WBS: 1.2.12
QA: QA

Civilian Radioactive Waste Management System
Management & Operating Contractor

Total System Performance Assessment for the Site Recommendation

TDR-WIS-PA-000001 REV 00 ICN 01

December 2000

Prepared for:

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Under Contract Number
DE-AC08-91RW00134

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CHANGE HISTORY

Revision Number	Interim Change No.	Description of Change
00	00	Initial issue
00	01	Changes throughout as indicated by change bars. Causes for change include DOE comments, typographical errors, and completion of supporting documents.

Revised reference callout format throughout the document and updated the reference list by adding and deleting Document Input Reference System (DIRS) numbers. References for added DIRSs numbers:

100061	148384	153002	153178
100746	148713	153038	153184
101173	148992	153039	153200
103748	149092	153105	153201
105155	149862	153111	153202
122137	149939	153122	153269
131861	151294	153123	
141284	151635	153126	
144567	151659	153127	
144927	151667	153128	
147299	152839	153132	

References for deleted DIRS numbers:

100065	130997	146099	151252
100066	131951	146104	151293
100362	133420	146376	151347
103445	135968	147120	151547
103805	139610	148449	151715
107538	140418	150532	151718
113534	141440	150824	152207
119414	143368	150826	152209
124151	144335	150924	152217
124314	144454	151160	
130590	144565	151064	

Incorporated updated climate for 1,000,000 year simulations. Incorporated additional analyses of secondary phases effect on performance.

This ICN utilized the FY2000 Technical Development Plan, since it is just a minor update of Rev 00. Technical Work Planning documentation will be developed for Rev 01.

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EXECUTIVE SUMMARY

This document presents the results of the total system performance assessment conducted for the *Site Recommendation Consideration Report* that is currently being developed. This assessment is one of an iterative series of analyses conducted about Yucca Mountain over the life of the Yucca Mountain Site Characterization Project to support the decision of the Secretary of Energy on whether to recommend the site to the President for construction of a geologic repository.

The performance assessment for the site recommendation is used to evaluate the ability of the engineered and natural systems of the geologic repository to isolate nuclear waste for ten thousand years. A separate document, the Environmental Impact Statement considers repository performance for an additional several hundred thousand years. This document will present some of those long-term analyses. The performance assessment analyzes the behavior of the reference design of the engineered repository components in the expected natural conditions at the Yucca Mountain site (nominal scenario). It also evaluates the contribution of the geologic setting to waste isolation and includes sensitivity and uncertainty analyses to illustrate the relative importance of the various components and parameters. Unexpected disruptive events and their effect on performance of the potential repository are also analyzed in the performance assessment (disruptive scenario class).

This document summarizes the performance assessment work performed for the site recommendation considerations report. Readers who would like more information on how the performance assessment was developed and performed should consult the *Total System Performance Assessment (TSPA) Model for Site Recommendation* (CRWMS M&O 2000 [148384]), as well as supporting Process Model Reports and Analysis Model Reports.

Document Organization

Section 1: General Description of the Total System Performance Assessment Process–Section 1 explains in detail what total system performance assessment is and why it is applicable to potential repository development. It also discusses, from the perspective of the international radioactive waste management community, the general approach for performing a total system performance assessment.

Section 2: Yucca Mountain Total System Performance Assessment for the Site Recommendation–This section describes the specific way in which the general performance assessment approach was adapted for the Total System Performance Assessment-Site Recommendation. It describes how the potential repository system is represented in the performance assessment, based on current knowledge of the site. This description traces the eventual release of radionuclides (or nuclide) to the biosphere using the attributes of repository performance. The section then explains the method used to build the computer model, and how uncertainty and variability were treated in the analyses. Finally, it describes the traceability of the information used in the model.

Section 3: Development of Model Components–The total system performance assessment model represents the entire system of repository behavior; this overall model is made up of a series of models or components that represent the processes that are expected to influence system performance. Section 3 presents a detailed description of how each component was developed, and provides some results of analyses for specific aspects of individual components.

Section 4: Performance Analyses–This section describes which aspects of the components were combined into a total system performance model and explains how and why it was done. It then reports modeling results in terms of the nominal case scenario, the disruptive case scenario, and a combined nominal and disruptive case. The modeling results from the stylized human intrusion scenario are also presented, followed by a discussion of potentially disruptive events not included in the analysis. Finally, the section includes an brief comparison of design alternatives to the reference design. The two alternatives analyzed are a case that includes the use of backfill, and a case that utilizes a low-thermal load approach.

Section 5: Sensitivity Analyses for Total System Performance Assessment Components–This section evaluates the importance of uncertainty to the nominal, disruptive, and combined scenarios. It discusses factors in each model about which significant uncertainties exist in the current scientific understanding, and it examines their relative importance to repository system performance. It also examines how sensitive those factors are to changes in the values assigned to them. Lastly, it addresses the robustness of the components of system performance.

Section 6: Summary and Conclusions–In contrast with the previous section, which deals with the uncertainty and sensitivity of various aspects of individual components, this section looks at uncertainty from a total system perspective.

EXPLANATION OF A TOTAL SYSTEM PERFORMANCE ASSESSMENT

The general total system performance assessment process has developed over time through its application on numerous projects by various international organizations involved in radioactive waste management and in consultation with the U.S. Nuclear Regulatory Commission. The TSPA must be based on a thorough understanding of the relevant processess that may affect performance and site-specific information, natural analogs that assist in building the confidence in the long term processes evaluated in the TSPA, and relevant laboratory data concerning the engineered materials. The TSPA approach allows an analysis of the system that appropriately incorporates and quantifies the uncertainty in such a long term projection of repository performance. The TSPA-SR aims to provide a defensible analysis of system behavior incorporating models and parameters that are based on scientific observations in order that decision-makers can assess the ability of the repository system to comply with proposed regulations.

The TSPA process can be visualized as a series of levels going up a pyramid (Figure ES -1). The base of the pyramid is built using all of the data and information collected by scientists and engineers involved in site characterization and engineering design. This information is used to develop appropriate models which describe the features, events, and processes that may be present in the potential repository system. The base is large because it represents the composite of all the information gathered by the repository program.

This information provides the basis for the development and testing of conceptual models. A conceptual model is a set of qualitative descriptions used to describe a system or subsystem for a given purpose. An example is a description of the movement of water molecules as they pass between rock and fractures. There may be several alternative conceptual models that provide a reasonable description of a particular system or subsystem.

The specific aspects for describing a process on a larger scale are then extracted and incorporated into computer models to deal with each of the relevant features, events, and processes. An example is a model for all water flow above the water table, which would incorporate flow interactions between the rock matrix and the rock fractures as well as many other specifics needed to describe how water flows throughout the rock mass. This abstraction or progressive simplification to a more compact and usable form is depicted by the slightly smaller width of the pyramid. The models that eventually analyze the evolution through time of all the various components of the system are generally the most compact or abstracted models of all. These abstracted models start with the results of the detailed process level modeling and create a representation that captures all the salient features of the process model, and the associated uncertainties. Abstraction is necessary for many reasons. One of these reasons is that many of the models are much too large to be run efficiently even on very large computers.

To capture the full detail of the uncertainty and variability in the behavior of the repository system, the total system performance assessment must be probabilistic, using multiple calculations (as opposed to deterministic or a single calculation using a single value for each parameter in the system). The models are run many times using many combinations of parameters. Each of the combinations of parameters has some definite possibility of representing the actual performance of the potential repository. These probabilistic analyses are intended to reflect the range of behaviors or values for parameters that could be appropriate, knowing that perfect or complete knowledge of the system will never be available and that the system is inherently variable.

A final reason to use abstraction is that, in some cases, an overly complex model would over represent the actual state of knowledge about a process, so a simpler model is more appropriate, i.e., the complex model could be more advanced than the data available for a system.

A more detailed depiction of the total system performance assessment process is shown in Figure ES-2. Here, collection of site data and incorporation of the data (or estimates, where data are not available) is illustrated first into conceptual models, then into mathematical equations, next into computer (numerical) models and, finally, into a total system model. The figure is a more detailed representation of the process that is depicted using the total system performance assessment pyramid in Figure ES-1.

How the Potential Repository System Is Visualized in the Total System Performance Assessment-Site Recommendation

In general, the potential repository system is visualized as a series of processes linked together, one after the other, spatially from top to bottom in the mountain. From a computer modeling point of view, it is important to break the system into "bite-size" portions that relate to the way information is collected. In reality, the potential geologic repository system will be completely interconnected, and essentially no one process will be independent of other processes. However, the complexity of the system demands that some idealization of the system be developed for an analysis to be performed.

The overall system, in progressively greater detail from mountain scale down to waste form scale, is shown in Figure ES-3. This figure illustrates several of the key natural and engineered barriers that contribute to the long-term isolation of waste from the biosphere. The natural barriers include semi-arid natural environment and the location of the repository about 300 m beneath the ground surface, and about 300 m above the water table. These natural barriers are enhanced by engineered barriers including the waste package and drip shield.

The attributes of the potential repository performance associated with this conceptualization are shown in Figure ES-4. Each of the attributes and the associated component models are shown on Figures ES-5 to ES-9 in their relative spatial sequence. Each model in the sequence is shown in Figure ES-10 and provides input to the following model and receives the output of the preceding model or models. The shape of the component model icons shown on these figures is determined by the attribute of the potential repository performance.

The attributes of the potential repository performance are the following:

- Limiting water contacting the waste packages
- Prolonging waste package lifetime
- Limiting radionuclide mobilization and release from the EBS
- Slower radionuclide transport away from the EBS
- Low mean annual dose even considering potentially disruptive events and processes.

The disruptive events icons are used to depict the models associated with off-normal or disruptive events such as volcanism. These events, if and when they occur, would affect the nominal case processes. Human intrusion to the potential repository is an additional scenario also evaluated in the TSPA.

The following is an abbreviated description of the expected behavior of the major components.

Limiting Water Contacting the Waste Packages–The changes in climate over time provide a range of conditions that determine how much water falls onto the ground surface and infiltrates into the ground below (Figure ES-5). Based on current scientific understanding including paleoclimate studies, the assumption in the total system performance assessment is that the current climate represents one of the driest climates that the Yucca Mountain site will ever encounter. All future climates are assumed to be either similar to current conditions or wetter. The water that is not lost back to the atmosphere by evaporation or transpiration enters the unsaturated zone flow system. Water infiltration is affected by a number of factors related to the climate state, such as increase or decrease in vegetation on the ground surface, total precipitation, air temperature, and runoff.

Water generally moves downward in the rock matrix and fractures. The rock mass at Yucca Mountain is composed of volcanic rock that is fractured to varying degrees as a result of contraction during cooling of the original nearly molten rock and also due to extensive faulting in the area. Water flowing in the fractures moves more rapidly than the water moving through the matrix. In some locations, some of the water collects into locally saturated zones in the rock or is diverted laterally by differences in the rock properties. The overall unsaturated flow system is heterogeneous, and the location of flow paths and velocities and volumes of groundwater flowing along these paths are expected to change many times over the life of the potential repository system.

The heat generated by the spent nuclear fuel in the potential repository will cause the temperature of the surrounding rock to rise to a peak (or maximum) level within decades to centuries after emplacement and then decay gradually back to ambient temperature over thousands of years. Much of the water and gas in the heated rock will be driven away from the potential repository during this heating period. The thermal output of the waste decreases with time, and as the rock temperature cools, percolating water (including some of the mobilized water) will likely flow back toward the potential repository. Some of the water that contacts the potential repository walls can drip or seep into the potential repository, but only in a relatively few places. The number of seeps that can occur and the amount of water that is available to drip into the drifts is restricted by the low volume of water flowing through Yucca Mountain and by draining through the rock pillars between the drifts. Drips also can occur only if the hydrologic properties of the rock mass cause the water to concentrate enough to feed a seep. Over time, the number of seeps increases and decreases, and their locations change, corresponding to increased or decreased infiltration based on changing climate conditions and on mineralogic changes to fractures. The drips will be directed away from the waste packages for a considerable time due to the protection afforded by the drip shield in the engineered barrier system.

Prolonging Waste Package Lifetime–Because the potential repository is located above the water table in the unsaturated zone, the most important process controlling nominal case waste package lifetime is moisture on the waste package (Figure ES-6), either from seeps or moisture in the air. The location of the seeps providing dripping water depends to some extent on the natural conditions of the rock, but also on the alterations caused by potential repository construction. Alterations, such as increased fracturing, may be caused by mechanical processes related to drilling the drifts or by thermal heating and expansion of the drift wall. The alterations in the seepage can also be caused by chemical alterations enlarging or constricting some of the pores and /or the fractures. This can occur due to evaporating water precipitating minerals, condensing water dissolving minerals, and engineered materials dissolving in water and reprecipitating in the surrounding rock. The chemistry in the drift changes because of the complex interactions among the incoming water, circulating gas, and materials in the drift (e.g., metals in the drift support system, drip shield, or waste package). The chemical evolution is strongly influenced by heat during the period of thermal heating.

In the reference design, the radioactive waste emplaced in the potential repository will be enclosed in a two-layer waste package. The layers will be constructed of two different materials that are expected to degrade at different rates and from different mechanisms as they are exposed to various potential repository conditions. The outer layer will be made of high-nickel alloy metal and the inner layer of a stainless steel. The design also has a drip shield made of titanium. These will be emplaced over the waste packages to reduce the potential for dripping water hitting the waste packages. Where the waste packages are exposed to dripping water after drip shield degradation or high relative humidity for long periods of time (i.e., thousands of years), the packages will corrode and eventually will be breached. The breaches are expected to occur as deep, narrow pits or cracks, or as broader areas called patches. The changing thermal, hydrologic, and chemical conditions in the potential repository all influence the corrosion rate of the waste packages.

Limiting Radionuclide Mobilization and Release from the Engineered Barrier System–When water eventually enters a waste package through the cracks, patches, or pits, contact may occur with the radioactive waste contained within the waste package. The majority of the radioactive waste is spent nuclear fuel from commercial reactors, but there are also spent nuclear fuel from U.S. Department of Energy reactors, naval fuel, and high-level radioactive waste from the reprocessing of fuel. The commercial spent nuclear fuel is the focus of this overview discussion. The effect on performance of other waste forms are discussed in the main body of the report.

After water enters the waste package, the water will first contact the thin layer (about 0.7 mm) of a zirconium alloy that covers the surface of most of the commercial spent nuclear fuel elements. This layer, called cladding, must be breached by mechanical or chemical processes before the radioactive fuel pellets can be exposed to water. Then the individual fuel elements start to degrade, making the radionuclides (which are distributed in low concentration throughout the uranium oxide fuel pellets) available for transport away from the waste form (Figure ES-7). The degradation process may involve several stages because the waste forms are sometimes altered to different chemical forms (or phases) before they reach a phase that will allow the nuclides (or radionuclide) to be released from the waste into the available water. Also, different radionuclides have different chemical properties themselves, so the reaction rates of the individual nuclides with water are greatly variable. In general, however, once the waste form begins to alter, it takes about 1,000 years for the commercial waste forms to completely degrade.

To move out of the waste package, the radionuclides are either dissolved in or move as extremely small particles (colloids) in flowing water, or they move in a thin stagnant film of water by diffusion. To escape from the waste package, the nuclides must exit through a pit, crack, or patch in the waste package and move out into the waste emplacement drift.

After escaping from the waste package, the radionuclides can then advance through materials on the drift floor, which consists mainly of tuff gravel and the corrosion products from the waste package and drift structural components. At this point, the nuclides may either adhere to some of the materials on the drift floor, continue to move in the water, or become attached to colloidal particles of clay, silica, or iron. Because of their molecular charge and physical size, these colloidal particles move through the rock mass under the potential repository somewhat differently than noncolloidal or dissolved particles.

Slow Radionuclide Transport away from the Engineered Barrier System–The radionuclides move downward beneath the potential repository at different rates based on the chemical characteristics of the nuclides and the rock they are passing through, and on the velocity of the water in which they are contained (Figure ES-8). The rock for several hundred meters underlying the potential repository is unsaturated, and the water movement behaves as described earlier. Some water moves rapidly in fractures and some much more slowly in the rock matrix. Pore water in the matrix also evaporates and recondenses elsewhere due to the ambient geothermal gradient in the mountain; radionuclides left behind in the rock pores by evaporation must dissolve in new water imbibing from fractures, or condensing from vapor, before it can be transported.

The transport rate through fractures and the matrix depends on the tendency of the individual nuclide to interact with the rock through which it moves. Some radionuclides move more quickly through the rock with little or no interaction to delay their transport. Other radionuclides adhere to some minerals in a process called sorption and are bound in the rock for long periods. Sorption can be irreversible in some instances, and in this case the nuclide will be bound permanently in the rock. In other cases, the nuclides may desorb at a future time and again move through the system. Radionuclides also can diffuse from higher concentrations in fracture water to lower concentrations in matrix water, which slows the overall transport rate. It is expected that eventually, some fraction of the available nuclides will travel through the unsaturated zone.

When the radionuclides reach the water table, they will enter the saturated zone flow system. Beneath Yucca Mountain, the water in the saturated zone flows in a generally southerly direction toward the Amargosa Valley. Nuclide sorption also occurs in the rocks and valley fill or alluvium along the flow paths in the saturated zone. Because of the differences in chemistry between the unsaturated and saturated zone rock and water, the rates, durations, and nuclides involved in sorption are different for the two zones. As the radionuclides move in the saturated zone along different paths and through different materials, they gradually become more dispersed and the concentration of the nuclides in any volume of water therefore decreases.

If the radionuclides are eventually pumped out of the saturated zone by water wells, the radioactive material can cause doses to humans in several ways. For example, the water from the well could be used to irrigate crops that are eaten by individuals or livestock, to water stock animals that provide milk or meat food products, or to provide drinking water. Also, if the water pumped from irrigation wells evaporates on the ground surface, the nuclides may be left as fine particulate matter that could be picked up by the wind and then inhaled by humans.

Addressing Effects of Potentially Disruptive Events and Processes–The attributes of the system, given in the previous sections, describe the continually ongoing processes that are expected to occur in and around the potential repository system. The term used to denote the sequence of anticipated conditions is "nominal scenario." In contrast, "disruptive scenarios" refer to discrete, unanticipated events that disrupt the nominal case system (Figure ES-9). Scenarios are developed for this level of analysis. A scenario is a well-defined, connected sequence of features, events, and processes that can be thought of as an outline of a possible future condition of the repository system. The only disruptive event included in this analysis is the formation of a volcano through or adjacent to the potential repository. Other potentially disruptive events were determined not to be significant to overall repository performance and were not included in the TSPA disruptive events analysis. The treatment of these disruptive events in TSPA are discussed in the following paragraphs.

Yucca Mountain's terrain has experienced volcanic activity in the geologic past. The rocks in which the potential repository will be constructed are volcanic in origin. However, scientific studies of the timing, volume, and other aspects of volcanism have concluded that volcanic activity in this area has been waning in the recent geologic past and that the probability of volcanic activity as a potential repository-disturbing event is highly unlikely. Nevertheless, for completeness, part of the total system performance assessment analysis is an assessment of the consequences of a small cinder cone formed by a dike that flowed up through, or close to, the potential repository drifts. Both direct release to the atmosphere of the waste package materials and indirect release to the unsaturated and saturated zones from damaged packages are considered.

Another disruptive event is an earthquake, or seismic activity. Although generally modest in size, earthquakes do happen frequently in and around Yucca Mountain. The seismic hazard exposure of the potential repository primarily results from ground motions rather than from direct offset along a fault. The primary potential effect of ground shaking is to disrupt the cladding of the waste and hasten rockfall into the drift. The effects of rockfall and seismic effects on the waste form are included in the nominal case analysis.

In previous total system performance assessment calculations, the effects of nuclear criticality, another potential disruptive event, have been assessed for both in-waste package and in-rock events. In those analyses, a series of unlikely events was assumed to occur. These unlikely events (such as filling the waste package with water or concentrating specific radionuclides in the rock mass) lead to the concentration of certain nuclides that, only in specific low-probability environments, might lead to a nuclear criticality. The result is a change in the nuclear material to more highly radioactive forms. The resulting increase in the radionuclide source term was then evaluated against the base case to determine if the resulting change in dose rate is significant, and it is not. Because the probability of occurrence of an in-package or a rock mass criticality is very low and the consequence of a criticality (should one occur) on the radiation dose is also very low, further analyses are not presented here.

Human Intrusion–Another disruptive event, human intrusion into the potential repository, is treated as a separate scenario in the analysis. Human intrusion is treated in a stylized manner based on the proposed regulatory description of such an event in which the contents of a waste package are exposed through the borehole of a well drilled directly through the potential repository into the uppermost aquifer 100 years after closure. The human intrusion is assumed to occur and the dose consequences are calculated and compared against the nominal scenario results to evaluate the robustness of the potential repository in the event of such an intrusion.

Results of Analyses–Although the total system performance assessment is usually discussed in terms of a sequence of processes linked one after the other in space (as described in the earlier section), this approach does not readily convey how all of the processes evolve with time. The following describes the results at various time intervals of interest, attempting to show the evolution in both time and space for the reference design and for the range of nominal case conditions. However, the assumptions underlying the modeling development drive the results. Different sets of assumptions can give different results. The intent of this total system performance assessment is not only to show how the system is thought to behave, but also to provide information on how much uncertainty is associated with each total system performance assessment component, as discussed later. Many of the results shown include a great deal of conservatism and also some large ranges of uncertainty. Conservatism is utilized in the analyses to add defensibility to the analyses in the case where a parameter or model has an uncertain range of performance. The conservative approach tends to promote under performance of the component in question. In terms of evaluating the safety of the site in a regulatory framework, this is a better approach to take than to perhaps trend toward less defensible, over performance of the potential repository because it may require less resources to defend the analyses. The results discussed below focus on the forecasted time-averaged behavior of the repository system. This behavior by itself cannot fully represent the ranges of uncertainty and variability in the system and its possible future states.

The approach to performance assessment model development is shown in Figure ES-10. The figure illustrates the identification and screening of the features, events, and processes, followed by modeling of various components of the potential repository system for each of the main scenarios.

How the Potential Yucca Mountain Repository is Projected to Evolve–Prior to describing the probable evolution of the repository system it is worthwhile to note that although the illustrations depict how the system is projected to degrade over time, there are large parts of the system that remain essentially unaltered for very long periods. Although this fact is reflected indirectly in the results, it is rarely shown explicitly. The sequence of results in Figures ES-11 to ES-15 show schematically what the waste package and engineered system might look like at various times after closure. However, the schematics are only representative of those packages that experience dripping water (or seeps). The percentage of all waste packages that experience significant corrosion of the resistant outer high-nickel alloy layer is expected to be small until late times (i.e., several tens of thousands of years). Even though the location and number of seeps changes with time, the majority of waste packages will likely never experience any significant seepage, even in a million years. Most of the waste packages are expected to remain relatively intact and continue to look essentially like the one depicted in Figure ES-11 with only minor breaches and not like the waste packages shown in subsequent figures depicting the total system performance assessment results. Note however, that waste packages may degrade even in the absence of seepage, due to moisture on the waste packages contributing to degradation.

Waste Emplacement to Several Thousand Years after Potential Repository Closure–As the waste packages are emplaced in the drifts, their combined heat output will cause the drift wall temperatures to rise, and much of the water and gas in the rock will be driven away from the potential repository. At 100 to 200 years after closure, the surfaces of some of the individual waste packages will start to cool below boiling, and the humidity in the drift will climb from preclosure values of about 50 percent to nearly 100 percent. Depending upon the local conditions around each waste package, the degradation of the high-nickel alloy outer layer will begin somewhere between 100 years and several thousand years, but proceed at a very slow pace. As a result, waste packages are not expected to be breached such that radionuclides could be exposed to water, if for several thousand years.

In Figure ES-11, the cutaway of the potential repository shows schematically the situation under nominal conditions at 1,000 years. There is not any forecasted release from the potential repository system at this time. Therefore, as shown in the final panel of Figure ES-11, there is no dose consequence for any of the cases calculated during this period in the region 20 km downgradient of the potential repository. The schematic picture of the waste package in Figure ES-11 shows an intact waste package that exhibits little or no corrosion or degradation. Note that the natural environment also provides an independent barrier for radionuclide transport for the first 1,000 years. This means that the bulk of the radionuclide inventory in the system will not be released to the accessible environment, either due to the engineered system or the natural system, and will not contribute to the expected dose to the average member of the critical group.

Several Thousand Years to 10,000 Years after Closure–The expected value of the peak dose is a function of the degree of conservatism incorporated in the models and analyses used to produce the peak dose estimate. Because the base case models used in the development of the nominal performance projections were designed to be reasonably conservative to maximize their defensibility during the 10,000-year compliance period, they are less appropriate for projections of the peak dose. More appropriate representations would include considerations of the long-term (post-10,000-year) climate states and the long term effects of secondary phases. The following discussion relates primarily to the nominal case for 10,000 year model. For the nominal scenario, the potential repository system still performs very well during this time period. The waste packages show minor corrosion. The heat in the system has begun to decay, and reduce back to ambient conditions. The large majority of the radionuclide inventory itself has decayed by this time. Figure ES-12 shows the lack of corrosion and release from the potential repository system. Note that the proposed regulatory compliance period is only for 10,000 years. Discussion of time periods past the 10,000 year compliance period are intended only to provide a context for better understanding of the compliance-period results. After a few thousand years, the engineered system is utilized to isolate the remaining small percentage of the inventory that has not decayed away at this time.

10,000 Years to 50,000 Years after Closure–By this time, the rock surrounding the drift is returning to its original temperature, and the original fluid flow patterns affected by the heating have been reestablished. Some permanent alterations of the rock may remain (such as fracture shear movement caused by thermal expansion and contraction), but this does not appear to be significant in terms of potential repository performance. The outer layer of the waste package continues to corrode, though very slowly. Dripping conditions now occur at discrete locations throughout the potential repository. Where the outer layer or a weld on the lid of the waste package has been perforated, corrosion of the inner barrier material is initiated (Figure ES-13). Inner barrier corrosion proceeds much more quickly than that for the outer layer. In the cases where the inner layer has been perforated, the water can enter the waste packages through small openings, alter the fuel in rods that have been perforated, and move out of the engineered barrier system. The potential repository cutaway in Figure ES-13 shows a few paths along which nuclides are being released into the rock under the potential repository. At this time, the median value for the number of breached waste packages is less than 10 percent of the total emplaced packages. The mean peak dose rate from a plume in the saturated zone 20 km south-southeast of the potential repository is calculated to be 0.25 mrem/year, primarily from ^{99}Tc and ^{129}I. This value is 0.08 percent of the average background radiation from nonmedical sources in the United States, which is about 300 mrem/year. Background non-medical radiation in the U.S. varies with location. For example, it is about 310 mrem/yr in Oak Ridge, Tennessee, 340 mrem/yr in Amargosa Valley, Nevada, and 1180-mrem/yr in Denver, Colorado. (see DOE 1999 [105155], Table 3-28, Volume 1). Radon dose contributes a substantial fraction of the background dose rate, about 200 mrem/yr on average. The radon dose around the country varies, with higher dose for uranium-bearing underlying rock, the use of basements in building construction, and tightly-sealed, energy-conserving buildings. The values listed above are based on an average radon exposure, except for Denver, which uses a location-specific value.

Another way to assess the ability of the potential repository system to isolate the waste is to show the radionuclide release information in the context of how much radioactivity remains isolated in the potential repository versus how much has escaped. Figure ES-16 illustrates how the total inventory in the potential repository at the time of emplacement (30 years) decays with time, and what amount of the total inventory has escaped from the potential repository at discrete times up to 100,000 years. Compared to the total amount of radioactivity in the potential repository at 30 years after waste emplacement at about 300 years after closure, the decay process has decreased the radioactivity to about 2 percent of the original amount. At 1,000 years the amount has decreased further to 0.8 percent, and at 10,000 years the remaining portion of the original total inventory is only about 0.2 percent. Of the 0.2 percent remaining at 10,000 years, none is projected to reach the edge of the potential repository. At 100,000 years, 0.01 percent of the original inventory remains. Of that remaining 0.01 percent, 3 percent is projected to reach the edge of the potential repository, 2 percent to reach the water table and be transported 20 km south of the edge of the potential repository, where it is assumed to be accessible to humans.

Fifty Thousand to 100,000 Years after Closure–The natural conditions in the rock remain unchanged from the previous period. The progression of corrosion of the packages is shown in Figure ES-14. Those nuclides that at earlier times are limited in their release from the spent nuclear fuel elements because of their chemistry become larger contributors to the dose rate. In particular, ^{237}Np becomes the dominant isotope controlling dose rate. The median number of packages breaching by the end of this time is about 50 percent of the total number. The mean peak dose rate at 20 km is 70 mrem/yr, or about 23 percent of the average background radiation from natural sources in the United States.

One Hundred Thousand to 1 Million Years after Closure–The individual waste packages continue to slowly corrode. The number of packages releasing nuclides by 1 million years after closure is about 100 percent of the total (Figure ES-15). Dose rates at the 20 km point continue to climb as more packages release their inventory, until a maximum is reached at approximately 250,000 years. The mean value for total dose rate at this time is approximately 460 mrem/yr and then declines to approximately 180 mrem/yr at 1 million years after closure. Although 400 mrem/yr due to repository pathways is about double the present nonmedical background dose rate in the Yucca Mountain area, it is well within the natural variability of background dose rates in the United States. Residents of Denver, Colorado for example, receive about triple the present background dose rates in the Yucca Mountain region. ^{237}Np remains the main contributor to the dose rate, but plutonium attached to colloids is the dominant contributor in some of the cases.

As noted in proposed 40 CFR 197.30, (64 FR 46976 [105065]), no regulatory standard applies to the results of the peak dose analyses. They are provided to support the development of the environmental impact statement EIS. Although these results do provide insights into the possible long term performance of a repository at Yucca Mountain, they should not be interpreted as accurate predictions of the likely performance over these time periods due to the large uncertainties and conservative approximations included in the models that were designed for assessing the 10,000-year compliance performance.

Sensitivity Analysis–An important role of performance assessment is to evaluate the uncertainty in the projected performance and the significance of the key component models and parameters in the projection. In general, the sensitivity analyses show, in a relative way, the parameters in which uncertainty most affects the results. In some cases, if future studies could reduce the range in uncertainty, the parameter might no longer appear as a parameter to which performance is highly sensitive. Conversely, if a parameter or component is assigned an inappropriately low uncertainty range, it might not show up as a particularly important parameter. These analyses must be performed with care to gain the necessary understanding about the parameters that are most important to actual repository performance.

Based on the sensitivity and uncertainty analyses of the total system performance assessment results, the following aspects of the total system performance assessment components have been determined to be most significant to the dose rates at 20 km from the potential Yucca Mountain repository. In some cases, the total system performance assessment results point to very specific aspects or parameters used to represent the total system performance assessment components, which in turn are captured in the attributes of potential repository performance. The results are shown for four different time periods because the relative importance of different aspects of the modeled system changes as the system evolves. The results are ranked from most important to least within each time period.

Table ES-1. Important Components of Potential Repository System for Different Time Periods

Performance Period	Most Sensitive Components or Parameters
Postclosure to 10,000 Years	Occurrence of volcanic event disrupting waste packages
10,000 to 50,000 Years after Closure	Occurrence of volcanic event disrupting waste packages
	Availability of water to contact the waste package (seepage into drifts)
	Rate of waste package degradation (loss of integrity of outer waste package barrier or of inner waste package barrier due to environmental conditions)
	Rate of cladding degradation (integrity of spent nuclear fuel cladding)
	Availability of water to contact exposed waste form surfaces (water into waste package)
Fifty Thousand to 100,000 Years after Closure	Rate of waste package degradation
	Rate of cladding degradation (integrity of spent nuclear fuel cladding)
	Neptunium Solubility
	Formation and transport of radionuclide-bearing colloids
One Hundred Thousand to 1 Million Years after Closure	Rate of waste package degradation
	Cumulative amount of degraded cladding (integrity of spent nuclear fuel cladding)
	Neptunium solubility

The details of the total system performance assessment parameters that feed these factors are described in several sections of this document. A brief, general summary of the main analyses is presented below.

Disruptive Events–Several disruptive, or unexpected, features, events, and processes are included in the analyses. The primary disruptive event in TSPA-SR is the volcanic scenario. This case is simulated and is the only contributor to the dose at times before 10,000 years, the proposed regulatory period. The mean peak dose is significantly below the standard during the first 10,000 years of the simulations. The analyses were conducted out to later times as well.

Human Intrusion–A disruptive event defined or stylized in the proposed regulation, is human intrusion. The nominal scenario for the TSPA-SR was utilized, and a stylized human intrusion was included. The case was run probabilistically for a 100,000 year time period, with stochastic parameters for many aspects of the case. The case included a borehole through a relatively intact waste package at 100 years after closure, that penetrated all the way to the saturated zone. The major components of the model include infiltration of water down the borehole into the penetrated waste package; mobilization and release of the waste within the package; transport of radionuclides down the borehole to the water table; transport of the radionuclides through the saturated zone; and biosphere exposure pathways as in the nominal case. Many aspects of this model are uncertain, and were varied in the probabilistic case. The doses generated from this case were significantly below the nominal and disruptive cases at late times, though there were early releases due to the penetration of the waste package at 100 years. A sensitivity analysis was conducted to look at a more realistic time of penetration of the waste package with a drill bit. The later intrusion time was based on degradation or thinning of the waste package, and also resulted in doses well below that of the nominal and disruptive cases.

Groundwater Protection Case–An additional case was also evaluated for TSPA-SR that incorporated pertinent radionuclides and simulated the concentration of radionuclides in the groundwater. The analyses indicate that the groundwater concentrations will be low, even beyond the proposed regulatory time period of 10,000 years.

Summary–The general total system performance assessment process has developed over time through its application on numerous projects by various international organizations involved in radioactive waste management and in consultation with the U.S. Nuclear Regulatory Commission. The TSPA-SR is the fifth major iteration of TSPA conducted by the DOE over the past decade in support of evaluating the suitability of the Yucca Mountain Site. It is based on internationally accepted approaches, including an initial development of features, events, and processes that may occur at the site. Individual models are based on appropriate site-specific information, analog data and relevant literature data sources that have been integrated by the principal scientific investigators to provide a reasonable and defensible characterization of each individual process relevant to postclosure performance The data, analyses, and models used as the technical basis for the TSPA-SR, as well as the assumptions, uncertainty, variability and conservatism that go along with these data, analyses and models are all traceable back to their source documents and data sets. This traceability allows all interested reviewers to examine the defensibility of the individual component models.

The current TSPA-SR Rev 00 has benefited from reviews of the TSPA-VA completed by a Peer Review Panel (Budnitz et al. 1999 [102726]), the NRC (Paperiello 1999 [146561]), Clark County, NV (Cohen 1999 [151783]), and the U.S. Geological Survey (Anderson et al. 1998 [101656]). Section 6.2 presents a summary of many of the most significant comments and how they have been addressed. There remains uncertainty in the individual process models and their abstraction into the TSPA-SR model. Much of this uncertainty has been quantified and is included in the TSPA-SR model. The TSPA-SR results reflect this quantified uncertainty. In addition to the quantified uncertainty in the TSPA-SR model, there is also unquantified uncertainty that has been generally represented by using a more bounded or conservative representation of a particular process model.

All of the above information and their integration in the context of this TSPA-SR provide a sound, traceable, and transparent technical picture of the possible performance of a potential repository at Yucca Mountain. These projections have incorporated the best available science and technology developed over years of investigating the Yucca Mountain site and the associated waste forms and waste packages. Although significant uncertainty exists in some of the component models underlying the TSPA-SR, these uncertainties have either been reasonably quantified, or in some cases of great complexity, conservatively bounded.

The documentation of the TSPA-SR, including the analysis model reports, process model reports, and the TSPA-SR model document, provide the scientific basis for evaluating the suitability of the Yucca Mountain site and for addressing the NRC acceptance criteria in the Total System Performance Assessment and Integration Issue Resolution Status Report.

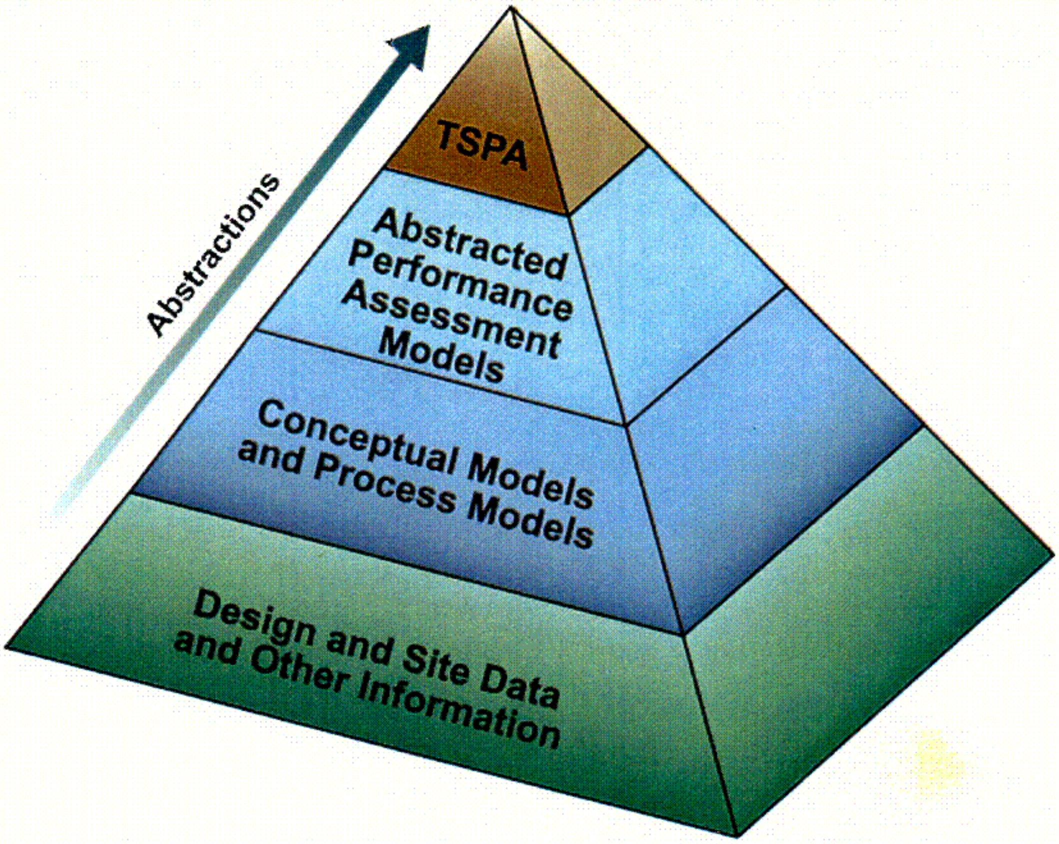

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Figure ES-1. Total System Performance Assessment Information Pyramid

C-1

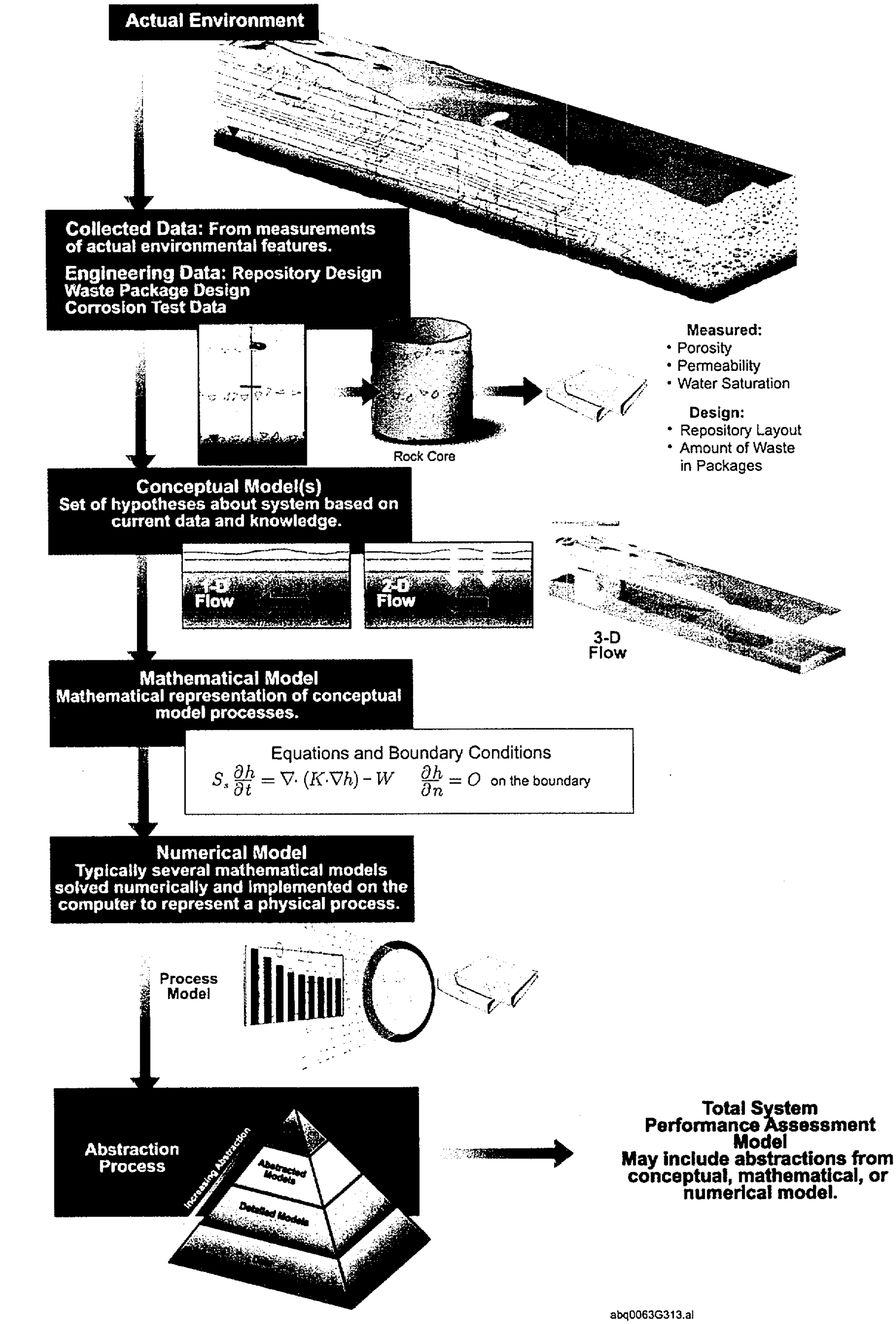

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Figure ES-2. Generalized Performance Assessment Approach

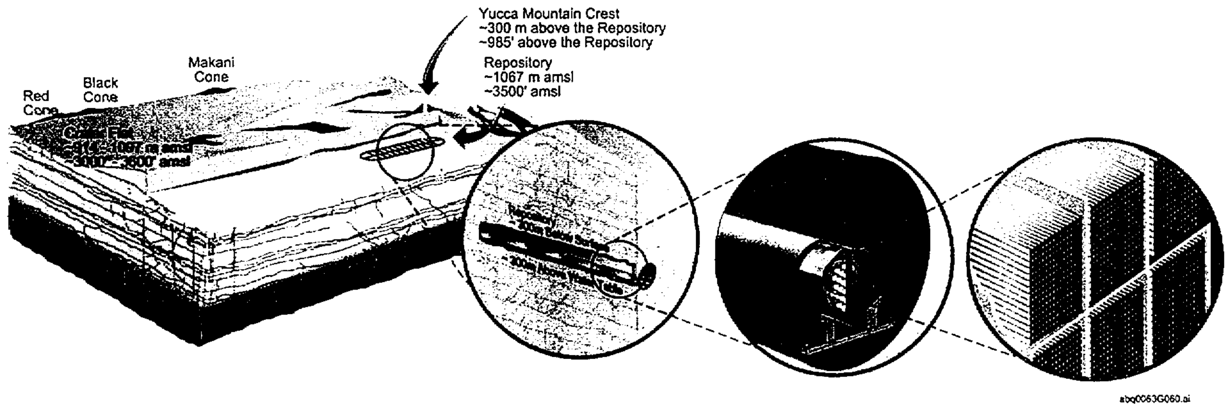

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Figure ES-3. Generalized Schematic of Potential Repository System from Mountain Scale to Repository Scale to Waste Package Scale to Waste Form Scale

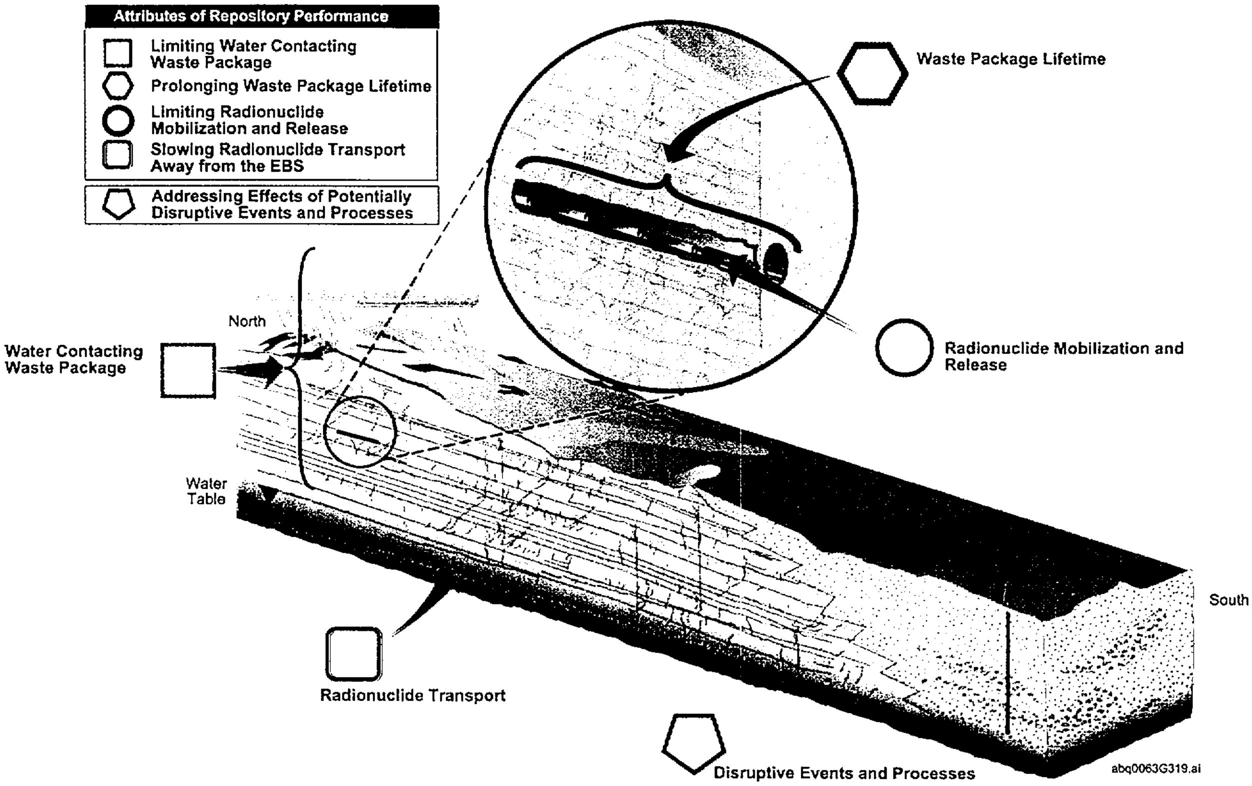

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Figure ES-4. Schematic of Attributes of Repository Performance

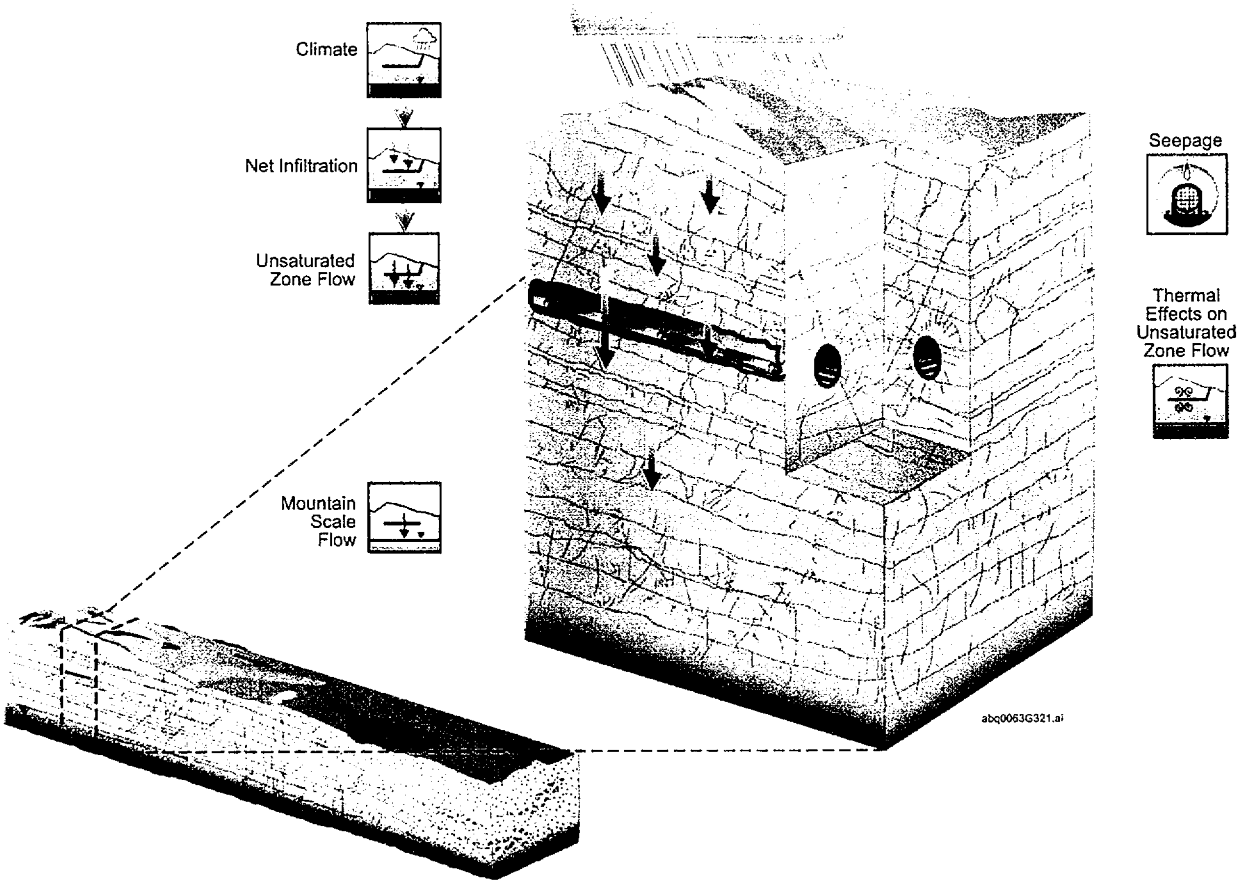

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Figure ES-5. Limiting Water Contacting Waste Package Attribute

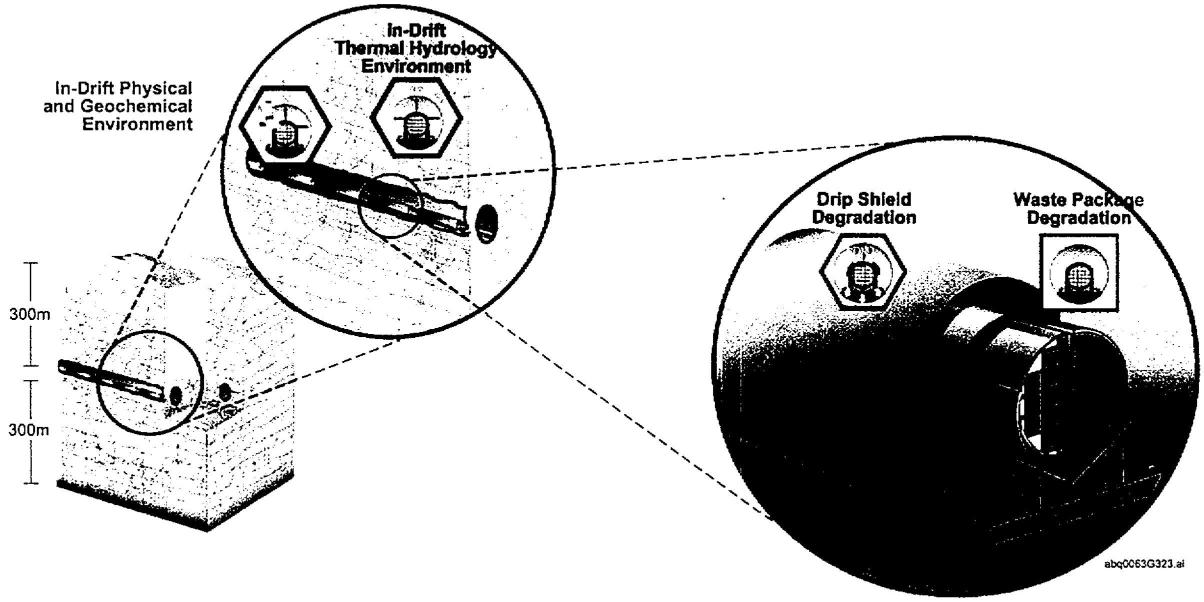

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Figure ES-6. Prolonging Waste Package Lifetime Attribute

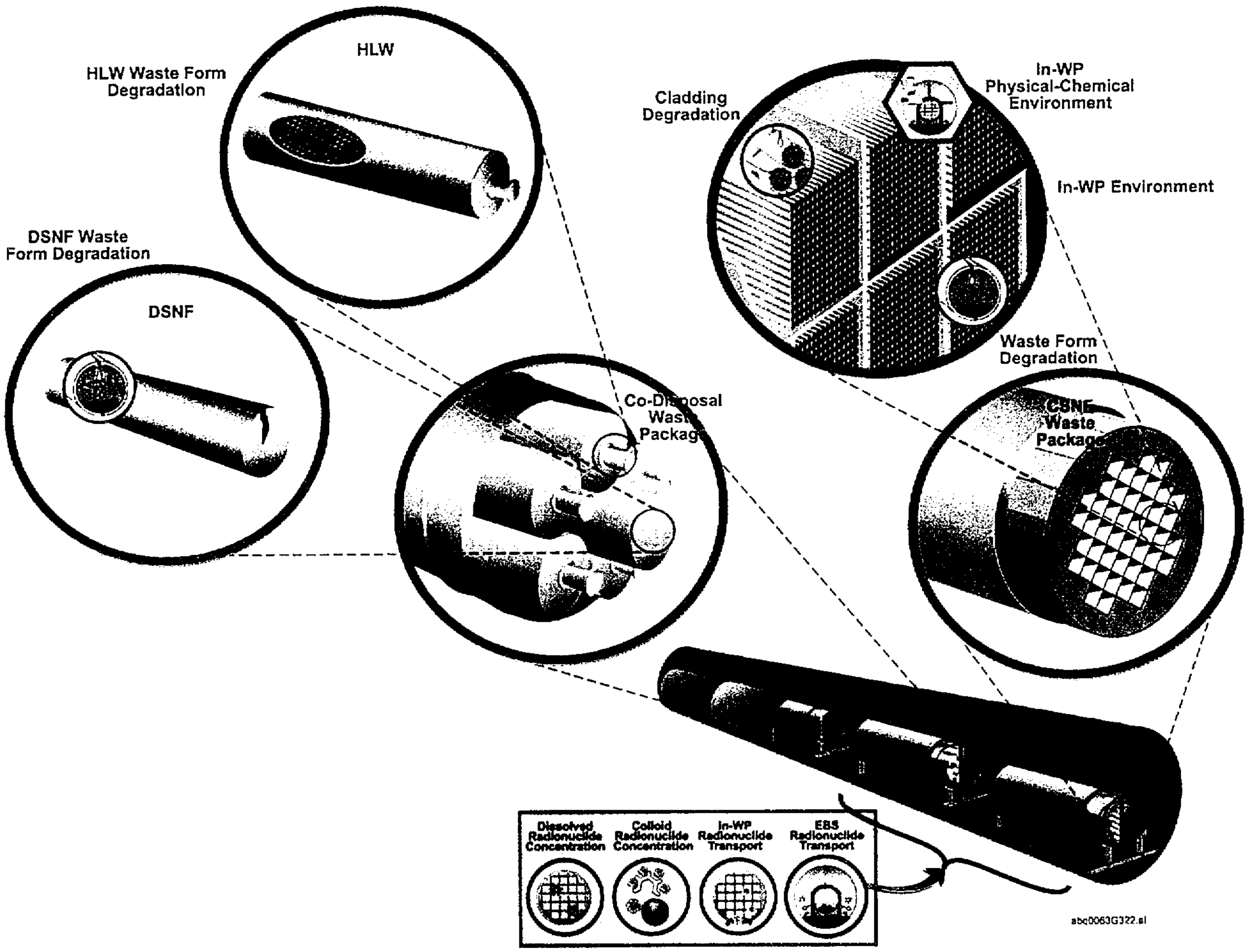

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Figure ES-7. Limiting Radionuclide Mobilization and Release Attribute

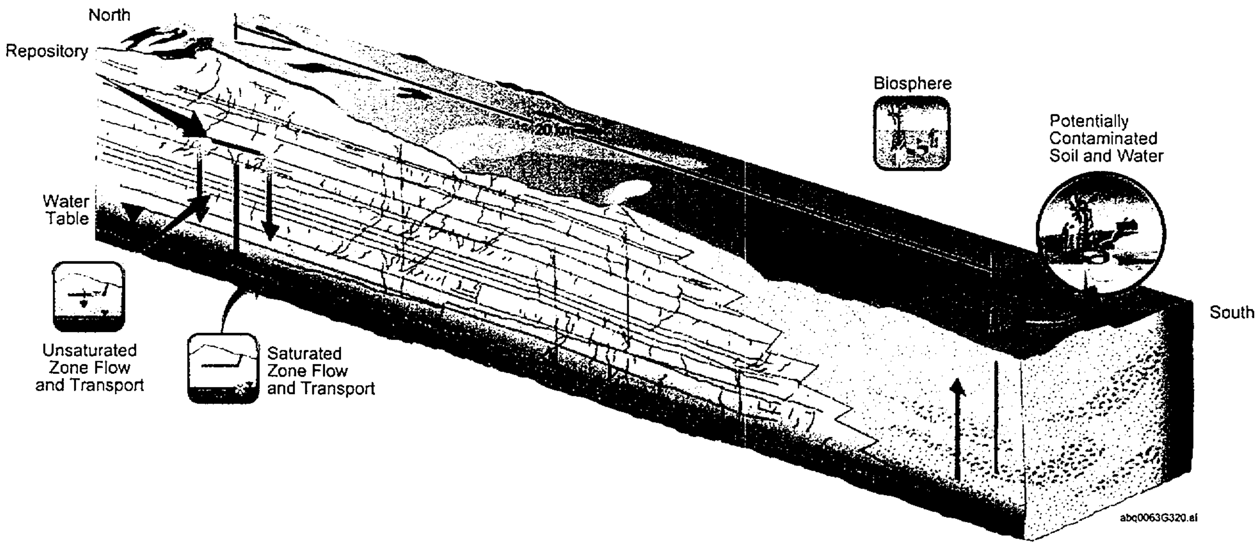

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Figure ES-8. Slow Radionuclide Transport Away from the Engineered Barrier System Attribute

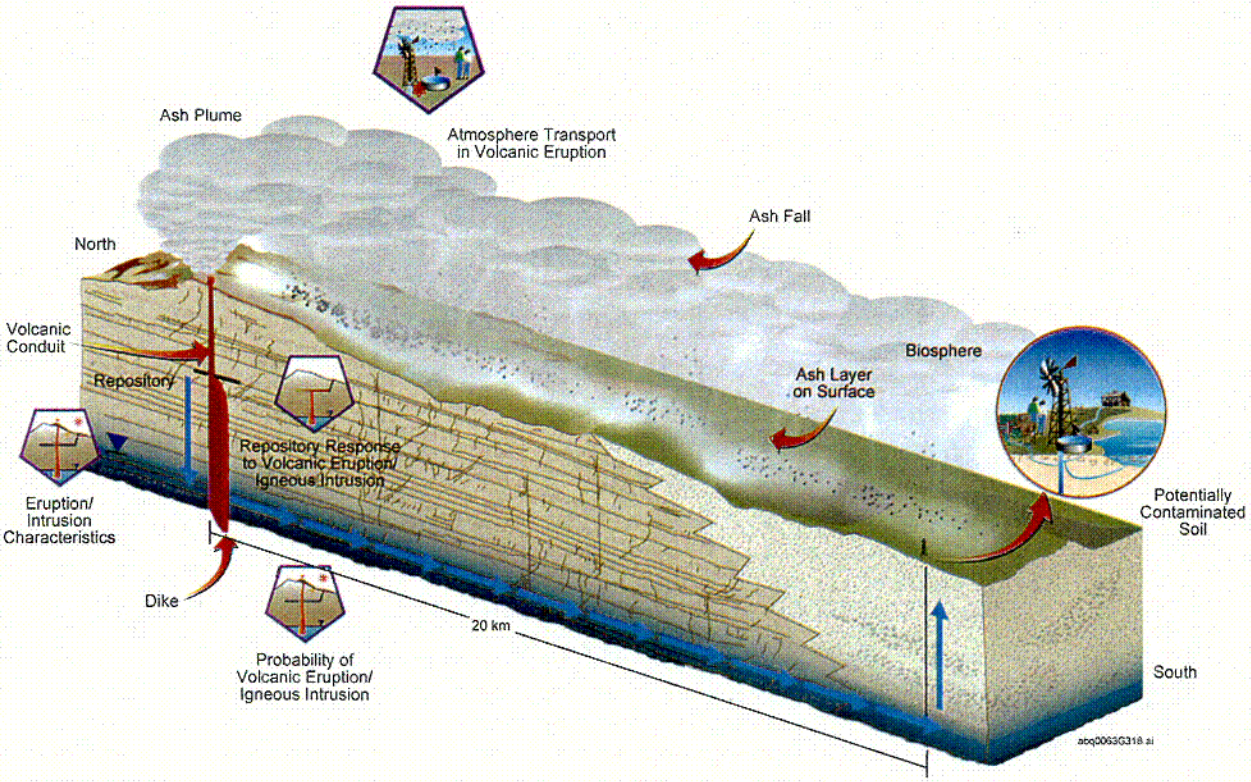

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Figure ES-9. Addressing Effects of Potentially Disruptive Events Attribute

C-2

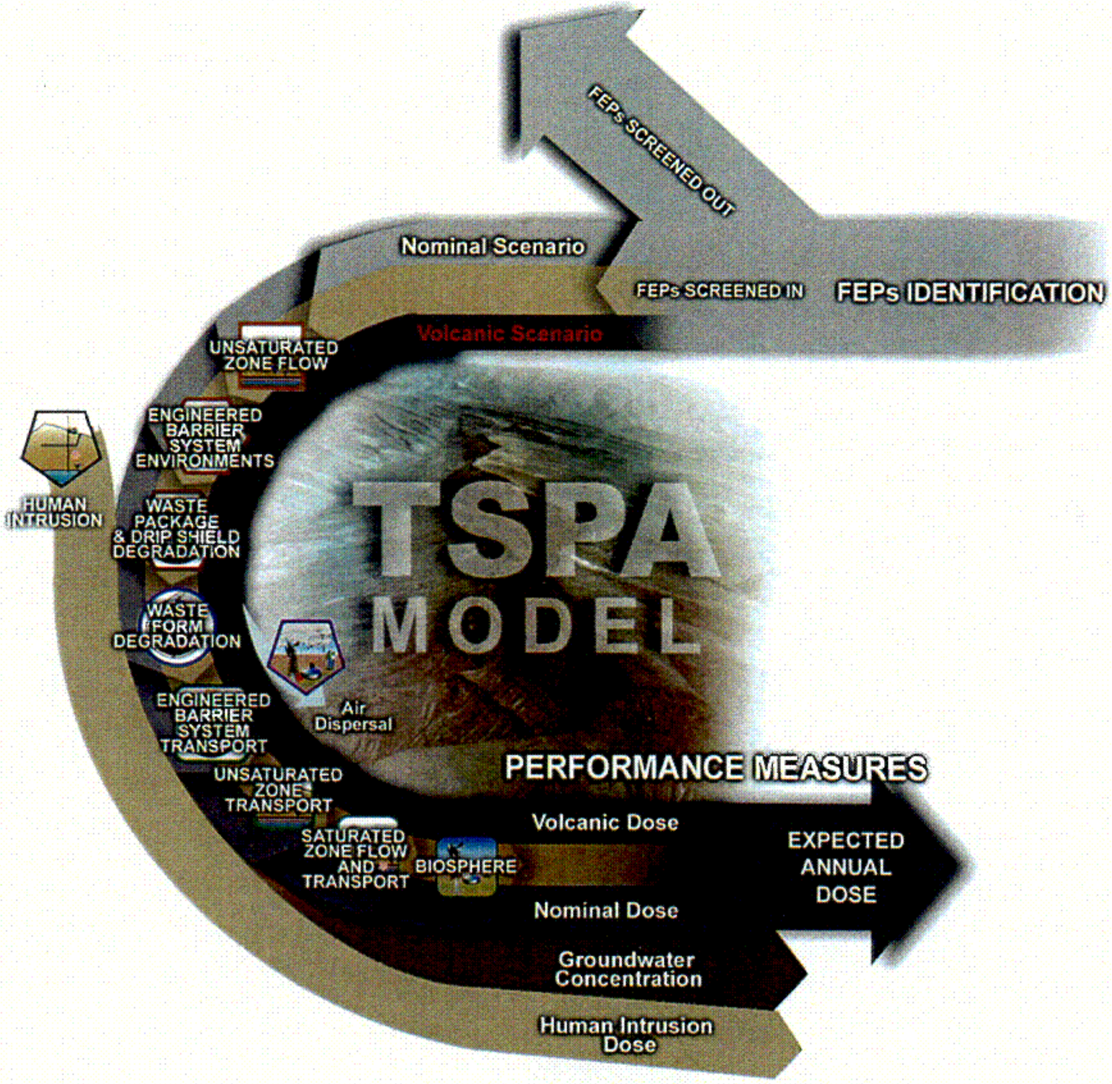

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Figure ES-10. Schematic Representation of the Development of TSPA-SR including the Nominal, Disruptive, and Human Intrusion Scenarios

C3

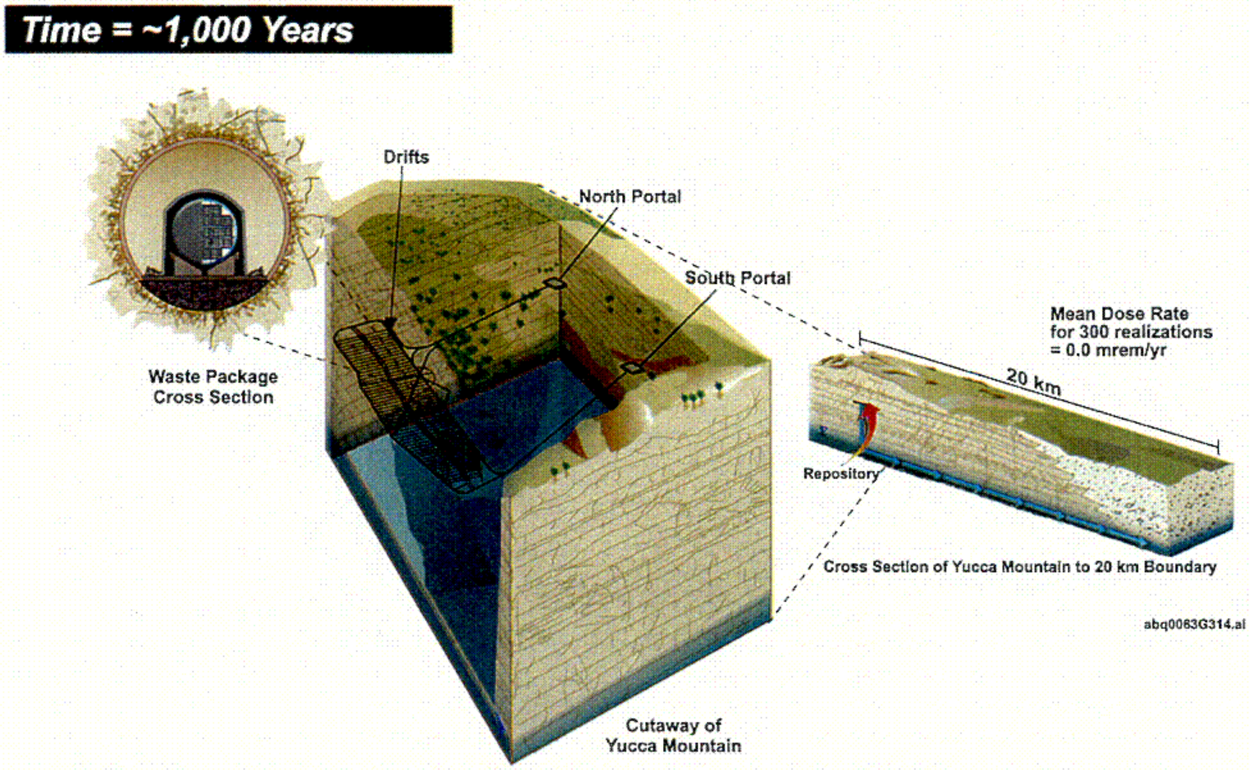

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Figure ES-11. Potential Radionuclide Release Conditions at About 1,000 Years

C-4

Time = ~10,000 Years

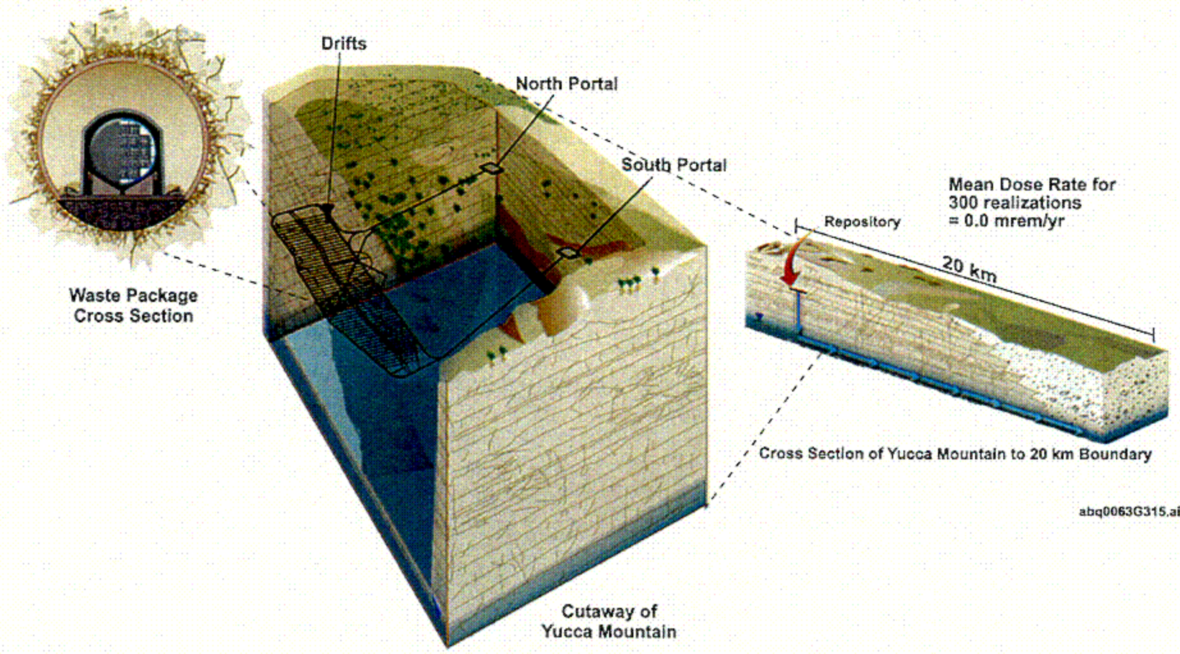

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Figure ES-12. Potential Radionuclide Release Conditions at About 10,000 Years

C-5

Time = ~50,000 Years

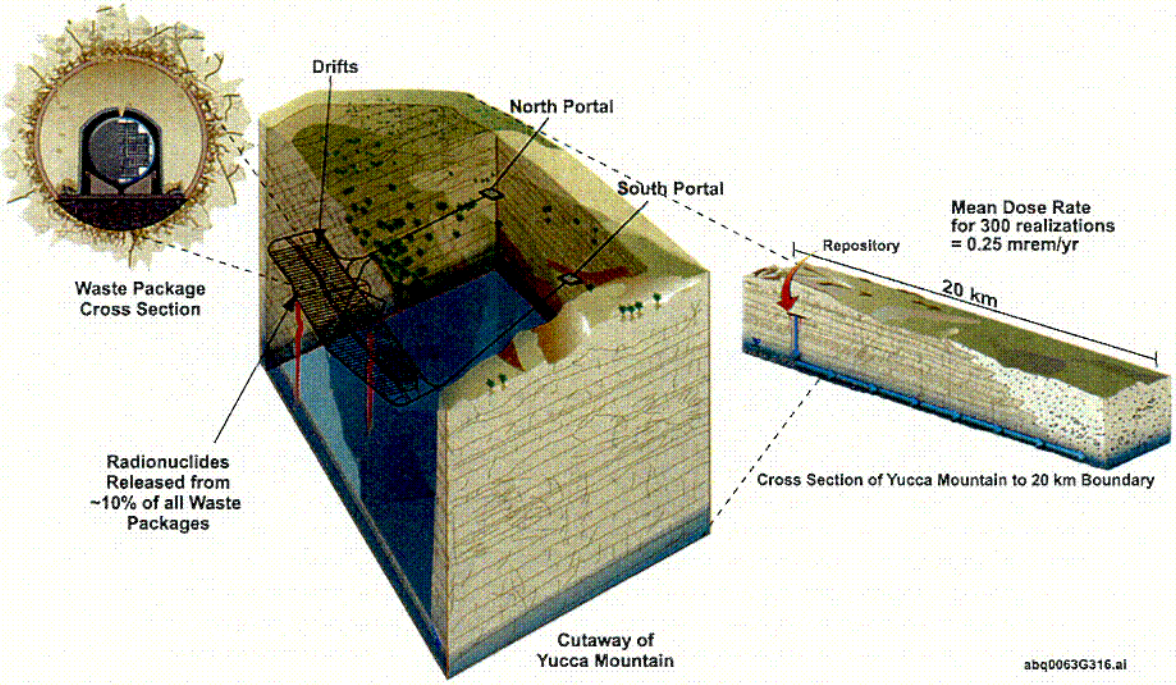

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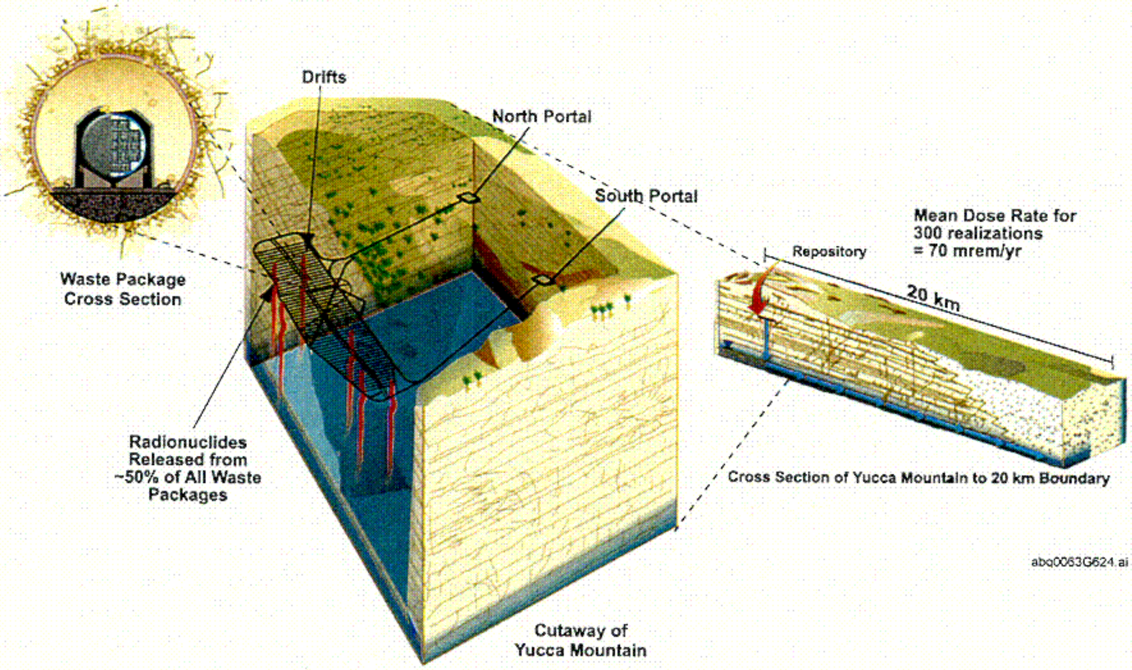
Figure ES-13. Potential Radionuclide Release Conditions at About 50,000 Years

C-6

Time = ~100,000 Years



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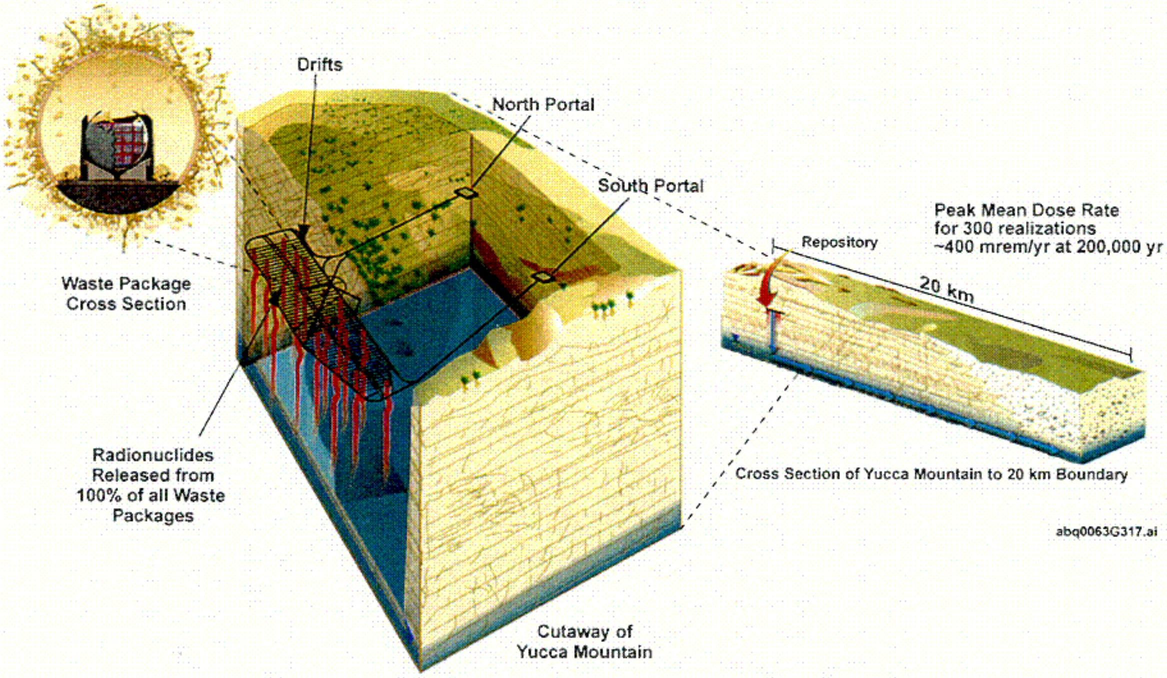
NOTE: The waste package cross section in the upper left is only applicable to the portion of waste packages experiencing the environmental conditions that may cause extensive general corrosion. The TSPA analyses detail the small number of waste packages that will experience such failure.

Figure ES-14. Potential Radionuclide Release Conditions at About 100,000 Years

C-7

Time = ~1,000,000 Years



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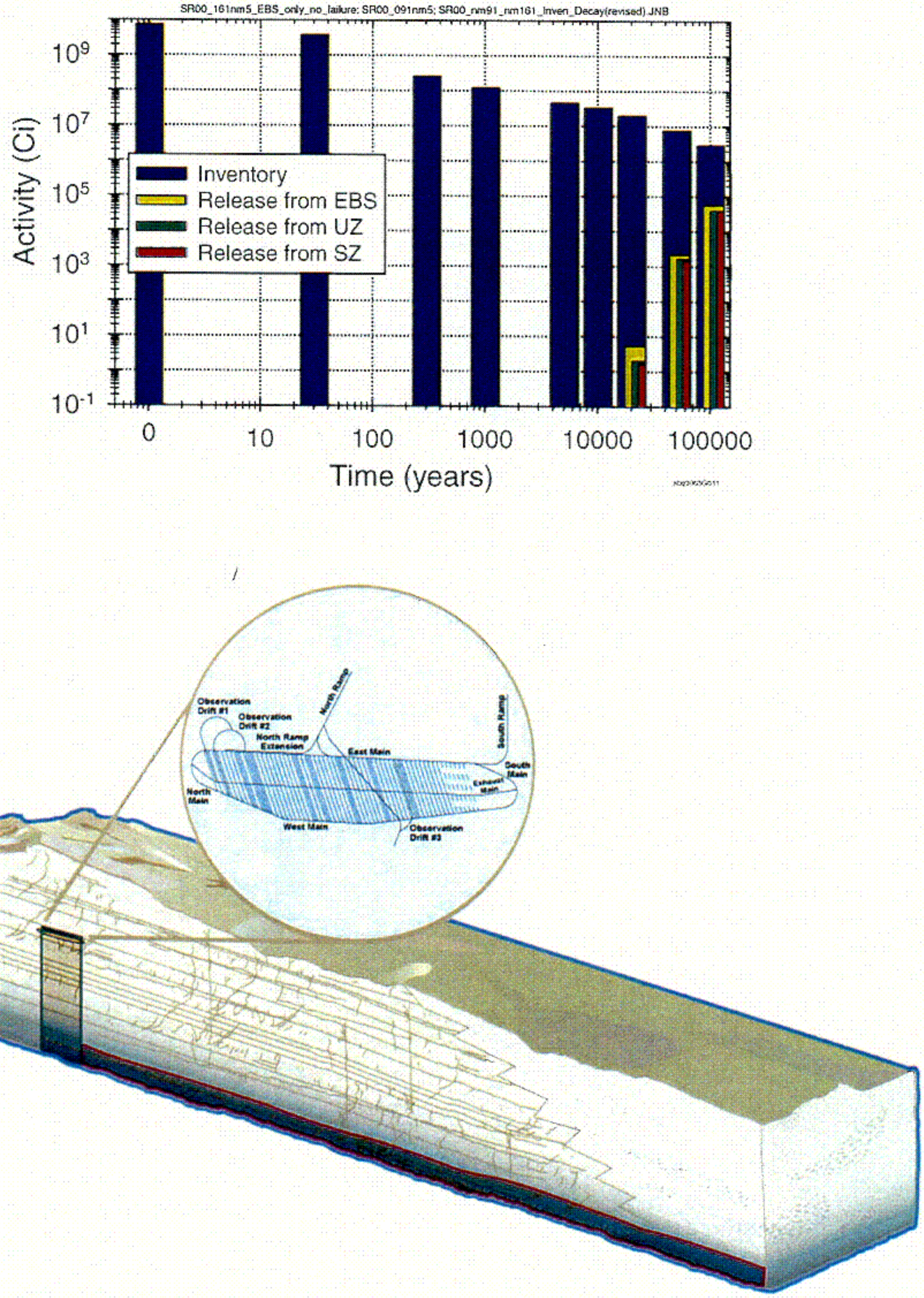
NOTE: The waste package cross section in the upper left is only applicable to the portion of waste packages experiencing the environmental conditions that may cause extensive general corrosion. Section 3.4 details the small number of waste packages that will experience such failure.

Figure ES-15. Potential Radionuclide Release Conditions at About 1,000,000 Years

C-8



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NOTE: The blue portion of the bar shows how much of the total radioactivity (in Curies) remains in the system at several points in time. The yellow portion shows the percentage of the remaining radioactivity that has passed through the floor of the repository into the underlying rock, the green indicates the amount of radioactivity that has reached the water table, and the red shows the amount that has moved to the accessible environment 20 km (12 miles) south of the repository. EBS - Engineered Barrier System; UZ - Unsaturated Zone; SZ - Saturated Zone.

Figure ES-16. Progressive Loss of Radioactivity Due to the Decay Process

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ACRONYMS AND ABBREVIATIONS

AMR	Analysis Model Report
BDCF	biosphere dose conversion factor
BWR	boiling water reactor
CDF	cumulative distribution function
CHLW	commercial high-level radioactive waste
CRM	corrosion resistant material
CSNF	commercial spent nuclear fuel
DFEP	disruptive feature, event, and process
DIRS	Document Input Reference System
DOE	U.S. Department of Energy
DSNF	DOE-owned spent nuclear fuel
EBS	engineered barrier system
EFEP	expected feature, event, and process
EIS	Environmental Impact Statement
EPA	U.S. Environmental Protection Agency
ESF	Exploratory Studies Facility
FEP	feature, event, and process
GVP	Gaussian variance partioning
HIC	hydrogen induced cracking
HLW	high-level radioactive waste
IRSR	Issue Resolution Status Report
KTI	key technical issue
LA	license application
MIC	microbiologically influenced corrosion
MTHM	metric tons of heavy metal
MTU	metric tons of uranium
NAS	National Academy of Sciences
NEA	Nuclear Energy Agency
NRC	U.S. Nuclear Regulatory Commission
NTS	Nevada Test Site
NWTRB	U.S. Nuclear Waste Technical Review Board
PMR	Process Model Report
PWR	pressurized water reactor

QA	quality assurance
RH	relative humidity
SCC	stress corrosion cracking
SNF	spent nuclear fuel
SR	site recommendation
SZ	saturated zone
THC	thermal-hydrologic-chemical
TEDE	total effective dose equivalent
TSPA	total system performance assessment
TSPA&I	Total System Performance Assessment and Integration
TSPA-LA	Total System Performance Assessment–License Application
TSPA-SR	Total System Performance Assessment–Site Recommendation
TSPA-VA	Total System Performance Assessment–Viability Assessment
UZ	unsaturated zone
VA	Yucca Mountain Site Characterization Project Viability Assessment
YMP	Yucca Mountain Site Characterization Project

RADIONUCLIDE ABBREVIATIONS

Ac	Actinium
Ar	Argon
Am	Americium
C	Carbon
Ce	Cerium
Cs	Cesium
I	Iodine
Pb	Lead
Ni	Nickel
Np	Neptunium
Pd	Palladium
Pu	Plutonium
Pa	Protactinium
Ra	Radium
Se	Selenium
Sr	Strontium

ACRONYMS AND ABBREVIATIONS (Continued)

Tc	Technetium
Th	Thorium
U	Uranium

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1. INTRODUCTION

This document reports the development of total system performance assessment (TSPA) for the site recommendation (SR). The first section defines the general process involved in developing any TSPA, describes the regulatory requirements for the Total System Performance Assessment-Site Recommendation (TSPA-SR), describes the overall TSPA process as implemented by programs in the United States and elsewhere in the world, and discusses the acceptability of TSPA as a process or tool for analyzing a nuclear waste repository system. It also presents information on previous TSPAs. Section 2 discusses the more specific use of the TSPA process for the TSPA-SR for Yucca Mountain, including approach and methods. Section 3 briefly discusses each of the component models that comprise the TSPA-SR. The TSPA-SR components are: unsaturated zone (UZ) flow, thermal hydrology, in-drift geochemical environment, engineered barrier system environments, waste package and drip shield degradation, waste form degradation, engineered barrier system (EBS) transport, UZ transport, saturated zone (SZ) flow and transport, and biosphere. For each of these components, this section introduces the conceptualization of each individual process, describes the data sources, and discusses model parameter development and computer methods used to simulate each component. Each TSPA component model represents a discrete set of processes. Volcanism is also included in this discussion. Section 4 explains the mechanics of how the individual TSPA components were combined into a nominal case, a disruptive case, and a combined case and provides the probabilistic results for each. In addition, the human intrusion analyses are presented. The section closes with a look at key disruptive events not included in the analyses and an alternative design case. Section 5 addresses sensitivity studies for each of the TSPA components to understand how uncertainty in various parameters within a component affect the TSPA results. Section 5 also contains a description of the probabilistic analyses and results that helps determine the relative importance of the various TSPA components or barriers and the data used to describe the components. Section 6 presents a summary of the findings of the sensitivity studies run on the various components in Section 5, and prioritizes the findings of the entire set of uncertainty and sensitivity studies of the components relative to each other. Section 6 also provides a discussion of factors affecting postclosure performance.

This document procedurally addresses the applicability of *Quality Assurance Requirements and Description* (QARD) (DOE 2000 [149540]) requirements to the work, systems, structures, components, models, analyses, and natural barriers that are discussed in the document. The document was prepared and the development of the model and analyses have been controlled utilizing the current quality assurance (QA) procedures for the project. The QAP-2-0, *Conduct of Activities* evaluation (CRWMS M&O 1999 [119602]), conducted by the Performance Assessment Department, concluded that all activities related to the development of this document or any information contained within it should be conducted utilizing the current QA procedures.

The methods used to control the electronic management of data as required by AP-SV.1Q [153202], *Control of the Electronic Management of Information*, were not specified in the Development Plan. With regard to the development of this report, the control of electronic management of data was evaluated in accordance with YAP-SV.1Q, *Control of the Electronic Management of Data*. The evaluation (CRWMS M&O 2000 [150105]) determined that current work processes and procedures are adequate for the control of electronic management of data for this activity. Though YAP-SV.1Q has been replaced by AP-SV.1Q, this evaluation remains in effect.

This document may be affected by technical product input information that requires confirmation. Any changes to the document that may occur as a result of completing the confirmation activities will be reflected in subsequent revisions. The status of the technical product input information quality may be confirmed by review of the DIRS database.

The document contains numerous appendices to provide additional detail on the TSPA-SR analyses that have been conducted, and to assist the reader in understanding the overall TSPA.

Appendix A–Provides a general glossary as well as a statistical terms glossary for the readers' use.

Appendix B–Provides a description of the feature, event, and process (FEP) database and the approach to development of the database. Tables summarizing the FEPs currently in the database are also provided.

Appendix C–Provides some useful analyses of natural analogs pertinent to the Yucca Mountain repository. In particular, comparisons are provided for radionuclide transport from Peña Blanca and volcanic eruption from Cerro Negro.

Appendix D–Provides useful correlation of the U.S. Nuclear Regulatory Commission's (NRC) Issue Resolution Status Reports (IRSRs) to the TSPA analyses and supporting documentation.

Appendix E–Provides a mapping of the inputs to the TSPA-SR model document (CRWMS M&O 2000 [148384]) from various supporting documents (Analysis Model Reports [AMRs]) in graphical and tabular form.

Appendix F–Provides a synthesis of the major assumptions and conservatisms in the TSPA-SR model. The assumptions may drive the results of the TSPA-SR performance, so it is crucial to understand them. The conservatisms may lead to poorer performance reported from the repository simulations than would be expected for a more realistic portrayal of the particular function involved. Often the conservatisms are utilized due to lack of defensible information concerning a particular process ongoing in the repository system.

Appendix G–Provides the data tracking information for the analyses conducted for the TSPA-SR. This information is listed in terms of data tracking numbers, model simulation run numbers, plot numbers, and so forth to provide ease of traceability of the analyses.

Appendix H–Provides a summary and response to review comments on previous Yucca Mountain TSPA iterations.

1.1 DEFINITION OF PERFORMANCE ASSESSMENT AND TOTAL SYSTEM PERFORMANCE ASSESSMENT

Performance assessment and TSPA are terms with very specific meanings in the high-level radioactive waste (HLW) management community. The process of constructing and implementing a TSPA is often described as a pyramid, where detailed information representing the various processes and components of a total system are distilled and linked into progressively more abstracted models used to analyze system performance.

1.1.1 Explanation of a Total System Performance Assessment

Performance assessment is a method of forecasting how a system, or parts of a system, designed to contain radioactive waste will behave over time. Its goal is to aid in determining whether the system can meet established performance requirements. A TSPA is the subset of performance assessment analyses in which all of the components of a system are linked into a single analysis.

The word forecast, rather than predict, is used to describe the expected outcome of a TSPA. Predict implies inference from facts or accepted laws of nature. Forecast has a similar meaning, but also implies anticipating eventualities and differs from predict in usually being concerned with probabilities instead of certainties. As discussed in Section 1.4, incorporation of probabilities and uncertainty is a critical aspect of TSPA which allows determination of reasonable assurance, as defined by regulatory agencies. However, it must be noted that NRC uses the term predictive models to express what NRC anticipates in proposed 10 CFR Part 63 (64 FR 8640 [101680]). (Note that whenever this document makes direct reference to 10 CFR 63 this document conveys a corresponding reference to Interim Guidance [Dyer 1999 [105655]]) The NRC defines a performance assessment as a probabilistic analysis that:

> (1) identifies the features, events and processes that might affect the performance of the geologic repository; and (2) examines the effects of such features, events, and processes on the performance of the geologic repository; and (3) estimates the expected annual dose to the average member of the critical group as a result of releases from the geologic repository. (10 CFR 63.2)

The process of performance assessment is somewhat different from a safety assessment or a probabilistic risk assessment. Safety assessments use a conservative bounding assessment of the entire system; performance assessments analyze the best understanding of the system and its components (Nuclear Energy Agency (NEA) 1995 [100480], pp. 28 to 36). In a safety assessment, a given process or event is assumed to happen, regardless of the likelihood of its occurrence. A performance assessment incorporates more information than a safety assessment by assuming that some processes or events are more likely to happen than others, and treating them accordingly in mathematical modeling. However, for some processes or events where information is limited, bounding analyses may be used in the performance assessment. The benefit of a performance assessment in this case is that a more realistic and, therefore, more defensible case is used. It must be noted that, in the community of nuclear waste management professionals, the distinction between a safety assessment and a performance assessment has become blurred such that, in informal usage, they are often used interchangeably. However, it is important to differentiate the two philosophies (i.e., use of conservative bounding cases versus use of the most realistic models possible). In addition, a safety case, as made before a licensing authority, could include both safety assessments and performance assessments as defined above.

Probabilistic risk assessment is a term generally applied to safety studies of nuclear power plants or other engineered systems, but it can be applied to any system that could fail in identifiable ways. Although this type of analysis incorporates variations in probability for different processes, the system and the time periods are very different than those used in a performance assessment. A probabilistic risk assessment is usually performed for discrete events of limited duration involving an engineered system and its components. Natural events such as earthquakes and volcanic eruptions are considered initiating events that may have an effect on overall system behavior, but are not a part of the system. The components can be tested on a time scale similar to that for the operational life of the system. Therefore, a set of requirements and specifications for these components is available, and the analyses are performed against criteria that have been, or can be, tested and validated.

A performance assessment treats both the engineered and natural system components. The engineered system is, to some extent, controllable, but the natural system is not. The responses of the total system extend over periods beyond those for which data have been, or can be, obtained.

1.1.2 The Performance Assessment Pyramid

The process for constructing a TSPA is shown in Figure 1.1-1 and described in more detail in Section 1.4. The Performance Assessment Pyramid shows how more detailed underlying information builds the technical basis for the total system models. The breadth of the lowest level of the pyramid represents the complete suite of process and design data and information (i.e., field and laboratory studies that are the first step in understanding the system). The next (higher) level indicates how these data are used to develop conceptual models as well as numerical process models of how the various individual system components are expected to perform under the anticipated repository-relevant conditions. Most of the information at these lower levels (e.g., data, conceptual models, and detailed process models) is synthesized in the Process Model Reports (PMRs) listed below.

- *Biosphere Process Model Report* (CRWMS M&O 2000 [151615])
- *Engineered Barrier System Degradation, Flow, and Transport Process Model Report* (CRWMS M&O 2000 [145796])
- *Waste Form Degradation Process Model Report* (CRWMS M&O 2000 [138332])
- *Integrated Site Model Process Model Report* (CRWMS M&O 2000 [146988])
- *Near Field Environment Process Model Report (PMR)* (CRWMS M&O 2000 [153178])
- *Saturated Zone Flow and Transport Process Model Report* (CRWMS M&O 2000 [145738])
- *Disruptive Events Process Model Report* (CRWMS M&O 2000 [141733])

- *Unsaturated Zone Flow and Transport Model Process Model Report* (CRWMS M&O 2000 [145774])

- *Waste Package Degradation Process Model Report* (CRWMS M&O 2000 [138396]).

The next (higher) level represents the synthesis of information from the lower levels of the pyramid into computer models. At this point, the subsystem behavior may be described by linking models together into representations, as described in Section 3. At this point performance assessment modeling usually begins. The term abstraction is used here to indicate the extraction of essential information. That is, information that is required to enable determination of the effect of a particular process on the overall system performance. In some cases, very little detail is eliminated from the data or the process model to develop the abstraction. Some of the component models are really linkage with a detailed process model. In other cases, the component model may be largely insignificant to performance, and may be reduced to only providing a limited set of information to the TSPA model. The abstraction though, must still represent the characteristics of the component model well enough for the overall TSPA to be a useful representation of the system.

The upper level shows the final level of distillation of information into the most critical aspects necessary to represent the total system. At this point, all of the models are linked together in the TSPA model. These are the models used to forecast total system behavior and estimate the likelihood that the behavior will comply with regulations and ensure long-term safety.

As information flows up the pyramid, it is generally distilled into progressively more simplified forms, or becomes more abstracted, as indicated in Figure 1.1-1. However, abstraction is not synonymous with simplification. If a particular component model can not be simplified without losing essential aspects of the model, it ceases to move up the pyramid and becomes part of the TSPA calculation tool. Thus, an abstracted model in a TSPA may take the form of something as simple as a table of values that were calculated using a complex computer model. The abstraction may also take the form of a fully three-dimensional computer simulation. It must be noted that even the most complex models of specific processes are still an abstraction of reality.

There are also some considerations that dictate the level of complexity used to represent a process. One is the sensitivity of the results of the TSPA to that particular process. The more sensitive the process or parameter, the more detailed the model representation tends to be. However, the degree of complexity is also limited by the state of knowledge concerning the model. It is very important not to misrepresent the degree of understanding about a process by embedding it in an overly complicated computer model.

Another aspect of the development of the TSPA model is the use of conservatism in the assumptions chosen to assist in development of the model. These conservative assumptions are utilized for several reasons including lack of data, incomplete knowledge of the uncertainty of a feature, and inability either from resources or timing to defend potentially positive performance, where "defensibility" in the licensing arena is a project objective. The major conservatism in the assumptions is presented in Appendix F. Conservative is used here to indicate that the assumption or model used may underestimate the positive performance of a particular part of the repository system, but allows a more defensible position for the analyses. Alternatively, conservatism may cause negative performance to be overstated which is potentially problematic if additional resources are required to bolster engineered systems to overcompensate for the conservatism embedded in the analyses. The project is undergoing a significant review of conservatism, and may cause some redirection in this area for future iterations of TSPA.

Subsystem level conservatism may not significantly impact the TSPA-SR model performance. However, there is a risk of compounding conservatism if multiple aspects of the system are given conservative or under performing characteristics that may lead to significantly degraded overall performance. This can be evaluated using less conservative assumptions for features of the repository system that are known to be important to performance.

1.2 OBJECTIVES OF TOTAL SYSTEM PERFORMANCE ASSESSMENT FOR THE SITE RECOMMENDATION

The objective of the TSPA for the SR, based on design concepts and scientific data and analysis currently available, is to provide an assessment of repository performance at the potential Yucca Mountain Site as part of the site recommendation process. The scope of the TSPA is guided by technical requirements proposed by the NRC at proposed 10 CFR Part 63 (64 FR 8640 [101680]), and radiation protection standards proposed by the EPA at proposed 40 CFR 197 (64 FR 46976 [105065]). The analyses must be traceable and transparent.

Assessing the performance of the system requires the following:

- Assimilating all the available scientific data and analyses that describe the geological setting into which the design concept is to be placed
- Defining the design concept that is to be used
- Describing the behavior of the potential repository system in a traceable, transparent manner
- Identifying the performance standards by which the TSPA will be judged.

The total system is comprised of geological and engineering components. Therefore, the TSPA uses the available scientific information about naturally occurring physical and chemical processes at the Yucca Mountain site. In addition, the TSPA includes the design concepts and scientific information about physical and chemical processes involving the engineered components.

The current overall system-performance standards utilized for this analysis of the potential Yucca Mountain repository are found in proposed 10 CFR Part 63 (64 FR 8640 [101680]) and proposed 40 CFR Part 197 (64 FR 46976 [105065]).

The U.S. Nuclear Regulatory Commission (NRC), in proposed 10 CFR Part 63 (64 FR 8640 [101680]), provided a measure of system performance that limits the annual committed dose from radionuclides released from the facility to the average member of the critical group residing in a farming community located 20 km downgradient from the potential repository. This distance was chosen to correspond to Lathrop Wells, the closest existing public or private well to the site, near the intersection of U.S. Highway 95 and Nevada State Route 373. The controlled area boundary for the DOE Nevada Test Site (NTS) also is approximately 20 km from the potential repository. Per proposed 10 CFR Part 63 (64 FR 8640 [101680]), the analyses must demonstrate "reasonable assurance" that the expected dose to the average member of the critical group will not exceed 25 mrem in 10,000 years. Per proposed 40 CFR Part 197 (64 FR 46976 [105065]), the DOE must demonstrate a "reasonable expectation" that a dose of 15 mrem/yr will not be attained in 10,000 years.

While the regulations require evaluation of a 10,000-year time period, the TSPA analyses will evaluate the consequences caused by the potential repository beyond that period. The analyses are extended to 100,000 and 1 million years in determining when the peak radionuclide doses or peak risk occurs. The analyses beyond 10,000 years are providing information to support assessments contained in the Program's Environmental Impact Statement (EIS) that will accompany the Site Recommendation (SR) to the President.

Although the goal of the TSPA is to provide a quantitative assessment of the performance of the potential repository system, it is important to recognize the uncertainties inherent in such analyses. The U.S. Environmental Protection Agency (EPA) and the NRC have recognized the care required in defining the degree of confidence needed from the analyses. EPA stated that (proposed 40 CFR 197.14(a) [64 FR 46976 [105065]]):

> Reasonable expectation: (a) requires less than absolute proof because absolute proof is impossible to attain for disposal due to the uncertainty of projecting long term performance; (b) is less stringent than the reasonable assurance concept that NRC uses to license nuclear power plants; (c) takes into account the inherently greater uncertainties in making long-term projections of the performance of the Yucca Mountain disposal system; (d) does not exclude important parameters from assessments and analyses simply because they are difficult to precisely quantify to a high degree of confidence; and (e) focuses performance assessments and analyses upon the full range of defensible and reasonable parameter distributions rather than only upon extreme physical situations and parameter values.

NRC also underscored this point in its discussion of reasonable assurance (10 CFR Part 60 [103540]):

> The Commission anticipates that licensing decisions will be complicated by the uncertainties that are associated with predicting the behavior of a geologic repository over the thousands of years during which HLW may present hazards to public health and safety.

These inherent uncertainties were recognized in developing the analysis tools that are described in Sections 2.2 and Section 3 of this volume. The potential effects of many of these uncertainties are presented in Section 5.

Given the uncertainty involved in a postclosure performance assessment, an important goal is to produce a transparent document describing the assumptions, the intermediate steps, the results, and the conclusions of the analyses.. The U.S. Nuclear Waste Technical Review Board (NWTRB) states that "transparency is the ease of understanding the process by which a study was carried out, which assumptions are driving the results, how they were arrived at, and the rigor of the analyses leading to the results" (NWTRB 1998 [100482], p. 21). The TSPA Peer Review Panel notes that "transparency is achieved when a reader or reviewer has a clear picture of what was done in the analysis, what the outcome was, and why" (Budnitz et al. 1997 [100427], pp. 9 to 10).

For the reader to have confidence in the analyses, the presentation must illustrate with sufficient clarity the following attributes:

- The conceptual basis for the individual components in the quantitative analyses (i.e., how the system is intended to work, which is presented in Section 2.1)
- How individual components are combined into an assessment of system behavior (Sections 2.2 and 4.1)
- The scientific understanding used to develop the quantitative analysis tools that describe the system's expected evolution (Sections 3.1 to 3.10)
- The system's expected evolution as defined by the spatial and temporal response of the system to waste emplacement (Sections 4.1 and 4.2)
- Uncertainty in the system's expected evolution and the significance of that uncertainty to the system-performance goals (Section 5).

1.3 REGULATORY REQUIREMENTS FOR THE TOTAL SYSTEM PERFORMANCE ASSESSMENT FOR THE SITE RECOMMENDATION

The regulatory requirements for the TSPA-SR have been almost three decades in the making. In 1978, an Interagency Review Group on Nuclear Waste Management began coordinating the interrelated activities already underway within the EPA, the NRC, and the DOE. Congress passed the Nuclear Waste Policy Act of 1982 [100014], Public Law No. 97-425, to establish the national policy. The three rules pertinent to this TSPA-SR were proposed in rulemaking proceedings for public review and comment in 1999. These rules, proposed 40 CFR Part 197 (64 FR 46976 [105065]), proposed 10 CFR Part 63 (64 FR 8640 [101680]), and proposed 10 CFR Part 963 (64 FR 67054 [124754]), define the relationships among the EPA, NRC, and DOE regarding the potential Yucca Mountain repository. This section of the TSPA-SR summarizes the developments leading to these regulations, and focuses on the resulting requirements for TSPA. Figure 1.3-1 illustrates the timeline of pertinent lawmaking and rulemaking events. The section discusses the method established by the NRC to track important issues in potential repository performance, with emphasis on the TSPA. A regulatory framework is provided for the analyses and results presented in this TSPA-SR.

1.3.1 Nuclear Waste Policy Act of 1982, as Amended

The foundation for the Nuclear Waste Policy Act of 1982 [101681], 42 U.S.C. 10101 et seq., was laid in the Nuclear Waste Policy Act of 1982 [100014], Public Law No. 97-425, which selected permanent disposal in deep geologic repositories to "provide a reasonable assurance that the public and the environment will be adequately protected from the hazards posed by [SNF and HLW]" (Nuclear Waste Policy Act of 1982 [100014], Public Law No. 97-425). The act established the DOE authority and responsibility for siting, constructing, and operating such repositories. It also assigned regulatory roles to the EPA and the NRC. In the Nuclear Waste Policy Amendments Act of 1987 [100016], Public Law No. 100-203, Congress amended the NWPA to designate Yucca Mountain as the only site to be characterized. Congress again amended the NWPA (DOE 1995 [122137]) in the Energy Policy Act of 1992 [100017], Public Law No. 102-486, That act also directed the EPA to promulgate radiation protection standards specifically for Yucca Mountain and directing the NRC to modify its technical requirements and criteria (10 CFR Part 60 [48 FR 28194 [100475]]) to be consistent with the new EPA standards. Congress required the EPA to contract with the National Academy of Sciences (NAS) to study radiation protection standards before setting the new standard. The new EPA standards are required to be based upon and consistent with the NAS findings and recommendations.

In *Technical Bases for Yucca Mountain Standards* (National Research Council 1995 [100018]), the NAS recommended an approach and content significantly different from those previously adopted by the EPA and the NRC. The NAS determined that analyses of potential repository behavior covering thousands of years are scientifically justifiable and possible. They found that a health standard based on risk to individuals of adverse health effects from releases from the potential repository (instead of the generic standards at 40 CFR Part 191 (58 FR 66398 [107802]), which contain both individual dose and release limits) would adequately protect the general public. They also found that predictions regarding the probability that a potential repository will be breached by human intrusion during a period of 10,000 years cannot be scientifically supported. The NAS recommended that the EPA include in its regulations a stylized human intrusion event to provide insight into the degree to which an intrusion would degrade the performance of a potential repository. The NAS concluded that the performance of the total system, rather than that of its individual elements in isolation, is crucial in the context of a risk-based standard, because subsystem performance requirements could result in a deficient potential repository design even if each subsystem element meets or exceeds the performance standard. The TSPA approach has been employed at Yucca Mountain since 1991.

1.3.1.1 U.S. Environmental Protection Agency Authority and Responsibility

The Nuclear Waste Policy Act of 1982 [101681], 42 U.S.C. 10101 et seq., as originally enacted directed the EPA to promulgate generic radiation standards, thus ensuring that the regulatory requirements for a potential repository would be set independently of potential repository development. In the Energy Policy Act of 1992 [100017], Public Law No. 102-486, Congress separated the EPA's health-based standard for Yucca Mountain from the generic EPA standards promulgated at 40 CFR Part 191 (58 FR 66398 [107802]). Congress also gave the EPA sole authority to set public health and safety radiation standards for Yucca Mountain. The EPA published proposed standards at proposed 40 CFR Part 197 (64 FR 46976 [105065]) on August 27, 1999.

1.3.1.2 U.S. Nuclear Regulatory Commission Authority and Responsibility

Under the Nuclear Waste Policy Act of 1982 [101681], 42 U.S.C. 10101 et seq., as amended, the NRC was directed to establish technical requirements and criteria, consistent with any comparable EPA standards, providing for the use of a system of multiple barriers and, if deemed appropriate, restricting retrievability. The Energy Policy Act of 1992 [100017], Public Law No. 102-486, requires the NRC to conduct a licensing proceeding before authorizing the construction of a potential repository. Separate licensing proceedings will also be required for authorization of operation and closure of the potential repository. The Nuclear Waste Policy Act of 1982 [101681], 42 U.S.C. 10101 et seq., as amended also required the NRC to modify its technical requirements and criteria within one year after the establishment of final EPA standards. The proposed regulations, 10 CFR Part 63 (64 FR 8640 [101680]) were published February 22, 1999. The NRC's technical requirements and criteria for construction, operation, and closure of a potential geologic repository will have a broader role for Yucca Mountain than just to implement the EPA standards. Those regulations will govern the licensing process if the Yucca Mountain site is recommended by the Secretary to the President, approved by the President, and is designated by Congress under the Nuclear Waste Policy Act of 1982, 42 U.S.C. 10101 et seq [101681]. However, the EPA standards drive the NRC performance objectives that determine the complexity of this TSPA-SR.

1.3.1.3 U.S. Department of Energy Authority and Responsibility

After Congress assigned to the DOE the responsibility to dispose of SNF and HLW in geologic repositories, the DOE promulgated guidelines for recommending candidate sites for site characterization at proposed 10 CFR Part 960 (49 FR 47714 [100562]). The *Site Characterization Plan Overview, Yucca Mountain Site, Nevada Research and Development Area, Nevada* (DOE 1988 [100281]) was required to include criteria for determining the suitability of a site for the location of a potential repository. In the Nuclear Waste Policy Act of 1982 [101681], 42 U.S.C. 10101 et seq., Congress also addressed site recommendation, approval, and construction authorization, which can only proceed as site characterization activities near completion. After Congress approves the site, the DOE must submit an application to the NRC for a construction authorization. The DOE has proposed new guidelines at proposed 10 CFR Part 963 (64 FR 67054 [124754]), published November 30, 1999. These guidelines provide detailed requirements for the TSPA, are consistent with the proposed NRC regulations, and adhere to the applicable radiation protection standards.

1.3.1.4 Synopsis of Performance Measures for the Postclosure Period

Whether the site can be determined to be suitable for recommendation depends on the estimated capability of the potential repository to satisfy the radiation protection standards. The NRC rule was developed in parallel with the EPA standards. As a result, the EPA and the NRC proposed different dose limits, the EPA proposed a ground water protection standard, and different approaches were taken for consideration of human intrusion. The DOE has, therefore, proposed to base its suitability determination on the "applicable radiation protection standard," i.e., the final EPA standard as implemented by the NRC (64 FR 67054 [124754], pp. 67074 and 67075). Tables 1.3-1, 1.3-2, and 1.3-3 present the proposed performance measures for the postclosure period contained in the three proposed rules.

Table 1.3-1. Proposed Performance Measures for Postclosure–Undisturbed Performance

Rule	Performance Measure
EPA Proposed 40 CFR PART 197	Individual-Protection Standard. 197.20 The DOE must demonstrate, using performance assessment, that there is a reasonable expectation that for 10,000 years following disposal the reasonably maximally exposed individual receives no more than an annual committed effective dose equivalent of 150 microsieverts (15 mrem) from releases from the undisturbed Yucca Mountain disposal system. The DOE's analysis must include all potential pathways of radionuclide transport and exposure. Ground Water Protection Standards. 197.35. In its license application to NRC, DOE must provide a reasonable expectation that, for 10,000 years of undisturbed performance after disposal, releases of radionuclides from radioactive material in the Yucca Mountain disposal system will not cause the level of radioactivity in the representative volume of ground water at the point of compliance to exceed Combined 226Ra and 226Ra: 5 pCi/L including natural background Gross alpha activity (including 226Ra but excluding radon and uranium): 15 pCi/L including natural background Combined beta and photon emitting radionuclides: 40 mSv/yr. (4 mrem/yr.) to the whole body or any organ.
NRC Proposed 10 CFR PART 63	63.113 Performance Objective For The Geologic Repository After Permanent Closure. (a) The geologic repository shall include multiple barriers, consisting of both natural barriers and an engineered barrier system. (b) The engineered barrier system shall be designed so that, working in combination with natural barriers, the expected annual dose to the average member of the critical group shall not exceed 0.25 mSv (25 mrem) TEDE (total effective dose equivalent) at any time during the first 10,000 years after permanent closure, as a result of radioactive materials released from the geologic repository. (c) The ability of the geologic repository to limit radiological exposures to those specified in 63.113(b) shall be demonstrated through a performance assessment that meets the requirements specified at 63.114, uses the reference biosphere and critical group specified at 63.115, and excludes the effects of human intrusion.
DOE Proposed 10 CFR PART 963	963.15 Postclosure Suitability Determination. DOE will apply the method and criteria described in Sections 963.16 and 963.17 to evaluate the suitability of the Yucca Mountain site for the postclosure period. If DOE finds that the results of the total system performance assessments conducted under 963.16(a)(1) show that the Yucca Mountain site is likely to meet the applicable radiation protection standard, DOE may determine the site suitable for the postclosure period. 963.16 Postclosure Suitability Evaluation Method. (a) DOE will evaluate postclosure suitability using the [TSPA] method.... (1) DOE will conduct a [TSPA] to evaluate the ability of the geologic repository to limit radiological exposures in the case where there is no human intrusion into the repository. DOE will model the performance of the geologic repository at the Yucca Mountain site using the method described in 963.16(b) and the criteria in Sec 963.17, excluding the criterion in 963.17(b)(4). DOE will consider the performance of the system in terms of the criteria to evaluate whether the geologic repository is likely to comply with the applicable radiation protection standard.

Sources: Proposed 10 CFR Part 63 (64 FR 8640 [101680]); proposed 40 CFR Part 197 (64 FR 46976 [105065]); proposed 10 CFR Part 963 (64 FR 67054 [124754])

NOTES: [1] Undisturbed performance means that human intrusion or the occurrence of "unlikely," disruptive, natural processes and events do not disturb the disposal system (64 FR 46976 [105065], p. 47014). The DOE defined disruptive features, events, and processes (DFEPs) to mean FEPs having a probability of occurrence during the period of performance of less than 1.0 but greater than 10^{-4} in 10^4 years (CRWMS M&O 1999 [123126], App. A).

[2] The EPA proposes to interpret the term "undisturbed," used by the NAS in its recommendations, to mean that the Yucca Mountain disposal system would not be disturbed by human intrusion, but could be disturbed by other processes or events that are "likely" to occur (64 FR 46976 [105065], p. 46998).

Table 1.3-2. Proposed Performance Measures for Postclosure Period–Disturbed Performance

Rule	Performance Measure
EPA Proposed 40 CFR PART 197	Individual-Protection Standard. 197.20 The DOE must demonstrate, using performance assessment, that there is a reasonable expectation that for 10,000 years following disposal the reasonably maximally exposed individual receives no more than an annual committed effective dose equivalent of 150 microsieverts (15 mrem) from releases from the undisturbed Yucca Mountain disposal system. The DOE's analysis must include all potential pathways of radionuclide transport and exposure.
NRC Proposed 10 CFR PART 63	63.113 Performance Objective For The Geologic Repository After Permanent Closure. (a) The geologic repository shall include multiple barriers, consisting of both natural barriers and an engineered barrier system. (b) The engineered barrier system shall be designed so that, working in combination with natural barriers, the expected annual dose to the average member of the critical group shall not exceed 0.25 mSv (25 mrem) TEDE [total effective dose equivalent] at any time during the first 10,000 years after permanent closure, as a result of radioactive materials released from the geologic repository. (c) The ability of the geologic repository to limit radiological exposures to those specified in 63.113(b) shall be demonstrated through a performance assessment that meets the requirements specified at 63.114, uses the reference biosphere and critical group specified at 63.115, and excludes the effects of human intrusion.
DOE Proposed 10 CFR PART 963	963.15 Postclosure Suitability Determination. DOE will apply the method and criteria described in Sections. 963.16 and 963.17 to evaluate the suitability of the Yucca Mountain site for the postclosure period. If DOE finds that the results of the total system performance assessments conducted under [§963.16(a)(1)] show that the Yucca Mountain site is likely to meet the applicable radiation protection standard, DOE may determine the site suitable for the postclosure period. 963.16 Postclosure Suitability Evaluation Method. (a) DOE will evaluate postclosure suitability using the [TSPA] method.... (1) DOE will conduct a [TSPA] to evaluate the ability of the geologic repository to limit radiological exposures in the case where there is no human intrusion into the repository. DOE will model the performance of the geologic repository at the Yucca Mountain site using the method described in 963.16(b) and the criteria in Sec 963.17, excluding the criterion in 963.17(b)(4). DOE will consider the performance of the system in terms of the criteria to evaluate whether the geologic repository is likely to comply with the applicable radiation protection standard. 963.17(b) Postclosure suitability criteria. DOE will evaluate the postclosure suitability of a geologic repository at the Yucca Mountain site using criteria that consider disruptive processes and events important to the total system performance of the geologic repository. The applicable criteria related to disruptive processes and events include: (1) Volcanism–or example, the probability and potential consequences of a volcanic eruption intersecting the repository; (2) Seismic events–for example, the probability and potential consequences of an earthquake on the underground facilities or hydrologic system; (3) Nuclear criticality–for example, the probability and potential consequences of a self-sustaining nuclear reaction as a result of chemical or physical processes affecting the waste either in or after release from breached waste packages.

Sources: Proposed 10 CFR Part 63 (64 FR 8640 [101680]); proposed 40 CFR Part 197 (64 FR 46976 [105065]); proposed 10 CFR Part 963 (64 FR 67054 [124754])

Table 1.3-3. Proposed Performance Measures for the Postclosure Period–Human Intrusion Case

Rule	Performance Measure
EPA Proposed 40 CFR PART 197	Human Intrusion Standard. Alternative 1 for 197.25: The DOE must demonstrate that there is a reasonable expectation that for 10,000 years following disposal the reasonably maximally exposed individual receives no more than an annual committed effective dose equivalent of 150 microsieverts (15 mrem) as a result of a human intrusion. The DOE's analysis of human intrusion must include all potential environmental pathways of radionuclide transport and exposure. Alternative 2 for 197.25: The DOE must determine the earliest time after disposal that the waste package would degrade sufficiently that a human intrusion (see 197.26) could occur without recognition by the drillers. The DOE must: (a) Demonstrate that there is a reasonable expectation that the reasonably maximally exposed individual receives no more than an annual committed effective dose equivalent of 150 microsieverts (15 mrem) as a result of a human intrusion, if complete waste package penetration can occur at or before 10,000 years after disposal. The analysis must include all potential environmental pathways of radionuclide transport and exposure; and (b) Include the results of the analysis and its bases in the environmental impact statement for Yucca Mountain as an indicator of long-term disposal system performance, if the intrusion cannot occur before 10,000 years after disposal.
NRC Proposed 10 CFR PART 63	63.113 Performance objective for the geologic repository after permanent closure. (d) The ability of the geologic repository to limit radiological exposures to those specified in §63.113(b), in the event of limited human intrusion into the engineered barrier system, shall be demonstrated through a separate performance assessment that meets the requirements specified at 63.114 and uses the reference biosphere and critical group specified at 63.115. For the assessment required by this paragraph, it shall be assumed that the human intrusion occurs 100 years after permanent closure and takes the form of a drilling event that results in a single, nearly vertical borehole that penetrates a waste package, extends to the saturated zone, and is not adequately sealed.
DOE Proposed 10 CFR PART 963	963.15 Postclosure suitability determination. DOE will apply the method and criteria described in Sections 963.16 and 963.17 to evaluate the suitability of the Yucca Mountain site for the postclosure period. If DOE finds that the results of the [TSPAs] conducted under [963.16(a)(2)] show that the Yucca Mountain site is likely to meet the applicable radiation protection standard, DOE may determine the site suitable for the postclosure period. 963.16 Postclosure Suitability Evaluation Method. (a)(2) Consistent with applicable NRC regulations regarding a stylized human intrusion case, DOE will conduct a [TSPA] to evaluate the ability of the geologic repository to limit radiological exposures in a stylized limited human intrusion case. DOE will model the performance of the geologic repository at the Yucca Mountain site using the method described in 963.16(b) and the criteria in Sec 963.17. DOE will consider the performance of the system in terms of the criteria to evaluate whether the geologic repository is likely to comply with the applicable radiation protection standard. The human intrusion evaluation under this paragraph will be separate from the evaluation conducted under 963.16(a)(1). 963.17 Postclosure Suitability Criteria. (b) DOE will evaluate the postclosure suitability of a geologic repository at the Yucca Mountain site using criteria that consider disruptive processes and events important to the total system performance of the geologic repository. The applicable criteria related to disruptive processes and events include: (b)(4) Inadvertent human intrusion–for example, consequences to repository system performance following a stylized human intrusion scenario.

Sources: Proposed 10 CFR Part 63 (64 FR 8640 [101680]); proposed 40 CFR Part 197 (64 FR 46976 [105065]); proposed 10 CFR Part 963 (64 FR 67054 [124754])

These performance measures define how robust the combined engineered and natural barrier systems must be to protect the public. The regulatory language also prescribes how the TSPA must analyze the potential repository's performance to demonstrate that robustness. TSPA is an inherently complex, multidisciplinary analysis that evaluates movement of radionuclides from the disposal system into the environment. Hence, cognizance of the requirements and criteria for demonstrating performance is necessary to frame the assessment. Cognizance of the regulatory objectives is necessary to evaluate the adequacy of the TSPA for supporting a decision on site recommendation. This TSPA-SR is concerned with the requirements and criteria for analyzing the performance of the potential repository, and with the radiation protection standards to the extent that they dictate where and how that performance will be analyzed.

1.3.2 Proposed 40 CFR Part 197: Environmental Radiation Protection Standards for Yucca Mountain, Nevada

The DOE is the only entity directly regulated by proposed 40 CFR Part 197 (64 FR 46976 [105065]); the NRC is affected because the Nuclear Waste Policy Act of 1982 [101681], 42 U.S.C. 10101 et seq., requires NRC's licensing regulation to be consistent with the EPA's final standards. Although separated from the generic standards, the proposed 40 CFR Part 197 (64 FR 46976 [105065]) reflects the experiences of the EPA in setting and implementing radiation protection standards for a potential geologic repository (e.g., Figure 1.3-1 shows the EPA rulemaking activities for the Waste Isolation Pilot Plant). This discussion covers the postclosure requirements.

In 1985, the EPA established generic standards for the management, storage, and disposal of SNF, HLW, and transuranic radioactive waste at 40 CFR Part 191 (50 FR 38066 [100495]). In 1987, the U.S. Court of Appeals vacated the disposal standards and remanded them to the EPA (*Natural Resources Defense Council, Inc. v. U.S. Environmental Protection Agency* 1987 [149706]). In 1992, the Waste Isolation Pilot Plant Land Withdrawal Act [131959], Public Law No. 102-579, reinstated the 40 CFR Part 191 (58 FR 66398 [107802]) disposal standards, requiring the EPA to replace those that were the specific subject of the remand. That act also exempted the Yucca Mountain site from the 40 CFR Part 191 (63 FR 27354 [151707]) disposal standards and designated the EPA as regulator for the Waste Isolation Pilot Plant. The EPA issued the final disposal standards at 40 CFR Part 191 in 1993 (58 FR 66398 [107802]). The court's concerns were addressed by conforming the groundwater protection requirements to the Safe Drinking Water Act [103937], 42 U.S.C. 300f et seq. Criteria for the certification of the Waste Isolation Pilot Plant were promulgated at 40 CFR Part 191 (61 FR 5224 [107682]) in 1996, and the EPA certified the Waste Isolation Pilot Plant in 1998 (by amending 40 CFR Part 191 [63 FR 27354 [151707]]). In contrast, the NRC will promulgate and implement procedures and requirements for the licensing of the potential Yucca Mountain repository, including requirements for compliance with the EPA standards.

Subpart B of proposed 40 CFR Part 197 (64 FR 46976 [105065]) contains the environmental standards for the disposal of radioactive waste in Yucca Mountain by the DOE. The NRC will determine compliance with Subpart B based upon the results of the DOE's performance assessments projecting the performance of the potential Yucca Mountain repository for 10,000 years after disposal. The DOE must demonstrate to the NRC that there is a reasonable expectation of compliance with Subpart B before the NRC can issue a license. The performance measures for Subpart B are contained in the Individual-Protection Standard (§197.20), the Human Intrusion Standard (§197.25), and the Ground Water Protection Standards (§197.35). These three standards prescribe the analyses that must be included in the TSPA.

For individual protection, the DOE must demonstrate, using performance assessment, a reasonable expectation that, for 10,000 years following disposal, the reasonably maximally exposed individual (proposed 40 CFR 197.21 [64 FR 46976 [105065]]) is safe (Tables 1.3-1 and 1.3-2). The analysis must include all potential pathways of radionuclide transport and exposure.

The consideration of human intrusion into the potential repository, as defined in proposed 40 CFR 197.26 (64 FR 46976 [105065]), must also demonstrate a reasonable expectation that following disposal the reasonably maximally exposed individual is safe (Table 1.3-3). The analysis must include all potential environmental pathways of radionuclide transport and exposure. Two alternatives for considering the time element are proposed. In the first, the time element is simply 10,000 years. In the second alternative, the DOE must determine the earliest time after disposal that the waste package would degrade sufficiently that a human intrusion by drilling could occur without recognition by the drillers.

Protecting ground water requires that the DOE must provide to the NRC a reasonable expectation that, for 10,000 years of undisturbed performance after disposal, releases of radionuclides from the disposal system will not cause the level of radioactivity in the representative volume (proposed 40 CFR 197.36 [64 FR 46976 [105065]]) of ground water at the point of compliance to exceed the limits specified (see Table 1.3-1).

The EPA defines *reasonable expectation* (proposed 40 CFR 197.14 [64 FR 46976 [105065]]) to mean that the NRC "is satisfied that compliance will be achieved based upon the full record before it." The EPA further specifies that reasonable expectation requires less than absolute proof because absolute proof is impossible to attain for disposal due to the uncertainty of projecting long-term performance. Reasonable expectation is seen by the EPA as "less stringent than the *reasonable assurance* concept that the NRC uses to license nuclear power plants" (see Section 1.3.3.2). The EPA intends reasonable expectation to take into account the inherently greater uncertainties in making long-term projections of the performance of the Yucca Mountain disposal system. However, important parameters should not be excluded from assessments and analyses simply because they are difficult to quantify precisely to a high degree of confidence. Moreover, the EPA intends for reasonable expectation to focus performance assessments and analyses upon the full range of defensible and reasonable parameter distributions, rather than only upon extreme physical situations and parameter values (64 FR 46976 [105065]).

Human society, biology, and knowledge will be assumed unchanging during the 10,000 years after the license submission to the NRC. However, factors related to the geology, hydrology, and climate of the site must be varied based on environmentally protective but reasonable scientific predictions of the changes that could affect the Yucca Mountain disposal system over the next 10,000 years (64 FR 46976 [105065]).

The DOE must also calculate the peak dose to the reasonably maximally exposed individual that would occur after 10,000 years following disposal, but within the period of geologic stability. While no regulatory standard applies to the results of this analysis, the DOE must include the results and their bases in the Environmental Impact Statement (EIS) for Yucca Mountain as an indicator of long-term disposal system performance (64 FR 46976 [105065]).

Performance must be assessed at the point of compliance. The EPA proposed four alternative definitions, numbers one and four of which place the point of compliance at any point on the boundary of the controlled area. Two alternative definitions of *controlled area* (proposed 40 CFR 197.12 [64 FR 46976 [105065], p. 47013]) are proposed. Alternative 1 limits the controlled area to no more than 100 square kilometers. Alternative 2 allows the DOE to include in the controlled area any contiguous area within the boundary of the NTS. One of these two alternatives will be applied if the EPA sets the "point of compliance" (proposed 40 CFR 197.37 [64 FR 46976 [105065], p. 47016]) at any point on the boundary of the controlled area, otherwise the concept of controlled area will not appear in the final rule) (proposed 40 CFR 197.12 [64 FR 46976 [105065], p. 47013]). Alternative 2 places the point of compliance at any point within a half-kilometer radius of the intersection of U.S. Route 95 and Nevada State Route 373. Alternative 3 places the point of compliance within the town of Amargosa Valley, Nevada, more specifically within the area bounded by Frontier Street on the north, Nevada State Route 373 on the east, the Nevada-California border on the south-southwest, and Casada Way on the west. However, if the NRC identifies another location about 20 kilometers (alternative three) from the center of the potential repository footprint where the representative volume would have a higher concentration of radionuclides that were released from the repository, the NRC must specify that location as the point of compliance (64 FR 46976 [105065]).

Performance assessments need not consider processes or events estimated to have less than one chance in 10,000 of occurring within 10,000 years of disposal. The EPA proposes to allow the NRC to change this limit to exclude slightly higher probability events. If so, the performance assessments need not evaluate, in detail, the impacts resulting from any processes and events or sequences of processes and events with a higher chance of occurrence if the results of the performance assessments would not be changed significantly (64 FR 46976 [105065]).

1.3.3 Proposed 10 CFR Part 63: Disposal of High-Level Radioactive Wastes in a Potential Geological Repository at Yucca Mountain, Nevada

The DOE is the only entity directly regulated by the proposed 10 CFR Part 63 (64 FR 8640 [101680], p. 8659). Note that whenever this document makes direct reference to proposed 10 CFR 63, this document conveys a corresponding reference to DOE's Interim Guidance (Dyer 1999 [105655]). This rule specifies how the NRC will carry out its licensing obligations under the Nuclear Waste Policy Act of 1982 [101681], 42 U.S.C. 10101 et seq., and how it will implement proposed 40 CFR Part 197 (64 FR 46976 [105065]) for the potential repository. The NRC criteria address the performance of the potential repository system, which must comprise both natural and engineered barriers. Also included are licensing procedures, criteria for public participation, records and reporting, monitoring and testing programs, performance confirmation, QA, personnel training and certification, and emergency planning. The proposed criteria will apply specifically and exclusively to Yucca Mountain. The proposed NRC rulemaking also affects 10 CFR Parts 2 [100502], 19 [103585], 20 [104787], 21 [140852], 30 [150331], 40 [151723], 51 [144582], 60 [103540], and 61 (64 FR 8640 [105065], p. 8658). Parts 2 [100502], 19 [103585], 20 [104787], 21 [140852], and 51 [144582] would be amended to apply to Part 63. Parts 30, 40, and 61 would be amended to exempt DOE for activities related to Part 63. Part 60 would be amended to clarify that it does not apply to, and cannot be the subject of litigation in, any NRC licensing proceeding for a potential repository at Yucca Mountain (64 FR 8640 [101680], p. 8640).

Generic regulations at 10 CFR Part 60 [103540] govern the licensing of the DOE to receive and possess source, special nuclear, and byproduct material at a geologic repository that is sited, constructed, and operated under the Nuclear Waste Policy Act of 1982 [101681], as amended, 42 U.S.C. 10101 et seq. Figure 1.3-1 includes an illustration of the evolution of this rule. The NRC's technical criteria assumed that the EPA standards would limit only cumulative radionuclide releases from a geologic repository. In 1985, the EPA issued final standards in 40 CFR Part 191 (50 FR 38066 [100495]) containing cumulative release limits, but also containing criteria for individual and groundwater protection. Although the NRC proposed "conforming amendments" to incorporate the EPA standards into the NRC regulations (51 FR 22288 [151059]; 64 FR 8640 [101680], p. 8640), they were abandoned in 1987 when the EPA standards were vacated by the U.S. Court of Appeals (64 FR 8640 [101680], p. 8640).

During the years since the initial technical criteria were promulgated, the technical methods for performance assessment have evolved significantly. "The implementation of these new methods for Yucca Mountain will avoid the imposition of unnecessary, ambiguous, or potentially conflicting criteria that could result from the application of proposed 10 CFR Part 60" (64 FR 8640 [101680], p. 8641). This discussion focuses on those parts of proposed 10 CFR Part 63 (64 FR 8640 [101680], p. 8641) that differ from 10 CFR Part 60 (46 FR 13971 [151057], 48 FR 28194 [100475], 50 FR 29641 [151083], 51 FR 27158 [151058], 54 FR 27864 [151082], 61 FR 64257 [104190]) and that apply to the TSPA analysis of postclosure performance.

1.3.3.1 Proposed Part 63 Subpart B–Licenses

Site characterization must be conducted prior to submittal of an application and in a manner that limits adverse effects on the performance of the potential geologic repository. The DOE must submit semiannual reports on the progress of site characterization. NRC staff may visit, inspect, and observe site characterization activities and comment on any aspect of site characterization and performance assessment. The License Application (LA) must include general information and a safety analysis report, and be accompanied by an EIS. Subpart B describes the information to be included in the safety analysis report (64 FR 8640 [101680]). The performance assessment, an assessment of how the FEPs of the site affect waste isolation, and an assessment of the responses of the natural systems to thermal loading are major portions of the safety analysis report. These analyses are integral to this TSPA-SR.

1.3.3.2 Proposed Part 63 Subpart E–Technical Criteria

Subpart E contains proposed performance objectives through permanent closure (preclosure) and after permanent closure (postclosure). It contains the requirements for the analyses used to demonstrate compliance with the performance objectives. Subpart E requires that compliance be demonstrated in the context of safety analyses of total system performance (64 FR 8640 [101680]).

The NRC recognized (proposed 10 CFR 63.101[a][2] [64 FR 8640 [101680]]) that complete assurance that the requirement will be met is not achievable. The general standard that the NRC requires is a *reasonable assurance*, based on the record before it, that the performance objective proposed in 10 CFR 63.113 (64 FR 8640 [101680]) will be met (see Section 1.3.2).

Proof that the potential geologic repository will be in conformance with the objective for postclosure performance is not to be had in the ordinary sense of the word because of the uncertainties inherent in the understanding of the evolution of the geologic setting, biosphere, and EBS. For such long-term performance, what is required is reasonable assurance, making allowance for the time period, hazards, and uncertainties involved, that the outcome will be in conformance with the objective for postclosure performance of the potential geologic repository. Demonstrating compliance will involve the use of complex predictive models that are supported by limited data from field and laboratory tests, site-specific monitoring, and natural analog studies that may be supplemented with prevalent expert judgment. Further, in reaching a determination of reasonable assurance, the Commission may supplement numerical analyses with qualitative judgments including, for example, consideration of the degree of diversity among the multiple barriers as a measure of the resiliency of the potential geologic repository (64 FR 8640 [101680], p. 8674).

The performance objective for the potential geologic repository after permanent closure, proposed 10 CFR 63.113 (64 FR 8640 [101680], p. 8676), requires the DOE to include a system of multiple barriers, comply with the individual annual dose limit, conduct a performance assessment, and assess the consequences of a specified human intrusion event. Requirements for the performance assessment to demonstrate compliance with the individual dose limit are shown in Table 1.3-4. Characteristics of the reference biosphere and critical group for the performance assessment are shown in Table 1.3-5. These requirements and characteristics define the scope of the TSPA-SR.

Table 1.3-4. Proposed U.S. Nuclear Regulatory Commission Requirements for Performance Assessment

Section of Proposed 10 CFR Part 63	Requirements
63.114(a)	Include data related to the geology, hydrology, and geochemistry (including disruptive processes and events) of the Yucca Mountain site, and the surrounding region to the extent necessary, and information on the design of the engineered barrier system, used to define parameters and conceptual models used in the assessment.
63.114(b)	Account for uncertainties and variabilities in parameter values and provide the technical basis for parameter ranges, probability distributions, or bounding values used in the performance assessment.
63.114(c)	Consider alternative conceptual models of features and processes that are consistent with available data and current scientific understanding, and evaluate the effects that alternative conceptual models have on the performance of the geologic potential repository.
63.114(d)	Consider only events that have at least one chance in 10,000 of occurring over 10,000 years.
63.114(e)	Provide the technical basis for either inclusion or exclusion of specific features, events, and processes of the geologic setting in the performance assessment. Specific features, events, and processes of the geologic setting must be evaluated in detail if the magnitude and time of the resulting expected annual dose would be significantly changed by their omission.

Table 1.3-4. Proposed U.S. Nuclear Regulatory Commission Requirements for Performance Assessment (Continued)

Section of Proposed 10 CFR Part 63	Requirements
63.114(f)	Provide the technical basis for either inclusion or exclusion of degradation, deterioration, or alteration processes of engineered barriers in the performance assessment, including those processes that would adversely affect the performance of natural barriers. Degradation, deterioration, or alteration processes of engineered barriers must be evaluated in detail if the magnitude and time of the resulting expected annual dose would be significantly changed by their omission.
63.114(g)	Provide the technical basis for models used in the performance assessment such as comparisons made with outputs of detailed process-level models and/or empirical observations (e.g., laboratory testing, field investigations, and natural analogs).
63.114(h)	Identify those design features of the engineered barrier system, and natural features of the geologic setting, that are considered barriers important to waste isolation.
63.114(i)	Describe the capability of barriers, identified as important to waste isolation, to isolate waste, taking into account uncertainties in characterizing and modeling the barriers.
63.114(j)	Provide the technical basis for the description of the capability of barriers, identified as important to waste isolation, to isolate waste.

Source: Proposed 10 CFR Part 63 (64 FR 8640 [101680])

Table 1.3-5. Proposed U.S. Nuclear Regulatory Commission Characteristics of the Reference Biosphere and Critical Group

Section of Proposed 10 CFR Part 63	**Characteristics**
63.115(a)	Reference biosphere.
63.115(a)(1)	Features, events, and processes that describe the reference biosphere shall be consistent with present knowledge of the conditions in the region surrounding the Yucca Mountain site.
63.115(a)(2)	Biosphere pathways shall be consistent with arid or semi-arid conditions.
63.115(a)(3)	Climate evolution shall be consistent with the geologic record of natural climate change in the region surrounding the Yucca Mountain site.
63.115(a)(4)	Evolution of the geologic setting shall be consistent with present knowledge of natural processes.
63.115(b)	Critical group.
63.115(b)(3)	The critical group resides within a farming community consisting of approximately 100 individuals, and exhibits behaviors or characteristics that will result in the highest expected annual doses.
63.115(b)(4)	The behaviors and characteristics of the average member of the critical group shall be based on the mean value of the critical group's variability range. The mean value shall not be unduly biased based on the extreme habits of a few individuals.
63.115(b)(5)	The average member of the critical group shall be an adult. Metabolic and physiological considerations shall be consistent with present knowledge of adults.

Source: Proposed 10 CFR Part 63 (64 FR 8640 [101680])

1.3.4 Proposed 10 CFR Part 963: Yucca Mountain Site Suitability Guidelines

In 1996, the DOE proposed (61 FR 66158 [100211]) to amend its general guidelines for site selection at 10 CFR Part 960 [126503], which it had promulgated under the Nuclear Waste Policy Act of 1982 [101681], 42 U.S.C. 10101 et seq. In 1998, the DOE issued the *Viability Assessment of a Repository at Yucca Mountain* (DOE 1998 [101779]) as required by the Energy and Water Development Appropriations Act 1997, Public Law No. 104-206 [100008]. The report contains the bases for the site suitability criteria the DOE proposes to use and the methodology for applying the criteria to a design for a potential repository at the Yucca Mountain site. The current proposed rulemaking will limit 10 CFR Part 960 to preliminary site screening for repositories located elsewhere than Yucca Mountain and establish new suitability guidelines at proposed 10 CFR Part 963 (64 FR 67054 [124754]) for the Yucca Mountain site.

The proposed rule contains site suitability criteria and methods for considering the Yucca Mountain site for a potential nuclear waste repository. The suitability evaluation methods are consistent with the methods proposed by the NRC. The suitability criteria reflect current technical and scientific understanding and regulatory expectations (NRC and EPA) regarding the performance and safety of a potential geologic repository. These criteria are part of the program of scientific and technical investigations of the site to determine its natural properties and features (64 FR 67054 [124754]).

The DOE stated that "the phrase 'likely to meet applicable radiation protection standard' in [proposed] 10 CFR Part 963 is meant to clarify the role of the EPA standards and the NRC regulations in evaluating suitability and reaching a suitability determination" (64 FR 67054 [124754], p. 67075). The DOE has structured its rule regarding the methods and procedure for evaluating suitability to be consistent with proposed NRC licensing criteria and requirements. This is in recognition of NRC's broader role in the licensing process, and in anticipation of submitting an application for a license (64 FR 67054 [124754]).

The DOE's assessment of whether the Yucca Mountain site is suitable is a more preliminary assessment than the subsequent NRC licensing decision; hence, proposed 10 CFR Part 963 (64 FR 67054 [124754]) does not include all the NRC licensing requirements. The intent of proposed 10 CFR Part 963 (64 FR 67054 [124754]), as proposed, is to establish guidelines for providing the DOE with sufficient information to determine whether the site should be recommended to the President based on, among other things, whether the site is likely to meet applicable regulatory standards for licensing. The proposed guidelines do not address the entire process of site recommendation (Nuclear Waste Policy Act of 1982 [101681], Section 114; 64 FR 67054 [124754]).

1.3.4.1 Proposed Subpart A–General Provisions

The purpose of the proposed rule is to establish the methods and criteria for determining the suitability of the Yucca Mountain site for the location of a potential geologic repository. These methods and criteria will allow the DOE to analyze data from site characterization conducted under the Nuclear Waste Policy Act of 1982. Subpart A includes definitions of certain words and terms to clarify the DOE's intent and meaning and to make the terms consistent with proposed 10 CFR Part 63 (64 FR 8640 [101680]; 64 FR 67054 [124754]).

1.3.4.2 Proposed Subpart B–Site Suitability Determination, Methods, and Criteria

The scope of Subpart B includes the basis for the DOE's suitability determination for the Yucca Mountain site (64 FR 67054 [124754]). Subpart B is divided into two sections corresponding to the preclosure and postclosure periods, and each period is divided into three subsections. The subsections describe for each period: (1) the suitability determination; (2) the suitability evaluation method; and (3) the criteria to be used for the evaluation.

If the evaluation shows that the potential geologic repository is likely to satisfy the radiation protection standards for the preclosure and postclosure periods, then the DOE may determine that the site is suitable (64 FR 67054 [124754]). Tables 1.3-1 through 1.3-3 list the performance measures for the postclosure determinations. Table 1.3-6 contains the postclosure suitability evaluation method and Table 1.3-7 contains the postclosure suitability criteria for nondisruptive processes and events (see Table 1.3-2 and 1.3-3 for the criteria for disruptive processes and events). This method and the associated criteria prescribe how the DOE will demonstrate the long-term performance of the potential repository.

Table 1.3-6. Proposed U.S. Department of Energy Postclosure Suitability Evaluation Method

Section of Proposed 10 CFR Part 963	Total System Performance Assessment
963.16(b)	In conducting a [TSPA] under this section, DOE will:
963.16(b)(1)	Include data related to the suitability criteria in Sec 963.17
963.16(b)(2)	Account for uncertainties and variabilities in parameter values and provide the technical basis for parameter ranges, probability distributions, and bounding values
963.16(b)(3)	Consider alternative models of features and processes that are consistent with available data and current scientific understanding, and evaluate the effects that alternative models would have on the estimated performance of the geologic potential repository
963.16(b)(4)	Consider only events that have at least one chance in 10,000 of occurring over 10,000 years
963.16(b)(5)	Provide the technical basis for either inclusion or exclusion of specific features, events, and processes of the geologic setting, including appropriate details as to magnitude and timing regarding any exclusions that would significantly change the expected annual dose
963.16(b)(6)	Provide the technical basis for either inclusion or exclusion of degradation, deterioration, or alteration processes of engineered barriers, including those processes that would adversely affect natural barriers, (such as degradation of concrete liners affecting the pH of ground water or precipitation of minerals due to heat changing hydrologic processes), including appropriate details as to magnitude and timing regarding any exclusions that would significantly change the expected annual dose
963.16(b)(7)	Provide the technical basis for models used in the [TSPA] such as comparisons made with outputs of detailed process-level models and/or empirical observations (for example, laboratory testing, field investigations, and natural analogs)
963.16(b)(8)	Identify natural features of the geologic setting and design features of the engineered barrier system important to isolating radioactive waste
963.16(b)(9)	Describe the capability of the natural and engineered barriers important to isolating radioactive waste, taking into account uncertainties in characterizing and modeling such barriers

Table 1.3-6. Proposed U.S. Department of Energy Postclosure Suitability Evaluation Method (Continued)

Section of Proposed 10 CFR Part 963	Total System Performance Assessment
963.16(b)(10)	Provide the technical basis for the description of the capability of the natural and engineered barriers important to isolating radioactive waste
963.16(b)(11)	Use the reference biosphere and group receptor assumptions specified in applicable NRC regulations
963.16(b)(12)	Conduct appropriate sensitivity studies.

Source: Proposed 10 CFR Part 963 (64 FR 67054 [124754])

NOTE: See Tables 1.3-1, 1.3-2, and 1.3-3 for requirements of proposed 10 CFR 963.16(a) (64 FR 67054 [124754]).

Table 1.3-7. Proposed U.S. Department of Energy Postclosure Suitability Criteria–Nondisruptive Processes

Section of Proposed 10 CFR Part 963 and Characteristic	Criteria
963.17(a)	DOE will evaluate the postclosure suitability...through suitability criteria that reflect both the processes and the models used to simulate those processes that are important to the total system performance of the geologic potential repository. The applicable criteria are:
963.17(a)(1) Site	(i) Geologic properties of the site–e.g., stratigraphy, rock type and physical properties, and structural characteristics; (ii) Hydrologic properties of the site–e.g., porosity, permeability, moisture content, saturation, and potentiometric characteristics; (iii) Geophysical properties of the site–e.g., densities, velocities and water contents, as measured or deduced from geophysical logs; and (iv) Geochemical properties of the site–e.g., precipitation, dissolution characteristics, and sorption properties of mineral and rock surfaces;
963.17(a)(2) Unsaturated Zone Flow	(i) Climate–e.g., precipitation and postulated future climatic conditions; (ii) Infiltration–e.g., precipitation entering the mountain in excess of water returned to the atmosphere by evaporation and plant transpiration; (iii) Unsaturated zone flux–e.g., water movement through the pore spaces, or flowing along fractures or through perched water zones above the potential repository; and (iv) Seepage–e.g., water dripping into the...potential repository openings from the surrounding rock;
963.17(a)(3) Near Field Environment	(i) Thermal hydrology–e.g., effects of heat from the waste on water flow through the site, and the temperature and humidity at the engineered barriers, and (ii) Near field geochemical environment–e.g., the chemical reactions and products resulting from water contacting the waste and the engineered barrier materials;
963.17(a)(4) Engineered Barrier System Degradation	(i) Engineered barrier system component performance–e.g., drip shields, backfill, coatings, or chemical modifications, and (ii) Waste package degradation–e.g., corrosion of waste package materials in the near-field environment;
963.17(a)(5) Waste Form Degradation	(i) Cladding degradation–e.g., corrosion or break-down of the cladding on the individual spent fuel pellets; and (ii) Waste from dissolution–e.g., the ability of individual radionuclides to dissolve in water penetrating breached waste packages;

Table 1.3-7. Proposed U.S. Department of Energy Postclosure Suitability Criteria–Nondisruptive Processes (Continued)

Section of Proposed 10 CFR Part 963 and Characteristic	Criteria
963.17(a)(6) Engineered Barrier System Degradation, Flow, And Transport	(i) Colloid formation and stability–e.g., the formation of colloidal particles and the adherence of radionuclides to these particles as they may be washed through the remaining barriers; and (ii) Engineered barrier transport–e.g., the movement of radionuclides dissolved in water or adhering to colloidal particles to be transported through the remaining engineered barriers and in the underlying unsaturated zone;
963.17(a)(7) Unsaturated Zone Flow And Transport	(i) Unsaturated zone transport–e.g., the movement of water with dissolved radionuclides or colloidal particles through the unsaturated zone underlying the potential repository, including retardation mechanisms such as sorption on rock or mineral surfaces; (ii) Thermal hydrology–e.g., effects of heat from the waste on water flow through the site;
963.17(a)(8) Saturated Zone Flow And Transport	(i) Saturated zone transport–e.g., the movement of water with dissolved radionuclides or colloidal particles through the saturated zone underlying and beyond the potential repository, including retardation mechanisms such as sorption on rock or mineral surfaces (ii) Dilution–e.g., diffusion of radionuclides into pore spaces, dispersion of radionuclides along flow paths, and mixing with non-contaminated ground water;
963.17(a)(9) Biosphere	(i) Reference biosphere and receptor–e.g., biosphere water pathways, location and behavior of receptor (ii) Biosphere transport and uptake–e.g., the consumption of ground or surface waters through direct extraction or agriculture, including mixing with non-contaminated waters and exposure to contaminated agricultural products.

Source: Proposed 10 CFR Part 963 (64 FR 67054 [124754])

1.3.5 U.S. Nuclear Regulatory Commission Issue Resolution Status Reports

The DOE's site characterization program and resolution strategy are closely coordinated with the NRC. The NRC prelicensing program focuses on topics most critical to potential repository performance, termed Key Technical Issues (KTIs). These issues address technical matters regarding the performance of the site or the data needed to assess that performance (NRC 1999 [137163]). A goal of the site characterization program is consensus between the DOE and the NRC that the remaining KTIs have been addressed adequately or that adequate plans are in place to address the issues (64 FR 67054 [124754], p. 67062).

Through IRSRs, the NRC provides the DOE feedback on how to resolve the KTIs during the prelicensing consultation period. A resolved issue may be reopened if warranted (DOE 1998 [100548], p. 4-11). The NRC's next revision of the IRSRs, to be completed by the end of Fiscal Year 2000, will update information on progress in subissue resolution for each KTI (NRC 1999 [137163]). The KTIs focus NRC evaluations and foster an independent understanding of the issues and their relative importance to potential repository system performance. Various combinations of the KTIs include all of the principal factors that support the DOE's potential repository safety strategy (see Section 1.5.4.2). The KTIs all directly or indirectly relate to performance assessment (DOE 1998 [100550], p. 2-5). Table 1.3-8 shows the KTIs and their subissues.

Table 1.3-8. Subissues in U.S. Nuclear Regulatory Commission Key Technical Issues

KTI (IRSR rev. date)	KTI Subissue
USFIC Unsaturated and Saturated Flow Under Isothermal Conditions (NRC 1997 [100292]; NRC 1998 [102115]; NRC 1999 [140371])	USFIC1 Climate change
	USFIC2 Hydrologic effects of climate change
	USFIC3 Present-day shallow groundwater infiltration
	USFIC4 Deep percolation (present and future)
	USFIC5 Saturated zone ambient flow conditions and dilution processes
	USFIC6 Matrix diffusion
TEF Thermal Effects on Flow (NRC 1997 [100405]; NRC 1998 [102112]; NRC 1999 [137273])	TEF1 Sufficiency of thermal hydrologic testing program to assess thermal reflux in the near field
	TEF2 Sufficiency of thermal hydrologic modeling to predict the nature and bounds of thermal effects on flow in the near-field
	TEF3 Adequacy of TSPA with respect to thermal effects on flow
ENFE Evolution of the Near-Field Environment (NRC 1997 [100327]; NRC 1998 [102117]; NRC 1999 [105950])	ENFE1 Effects of coupled thermal-hydrologic chemical (THC) processes on seepage and flow
	ENFE2 Effects of coupled THC processes on waste package chemical environment
	ENFE3 Effects of coupled THC processes on chemical environment for radionuclide release
	ENFE4 Effects of THC processes on radionuclide transport through engineered and natural barriers
	ENFE5 Coupled THC processes affecting potential nuclear criticality in the near-field
CLST Container Life and Source Term (NRC 1998 [100410]; NRC 1998 [102114]; NRC 1999 [137277])	CLST1 Effects of corrosion on container lifetime and the release of radionuclidies to the near-field environment
	CLST2 Effects of materials stability and mechanical failure on container lifetime and the release of radionuclides to the near-field environment
	CLST3 Rate of degradation of SNF and the rate at which radionuclides in SNF are released to the near-field environment
	CLST4 Rate of degradation of HLW glass and the rate at which radionuclides in HLW glass are released to the near-field environment
	CLST5 Design of waste package and other components of the EBS for prevention of nuclear criticality
	CLST6 Effect of alternate design features on container lifetime and radionuclide release
RT Radionuclide Transport (NRC 1998 [102116]; NRC 1999 [136103])	RT1 Radionuclide transport through porous rock
	RT2 Radionuclide transport through alluvium
	RT3 Radionuclide transport through fractured rock
	RT4 Nuclear criticality in the far field
TSPAI Total System Performance Assessment and Integration (NRC 1998 [100296]; NRC 1998 [103760]; NRC 2000 [149372])	TSPAI1 System description and demonstration of multiple barriers
	TSPAI2 Scenario analysis within the TSPA methodology
	TSPAI3 Model abstraction within the TSPA methodology
	TSPAI4 Demonstration of the overall performance objective

Table 1.3-8. Subissues in U.S. Nuclear Regulatory Commission Key Technical Issues (Continued)

KTI (IRSR rev. date)	KTI Subissue
IA Igneous Activity (NRC 1998 [100297]; NRC 1998 [103603]; Reamer 1999 [119693])	IA1 Probability of future igneous activity
	IA2 Consequences of igneous activity within the potential repository setting
SDS Structural Deformation and Seismicity (NRC 1997 [100290]; NRC 1998 [101101]; NRC 1999 [135621])	SDS1 Faulting
	SDS2 Seismicity
	SDS3 Fracturing and structural framework of the geologic setting
	SDS4 Tectonics and crustal conditions
RDTME Repository Design and Thermal-Mechanical Effects (NRC 1997 [100404]; NRC 1998 [102113]; NRC 1999 [137163])	RDTME1 Implementation of an effective design control process within the overall quality assurance program
	RDTME2 Design of the geologic potential repository operations area for the effects of seismic events and direct fault disruption
	RDTME3 TM effects on underground facility design and performance
	RDTME4 Design and long-term contribution of potential repository seals in meeting pos-closure performance objectives

Sources: NRC 2000 [149372], App. B; DOE 1998 [100550], p. 2-5 ; NRC 2000 [151753]

NOTE: USFIC = Unsaturated and Saturated Flow under Isothermal Conditions; TEF = Thermal Effects on Flow; ENFE = Evolution of the Near-Field Environment; CLST = Container Life and Source Term; RT = Radionuclide Transport; TSPAI = Total System Performance Assessment and Integration; IA = Igneous Activity; SDS = Structural Deformation and Seismicity; RDTME = Repository Design and Thermal-Mechanical Effects

Each IRSR contains an (1) introduction, (2) definition of the KTI and all related subissues and the scope of the particular subissue(s) that is the subject of the IRSR, (3) importance of the particular subissue(s) to potential repository performance, (4) review methods and acceptance criteria, (5) status of resolution of the subissues, (6) references, and (7) an appendix summarizing those items resolved at the staff level and those items remaining open. The IRSR provides the technical basis for resolution of the subissues that will be used in subsequent reviews of the DOE submittals (NRC 1999 [137277], p. 2). Each IRSR is hierarchical, i.e., the IRSR identifies the subsystem affected (e.g., EBS), the primary issue (e.g., adequacy of EBS to provide long-term containment and limit releases), subissues (e.g., effects of corrosion processes on container lifetime), and components of subissues (e.g., humid-air corrosion and uniform aqueous corrosion).

1.3.5.1 Total System Performance Assessment and Integration Issue Resolution Status Report

Guidance for the NRC review of the TSPA is contained in the Total System Performance Assessment and Integration (TSPA&I) IRSR. The TSPA&I KTI describes an acceptable methodology for assessing potential repository performance and for using these assessments to demonstrate compliance with the overall performance objective and requirements for multiple barriers. Integration of information from many technical disciplines into the modeling and abstraction of the engineered system and natural FEPs is critical for an acceptable TSPA. The NRC included acceptance criteria for this integration in the TSPA&I IRSR to ensure that the transfer of information among the technical disciplines and to DOE's TSPA occurs, the analysis is focused on the integrated total system assessment, and the assessment is transparent, traceable, defensible, and comprehensive (NRC 2000 [149372], p. 3). The four TSPA&I subissues and their acceptance criteria describe the critical aspects of a TSPA methodology. These subissues and implications of their resolution follow.

System Description and Demonstration of Multiple Barriers–This subissue will ensure that the DOE has identified the design features of the EBS and natural features of the geologic setting that are considered important barriers to waste isolation, described the capability of the barriers important to waste isolation, and provided a technical basis for that description. It also ensures that compliance calculations in the TSPAs are clear and consistent and that the technical basis for the TSPA is sufficiently transparent and traceable.

Scenario Analysis–This subissue ensures that the TSPA appropriately considers likely processes and events by identifying, screening, and selecting the FEPs to be used in formulating scenarios in the TSPA. Guidance is provided on the construction of and assignment of probabilities to scenario classes, and their incorporation into an overall system performance.

Model Abstraction–This subissue ensures that the assumptions, conceptual approaches, data, models, and abstractions used in the TSPAs are appropriately integrated and technically defensible, and that technical support is commensurate with contribution to risk.

Demonstration of Overall Performance Objective–This subissue ensures the appropriate execution of the TSPA to demonstrate that the potential repository will satisfy the overall performance objectives under a range of FEPs. The objectives incorporate the standards to be set by the EPA at proposed 40 CFR 197 (64 FR 46976 [105065]) and adopted by the NRC in the final implementing rule, at proposed 10 CFR 63 (64 FR 8640 [101680]).

Because the TSPA&I IRSR addresses all subsystems, the issue hierarchy is somewhat different from that of the other IRSRs. The model abstraction subissue is further subdivided into integrated subissues of the potential repository system that must be appropriately abstracted into a TSPA (NRC 2000 [149372], p. 30). (In Revision 2 of the Total System Performance Assessment and Integration IRSR, the NRC replaced the term "KESA" (key elements of subsystem abstractions) with "ISI (integrated subissues)." These integrated subissues are related to the NRC KTIs as shown in Table 1.3-9. Figure 1.3-2 illustrates the hierarchy for the TSPA&I. The NRC "staff is currently developing a risk-informed and performance-based [Yucca Mountain] Review Plan for a potential [Yucca Mountain] potential repository LA based primarily on the Acceptance Criteria currently found in the *other* [emphasis added] KTI IRSRs" (NRC 2000 [149372], p. 2).

Table 1.3-9. Integrated Subissues for Nuclear Regulatory Commission Review of Model Abstraction within the Total System Performance Assessment Methodology Subsystem

Subsystem	Integrated Subissues	Related KTI Subissues
Engineered System	ENG1 Degradation of Engineered Barriers	TEF1,2 ENFE2 CLST1,2,6 RDTME3
	ENG2 Mechanical Disruption of Engineered Barriers	CLST1,2,5,6 IA2 SDS1-4 RDTME2,3
	ENG3 Quantity and Chemistry of Water Contacting the WPs and WFs	USFIC4 TEF1,2 ENFE1-3 CLST1,3,4,6 SDS3 RDTME3
	ENG4 Radionuclide Release Rates and Solubility Limits	ENFE3-5 CLST3-6

Table 1.3-9. Integrated Subissues for Nuclear Regulatory Commission Review of Model Abstraction within the Total System Performance Assessment Methodology Subsystem (Continued)

Subsystem	Integrated Subissues	Related KTI Subissues
Geosphere	UZ1 Spatial and Temporal Distribution of Flow	USFIC1,3,4 TEF1,2 ENFE1 SDS2,3 RDTME3
	UZ2 Flow Paths in the UZ	USFIC4 TEF1,2 ENFE1 SDS3
	UZ3 Radionuclide Transport in the UZ	USFIC4,6 ENFE4 RT1,3,4 SDS3
	SZ1 Flow Paths in the SZ	USFIC1,4,5 SDS3,4
	SZ2 Radionuclide Transport in the SZ	USFIC5,6 RT1-4 SDS3
	Direct1 Volcanic Disruption of Waste Packages	CLST1,2 IA1,2 SDS1,4
	Direct2 Airborne Transport of Radionuclides	IA2
Biosphere	Dose1 Dilution of Radionuclides in Groundwater due to Well Pumping	USFIC5
	Dose2 Redistribution of Radionuclides in Soil	IA2
	Dose3 Lifestyle of the Critical Group	IA2

Source: NRC 2000 [149372], p. 31

NOTE: Subissue 3–Integrated Subissues for U.S. Nuclear Regulatory Commission Review of Model Abstraction within the Total System Performance Assessment Methodology and Related KTI Subissues

See note in Table 1.3-8 for additional abbreviations WP = waste package; WF = waste form.

The NRC bases its judgment about which elements to abstract on "staff TSPAs performed in the past, review of the DOE's TSPAs, and knowledge of the design options for the [Yucca Mountain] site and [Yucca Mountain] site characteristics. Because TSPAs are considered iterative, some adjustment of the key elements may occur as future TSPAs and other relevant analyses are completed and site data are collected" (NRC 2000 [149372], p. 30). The NRC will review "elements of the DOE's total system performance demonstration and the relative contributions of potential repository subsystems or their components to identify those areas that require greater emphasis" (NRC 2000 [149372], p. 30). The NRC's completeness review will consider FEPs that could significantly impact performance. The adequacy review will consider how these FEPs are abstracted and integrated into the TSPA. The NRC will examine whether the engineered designs, site characteristics, and interactions among them have been appropriately identified, incorporated, and analyzed in the TSPA. The review will focus on understanding the importance to performance of the various assumptions, models, and input data in the TSPA and on ensuring that the degree of technical support for models and data abstractions is commensurate with contribution to risk.

1.3.5.2 Issue Resolution Status Report Treatment in Process Model Reports

Nine PMRs form the basis for the TSPA. These reports summarize the data, assumptions, and analyses documented in detail in subsidiary analysis and model reports.

- *Integrated Site Model Process Model Report* (CRWMS M&O 2000 [146988])
- *Unsaturated Zone Flow and Transport Model Process Model Report* (CRWMS M&O 2000 [145774])

- EBS: *Engineered Barrier System Degradation, Flow, and Transport Process Model Report* (CRWMS M&O 2000 [145796])

- WP: *Waste Package Degradation Process Model Report* (CRWMS M&O 2000 [138396])

- WF: *Waste Form Degradation Process Model Report* (CRWMS M&O 2000 [138332])

- NFE: *Near Field Environment Process Model Report (PMR)* (CRWMS M&O 2000 [153178])

- SZ: *Saturated Zone Flow and Transport Process Model Report* (CRWMS M&O 2000 [145738])

- Bio: *Biosphere Process Model Report* (CRWMS M&O 2000 [151615])

- DE: *Disruptive Events Process Model Report* (CRWMS M&O 2000 [141733]).

Table 1.3-10 correlates the NRC TSPA&I Integrated Subissues with the DOE PMRs. Refer to tables D.1-4 and D.1-5 of Appendix D, *Issue Resolution Status Reports Tracking Database,* of this report for details of the approach used in the relevant PMRs for each of the TSPA&I Integrated Subissues, and for a crosswalk of the KTIs to the PMRs.

Table 1.3-10. Correlation Between the U.S. Nuclear Regulatory Commission's Total System Performance Assessment and Integration Integrated Subissues and the U.S. Department of Energy's Process Model Reports

TSPA&I ISIs	DOE Process Model Reports								
	ISM	Bio	DE	EBS	NFE	SZ	UZ	WF	WP
ENG1				■				■	■
ENG2			■	■				■	
ENG3				■	■			■	■
ENG4			■					■	
UZ1					■		■		
UZ2					■		■		
UZ3					■		■		
SZ1						■			
SZ2						■			
DIRECT1			■						■
DIRECT2		■	■						
DOSE1		■				■			
DOSE2		■	■						
DOSE3		■				■			

1.4 PHILOSOPHY OF TOTAL SYSTEM PERFORMANCE ASSESSMENT

The TSPA has become the internationally recognized method for analyzing system behavior for nuclear waste repositories. It is important to understand why TSPAs are performed, the unique nature of a TSPA compared to other types of analyses, and why the confidence in TSPA as a process has been established at such a global level.

1.4.1 Why Total System Performance Assessments Are Performed

Performance assessments are used to forecast how a specific system and all of its components evolve over time. Comparing the results to performance requirements allows analysts to estimate whether the amount of harmful material that may become accessible in the environment is acceptably low. The requirements, usually in the form of regulatory criteria, are generally established by governmental oversight agencies. The ultimate determination of whether a system complies with the requirements lies with the legally responsible regulatory group. The task of proposing a nuclear waste repository is to provide reasonable assurance that the safety standard will be met, which, in turn, requires that:

- The proposed system and all of its components are understood.
- The capability to model the system can be demonstrated.
- The uncertainties in the analysis can be adequately accounted for and treated.
- The information in the model provides reasonable assurance that safety standards will be met.

In addition to providing a tool for determining whether a system meets regulatory requirements, TSPA also provides a rigorous method for aiding management in establishing the priority of information-gathering activities during the site selection, site characterization, and design phases. As more information is gathered, the TSPA process iterates to incorporate revised and updated information into successive TSPA models. This allows the program to progress toward more reasonable and defensible total system models. Results of each TSPA, particularly the sensitivity and uncertainty studies, provide information about the relative importance of ongoing or proposed information-gathering activities addressing site characterization and design development. Successive TSPAs require that the total system models become more representative. Several TSPAs have been completed on the proposed Yucca Mountain repository system (Sinnock et al. 1984 [100553]; Barnard and Dockery 1991 [100307]; Barnard et al. 1992 [100309]; Eslinger et al. 1993 [100554]; Wilson et al. 1994 [100191]; CRWMS M&O 1994 [100111]; CRWMS M&O 1998 [108000]). These efforts, along with studies done by other organizations (Wescott et al. 1995 [100476]; Kessler et al. 1996 100558]), have contributed to the iterative process of the TSPA for the SR. The progression of these analyses is described in Section 1.5.

A TSPA is unique in that the analysis links all the system components together. This linkage is important because it allows each component to be viewed in the context of the behavior of the entire system. Even the simplest system has various aspects that are easier to understand when studied separately (e.g., waste package material degradation may be characterized by laboratory tests of corrosion). However, the geologic system in which the waste package is to be emplaced may be analyzed using field studies of the host rock for properties that are only observed on a large scale (e.g., fracture density), as well as laboratory studies of other aspects (e.g., water chemistry). In a functioning system, these elements provide feedback to one another. The influence of thermal output from the waste on the water chemistry in the near-field could lead to altered corrosion of the waste packages. This very simple example shows an obvious potential for feedback. When the numerous components of a very complex system are brought together and simulated as a single, integrated system in a TSPA, interactions among the components that would not otherwise be identified in a single component analysis may be identified in the TSPA analysis.

The proposed repository safety strategy for the Yucca Mountain Site Characterization Project (YMP) (CRWMS M&O 2000 [148713]) relies on a multiple barrier system. This isolation strategy means that the components of the natural and engineered systems form a series of barriers. Because the behavior of each component in the series is governed by a different set of physical or chemical processes, this strategy provides a strong argument that the entire system is very unlikely to fail in response to a single mechanism. Also, the use of different types of barriers precludes reliance on complete knowledge about any one process. Therefore, the incorporation of multiple barriers helps to answer the question that frequently arises (i.e., How can the analysis account for what is not known?). Given the uncertainty inherent in a forecast, one way to deal with an unanticipated response by one component of the system is to have multiple additional components that will continue to operate as barriers in the face of the unanticipated response.

The concept of reasonable assurance used by the NRC in its proposed regulations for the potential Yucca Mountain repository does not require absolute certainty for the results of an analysis. The incorporation of uncertainty into the TSPA, using various mathematical methods, allows the regulator and others to determine if the goal of reasonable assurance has been met. (See Section 5 for the study of uncertainty.) However, some of the general methods of treating uncertainty include developing distributions to represent various types of data and assigning probabilities to different conceptual models to encompass a range of potential behaviors (or responses) of certain components.

1.4.2 Why Total System Performance Assessments Are the Appropriate Tool for Analyzing the Safety of Repository Systems

A question that often arises is whether or not performance assessment is a useful tool for the purpose of analyzing safety. The consensus of the international waste management community is that, in the realm of providing reasonable assurance, performance assessment is an adequate tool. In support of this consensus, the Nuclear Energy Agency (NEA) Radioactive Waste Management Committee and the International Atomic Energy Agency International Radioactive Waste Management Advisory Committee issued a collective opinion that they...

> Confirm that safety assessments are available today to evaluate adequately the potential long-term radiological impacts of a carefully designed radioactive waste disposal system on humans and the environment, and consider that appropriate

> use of safety assessment methods, coupled with sufficient information from proposed disposal sites, can provide the technical basis to decide whether specific disposal systems would offer to society a satisfactory level of safety for both current and future generations (Nuclear Energy Agency 1991 [100477], p. 7).

Although TSPAs can never be proven to be absolutely valid, many environmental problems require modeling of long-term interactions of man-made and geologic systems. Using the term model acknowledges that whether or not the descriptions of geologic FEPs are unique and represent absolute reality will never be known. Validation of a long-term predictive model means that, on the basis of tests of the assumptions, inputs, outputs, and sensitivities, the model adequately reflects the recognized behavior of the portion of the system it is intended to represent. Adequacy is driven by the needs of the application for which the model is developed (Boak and Dockery 1998 [100368], pp. 178 to 180).

Scientists assessing long-term risk use the following mechanisms to establish the adequacy of their models (Boak and Dockery 1998 [100368], pp. 181 to 182):

- Conservatism–in assigning parameter values and process descriptions, including ignoring some potentially mitigating processes
- Stochastic simulation–to assess the effect of uncertainty in descriptions and the sensitivity of performance predictions to uncertainty and to examine alternative scenarios and process models
- Expert judgment–to assign appropriate ranges of parameters where data are sparse, controversial, or unobtainable.

Measures undertaken to demonstrate that the effort to ensure adequacy has been comprehensive include (1) documentation of the model structures, including justification for assumptions and simplifications, as well as the examination of alternative conceptualizations for the system, and (2) review by the scientific community and those who have a stake in the decisions that these models support (Boak and Dockery 1998 [100368], p. 182).

Uncertainty is an inherent part of all total system studies. Information-gathering activities are directed at reducing uncertainty as much as is practical. However, because of natural variability in the systems being studied and limited understanding about how processes will operate in the future, uncertainty will always have to be explicitly included in TSPA calculations.

1.4.3 Evaluating Confidence

Evaluating confidence in the TSPA requires a combination of the efforts to demonstrate adequacy and to evaluate uncertainties. A case needs to be built for the defensible basis of reasonable assurance that the long term impacts are either reasonably or conservatively evaluated, and clearly and traceably documented.

To provide a statement of confidence, several assurances must be given in proper documentation. Assurances must be provided of the systematic, and arguably complete nature of the FEPs identification and selection approaches. Assurances must be provided that the selection of FEPs, and the exclusion of FEPs, has been carefully and correctly done in a systematic, traceable way. There needs to be a clear path from data to process models and finally to abstractions of models used in the TSPA model itself.

Then the TSPA, and its internal and external linkages need to be shown to be properly based in science, and not arbitrary. Finally, the aforementioned uncertainty and sensitivity analyses need to be used, and thus need to be selected to be useful for, demonstrating the value of information from data and models, providing an ability to make risk-informed, performance-based findings of fact based on TSPA results. Utilization of this approach provides confidence in the analyses presented herein.

1.5 PREVIOUS U.S. DEPARTMENT OF ENERGY TOTAL SYSTEM PERFORMANCE ASSESSMENTS FOR THE YUCCA MOUNTAIN SITE

TSPA provides a tool for evaluating the significance of uncertainties in properties and processes by evaluating the sensitivity of calculated results to different assumptions about these properties and processes. The site characterization process proceeds iteratively (i.e., new data and design changes are incorporated into updated TSPA models, and updated TSPA sensitivity studies suggest where new data and design enhancements might be valuable). Over time, this iterative process reduces uncertainty in the forecasted performance of the potential repository. The TSPA tool has been used by the DOE to identify needs and to set priorities for site characterization work, materials-properties investigations, and other design-related investigations, including repository and waste package design options. Figure 1.5-1 illustrates the major TSPA iterations.

The DOE conducted benchmark performance assessments of the total potential repository system in 1991, 1993, 1995, and 1998. As a result, the DOE TSPA has become much more sophisticated and representative. The tool and the analyses have evolved as new data have been collected. The DOE has continually added component models that provide more details of system behavior. The abstractions of the components of the system have become more sophisticated with each DOE TSPA. This is described in detail in this section, which briefly describes the purpose, objectives, and goals of each TSPA, identifies the primary issues investigated, and summarizes the conclusions reached.

1.5.1 Total System Performance Assessment-1991

In 1991, the DOE conducted the *TSPA-1991: An Initial Total-System Performance Assessment for Yucca Mountain* (Barnard et al. 1992 [100309]). Sandia National Laboratories performed the TSPA for the YMP.

1.5.1.1 Purpose

The primary purpose of the 1991 TSPA effort was the derivation of abstracted representations capturing the essence of the complex processes that contribute to the behavior of a repository system. Defensible, abstracted representations were deemed to be necessary tools for producing useful estimates of the principal performance measure for evaluating compliance with the EPA standard, 40 CFR Part 191 (50 FR 38066 [100495]). A secondary purpose was to demonstrate that complex combinations of probabilistic data could be assembled to provide a reasonable overall estimate of system performance. Because of the limited number of components included, this performance estimate did not evaluate the suitability of Yucca Mountain as a site for a potential radioactive waste repository. The results were intended to provide guidance for site characterization and for the next iterations of TSPA (Barnard et al. 1992 [100309], p. 1-2).

1.5.1.2 Conclusions

TSPA-1991 showed that complex processes can be abstracted into more simplified representations that retain the necessary degree of sensitivity, consistent with the understanding of the processes and work done using other models and techniques. As prescribed in 40 CFR Part 191 (50 FR 38066 [100495]), the results were combined into a conditional, total-system, complementary, cumulative-distribution function, thereby demonstrating that total system performance can be estimated (Barnard et al. 1992 [100309], p. 10-1).

The results reflected considerable uncertainty and many conservative assumptions, which were attributed to the lack of site-specific data. Uncertainty in the models was partially addressed by using two alternative conceptual models of flow in the UZ. The calculated releases were sensitive to the choice of flow model. Because a sensitivity study was not done, the most important parameters for nominal conditions were not identified. Because of the uncertainty and conservatism, the analyses were not an appropriate basis for site suitability recommendations (Barnard et al. 1992 [100309], p. 10-1). Figure 1.5-2 illustrates the subsystem component model abstractions that were available for the 1991 TSPA. The analyses were considered adequate for guiding site characterization activities. The 1991 TSPA provided the following general recommendations for future work:

- Develop an exhaustive set of scenario categories
- Select a formal method for future calculations
- Continue to validate the abstractions used in the TSPA
- Develop and integrate new alternative conceptual models
- Use TSPA analyses to help guide site characterization
- Analyze new site characterization data for incorporation into TSPA analyses
- Investigate the effects of disturbing conditions
- Investigate general thermal effects caused by potential repository heating.

Recommendations for five components of the analyses were also provided (see Table 1.5-1). These components were parameters, aqueous flow and transport, gaseous flow and transport, human intrusion, and basaltic igneous activity (Barnard et al. 1992 [100309], p. 10-1).

Table 1.5-1. Parameter-Specific Recommendations for Future Work from the 1991 Total System Performance Assessment

Components	Recommendations
Data Set	Develop alternative interpretations of the Yucca Mountain geohydrologic stratigraphy
	Conduct a formal sensitivity study to identify the most important parameters
	Refine further the elicitation techniques employed to develop the data set
	Refine parameter distributions, as additional information becomes available
	Analyze correlation among parameters

Table 1.5-1. Parameter-Specific Recommendations for Future Work from the 1991 Total System Performance Assessment

Components	Recommendations
Data Set (Continued)	Develop hydrogeologic and geochemical parameter values for the SZ
	Quantify the effects of scale on the model parameters
	Investigate the effects of heterogeneity among the stratigraphic units
	Investigate the validity of the one-dimensional modeling
Source Term	Develop more accurate, correlated, and defensible parameter distributions
	Perform aqueous-transport analyses, including all significant radionuclides
	Include the waste container and the fuel-rod cladding more realistically
	Develop submodels for additional release modes
	Verify the validity of the alteration-limited-release model
Geochemistry	Refine parameter distributions
	Develop retardation information for all significant radionuclides
	Include retardation for transport in fractures, if it can be shown to be significant
	Study the effects of colloids, especially of plutonium and americium
	Investigate methods for modeling radionuclide transport other than K_d values
Aqueous Flow and Transport in the UZ	Study and include the effects of spatial correlation
	Refine the weeps model
	Study climate change and its effects on percolation flux
	Investigate effects of repository heating on groundwater flow and transport
	Verify the conceptual models in the TSPA
Aqueous Flow and Transport in the SZ	Improve the coupling of the UZ and the SZ and account for the uncertainty in travel time
	Investigate effects of matrix and fracture coupling
	Investigate effects of seismic, tectonic, and volcanic activity
Gaseous Flow and Transport	Calculate aqueous and gaseous releases together
	Characterize gas permeability throughout the UZ
	Include the uncertainty in the permeabilities of welded and nonwelded tuff
	Calculate the travel-time distributions for the potential repository-temperature curve realistically
	Characterize the ^{14}C inventory, prompt fraction, and release rate
	Calculate travel-time distributions with a model that couples gas flow and thermal effects
	Continue to investigate carbon geochemistry and rock interactions
Human Intrusion	Determine the likelihood that commercially attractive natural resources are present
	Complete the human-intrusion event tree
Basaltic Igneous Activity	Review the complete event tree for igneous events and estimate probabilities for igneous activity
	Consider nonmechanical interactions between magma and waste
	Investigate the interaction depth for wall-rock erosion
	Obtain a better understanding of the depth at which vesiculation occurs

Source: Barnard et al. 1992 [100309], Chapter 11

1.5.2 Total System Performance Assessment-1993

Beginning in fiscal year 1993, the Civilian Radioactive Waste Management System Management and Operating Contractor (CRWMS M&O) was assigned the responsibility to plan, coordinate, and contribute to the second iteration of TSPA *Total System Performance Assessment-1993: An Evaluation of the Potential Yucca Mountain Repository* (CRWMS M&O 1994 [100111], p. 1-2).

Both the CRWMS M&O and SNL (Wilson et al. 1994 [100191]) conducted TSPA analyses for the 1993 iteration. The CRWMS M&O work is summarized here. Although they used two different computational tools for assessing the total system performance, the primary difference in the two approaches was the level of detail incorporated into the abstraction from the process models. The assumptions made in the two sets of analyses were much more important to the results than was the computational scheme embodied in the codes used. Subsequently, the computational scheme used by the CRWMS M&O was selected for future TSPA analyses.

1.5.2.1 Goals and Objectives

The goals of the CRWMS M&O in TSPA-1993 were to (1) enhance the realism and representativeness of the analyses, (2) incorporate new information and designs that had become available since the completion of TSPA-1991, (3) test the sensitivity of the predicted performance against various conceptual model-and-parameter uncertainties, and (4) evaluate alternate measures of postclosure performance (CRWMS M&O 1994 [100111], p. 1-2). The analyses, aimed at identifying the key assumptions and the sensitivity of the results to those assumptions, had eight major objectives (CRWMS M&O 1994 [100111], p. 1-4).

- Incorporate thermal dependency on individual processes and parameters
- Evaluate the effects of alternate thermal loads
- Evaluate the effects of alternate waste package designs
- Evaluate alternate measures of total system performance
- Incorporate new site and design information
- Incorporate a more representative inventory, including high-level waste
- Conduct sensitivity analyses to identify the key processes and parameters
- Provide guidance to site characterization and design activities.

1.5.2.2 Primary Issues

At the time of TSPA-1993, the National Academy of Sciences (NAS) was evaluating the appropriateness of a dose-based standard for Yucca Mountain (Section 1.3.1.1). Therefore, the performance measure was itself a primary issue. Another issue arising from the lack of a standard was the time period of regulatory concern. (CRWMS M&O 1994 [100111], p. 1-2)

The ability to forecast performance of the site and engineered barriers in containing and isolating radioactive wastes from the accessible environment depended on two primary issues. These were the understanding of flow and transport through the fractured-porous media and the uncertainty in the magnitude of the percolation flux through the UZ (CRWMS M&O 1994 [100111], p. 4-14). The primary design issues affecting the migration of radionuclides away from the disposal area were the thermal load and the waste package design, and their effects on aqueous corrosion of the waste form (CRWMS M&O 1994 [100111], p. 4-12).

1.5.2.3 Conclusions

Although the TSPA-1993 (CRWMS M&O 1994 [100111]) analyses significantly extended the work performed in TSPA-1991 (Barnard et al. 1992 [100309]), uncertainties remained. The sources of significant uncertainty in TSPA-1993 and the associated recommendations for future work (CRWMS M&O 1994 [100111]) are given in Table 1.5-2. Figure 1.5-3 illustrates the subsystem component model abstractions that were available for the 1993 TSPA. Many of these recommendations were also made in the SNL TSPA for 1993. The following additional recommendations were made by SNL (Wilson et al. 1994 [100191], p. ES-21).

- Characterize the spatial distribution of bulk permeability
- Collect data on adsorption of CO_2 to tuff
- Characterize the horizontal and vertical dispersion in the SZ
- Evaluate heterogeneity and spatial correlation for geostatistical modeling
- Evaluate cross-correlation among parameters
- Determine thermal and hydraulic properties of proposed backfill materials
- Characterize fault-zone hydrogeologic properties.

Table 1.5-2. Sources of Uncertainty and Recommendations from Total System Performance Assessment-1993

Sources of Significant Uncertainty	Recommendations
Panel and drift scale thermo-hydrologic analyses	Perform additional analyses to evaluate the effect of uncertain and spatially variable thermo-hydrologic properties, uncertain fracture-matrix conceptual models, and uncertain ambient percolation fluxes on the expected far-field, near-field, and very-near-field (waste package scale) thermal and hydrologic regimes as a function of space and time.
Initiation and rates of aqueous corrosion processes	Develop a greater understanding of the cathodic protection of the inner container, the processes affecting pitting, and even the definition of waste package failure, in order to provide a more defensible argument for the range of likely waste package lifetimes.
Ambient UZ percolation flux	Employ direct or indirect observations to better quantify the expected UZ percolation flux and its uncertainty.
Fracture-matrix interactions as water moves through the UZ	Incorporate the preliminary, site-scale, UZ model to be completed by the U.S. Geological Survey in fiscal year 1994.
	Conduct further testing to determine the relative significance of alternate conceptualizations to the composite porosity model of fracture-matrix interaction.
	Validate the simplified K_d representation of radionuclide transport through the UZ.

Source: CRWMS M&O 1994 [100111], pp. 4-17 to 4-18

Sandia National Laboratory also concluded that regulatory change could lead to significant changes in program priorities for site characterization. A performance measure based on individual dose for the time period of regulatory concern, as in proposed 40 CFR Part 191 (58 FR 66398 [107802]), would require additional characterization of the biosphere. A longer time period would lead to more emphasis on determining radionuclide release rates (Wilson et al. 1994 [100191], p. ES-22).

1.5.3 Total System Performance Assessment-1995

The work performed across the gamut of the YMP had been melded into a single TSPA effort by the time the *Total System Performance Assessment-1995: An Evaluation of the Potential Yucca*

Mountain Repository (CRWMS M&O 1995 [100198]) was initiated. Four specific goals were identified for the 1995 iteration of TSPA (CRWMS M&O 1995 [100198], pp. 1-5 to 1-7).

1. Utilize what were believed to be more representative conceptual models that built upon the assumptions employed in TSPA-1993, in particular, for the treatment of the EBS, including the waste package, using reasonably conservative representations of the relevant processes and parameters affecting total system performance.

2. Incorporate more recent design information than was available for TSPA-1993, evaluating a range of alternative conceptual models and parameters to explicitly address the uncertainty and variability in the understanding and the significance of that uncertainty on the predicted performance.

3. Utilize the most recent site information and models, acknowledging their uncertainty and variability, focusing the analyses on those components of the waste containment and isolation system that are most sensitive.

4. Evaluate the EBS release performance measure, as well as alternative measures of total system performance, using a range of possible measures of safety, including cumulative radionuclide releases, peak concentrations, or doses.

The focus of the 1995 TSPA was on those components of the system that were determined in the 1993 TSPA to be most significant in containing and isolating radioactive wastes from the biosphere. These were the engineered components of the system and the near-field environment in which the engineered components reside (CRWMS M&O 1995 [100198], p. 1-3).

1.5.3.1 Primary Issues

As the EPA had not yet proposed an environmental standard for Yucca Mountain (Section 1.3.2), the performance measure remained an issue. Technical issues (CRWMS M&O 1995 [100198], pp. 10-1 to 10-2) were:

- Alternative models of the thermo-hydrologic environment near the waste package
- Alternative assumptions about the degradation of the waste package materials
- Alternative assumptions about capillary barriers in the drifts
- Alternative concepts of advective flow in the drifts and percolation flux in the UZ
- Alternative conceptual models of transport in the UZ
- Alternative thermal-loading designs and backfill emplacement options.

1.5.3.2 Conclusions

Five different measures of performance were evaluated in the 1995 TSPA (CRWMS M&O 1995 [100198]). The first two considered subsystems: the waste package (substantially complete containment) and the EBS (the peak radionuclide release rate). The remaining three measures quantified total system performance: the cumulative radionuclide release at the accessible environment over 10,000 years; and the maximum radiation doses in both 10,000 and 1 million years to an individual located at the accessible environment boundary. Table 1.5-3 presents the factors determined to affect performance in the 1995 TSPA. Figure 1.5-4 illustrates the subsystem component model abstractions that were available for the 1995 TSPA. The TSPA team identified a detailed technical analysis of the robustness of the process models under development as the performance assessment activity having the highest priority in preparation for the next full iteration of TSPA. Equally significant was assuring that the developed and substantiated process models could be appropriately abstracted for use in the next TSPA (CRWMS M&O 1995 [100198], p. 10-26). The necessary process models are shown in Table 1.5-4.

Table 1.5-3. Factors Affecting Performance in the 1995 Total System Performance Assessment

Performance Measure	Factor Affecting Performance
Substantially Complete Containment at the Waste Package	The rate of container degradation was not directly correlated with the thermal load, given the assumptions (validity of assumptions needed substantiation).
	Incorporating cathodic protection significantly extends the lifetime of the waste packages (sensitivity analyses with unconfirmed, first-order approximations).
	Incorporating time dependence for pitting of corrosion-resistant materials significantly affects the predicted failure distribution (sensitivity analyses in lieu of an improved, experimentally derived model).
	Conceptual representations of drift scale thermal-hydrology and corrosion-degradation models significantly affect the waste package failure distribution over the first 10,000 years but are less significant for longer times.
Peak Release Rate from the EBS	The conceptualization of diffusion resulted in very small diffusive releases (drip rate required substantiation).
	When advection dominated the EBS release, the infiltration-rate distribution had a significant effect and the conceptualization (e.g., assuming a capillary barrier) of how dripping water contacts the waste package was important.
	The mode of radionuclide transport, gas phase or dissolved in liquid, affected the peak EBS release rates and peak doses at the accessible environment.
	The dissolution rate did not significantly affect the peak EBS release rate.
Cumulative Release of Radionuclides at the Accessible Environment–10,000 years	Certain conceptual assumptions resulted in engineered barriers that provided complete containment and natural barriers that provided complete isolation.
	The most conservative assumptions for both EBS and natural-barrier performance resulted in the system being dominated by the percolation flux distribution (affecting the likelihood of dripping, the magnitude of the advective release from the EBS, and the distribution of radionuclide transport and matrix velocity through the UZ).
Peak Radiation Dose to Reasonably Maximally Exposed Individual at the Accessible Environment–10,000 Years	Factors that delayed the arrival of the peak concentration of radionuclides at the accessible environment were significant, primarily the percolation flux distribution, but sorption, matrix diffusion, and fracture-flow path length also affected arrival time.
	Predicted peak arrival time generally occurred between 10,000 and 1 million years, depending on the nuclide and the flow and transport conceptualization.
	Dispersion in the UZ reduced the arrival time and increased the peak dose during the 10,000-year time period.
	Dilution of radionuclide concentrations in the SZ, dependent on the local Darcy flux distribution within the SZ, controlled both peak concentrations and peak doses, but not cumulative releases.

Table 1.5-3. Factors Affecting Performance in the 1995 Total System Performance Assessment (Continued)

Performance Measure	Factor Affecting Performance
Peak Radiation Dose to Reasonably Maximally Exposed Individual at the Accessible Environment–1 million Years	Factors that delayed the arrival of the peak concentration at the accessible environment were less significant because of the extremely long time period and the long half-lives of some key radionuclides.
	Waste package and site performance helped contain and isolate radioactive wastes, but were unlikely to preclude the release of ^{99}Tc, ^{237}Np, and ^{129}I over a 1-million-year time period.
	Dispersion and dilution in the geosphere were significant processes in reducing peak concentrations and peak doses.
	Diffusion-dominated releases from the EBS significantly reduce the peak release rate with either a very low percolation flux distribution or an efficient capillary barrier.

Source: CRWMS M&O 1995 [100198], pp. 10-3 to 10-8

Table 1.5-4. Process Models Necessary for Development of Abstractions Beyond Those in the 1995 Total System Performance Assessment

Priority	Process Model	Notes
1	Site scale UZ hydrology model(s) (ambient)	UZ: unsaturated zone
3	Repository scale UZ TH model(s)	TH: thermal-hydrology
3	Site scale UZ geochemical model(s) (ambient)	
1	Drift scale TH model(s)	
3	Drift scale TC model(s)	TC: thermal-chemical
4	Drift scale TM model(s)	TM: thermal-mechanical (potentially higher priority, if no backfill in drift)
4	Drift-scale-coupled THCM model(s)	THCM: thermal-hydrological-chemical-mechanical
2	Waste package degradation model(s)	
4	Cladding degradation model(s)	
3	Waste form dissolution model(s)	
2	Waste package scale TC model(s) (solubility)	
2	Drift scale transport model(s)	
3	Site scale UZ transport model(s)	
3	Regional and site scale SZ flow model(s)	SZ: saturated zone
3	Site scale SZ transport model(s)	
3	Biosphere transport model(s)	(Because no standard had been promulgated, the recommendation was that the EPA should prescribe model for dose or risk standard)
4	Tectonics direct and indirect effects model(s)	
3	Volcanic direct and indirect effects model(s)	
2	Climate change indirect effects model(s)	

Source: CRWMS M&O 1995 [100198], p. 10-27

1.5.4 Total System Performance Assessment-1998

The *Viability Assessment of a Repository at Yucca Mountain* (DOE 1998 [101779]), proposed by the DOE in 1996 and mandated by Congress in 1997, was designed to provide the President, Congress, and the public with information on the progress of the YMP. The assessment also identified the critical issues that should be addressed before a decision can be made by the Secretary of Energy on whether to recommend the Yucca Mountain site for a potential repository. The keystone of the viability assessment was the TSPA, documented in Volume 3 (DOE 1998 [100550]).

1.5.4.1 Goals

The statutory goal of the viability assessment TSPA was to describe the probable behavior, relative to the overall system performance standards, of a potential repository in the Yucca Mountain geologic setting, based on the design concept and the scientific data and analyses available by 1998 (DOE 1998 [100547], p. 1). The DOE also wanted to assess quantitatively the total system performance so that the significance of each of the key components in the potential repository safety strategy could be defined to assist in a systematic refocusing of the project resources.

This was accomplished by examining the relative importance of the various TSPA components and parameters through sensitivity and uncertainty analyses. The information about uncertainty assisted the DOE in defining the work required either to reduce uncertainty or to modify the potential repository design to accommodate this uncertainty before proceeding with the Site Recommendation. The TSPA also provided a vehicle for prelicensing discussions with the NRC. An important role of the TSPA was to evaluate the potential significance of KTIs identified by the NRC (Section 1.3.5.1). Another goal was to produce a document that transparently described for all interested parties the assumptions, the intermediate steps, the results, and the conclusions of the analyses (DOE 1998 [100550], p. 2-3).

1.5.4.2 Primary Issues

The primary issues were the KTIs that the NRC considered most important to potential repository performance. These were:

- Total System Performance Assessment and Integration
- Unsaturated and Saturated Flow under Isothermal Conditions
- Evolution of the Near-Field Environment
- Container Life and Source Term
- Repository Design and Thermal Mechanical Effects
- Thermal Effects on Flow
- Radionuclide Transport
- Structural Deformation and Seismicity
- Igneous Activity.

All relate to performance assessment (DOE 1998 [100550], Volume 3, p. 2-5). As was true for the preceding TSPAs, the EPA had not yet proposed an environmental standard for Yucca Mountain. Consequently, the NRC had not proposed revising 10 CFR Part 60, which governed such repositories (Section 1.3.1.1).

1.5.4.3 Conclusions

By the time of this TSPA iteration, the DOE had developed a potential repository safety strategy (DOE 1998 [100550], Volume 3) having four key attributes for system performance. The attributes are (1) limited water contacting waste packages, (2) long waste package lifetime, (3) low rate of release of radionuclides from breached waste packages, and (4) radionuclide concentration reduction during transport from the waste packages. The YMP had identified nineteen principal factors for analyzing system performance and developed modeling components to examine the factors.

The probable behavior of the reference design suggested that the vast majority of radionuclides in the waste are immobile and never leave the potential repository, even if in contact with water. A few radionuclides appeared sufficiently mobile under some conditions that they could reach the biosphere downgradient from the potential repository. Hence, the most important factors for system performance over time were the amount of water likely to contact the waste packages and the amount of waste exposed to that water. Consequently, factors that limit the contact of water with the waste were considered highly important to performance. Under the base-case scenario, the quantities of radionuclides reaching the biosphere were small: a negligible amount in 10,000 years and a dose rate for hundreds of thousands of years that is comparable to natural background activity (DOE 1998 [100550], Volume 3, p. 6-5). Figure 1.5-5 illustrates the subsystem component model abstractions that were available for the viability assessment TSPA and identifies remaining uncertainties.

Table 1.5-5 shows the four key attributes of the DOE strategy for repository safety and the associated nineteen principal factors as addressed by the components of the TSPA. This table relates the key attributes, the principal factors, and the model components to the corresponding issues identified by the NRC. The sensitivity of the results to uncertainties in the estimates is also summarized for three periods of performance. High significance means that uncertainty in the principal factor, or its absence, results in a factor of over 50 increase (or decrease) in peak dose rate from the expected value. Medium significance means a factor of 5 to 50 increase (or decrease), and low significance means less than a factor of 5 increase (or decrease) in peak dose rate from the expected value. These indicators of sensitivity guided additional work. (DOE 1998 [100548], Volume 3, p. 6-12).

Table 1.5-5. Total System Performance Assessment-Viability Assessment: Attributes and Principal Factors with Significance of Uncertainty, Model Components, and Key Technical Issues

Attributes of the Potential Repository Safety Strategy	Principal Factor	Significance of Uncertainty by Performance Period (x 1,000 years)			TSPA Model Component	U.S. Nuclear Regulatory Commission Key Technical Issue
		10	100	1,000		
Limited water contacting waste packages	Precipitation and infiltration of water into the mountain	Low	Med.	Low	UZ Flow	Unsaturated and Saturated Flow under Isothermal Conditions
	Percolation to depth	Low	Low	Low		
	Seepage into drifts	High	High	High	Seepage	Repository Design and Thermo-mechanical Effects
	Effects of heat and excavation on mountain scale flow	Not Available				
	Effects of heat and excavation on drift scale flow	Low	Med.	Low		
	Dripping onto waste package	Low	Low	Low	Thermal Hydrology Mountain and Drift Scales	Thermal Effects on Flow
	Humidity and temperature at waste package	Low	Low	Low		
Long waste package lifetime	Chemistry of water on waste package	High	Low	Low	Near-Field Geochemical Environment	Evolution of Near-Field Environment
	Integrity of outer carbon-steel barrier	Not Available			Waste Package Degradation	Container Life and Source Term
	Integrity of inner corrosion-resistant barrier	High	High	Med.		
Low rate of release of radionuclides from breached waste packages	Seepage into waste package	Low	Low	Low		
	Integrity of cladding	High	Med.	Med.	Waste Form Degradation, Radionuclide Mobilization, and EBS Transport	
	Dissolution of UO_2 and glass waste form	Low	Med.	Low		
	Solubility of ^{237}Np	Low	Med.	Low		
	Formation and transport of radionuclide-bearing colloids	Low	Med.	Low		
	Transport through and out of the EBS (including waste packages)	Low	Low	Low		
Radionuclide concentration reduction during transport from the waste packages	Transport through the UZ	Low	Low	Low	UZ Transport	Unsaturated and Saturated Flow under Isothermal Conditions and Radionuclide Transport
	Flow and transport in the SZ	Med.	Med.	Med.	SZ Flow and Transport	
	Dilution from pumping	High	High	High		
	Biosphere transport	Med.	Med.	Med.	Biosphere Transport and Uptake	

Source: DOE 1998 [100550], Volume 3, pp. 2-5, 6-12

1.5.5 Summary and Conclusions

This synopsis of individual TSPAs from 1991, 1993, 1995, and 1998, and the clear continuity in how each builds on its predecessors, demonstrates that the general approach and methodology for the TSPA are well established. The DOE has been developing TSPAs for the potential Yucca Mountain site for almost 20 years. While the overall approach has remained the same, the implementation of additional site information, the incorporation of the design into the analyses, and the process models have evolved significantly. Figure 1.5-6 illustrates how the abstractions of components of the system have evolved over the course of the four TSPAs described here. This figure is a composite of Figures 1.5-2, 1.5-3, 1.5-4, and 1.5-5, each of which provides details on progress or remaining issues in each component.

1.6 GENERAL APPROACH FOR CONDUCTING A PERFORMANCE ASSESSMENT

In general, the goal of performance assessment is to provide decision makers with a reasonable estimate of the realistic future performance of the disposal system and a clear display of the extent to which uncertainty in the present understanding of the system affects that estimate. Internationally, most radioactive waste management programs have adopted performance assessments that rely, in one form or another, on computer models as a key element of their safety cases.

Total system performance assessment (TSPA), such as that conducted for the potential Yucca Mountain repository, links models of the components of a disposal system into a single analysis that provides an estimate of overall system performance. Examples of possible system level performance measures that have been adopted or proposed for other repository programs include peak dose to humans from all pathways, cumulative releases of radionuclides from the system, and concentrations of radionuclides in groundwater. For Yucca Mountain, the primary system level performance measures are (1) expected annual dose to humans during the next 10,000 years, and (2) peak concentrations of radionuclides in groundwater (defined in the regulations described in Section 1.3).

Because regulatory requirements specify a consideration of the uncertainty in that estimate, the Yucca Mountain TSPA uses a probabilistic approach similar to that adopted by many other repository programs internationally. This approach has five major steps, shown schematically in Figure 1.6-1 and briefly summarized below. This probabilistic approach was adopted by the EPA in 1985 in the original radiation protection standards, 40 CFR Part 191 (50 FR 38066 [100495]). That rule required a probabilistic performance assessment in the Containment Requirements, with results displayed as a complementary cumulative distribution function showing probability of exceeding specified release limits. Although the currently proposed EPA standards for Yucca Mountain do not include containment limits, a probabilistic performance assessment is still required by the EPA.

1.6.1 Identifying and Screening Potentially Relevant Features, Events, and Processes to Develop Scenarios

The first step in the TSPA is to decide what representations of possible future states of the potential repository (i.e., scenario classes and scenarios) are sufficiently important to warrant quantitative analysis. A further definition of scenario classes and scenarios is found in Appendix A (Glossary). TSPAs can analyze only a relatively small number of the essentially infinite combinations of processes and events that could conceivably affect the system, and it is therefore important that the scenarios chosen for analysis provide a sound basis for evaluating the performance of the site. Specifically, the chosen scenarios must be representative of the conditions of greatest relevance to regulatory requirements and the long-term safety of the site. For the probabilisitic approach required for the Yucca Mountain, estimates must be provided of the probability that the chosen scenarios will occur. Section 2.1 documents the scenario development process adopted for the TSPA-SR, including the basis for identification and screening of potentially relevant FEPs and the selection of the nominal (i.e., undisturbed) and disruptive scenarios classes and their underlying scenarios.

1.6.2 Developing Models

In this step, models are developed to represent components of the system that are potentially important in the chosen scenario classes and scenarios. These models are first developed as conceptual models that describe the behavior of the system. Mathematical models are developed that quantify the conceptual models, and then, in most cases, the mathematical models are implemented in computer codes. (Major models in the Yucca Mountain TSPA are described in Section 3.)

1.6.3 Estimating Parameter Ranges and Uncertainties

Many parameters used in the TSPA models, such as those that describe common rock properties (i.e., porosity and permeability), have natural variability. Uncertainty regarding parameter values also arises from incomplete knowledge (e.g., when the future state of a property must be estimated from assumptions rather than from measurements). In the context of the component models of the TSPA, described in Section 3, uncertainty associated with the selection of parameter values is accounted for by developing distributions of values for important, and imprecisely known, parameters rather than using single values. Each distribution describes a range of values within which the true value is believed to fall, with an expected value (i.e., the mean) that corresponds to the best estimate of the true value. Not all parameters in the TSPA require uncertainty distributions. Single values are used to describe properties that are well known or for which uncertainty has been shown to have little or no effect on overall performance. In cases where realistic uncertainty distributions or parameter values cannot be adequately justified based on available information, parameter distributions or values may be chosen that are deliberately conservative, in the sense that they result in a calculation of performance that is poorer than would result form more realistic input values. The use of conservative or bounding values for input parameters has a potential to mask effects of processes that are treated more realistically, and conservatism should be used cautiously in TSPA.

1.6.4 Performing Calculations

As described in Section 2.2, computer models are linked to allow calculation of the overall system behavior. Uncertainty associated with the selection of scenarios is included in the TSPA by conducting separate analyses for each scenario class. Uncertainty associated with the model parameters is included in the TSPA by conducting multiple calculations for each scenario using values sampled from the ranges of possible values. Each individual calculation uses a different set of sampled input values. In a statistical sense, the result of each individual TSPA calculation represents a different possible realization of the future performance of the system, consistent with the uncertainty in the input parameters.

The expected (i.e., mean) behavior of the system for each scenario class is shown by the mean of the results of the individual calculations, and the uncertainty associated with that mean is shown by the range of calculated outcomes. The overall expected annual dose estimate is determined by summing the expected annual dose calculated for each scenario class, weighted by the probability that the underlying scenarios will occur. The TSPA is, therefore, a probabilistic analysis, consistent with the regulatory requirements described in Section 1.3, in the sense that it takes into account both the estimates of the probability of occurrence of the different scenario classes and scenarios and the uncertainty associated with input parameters.

In addition to the overall TSPA expected annual dose estimate, mean groundwater concentrations are calculated for the nominal scenario to evaluate the groundwater protection performance measure, and a human intrusion expected annual dose is calculated.

1.6.5 Interpreting Results

Results of preliminary performance assessments can be analyzed at the system and subsystem levels to identify the models and parameters that have the greatest effect on the behavior of the system. Identification of the uncertainties that are most important in preliminary TSPAs can help guide testing for site characterization, model development, and repository design. When the TSPA models are sufficiently well developed and documented to support regulatory decisions, results can be used to evaluate compliance with applicable long-term requirements.

1.6.6 Repository Safety Strategy and the Principal Factors

The philosophy and approach to developing the case regarding postclosure safety is presented in the Repository Safety Strategy (CRWMS M&O 2000 [148713]). The postclosure safety case comprises the information the DOE intends to use to assure a potential repository at Yucca Mountain would adequately protect public health and safety after the potential repository is permanently closed. This postclosure safety case is built on a sound technical basis, including information about the Yucca Mountain site, a robust design for the system, comprehensive safety assessments, and assessments of the confidence in that information.

The postclosure safety case described in the Repository Safety Strategy (CRWMS M&O 2000 [148713], Section 1.3) is structured into five elements:

- Performance assessment
- Safety margin and defense-in-depth
- Potentially disruptive processes and events
- Natural analogues
- Performance confirmation.

The safety case focuses on an analysis of 8 factors potentially important to the nominal performance of the potential repository (CRWMS M&O 2000 [148713], Section 4).

1.7 REPOSITORY DESIGN DESCRIPTION

The base case design for the TSPA-SR analyses, the so-called "Reference Design," has recently been updated (CRWMS M&O 2000 [149638]). The basis for the base case design is presented in this section. The design has been formulated with the intention of enhancing system performance with respect to the following key system attributes: 1) water contacting waste package, 2) waste package lifetime (containment), 3) radionuclide mobilization and release, 4) radionuclide transport, and 5) disruptive events and processes. The design strategy seeks to use engineered components to tailor the environmental variables (i.e., temperature, relative humidity, seepage flux) to be as benign as possible.

1.7.1 Base Case Design

A schematic of the base case design at the time of potential repository closure is presented in Figure 1.7-1. In general, the major components of the base case design will include a low areal mass load (60 metric tons of uranium [MTU]/acre), with "line loading" of the waste packages. The EBS will include a drift liner (steel sets with welded wire and rock bolts), an initial air gap in the drift (no backfill), a drip shield, a two-layer waste package (2 cm corrosion-resistant outer material surrounding 5 cm inner structural material), in-drift emplacement of the waste packages, placement of the waste packages on a corrosion resistant emplacement pallet (Alloy-22 and stainless steel), and an invert (steel structure and granular ballast fill [e.g., crushed, welded tuff]) at the base of the drift. The following discussion provides more detail as to the basis for each of these design components.

Drift Support (steel sets with welded wire and rock bolts)–A drift support system has been included in the design, primarily in support of preclosure safety. While the support is intact, it is a potential barrier to seeping water. Seeping water has the potential to drain through the small space between the support and the host rock and also to film flow along the inside surface of the support. Both of these modes of flow reduce or eliminate dripping directly onto the waste package. However, water may also seep through the drift support onto the drip shield.

Air Gap (capillary barrier)–The air gap between the drift support or drift wall and the waste packages provides a means by which percolation flux may be diverted around the opening as matrix or film flow. This advantageous property will be in effect until the drift collapses and fills with rubble.

Drip Shield (titanium alloy)–The drip shield is continuous in the drift over the waste packages. It serves to reduce the effect of rock fall and dripping on the waste package. There is also an initial air gap between the drip shield and the waste package. This will be in effect until the drip shields degrade or collapse onto the waste packages.

Waste Package Corrosion Resistant Material–The outer layer of the waste package is a nickel-based alloy that is very resistant to aqueous corrosion and nearly totally resistant to humid air corrosion. The current reference corrosion-resistant material is 2 cm of Alloy-22.

Waste Package Structural Material–Because the waste package is the single component that is expected to have absolute containment at the time of emplacement, the design strategy is to make the waste package robust. The inner structural material is 5-cm thick and serves three functions.

First, it provides structural strength to resist rock falls, to support the internal components, to be supported by the emplacement pallet and to be handled. Second, the inner layer provides radiation shielding to reduce the waste package exterior surface contact dose rate. Coupled with the Mined Geologic Repository shielded transport, the shielding is enough to protect workers. Third, the inner layer acts as a limited containment barrier for the radioactive waste inside the waste package. The current structural material in the design is stainless steel.

Large Waste Packages–A large waste package reduces cost, handling, closure operations, nondestructive evaluation operations, and allows efficient use of the drift length. The current large waste package reference design is based on a 21 pressurized water reactor spent nuclear fuel assembly waste package. Roughly the same size waste package can also accommodate 44 of the smaller boiling water reactor (BWR) SNF assemblies, five defense high level waste glass "logs" surrounding a central canister of DOE-owned SNF, or a naval spent nuclear fuel canister. For high-heat-producing or high-criticality-potential assemblies, a smaller waste package, for 12 pressurized water reactor (PWR) SNF assemblies, is used. The number of 12 PWRs is small relative to the overall number of waste packages, so they are accounted for indirectly in the mountain scale model, but not in the drift scale model.

In-Drift Emplacement of Waste Packages–The design calls for in-drift emplacement. This is a consequence of large waste packages being well suited to in-drift emplacement; consequently, the amount of excavation is minimized. Nondrift emplacement would require additional excavation.

Invert–The invert is designed to provide support for the waste package emplacement pallets and the drip shields. It will be composed of granular ballast (e.g., crushed, welded tuff), between steel beams that support the rails used during the preclosure period for waste emplacement and performance confirmation equipment.

Alloy 22 Emplacement Pallet–The emplacement pallets provide support for the waste packages during the preclosure period. The pallets will be emplaced along with the waste packages. Each waste package will rest on one pallet.

Thermal Design-Areal Mass Load (Medium) and Thermal Design-Waste Package Spacing (line)–In this reference case, the capacity of the potential repository is designed for the emplacement of 70,000 metric tons of heavy metal (MTHM) (63,000 MTHM commercial spent nuclear fuel (CSNF) and 7,000 MTHM DSNF and HLW).

An areal mass loading of approximately 60 MTU/acre, combined with preclosure ventilation for at least 50 years from the start of emplacement, will prevent the boiling zones from coalescing in the pillars between emplacement drifts. Waste packages are placed in the emplacement drifts in a line load configuration with a waste package to waste package spacing of approximately 10 cm. The diameter of a waste emplacement drift is 5.5 m. Emplacement drifts are arranged with a uniform spacing of 81 m between their centerlines. The total emplacement drift length is calculated from adding the waste package inventory (including DOE waste packages) and the package-to-package gaps. The emplacement area encompasses 1,050 acres in the upper emplacement level of the characterized area.

Thermal Design-Spent Nuclear Fuel Assembly Blending-To Meet 11.8 kW Limit–Each spent nuclear fuel assembly has a specific set of characteristics: enrichment, burnup, and age. These characteristics determine how much thermal power the assembly produces and the rate of decline of that power. Waste package heat output at emplacement is not to exceed 11.8 kW. This specification requires blending commercial fuel assemblies to no more than 20 percent above the average PWR thermal heat output (9.8 kW per package). The average age of the CSNF is assumed to be 26 years, with no additional aging beyond that imposed by reactor and potential repository operation schedules.

1.7.2 Design Option Sensitivity Cases

The SR base case design does not include backfill in the emplacement drifts. However, one design option that will be analyzed is the case that includes backfill. It provides additional protection of the drip shield from the rock fall. Another design option is a low thermal load option. See Section 4.6 for these analyses.

Backfill Rock Fall Protection–During the postclosure period, the drift ground support and parts of the near-field rock may fall into the drift. These rock falls have the potential to affect the performance of the drip shield. Analyses have concluded that the probability of generating a through-going crack on a drip shield is negligible (CRWMS M&O 2000 [149574]). Even if a crack is generated, the in-growth of corrosion products and calcite deposition are expected to effectively seal the crack (CRWMS M&O 2000 [151949]). Therefore the effects of rock fall on system performance have been screened out of the TSPA analyses.

1.8 SITE DESCRIPTION

Characteristics of the natural system at Yucca Mountain, such as its semiarid climate and deep water table, led, in part, to its current consideration as the setting for a potential geologic repository for HLW. These characteristics provide an environment that could potentially isolate the waste from the effects of water for long periods.

1.8.1 General

Characteristics of the natural system at Yucca Mountain that may affect potential repository performance include climate, site geology, and site hydrogeology. Characteristics of the site geology and hydrogeology that will affect potential repository performance include groundwater flow through the UZ and SZ, radionuclide transport, and disruptive events such as volcanism and earthquakes. Other factors considered and analyzed when describing the site are population distribution and land use around Yucca Mountain. Figure 1.8-1 provides an illustration of the processes affecting potential repository performance, including physical characteristics of Yucca Mountain. This section provides a brief description of the current understanding of the natural system at Yucca Mountain and is based on Section 2 of the Viability Assessment (DOE 1998 [100548]). Detailed information on Yucca Mountain site characteristics and descriptions of the investigations conducted at Yucca Mountain can be found in the *Yucca Mountain Site Description* (CRWMS M&O 2000 [137917]) that comprehensively reports current knowledge about the site and its surrounding region.

Both surface-based and underground investigations have been used to characterize the Yucca Mountain site. These studies have included the following:

- Monitoring the present meteorology to support development of infiltration models, completion of environmental analyses, design of potential repository facilities, and calculation of atmospheric dispersion
- Mapping geologic structures, including rock units, faults, fractures, and volcanic features
- Using gravitational, magnetic, electrical, and seismic methods to infer the distribution and properties of geologic units and structures at depth
- Monitoring earthquake activity
- Characterizing earthquake faults at the potential repository horizon
- Drilling boreholes into the mountain to identify the geologic units present, measure the depth to groundwater, measure the properties of the hydrologic system, and determine air- and water-movement properties above the water table
- Heating a large block of Topopah Springs tuff to observe the subsequent effects of heat on its hydrologic and chemical properties
- Excavating a 7.9-km main tunnel Exploratory Studies Facility Main Loop) into Yucca Mountain adjacent to the potential repository site and second tunnel 2.7-km long crossing 15-20 m above the potential repository area in a southwest direction
- Monitoring seepage into the Exploratory Studies Facility, including the effects of ventilation and injected pulses of water
- Conducting two thermal tests in the Exploratory Studies Facility at the potential repository horizon.

1.8.2 Physiography

Yucca Mountain is located in southern Nevada approximately 161 km northwest of Las Vegas (Figure 1.8-2). The mountain is an irregularly shaped volcanic upland varying in elevation at its crest from 1,500 m to 1,930 m above mean sea level and characterized by approximately 650 m of relief. An aerial photograph of Yucca Mountain is provided as Figure 1.8-3, showing the location of the entrance to the Exploratory Studies Facility Main Loop.

Yucca Mountain is located in the Basin and Range province of the western United States, within the region known as the Great Basin (Figure 1.8-4). The Great Basin encompasses nearly all of Nevada and parts of Utah, Idaho, Oregon, and California. The mountain ranges of the Great Basin are mostly north-south aligned, tilted, fault-bounded blocks that may extend more than 80 km in length and are generally 8 to 24 km wide. Relief between valley floors and mountain ridges is typically 300 to 1,500 m, and valleys occupy approximately 50 to 60 percent of the total land area. The valleys are filled with thick deposits of alluvium derived from erosion of the adjacent ranges. In general, the ranges are separated (north and south) by roughly 25 to 30 km. However, some ranges arc toward each other and merge together.

1.8.3 Land Use and Population Density

Yucca Mountain occupies land controlled by three federal agencies: the U.S. Air Force (i.e., Nellis Air Force Range), DOE (i.e., Nevada Test Site), and the U.S. Bureau of Land Management. Nearly all the area surrounding Yucca Mountain is federally owned, and very little is developed or urban land. A large percentage of the land around Yucca Mountain is anticipated to remain federally owned or withheld from public use in the future. The area surrounding the site includes Nye, Lincoln, Esmeralda, and Clark Counties in Nevada and Inyo County in California (Figure 1.8-4).

Population density near Yucca Mountain is low. Nye County, which encompasses the site, has 0.62 persons per square kilometer. Of the total population of 29,730 in Nye County, 68 percent live in the unincorporated town of Pahrump, 70 to 80 km south-southeast of Yucca Mountain (CRWMS M&O 2000 [137917], p. 2.3-1). Larger concentrations of population are found in Clark County to the southeast, in the incorporated and unincorporated areas of the Las Vegas valley.

1.8.4 Climate

Climate, and its changes over time, directly affects system performance at Yucca Mountain.

Precipitation and surface weather conditions limit the infiltration of water into and through the mountain. While the Yucca Mountain climate is currently very dry and hot, past climate records show this was not always the case. Future climate will likely be similar to past climates, which have been wetter and cooler than that of the present.

1.8.4.1 Present-Day Climate

Present-day climate in southern Nevada is semiarid, with hot summers and mild winters. Local and regional monitoring stations provide weather data for the Yucca Mountain vicinity. Average annual precipitation over a 30-year period for meteorological stations in the Yucca Mountain area range from 112 mm to 144 mm (CRWMS M&O 2000 [137917], Table 6.2-3). The estimated annual potential evapotranspiration in Las Vegas is 1,067 mm per year (Houghton et al. 1975 [106182], p. 63, Figure 61). Snowfall is infrequent, light, and short lived below about 1,070 m above mean sea level. The estimated maximum daily rainfall is bounded by a value of 125 mm (CRWMS M&O 1997 [100117], pp. 4 to 21).

The annual average temperature in the Yucca Mountain area ranges from about 15° to 18°C, depending on elevation (CRWMS M&O 2000 [137917], Section 6.2.3.2). Summer temperatures can exceed 40°C and winter temperatures occasionally fall below 0°C. The annual average dew point temperature is about -5°C. Regional weather systems and the mountain and valley topography cause a regular wind pattern of well-mixed airflow toward the north during the daytime and stable, low-mixing airflow toward the south into Amargosa Valley at night.

Aridity and warm temperatures result from a combination of large-scale atmospheric circulation patterns and the large mountain ranges, such as the Sierra Nevada, on the pathway from the primary moisture source, the Pacific Ocean. The Yucca Mountain area is affected by typical midlatitude global circulation patterns, with weather systems moving from west to east. Storms moving into the area from the southwest during winter tend to have the greatest potential for high precipitation as rain or snow. Significant late summer, southwest monsoon precipitation events occur with moist airflow from the south, originating either in the Gulf of Mexico or the Pacific Ocean. Naturally recurring short-term changes in typical circulation patterns alter storm paths and precipitation patterns. One example is the El Niño pattern, which tends to increase winter precipitation in Southern Nevada by approximately 50 percent.

1.8.4.2 Paleoclimate

Evidence of the cyclic nature of climate comes from long-term climate records. Ongoing scientific studies indicate that microfossils and stable isotopes from oceanic and lacustrine sediments vary in response to climate change and act as proxies or substitutes for direct observation of past climates.

Long-Term Climatic Records–Three long-term climatic records occur within 100 miles of Yucca Mountain: Devils Hole, Owens Lake, and Death Valley.

Devils Hole (about 60 km southeast of Yucca Mountain) yields a well-dated, stable isotope record from calcite that was deposited on the submerged walls of a fissure within the regional carbonate aquifer (Winograd et al. 1996 [109468]). The Devils Hole record, with its extensive and accurate chronology, establishes the timing and duration of glacial periods in the Yucca Mountain region (CRWMS M&O 2000 [137917], p. 6.3-11).

Owens Lake contains a long record of lacustrine sediments containing fossil and stable isotope evidence of climate change. Owens Lake is a present-day playa in Inyo County, California, approximately 160 km west of Yucca Mountain. Interpretation of the Owens Lake climate record provides information about the magnitude of change in precipitation and air temperature during past climate periods and, therefore, complements the Devils Hole record (Smith and Bischoff 1997 [100077]). Over the past 400,000 years, Owens Lake has been fresh (implying a glacial climate, wetter than present) for approximately 80 percent of the time and saline (implying climates like the present) 20 percent of the time (CRWMS M&O 2000 [137917], p. 6.3-17).

Data from a 185-m sedimentary core taken in Death Valley, California, spanning a time period of about 200,000 years, indicate that this area was filled by a large, deep lake during an earlier glacial period (Li et al. 1996 [100054]). The persistence of lakes during cooler and wetter climate periods illustrates that effective moisture levels were much higher during glacial periods.

Short-Term Climatic Records–A number of important short-term climatic records exist within the Yucca Mountain area. They include pack-rat middens, paleowetland deposits, and paleospring deposits. These records document past climates in the Yucca Mountain region during the last 50,000 years before the present.

Pack-rat middens are deposits of fossil plant remains and other material cemented by crystallized urine. Analysis of the middens provides information on climate conditions over time, because the plants available to the rats are indicative of existing climate conditions and because the plants and other organic matter can be dated by radiocarbon techniques. Studies of plant fossils from middens in the Yucca Mountain area from approximately 35,000 to 12,000 years ago reveal that conditions during the last glacial period were cooler and wetter than today (Spaulding 1990 [100078], Chapter 9).

Sedimentary deposits found on valley floors throughout southern Nevada indicate that during the last glacial period there were wetlands, flowing springs, and streams at low elevation (Quade et al. 1995 [100074]). Aquatic vegetation was common on the alluvial fan deposits sloping down from adjacent mountains and in the wetlands. The springs and wetland sediments contain vertebrate fossils that indicate cooler, wetter conditions existed. The existence of wetlands throughout the region, together with the types of fossils found, indicates that recent glacial periods were colder and wetter than today.

Interpretation of data from the Crater Flat Deposit, a paleospring deposit located approximately 15 km southwest of Yucca Mountain, suggests the regional water table was at the surface at this site during glacial periods (Paces, Forester et al. 1996 [101281], Section 2.2). Today, the regional water table at this location is approximately 100 m below ground surface.

Site Records of Climate Change–Stable carbon and oxygen isotope values of calcite that precipitated in fractures within Yucca Mountain provide potential climate information related to infiltration. Quade and Cerling (1990 [100073], pp. 1549 to 1552) concluded that the carbonate in pedogenic calcrete filling the Bow Ridge fault formed during climates that were colder and wetter than the present. The authors correlated these carbon isotope values to those of modern soil carbonate forming at elevations of 1,800 to 2,000 m, which is comparable in today's climate to the flanks of Rainier Mesa.

1.8.4.3 Future Climate

Forecasting future climate depends on the assumption that climate is related to measurable and predictable processes, such as the variation of insolation caused by changes in earth orbit. Assumptions used for forecasting future climate include (CRWMS M&O 2000 [137917], Section 6.4.3):

- Climate is cyclical, and past climates provide insight into potential future climates.
- A relationship exists between the timing of past long-term climate change and earth-orbital cycles.
- A relationship exists between the characteristics of past climates and the sequence of those climates in the 400,000-year long-term earth-orbital cycle.
- Long-term, Earth-based, climate-forcing processes, such as tectonics, have remained relatively constant over the past 400,000 years or so and should remain so for the period of interest for performance assessment.

Based on these assumptions and the long-term paleoclimate records described above, the following forecast for future climate at Yucca Mountain has been developed: the modern-day climate at Yucca Mountain should persist for 400 to 600 years, followed by a warmer and much wetter monsoon climate for 900 to 1,400 years, followed by a cooler and wetter glacial-transition climate for 8,000 to 8,700 years (CRWMS M&O 2000 [137917], Section 6.5.3).

1.8.5 Geology

The understanding of Yucca Mountain geology has evolved following years of extensive studies, resulting in the construction of a detailed, integrated site geological model (CRWMS M&O 2000 [146988]) containing stratigraphic and structural relationships, as well as rock-property and mineralogical data.

1.8.5.1 Regional Geology

Yucca Mountain is in the Great Basin Region of the Basin and Range Province, which is characterized by mostly north-south aligned, tilted, fault-bounded blocks, with wide valleys filled with thick deposits of alluvium derived from erosion of the adjacent ranges. This pattern is the result of generally east-west-directed crustal extension that began in the Tertiary period and continues at present (Hamilton 1988 [100037], Chapter 5). The extension has caused complex faulting, resulting in ranges composed of tilted fault blocks bounded by major range-front faults. Seismic reflection geophysical studies show this style of deformation extends beneath the intervening basins, where it is buried by alluvium (Brocher et al. 1998 [100022], pp. 947 to 971). Rocks from Precambrian to Quaternary in age have been deformed by this extension.

Yucca Mountain lies within the Walker Lane structural domain, which extends northwestward from Las Vegas, parallel to the Nevada-California border. This structural domain is characterized by northwest-trending, right-lateral faults and northeast-trending, left-lateral faults (Stewart 1988, [100083] p. 3).

The Inyo-Mono domain to the southwest of Yucca Mountain has the highest rate of seismic and volcanic activity in the southwestern Great Basin and is an important part of the regional geologic setting. This domain includes Death Valley Basin and the Panamint Range (CRWMS M&O 2000 [137917], Section 4.2.1.3).

Due to the deep-seated block faulting, rocks from the Precambrian Era through recent sedimentary and volcanic deposits are exposed in the Great Basin:

- Precambrian rocks (540 Ma to 4550 Ma) include an older, metamorphosed assemblage and a younger, metasedimentary assemblage (CRWMS M&O 2000 [137917], Section 4.2.2.1.1). Both groups tend to retard the groundwater flow where extensive faulting or fracturing is present.

- Paleozoic rocks (250 Ma to 540 Ma) include older carbonate strata; middle, fine-grained shale, siltstone, and sandstone unit; and an upper carbonate unit. The carbonate units form important aquifers throughout southern Nevada (Winograd and Thordarson 1975 [101167], pp. C9 to C12).

- Mesozoic rocks (65 Ma to 250 Ma) are generally absent near Yucca Mountain (CRWMS M&O 2000 [137917], Section 4.2.2.1.3) because the Mesozoic was a period of active tectonic activity characterized by regional compression in this area.

- Cenozoic rocks (Present to 65 Ma) near Yucca Mountain fall into three groups: premiddle Miocene sedimentary rocks, mid-to-late Miocene volcanic (including Yucca Mountain), and Plio-Pleistocene basalt and basin sediments (CRWMS M&O 2000 [137917], Section 4.2.2.2).

1.8.5.2 Site Stratigraphy

The entire sequence at Yucca Mountain is composed of mid-to-late Miocene volcanic rocks formed by eruptions of ash or magma from volcanic vents to the north (Sawyer et al. 1994 [100075], pp. 1304 to 1318; Buesch et al. 1996 [100106]). Most of the rocks are ash flow tuffs, which occur as welded tuffs, nonwelded tuffs, air-fall tuffs, or bedded tuffs (reworked by stream action). Figure 1.8-5 is a simplified cross section through Yucca Mountain and depicts the major units present. Stratigraphic units relevant to the potential repository are the Paintbrush Group, the Calico Hill Formation, and the Crater Flats Group. The Paintbrush Group is subdivided into the Tiva Canyon tuff, Yucca Mountain and Pah Canyon tuffs (the latter two are referred to as the pre-Tiva Canyon tuff in Figure 1.8-5), and Topopah Spring tuff (CRWMS M&O 2000 [137917], Section 4.5.4.7). The potential repository is located within the Topopah Spring tuff.

The Tiva Canyon tuff is a large-volume, regionally extensive ash flow tuff that comprises most of the rocks exposed at the surface of Yucca Mountain. The unit is divided into two members with differing chemical compositions: a lower crystal-poor rhyolite member and an upper crystal-rich quartz-latite member (Buesch et al. 1996 [100106], pp. 16 to 18, Figure 2). The thickness of the formation ranges from less than 50 m to as much as 175 m respectively. The Yucca Mountain and Pah Canyon tuffs vary in texture from nonwelded to densely welded and in thickness from 0 to 77 m (Buesch et al. 1996 [100106], pp. 18 to 19).

The Topopah Spring tuff, which is the host rock for the potential repository, has a maximum thickness of about 380 m near Yucca Mountain (Buesch et al. 1996 [100106], pp. 19 to 21). Like the Tiva Canyon tuff, the Topopah Spring tuff is compositionally zoned from a lower crystal-poor (less than 10 percent phenocrysts) rhyolite to an upper crystal-rich quartz latite. Each member is further divided by degree of vitrification and the abundance of lithophysae (voids in the rock caused by bubbles of volcanic gases trapped in the rock matrix during cooling). The crystal-poor member is divided into a vitric zone near the base and devitrified rocks of the lower nonlithophysal, lower lithophysal, middle nonlithophysal, and upper lithophysal zones. The latter three zones are densely welded and comprise the potential repository horizon. The nature, size, and abundance of lithophysae in the tuffs are important because they may affect the mechanical and hydrologic properties of the rock.

The Calico Hills Formation is a series of rhyolite tuffs and lavas (Sawyer et al. 1994 [100075], p. 1307) and is significant to the potential repository because of its hydraulic properties and mineralogical composition. The formation thins southward, from a total thickness of 460 m north of the potential repository block, to 15 m to the south (CRWMS M&O 2000 [137917], Section 4.5.4.6). None of the Calico Hills ash flows are strongly welded; therefore, the rocks have much lower strength and higher porosity than the Topopah Spring tuff. Because of their lower strength, fractures are rare or absent in the Calico Hills. The sparsity of continuous fracture pathways may have important implications for water flow in the UZ. Another important attribute of the Calico Hills is an abundance of zeolite minerals (Broxton et al. 1993 [107386], pp. 19 to 22). Zeolites have the ability to sorb radionuclides that may be transported in water. Sorption may significantly slow the movement of many radionuclides away from a potential repository.

The Crater Flat Group consists of three sequences of rhyolitic, moderate- to large-volume ash flow deposits and interlayered, bedded tuffs. In descending order, these formations are the Prow Pass, Bullfrog, and Tram tuffs (Sawyer et al. 1994 [100075], Table 1). The Prow Pass tuff is a sequence of variably welded ash flow deposits ranging from about 60 to 228 m in thickness and commonly zeolite-altered. The Bullfrog tuff consists of upper and lower zones of welded to partially welded zeolite-altered tuff, separated by a central zone of moderately to densely welded tuff. The measured thickness of the entire sequence ranges from 76 m to as much as 400 m. The Tram tuff includes a lower, lithic-rich unit and an upper, lithic-poor unit. The lithic-poor unit is normally more densely welded than the underlying lithic-rich unit. Both units contain clay and zeolite alteration. The thickness of the Tram tuff ranges from about 60 to 396 m (CRWMS M&O 2000 [137917], Section 4.5.4.5).

1.8.5.3 Site Structural Geology and Earthquake Hazard

Yucca Mountain is part of a down-dropped block bounded on the west by a steeply eastward dipping fault, the Bare Mountain fault. Beneath Crater Flat, the block is segmented by a series of eastward dipping faults, and beneath Yucca Mountain and Jackass Flats generally westward dipping faults are interpreted. The block-bounding faults of Yucca Mountain (e.g., the Solitario Canyon, Bow Ridge, Paintbrush Canyon, and Windy Wash faults) and the Bare Mountain fault appear to be discrete, planar faults, at least some of which may descend to the base of the earth's brittle crust. Locations of the major faults at Yucca Mountain are shown on Figure 1.8-6.

Faults within 100 km of Yucca Mountain have been examined using aerial photographs. All faults with suspected Quaternary movement were evaluated. Natural exposures were cleared, and approximately 60 trenches have been excavated across faults within and near the site. Information from these trench studies indicates that estimated slip rates for faults at Yucca Mountain are low, varying from 0.0001 mm per year to 0.03 mm per year (Whitney et al. 1996 [107313], pp. 5 to 11). The average time interval between surface displacement events varies from 13,000 to 100,000 or more years (Whitney et al. 1996 [107313], pp. 5 to 11). Offsets of the earth's surface range from 3 to 167 cm per large event (Whitney et al. 1996 [107313], Table 5-1).

Vibratory ground motion and fault displacement hazards at Yucca Mountain have been analyzed probabilistically. A preliminary probabilistic study was carried out to support design of the Exploratory Studies Facility (CRWMS M&O 1994 [100112], Table 1). Results indicated ground motions of 265 cm per square second and 647 cm per square second are expected to be exceeded on average every 1,000 and 10,000 years, respectively. This earlier analysis of seismic hazards was updated by two expert panels (USGS 1998 [100354], CRWMS M&O 2000 [142321]). To determine ground motion and fault displacement hazard at Yucca Mountain, the experts' assessments were integrated along with their evaluations of uncertainties. The vibratory ground motion hazard was computed at a reference rock outcrop, which corresponds to the proposed waste emplacement depth. Ground motion was computed at this reference location as a control motion to facilitate the subsequent determination of design basis motions for surface locations and potential waste-emplacement level locations following completion of geotechnical investigations. For peak ground acceleration, results with a 10^{-3} and 10^{-4} annual frequency of being exceeded are, respectively, 165 and 523 cm per square second for the horizontal component and 108 and 383 cm per square second for the vertical component (USGS 1998 [100354], Table 7-1).

Probabilistic analysis based on expert assessments indicates that geologic fault displacement hazard is generally low. For sites not located on a major block-bounding fault, displacements greater than 0.1 cm will be exceeded on average less than once in 100,000 years. For this same time period, the mean displacements that are expected to be exceeded on two of the block-bounding faults (Bow Ridge and Solitario Canyon faults) are 7.8 and 32 cm, respectively (USGS 1998 [100354], Table 8-1). The primary design approach to mitigate fault displacement effects involves avoiding faults in laying out potential repository facilities.

Modern seismicity has been monitored at the Nevada Test Site since 1968. In 1979, a network of seismic stations was established in the southern Great Basin to monitor earthquakes near Yucca Mountain (Rogers et al. 1987 [100176], p. 3). The largest earthquake detected by the monitoring network was the magnitude 5.6 event near Little Skull Mountain, located about 12 mi north of Yucca Mountain, on June 29, 1992.

1.8.5.4 Volcanology and Volcanic Hazard

Rocks composing Yucca Mountain are part of the southwestern Nevada volcanic field. This field was formed by the eruption of large volumes of volcanic rocks from multiple sources to the north. The explosive volcanism that culminated in the formation of the southwestern Nevada volcanic field is the most significant depositional event of the Cenozoic era near Yucca Mountain. This event formed six major calderas between 15 million and 7.5 million years ago (Sawyer et al. 1994 [100075], p. 1,304). This event also created the rocks of Yucca Mountain.

The most recent events are infrequently erupted basaltic volcanic rocks. The basaltic eruptions represent a continuation of the activity during the mid- to late-Miocene epoch (CRWMS M&O 2000 [141044], Section 6). Following an episode 3.7 million years ago, a subsequent basaltic eruption occurred between 1.7 million and 0.7 million years ago consisting of four cinder cones (Little Cone, Red Cone, Black Cone, and Makani Cone) aligned north-northeast along the Crater Flat axis. The final episode of basaltic volcanism created the Lathrop Wells Cone, which includes fissure eruptions, spatter and scoria cones, and basaltic lava flows. The Lathrop Wells Cone complex is approximately 80,000 years old (CRWMS M&O 2000 [137917], p. 4.10-2). The eruption volume of individual basaltic volcanic events has also been decreasing progressively through time. The decreased rate of volcanic activity correlates with the decreased rate of regional extension and faulting.

To assess the likelihood of volcanic activity disrupting a potential repository, a panel of ten experts representing a wide range of expertise in the fields of physical volcanology, volcanic hazards, geophysics, and geochemistry conducted an assessment (CRWMS M&O 1996 [100116]). The scientists reviewed extensive information presented by representatives of DOE, U.S. Geological Survey, the State of Nevada, NRC, and others regarding the spatial and temporal distribution of future volcanic activity near Yucca Mountain. That work was supplemented by analyses conducted for the TSPA-SR (CRWMS M&O 2000 [141044], Section 6). A probability distribution, revised for the current potential repository footprint, gives a mean value of 1.6×10^{8}, which corresponds to approximately one chance in 6,250 of a volcanic event (dike intrusion) disrupting the potential repository during the first 10,000 years after closure.

1.8.6 Hydrogeology

1.8.6.1 Regional Hydrogeology

Yucca Mountain lies within the Alkali Flat-Furnace Creek groundwater subbasin, one of several that comprise the Death Valley regional flow system (Luckey et al. 1996 [100465], p. 13). The subbasins are structural basins formed during mid-Tertiary crustal extension that are filled with gravel, sand, silt, and clay eroded from the adjacent uplands, forming a major aquifer hundreds of meters thick.

Recharge to the northeastern quadrant of the Death Valley system occurs principally at higher elevations. The area north of Yucca Mountain, including Central Pahute Mesa, Timber Mountain, and Shoshone Mountain provides most of the recharge to the Alkali Flat-Furnace Creek subbasin. Regional water level contours show a southward slope of the water table from recharge areas in the northern part of the Alkali Flat-Furnace Creek subbasin toward discharge areas in the southern Amargosa Desert. The Yucca Mountain site occupies an intermediate position along this path in an area where the contours indicate a probable southeastward flow direction. North-south and northwest-southeast oriented faults and fractures probably assert a strong influence on flow direction and contribute to continued southerly flow.

The dominant regional aquifer underlying the southern part of the Alkali Flat-Furnace Creek subbasin is in Paleozoic marine limestones, dolomites, and minor clastic sediments that are thousands of meters thick (carbonate aquifer). Fractures enlarged by dissolution provide the large permeability associated with this aquifer. The carbonate aquifer hydrologically connects many valleys and intervening ranges. Beneath the carbonate aquifer are relatively impermeable, metamorphosed older rocks, known as the lower clastic aquitard or the Paleozoic-Precambrian clastic confining units (D'Agnese et al. 1997 [100131], p. 20). These rocks form the effective hydraulic basement for groundwater flow.

1.8.6.2 Site Hydrogeology

Results of hydrologic investigations at and near Yucca Mountain have been summarized (Luckey et al. 1996 [100465]). Except for one borehole, the drilling program has not reached the base of the Tertiary volcanic section. North of the potential repository, the volcanic rocks are at least 1,829 m thick. Near the southern boundary, drilling has established a minimum depth of 1,533 m. Based on rock type and flow properties, Luckey et al. (1996 [100465], pp. 18 to 20, Figure 7) have divided the volcanic rocks below the water table into four hydrogeologic units. These are known, from the top down, as the upper volcanic aquifer, the upper volcanic confining unit, the lower volcanic aquifer, and the lower volcanic confining unit. The upper volcanic aquifer is composed of the Topopah Spring welded tuff, which occurs in the UZ near the potential repository but is present beneath the water table to the east and south of the potential repository and in Crater Flat. The upper volcanic confining unit includes the Calico Hills nonwelded unit and the uppermost, unfractured part of the Prow Pass tuff where they are saturated. The lower volcanic aquifer includes most of the Crater Flat Group, and the lower volcanic confining unit includes the lowermost Crater Flat Group and deeper tuffs, lavas, and flow breccias.

The main distinction between volcanic aquifers and confining units is that the aquifers tend to be more welded and contain more permeable fractures. However, alteration of the tuffs to zeolites and clays, which reduces permeability, is more pronounced at depth, and the greater pressure tends to reduce fracture permeability. Consequently, a combination of factors including fracture properties, mineralogy, and depth, rather than just rock type, determines the hydrologic character of the volcanic rocks below the water table at Yucca Mountain.

Hydraulic tests have been performed to determine the properties of the units. The analyses are limited by significant uncertainties about the extent to which fractures affect the unit hydraulic conductivity (Luckey et al. 1996 [100465], pp. 32 to 36). However, ranges of hydraulic conductivity values are reported to provide comparison among the units. The confining units have low hydraulic conductivity that ranges from 0.0000055 m/day to a maximum of 0.26 m/day respectively, with the aquifers ranging from 0.0037 to 1.4 m/day respectively (Luckey et al. 1996 [100465], Table 4).

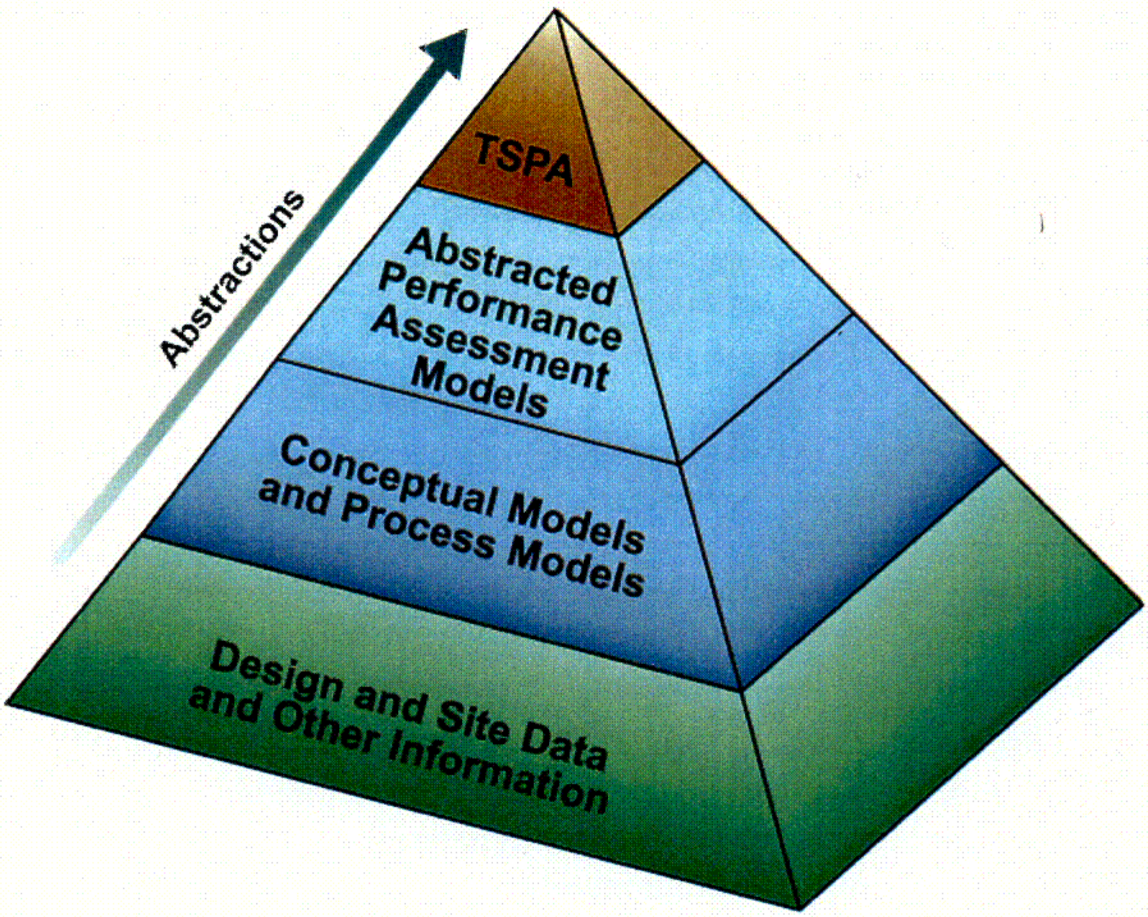

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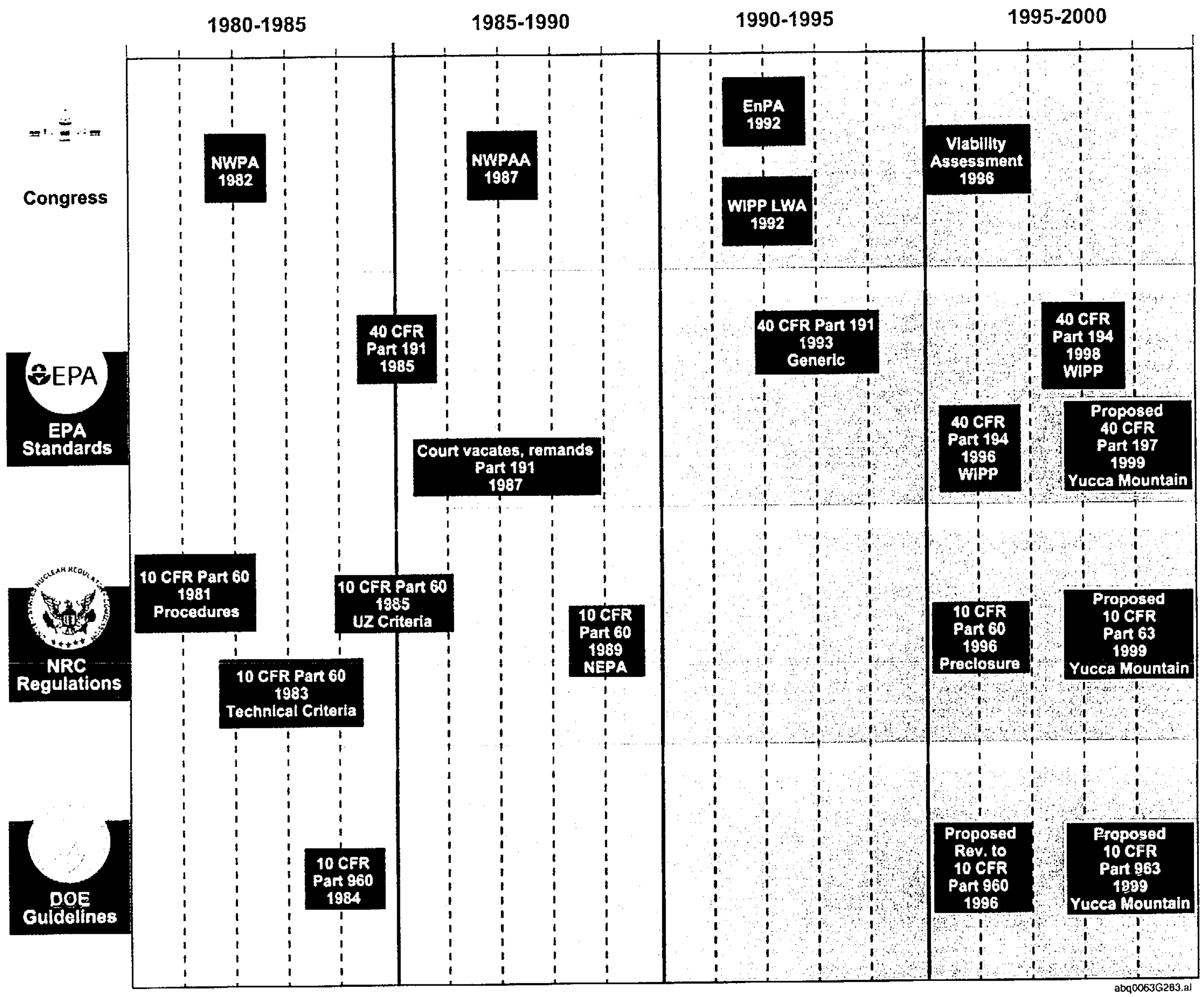
Figure 1.1-1. Total System Performance Assessment Information Pyramid

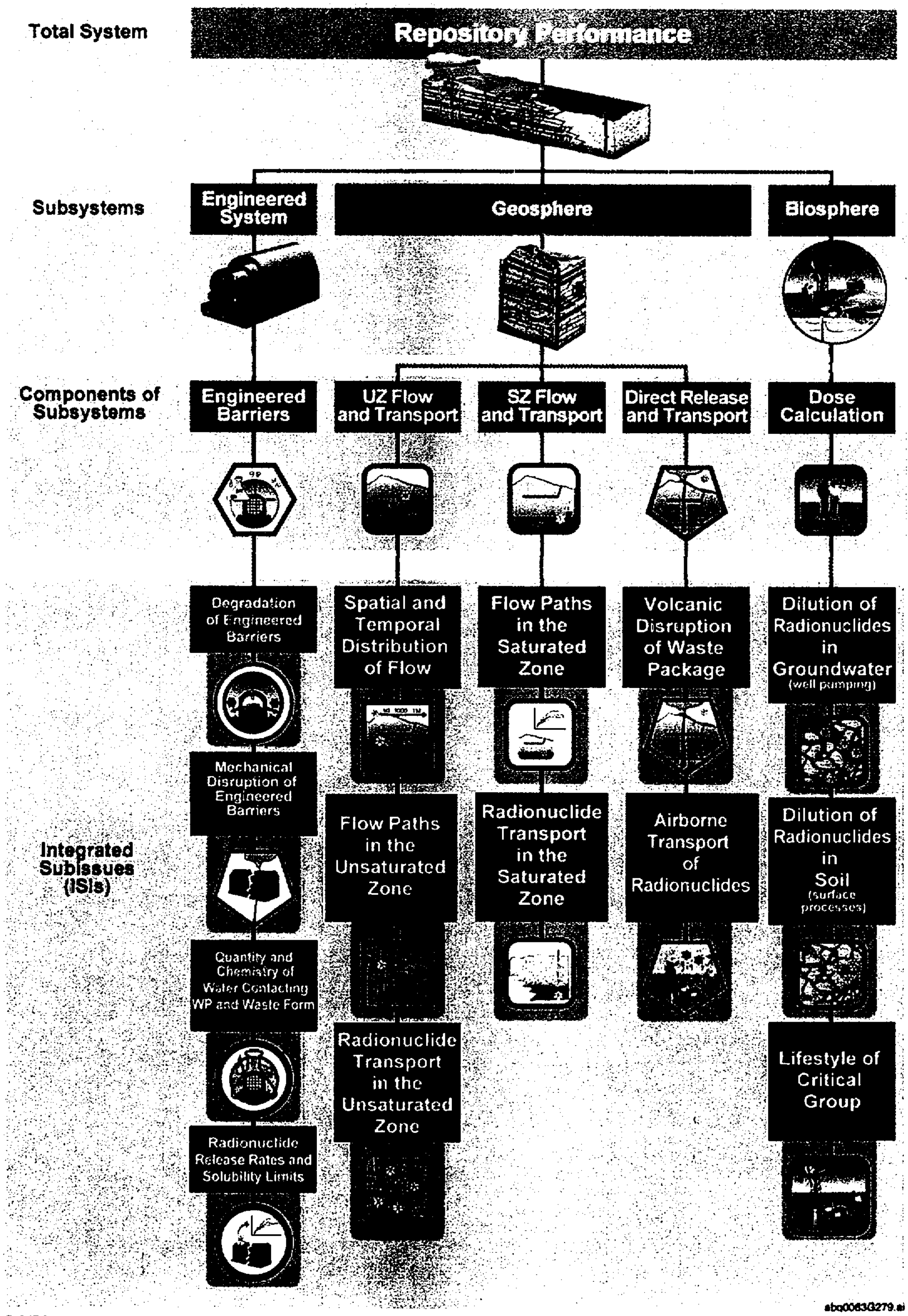
c-10



abq0063G283

NOTE: NWPA – Nuclear Policy Act of 1982, NWPAA – Nuclear Waste Policy Amendment Act of 1987, EnPA – Energy Policy Act of 1992, WIPP LWA – Waste Isolation Pilot Plant Land Withdrawal Act of 1992.

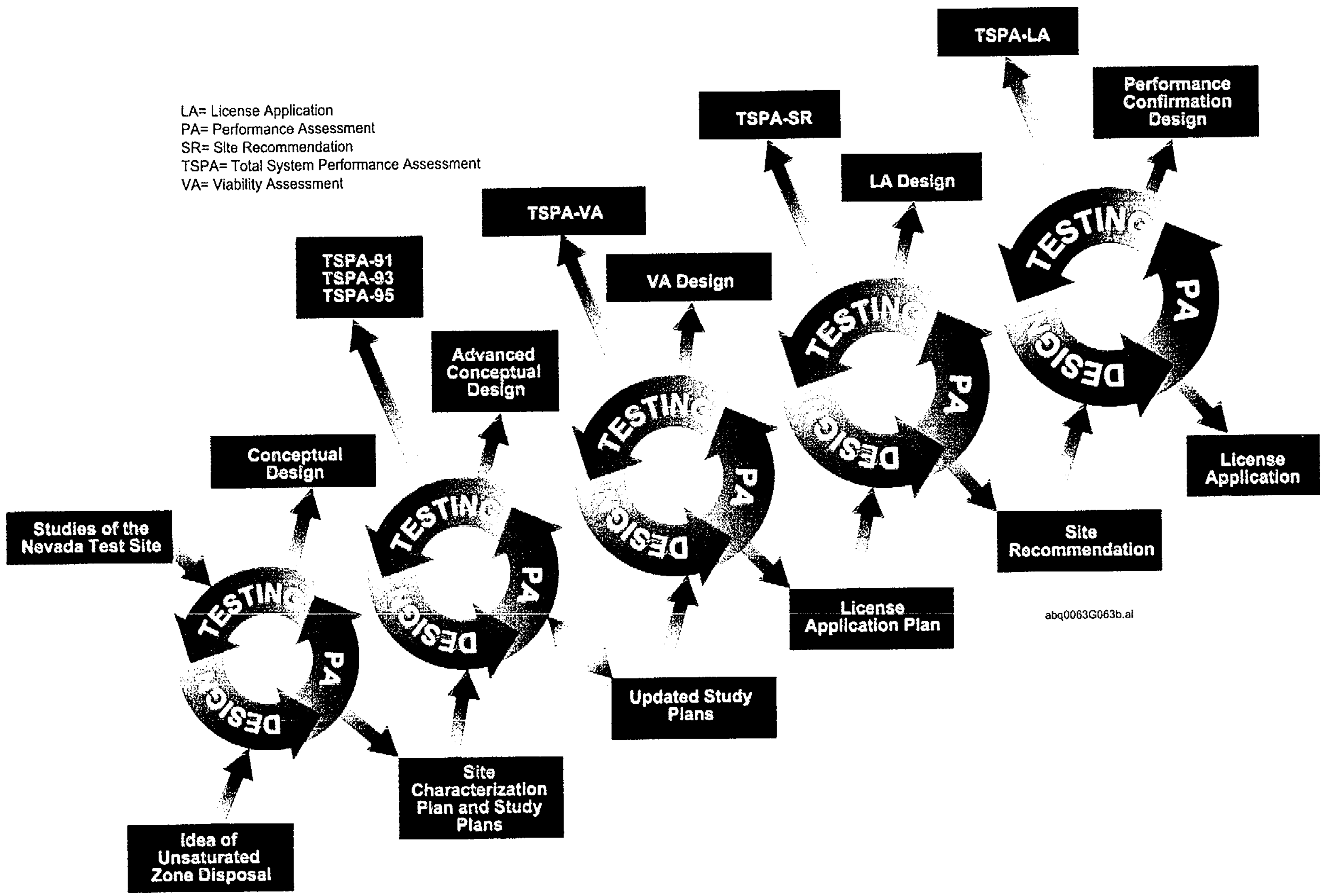
Figure 1.3-1. Timeline of Legislative and Regulator Events, 1980 to 2000



abq0063G279

Source: NRC 2000 [149372]

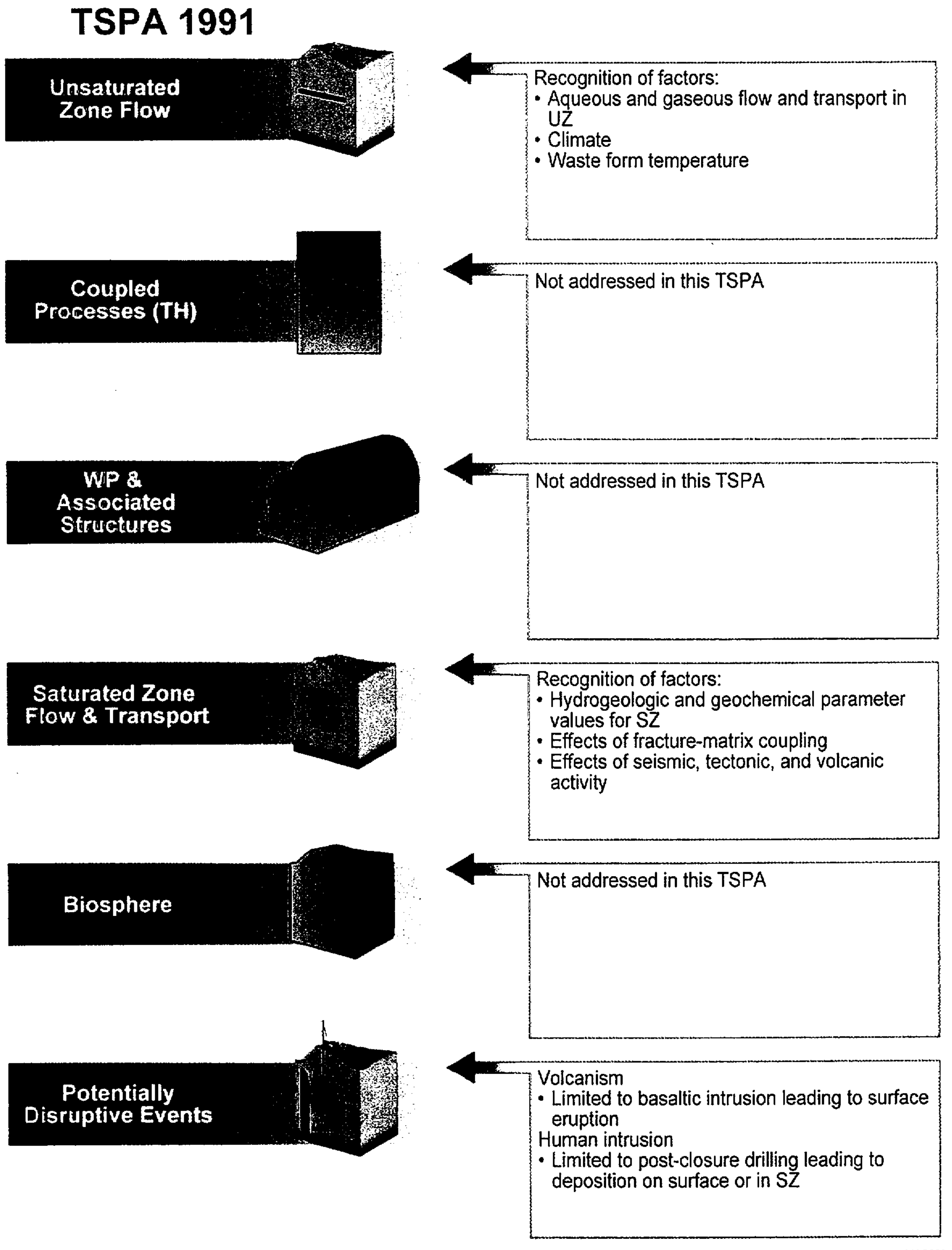
Figure 1.3-2. Integrated Subissues of Model Abstraction Subissue for Total System Performance Assessment and Integration Issue Resolution Status Report



abq0063G063b

Source: DOE 1998 [100550], Volume 1, Figure 1-4, p. 1-21.

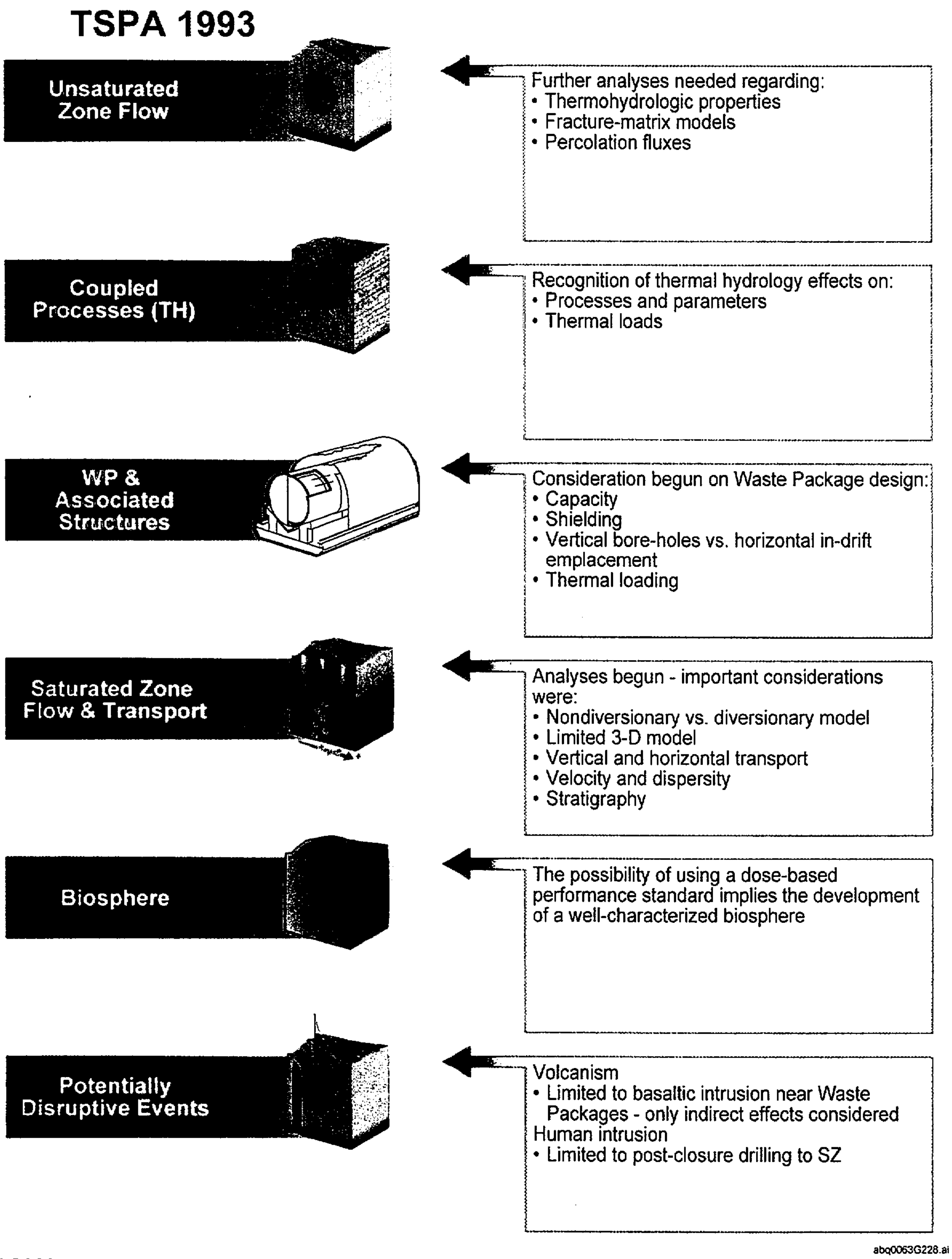
Figure 1.5-1. Iterative Application of the Total System Performance Assessment Tool to Advance Understanding of the Yucca Mountain System



abq0063G226

NOTE: TH – thermal hydrology; WP – waste package

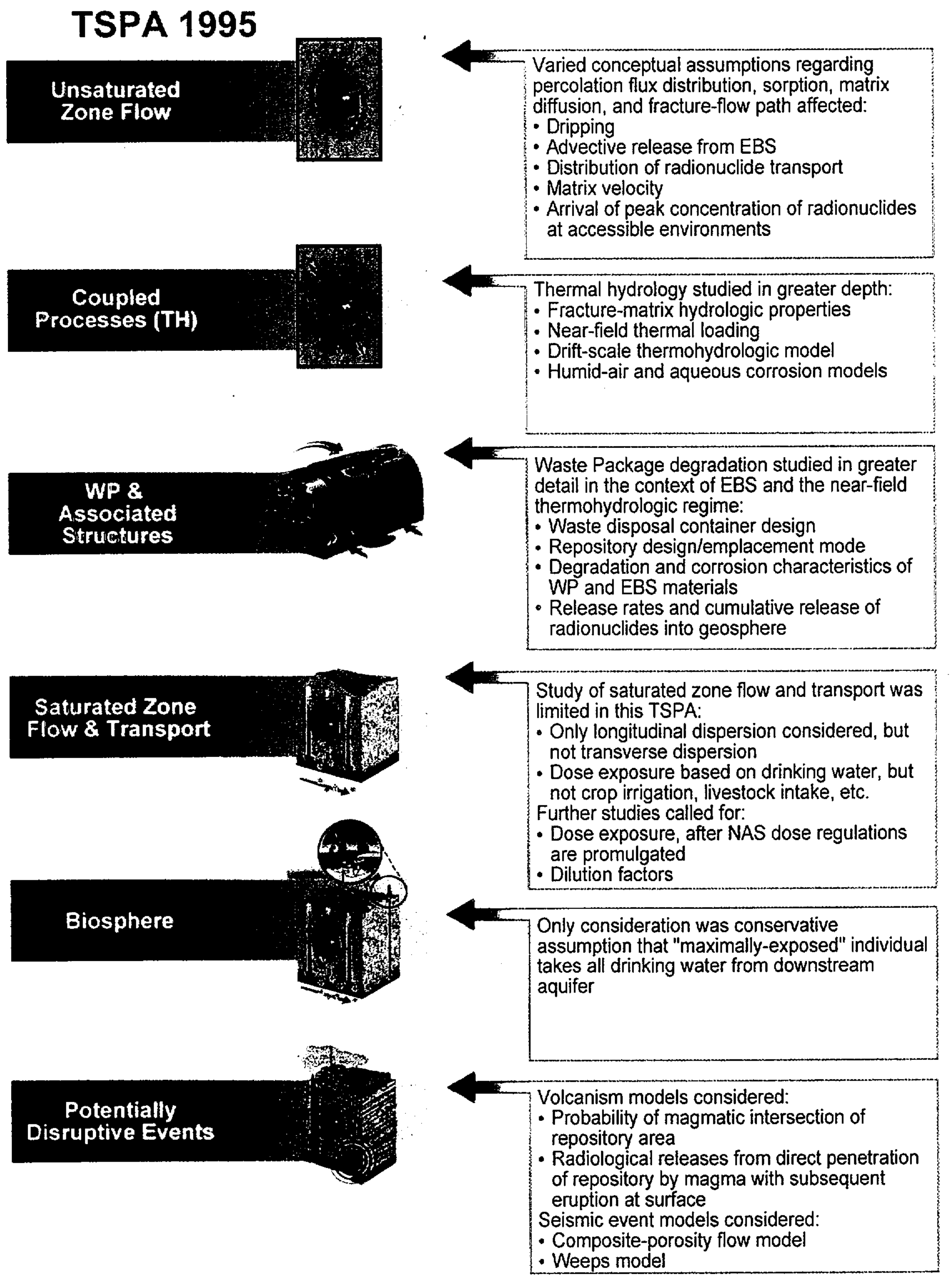
Figure 1.5-2. Subsystem Model Abstractions Available for the 1991 Total System Performance Assessment



abq0063G228

NOTE: TH – thermal hydrology; WP – waste package

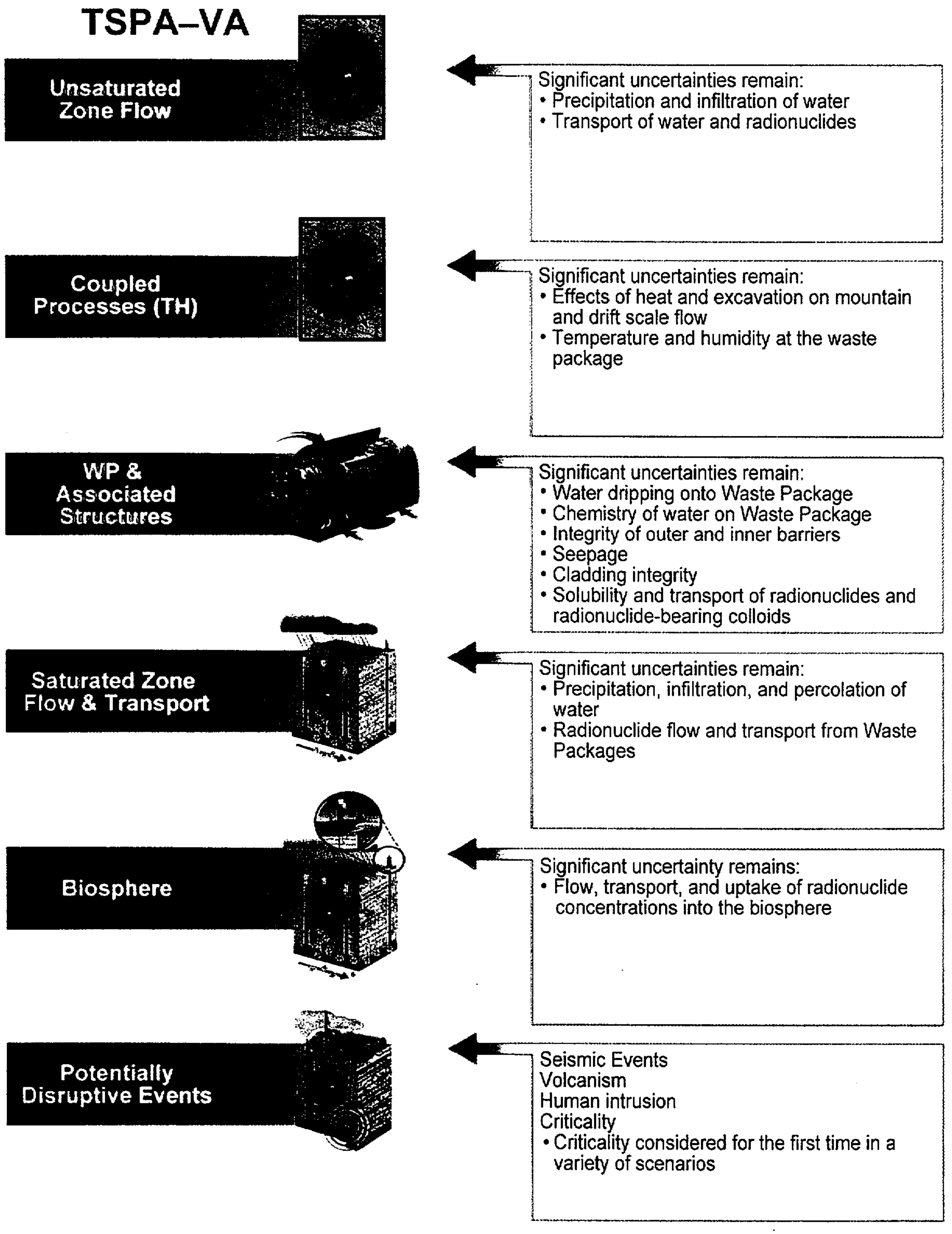
Figure 1.5-3. Subsystem Model Abstractions Available for the 1993 Total System Performance Assessment



abq0063G229

NOTE: TH – thermal hydrology; WP – waste package

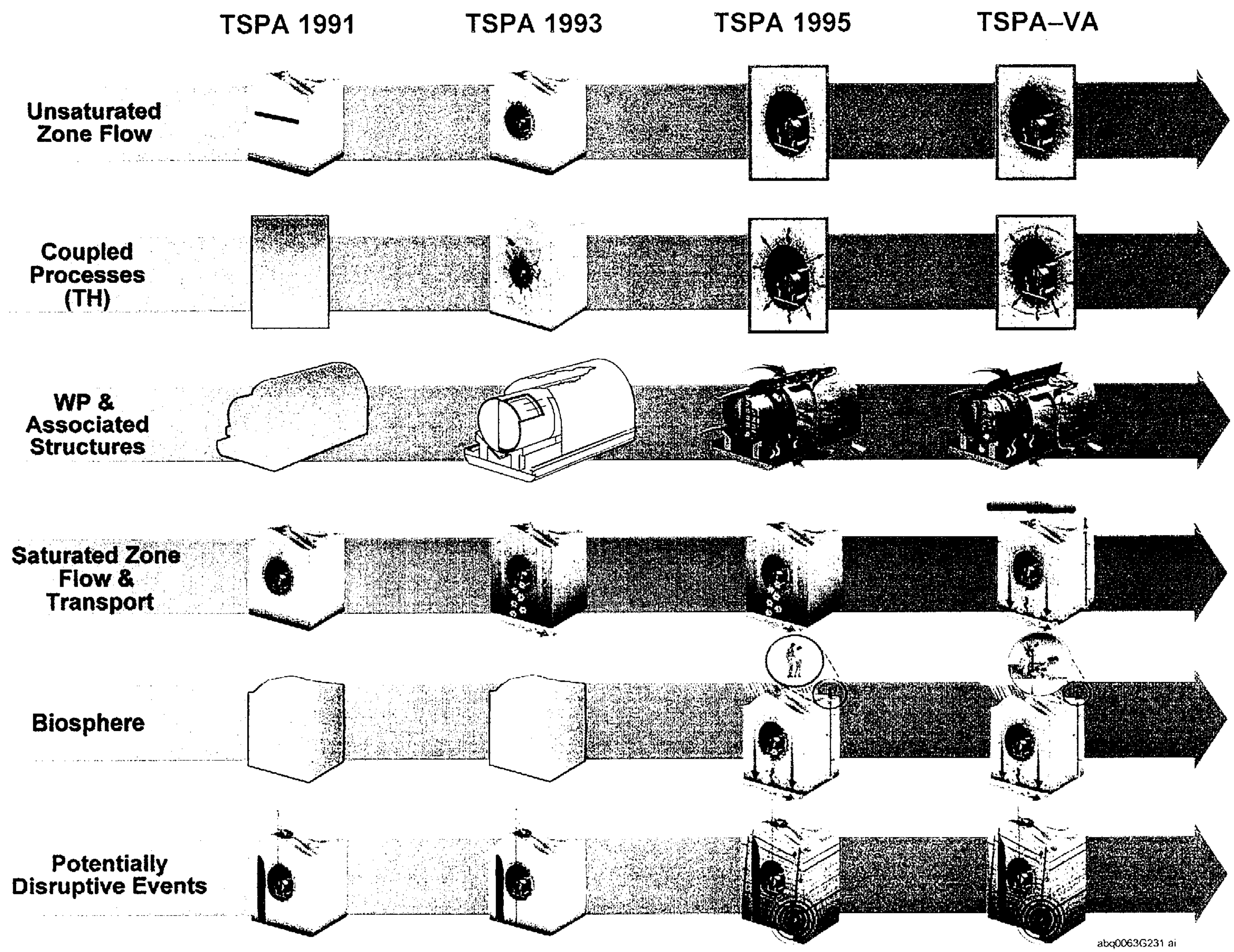
Figure 1.5-4. Subsystem Model Abstractions Available for the 1995 Total System Performance Assessment



abq0063G230

NOTE: TH – thermal hydrology; WP – waste package

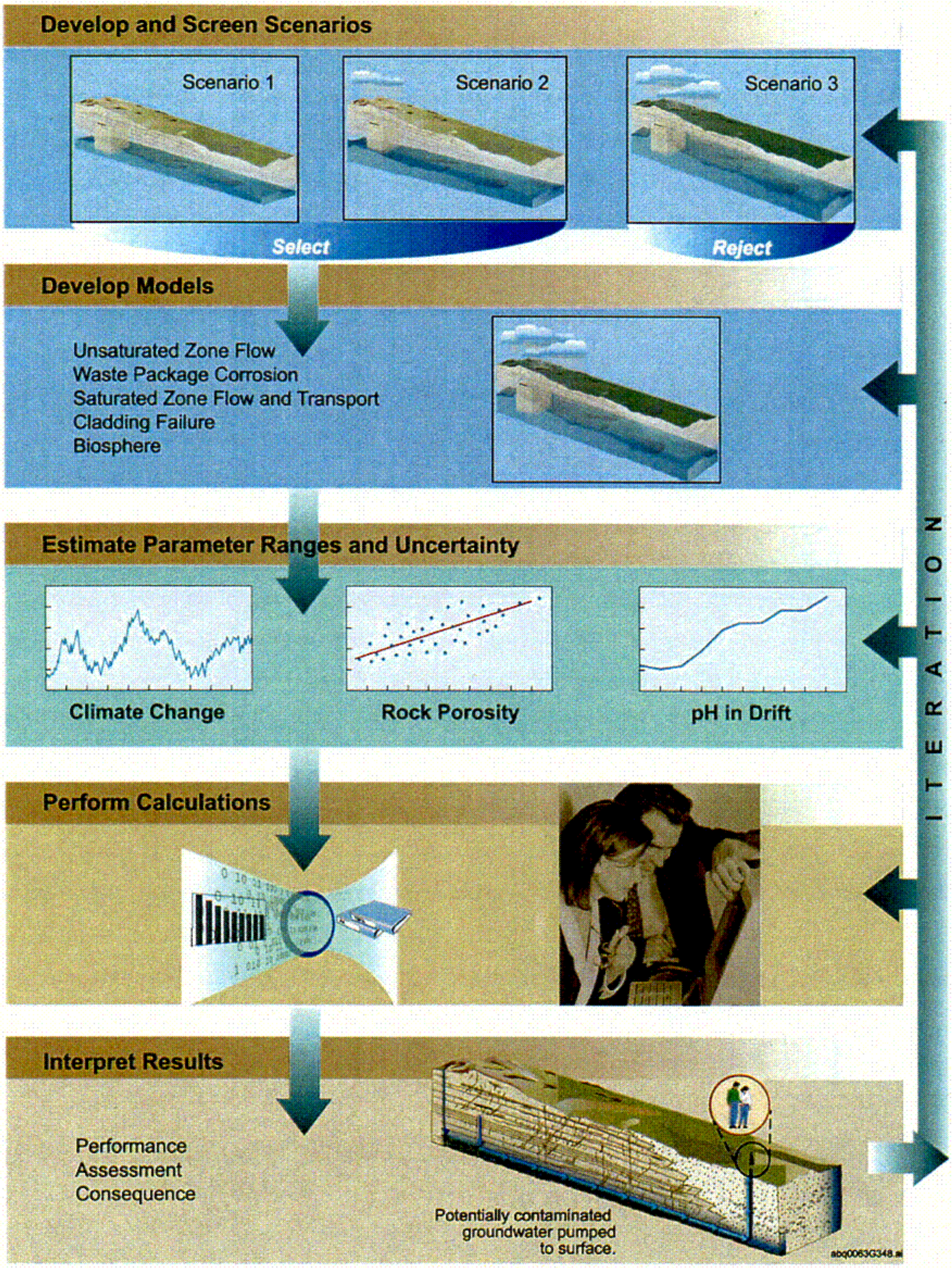
Figure 1.5-5. Subsystem Model Abstractions Available for the Viability Assessment Total System Performance Assessment



abq0063G231

NOTE: TSPA-VA – Total System Performance Assessment – Viability Assessment; TH – thermal hydrology; WP – waste package.

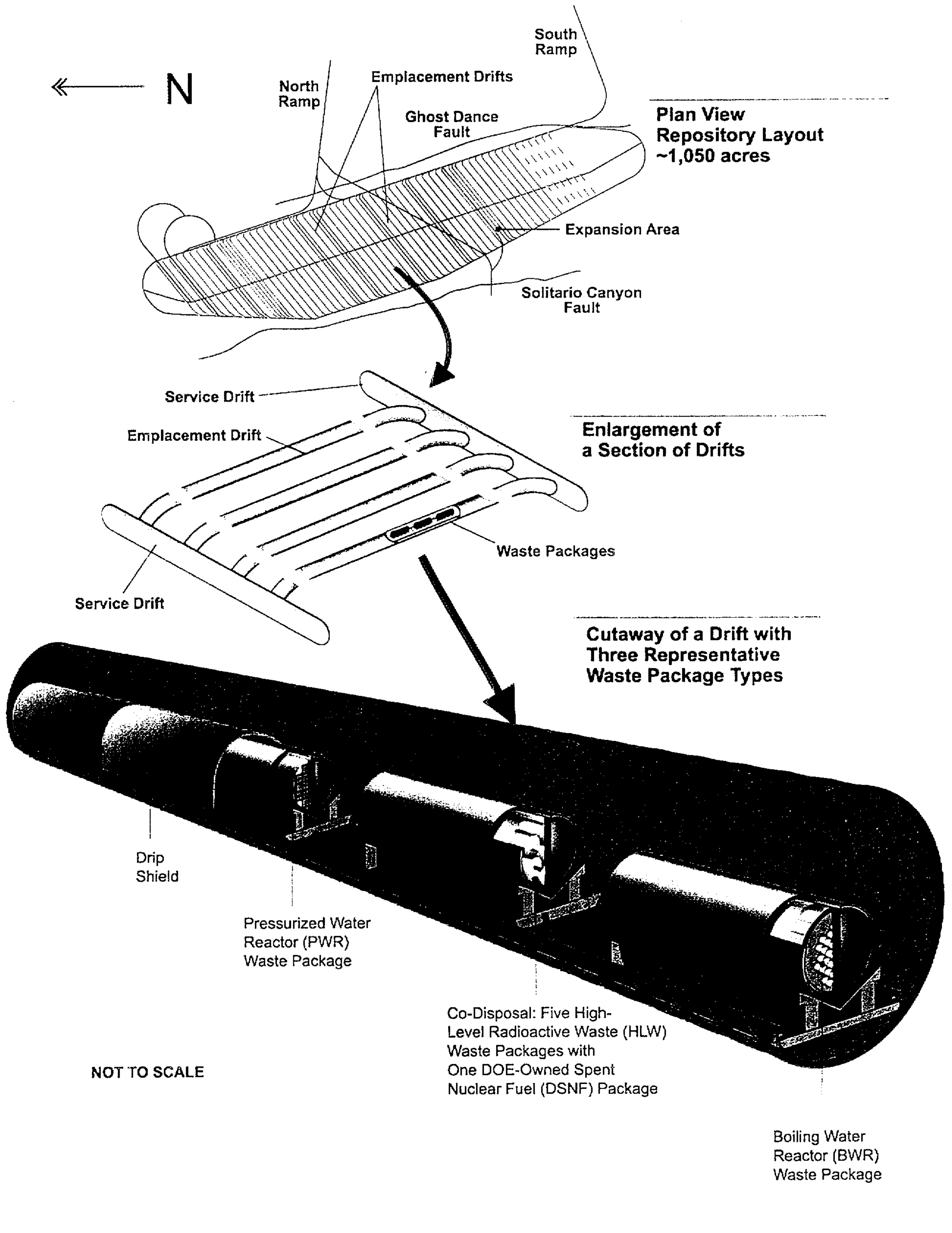
Figure 1.5-6. Increase in Sophistication of Subsystem Component Models with Successive Iterations of Total System Performance Assessment



abq0063G348

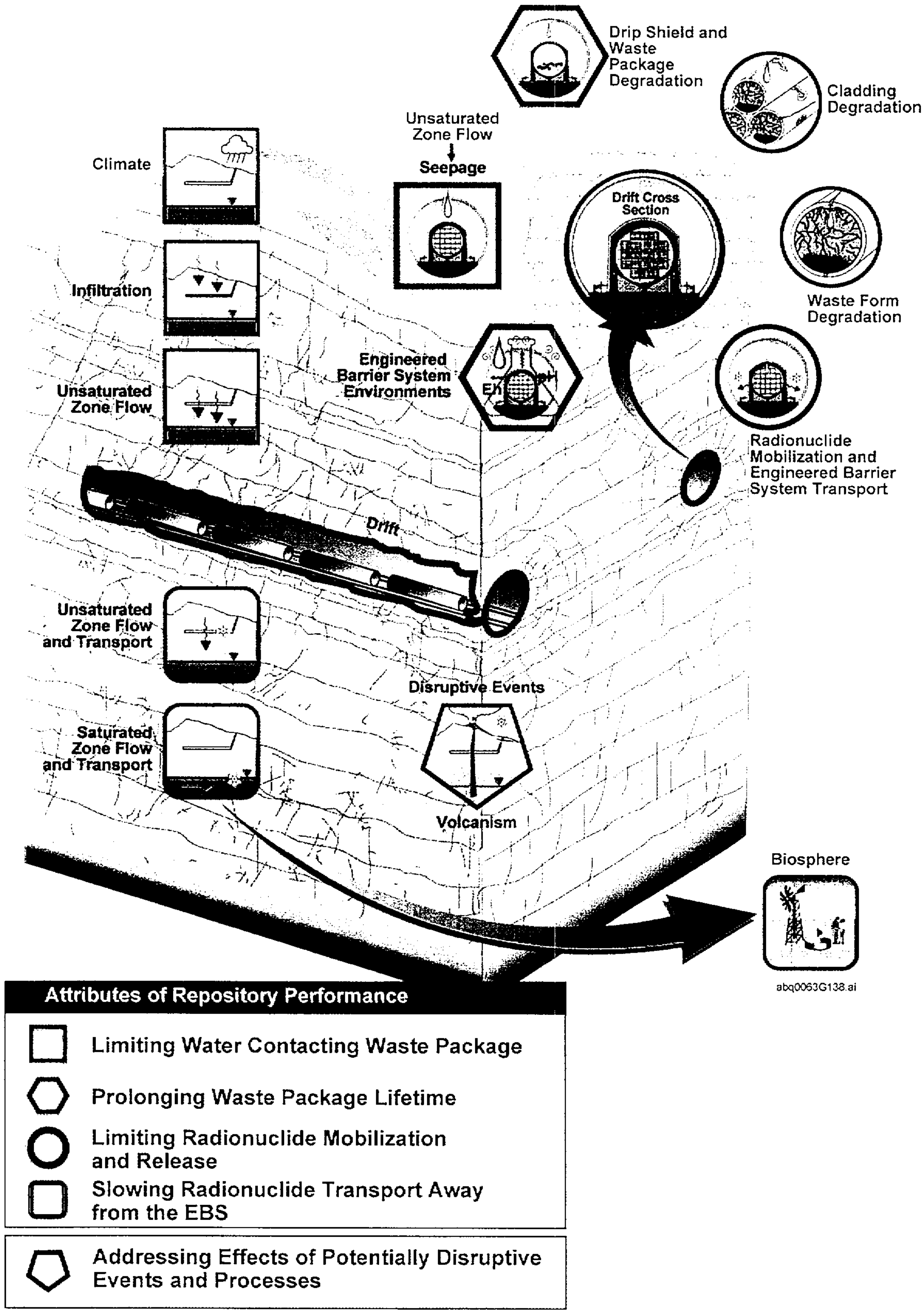
Figure 1.6-1. Major Steps in a Generic Performance Assessment

C-11



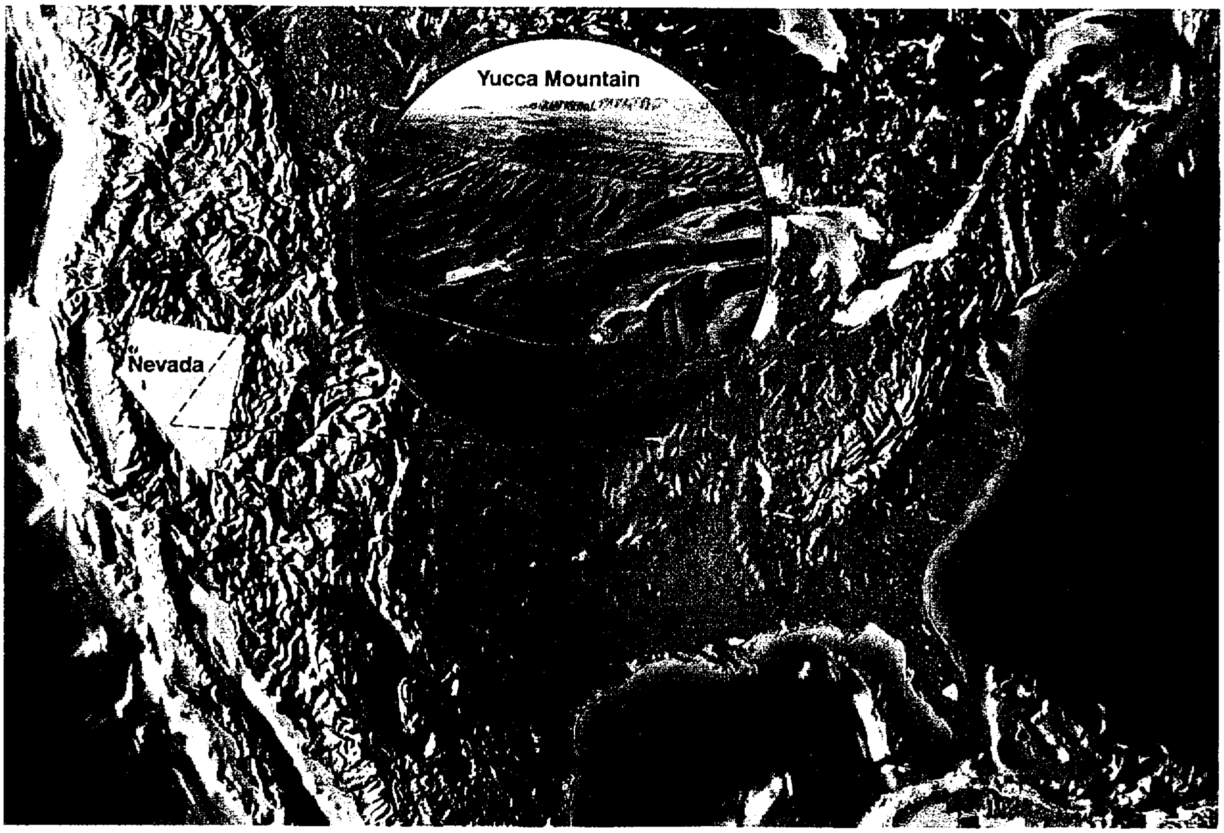
abq0063G116

Figure 1.7-1. Base Case Repository Design at Time of Closure



abq0063G138

Figure 1.8-1. Attributes of Repository Performance



abq0063G416

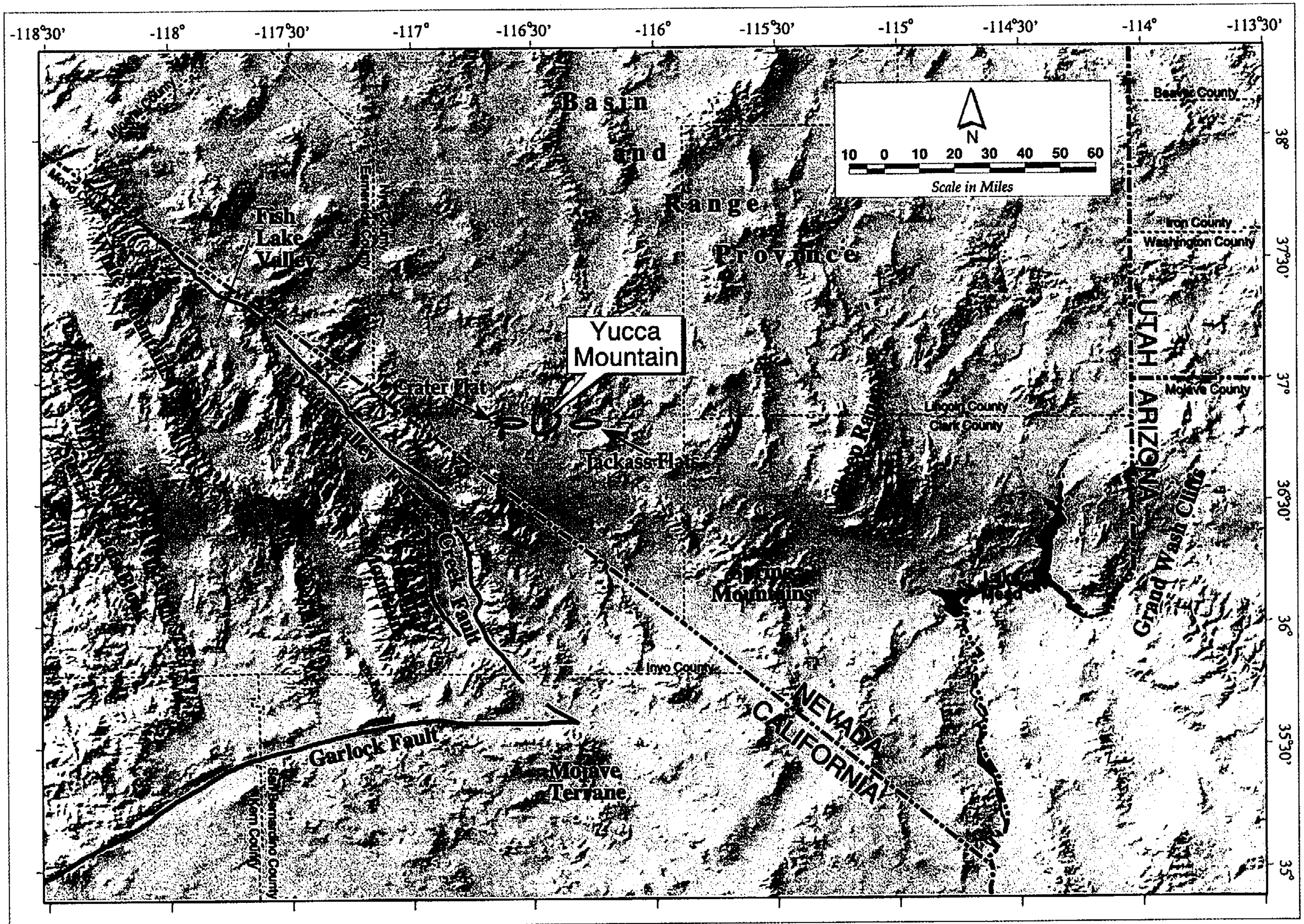
abq0063G416.ai

Figure 1.8-2. Location of Yucca Mountain

Yucca Mountain

abq0063G072

Figure 1.8-3. Yucca Mountain Area

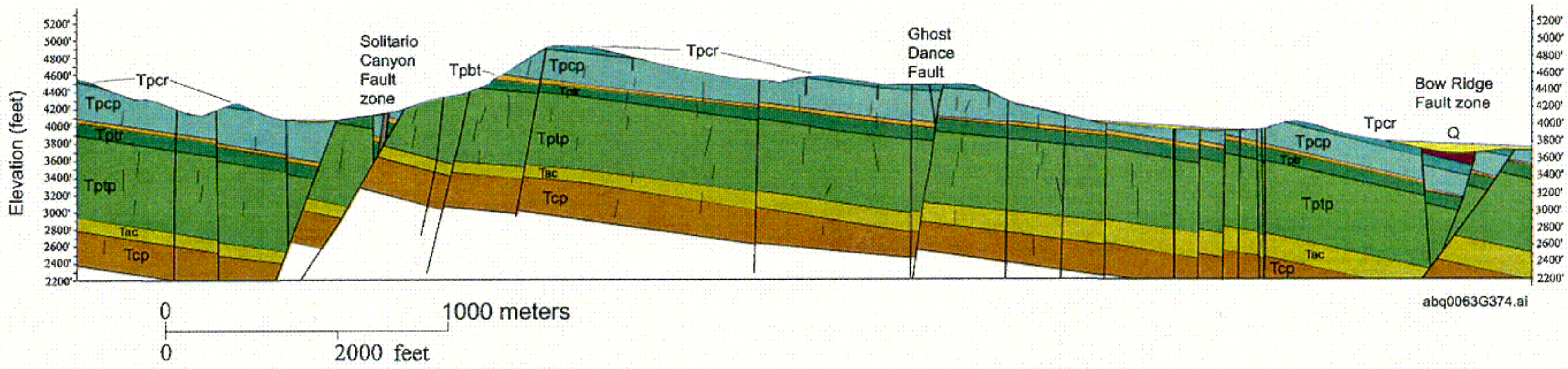


Note: Only faults with the highest rates of activity are shown

abq0063G372

Source: DOE 1998 [100548], Figure 2-11

Figure 1.8-4. Physiographic Map of the Southern Basin and Range Province



Legend:

- Alluvial and Colluvial Deposit (Q)

Timber Mountain Group

- Rainier Mesa Tuff (Tmr)

Paintbrush Group

- Tiva Canyon Tuff, crystal-rich member (Tpcr)
- Tiva Canyon Tuff, crystal-poor member (Tpcp)
- Pre-Tiva CanyonTuff, bedded tuffs (Tpbt)
- Topopah Spring Tuff, crystal-rich member (Tptr)
- Topopah Spring Tuff, crystal-poor member (Tptp)

- Calico Hills Formation (Tac)

Crater Flat Group

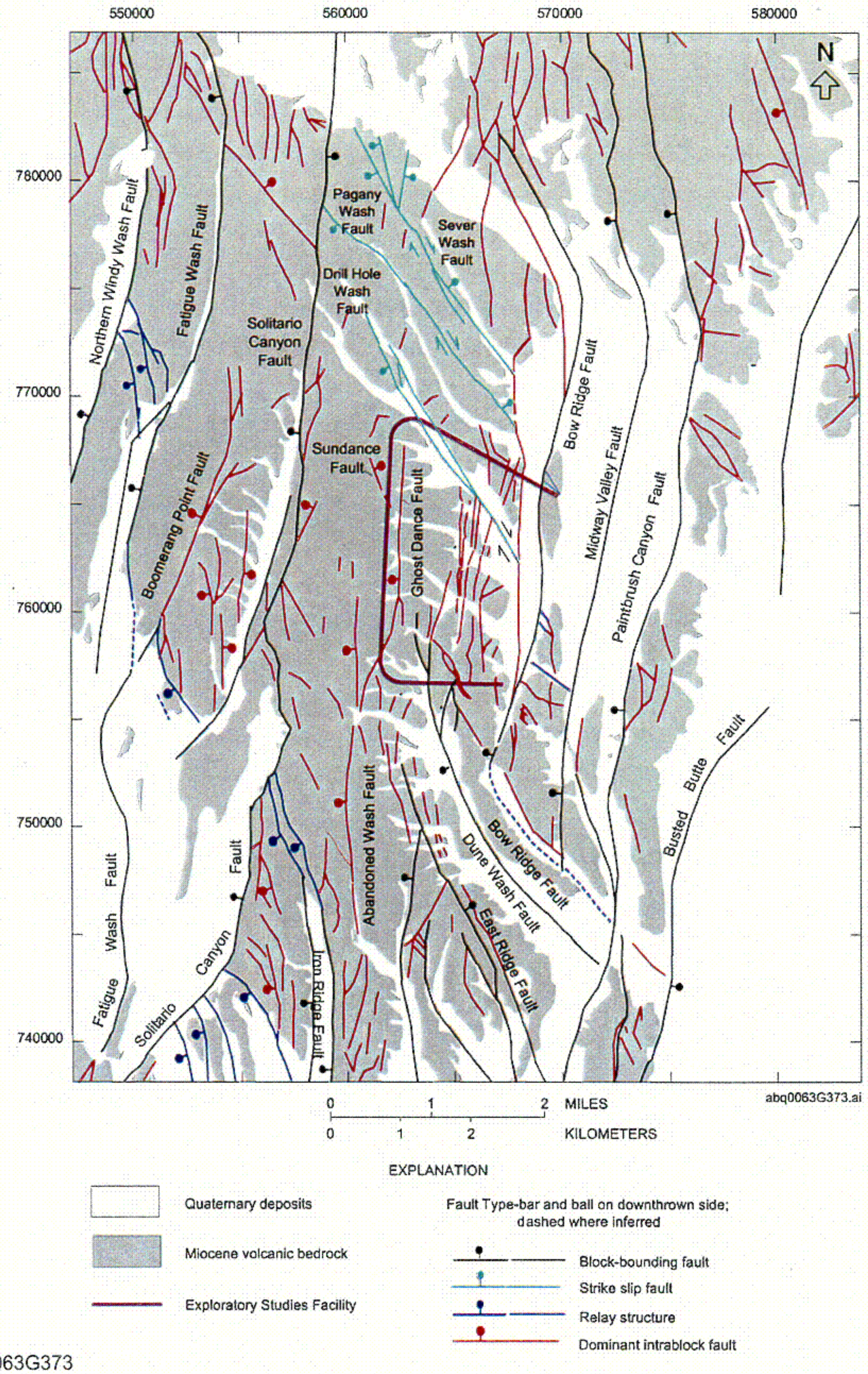
- Prow Pass Formation (Tcp)

abq0063G374

Source: Day et al. 1997 [100133], Plate 1

Figure 1.8-5. Generalized Cross Section through Yucca Mountain

C02



abq0063G373

Source: Day et al. 1997 [100133], Figure 3

Figure 1.8-6. Location of Faults at Yucca Mountain

C03

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2. YUCCA MOUNTAIN SITE CHARACTERIZATION PROJECT TOTAL SYSTEM PERFORMANCE ASSESSMENT FOR THE SITE RECOMMENDATION

The concept of TSPA and the generic TSPA process are described in Section 1 of this report. The acceptability of TSPA as a tool for analyzing a nuclear waste repository system is also described in that section. Section 2 of this report discusses the more specific use of the TSPA process for Yucca Mountain, including the approach and specific method.

Section 1.2 discusses the objectives of the TSPA-SR. The primary objective was to evaluate the performance of the system in support of the SR. To accomplish this objective, available scientific information about the natural geologic setting was used in the TSPA, along with data about the engineered components and their interactions with the geologic setting.

The primary performance measure used for evaluation of system performance is dose to the average member of the critical group at 20 km from the potential repository boundary. The time scale of regulatory concern for the analysis was primarily 10,000 years, although the evaluation was extended to fully consider some of the processes affecting release of radionuclides from the system.

Section 2.1 contains a general discussion of the approach used to analyze the potential Yucca Mountain repository system in the TSPA-SR. Building the capability for an integrated system analysis requires input from many individual disciplines. In addition, the analyses benefited from comments received from both internal and external reviewers of previous system analyses conducted for the potential repository. Sources of data and information for constructing the TSPA-SR include previous TSPAs; documented models of the principal components; workshops to abstract, or simplify, the process model components; expert elicitations of some model components; and external reviews. Nine principal components in the TSPA models are combined to evaluate the overall potential repository system. The presence of water is a key factor in initiating release of radionuclides from waste packages and moving them through the environment to a contact point with humans. For this reason, evaluation of the model components focused on the ability either to keep water from contacting the waste or to minimize releases of radioactivity from the potential repository if waste packages are breached.

Section 2.2 provides a detailed description of the method used to analyze the potential repository system in the TSPA. While Section 2.1 discusses the process model components as individual models, Section 2.2 provides a road map for reassembling, or coupling, the component models into one integral whole. Section 2.2 presents an overview of the TSPA-SR method for mathematical and numerical modeling of the individual processes, including their uncertainty, and the approach for combining them into an overall model and computer code. It includes discussions about information flow between the models and the architecture of the computer program for the TSPA-SR that facilitates the information flow. It also discusses the method for presenting the key results; in particular, it discusses how to show the influence of uncertainty of inputs on performance estimations and the effect of uncertainty on the base case.

2.1 TOTAL SYSTEM PERFORMANCE ASSESSMENT APPROACH

2.1.1 Development of an Integrated Total System Performance Assessment Approach

The potential Yucca Mountain repository system is a combination of integrated processes that can be summarized in 1 basic objective, 4 attributes, and 25 factors for the nominal case. An additional attribute and 8 factors are included as disruptive events and processes. The basic objective of the waste disposal system is to contain and isolate radioactive waste so that the dose impact to humans is attenuated to a relatively benign level. This objective manifests itself in the following attributes of nominal repository performance:

- Limiting water contacting the waste packages
- Prolonging waste package lifetime
- Limiting radionuclide mobilization and release from the EBS
- Slow transport away from the EBS.

The attribute of disruptive repository performance is:

- Low mean annual dose even considering effects of potentially disruptive processes and events.

Table 2.1-1 shows these attributes and the factors associated with them, as well as the TSPA-SR model components that are pertinent to the nominal and disruptive factors.

Building an integrated system analysis capability requires input from the many disciplines that compose the system. The construction of the model also benefits from comments from internal and external reviewers of previous system analyses conducted for the potential repository. The analyses documented in this volume have benefited from such interactions. The final approach and methods used in the analyses have evolved following completion of the *Total System Performance Assessment-Site Recommendation Methods and Assumptions* (CRWMS M&O 2000 [147323]). The major sources of information that form the bases for the development of the FEPs; subsequent methods; assumptions; and component models used in the TSPA-SR documented here are illustrated in Figure 2.1-1. The major sources for development of FEPs and other information required in the TSPA-SR include the following:

- DOE and non-DOE TSPAs of Yucca Mountain

- Documented models and analyses describing each of the principal components of the TSPA

- Workshops on abstractions of individual process model components used in the TSPA

- Reviews of the TSPA plans, methods, and assumptions

- NRC IRSRs which address the status of key technical issues assessed in the TSPA

- Expert elicitations of key process model components used in the TSPA.

Table 2.1-1. Factors Affecting Expected Postclosure Performance for the Site Recommendation and Their Corresponding Total System Performance Assessment-Site Recommendation Model Components

Attributes of Repository Performance	Factors[a]	TSPA Model Components
Limiting water contacting waste packages	Climate	UZ Flow
	Net Infiltration	
	UZ Flow	
	Coupled Effects on UZ Flow	
	Seepage into Emplacement Drifts	Seepage
	Coupled Effects on Seepage	
	In-Drift Physical and Chemical Environments (Environments on Drip Shield; Environments on Waste Package)	EBS Environments
	In-Drift Moisture Distribution (Moisture on Drip Shield; Moisture on Waste Package)	
Prolonging waste package lifetime	Drip Shield Degradation and Performance	Waste Package Degradation
	Waste Package Degradation and Performance	
Limiting radionuclide mobilization and release from the EBS	Radionuclide Inventory and Distribution in Repository	Waste Form Degradation Radionuclide Mobilization and EBS Transport
	In-Package Environments	
	Cladding Degradation and Performance	
	CSNF Degradation and Performance	
	DSNF Degradation and Performance	
	DHLW Degradation and Performance	
	Dissolved Radionuclide Concentrations	
	Colloid-Associated Radionuclide Concentrations	
	In-Package Radionuclide Transport	
	EBS (Invert) Degradation and Performance	
Slow radionuclide transport away from the EBS packages	UZ Radionuclide Transport (Advective Pathways, Retardation, Dispersion)	UZ Transport
	Coupled Effects on UZ Radionuclide Transport	
	SZ Radionuclide Transport (Advective Pathways, Retardation, Dispersion)	SZ Flow and Transport
	Wellhead Dilution	
	Biosphere Dose Conversion Factors	Biosphere Transport and Uptake
Low mean annual dose even considering effects of potentially disruptive processes and events	Probability of Volcanic Eruption	Volcanic Eruption
	Characteristics of Volcanic Eruption	
	Effects of Volcanic Eruption	
	Atmospheric Transport of Volcanic Eruption	
	Biosphere Dose Conversion for Volcanic Eruption	
	Probability of Igneous Intrusion	Igneous Intrusion
	Characteristics of Igneous Intrusion	
	Effects of Igneous Intrusion	

Source: [a] Modified after *Repository Safety Strategy Revision 4* (CRWMS M&O 2000 [148713])

Each of these sources is described in the following paragraphs. In addition, indirect information derived from other radioactive and nonradioactive waste programs has been used in the development of the approach and methodology used in the TSPA-SR. The detailed technical basis for the TSPA is documented in the *Total System Performance Assessment (TSPA) Model for Site Recommendation* (CRWMS M&O 2000 [148384]).

DOE contractors completed previous TSPA analyses in 1991, 1993, 1995, and 1998. These analyses are documented in *TSPA 1991: An Initial Total-System Performance Assessment for Yucca Mountain* (Barnard et al. 1992 [100309]), *Total-System Performance Assessment for Yucca Mountain - SNL Second Iteration (TSPA-1993)* (Wilson et al. 1994 [100191]), *Total System Performance Assessment - 1995: An Evaluation of the Potential Yucca Mountain Repository* (CRWMS M&O 1995 [100198]), and *Total System Performance Assessment,* Volume 3, of *Viability Assessment of a Repository at Yucca Mountain* (DOE 1998 [100550]). The general objective of these scoping analyses was to refine the methods and approach that would be applied in the development of the Site Recommendation and, ultimately, in the License Application. An additional objective was to assist DOE in prioritizing design and scientific investigations on the key components that most significantly impact performance. The knowledge gained in these analyses has assisted DOE in identifying which components significantly influence the performance of the potential repository system and has aided in prioritizing the data gathering activities needed to support the development of defensible models of these components. These TSPA analyses are described in more detail in Section 1.5.

Other TSPA analyses not sponsored by DOE have been conducted by the Electric Power Research Institute and the NRC. The Electric Power Research Institute's most recent iteration of a TSPA is documented in *Alternative Approaches for Assessing the Performance and Suitability of Yucca Mountain for Spent Fuel Disposal* (McGuire et al. 1998 [152193]). The NRC conducted an iterative performance assessment (NRC 1999 [152183]) in parallel with the DOE TSPA conducted for the VA. Each iterative analysis of total system performance, whether performed by DOE and its contractors, NRC and its contractors, or the Electric Power Research Institute and its contractors, leads to incorporation of current lab and field information and improved insights about the performance of the potential repository system. In addition, a review of the conceptual models and parameters used in the analyses provides a basis for defining the significance of the range of uncertainties examined. In general, all of these analyses converge on a few key components analogous to the factors identified in Table 2.1-1. These factors are reflected in the NRC key technical issues and the Issue Resolution Status Reports, which address portions of the key technical issues.

TSPAs are based on a number of building blocks. Principal among these are models that describe how Yucca Mountain behaves in the presence of a repository and how the engineered system behaves within the environmental setting. These process models are designed to describe the behavior of individual and coupled physical and chemical processes. A significant portion of the DOE site characterization program has been aimed at developing the scientific bases for the most reasonable representation of the Yucca Mountain site and its associated engineered barriers. Those scientific bases serve as the foundation for the process models used in the TSPA. The basis for these models is described in more detail in the process model reports, and their use in the TSPA is discussed in Section 3.

To ensure that this TSPA would be based on the most current scientific knowledge, a series of workshops were held in 1998 and 1999 to bring together YMP scientists, engineers, and performance assessment analysts. These individuals consisted of scientists and engineers from the DOE, national laboratories, the U.S. Geological Survey, and the Civilian Radioactive Waste Management System Managing and Operating Contractor. Observers at these workshops included technical staff from such regulatory agencies as the NRC and the EPA and their contractors, along with external oversight groups, such as the Nuclear Waste Technical Review Board. The aim of these workshops was to develop a strategy for identifying and incorporating the relevant aspects of the individual process models into the TSPA analyses. In addition to defining the appropriate approach for abstracting the important elements of each process model, these workshops assisted the DOE in defining and prioritizing the major technical issues that had to be addressed in the TSPA. Many of these issues correspond directly with the key technical issues raised by the NRC. Each workshop culminated in a plan for incorporating that component in the TSPA and linking it to other portions of the TSPA. These plans were summarized in *Total System Performance Assessment-Site Recommendation Methods and Assumptions* (CRWMS M&O 2000 [147323]).

Acknowledging diverse technical and scientific opinions is an important part of any engineering and scientific endeavor that is as complex as analyzing the design and performance of a potential disposal facility for high-level radioactive waste. For the VA, the DOE sponsored 5 expert elicitations on key process models for the TSPA. The goal of these elicitations was to solicit the judgment of nationally and internationally recognized scientists in quantifying the uncertainty associated with each of these process models and the uncertainty in the parameter values used in those models. The process followed the procedures and approaches for eliciting expert judgments that have been formalized in documents like the DOE guidance for the formal use of expert judgment (YMP 1995 [100381]) and the NRC Branch Technical Position on the use of expert elicitation in the high-level radioactive waste program (Kotra et al. 1996 [100909]). The assessments and probability distributions from these elicitations provide a reasonable aggregate representation of the knowledge and uncertainties about issues in evaluating the various processes important to potential repository performance. The five areas evaluated in the elicitations were:

- UZ flow (CRWMS M&O 1997 [100335])
- Waste package degradation (CRWMS M&O 1998 [100349])
- SZ flow and radionuclide transport (CRWMS M&O 1998 [100353])
- Near-field environment (CRWMS M&O 1998 [100351])
- Waste form degradation (CRWMS M&O 1998 [100374]).

In addition to these elicitations, the DOE conducted external elicitations of the potential hazards associated with either volcanically or seismically induced events. The use of these results in the analysis of the potential effects of disruptive scenarios is described in Section 3.10. Following the VA, additional work was conducted to eliminate the need for utilization of the results of these expert elicitations in TSPA-SR, with the exception of the SZ expert elicitation results, potential volcanic hazard analysis and potential seismic hazard analysis.

In addition to DOE-sponsored development of the TSPA models, several external oversight groups provided input throughout the process of defining and implementing the approach and methods. These groups include the NRC and its contractor, the Center for Nuclear Waste Regulatory Analysis; the NRC Advisory Committee for Nuclear Waste; and the congressionally chartered Nuclear Waste Technical Review Board. These organizations have published a range of technical comments on the TSPA and conducted numerous briefings over the last two years on the progress of the TSPA. Their comments have aided in defining the most appropriate means of describing and analyzing the performance of the Yucca Mountain site and the engineered barriers associated with the reference design and design options.

The approach to developing the TSPA-SR models, as noted above, included the development of FEPs, the screening of these FEPs, and construction of scenario classes, which are groupings of closely related FEPs and scenarios that have been combined for the purpose of assigning probabilities and screening, consistent with guidance provided by the NRC (NRC 2000 [149372], Section 4.2.4, 4.2.5). This FEPs approach is discussed in Section 2.1.1.1.

2.1.1.1 Implementation of the Features, Events, and Processes Approach

A series of DOE-sponsored TSPA scoping analyses were performed between 1991 and 1998 (see Section 1.5). During the iterative process of performing these analyses, knowledge was gained regarding (1) the TSPA methods and approach, (2) key features of the potential Yucca Mountain repository system, and (3) events and processes that most significantly impact postclosure performance. Additional information about the important FEPs relevant to Yucca Mountain was collected from non-DOE-sponsored TSPAs, process model workshops and analyses, NRC IRSRs, expert elicitations, and external oversight groups (see Section 2.1.1). The collective results of these activities, which represent an informal approach to identifying the FEPs and scenarios important to the postclosure performance of the potential Yucca Mountain repository system, will provide input to successive iterations of the Repository Safety Strategy (CRWMS M&O 2000 [148713]). This informal FEPs approach identified 5 attributes and 33 factors important to postclosure performance (Table 2.1-1). The approach also identified a nominal scenario class (4 attributes and 25 factors), a disruptive event scenario class (1 attribute and 8 factors), and associated model components.

Under the provisions of the DOE's Interim Guidance (Dyer 1999 [105655], Section 102[j]), a performance assessment is defined as a systematic analysis that (1) identifies the FEPs that might affect the performance of the potential geologic repository, (2) examines the effects of such FEPs on the performance of the geologic potential repository, and (3) estimates the expected annual dose to a specified receptor group. The performance assessment must also provide the technical basis for inclusion or exclusion of specific FEPs in the performance assessment (Dyer 1999 [105655], Section 114). To address these requirements, a formal approach to selecting scenario classes for analysis in the TSPA-SR was implemented, based on the identification and screening of FEPs potentially relevant to the postclosure performance of the potential repository. The formal FEPs approach builds from the attributes, factors, scenarios, and model components identified in the previous informal approach.

The formal FEPs and scenario development process adopted for the TSPA-SR is based on the methodology developed by the NRC (Cranwell et al. 1990 [101234], Section 2.0). The approach is fundamentally the same as that used in many performance assessments, including a recent analysis of the potential Yucca Mountain repository by the NRC (Wescott et al. 1995 [100476]);

it has also been used by the DOE for examining the Waste Isolation Pilot Plant (DOE 1996 [100975], Section 6.2), by the Nuclear Energy Agency (1992 [100479]), and by other international radioactive waste programs (e.g., Skagius and Wingefors 1992 [101018], Section 2).

The five principal steps in the scenario development process are illustrated in Figure 2.1-2, discussed in detail in subsequent subsections, and outlined below:

1. Identify FEPs potentially relevant to the long-term performance of the disposal system.

2. Classify the FEPs to support evaluation of completeness and to facilitate screening.

3. Screen the FEPs using defined criteria to identify those that should be included in the TSPA analysis and those that can be excluded from the analysis.

4. Construct scenario classes (sets of related scenarios) from the retained (included) FEPs, as appropriate.

5. Screen the scenarios classes using the same criteria applied to the FEPs to identify any scenario classes or scenarios that can be excluded from the TSPA analysis.

These 5 steps differ slightly from those identified in the *Total System Performance Assessment-Site Recommendation Methods and Assumptions* (CRWMS M&O 2000 [147323], Section 2.2). The changes were made so the 5 steps of the TSPA-SR approach would correspond directly to the 5 elements of scenario analysis acceptance criteria outlined in the *TSPA&I IRSR* (NRC 2000 [149372], Section 4.2).

A YMP FEP database was developed to catalog the following information: a comprehensive list of FEPs that have the potential to influence repository performance, a systematic classification structure for FEPs that helps to evaluate completeness and facilitate screening, and screening information that summarizes the technical basis for inclusion or exclusion of each FEP in the TSPA-SR analyses. The YMP FEP Database serves as a communication tool for FEPs information. The information contained in the database was generated in separate Analysis Model Reports. The YMP FEP database REV00 (the current version) and documentation of its development are contained in *The Development of Information Catalogued in REV00 of the YMP FEP Database* (CRWMS M&O 2000 [150806]). The database documentation is also summarized in Appendix B of this report.

Step 1: Identification of FEPs–The development of a comprehensive list of FEP potentially relevant to the postclosure performance of the potential Yucca Mountain repository is an ongoing, iterative process based on site-specific information, design, and regulations. The YMP FEP list was initially developed from a comprehensive list of FEPs from other international radioactive waste disposal programs (see Appendix B of this report and CRWMS M&O 2000 [150806], Section 2.1) and was supplemented with additional YMP-specific FEPs from project literature, technical workshops, and reviews (see Appendix B of this report and CRWMS M&O 2000 [150806], Sections 2.2 through 2.4). The YMP FEP list is open and may continue to expand if additional FEPs are identified during the Site Recommendation and License Application processes.

The sources identified above produced 1,646 specific FEPs. These FEPs, when combined with the 151 general FEP classifications (described in Step 2 below), result in a YMP FEP list that contains 1,797 entries.

The NRC acceptance criteria for the identification of FEPs (NRC 2000 [149372], Section 4.2.1) address the comprehensiveness of the FEP list. Absolute proof of comprehensiveness is not possible. However, the comprehensiveness of the YMP FEP list derives from (a) the diverse backgrounds of the international waste disposal programs contributing to the list, (b) the variety of methods used to identify FEPs including expert judgment, informal elicitation, event tree analysis, stakeholder review, and regulatory stipulation, (c) the iterative discussions and reviews (i.e., at technical workshops and in analysis model reports) of important YMP attributes, factors, and model components, (d) the systematic and comprehensive classification structure (as described in Step 2 below) that ensures that no relevant subject area is overlooked, and (e) the fact that FEPs cannot be removed from the list, they can only be screened out (excluded) from the analysis.

Step 2: Classification of FEPs–The all-inclusive approach used to identify FEPs (described in Step 1 above) produced a large number (1,646) of specific FEPs, and resulted in considerable redundancy in the FEP list, because the same FEPs were frequently identified by multiple sources. To better organize these FEPs and to help evaluate the completeness of the FEP list, a hierarchical classification structure was adopted within the YMP FEP database (see Appendix B of this report and CRWMS M&O 2000 [150806], Section 3.1). The FEP classification structure was defined by 4 high-level layers, 12 associated categories, and 135 underlying headings. Each of the 1,646 specific FEPs identified in Step 1 was assigned (mapped) to a single heading in the YMP FEP database. This mapping resulted in a classification where all related FEPs were grouped together under the same classification heading (with additional relationships to the overarching categories and levels). The implementation of the classification structure in the database produced a YMP FEP list containing 1,797 entries, composed of the 1,646 specific FEPs and the 151 classification (layer, category, and heading) entries.

To eliminate the redundancy and to create a more efficient aggregation of FEPs to carry forward into the screening process (described in Step 3 below), each of the 1,797 entries in the YMP FEP database was further identified as either a primary, secondary, or classification (layer, category, or heading) entry. The process and criteria for assigning FEPs to one of these categories is described in Appendix B of this report and in *The Development of Information Catalogued in REV00 of the YMP FEP Database* (CRWMS M&O 2000 [150806], Section 3.2).

Primary FEPs encompass a single process or event, or a few closely related or coupled processes or events that can be addressed by a specific screening discussion. A primary FEP may also include one or more related secondary FEPs that are covered by the same screening discussion. Secondary FEPs are (1) redundant to another FEP (e.g., several international programs identified the same FEP), (2) specific to another program (and captured more generally in a different YMP-specific FEP), or (3) better captured or subsumed in another similar but more broadly defined YMP-specific FEP. Each secondary FEP was mapped to a primary FEP and was completely addressed by the screening discussion of that primary FEP.

Classification entries represent the hierarchical levels of classification within the database. They are defined too broadly to be addressed by a single screening discussion (as with a primary FEP) and cannot be encompassed by an overlying FEP (as with a secondary FEP). Rather, they classify one or more underlying related primary FEPs and do not require screening discussions. If the FEPs grouped under a specific heading entry were closely enough related that they could all be addressed by a screening discussion at the overlying heading level, the heading entry (which would otherwise be defined as a classification entry) was designated as a primary FEP. The underlying FEPs were designated as secondary FEPs to the heading-level primary FEP.

The classification approach described in this Step resulted in 111 classification entries (151 less 40 heading entries that were reclassified as primary FEPs), 323 primary FEP entries (including the 40 headings) and 1,363 secondary FEP entries. The classification approach was designed to produce a set of primary FEP entries that capture all of the issues relevant to the postclosure performance of the potential Yucca Mountain repository. Therefore, it was only necessary to carry forward the 323 primary FEPs for screening (as described in Step 3 below). Screening of the secondary (and classification) FEPs was not required because the aspects of the secondary FEPs were encompassed by the primary FEPs.

The NRC acceptance criteria for the classification of FEPs (NRC 2000 [149372], Section 4.2.2) address the grouping and categorization of FEPs. NRC guidance accompanying these criteria suggests grouping potentially disruptive events into "event classes" that contain related events, to ensure that event probabilities are not underestimated by defining events too narrowly (NRC 2000 [149372], Section 4.2.2). The classification approach adopted for TSPA-SR produced an aggregated set of primary FEPs for screening that covered all identified potentially relevant Yucca Mountain FEPs. Although the DOE has not adopted the term "event class" because it is inconsistent with the proposed regulatory requirement to consider all FEPs rather than just events, the evaluation of probabilities for primary FEPs achieves the goal of assigning probabilities at an appropriately broad level of categorization. Documentation of the grouping and categorization of YMP FEPs is in Appendix B of this report and in *The Development of Information Catalogued in REV00 of the YMP FEP Database* (CRWMS M&O 2000 [150806], Section 3).

Step 3: Screening of FEPs–Each of the 323 primary FEPs identified in Step 2 above was screened for inclusion or exclusion in the TSPA on the basis of three criteria, developed from DOE's Interim Guidance (Dyer 1999 [105655]). The three criteria, described in Appendix B of this report and in *The Development of Information Catalogued in REV00 of the YMP FEP Database* (CRWMS M&O 2000 [150806], Section 4), are outlined below:

- **Regulatory**–FEPs that are inconsistent with regulatory guidance (Dyer 1999 [105655], Subpart E) may be excluded (screened out) from the TSPA analysis. The most notable examples are the regulatory specification of the human intrusion scenario and the critical group characteristics.

- **Probability**–FEPs that have less than one chance in 10,000 of occurring over 10,000 years may be excluded (screened out) from the TSPA on the basis of low probability.

- **Consequence**–FEPs whose exclusion would not significantly change the expected annual dose may be excluded (screened out) from the TSPA on the basis of low consequence.

Because DOE's Interim Guidance (Dyer 1999 [105655], Section 114) allows exclusion of FEPs on the basis of either low probability or low consequence, a FEP need not be shown to be both of low probability and low consequence to be excluded. Therefore, the order in which the criteria are applied is not essential. In practice, FEPs were screened as shown in Figure 2.1-3. Regulatory criteria were examined first, and then either probability or consequence criteria examined next at the discretion of the analyst. In some cases, one component of a FEP was included while another component of the FEP was excluded.

This application of the analyst's judgment regarding the order in which to apply the criteria does not affect the final decision. FEP that were retained on one criterion were then considered against the other. Needless work developing quantitative probability arguments for low consequence events or complex consequence models for low-probability events was prevented by allowing the analyst to choose the most appropriate criterion to apply at this step (e.g., there is no need to develop detailed models of the response of the disposal system to the impact of a large meteorite if it can be shown that this event has a probability below the regulatory cutoff).

The FEP screening was performed by subject matter experts and documented in FEP analysis model reports (listed in Appendix B). Specific guidelines for the basis of screening decisions and the content of screening documentation are outlined in Appendix B of this report and in *The Development of Information Catalogued in REV00 of the YMP FEP Database* (CRWMS M&O 2000 [150806], Section 4.2).

Probability screening, in general, requires some information about the magnitude of the event (e.g., the probability of meteorite impacts depends on the size of the meteorite of interest). Impacts of meteorites sufficiently large to create large craters at Yucca Mountain are much less probable than smaller impacts. Thus, meteorites large enough to affect the disposal system may be screened out on the basis of low probability, but smaller meteorite impacts that produce no significant change to the disposal system may be more appropriately screened out on the basis of low consequence. Probability screening is also sensitive to the spatial and temporal scales at which FEPs are defined (meteorite impacts are less likely in shorter time intervals and at smaller locations), and probability screening must therefore be performed at reasonably coarse scales.

Consequence screening does not necessarily require detailed calculations of the consequences (i.e., expected annual dose) (NRC 2000 [149372], Section 4.2.3). The amount of information required may vary from FEP to FEP, based on the processes and events involved. Consequence screening may rely on reasoned arguments based on literature research (e.g., consequences of many geomorphic processes, such as erosion and sedimentation, can be evaluated by considering bounding rates reported in geologic literature), TSPA sensitivity analyses, or modeling studies performed outside of the TSPA (e.g., detailed criticality analyses). Consequence screening may also be based on an intermediate performance measure (e.g., radionuclide mass release to the SZ) as long as a qualitative link to the change in expected annual dose can be demonstrated.

The NRC acceptance criteria for the screening of FEPs (NRC 2000 [149372], Section 4.2.3) address the screening criteria. Guidelines were established to ensure that the screening basis and content for each primary FEP of the screening data was sufficient to satisfy the screening criteria for low probability, low consequence, or regulatory exclusion.

Step 4: Formation of Scenario Classes–The objective of scenario development is to define a limited set of scenarios that can reasonably be analyzed quantitatively while still maintaining comprehensive coverage of the range of possible future states of the disposal system. There are an essentially infinite number of possible future states, and for scenario development to be useful, it must generate scenarios that are representative of the range of futures that are potentially relevant to the licensing of the facility.

For TSPA-SR, the term "scenario" was defined as a subset of the set of all possible futures of the disposal system that contains futures resulting from a specific combination of FEPs. At a coarser level, the term "scenario class" was adopted to refer to a set of closely related scenarios. More specifically, a scenario class is defined as a set of scenarios that share sufficient similarities that they can usefully be aggregated for the purposes of a specific analysis. Further definition of these terms is found in Appendix A. Consistent with NRC guidance (NRC 2000 [149372], Sections 4.2.4, 4.2.5), scenarios are grouped into scenario classes for TSPA-SR for the purposes of probability assignment and screening. Note, however, neither the term "scenario" nor "scenario class" is defined in the proposed regulations (64 FR 8640 [101680], Section 63.2) or in the NRC acceptance criteria (NRC 2000 [149372], Section 4.2).

The number and breadth of scenario classes depends on the resolution at which scenarios have been defined. Coarsely defined scenarios result in fewer, broad scenario classes, whereas narrowly defined scenarios result in many narrow scenario classes. In turn, the number and breadth of scenarios depends on the resolution at which FEPs have been defined. There is no uniquely correct level of detail at which to define scenario classes, scenarios, and FEPs. Decisions regarding the appropriate level of resolution for the analysis are made based on consideration of the importance of the scenarios, their effects on overall performance, and the resolution desired in the results. For efficiency, scenario classes, scenarios, and FEPs should be aggregated at the coarsest level at which a technically sound argument can be made, while still maintaining adequate detail for the purposes of the analysis.

As described at the beginning of this section, an informal approach was used to identify FEPs and scenarios based on the results of prior TSPA scoping analyses, process model workshops and analyses, NRC Issue Resolution Status Reports, expert elicitations, and external oversight groups. These prior analyses identified two scenario classes: nominal performance and disruptive performance. Formal scenario development for TSPA-SR used these scenario classes (along with the attributes, factors, and model components identified in Table 2.1-1) as a basis.

All primary FEPs not excluded (screened out) from the TSPA in Step 3 above were retained for inclusion in one or more scenario classes. Each of the retained primary FEPs was identified as either an expected FEP (EFEP) or a disruptive FEP (DFEP). EFEPs are those retained FEPs that were assumed, for the purposes of the TSPA, to have a probability of occurrence equal to 1.0 (although they may have uncertain consequences). DFEPs are those retained FEPs that have a probability of occurrence less than 1.0 (but greater than the low-probability screening threshold noted in Step 3 above). The nominal performance scenario class and the associated models were constructed to include all EFEPs. The disruptive performance scenario class and the associated models were constructed to include all DFEPs in addition to all EFEPs.

Proposed 10 CFR 963.17(b) (64 FR 67054 [124754]) identifies four disruptive events that require explicit consideration in the site suitability evaluation: volcanism, seismic events, nuclear criticality, and human intrusion. For TSPA-SR, the retained DFEPs were all associated with igneous activity (volcanism) or human intrusion. In proposed 10 CFR 963.16 (64 FR 67054 [124754]) there is a requirement for human intrusion to be evaluated in a separate performance assessment (see Section 4.4). Therefore, for TSPA-SR, the disruptive performance scenario class contained only FEPs related to igneous activity and was also referred to as the igneous disruption scenario class. Within the igneous disruption scenario class, two scenarios were identified: volcanic eruption (direct release) and igneous intrusion (indirect release via groundwater).

FEPs related to seismic damage to cladding were included in the nominal scenario class (see Section 3.5.4), rather than as a disruptive scenario. This was done primarily for pragmatic, computational reasons. The damage has no effect on performance as long as waste packages remain intact, and it was determined to be more computationally efficient to treat it as a parametric uncertainty in the nominal case as opposed to building another disruptive event scenario. Other FEPs related to seismic events (ground motion and fault displacement) and the FEPS related to nuclear criticality were screened out of TSPA-SR on the basis of low consequence (for seismicity) and low probability (for nuclear criticality). Further discussion of the treatment of these and other potentially disruptive FEPs not included in TSPA-SR is provided in Section 4.5.

The two TSPA-SR scenario classes are displayed graphically using a Latin Square scenario diagram in Figure 2.1-4. This diagram shows the probability of occurrence of each scenario class, which sum to 1.0. As discussed in Section 3.10.1, the probability of occurrence for the igneous disruption scenario class is derived from expert elicitation of the annual frequency of igneous activity in the Yucca Mountain region. The probability of the nominal scenario class is one minus probability of the igneous disruption scenario class. Implementation of these probabilities in the TSPA is described in Sections 4.2 and 4.3.

The NRC acceptance criteria for the formation of scenario classes (NRC 2000 [149372], Section 4.2.4) address whether the scenario classes provide comprehensive coverage of all retained FEPs. The two scenario classes identified for TSPA-SR, nominal and igneous disruption, are broadly defined and mutually exclusive. All retained FEPs (both EFEPs and DFEPs) are contained in one or both of the scenario classes.

Step 5: Screening of Scenario Classes–In Step 4 above, 2 scenario classes were identified for screening: nominal and igneous disruption. These 2 scenario classes contain all retained FEPs. The relative probabilities of these 2 scenario classes are illustrated in Figure 2.1-4 and described in more detail in Section 4.3. The screening of scenario classes was performed to identify any scenario classes or scenarios that could be excluded from the TSPA on the basis of the same regulatory, probability, and consequence criteria defined in Step 3 for screening FEPs.

Scenario screening is used to identify scenarios that contain a combination of FEPs whose combined probability of occurrence (or consequence) is low enough to permit exclusion from the TSPA, even though the probability (or consequence) of the individual FEPs requires them to be retained. For a scenario class or scenario to be screened out, the combined low probability (or consequence) should not result from an inappropriately narrow scenario definition that artificially reduces the probability (or consequence) below the regulatory cutoff.

For TSPA-SR, detailed screening was performed on FEPs (as described in Step 3 above). The scenario classes and scenarios formed in Step 4 were composed of retained FEPs only. No additional exclusions were made during scenario screening. As was noted in Step 4, criticality was excluded from the TSPA at the FEP level rather than at the scenario level.

The nominal scenario class was implemented in TSPA-SR (Sections 3.1 to 3.9) by treating the retained expected FEPs through explicit incorporation in model components or through uncertainty included in the assignment of parameter values used in the model components. The igneous disruption scenario class (Section 3.10) and human intrusion scenario (Section 4.4) were implemented by treating the disruptive FEPs in similar fashion.

The NRC acceptance criteria for the screening of scenario classes (NRC 2000 [149372], Section 4.2.5) address the screening criteria and the appropriateness of applying the criteria to scenarios. For TSPA-SR, scenario screening criteria were evaluated, but all scenario classes and scenarios formed in Step 4 were retained.

2.1.2 Components of the Potential Yucca Mountain Repository System Evaluated in the Total System Performance Assessment

The potential Yucca Mountain repository system consists of the geologic setting and engineered barriers that, considered together, are aimed at reducing the exposure of humans to radioactive materials to acceptable levels. This section briefly describes the key aspects of the individual component models identified in Table 2.1-1 and Figures 2.1-5 to 2.1-8. Figure 2.1-5 depicts the general flow of information for the major scenario classes of the TSPA-SR and the components of these scenario classes. The scenario classes include the nominal (undisturbed) scenario class, the disruptive event (igneous/volcanic) scenario class, and the human intrusion scenario class.

- **Nominal Scenario Class**–Considers FEPs expected to occur during the time period of evaluation.

- **Disruptive Event Scenario Class**–Considers igneous disruption (i.e., volcanism) as an additional event that has a low probability of occurrence during the time period of evaluation. This scenario class includes two scenarios, igneous intrusion (indirect releases via groundwater) and volcanic disruption (direct releases).

- **Human Intrusion Scenario Class**–Considers a stylized event of human intrusion into the potential repository as defined in the governing regulations.

The nominal and disruptive scenario classes together contribute to the expected annual dose (Figure 2.1-5). Figures 2.1-6 to 2.1-8 show the individual flow-of-information wheels for the nominal scenario, the 2 disruptive scenarios, and the human intrusion scenario. These figures provide a visualization of how major information flows within each of the scenario classes and scenarios, and of the factors (or important submodels) for each of the components. Note that the nominal and human intrusion utilize essentially the same models and parameters, so these wheels look very similar.

The model components related to the first attribute of repository performance—limiting water contacting waste packages—include climate, infiltration, UZ flow, and seepage. Together, these components define the temporal and spatial distribution of water flow through the unsaturated tuffs above the water table at Yucca Mountain and the temporal and spatial distribution of water seeps into the repository drifts. There could be long-term (thousands to hundreds of thousands of years) climate variations. In addition, the thermal regime generated by the decay of the radioactive wastes can mobilize water over the first hundreds to thousands of years. For these reasons, the amount of water flowing in the rock and seeping into drifts is expected to vary with time.

The model components related to the second attribute of repository performance—prolonging waste package lifetime—include all of the above components plus EBS environments, drip shield degradation, and waste package degradation. Together, these components define the times when waste packages are expected to be breached. The thermal, hydrologic, and geochemical processes acting on the waste package surface are the most important environmental factors affecting the waste package containment time. As noted in Section 3.4, the mechanical degradation processes are currently estimated to be insignificant in affecting the containment time.

The environmental processes acting on the waste package surface as well as the timing and extent of waste package degradation are directly related to the selected design. Reviewing the key aspects of the site recommendation reference design as they relate to the expected behavior of the potential repository system is appropriate. Details of the reference design are described in Section 1.7 and are not repeated here. A schematic of the reference waste package design, including the types of waste forms to be emplaced in the potential Yucca Mountain repository, is depicted in Figure 2.1-9. Of particular relevance to performance are that the waste package reference design consists of 2 barrier metals—an inner structural liner consisting of 5 cm of stainless steel and an outer metallic barrier of 2 cm of corrosion-resistant high-nickel alloy (Alloy-22) (ASTM B 575-94 1994 [100497]) and the design and closure (post-weld heat treatment) of the lids of the waste package. For DOE-owned waste, the outer barrier is 2.5 cm thick.

The principal waste forms to be disposed of within these waste packages consist of the following:

- Commercial spent nuclear fuel derived from pressurized water reactors or boiling water reactors

- DSNFs including N-Reactor fuel from Hanford, Washington; research reactor fuel; and naval spent nuclear fuel

- High-level radioactive waste in the form of glass logs placed in stainless-steel canisters from Savannah River, South Carolina; West Valley, New York; Hanford, Washington; and the Idaho National Engineering and Environmental Laboratory, Idaho

- DOE-owned immobilized excess weapons-useable plutonium.

The waste packages are designed to contain up to 21 pressurized-water reactor assemblies, 44 boiling-water reactor assemblies, 5 glass logs and codisposal of DSNF fuel assemblies, and direct disposal of other canisterized DSNFs including naval spent nuclear fuel.

A schematic of the potential reference repository and EBS designs is depicted in Figure 2.1-10. Key aspects of the potential repository and EBS reference design that influence the long-term performance of the disposal system include the following:

- Areal thermal loading, which is determined by the waste package capacity, the spacing between waste packages and the spacing between emplacement drifts

- Size of the drifts

- Lining of the drifts for mechanical stability

- Characteristics of the engineered materials placed in the drifts to support the waste package (the waste package supports and inverts).

The model components related to the third attribute—limiting radionuclide mobilization and release from the EBS—include all of the above components plus seepage into the waste package, in-package chemistry, cladding degradation, colloid formation and stability, waste form degradation, and transport within the waste package. Together, these components lead to a determination of the spatial and temporal distribution of the mass of radioactive wastes released from the waste packages. Each component depends on the thermal, hydrologic, and geochemical conditions inside the waste package, which change with time.

The model components related to the fourth attribute of potential repository performance—slow transport of radionuclides away from the EBS—include all of the above components plus radionuclide transport through the EBS, the UZ, and the SZ; dilution from pumping; and radionuclide transport in the biosphere. Together, these components determine the spatial and temporal variation of radionuclide concentrations in groundwater. The groundwater concentration ultimately yields the mass of radionuclides that may be ingested or inhaled by individuals exposed to that groundwater, which in turn causes a level of radiological dose or risk associated with that potential exposure. Radionuclide transport may either be by advection (radionuclide movement that occurs with the bulk movement of the groundwater) or diffusion (radionuclide movement that occurs because of a concentration gradient). The concentration depends on both the mass release rate of the radionuclides as well as the volumetric flow of water along the different pathways in the different components. If the volumetric flow of water from the pumping well is greater than the volumetric flow in which the radionuclides are contained, then dilution of radionuclide concentrations can occur at the pumping well. The volume to be used in the TSPA-SR is based on water usage for the critical group, as defined by the proposed regulation.

Each of these key attributes and TSPA model components are used to evaluate the nominal performance of the potential Yucca Mountain repository system. These components describe the FEPs that are expected to occur throughout the period of interest (i.e., the expected FEPs). The FEPs that have a low (less than 1.0) probability of occurring over the period of interest (i.e., the disruptive FEPs), are considered in the disruptive event scenario class that is analyzed both separately and in combination with the nominal case. Human intrusion is analyzed separately (see Section 4.4) according to the stylized case defined in the proposed regulations.

2.1.3 Conceptual Description of Processes Relevant to an Evaluation of Postclosure Performance

The TSPA is an analysis of the long-term behavior of the repository system and the uncertainty in the analysis of that behavior. Before discussing how the analysis is performed (see Section 2.2), it is important to describe what is being analyzed. To describe what is being analyzed, it is necessary to describe the overall potential repository system and the components relevant to the evaluation of the repository system behavior.

The major components to be considered in the assessment of system performance and the relationship of those components to the repository safety strategy were presented in the previous sections. Described in this section are the key concepts of how the potential repository system is intended to work.

The basic principle of the potential Yucca Mountain repository safety strategy is to keep water away from the wastes. If water does contact the wastes, then the other principle of the safety strategy is to minimize the release rate of the radioactivity from the engineered barriers and reduce the concentration of any dissolved radionuclides as they migrate from the potential repository. The discussion that follows focuses on the small group of radionuclides that are mobile in the Yucca Mountain environment. Other radionuclides that either are very insoluble and/or highly retarded in the Yucca Mountain environment pose little risk to the environment.

Because the potential repository is approximately 300 m beneath the land surface and the wastes are solids (with minor gaseous constituents), the primary means for the radioactive constituents of the wastes to reach the biosphere, and ultimately humans, is along groundwater pathways. The wastes pose minimal risks to humans unless all of the following events occur:

- Waste forms are exposed to water.
- Radionuclides within these waste forms are dissolved in the water.
- Dissolved radionuclides are transported with the water.

- Radionuclide-containing water is discharged, either naturally or at a pumping well, from the aquifer.

- Humans or any part of the food chain uses this water.

If water is kept away from the wastes, the wastes pose little or no threat to humans.

The presence of water is of primary concern as it contacts the waste and as any dissolved radionuclides migrate within the groundwater to expose humans to the potential effects of radiation. One of the reasons for the primary issue being related to aqueous processes is that in the TSPA-SR, the performance measure of concern is dose to individuals. Although gaseous transport of some radionuclides (notably ^{129}I and ^{14}C) can occur, doses attributed to these release and transport mechanisms are expected to be insignificant. In following the water movement through Yucca Mountain, the major components and processes affecting the long-term isolation of radioactive wastes in the potential Yucca Mountain repository system are described. Also, this section depicts how the repository system is intended to work and provides a series of illustrations that picture the basic concepts that will be quantified in the TSPA.

In addition to tracking the movement of water through the repository system, the following discussion addresses a range of spatial and temporal scales. Being explicit in the definition of the scale being used is important because processes that might be explained at a spatial scale of kilometers must also be discussed at the scale of millimeters. Also, although time scales on the order of days and years are familiar concepts, it is sometimes difficult to extrapolate to the thousands or tens of thousands of years of importance in geologic systems. The discussion has been divided into six topics:

- Water movement in the unsaturated rocks above the potential repository

- Water and water vapor movement around the repository drifts

- Water movement within the EBS

- Water movement and radionuclide migration out of the EBS

- Water movement and radionuclide migration through the unsaturated tuffs below the potential repository

- Water movement and radionuclide migration through the SZ aquifers and biosphere.

Each of these areas is discussed below.

2.1.3.1 Water Movement in the Unsaturated Tuffs above the Potential Repository

Figure 2.1-11 illustrates the key concepts associated with water movement in the UZ at Yucca Mountain. Water at the repository horizon in the UZ at Yucca Mountain has as its source precipitation at the surface. This precipitation occurs as rainfall and snow and varies over time and space. The spatial variability is defined by precipitation being generally higher at higher elevations, such as along the crest of Yucca Mountain, and lower at lower elevations. The temporal variability is characterized by most of the precipitation occurring in the winter months or during brief summer thunderstorms, with the precipitation being higher during El Niño years. Because of long-term (thousands of years) climatic variations, the average precipitation in southern Nevada is expected to increase from current conditions. These long-term, transient precipitation changes may be affected by human-induced changes.

A significant fraction of the rainfall and snowmelt on the surface of Yucca Mountain either runs off into the washes that bisect the mountain, evaporates from the surface, or transpires from the native plants in the area. The remaining water continues downward through the soil horizon and eventually infiltrates into the rock. The net amount of total precipitation that infiltrates is called net infiltration. The net infiltration varies with space and time. The spatial variability is caused by variations in precipitation, soil conditions (permeability, thickness, and antecedent water content), geographic conditions (slope angle and slope direction), and vegetation conditions. The temporal variability is caused by the variability in precipitation.

The net infiltration of water moves downward through the UZ, driven primarily by gravity. In the UZ, this downward movement of water is called percolation flux to distinguish it from infiltration, or movement of water in the soil horizon. Some lateral diversion of water occurs as it moves downward from the soil horizon through the UZ. This lateral diversion is caused by the eastward dip of the geologic strata and the heterogeneities in the rock because of the different welded and nonwelded tuffaceous lithologic units between the surface and the potential repository. Although the water may be spatially and temporally distributed at depth, this distribution is generally a subdued reflection of the infiltration distribution at the surface because gravity drainage drives the groundwater flow system in the UZ (CRWMS M&O 2000 [145774]).

Water movement or flux in the unsaturated, fractured tuffs occurs in the matrix and the fractures of the rock. Generally, the welded tuff layers have more of the total flux within the fractures because the permeability of the matrix is low, while the nonwelded lithologic layers have more of the total flux within the matrix. Capillary forces tend to cause the water to move from the fractures, which are characterized as having a low suction, into the matrix, which has a high suction. This process is called matrix imbibition. The process is more prevalent in rock units with lower matrix saturation (e.g., the Tiva Canyon welded unit) and less significant when the matrix saturation is higher (e.g., the Topopah Spring welded units) or the fracture spacing is large (e.g., the Paintbrush non-welded unit) (CRWMS M&O 2000 [145774]).

2.1.3.2 Water and Water Vapor Movement around the Potential Repository Drifts

Figure 2.1-12 illustrates the key concepts associated with water movement around the repository drifts after waste emplacement at Yucca Mountain. Without heat-producing wastes in the drifts, the water in the unsaturated rocks around the repository drifts will tend to stay in the rocks and flow around the drifts rather than drip into the drifts. Water stays in the rocks because the rocks' capillary forces, including the fractures that contain most of the water flux, are greater than the gravitational forces required for causing a seep unless the fractures are almost fully saturated (see Section 3.2).

The characteristics of the rock around the potential repository openings may change with time. The fracture permeability could increase because of mechanical stress relaxation following the construction of the repository drifts and ultimately the collapse of the drifts. The fracture permeability may also change due to rock thermal expansion and mineral precipitation. The capillary suction of the fractures could either increase or decrease because of these same processes. However, these changes are expected to be within the range of natural variability existing before construction of the facility. The net amount of seepage and the fraction of the potential repository area in which seepage is expected to occur are important factors in the overall performance assessment because they determine the likelihood that individual waste packages will be contacted by seepage water (see Section 3.1).

Water seepage from the rock into the drifts will be affected during the operational phase of the facility by the ventilation of the potential repository. The ventilation will take moisture from the drifts and the rock in the form of water vapor.

Following waste emplacement, the heat generated by radionuclide decay will drive moisture in the rock away from the heat source, i.e., away from the spent nuclear fuel containers in drifts. This water will recondense in areas of lower temperature above, below, and between the hotter drifts. During the first few hundreds of years, there will be little or no seepage of liquid water into the drifts, because the water is generally being driven away. During this time, water in the drifts is in the form of water vapor or humid air. During the early periods, the RH in the drifts is reduced, but the RH eventually returns to close to 100 percent, as in ambient unventilated rock openings.

The distribution of liquid water and humid air within and around the repository drifts is variable in space and time. The spatial variability is caused by heterogeneity in the rock properties and variations in the ambient percolation flux. In addition, differences in the thermal output of different waste packages cause a range of thermal-hydrologic conditions in the potential repository. For example, cooler regions are expected along the edges of the potential repository and near low-thermal output waste packages. The temporal variability in water movement around the drifts is caused in the short-term by the thermal output of the wastes that eventually declines to minimal values (hundreds of years of drying and several thousand years of cooling and rewetting). In the long-term, the water movement is controlled by the climatic variability discussed in Section 2.1.3.1.

2.1.3.3 Water Movement within the Engineered Barrier System

Figure 2.1-13 illustrates the key concepts associated with water movement within the drifts and the contact of water with the waste package. Note that Figure 2.1-13 is only illustrative for waste packages experiencing seeps, which is expected to be a small fraction of the total number of waste packages. Water in aqueous or vapor form can cause slow degradation of the metallic waste package barrier. The dominant degradation mode of the outer Alloy-22 is by aqueous or humid air corrosion. At low relative humidities and in the absence of liquid water, the corrosion rate of Alloy-22 is generally low; however, at high relative humidities or in the presence of liquid water, this metal can corrode, albeit relatively slowly, exposing the inner structural liner composed of stainless steel.

The Alloy-22 layer generally degrades only in the presence of liquid water, i.e., when water drips directly on the waste package. Alloy-22 is generally immune to localized pitting and crevice corrosion and most failures will be by slow general corrosion, or by SCC.

The degradation rates of the stainless steel and high-nickel alloys are also affected by the temperature of the waste package surface, the chemistry of the water in contact with the waste package surface, the mechanical stress, and the degradation characteristics of the metals themselves. Because these environmental parameters are spatially variable and because the metal fabrication is variable, the waste package degradation is also expected to be variable in space and time. Not all of the waste packages are expected to be breached at the same time. In addition, the temporal variability in degradation rate implies that, once a single opening exists through the metallic waste package, it takes additional time before more openings penetrate through the waste package.

Until the same waste package has been sufficiently degraded to allow an opening to form through the two metallic barriers, there is no potential for water to come into contact with the wastes. During this period, the wastes are completely contained within the waste package. Once an opening exists, some of the seepage water falling on the waste package could enter the package.

2.1.3.4 Water Movement and Radionuclide Migration out of the Engineered Barrier System

Figure 2.1-14 illustrates the key concepts associated with water moving into the waste package and contacting the waste form. Also illustrated is migration through the EBS, of radionuclides that may exist as either dissolved species or adsorbed onto colloidal particles.

After the waste package has been breached, water may enter the waste package and contact the waste forms. For commercial spent nuclear fuel and many types of DOE-owned spent nuclear fuel, this water will first come into contact with the Zircaloy cladding around the spent nuclear fuel pellets. Zircaloy is a highly corrosion-resistant metal alloy; it is even more resistant to the effects of generalized or localized corrosion than Alloy-22. (Although Zircaloy has been considered as a candidate waste package material, the high cost of this alloy precludes its use in the site recommendation reference design.) Zircaloy will eventually degrade with time under several different mechanisms, but for a certain period it will prevent water from directly contacting the wastes. For high-level radioactive waste, a stainless-steel pour canister surrounds the waste glass. For much of the DOE-owned spent nuclear fuel, the wastes are contained within aluminum or Zircaloy cladding that is not fully intact, which in turn are planned to be placed in stainless steel or other metal alloy canisters. Aluminum and stainless steel are not as corrosion resistant as Zircaloy. When the material surrounding the actual waste form has degraded, the wastes are exposed to the environment inside the waste package and liquid water can contact a portion of the exposed waste. If water contacts the waste form, the radionuclides can dissolve in the water. Some radionuclides are highly soluble in water, while others are very insoluble in the water that is likely to contact the waste. Some radionuclides may attach to very small colloids that are mobile in the water.

When radionuclides are released from the solid waste form into the mobile liquid phase, they are available for transport. The transport mechanism depends on the distribution of water on the waste form surface and between the waste form surface and the outer edge of the degraded waste package. If water has dripped into the waste package, it is possible that advective transport of radionuclides to the edge of the waste package could occur. If the water has not dripped into the waste package, then a continuous, interconnected water film along which radionuclides may diffuse is required.

After radionuclides are transported through the degraded internal material of the waste package to the edge of the waste package, they may be transported through the degraded invert materials beneath the waste package. Radionuclides may be transported through the degraded invert by either moving water if there is seepage water, or diffusion through the pores of the invert materials. The radionuclides transported through the degraded invert are ultimately released to the tuff rock units to be transported in the UZ below the potential repository and ultimately to the SZ.

The rate at which radionuclides are released and transported from the potential repository depends on the following:

- Degradation rate of the engineered barriers
- Dissolution rate of the waste forms
- Form of the released radionuclides
- Solubility of the aqueous radionuclides
- Rate of water movement and volume of water that flows or diffuses through the engineered barriers.

2.1.3.5 Water Movement and Radionuclide Migration through the Unsaturated Tuffs below the Potential Repository

Figure 2.1-15 illustrates the key concepts associated with water movement in the unsaturated rocks beneath the potential repository and the migration of radionuclides in these rocks. After the dissolved or colloidal radionuclides are released into the unsaturated tuffs beneath the potential repository, they may be transported with the water to the water table. The rate at which these radionuclides are transported to the water table is a function of the following:

- Percolation flux in the unsaturated tuffs
- Distribution of the percolation flux between fractures and matrix
- Effective velocity of the groundwater within the fractured rocks
- Adsorption of radionuclides within the rock.

Because each of these characteristics of the natural environment is variable in space and time, radionuclide transport is also variable. Part of the temporal variability relates to long-term climatic changes that not only change the percolation flux through the system but also cause the water table beneath Yucca Mountain to rise (in the case of wetter climates) or fall (in the case of drier climates).

2.1.3.6 Water Movement and Radionuclide Migration through the Saturated Zone Aquifers and Biosphere

Radionuclides that are transported through the UZ are released to the saturated aquifers beneath the potential repository. Figure 2.1-16 illustrates the key concepts associated with water movement in the saturated aquifers beneath and downgradient from the Yucca Mountain site and the migration of radionuclides in these aquifers. Also illustrated are the pathways by which any dissolved radionuclides may come into contact with humans.

When the radionuclides reach the SZ, they will be transported laterally within the SZ. The general direction of groundwater flow in the SZ is to the southeast, and then possibly to the south and southwest. The concentration of the radionuclides in the aquifers at any point downgradient from the potential repository is a function of the following:

- Radionuclide concentrations in the water that enters the SZ
- Dispersion of these radionuclides as they are transported
- Adsorption of these radionuclides on the mineral surfaces along the flow path.

The time for radionuclides to reach any specified point downgradient from the potential repository, such as the 20-km point chosen for evaluating the system performance, depends primarily on the groundwater velocity and the retardation of radionuclides that may sorb on the mineral surfaces within the tuff or alluvial aquifers.

There is minimal risk associated with radionuclide releases as long as the concentration of radionuclides in water that is pumped from the aquifers downgradient from the potential repository is sufficiently low. Should radionuclides reach a location downgradient from the potential repository where water is pumped from the aquifer, the potential exists for radionuclides to come into contact with humans through biosphere pathways. The principal biosphere pathways to humans consist of the following:

- Direct consumption of water containing dissolved radionuclides

- Consumption of crops produced using water containing dissolved radionuclides

- Watering of livestock with contaminated water and/or feeding of livestock with contaminated crops, and the subsequent consumption of meat or milk

- Direct exposure to contaminated soil

- Inhalation of dust that may contain attached radionuclides.

The previous discussion outlined how the various components of the potential Yucca Mountain repository system fit together to describe how the system is intended to work. The general conceptual aspects of each key component and processes that affect the expected behavior of the repository system have been described. The next section (Section 2.2) describes the approach used to assemble the representations of the individual components into a description of the entire system. The details of each of the component models used in the TSPA and the scientific bases for these models are presented in Section 3 of this document, and in Section 6 of the *Total System Performance Assessment (TSPA) Model for Site Recommendation* (CRWMS M&O 2000 [148384]), as well as in the process model reports and analysis model reports.

2.2 METHODOLOGY

This section presents an overview of the method for mathematical and numerical modeling of each process and component introduced in Section 2.1, including their uncertainty, and the approach for combining them into an overall model and computer code. The overview includes discussions about information flow between the models (Section 2.2.1) and the computer code architecture that facilitates the information flow (Section 2.2.2). This section also provides a road map showing how to recouple the component models into one integral whole, as well as how to reassemble the analyzed pieces and pass information between them to develop reasonable assessments of overall system performance. The method for correctly coupling the component models to make robust predictions of repository behavior is composed of the basic activities outlined in Section 1.6.

2.2.1 Information Flow between Component Models

A stylized conceptualization of the TSPA-SR model hierarchy and information flow is shown in Figures 1.1-1 and 2.2-1. These figures indicate a continuum of information and models, from the most basic, detailed level to the level of the total system model. The data and associated conceptual and process-level models rest at the base of the pyramid (Figure 1.1-1). These process-level models may be simplified or abstracted ("abstraction" is used to connote the development of a simplified mathematical and/or numerical model that reproduces and bounds the results of an underlying detailed process model), if necessary, because of computational constraints or lack of information. Much of the modeling of the potential repository (and its components) is complex, uncertain, and variable, involving a variety of coupled processes (thermal-hydrologic-chemical and thermal-hydrologic-mechanical) operating in three spatial dimensions on a variety of different materials (e.g., fuel rods, waste packages, invert, and host rock) and changing over time. For these reasons, it is often necessary to make some simplifications to the detailed process-level models. The need for simplification is particularly evident in the TSPA, which has a significant component of probabilistic risk analysis.

The general approach of using probabilistic risk analysis is appropriate because of the inherent uncertainties in predicting physical behavior many thousands of years into the future in a geologic system with properties that can never be fully characterized deterministically. Because of the large number of uncertain parameters in the component TSPA models, probabilistic risk analysis involves a Monte Carlo method of multiple realizations of system behavior, which requires significant computational resources. For this reason, and because the lack of certain data makes some detailed models difficult to quantify, model abstractions are often employed. The abstracted performance assessment models may have a one-to-one correspondence with the detailed process-level models or may represent a combined subsystem model covering several aspects of the overall system. The performance assessment models form the components of the overall TSPA model at the top of the pyramid. Total system model simulations can then be performed in the computationally intensive probabilistic framework necessitated by a Monte Carlo approach to performance assessments.

For this model simplification process, there are two key factors in accurately representing the performance of the overall system. First, information and assumptions passed up the model pyramid must be consistent. For example, an infiltration flux used to generate liquid flow fields from the detailed process model for the UZ must be used in all subsequent analyses based on those particular flow fields. The same flux must be used when calculating seepage flux in the abstracted seepage subsystem model (Section 3.2) and when calculating thermal hydrologic response (temperature and relative humidity [RH]) in the near-field environment (Section 3.3). Second, the parameters that most affect performance in the detailed process models must be appropriately represented in the subsequent subsystem and total system models, including the appropriate uncertainty range of the parameters.

A key feature of the methodology is the approach utilized to pass uncertainty at one level to uncertainty at another level. Transfer of uncertainty must go in both directions, from bottom up and from top down. When analyzing uncertainty at the bottom levels (data, conceptual models, and process models), the analyses look at the effect of uncertain parameters on surrogate or subsystem performance measures, such as the amount of fracture flow in the UZ. The sensitivity of the surrogate measure to component model uncertainty is then used to decide whether to carry this uncertainty through to the total system analyses. However, sometimes important parameters at the subsystem level prove to be unimportant at the overall system level, and this information is then passed down the pyramid to indicate the relative unimportance of collecting more physical data about this parameter.

Traceability of data transfer among models and quality assurance of the data are very important aspects of the information flow process. The Process Model Reports and Analysis Model Reports, which support the TSPA results presented here, explicitly identify the sources and status of data, computer codes, and computer input and output files used in the Site Recommendation. Following prescribed procedures, the DOE is reviewing the data, assumptions, computer codes, and information used in the TSPA analyses to ensure the models are valid, defensible, and appropriate. To be fully qualified, there must be clear documentation that the TSPA models are supported by qualified data, and the numerical models and computer codes are documented and appropriately controlled.

Figure 2.2-1 is a more detailed, but still simplified, look at information flow among the component models: UZ flow (and seepage), thermal hydrology, engineered barrier system geochemistry, waste package and drip shield degradation, waste form degradation, EBS transport, UZ transport, SZ flow and transport, biosphere, and volcanism. It does not show all of the couplings among TSPA-SR component models but does illustrate major model connections, abstractions, and information feeds.

The information transfer between component models is activated in several ways. One approach is use of a "response surface," which means a multidimensional table of output from one model to be used as input in another model. When interpolating among points in the table, linearity is generally assumed. Usually a response surface has more than one independent variable (e.g., both time and percolation flux). However, in the usage in Figure 2.2-1, occasionally time is the only independent variable, and the data are provided directly "as is" to the next model, so no interpolation is required.

Figures 2.2-2a and 2.2-2b give a more detailed description of information flow in the TSPA-SR, showing the principal pieces of information passed between the various component models. Figure 2.2-2a shows the overall system, while Figure 2.2-2b shows the details of the engineered barrier system. These details of information flow are explained in greater depth in the discussion of the TSPA-SR code architecture in Section 2.2.2. The conceptual and experimental basis for this depiction of information flow is given in detail in Section 3. For example, the division of the repository horizon into five bins based on thermal hydrologic response and infiltration flux is discussed in Section 3.3; the division of the SZ water table into four regions, unrelated to the five repository bins (based on stratigraphy and other factors), is discussed in Section 3.8.

The decoupling of the physical-chemical processes into component models, shown in Figures 2.2-1, 2.2-2a and 2.2-2b, is facilitated by a natural division of the potential repository system into a series of sequentially linked spatial domains (e.g., the waste package, emplacement drift, host rock near the drift, UZ between the drift and the water table, SZ, and biosphere). This division works best from the standpoint of radionuclide transport, which is the primary consideration of the TSPA models. The TSPA-SR model architecture and information flow becomes, therefore, a sequential calculation in which each spatially based transport model may be run in succession, with output as "mass versus time" from an upstream spatial domain serving as the input of mass versus time for the spatial domain immediately downstream.

An additional complexity to this approach to transport is brought on by the inclusion of the disruptive event, volcanism, and its effects on the system. The systematic transport in the nominal system is disrupted or disconnected when volcanic events are included in the model. However, this is accommodated in the overall information flow by integrating the volcanism effects into the nominal model.

2.2.2 Code Architecture

The overall information flow, discussed in Section 2.2.1, forms the basis for the architecture of the TSPA-SR computer code. The executive driver program, or integrating shell, that links all the various component codes is GoldSim (Golder Associates 2000 [151202]). It is a probabilistic sampling program that ties all the component models, codes, and response surfaces together in a coherent structure that allows for consistent parameter sampling among the component models. The GoldSim program is used to conduct either single-realization runs of the entire system or multirealization runs of the system. The latter realizations yield a probability distribution of dose rate in the biosphere that shows uncertainty in dose rate based on uncertainty in all the component models.

Because of the need to conduct multiple realizations of the total system behavior, GoldSim is generally designed to model various components in a simplified fashion. However, the current version of GoldSim has some very useful features, such as cells and environments, that allow certain processes to be modeled in reasonable detail. The GoldSim program is also very flexible in representing various component processes in the total system model. The four ways that component models may be coupled into GoldSim, from most complex to least complex, include the following:

- External function calls to detailed process software codes (e.g., UZ transport software or waste package degradation software)
- Cells, which are basically equilibrium batch reactors that, linked in series, can provide a reasonably accurate description of transport through selected parts of the system (e.g., the engineered barrier system)
- Response surfaces, which take the form of multidimensional tables representing the results of modeling with detailed process models before running the TSPA code (e.g., thermal hydrology input)
- Functional or stochastic representations of a component model built directly into the GoldSim architecture.

The method used for each TSPA-SR component model is described briefly below and in greater detail in the corresponding parts of Section 3.

As described above for the third coupling method, much of the computational work that goes into the TSPA-SR model is done outside of GoldSim, before running the actual total system computations. For example, the UZ flow fields were computed using Transport of Unsaturated Groundwater and Heat (TOUGH2) (Pruess 1991 [100413]), a three-dimensional, finite-volume numerical simulator representing the entire UZ model domain (for the dual-permeability model). Other component models that were also run using computer codes outside of GoldSim include drift scale thermal hydrology (NUFT), the biosphere (GENII-S), in-drift and in-package chemistry (EQ3/6), and SZ radionuclide transport (FEHM). The results of these detailed process-level runs were provided as multidimensional tables that are read into GoldSim at run time. Examples of these multidimensional tables include (1) liquid flux and velocity fields for the UZ as a function of spatial position, time, and uncertain parameters such as infiltration flux and (2) temperature versus time.

Figure 2.2-3, in conjunction with Figure 2.2-1, provides a better understanding of the TSPA-SR code architecture (i.e., the actual computer codes used and the connections [information transfer] between codes). It includes both the codes run before the GoldSim program and those run in real time that are coupled to (external function calls), or within (cells and tables), the GoldSim program. Based on the schematic information transfer shown in Figure 2.2-3, some response surfaces generated by codes external to GoldSim only provide data to other codes external to GoldSim. Other response surfaces, such as liquid saturation, temperature, and seepage flux, will provide data directly into GoldSim as response surfaces that influence such things as waste form degradation rates. Not all couplings or all models are shown in Figure 2.2-3, (e.g., in-drift geochemical modeling is too complex to show all of its aspects in this figure) (Section 3.3).

Coupling of the various models is affected by the climate model, which impacts almost all the other models in one way or another, because it alters water flow throughout the system. The climate is assumed to shift in a series of step changes between three different climate states in the first 10,000 years: present-day climate, monsoon climate (about twice the precipitation of the dry climate), and glacial transition climate (colder than monsoon but similar precipitation). These climate shifts are implemented as a series of steady-state flow fields in the UZ and SZ (including changes in the water table elevation). Within the GoldSim program, these shifts require coordination among the coupled submodels because they must all simultaneously change to the appropriate climate state.

In general terms, the coding methods and couplings to be used for the major components are discussed below.

Mountain Scale, Unsaturated Zone Flow–This process is modeled directly with the three-dimensional, site-scale, UZ flow model (Section 3.2) developed by the YMP, using a volume-centered, integral-finite-difference, numerical flow simulator, called TOUGH2 (Pruess 1991 [100413]). Steady-state flow is assumed, and three-dimensional flow fields are generated for three different infiltration boundary conditions, three different climate states, and several values of rock properties. These "pregenerated" flow fields (i.e., developed externally and before the GoldSim simulations) are then placed in a library of files to be read by the finite element heat and mass (FEHM) code for UZ transport during the real time GoldSim simulations. Fracture and matrix liquid fluxes, along with liquid saturation, are passed to FEHM in these tables. To generate the library of flow fields, an inverse model, ITOUGH2 (Finsterle et al. 1996 [100393]) is used to calibrate the model-predicted ambient liquid saturations and other properties to measured liquid saturations and other properties in the matrix. This calibration is done when generating the flow fields for the three different infiltration conditions and the different fracture properties at present-day climate conditions. For future-climate conditions, flow fields are generated based on the present—day climate calibrations. Climate change is modeled within TSPA-SR UZ calculations by assuming a series of step changes in boundary conditions, meaning that different flow fields are provided at the appropriate time with the assumption of instantaneous pressure equilibrium. Based on the particular history of climate changes sampled by the TSPA model at the beginning of a given realization, the UZ flow field library is interrogated for a different flow field every time during the simulation that a step change is indicated. This change in a flow field is assumed to apply instantaneously to the transport model. The validity of this approach is discussed briefly in Section 3.7. The UZ flow fields are also provided to the TOUGH2 drift scale seepage models, to the SZ models, and to the engineered barrier system transport models. UZ hydrologic properties are passed to the drift scale, thermal hydrology model.

Seepage of Water into Emplacement Drifts (i.e., Drift Scale, Unsaturated Zone Flow)–This process is also modeled externally (Section 3.2) before the GoldSim simulations using TOUGH2 on a finely discretized grid around the drift and then abstracted for use in GoldSim. Simulations are conducted over a heterogeneous fracture permeability field (based on permeability measurements in the Exploratory Studies Facility) at a variety of percolation rates (from the mountain scale UZ flow model), and a variety of mean values and standard deviations for the fracture permeability distribution and the fracture "alpha" distribution (Section 3.2). These simulations become an uncertain response surface of seepage flux into the drift as a function of percolation flux and a response surface of the number of packages that are dripped on (by seeps) as a function of percolation flux. During the thermal pulse, the perturbed (increased) percolation flux is used as input to the response surface (increasing seepage), but no credit is taken for seepage reductions due to either evaporation of percolation flux entering the near-drift region or imbibition of percolation flux into dry pores in the same region; this is a conservative treatment of perturbed seepage.

Drift Scale, Unsaturated Zone Thermal Hydrology–This process is modeled with the finite-difference computer program NUFT (Nitao 1998 [100474]) in one, two, and three dimensions before the GoldSim simulations. The drift scale thermal-hydrology model uses a complicated set of embedded abstractions at different levels of spatial and process detail (e.g., conduction only versus conduction and convection), as described in Section 3.3. Outputs include:

- Waste package surface temperature and waste package surface RH for seven different package types within discrete environments. These values are provided to drip shield, waste package, and waste form models in GoldSim.

- Average waste form temperature and liquid saturation in the invert in each of the five repository level bins. Waste form surface temperature is actually assumed to be equal to the waste package surface temperature. These temperature and saturation values are provided to the waste form degradation and EBS transport models in the GoldSim program.

- Average drift wall temperature, RH, and liquid saturation in the invert in the potential repository. These values are provided to the EBS environment models. The outputs are in the form of response surfaces or multidimensional tables.

- Perturbed percolation flux above the drift. These values are used as inputs to the seepage response surface.

Engineered Barrier System Environment (i.e., Drift Scale Thermal Chemistry)–This process is modeled in the base case calculations outside of the GoldSim simulations by assuming a certain scenario for water flow through the drift and the types of materials the water contacts. Equilibrium batch-reaction calculations with EQ3/6 (Wolery 1992 [100836]; Wolery and Daveler 1992 [100097]) are performed at several places within the drift and then the output from one batch calculation is passed to the input of the next batch calculation at a different spatial location (Section 3.3). Output is a response surface of various chemical composition parameters. These values are provided to GoldSim directly as input tables for the waste form degradation and colloid models within GoldSim.

Drip Shield and Waste Package Degradation–This process is modeled within GoldSim using the WAPDEG computer code (CRWMS M&O 1998 [130755]), which includes corrosion-rate variability both on a given package and from package to package (Section 3.4). The code is linked to GoldSim and runs at the start of each realization to provide output in the form of several tables of the cumulative number of package failures per time, average patch area per package versus time, average crack area per package versus time, and average pit area per package versus time.

Cladding Degradation by Physical-Chemical Processes such as Creep Rupture–This process is modeled within GoldSim using functional relationships (and leads to a percentage value of failed cladding versus time exposed waste form area versus time [Section 3.5]). Other cladding degradation modes such as mechanical failure are also modeled within the GoldSim program. (CRWMS M&O 2000 [147210]) The major inputs to the cladding process model are measured characteristics (examples: oxide thickness, fission gas release) of commercial spent fuel which were collected and fit with first or second order equations. The input parameters for the abstraction are 1) peak waste package surface temperature, 2) water ingression rate into the waste package, and 3) temperature and chemical composition of the water inside the waste package.

Waste Form Degradation–This process is modeled as an equation within the GoldSim program using empirical degradation rate formulas developed from available data and experiments for the three different waste form types: CSNF, DSNF, and high-level radioactive waste (HWL) (Section 3.5). Output from the waste form degradation model is the mass of waste form exposed per time and the volume of water in contact with this waste form versus time, which is used directly in the GoldSim waste form cells. There are a variety of these waste form cells in the GoldSim program, corresponding to three different waste form types and several different seepage scenarios. The amount of inventory that can ultimately enter each waste form cell is a linear function of the number of packages emplaced in each inventory, seepage, and thermal hydrologic environment. There are 45 such environments, representing the product of 5 thermal-hydrologic regions, 3 inventory types, and 3 seepage environments. The entire waste inventory is composed of hundreds of different radionuclides. Of these hundreds, 39 were found to be present in sufficient quantity to warrant modeling in the near-field model components of the TSPA. Of these 39, only the 26 most important radionuclides—most important from the standpoint of delivering, or potentially delivering, the greatest dose rate at the biosphere location 20km downgradient of the repository—were tracked through all the system models. See Section 3.5 for details on the radionuclide inventory.

Engineered Barrier System Transport–This process is modeled directly within GoldSim at run time using the GoldSim cells algorithm. The modeling is based on an idealized representation (basically a linked series of equilibrium batch reactors) of drip shield, waste package, waste form, and invert, and how radionuclides move through them via diffusion and advection both as solutes and as colloids (Section 3.6). Output from EBS transport is radionuclide mass flux (for each of the modeled radionuclides) at each time step, passed during the GoldSim simulations to the directly coupled, three-dimensional, dual-permeability, FEHM particle tracker (Zyvoloski et al. 1995 [100528]) used for UZ transport. As shown in Figure 2.2-2a, the repository area is divided into five bins based on infiltration. The mass releases from these five source-term groups enter the grid blocks in FEHM that reside within the corresponding areas of the regions. The number of grid blocks receiving release is dependent on the number of packages failed. A key part of EBS transport is waste form or radionuclide mobilization, which is a direct function of both seepage flux and radionuclide solubility in the groundwater. Solubility for the various radionuclides is input directly into the GoldSim program in various forms (e.g., probability density functions, point values, and explicit functions). (See Section 3.5) Several types of colloid types are also modeled in the EBS transport component utilizing GoldSim functions. (See Sections 3.5 and 3.6).

Unsaturated Zone Transport–This process is modeled at run time using the directly coupled, three-dimensional, dual-permeability, finite-element code FEHM, which is accessed as an external function by the GoldSim program. Flow fields and property sets are accessed directly by FEHM from table files residing in the TSPA-SR controlled database. The UZ transport model is based on the UZ flow model and uses the same flow fields (generated by the TOUGH2 UZ flow code) and the same climate states. As with UZ flow, a dual-permeability model is assumed, and transport is modeled with the FEHM particle tracker in three dimensions. The FEHM particle tracker transports particles on the same dual-permeability TOUGH2 spatial grid as used in the flow model (using the same material properties, infiltration, and liquid saturation). When the climate shifts, a new TOUGH2 flow field is provided from the run-time file directory, and the particles are assumed to be instantly traveling with the new velocities. In addition, for multirealization runs, a matrix of uncertain UZ transport property values is created before simulation time by the GoldSim program and then accessed by FEHM during the simulations. The FEHM code steps through the uncertainty matrix row by row, where each row represents one realization of the uncertain UZ transport parameters, including K_ds (K_d is the measure of the partitioning of the mass of a given radionuclide sorbed or residing on the immobile rock phase to the mass dissolved in the aqueous phase) for each radionuclide, matrix diffusion coefficients, dispersivity, and K_c (K_c is the measure of the partitioning of the mass of a given radionuclide sorbed or residing on colloidal particles to the mass dissolved in the aqueous phase) values. Output from the FEHM code at each time step is mass flux from the fractures and matrix at the water table. The location of these output grid points is a vertical function of the climate state, increasing in elevation for wetter climates. The fracture and matrix mass fluxes from FEHM are combined appropriately for each of the 4 SZ capture zones in 4 GoldSim mixing cells and then fed to the SZ convolution integral SZ_CONVOLUTE at each GoldSim time step.

Saturated Zone Transport–This process is modeled using two models of SZ flow and transport (Section 3.8). A three-dimensional process level model (FEHM) is used to calculate, in detail, the transport of individual radionuclides important to dose. A one-dimensional flow tube model implemented in GoldSim is used to calculate the transport of daughter radionuclides (radionuclides that form by the decay of other radionuclides) of lesser importance. The models extend from 4 source regions at the bottom of the repository at the water table to the 20 km distance downgradient. The three-dimensional flow and transport simulations are done outside the GoldSim program for each of the selected radionuclides over 100 realizations of uncertain SZ model parameters. These uncertain parameters include effective porosity in the tuff and alluvium, K_d in the tuff and alluvium, colloid K_c, longitudinal dispersivity, fraction of flow path in the alluvium, and dilution factor (which mimics transverse dispersivity). The choice of 4 source regions is based on (1) examination of the releases from the UZ to the SZ showing roughly 4 areas of radionuclide input, and (2) minimization of source regions because each requires approximately 800 more breakthrough curves. Output from the FEHM stream tube simulations is concentration versus time at 20 km for a constant mass release rate source term. These breakthrough curves reside in files in the GoldSim run time directory and are accessed when needed by the SZ_CONVOLUTE external function (which convolves, or integrates, the real source term with the pregenerated unit breakthrough curves) called by the GoldSim program.

Biosphere Transport–This process is modeled within TSPA calculations using biosphere dose conversion factors that convert SZ radionuclide concentration to individual radiation dose rate. The biosphere dose-conversion factors are developed outside the GoldSim program using a computer program named GENII-S (Leigh et al. 1993 [100464]). The factors are then entered as table values in the GoldSim front-end menus. These factors are multiplied by the concentrations in the SZ stream tubes to compute individual doses, which are the end product of the calculations.

Disruptive Events–Igneous activity (indirect and direct volcanic effects) is modeled as a separate scenario. Seismic activity is modeled in the cladding model. Indirect volcanism is modeled within the TSPA model. This scenario utilizes many aspects of the nominal scenario and simply overlays an intrusive event, as characterized by its probability and physical properties (e.g., number of waste packages damaged by intrusion, extent of damage to waste packages, etc). After these effects are incorporated to the model, releases are handled as in the nominal scenario. Direct volcanic effects (i.e., radionuclides carried by ash plumes from volcanic eruptions) are modeled using the code ASHPLUME (LaPlante and Poor 1997 [101079]) that is directly coupled to the TSPA model at run time.

Human Intrusion–This scenario is analyzed separately, consistent with the scenario defined by the proposed regulations. The model is developed within the TSPA model utilizing inherent functions for release and transport of radionuclides assuming various conditions for the breach of the waste package. (See Section 4.4).

2.2.3 Testing of Integrated Total System Performance Assessment-Site Recommendation Model

This section presents the testing of the integrated Total System Performance Assessment-Site Recommendation Model. The performance assessment has been carried out using the code: GoldSim, which includes some process models, such as WAPDEG and FEHM. Also, several sub-models have been used to derive "abstractions" of other processes not directly simulated in GoldSim. An overview of the all computer codes used in this study, including their verification is presented in Section 3.0 of *Total System Performance Assessment (TSPA) Model for Site Recommendation* (CRWMS M&O 2000 [148384]). Further details of those codes is available from the relevant AMRs, which are also cited in the same document. Moreover, the performance of GoldSim, and its verification and validation in respect of each of the different physical processes modeled therein, such as, climate, infiltration, in-drift thermo-hydrology, UZ flow, waste package degradation, in-package chemistry, EBS transport, UZ transport, SZ flow and transport, biosphere doses, have been discussed in detail in Section 6.3 of the document cited. Also, Section 6.5 of the cited document does provide more details of the integrated model testing being presented here. In what follows, the strategy for the verification of the integrated model, *given* that the GoldSim model and its component models and the supporting models have been already verified, is discussed.

The verification and testing of the integrated TSPA-SR model has been conducted in two phases. The two phases are described below.

Phase 1:

In this phase, the computer model refers to a digital rendering of the conceptual model of the true physical system viz., the YMP site. The verification thus relates to checking that all aspects of the conceptual model are correctly implemented in the construction of the input for the simulation code GoldSim.

Phase 2:

Verification in this phase is directed to ensure that the simulation code GoldSim provides correct results for a given input (model). This verification was undertaken with a focus on the complexity in the different simulated processes related to the natural barrier system and the EBS, and also with a focus on architecture or the structure of the code. Figure 2.2-4 illustrates the 2 phases of this verification scheme. Verification of the code input and verification of the code output for a given input provides assurance that the performance assessment results are correct as modeled.

2.2.3.1 Phase-1: Verification of the Total System Performance Assessment-Site Recommendation Model

The verification of the TSPA-SR model (i.e., specifically the input model for GoldSim) consisted of assuring that the input construction is in complete accord with the conceptual models of the different processes as developed in a series of relevant and applicable analysis model reports. The conceptual models provided in various analysis model reports were converted into corresponding segments of the model input, which was then integrated to become the TSPA-SR model.

Translation of the conceptual model to the input model for the TSPA-SR model was accomplished and all components of the conceptual model have been reviewed to ensure that they are incorporated into the input. This activity of checking the input construction is arranged in a tabular form. This tabular form lists the different elements of the conceptual models and records their manner of incorporation in the input (as a data element, a function or an external dynamically linked library (DLL) routine). This tabular form utilizes an independent review process involving the author of each analysis model report, to ensure that the conceptual model was correctly translated into the corresponding segment of the input files. Figure 2.2-5 illustrates this procedure.

2.2.3.2 Phase-2: Verification of GoldSim

Phase 1 verification provides assurance that the TSPA-SR model is in full conformity with the conceptual model of the YMP site. Phase 2 verification ensures that the GoldSim model provides the correct output for a given input model embodying the full-scale complexity of the YMP site.

GoldSim has passed through a series of tests by its developers to demonstrate that it performs its numerical and logical operations correctly (Golder Associates 1998 [100449]). Nevertheless, considering the complexity of the processes simulated in the natural barrier system and EBS at the YMP, many of which are handled via external routines (e.g., WAPDEG, SEEP, FEHM), and considering the fact that some of these routines derive their input from the output of another preceding routine(s), the need to validate the code performance under the full-scale complexity of a realistic YMP model is warranted. Phase 2 verification addresses the verification of GoldSim from this perspective.

The Phase 2 verification consisted of three stages. Figure 2.2-6 explains stages 1 and 2, and Figure 2.2-7 explains stage 3.

Stage 1: Data Elements and Functions–GoldSim can compute some functions with data elements employing the user-prescribed functions, which can depend upon the intermediate output (e.g., waste form dissolution rate) of another process model. For example, the calculation of the pH values for seepage water entering the waste package and the solubilities of the radionuclides are all computed based on algebraic expressions, using the current values of some geochemical/thermal parameters, as computed by process models in the near-field environment. Such internal direct computations of some model (intermediate) outputs are verified by hand calculation at selected times, taking the output of the appropriate upstream process model as called for. Numerous examples of such verifications are provided in *Total System Performance Assessment (TSPA) Model for Site Recommendation* (CRWMS M&O 2000 [148384], Section 6.3).

Stage 2: Dynamically Linked Library Routines–Besides the direct computations undertaken within GoldSim, major process simulations are performed via external routines (i.e., WAPDEG, FEHM). First, these routines are built as independent stand-alone codes and are verified. Second, they are incorporated into GoldSim as dynamically linked libraries. For the dynamically linked libraries, some data are transmitted from GoldSim through an argument list and other data are read from the data files, most of which are output from another process model within or outside GoldSim. The user also generates some data files read by a DLL through implementation of the applicable analysis model report for that process. The correctness of each of these types of inputs to a DLL was verified.

The verification of each individual process model, both as a stand-alone code and as a DLL in GoldSim, is being documented. (See for example, Verification Test Plan for WAPDEG [CRWMS M&O 1999 [149099]]).

Stage 3: Integrated Model Output Testing–When the full scale TSPA-SR model is implemented, where the inputs to a DLL are drawn from the outputs of another DLL, the final verification is done as follows.

The time-dependent inputs to a DLL are written to an output file of GoldSim, taking care to identify the DLL from where the data is printed. Those data are compared to the correct values of those input data, since they are known to be the outputs from another upstream dynamically linked library, which are also output from that dynamically linked library. This process ensures that the data transfers between the different process models are error-free. Since each DLL is validated individually under GoldSim, the verification of error-free data transfers between the models in GoldSim (when the integrated model is implemented) provides assurance that the output from GoldSim is correct, even for an input model which encompasses the full complexity of the conceptual model of the YMP site.

2.2.4 Treatment of Uncertainty in Total System Performance Assessment Analyses

2.2.4.1 Nature and Sources of Uncertainty

The assessment of long-term performance for the potential high-level radioactive waste repository at Yucca Mountain is a complex endeavor. It requires modeling various coupled hydrologic, geochemical, thermal, and/or mechanical processes taking place within the engineered and natural barriers over extended periods of time. In addition, the future evolution of the geologic and environmental conditions surrounding the disposal facility must also be considered, albeit in a somewhat stylized manner. Such integrated assessments of the future behavior of the disposal system are also complicated by uncertainties which arise due to incomplete understanding, limited information, and/or paucity of data. These uncertainties may be further categorized as follows:

- Scenario uncertainty
- Model uncertainty
- Parameter uncertainty and/or variability.

Scenario uncertainty stems from the fact that future evolution of geologic and environmental conditions surrounding the disposal facility, over tens of thousands of years, is inherently unpredictable. Scenarios of plausible future states of the system, and their likelihood of occurrence, must therefore be inferred from direct and/or indirect field evidence and incorporated into the performance assessment analyses. Examples of uncertain scenarios are (1) volcanic activity resulting in upward magma flow to the repository horizon and damage to waste containers and (2) change in climate from present-day conditions to a wetter, monsoon-type climatic regime.

Model uncertainty includes uncertainty in conceptual models and assumptions, uncertainty in mathematical descriptions of these conceptual models, as well as uncertainty in numerical implementations in computer codes. Because of incomplete understanding and characterization of FEPs, multiple plausible alternative conceptual models may be considered equally likely or defensible. This is often the major source of model uncertainty. Translation of a conceptual model into a mathematical model also results in uncertainties because of simplifications and approximations commonly employed to make the problem tractable. An example of model uncertainty is the representation of unsaturated flow at Yucca Mountain using the active fracture model (Liu et al. 1998 [105729]). Conceptually, the problem involves simplifying the characterization of water flow through a complex fractured rock mass using a simple dual-continuum fracture-matrix model. Additional uncertainty is introduced through the assumptions inherent in mathematical representations of fracture-matrix interaction and numerical solution of the governing equations, and calibration to field conditions using only a limited amount of data.

The parameters of the model used to predict the performance of the disposal system are also subject to uncertainty and/or variability. Uncertainty in model parameters arises because of imperfect knowledge or limited data and, in principle, can be reduced with additional measurements. For example, the solubility of neptunium in groundwater is not known with certainty but could be with enough additional measurements. Variability refers to the randomness or heterogeneity in physical and/or behavioral characteristics. It is an intrinsic property of the system and cannot be reduced by additional information. An example is the infiltration flux into the UZ at the surface of Yucca Mountain. Often, variability and uncertainty in a parameter are commingled because of imprecise knowledge. An example would be the seepage flux contacting waste packages. This flux varies from location to location within the repository horizon because of underlying heterogeneities in hydrogeologic properties. In addition, there is uncertainty about the value of flux at any given location because of limited characterization of the natural system.

This leads to a situation where the inputs of the TSPA model (i.e., scenarios, mathematical and conceptual models, and parameters) are uncertain and/or variable, which will therefore result in the output of the model being uncertain as well. As described in the following sections, a probabilistic framework has been adopted in TSPA-SR for translating uncertainties in model inputs to corresponding uncertainties in model predictions. This approach is also consistent with the regulatory standards proposed by the NRC and the EPA.

2.2.4.2 Regulatory Drivers

The NRC currently is in the process of developing the standard that will apply to the disposal of high-level radioactive wastes in the potential repository at Yucca Mountain (proposed 10 CFR Part 63 [64 FR 8640] [101680]). In the Supplementary Information published with the rule, the NRC has stipulated the application of a probabilistic framework for TSPA:

> Demonstration of compliance with the postclosure performance objective specified at § 63.113(b) requires a performance assessment that quantitatively estimates the expected annual dose, over the compliance period and weighted by probability of occurrence, to the average member of the critical group. Performance assessment is a systematic analysis of what can happen at the repository after permanent closure, how likely it is to happen, and what can result, in terms of dose to the average member of the critical group. Taking into account, as appropriate, the uncertainties associated with data, methods, and assumptions used to quantify repository performance, the performance assessment is expected to provide a quantitative evaluation of the overall system's ability to achieve the performance objective (64 FR 8640 [101680]).

Note that the NRC not only anticipates that there will be significant uncertainties (proposed 10 CFR 63.101), but the NRC also requires the TSPA take into account uncertainties in characterizing and modeling the barriers (proposed 10 CFR 63.114 [64 FR 8640 [101680]]). Furthermore, proposed 10 CFR 63.113(b) (64 FR 8640 [101680]) requires a demonstration of compliance by calculating an expected annual dose, defined as follows:

> The expected annual dose is the expected value of the annual dose considering the probability of the occurrence of the events and the uncertainty, or variability, in parameter values used to describe the behavior of the geologic repository (the expected annual dose is calculated by accumulating the dose estimates for each year, where the dose estimates are weighted by the probability of the events and the parameters leading to the dose estimate) (64 FR 8640 [101680]).

The EPA has recently proposed public health and safety standards in proposed 40 CFR Part 197 (64 FR 46976 [105065]), with which the potential repository at Yucca Mountain must comply. The EPA has also specified the application of a probabilistic framework where uncertainties associated with scenarios, models, and parameters are explicitly incorporated into the performance assessments for demonstration of compliance. The regulation specified by the NRC in proposed 10 CFR Part 63 (64 FR 8640 [101680]) is intended to implement EPA's standards and must ultimately be consistent with the EPA requirements.

2.2.4.3 Quantified and Unquantified Uncertainties

In the process models and the TSPA model, some uncertainties are quantified and others are unquantified. Quantified uncertainties are those for which a detailed, unbiased quantitative description of uncertainty (e.g., probability distributions) have been developed from available data. An unbiased estimate is one that neither deliberately overstates nor deliberately understates the uncertain quantity being estimated. In some cases, unbiased quantitative estimates of uncertainty are not feasible, for example, because of limited availability of data or process complexity. Unquantified uncertainties include alternative models, alternative hypotheses, assumptions and/or single point parameter values being used to represent an uncertain property. Unquantified uncertainty may also exist when model inputs are treated probabilistically, if the range of the inputs is chosen to be a conservative bound on the range of all possible values. Uncertainty that results from the plausibility of alternative conceptual models is often unquantified as well.

The computational framework for the TSPA-SR is the primary vehicle by which uncertainties are modeled and their impacts estimated and communicated. It is designed with sufficient flexibility that a range of parameters and models can be used to describe each component of the system. That flexibility also makes it possible to conduct extensive sensitivity and uncertainty analyses to estimate the impact and importance of modeled uncertainties on overall dose estimates. The strategy adopted in TSPA-SR has been to use unbiased and reasonable descriptions of the models and parameters, and their associated uncertainties, in the process models and abstractions when possible. When the processes of interest are too complex to model defensibly, and/or there is insufficient data to defend a specific definition of a model or parameter, a conservative bounded approach is used.

Defensible, in this sense, refers to models and data that can be defended in a regulatory environment on the basis of information available for use in the SR at the time it is submitted. The word conservative implies that models and parameters are chosen such that the ultimate dose estimates produced by the model will be deliberately overestimated. The use of such conservative estimates can sometimes eliminate the need to explicitly consider and model overly complex, sometimes intractable, uncertainties. This approach was chosen because it results in some modeling simplifications, and it is believed to result in dose estimates that can be defended in a regulatory setting as being conservative. In addition, the conservative approach is supported by peer review and regulatory perspectives, and there is precedence for the approach in some other international performance assessment programs.

Note that such a hybrid approach, consisting of a mixture of credible probability distributions and conservative single-point estimates and/or models, tends to lead to a projected outcome that is conservative – although the degree of conservatism implied by the results cannot be readily ascertained. Also note that the significance of unquantifed uncertainties can be masked by the impact of those quantities/models included in the model as quantified uncertainties.

2.2.4.4 Probabilistic Framework

The probabilistic framework used in TSPA calculations is a well-established methodology for incorporating the effects of quantified uncertainties in scenarios, conceptual models, and/or parameters. It has been extensively used in probabilistic risk analyses for evaluating the safety of nuclear reactors and power plants (Rechard 1999 [145383]). Several probabilistic performance assessments have also been carried out within the U.S. radioactive waste disposal program. These include a series of performance assessment studies for the disposal of transuranic waste at the Waste Isolation Pilot Plant (Helton et al. 1998 [100951]), as well as a series of calculations performed for the disposal of high-level radioactive waste at Yucca Mountain by the DOE (Barnard et al. 1992 [100309]; Wilson et al. 1994 [100191]; CRWMS M&O 1994 [100111]; CRWMS M&O 1996 [100962]; CRWMS M&O 1998 [108000]) and the NRC (Codell et al. 1992 [103714]; Wescott et al. 1995 [100476]).

Monte Carlo simulation, the most commonly employed technique for implementing the probabilistic framework in engineering and scientific analyses, is a numerical method for solving problems by random sampling (Morgan et al. 1990 [149538]). As shown in Figure 2.2-8, this method allows a full mapping of the uncertainty in model parameters (inputs) and future system states (scenarios), expressed as probability distributions, into the corresponding uncertainty in model predictions (output), which is also expressed in terms of a probability distribution. Uncertainty in the model outcome is quantified via multiple model calculations using parameter values and future states drawn randomly from prescribed probability distributions. Monte Carlo simulation is also known as the method of statistical trials because it uses multiple realizations of the inputs to compute a probabilistic outcome.

In some situations, the uncertainty in model inputs (e.g., processes, parameters) cannot be quantified using statistical approaches, either because of insufficient information or due to significant complexity. In TSPA-SR, such unquantified uncertainties have been generally represented in a bounded or a conservative manner, as summarized in Appendix F.

The probabilistic modeling approach is computationally burdensome because it requires several hundred model calculations for each scenario of interest. However, it also provides important information not available from a deterministic "best-guess" or "worst-case" calculation. The benefits of probabilistic modeling include (1) obtaining the full range of possible outcomes (and the likelihood of each outcome) to quantify predictive uncertainty and (2) analyzing the relationship between the uncertain inputs and the uncertain outputs to provide insight into the most important parameters.

2.2.4.5 Propagation of Uncertainty

A Monte Carlo analysis of the TSPA model involves the following four steps:

1. Select imprecisely known model input parameters to be sampled
2. Construct probability distribution functions for each of these parameters
3. Generate a sample set by selecting a parameter value from each distribution
4. Calculate the model outcome for each sample set and aggregate results for all samples (equally likely parameter sets).

A brief explanation of each of these steps is described in the following paragraphs. Note that in the TSPA-SR methodology, the Monte Carlo approach is applied to each scenario separately, and the results are combined based on the probability of each scenario.

Selecting Imprecisely Known Model Input Parameters To Be Sampled–The TSPA-SR model consists of approximately 1,000 parameters, many of which are uncertain and/or variable. A determination as to which of these have a significant range of uncertainty or variability, and thus need to be statistically sampled during model calculations, is made during the development of individual process models and/or abstractions thereof. Further discussion on the selection of these parameters can be found in the TSPA-SR model analysis model report (CRWMS M&O 2000 [148384]).

Constructing Probability Distribution Functions for Each Parameter–The probabilistic framework employed in Monte Carlo simulations requires that the uncertainty in model inputs be quantified using probability distributions. As noted earlier, not all uncertain parameters have been treated probabilistically in TSPA-SR. Some parameters have been chosen to be represented by conservative or bounding single-point values rather than probability distributions. Examples of such representations can be found in the descriptions of various TSPA component models in Sections 3.2 to 3.10, as well as in Appendix F. As in previous TSPAs (e.g., CRWMS M&O 1998 [108004]), a variety of sources have been used for generating information related to the distribution of stochastic inputs:

- Actual measurements (e.g., porosity of various hydrogeologic units)
- Expert elicitation (e.g., dilution factors in the SZ)
- Process model output (e.g., fraction of waste packages exposed to seeps).

Per NRC and EPA guidance, the construction of probability distributions has focused on the full range of defensible and reasonable parameter distributions that can be justified on the basis of available information and/or expert elicitation. These distributions are specified either as empirical distribution functions (i.e., individual values and their likelihood), or as the coefficients of parametric distributions fit to data (e.g., mean and standard deviation of a normal distribution fit to porosity data).

Generating a Sample Set by Selecting a Parameter Value from Each Distribution–The next step in the Monte Carlo process requires generating a number of equally likely input data sets, which consist of parameter values randomly sampled from the prescribed range and distributions. An improved form of random sampling is the Latin hypercube sampling procedure, where the range of each parameter is divided into several intervals of equal probability and a value is selected at random from each interval (Helton 1993 [100452]). Latin hypercube sampling, which is employed in TSPA-SR, helps achieve a more uniform coverage of the uncertain parameter range as compared to purely random sampling. The issue of interdependence or statistical correlation between parameters is also important from the perspective of maintaining the necessary dependence between random variable pairs. The sampling algorithm used in TSPA-SR ensures that any desired correlation between input parameters is retained.

Calculating Outcomes for the Sample Set and Aggregating Results for All Samples–In this step of the Monte Carlo methodology, the model describing the behavior of the system for the scenario of interest is evaluated for each of the randomly generated parameter sets. This is a simple operation consisting of multiple model calls, where the outcome (i.e., annual dose as a function of time) is computed for each sampled parameter set. Once all of the required model runs have been completed, the overall uncertainty in the predicted outcome can be characterized by (1) summary statistics such as the mean and median and (2) the cumulative probability distribution.

The NRC regulations in proposed 10 CFR 63.113(b) (64 FR 8640 [101680]) require that the mean annual dose history be computed for each scenario (nominal as well as disruptive) and weighted by the probability of that scenario to determine the overall expected annual dose history over the 10,000-year compliance period. The EPA regulations in proposed 40 CFR 197.13 (64 FR 46976 [105065]) require compliance demonstration using the mean or median dose history, whichever is higher. The regulations are thus focusing on the statistical average result, although further analyses of the full range of model outcomes will be necessary for developing reasonable assurance arguments for the NRC and reasonable expectation arguments for the EPA. The cumulative probability distribution is also useful for unraveling the relationship between input and output variables implicit in the TSPA model and for determining the relative importance of various uncertain inputs (Section 2.2.5).

As noted earlier, the procedure outlined above for translating input uncertainties into output uncertainties reflects the effects of the quantified uncertainties. Because unquantified uncertainties are represented via conservative/bounding values, their impact is believed to be restricted to over-estimating system performance in a pessimistic direction (i.e., increasing expected value of individual dose). It is also important to point out the uncertainty associated with developing models of credible features, events, and processes, based on scientific observations and/or inferences, is not explicitly incorporated in this methodology. The decision was generally made to focus on the most reasonably defensible model representation, but to err on the side of conservatism so as not to under-predict the possible consequences or risks.

2.2.4.6 Presentation of Uncertainty Analysis Results

For any given scenario (nominal or disruptive), the Monte Carlo methodology requires the TSPA-SR computer model to be evaluated for each of the equiprobable parameter sets sampled from their prescribed distributions. Thus, each realization results in a total dose history (i.e., table of dose rate as a function of time). The aggregation of all dose histories produces a picture of the overall uncertainty in predicted performance. Such information may be graphically presented in several ways:

- A graph of dose rate versus time showing results from all realizations. This is the so-called "horse-tail plot," which provides an indication of the overall spread in model results given the uncertainties in the inputs.

- Superimposing the mean dose rate history on the horse-tail plot. This is the arithmetic average dose calculated for each point in time. It is also the benchmark quantity for comparing the performance of the disposal system against regulatory standards.

- Superimposing the median dose rate history on the horse-tail plot. For each point in time, the median dose is the value above which lie 50 percent of the results and below which lie 50 percent of the results. The median dose rate history is a potential benchmark quantity per the EPA regulations.

- Superimposing the 5th and 95th percentile dose rate histories on the horse-tail plot. For each point in time, the 5th (95th) percentile dose is that value below which lie 5 percent (95 percent) of the results. These two values provide a reasonable indication as to the spread in computed model outcomes.

Figure 2.2-9 presents an example of such a composite graph, showing the dose rate history for all realizations, along with the median, the mean, and the 5th and 95th percentile dose rate histories. Note that this figure is for demonstration purposes only, and does not contain any actual results.

2.2.5 Sensitivity Analyses

2.2.5.1 Objectives of Sensitivity Analyses

The TSPA-SR model represents the behavior of a complex system with hundreds of parameters. Many of the parameters are uncertain and/or variable, and their interaction with one another can also be complex and/or highly nonlinear. It is difficult to obtain an understanding exactly how the model works and what the critical uncertainties and sensitivities are from a simple evaluation of model results. To this end, sensitivity analysis provides a useful and structured framework for unraveling the results of probabilistic performance assessments by examining the sensitivity of the TSPA-SR model results (and their uncertainties) to the uncertainties and assumptions in model inputs. Specifically, the goal of sensitivity analysis is to answer questions such as:

- Which uncertain variables have the greatest impact on the overall uncertainty (spread) in probabilistic model outcomes?

- How do different variables affect the model outcome when their values are varied over a range?

- How robust are the probabilistic model results to underlying assumptions regarding bounding/conservative values and/or conceptual models?

TSPA-SR uses uncertainty importance analysis, explanatory "one-off" analysis, and robustness analysis, respectively, to answer these questions. Details of each of these methods are described in the following sections.

2.2.5.2 Uncertainty Importance Analysis

The objective of uncertainty importance analysis is to identify those input parameters that have the greatest influence on the spread (uncertainty) of the probabilistic model results. This is accomplished qualitatively using scatter plots, and quantitatively using statistical methods such as correlation-regression analysis and classification and regression tree analysis. The analyses are carried out using results from the probabilistic calculations at a fixed point in time, with the sampled inputs corresponding to each of the realizations being treated as independent variables and the computed outputs being treated as dependent variables. Note that the outputs can either be total system-level performance measures, such as annual dose rate to a receptor, or they can be subsystem-level performance measures, such as cumulative radionuclide mass flux at the water table.

Scatter Plot Analysis–A scatter plot is a simple graphical tool for determining the strength of the relationship between an uncertain input parameter and the calculated output variable. Sampled values of the input parameter are plotted against the corresponding computed outcomes, after transforming the actual numerical values into ranks (i.e., the lowest value has rank 1, the next highest value has rank 2, and so on). If little or no relationship exists between an independent variable and the model outcome, the scatter plot will resemble a random distribution of points. However, if a significant relationship does exist, the plotted points will cluster and exhibit a recognizable form—either as an upward-trending cloud (meaning that the input-output relationship is positive) or as a downward-trending cloud (meaning that the input-output relationship is negative). Scatter plots also help reveal threshold phenomena and nonlinearities (or lack thereof) in the input-output relationship. Figure 2.2-10 shows some example scatter plots between two random variables. The top panel shows an upward trending relationship, the middle panel shows no apparent relationship, and the bottom panel shows a downward trending relationship until the threshold for an upward trending relationship is encountered.

Correlation and Regression Analysis–Scatter plots are valuable for identifying a relationship between an input variable and an output variable, but they do not quantify the intensity of that relationship. In performance assessment studies, multiple linear regression modeling is commonly used for this purpose (Helton 1993 [100452]). Using regression models, it is possible to identify input variables that contribute the most to the calculated uncertainty (variance) in the performance measure. The primary technique for regression modeling is stepwise linear regression using rank transformations of the input and output values. In the stepwise approach, a sequence of regression models is constructed starting with a single selected input parameter (usually the parameter that explains the largest amount of variance in the output), and including one additional input variable at each successive step (usually the parameter that explains the next-largest amount of variance) until all of the input variables that explain statistically significant amounts of variance in the output have been included in the model. This approach avoids having to treat all of the independent uncertain variables simultaneously in a single model.

Two indicators are used to rank the input variables: partial rank correlation coefficient and R^2-loss (where R^2 denotes the coefficient of determination for the regression model). Both of these indicators are calculated during stepwise regression modeling. The partial rank correlation coefficient for a particular input variable measures the correlation between the output and the selected input variable, after the linear influences of the other variables in regression have been eliminated (Helton 1993 [100452]). The second importance indicator used, R^2-loss, represents the loss in R^2 of the current *n*-variable regression model, if the variable of concern is dropped from the regression model (RamaRao et al. 1998 [100487]). A large value of R^2-loss (i.e., a large decrease in explanatory power) indicates that the removed variable explained a large proportion of the variance in the output and, therefore, the variable is an important component of the model. In TSPA-SR, the R^2-loss value is divided by the regression R^2 in order to facilitate the comparison of importance ranking from different times and/or for different simulations. This normalized metric, defined as the uncertainty importance factor, is essentially equivalent to the fraction of total variance explained by the variable of interest.

Classification and Regression Trees Analysis–Linear regression is useful for analyzing entire spectra of output data. However, analyzing small categories of output data may require a more specialized approach. Classification and regression tree analysis is a categorical method for determining what variables or interactions of variables drive output into particular categories (Breiman et al. 1998 [151294]). For example, classification and regression tree can be used to analyze the extreme values in a set of output data. Those realizations that yield the highest and lowest outcomes are grouped into high and low categories. The classification and regression tree analysis will then provide insight into what variable or variables are most important in determining whether outputs fall in one or the other category.

A binary decision tree is at the heart of the classification and regression tree analysis. The decision tree is generated by recursively finding the variable splits that best separate the output into groups where a single category dominates. The domination of a single category resulting from a split is called the purity of that split. For each successive fork of the binary decision tree, the classification and regression tree algorithm searches through the variables one by one to find the purest split within each variable. The splits are then compared among all the variables to find the best split for that fork. The process is repeated until all groups contain a single category. In general, the variables that are chosen by the algorithm for the first several splits are most important, with less important variables involved in the splitting near the terminal end of the tree.

The Figure 2.2-11 depicts a binary decision tree generated from a classification and regression tree analysis. The realizations which yielded the 30 highest and 30 lowest (including zero) outputs were grouped into high and low categories. Starting at the left side of the figure, the first split is based on the variable X1. If ($X1 > 1$) then the upper branch is followed, whereas if ($X1 < 1$) then the lower branch is followed. This split yields two groups: the upper branch contains 29 high values and 8 low values, while the lower branch contains 20 low values. The lower branch is pure so no additional splitting is required. The upper branch continues to a second split based on X2. This split divides the 29 high and 8 remaining low values into groups. All groups are now pure so the tree is terminated. Note that for simplicity, some branches of low importance may be left off of the tree. In this example, 29 of 30 high outputs and 28 of 30 low outputs are represented. The classification and regression tree analysis in this example has shown that the input values of variables X1 and X2 determine whether high or low outputs will result.

2.2.5.3 Probabilistic One-Off Analysis

A "one-off" analysis is a variation on some reference case calculation where the parameter of interest is modified from its original value while all other parameters are kept unchanged. In a probabilistic one-off analysis, as implemented in TSPA-SR, the probability distribution for the parameter of interest is replaced with its 5th or 95th percentile value (whichever yields the more conservative model outcome). Thus, the parameter of interest is given a single value while all other parameters are characterized using their full probability distributions.

The motivation for carrying out such an analysis is twofold. First, it allows an exploration of the sensitivity of model performance to extreme (but realistic) values in model parameters. Second, the analysis provides an indication of what can happen when the system is stressed to the extent that the parameter of interest is assigned a value which has only a relatively low likelihood of occurrence. This analysis is not necessarily intended to show how the reference system behaves, rather it suggests how the reference system is resilient when its parameters take on pessimistic values.

With respect to the actual implementation of the methodology, the first step is to screen for candidate parameters based on the results of uncertainty importance analysis. The objective here is to identify those parameters important at the system level (affecting receptor dose) as well as the subsystem level (affecting waste package failure, EBS release, UZ release, etc.). The next step is to pick the 5th or the 95th percentile value at which these parameters would be fixed during the one-off calculations. The probabilistic calculations with this modified parameter set are then carried out, and the expected dose (or other outcomes of interest) compared against the corresponding result from the reference case.

2.2.5.4 Robustness Analysis

The TSPA-SR model includes parameters which are treated as constants, parameters described via probability distributions to represent inherent uncertainty and/or variability, as well as imprecisely known parameters represented with conservative and/or bounding values. Because of this mixture of representations, it has been pointed out that care should be taken in interpreting the results of statistical sensitivity or uncertainty importance analyses (Budnitz et al. 1999, [102726]).

In order to further analyze results from models with such heterogeneous sources of information about uncertainty (i.e., probability distributions versus bounding values), TSPA-SR uses a modified form of the range/confidence estimate approach proposed by Richards and Rowe (1999 [148939]). Additional probabilistic analyses are used to explore the robustness of the reference probabilistic model results to the underlying assumptions of imprecise parameter representations. The probabilistic one-off analyses described previously are restricted to the 5th and 95th percentiles of the distributions used in the reference probabilistic case. In robustness analyses, the shape and the range of the distribution itself can be changed based on new information, alternative points of view and/or what-if scenario assumptions. Another form of robustness analysis focuses on parameters described with bounding/conservative values. Utilizing more realistic values in a manner similar to the range/confidence estimating protocol suggested by Richards and Rowe (1999 [148939]) provides an indication of the degree of conservatism in the original results. Uncertainty importance analyses for the scenario with these modified parameters also shows the sensitivity of the importance rankings to underlying uncertainties in parameter representations.

2.2.5.5 Sensitivity Analyses and Reasonable Assurance

In proposed 10 CFR Part 63 (64 FR 8640 [101680]), the NRC recognizes that complete assurance of compliance with regulatory standards cannot be obtained based solely on the results of probabilistic performance assessments because of the uncertainties inherent in the understanding of the evolution of the geologic setting, biosphere, and EBS. Even though the TSPA-SR model incorporates the best state of current knowledge with respect to the uncertainties in its component models and parameters, residual uncertainties are likely to remain. The NRC therefore requires a demonstration of reasonable assurance, making allowance for the time period, hazards, and uncertainties involved, that the predicted outcome will satisfy the prescribed performance objectives. The suite of sensitivity analyses used in TSPA-SR support the development of reasonable assurance arguments in the following manner:

- Identifying the key uncertain parameters so that more effort can be directed at minimizing these uncertainties, if possible
- Examining what happens when the system is stressed via unfavorable parameter values and/or conceptual models to obtain a better sense of the range/confidence of performance predictions
- Testing the robustness of predicted model outcomes to underlying assumptions about model and parameter structure.

By addressing the importance of known uncertainties with respect to conclusions and the issue of confidence in the TSPA-SR model results, the sensitivity analyses provide additional lines of evidence toward building reasonable assurance.

2.2.6 Control of Information in TSPA

The TSPA-SR model utilizes information from a large number of sources, including AMR's, literature data, and information housed within the Technical Data Management System. In all, there are over 6,500 parameter values within the TSPA model, plus over 20 data tables attached to the model file, as well as the 4 external process models (i.e., ASHPLUME, WAPDEG, FEHM particle tracker, SZ_CONVOLUTE) and 3 software routines (i.e., Seep, Soil, GVP) attached to the model.

The receipt and use of this information is controlled procedurally primarily by *Transmittal of Input*, AP-3.14Q [152629]; *Managing Technical Product Inputs*, AP-3.15Q [153184]; *Submittal and Incorporation of Data to the Technical Data Management System*, AP-SIII.3Q [149901]; *Software Management*, AP-SI.1Q [153201]; and *Analyses and Models*, AP-3.10Q [152363].

These procedures provide the protocol for transmittal and utilization of the information in a controlled, traceable fashion.

The status of the data, software or models in this technical product is presented in several ways. The software status is shown in Table 2.2-1. All qualified software used in the TSPA-SR analyses were obtained from Configuration Management and used within the range of validation. The unqualified software used in the TSPA-SR analyses are being controlled in accordance with AP-SI-1Q [153201], and AP-3.15Q [153184], as indicated in the table and in the associated DIRS. The major software inputs are documented in the TSPA-SR model document. Other inputs (as well as outputs) are documented in Appendices E and G.

Changes to this report may be required as confirmation activities associated with unresolved TBX's and Urn inputs are completed. Software qualification may also lead to changes in the analyses if additional simulations are required. The input status of the data and models utilized in this technical product are indicated for the references in the DIRS. Status of inputs need to be indicated in the DIRS.

Figure 2.2-12 schematically shows the major components of data, codes or software, and models that must be controlled. Data are developed or acquired, submitted to the Technical Data Management System and given a data tracking number that provides traceability to the specific information utilized. The data tracking number identifies the source, type of data, and who can be contacted to find out more about the data. Software or codes required to run the models are also controlled, both during initial development and after maturity. The Software Configuration Management Organization is responsible for centralized control of the software. The qualification procedure requires testing and documentation of the software in a very thorough manner. This process provides a thorough check that the software is calculating what it was designed to calculate as long as it is used within its design specifications. Models, and submodels, are also developed and controlled in a manner that provides suitable documentation and review of the assumptions (inputs and outputs) from the model. The validation of the model is also contained in the model documentation, demonstrating that the model operates according to its design.

Figure 2.2-13 schematically shows a more detailed look at the approach to obtaining information, controlling it in the TSPA database for use in the TSPA-SR model. This database will be controlled within the Technical Data Management System, yet allow access from the TSPA-SR model to obtain input files and run the model. A new procedure, *Verification of Data Entry into the Total System Performance Assessment Database,* LP-IM-001Q-M&O [152182], was developed to catalogue information required by the TSPA-SR model that is housed within Technical Data Management System into a useable form for access by the TSPA-SR model over an electronic connection.

A summary table of software utilized in the TSPA-SR model is presented as Table 2.2-1.

Table 2.2-1. Listing of Software Utilized in the TSPA-SR

Computer Code	Version	STN/CSCI/AMR	Qualification Status	Platform
GoldSim	6.04.007	10344-6.04.007-00	Unqualified	Windows NT 4.0
FEHM	2.1	10086-2.10-00	Unqualified	Windows NT 4.0
T2_BINNING	1.0	MDL-WIS-PA-000002[1]	Qualified	Windows NT 4.0
WT_BINNING	1.0	MDL-WIS-PA-000002[1]	Qualified	Windows NT 4.0
MAKEPTRK	2.0	MDL-WIS-PA-000002[1]	Qualified	Sun OS 5.7
WAPDEG	4.0	1000-4.0-00	Unqualified	Windows NT 4.0
ASHPLUME	1.4LVdll	10022-1.4LVdll-00	Qualified	Windows NT 4.0
SZ_CONVOLUTE	2.0	10207-2.0-00	Qualified	Windows NT 4.0
SEEPDLL	1.0	MDL-WIS-PA-000002[1]	Qualified	Windows NT 4.0
SOILEXP	1.0	MDL-WIS-PA-000002[1]	Qualified	Windows NT 4.0
GVP	1.02	10341-1.02-00	Qualified	Windows NT 4.0
MFD	1.01	10342-1.01-00	Qualified	Windows NT 4.0
SCCD	2.00	10343-2.0-00	Qualified	Windows NT 4.0
PREWAP	1.0	MDL-WIS-PA-00002[1]	Qualified	Windows NT 4.0
MVIEW	2.10	10072-2.10-00	Qualified	Irix 6.3 or greater, HP-UX 10.2, Solaris 2.6, Digital Unix V4
SATOOL	1.0	10084-1.0-00	Qualified	Windows 98
PDFSENS	1.0	10190-1.0-00	Qualified	Windows 98 Windows 95
EQ3/6	7.2b	LLNL:UCRL-MA-110662	Qualified	HP-UXB, 10.20, Windows 98

NOTE: [1]CRWMS M&O 2000 [148384]

Oversight

NRC Technical Exchanges, Appendix 7 Meetings
NWTRB Panel Meetings, Reports to Congress
State of Nevada; Affected Units of Local Government
Public

Prior TSPAs

DOE TSPA-91, 93, 95, VA
NRC IPA-1, -2, -3
EPRI TSPA Phases 1, 2, and 3

Process Model Abstraction

Unsaturated Zone Flow
Engineered Barrier System Environments
Waste Package & Drip Shield Degradation
Waste Form Degradation
Engineered Barrier System Transport
Unsaturated Zone Transport
Saturated Zone Flow and Transport
Disruptive Events
Biosphere

Process Models

Unsaturated Zone Flow Model
Seepage Model
Near Field Geochemistry Model
In-Drift Environment Model
Multi-Scale Thermal Hydrological Model
Waste Package and Drip Shield Corrosion Model
Unsaturated Zone Transport Model
Saturated Zone Flow and Transport Model
Volcanic Eruption Model

Site and Design Information

Site Description Document
Repository Design
Waste Package Design
Laboratory Data
In-Situ Data
Analog Data

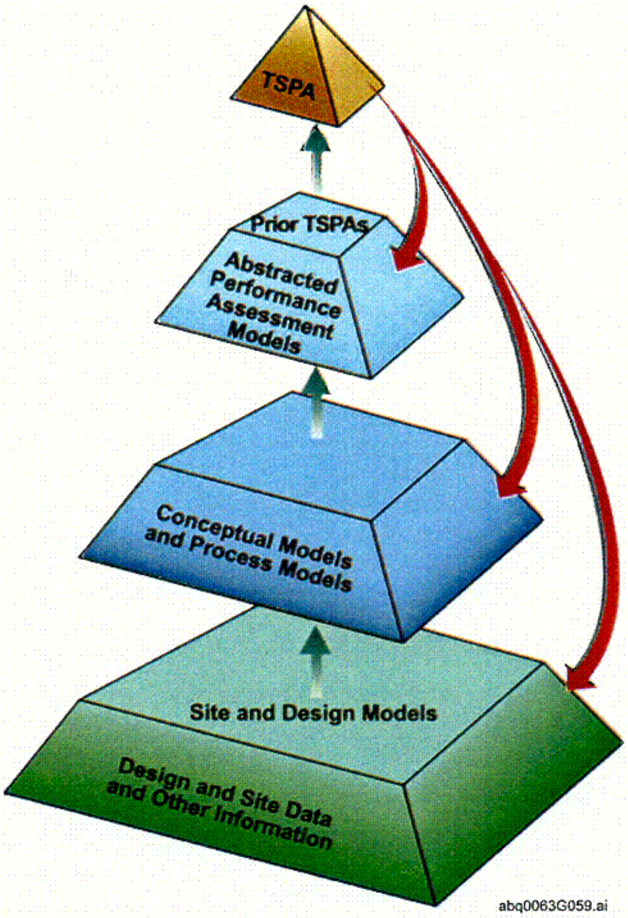

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Figure 2.1-1. Major Sources of Information Used in the Development of the Total System Performance Assessment-Site Recommendation

C-14

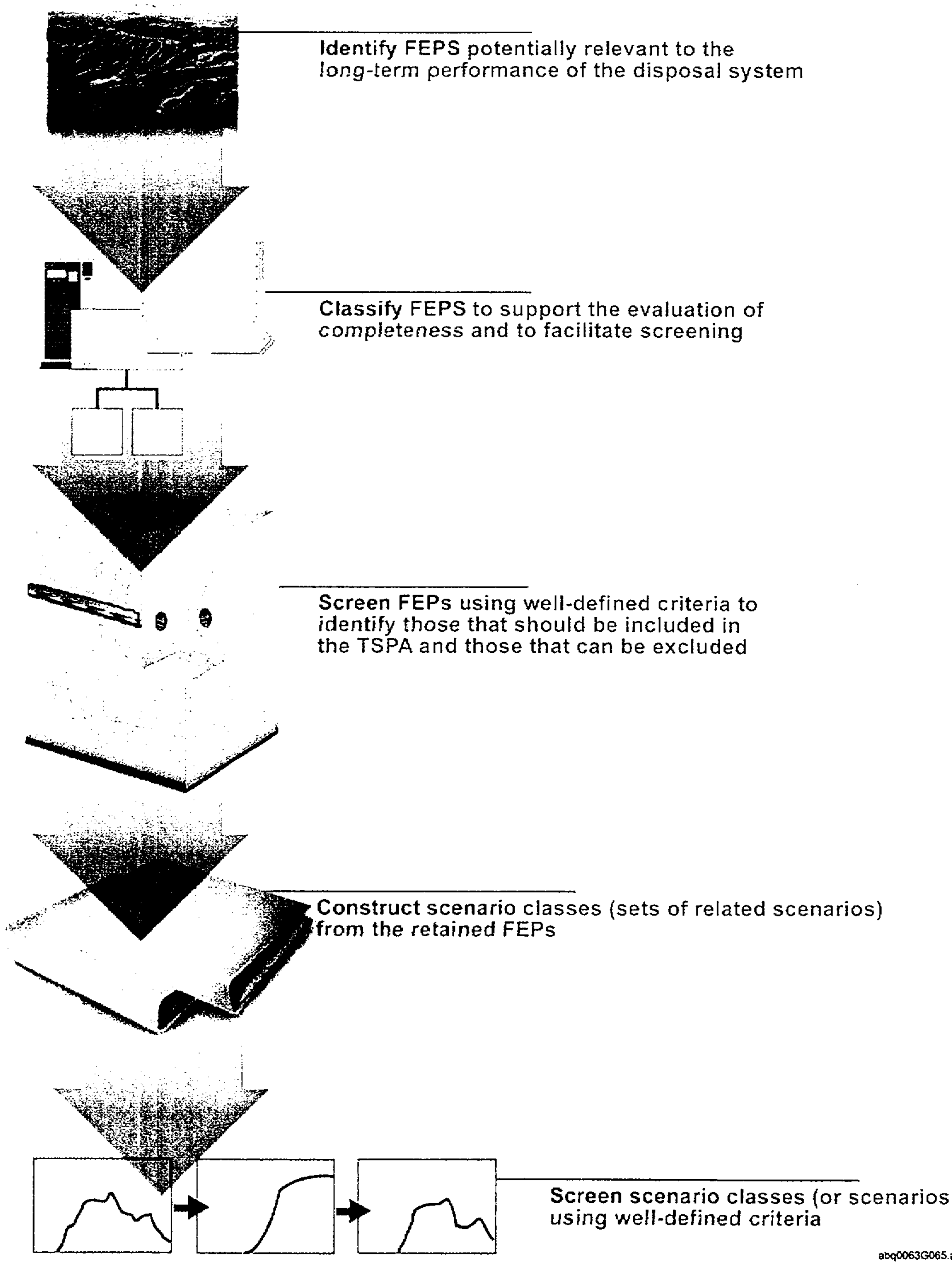

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Figure 2.1-2. The Five Steps in the Formal FEPs Approach for Scenario Development Implemented in Total System Performance Assessment-Site Recommendation

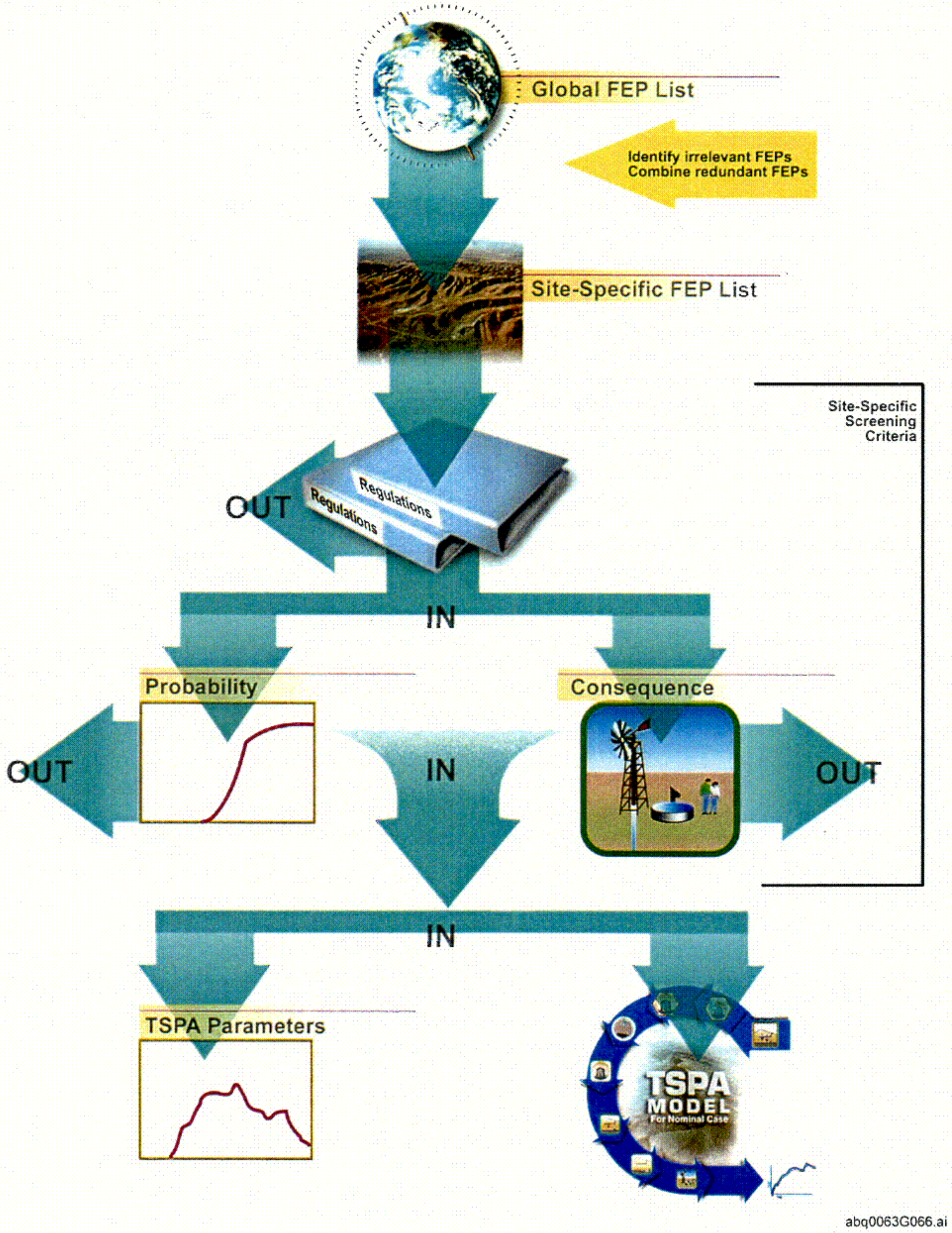

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Figure 2.1-3 Process for Screening FEPs in Total System Performance Assessment-Site Recommendation

C-15

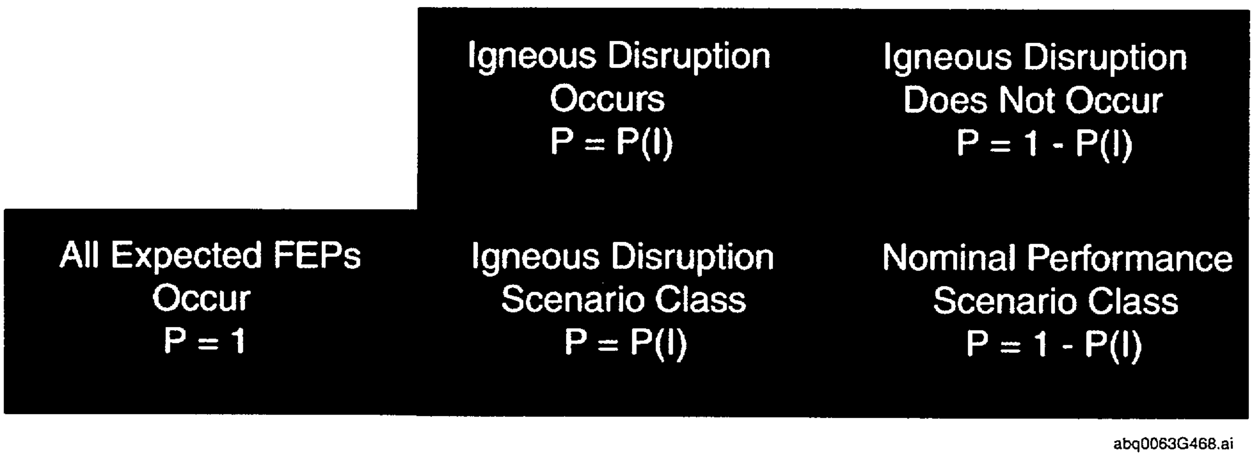

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Figure 2.1-4. Latin Square Scenario Diagram of the Total System Performance Assessment-Site Recommendation Scenario Classes

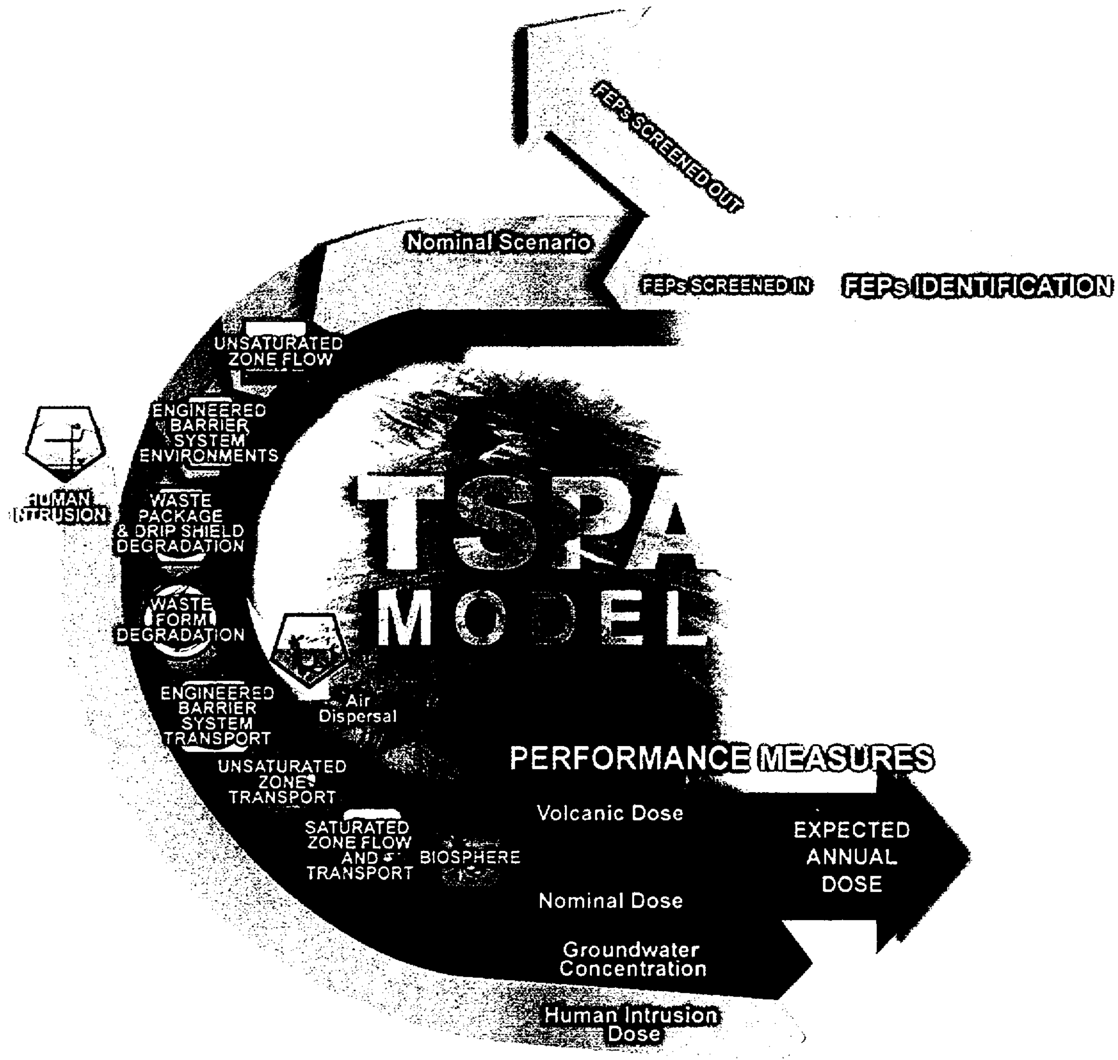

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Figure 2.1-5. Schematic Representation of the Development of Total System Performance Assessment-Site Recommendation Including the Nominal, Disruptive, and Human Intrusion Scenario Classes

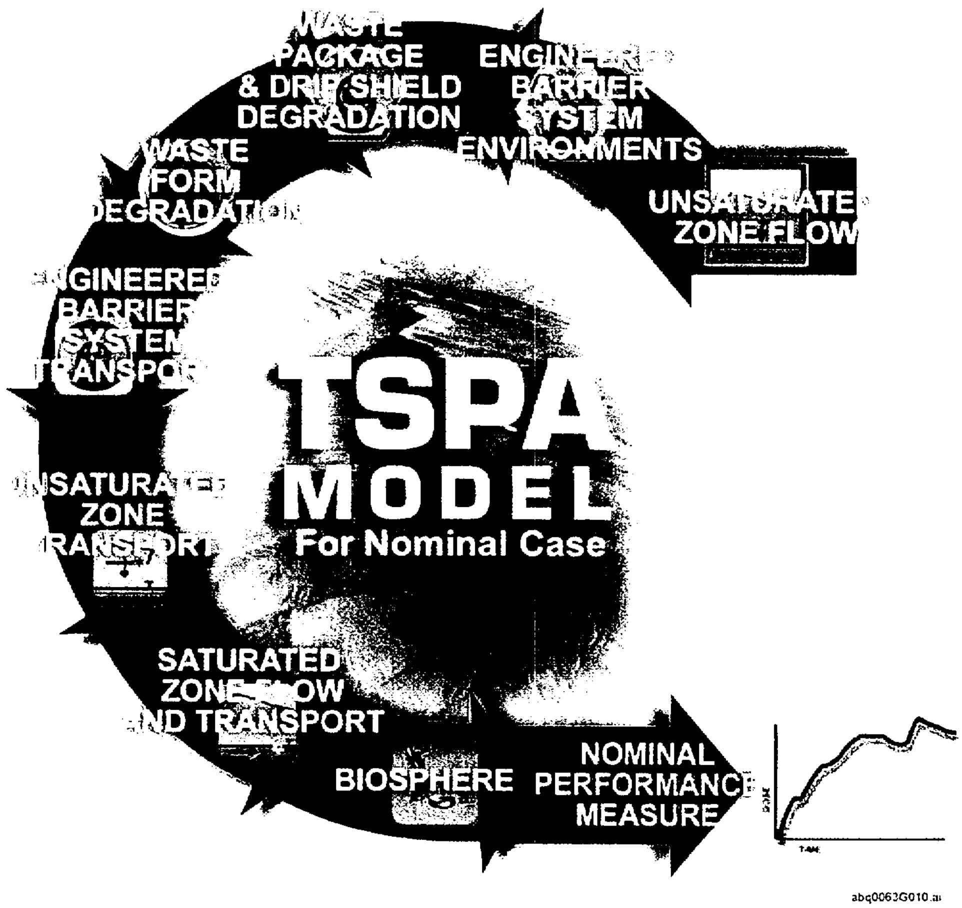

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Figure 2.1-6. Schematic Representation of the Components of the Total System Performance Assessment-Site Recommendation Nominal Scenario Class

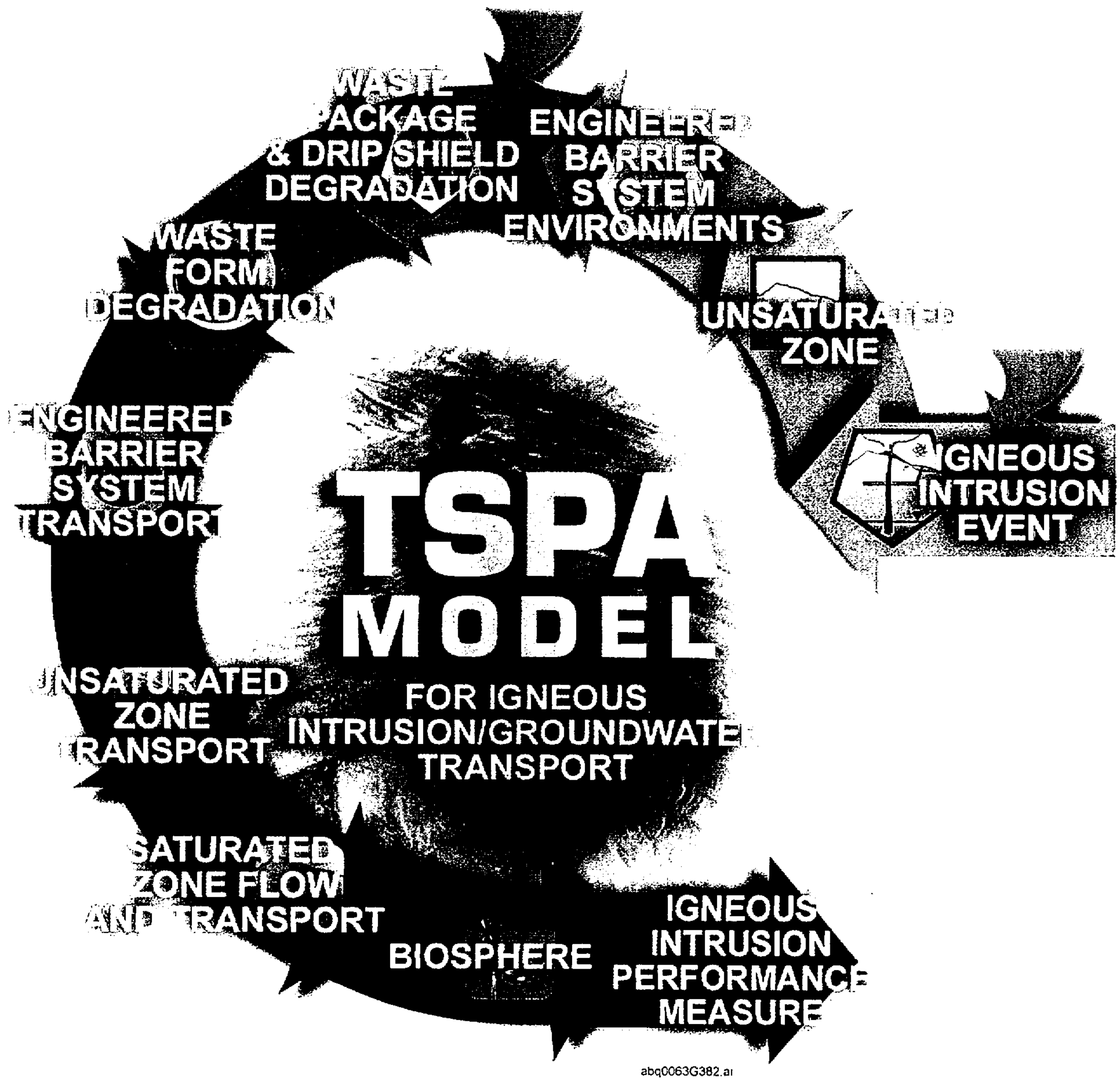

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Figure 2.1-7a. Schematic Representation of the Components of the Total System Performance Assessment-Site Recommendation Disruptive Scenario Class (Igneous Intrusion Scenario)

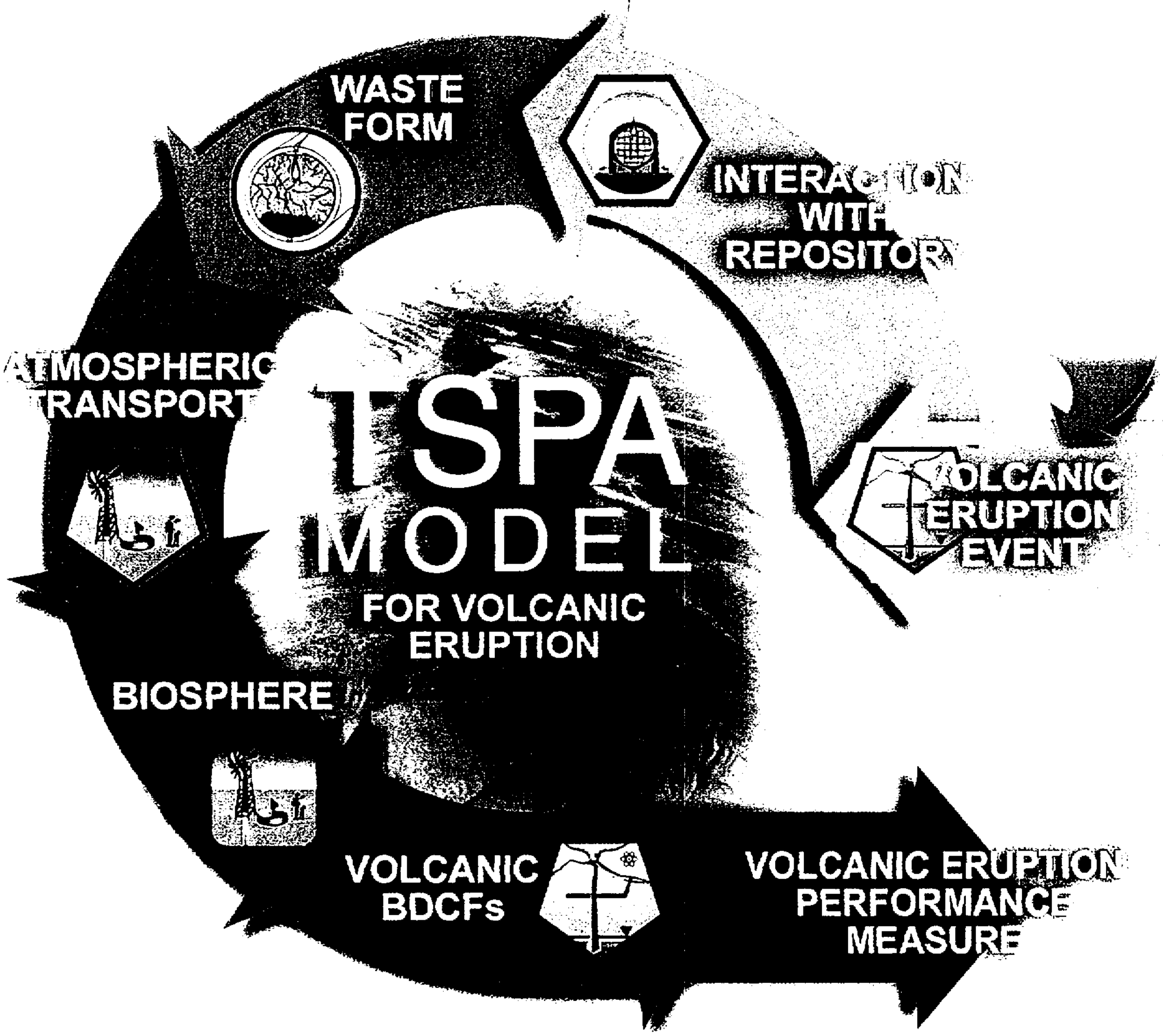

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Figure 2.1-7b. Schematic Representation of the Components of the Total System Performance Assessment-Site Recommendation Disruptive Scenario Class (Volcanic Eruption Scenario)

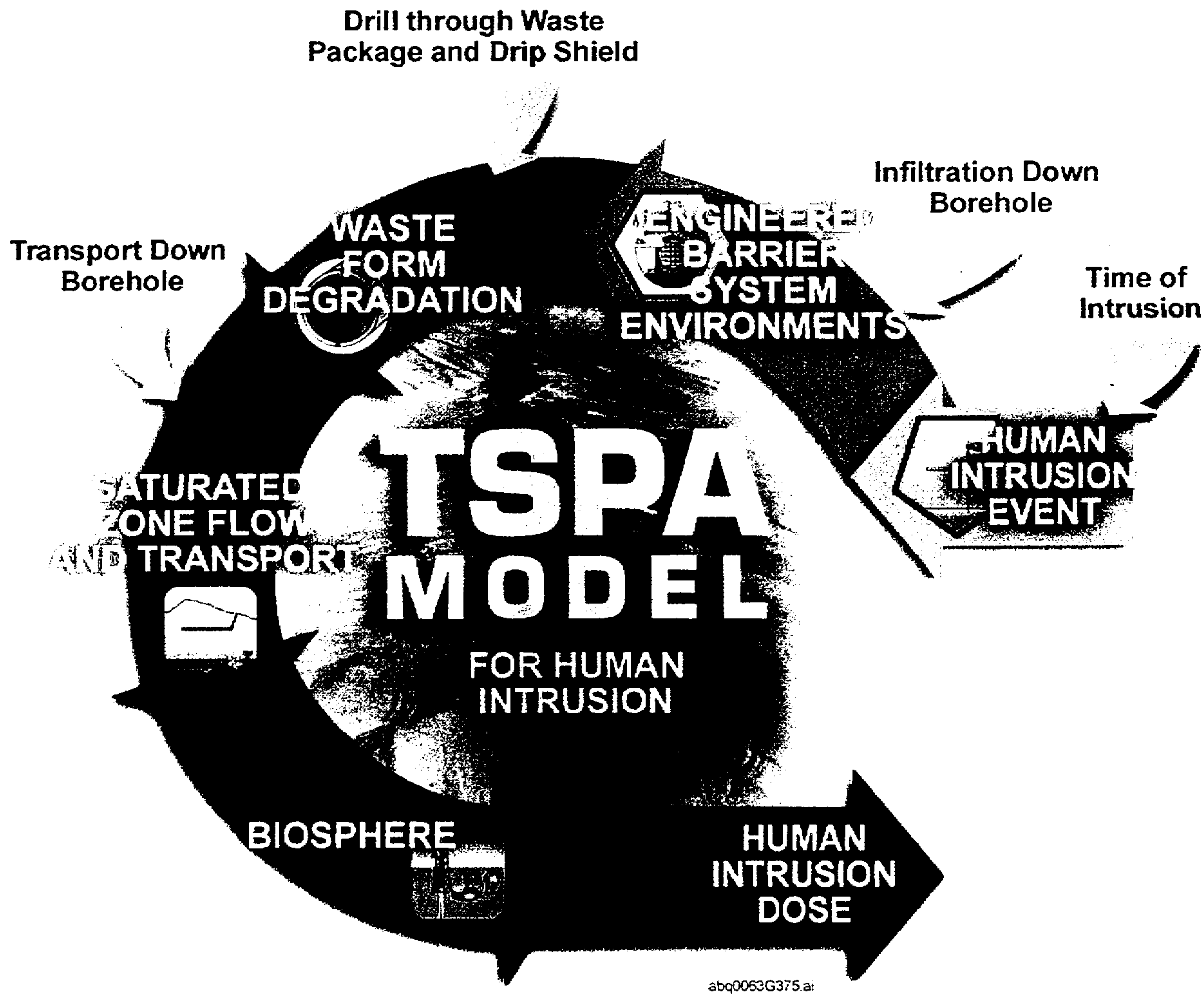

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Figure 2.1-8. Schematic Representation of the Components of the Total System Performance Assessment-Site Recommendation Human Intrusion Scenario Class

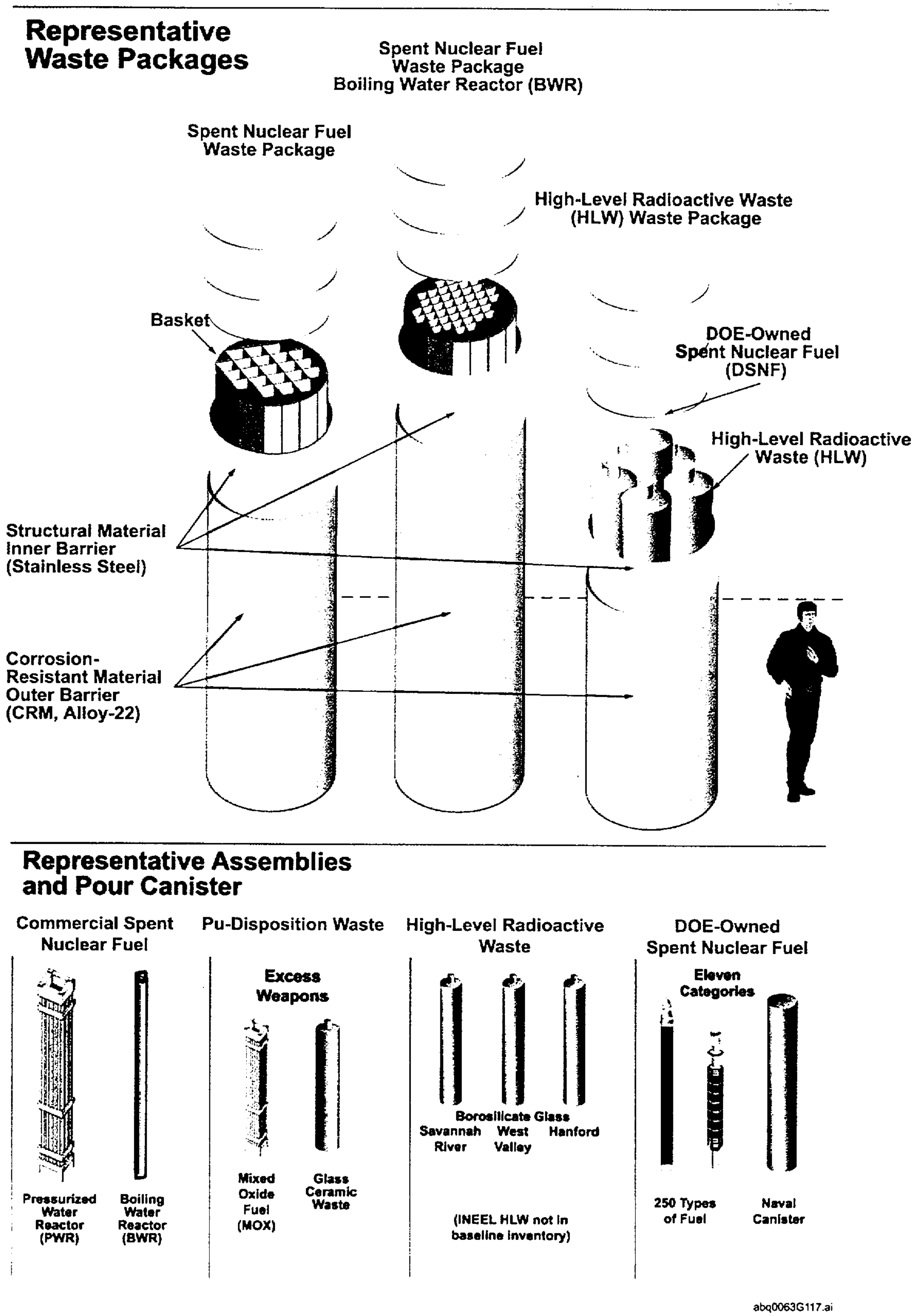

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Figure 2.1-9. Schematic of the Reference Waste Package and Waste Form Designs Used in the Total System Performance Assessment-Site Recommendation

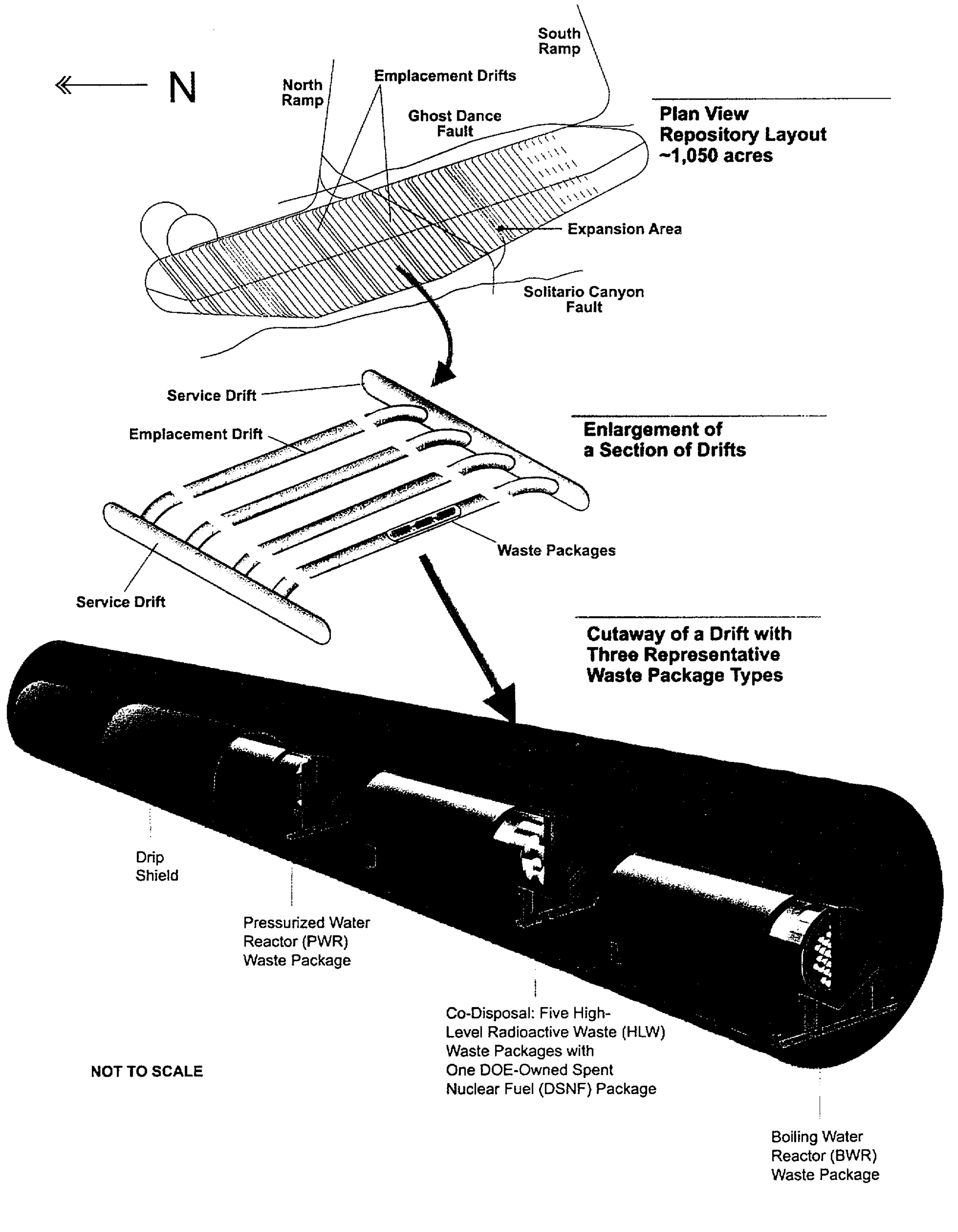

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Figure 2.1-10. Generalized Schematic of Potential Repository System from Mountain Scale to Repository Scale to Waste Package Scale to Waste Form Scale

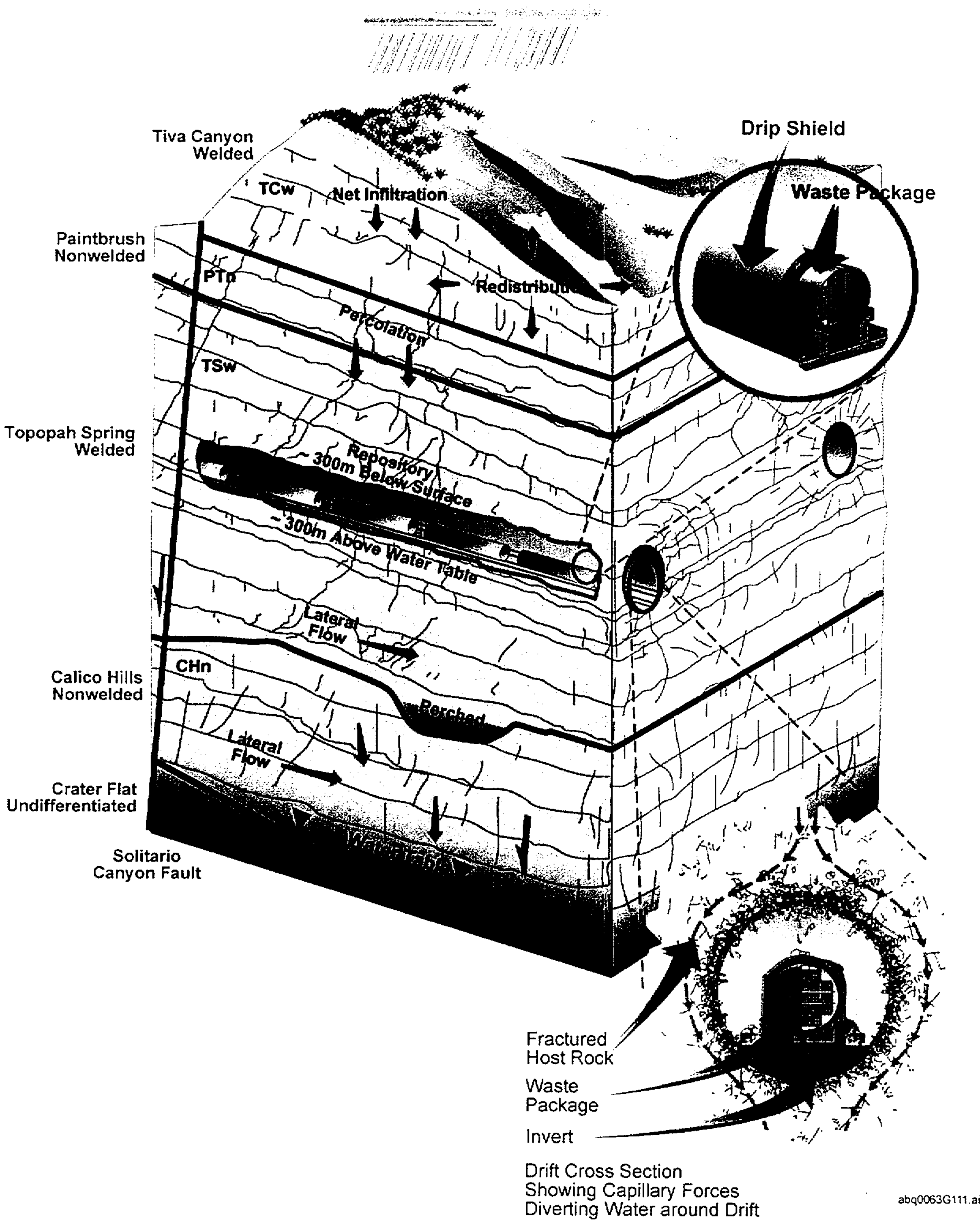

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Figure 2.1-11. Water Movement at Yucca Mountain

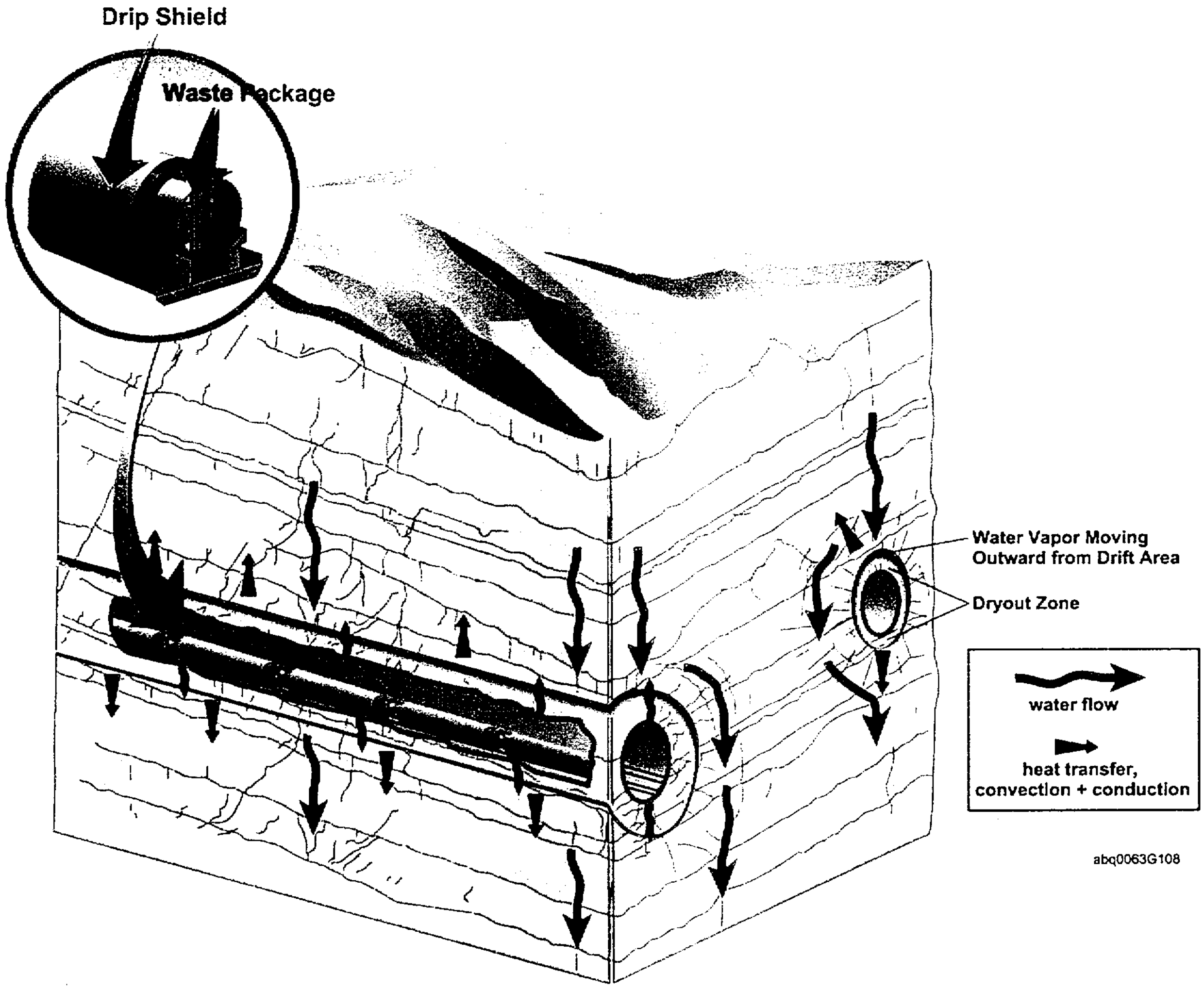

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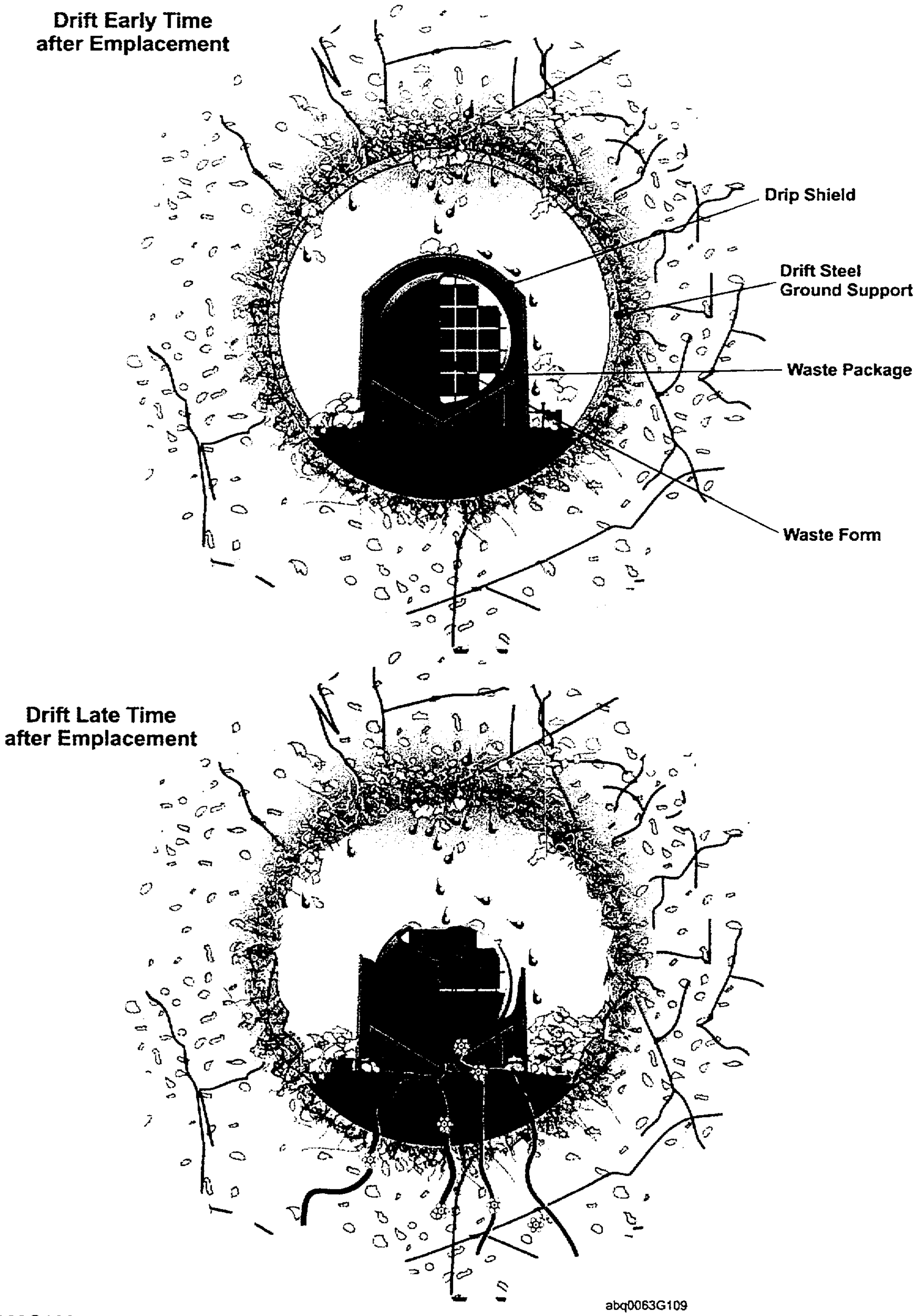
Figure 2.1-12. Water and Vapor Movement at Yucca Mountain Around Drifts



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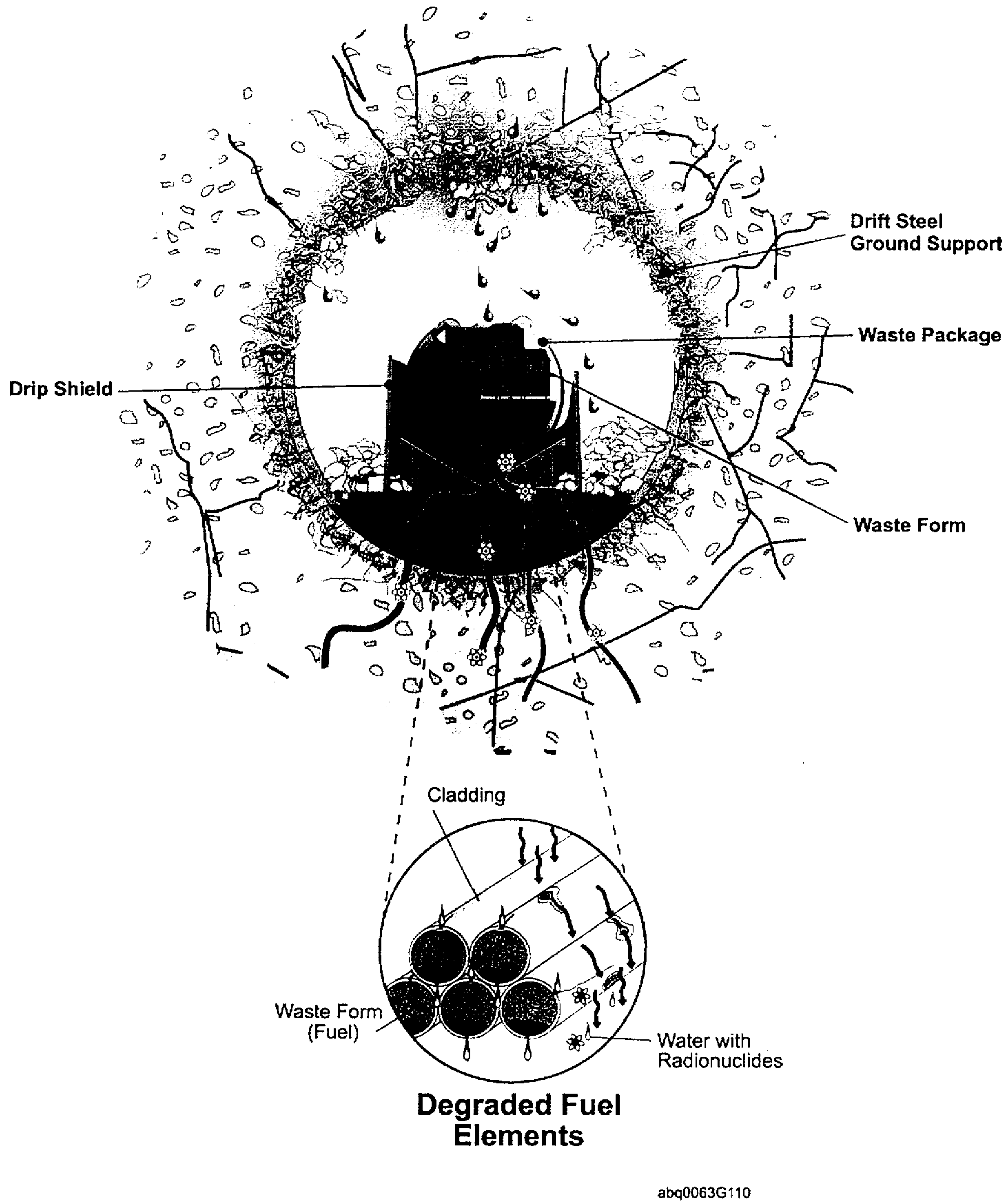
NOTE: The amount of water shown is illustrative and exaggerated from expected conditions.

Figure 2.1-13. Water Movement within Engineered Barrier System



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NOTE: The amount of water shown is illustrative and exaggerated from expected conditions.

Figure 2.1-14. Water Movement and Radionuclide Migration out of Engineered Barrier System

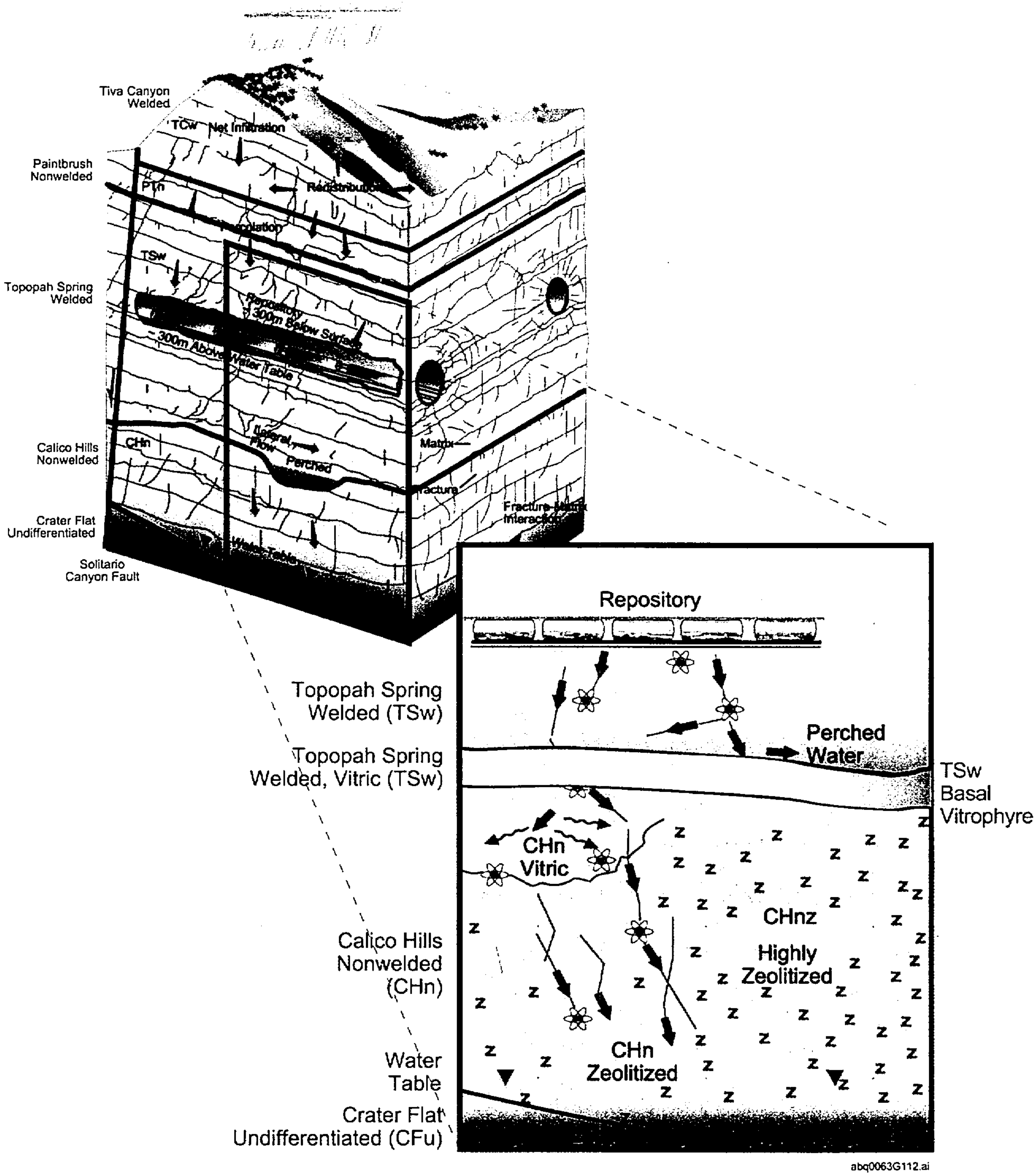

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Figure 2.1-15. Water Movement and Radionuclide Migration through Tuffs

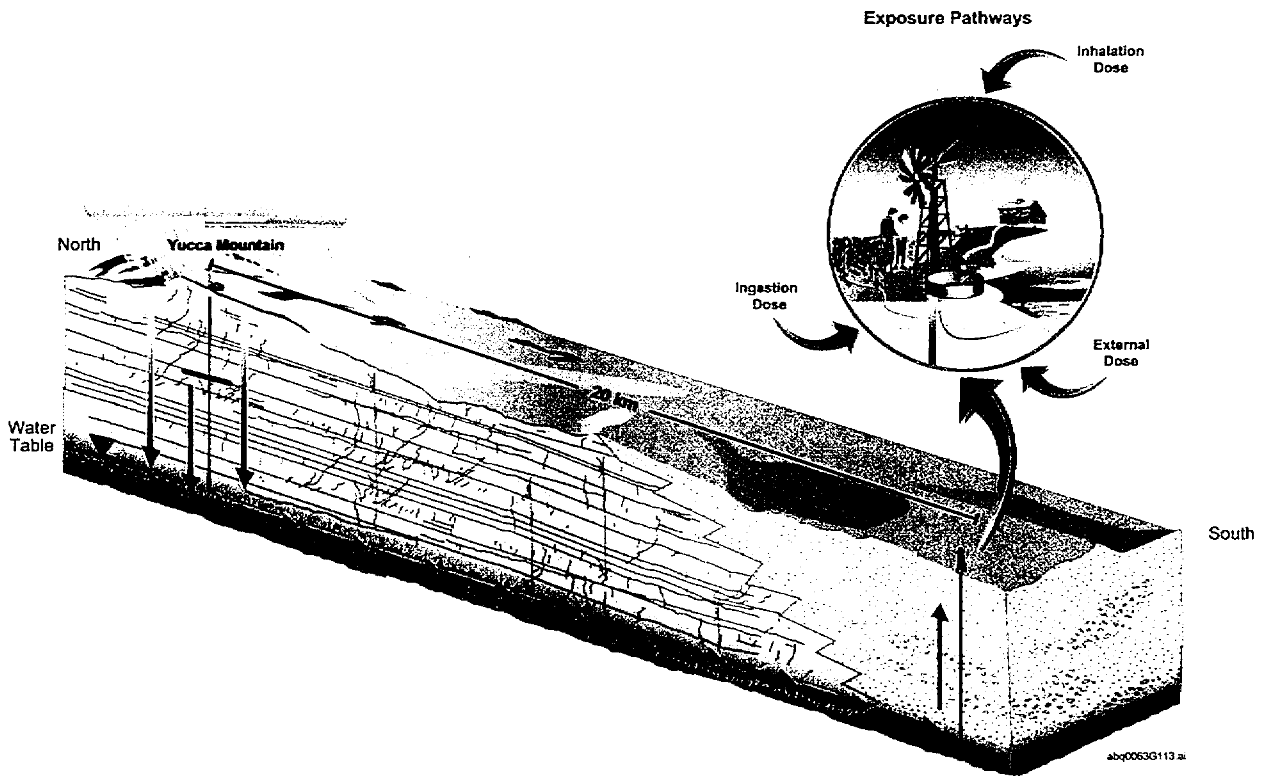

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Figure 2.1-16. Water Movement and Radionuclide Migration through Saturated Zone and Biosphere

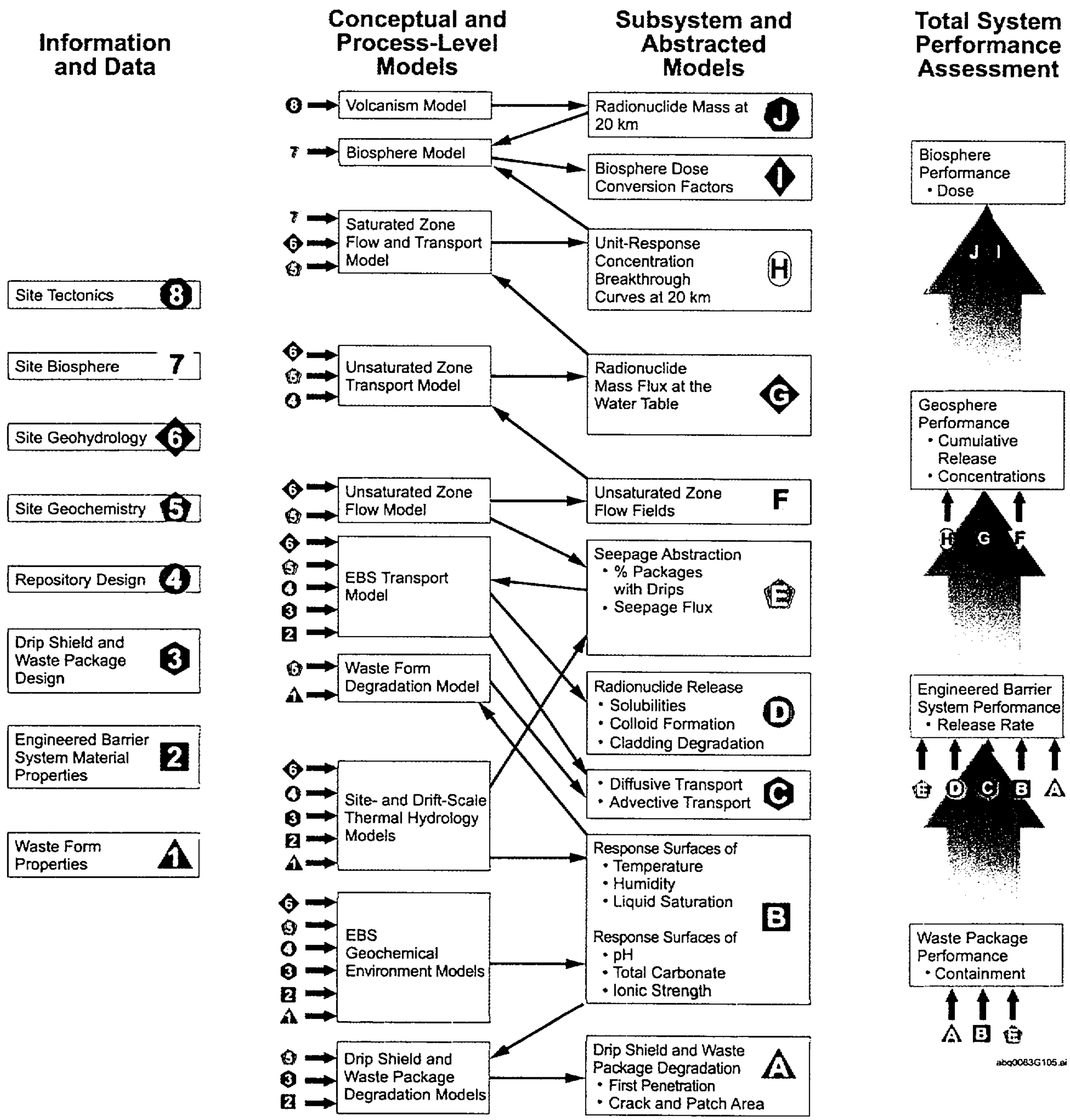

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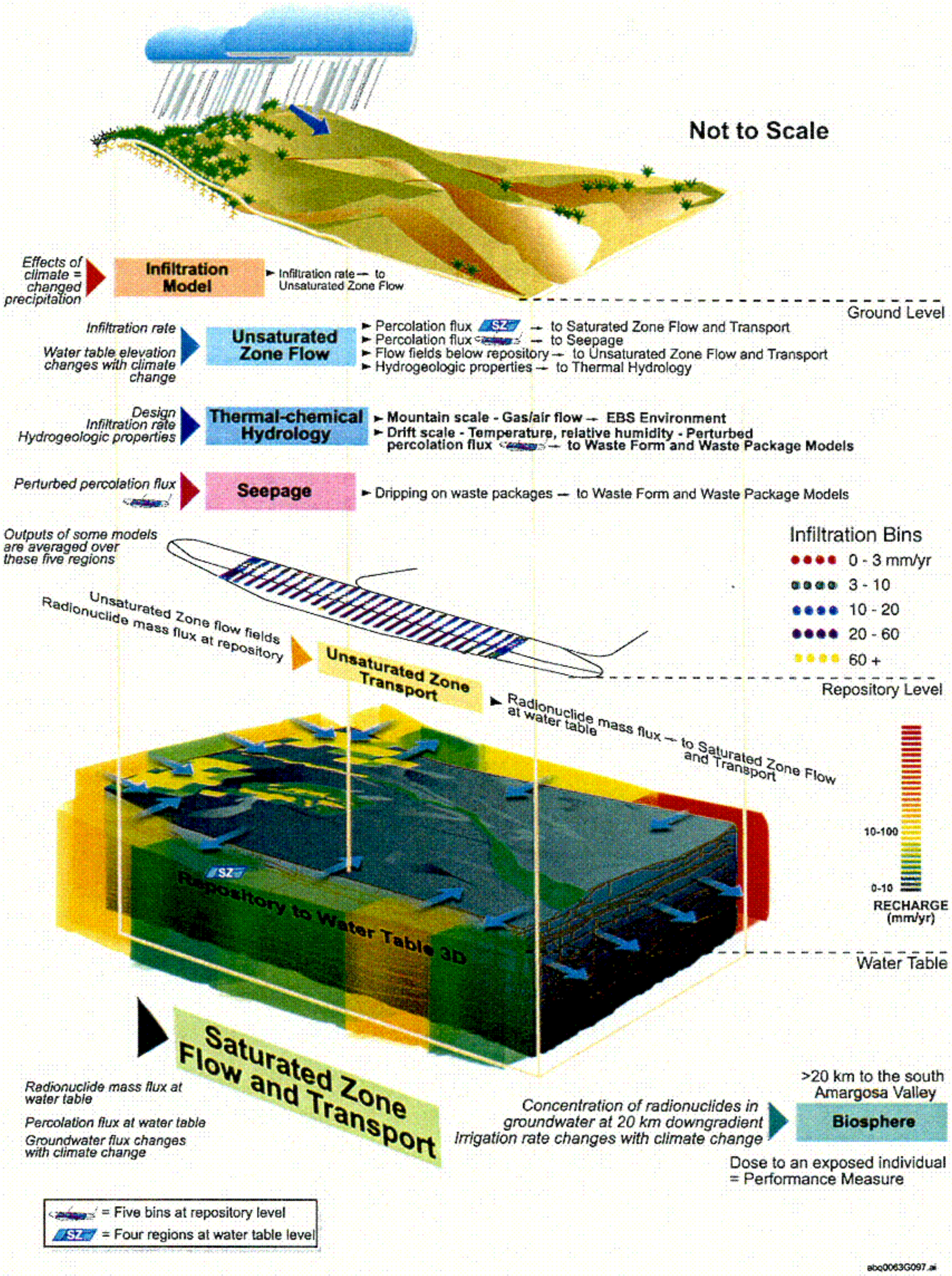
Figure 2.2-1. Simplified Representation of Information Flow in the Total System Performance Assessment-Site Recommendation between Data, Process Models, and Abstracted Models



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NOTE: The Figure is in two parts with the detail of the waste package and waste form models shown in Figure 2.2-2b.

Figure 2.2-2a. Detailed Representation of Information Flow in the Total System Performance Assessment-Site Recommendation

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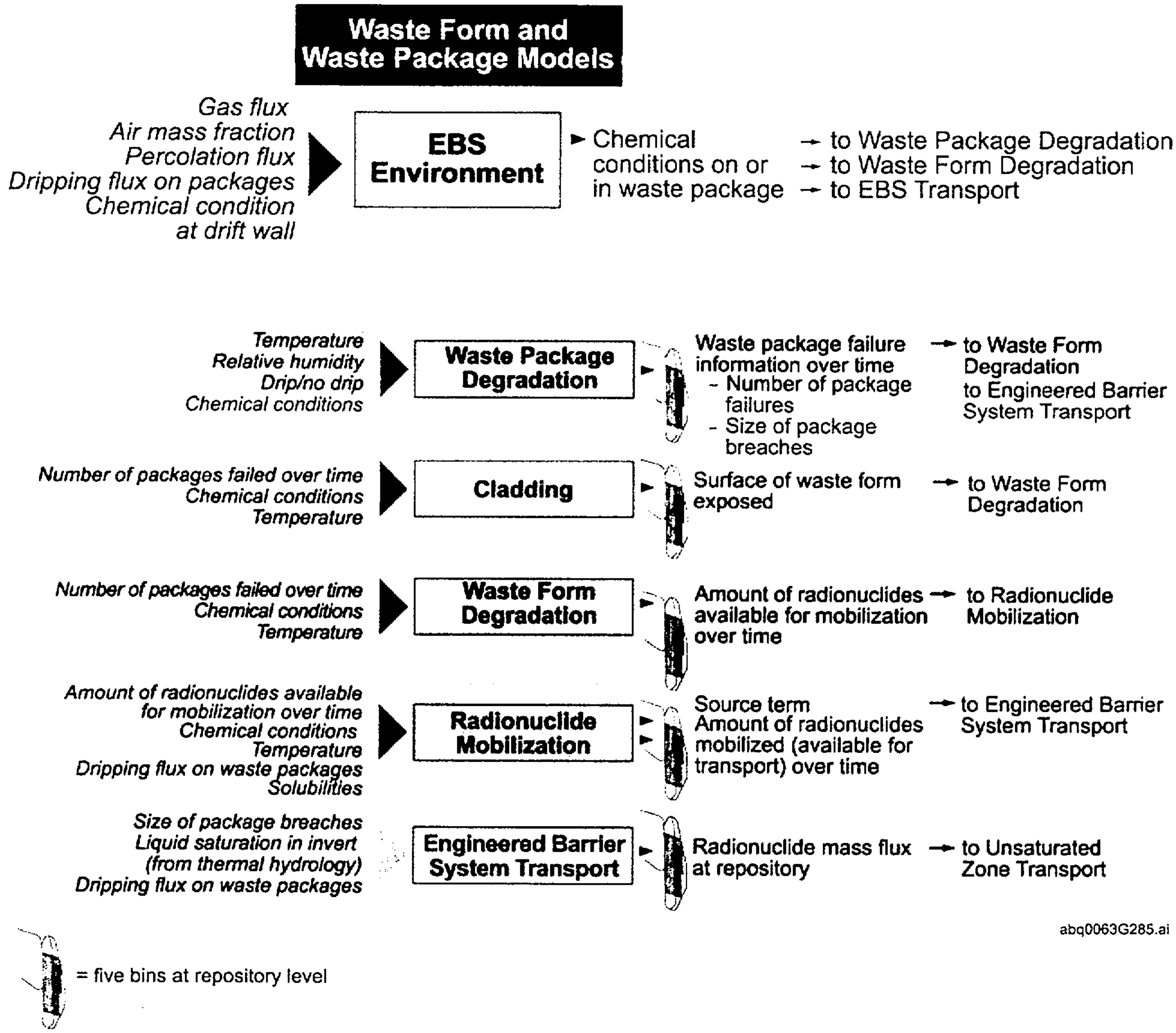

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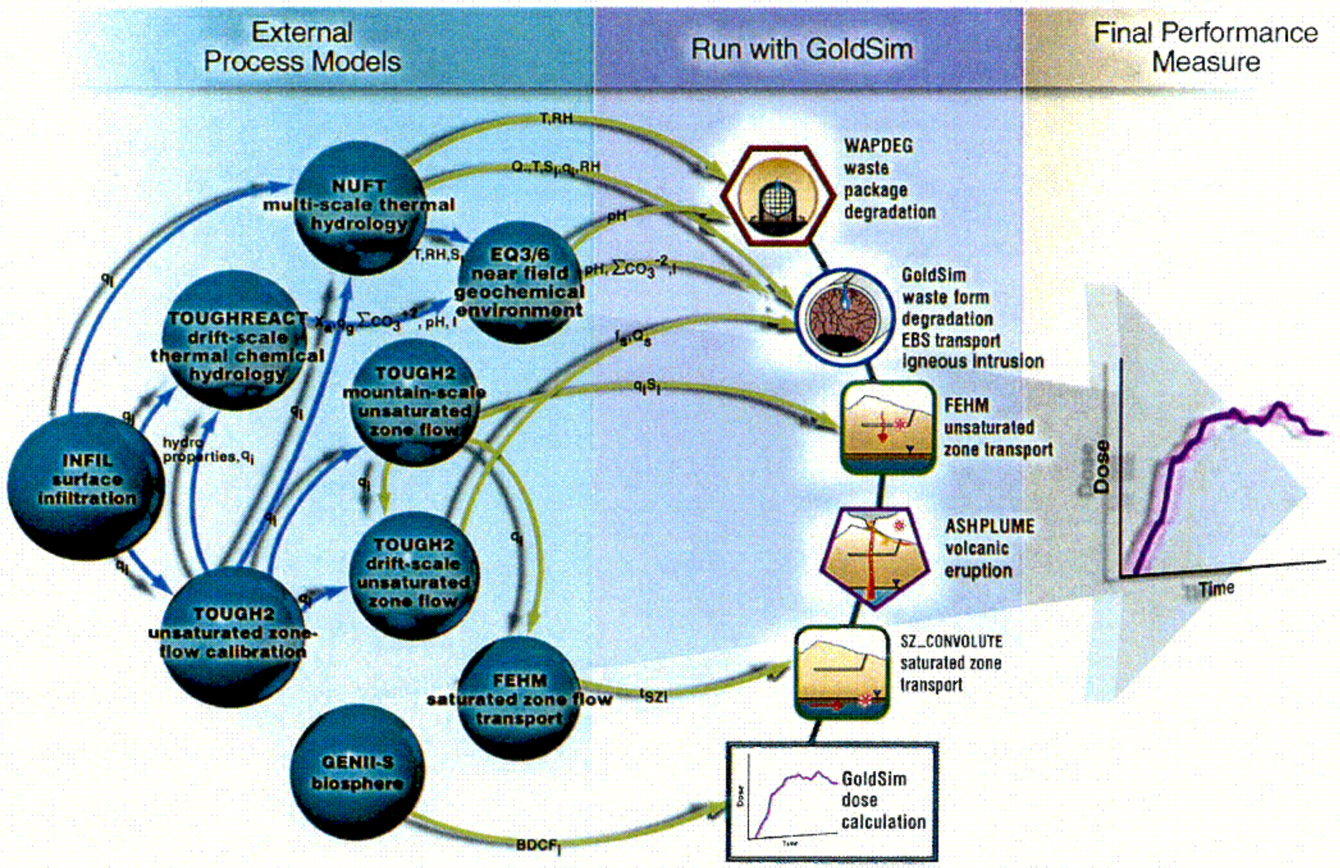
Figure 2.2-2b. Detailed Representation of Information Flow in the Total System Performance Assessment-Site Recommendation



Output Parameters

f_S	Fraction of WPs with Seeps	T	Temperature	I	Ionic Strength
EBS	Engineered Barrier System	RH	Relative Humidity	t_{SZi}	Saturated Zone Transport Time
Q_S	Seep Flow Rate	S_l	Liquid Saturation	$BDCF_i$	Biosphere Dose Conversion Factor
Q.	Evaporation Rate	X_a	Air Mass Fraction	q_g	Gas Flux
pH	pH	q_l	Liquid Flux		
ΣCO_3^{-2}	Carbonate Concentration	q_i	Infiltration Flux		

Legend

Response Surface Between Process Models

Response Surface from Process Model to GoldSim

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Figure 2.2-3. Total System Performance Assessment-Site Recommendation Code Configuration: Information Flow Among Component Computer Codes

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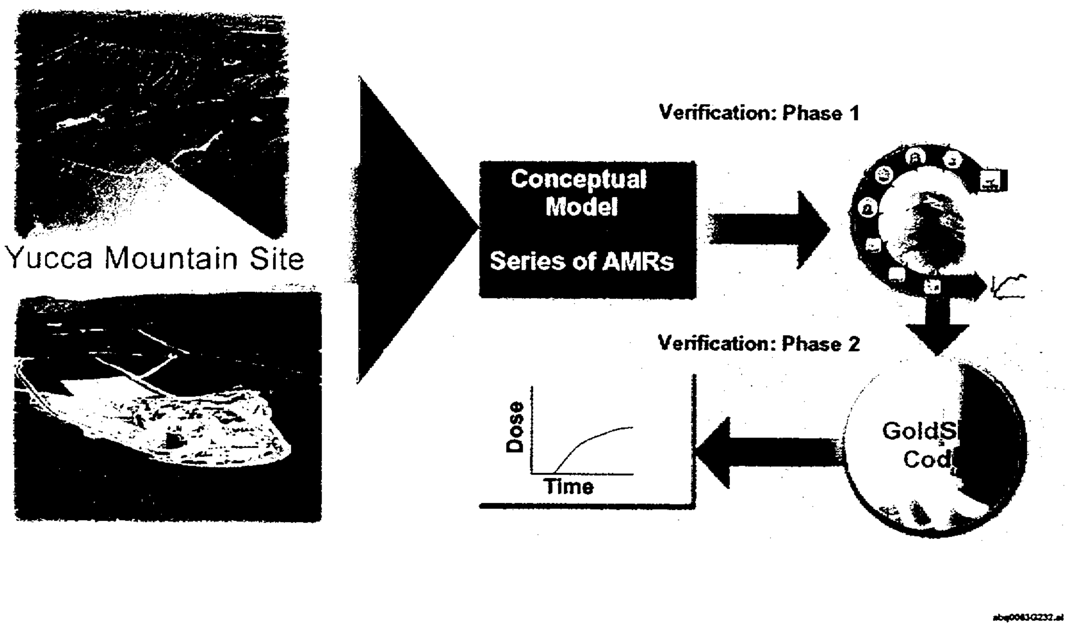

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Figure 2.2-4. Testing of Integrated Total System Performance Assessment-Site Recommendation Model

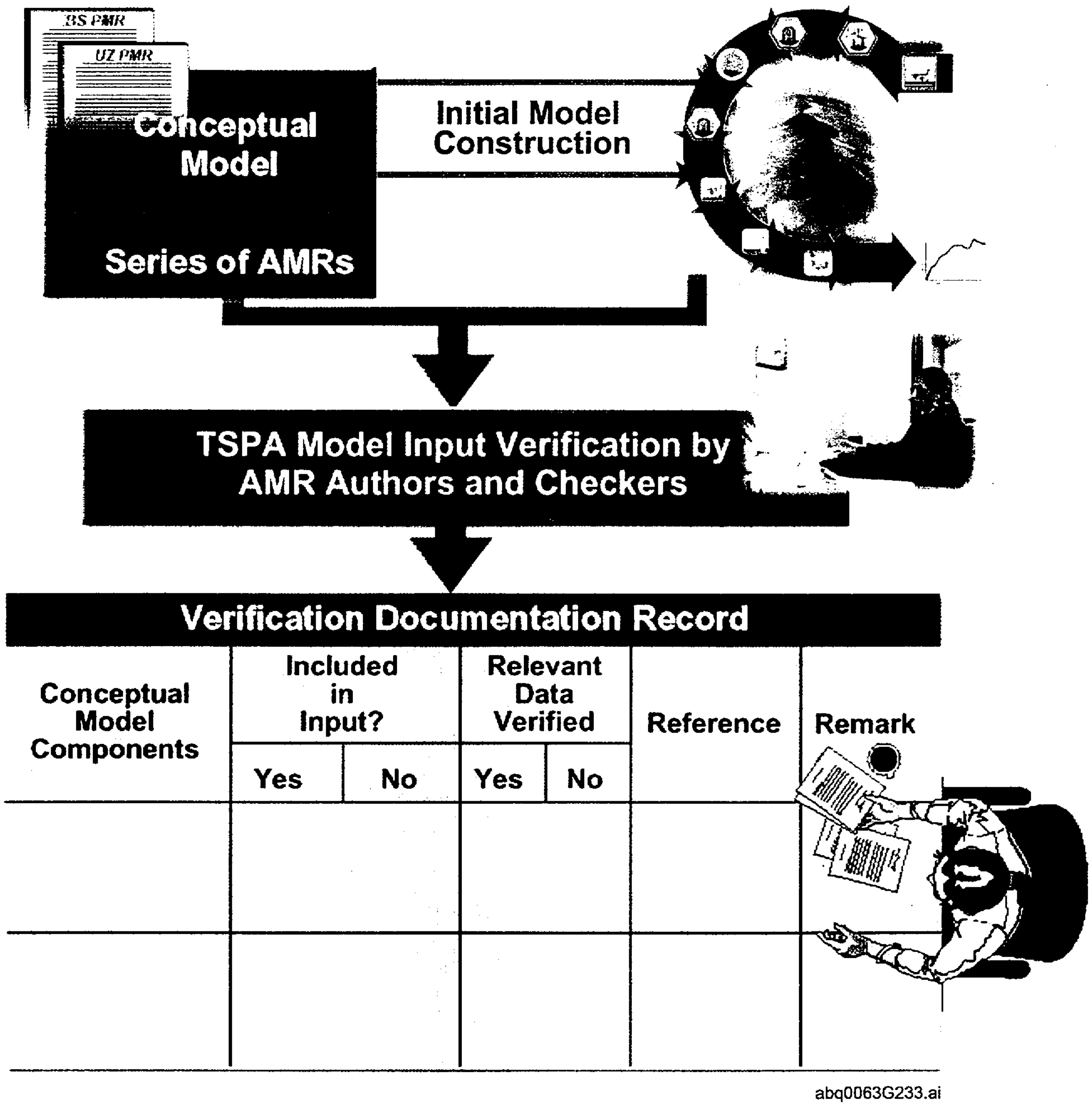

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Figure 2.2-5. Phase 1: Verification of Total System Performance Assessment-Site Recommendation Model

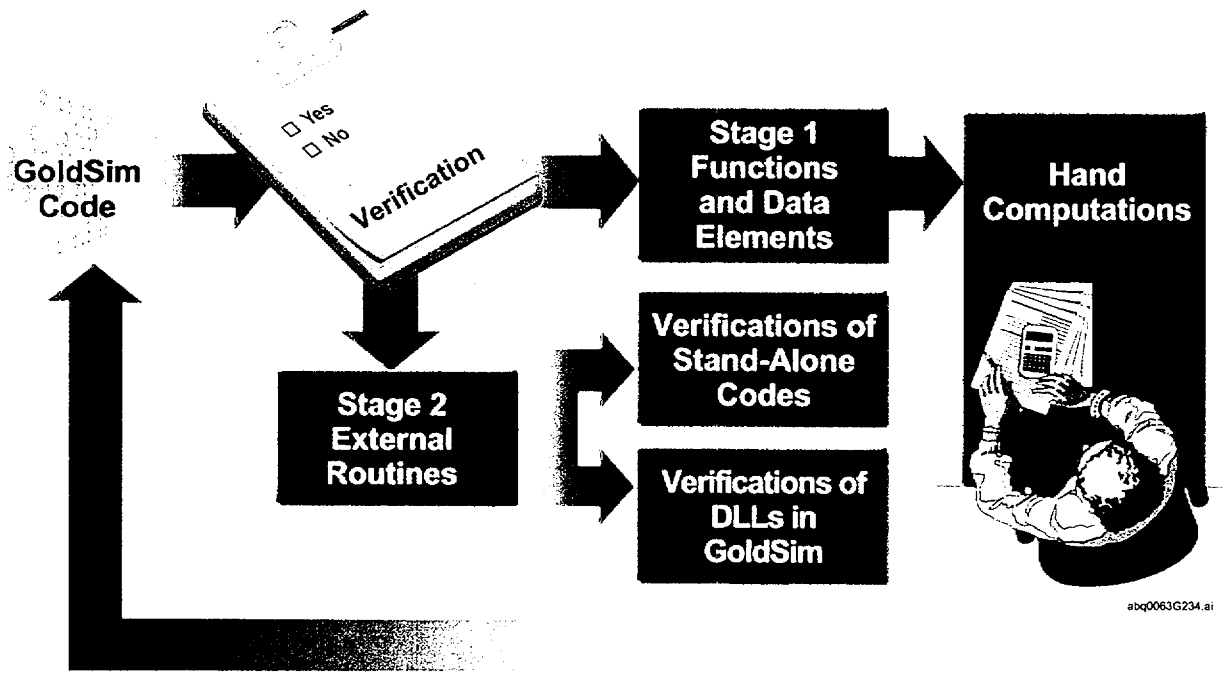

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Figure 2.2-6. Phase 2: Verification of Total System Performance Assessment -Site Recommendation Model (Stages 1 and 2)

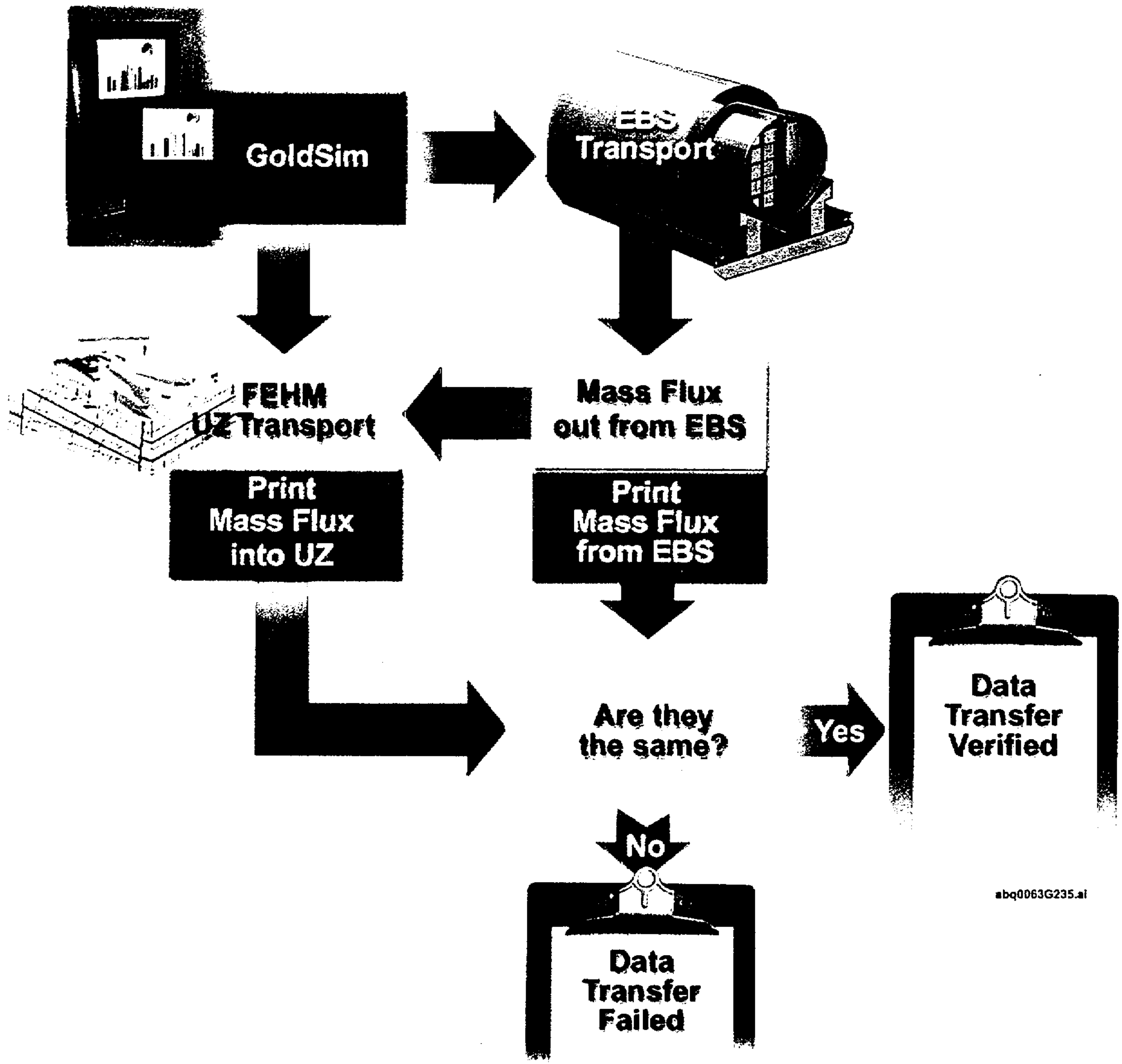

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Figure 2.2-7. Phase 2: Verification of Total System Performance Assessment -Site Recommendation Model (Stage 3)

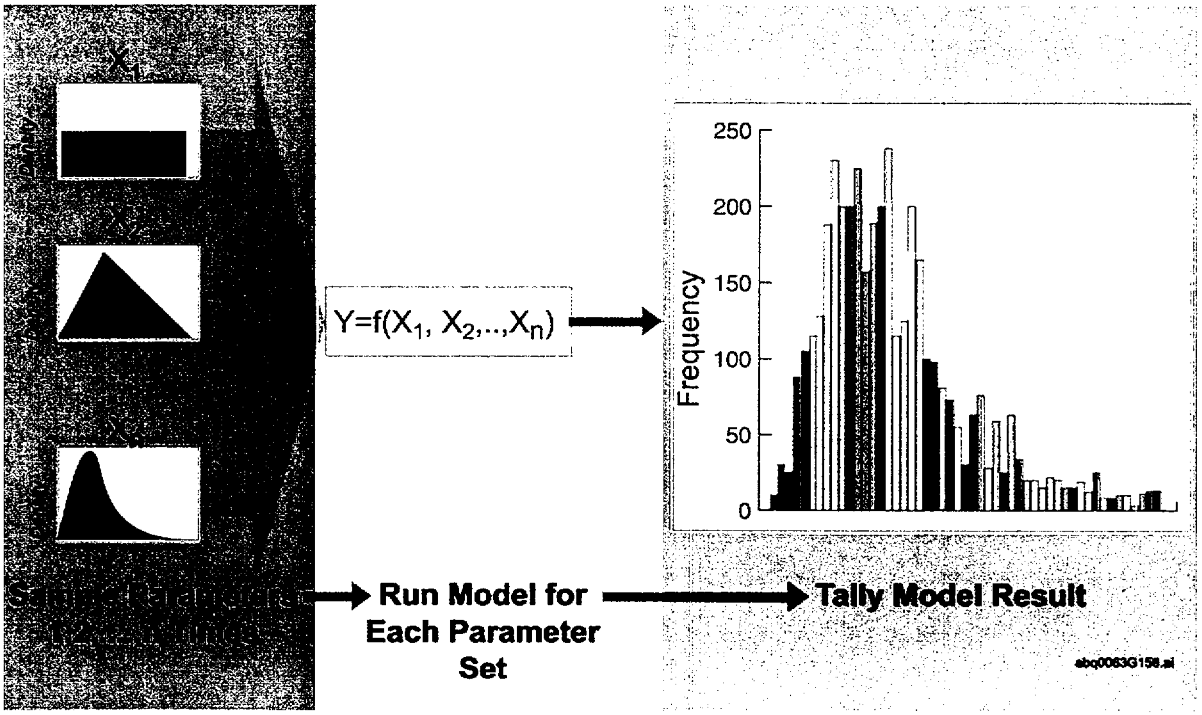

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Figure 2.2-8. Schematic of Monte-Carlo Simulation Methodology

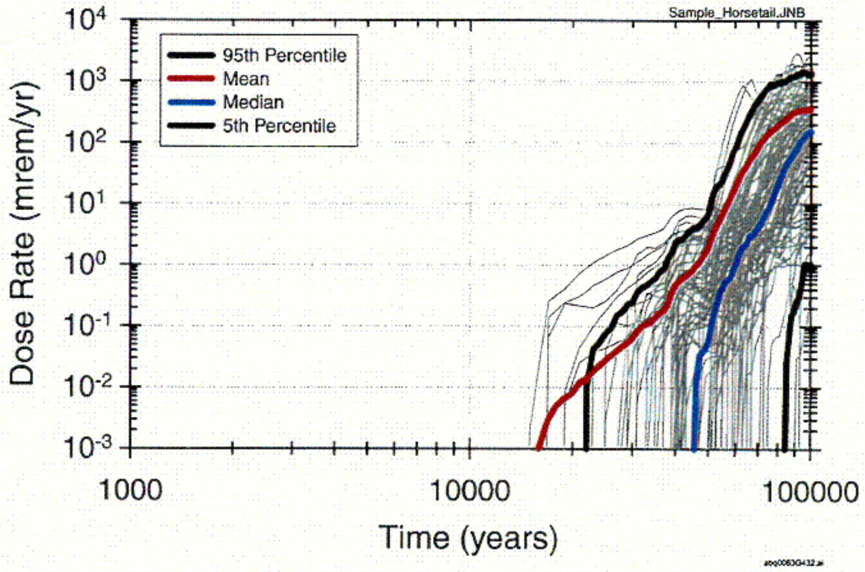

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Figure 2.2-9. Format for Presenting Probabilistic Model Results in Total System Performance Assessment-Site Recommendation

C06

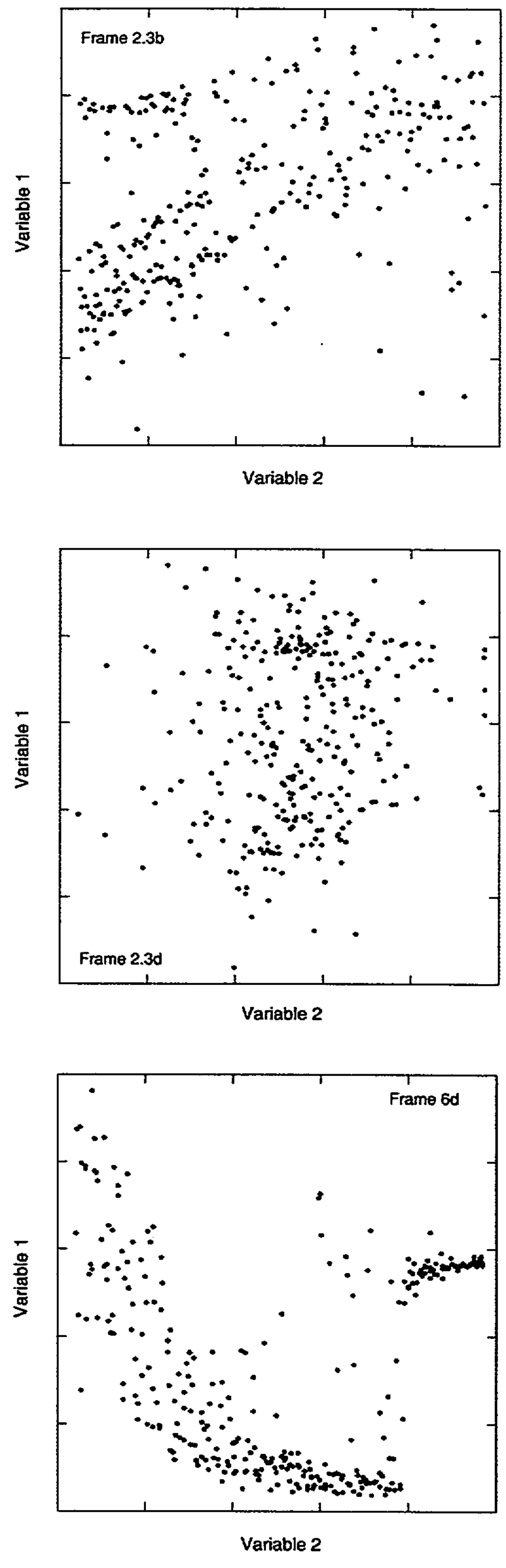

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Figure 2.2-10. Example Scatter Plots

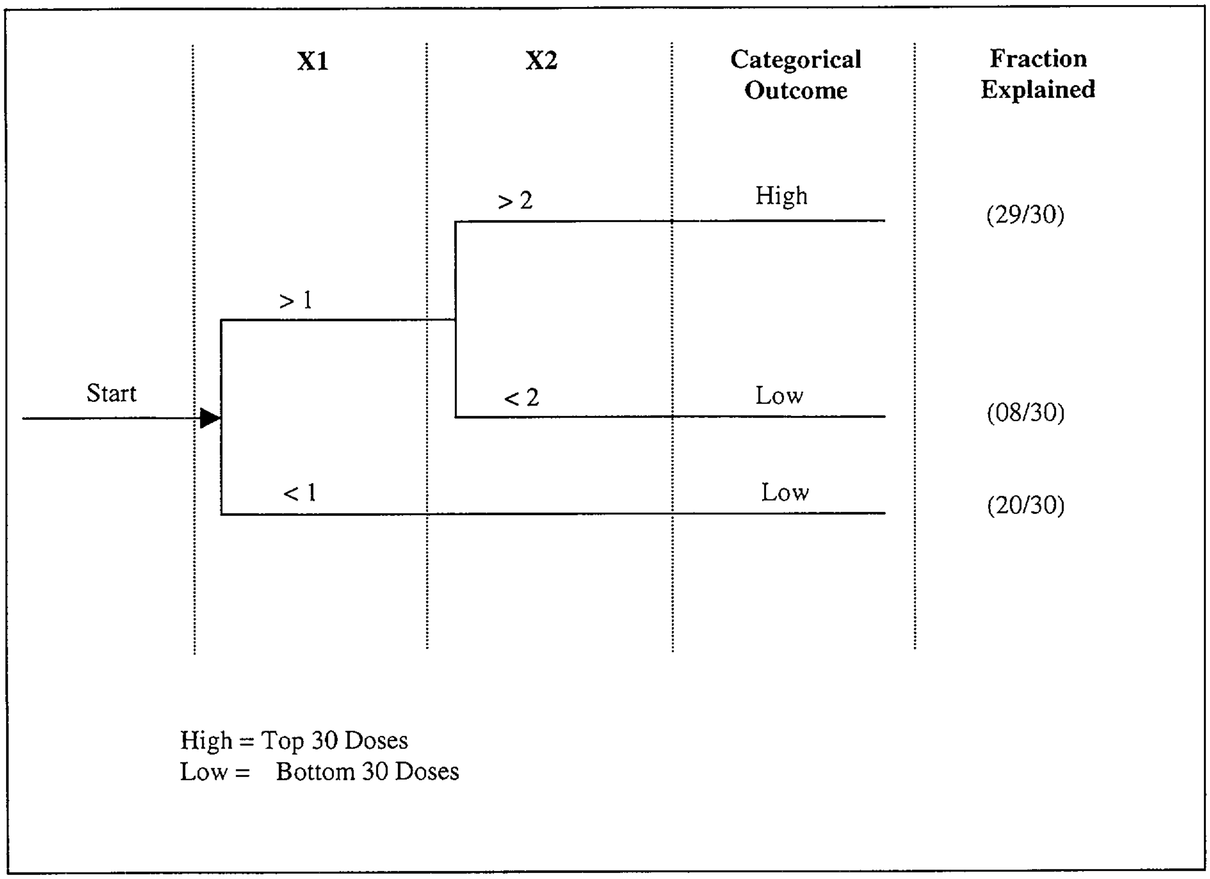

Figure 2.2-11. Example Binary Decision Tree

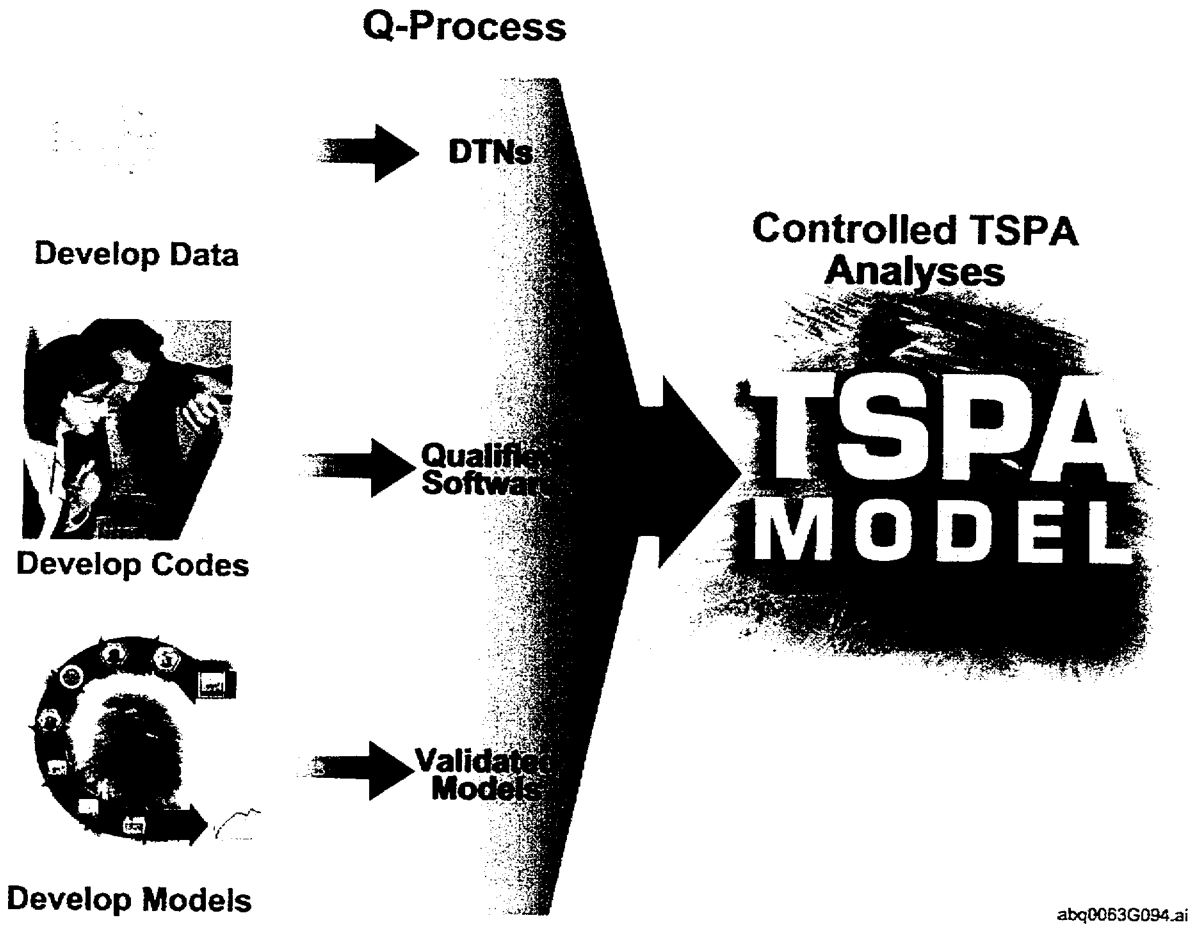

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Figure 2.2-12. Control of Total System Performance Assessment Model Development and Analyses

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Figure 2.2-13. Control of Information Flow into Total System Performance Assessment-Site Recommendation Model

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