermal conductivity, and heat capacity on the drift scale	Confirm behavior of underground openings - design assumptions for drift size, ground support requirements	12/91, continuing beyond 1/95	8.3.1.15.1.6.5
Near-field thermally perturbed hydrologic properties	Underground facility - repository level and laboratory testing	Determine near-field hydrologic properties	Confirm design assumptions about water inflow to waste packages	6/92, continuing beyond 1/95	8.3.1.2.2.4.3
In situ testing of scale components	Repository level of ESF	Verify behavior of sealing components under in situ conditions	Improve confidence in seal performance	1/93 through repository construction	8.3.3.2.3

[a]For more specific details on locations of tests to be conducted, see Section 8.4.2.2.3.

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test currently identified in this category is the heated room test shown in Table 8.3.5.16-2. These lists are not intended to be complete, but rather to indicate the tests that have been tentatively identified at this time as being useful for performance confirmation. As issue resolution proceeds during site characterization, confirmation phase testing and monitoring activities may be added or deleted.

The performance confirmation program draws upon baseline data collected during site characterization. The manner in which these baseline data are used in performance assessment determines the extent of the testing and monitoring activities needed. During the baseline phase, details of the performance confirmation program will evolve in parallel with the development of the performance assessments. In the license application, the assessments of site performance will be presented, accompanied by information that describes the testing and monitoring needed to evaluate the accuracy and adequacy of the information and models used in those assessments. The repository design presented in the license application will also contain any features (test rooms, monitoring stations, etc.) determined to be necessary for the testing and monitoring activities to be conducted as part of the performance confirmation program.

As shown in Figure 8.3.5.16-1, the confirmation phase follows the baseline phase. During the confirmation phase, predictions of baseline conditions and the changes caused by repository construction and operation are to be confirmed (objective 2), to the extent practicable, along with barrier and seal performance (objective 3). The confirmation phase consists of three divisions: the interim confirmation period (the period after the license application submittal until issuance of the construction authorization) and the construction and operation period (beginning with repository construction and ending with the receipt of the license to accept waste), and the operations period (ending with the approval of the license amendment for permanent closure). During license application review (the interim confirmation period), the DOE will continue to conduct testing and monitoring activities, such as those indicated in Tables 8.3.5.16-1 and -2, both at the site and in the exploratory shaft facility. This testing will serve to confirm baseline conditions and support the predictions of changes to these conditions. Once the construction phase begins, predicted changes in site conditions (10 CFR 60.141), as well as the assumed performance of the natural and engineered systems (10 CFR 60.142), can be confirmed by the testing and monitoring programs conducted during this phase. During the operation period, the performance confirmation program designed to meet the requirements in 10 CFR 60.141 and 60.142 will be continued and additional confirmation activities will be initiated to meet the requirements of 10 CFR 60.143.

As mentioned previously, results of postclosure performance assessments are based on the site characterization and involve predictions of performance into the postclosure time frame. These long-term predictions are made on the basis of conceptual models that are evaluated using data acquired over shorter time frames, and possibly through the use of natural analogs. To confirm these performance assessments, surrogates for the barrier performance that can be measured by field and laboratory testing must be defined. These surrogates are appropriately referred to as confirmation measures. These measures are not substitutes for performance but rather testable measures

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that, if they achieve target values or goals, will give confidence that the performance objectives will be met. These measures are then the focus of the testing, monitoring, and analysis efforts designed to confirm their predicted behavior. For example, corrosion rates for container materials could be used as a confirmation measure for the waste-package containment performance objective.

The confirmation measures eventually identified will probably be closely related to some of the performance measures or parameters developed through the performance allocation process. Confirmation measures will be derived that relate to waste package containment, engineered barrier release, and backfill and seal behavior. Based on site-specific needs, additional measures may be identified. Testing to confirm the predicted values of confirmation measures may be initiated as early as site characterization, but will most likely take place during the construction/operation phase.

Postclosure performance predictions are largely based on numerical modeling, and therefore, a program for the evaluation of the numerical models to be be used is an important part of the confirmation program. The models of concern to the performance confirmation program are those used in the license application to predict long-term performance and from which the values of the confirmation measures may be identified. Evaluations of these models will have been begun during the site characterization period and will continue as needed until permanent closure and the models are considered to be consistent with site data and to adequately represent the conditions and processes at the site. Parameters critical to the evaluation of models will be identified during the baseline phase (site characterization). Any confirmation phase testing judged necessary to supply added confidence to model evaluation efforts will be identified and may be initiated during the license application review period, consistent with the development of the detailed plans for confirmation phase testing and monitoring. Section 8.3.1.1 discusses alternate model evaluations and hypothesis testing, while Section 8.3.5.20 discusses numerical model validation and the specific testing currently planned.