U.S. Department of Energy
Office of Civilian Radioactive Waste Management

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Overview of U.S. Department of Energy Total System Performance Assessment for the Yucca Mountain Repository

Presented to:
Nuclear Waste Technical Review Board

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Outline

- Total System Performance Assessment - Introduction
- TSPA History
- Regulatory Requirements for Performance Assessment
- TSPA Process and Approach
- Barriers, Features, and Components in TSPA
- TSPA Model Architecture and Model Components
- Summary Model Changes for TSPA-LA
- Summary

Total System Performance Assessment (TSPA)

- **TSPA is a system-level analysis using numerical models of events and natural processes to evaluate future performance of a repository system's natural and engineered components**
  - **Future performance means performance after the operational period and emplacement of final seals**
- **TSPA models are based on the data collected during field, underground, and laboratory studies of natural and engineered system components, and consider the events and processes that may affect their behavior**
- **TSPA and supporting technical bases will be summarized in the License Application to be submitted by the DOE to the NRC**

Representative Uses of TSPA

- Evaluate regulatory requirements
- Quantify performance margin and barrier capability
- Determine most sensitive models and parameters
- Prioritize information and testing needs
- Evaluate design options/alternatives
- Evaluate consequences of features, events and processes
- Determine significance of data, parameter and model uncertainty
- Prioritize repository risks

Purpose of TSPA

- Performance Assessments provide answers to four questions:
  1. What events and processes can take place at the facility?
  2. How likely are these events or processes?
  3. What are the consequences of these events or processes?
  4. How reliable are the answers to the first 3 questions?
- TSPA evaluates the uncertainty in the evolution of the geologic setting and engineered barrier system
  - Predictive models are supported by field and lab tests, in-situ monitoring and natural analogs
  - Uncertainties in these models and associated parameters exist
- TSPA uses a range of defensible and reasonable parameter distributions and propagates the uncertainty to evaluate the effect and consequence

Yucca Mountain TSPAs

- System-level safety evaluations of a Yucca Mountain repository have been performed by DOE since the mid to late 1980s
- These analyses have been reviewed by NRC as part of Key Technical Issue resolution (KTI)
- NRC and EPRI have performed system-level analyses over this same time period
- All of the above analyses have been reviewed by technical oversight boards (NWTRB and ACNW)
- The DOE TSPA has been peer reviewed twice
  - Budnitz, Ewing, Moeller, Payer, Whipple and Witherspoon 1999
  - OECD/NEA-IAEA, 2002

"An International Peer Review of the Yucca Mountain Project TSPA-SR"

- This document observed:
  - . . . the general approach to TSPA, and the USDOE approach of building on an iterative series of performance assessments conform to international best practice. . . .
  - . . . structure of the TSPA-SR methodology, and . . . [the] approach of building on an iterative series of performance assessments, conform to international best practice.
  - The structured abstraction process linking process-level models to assessment models is at the forefront of international developments.
  - . . . the FEP methodology. . . [is] in agreement with international best practice, . . .
  - . . . places far greater emphasis on probabilistic assessment than equivalent programs in other countries . .
  - . . . does not emphasize natural analogues as much as in some other international studies.
  - "While presenting room for improvement, was soundly based and has been implemented in a competent manner."

International Approaches for Probabilistic TSPA

- The nations primarily relying on a probabilistic approach are the US, UK, Canada, Belgium and the Netherlands.
- Probabilistic and deterministic PA demonstrations have been performed by Spain, Germany, Belgium and the Netherlands as part of a study sponsored by the European Commission
- Sweden, Switzerland and Japan have done limited probabilistic analyses to provide insight on specific aspects of their deterministic system-level analyses.
- For those countries using deterministic approaches, uncertainty is evaluated using a range of sensitivity calculations

History of DOE Yucca Mountain TSPAs

TSPA Iteration	Summary of Key Results
1988 Site Characterization Plan	• Applied basic methodology for Monte Carlo uncertainty analyses based on scenarios.
TSPA-1991	• Demonstration of TSPA approach. • Models limited to UZ and SZ, and volcanism identified importance of uncertainty in UZ flow paths.
TSPA-1993	• Improved models for UZ, SZ, early models for coupled processes, EBS, biosphere. • Importance of uncertainty in thermal hydrology, UZ flow, corrosion of engineered materials.
TSPA-1995	• Incorporate new science and design, evaluate alternative models. • Importance of robust process models for WP degradation, seepage, UZ and SZ transport.
TSPA-VA	• Supported the 1998 Viability Assessment, models based on best current information. • Ranked importance of uncertainty in each of the major components for 10,000, 100,000, and 1,000,000 years. • Emphasis on seepage, water chemistry, corrosion, and SZ.
1999 License Application Design Selection (LADS)	• TSPA tools used to evaluate relative merits of design alternatives. • Demonstrated that multiple designs were viable for long-term performance.
TSPA for Site Recommendation (2000)	• Robust modeling system using fully qualified inputs • Conservative approach to some components. • Regulatory importance of volcanism identified. • Conservative treatments of uncertainty complicated realistic understanding.
FY 2001 Supplemental Science and Performance Analyses (SSPA)	• More realistic treatment of uncertainty. • Incorporation of new information since TSPA-SR. • Confirmed potential suitability. • Confirmed importance of volcanism and EBS performance for 10,000 years. • Insights into EBS and natural system effects on peak dose.
TSPA for the Final Environmental Impact Statement (2001)	• Updated SSPA to include new information, revised regulatory boundary.
2002 Sensitivity Analyses (one-on and one-off)	• Insight into barrier performance. • Risk-importance information regarding model components. • Importance of volcanic disruption for 10,000-yr regulatory compliance.
TSPA-LA	• Models updated to current information.

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Post Closure Performance Objectives

- **§ 63.113 Performance objectives for the geologic repository after permanent closure**
  - **(a) The geologic repository must include multiple barriers, consisting of both natural barriers and an engineered barrier system**
  - **(b) Radiological exposures to the reasonably maximally exposed individual are within the limits specified at § 63.311**
  - **(c) Releases of radionuclides into the accessible environment are within the limits specified at § 63.331**
  - **(d) Radiological exposures to the reasonably maximally exposed individual, in the event of human intrusion must be demonstrated through an analysis that meets the requirements at §§ 63.321 and 63.322**

Postclosure Performance Assessment

- **§ 63.114 Requirements for performance assessment**

  Any performance assessment used to demonstrate compliance with § 63.113 must:

  (a) Include data related to the geology, hydrology, and geochemistry (including disruptive processes and events)

  (b) Account for uncertainties and variabilities in parameter values

  (c) Consider alternative conceptual models of features and processes

  (d) Consider only events that have at least one chance in 10,000 of occurring over 10,000 years

  (e) Provide the technical basis for either inclusion or exclusion of specific features, events, and processes in the performance assessment

  (f) Provide the technical basis for either inclusion or exclusion of degradation, deterioration, or alteration processes of engineered barriers in the performance assessment

  (g) Provide the technical basis for models used in the performance assessment

Postclosure Performance Assessment
(continued)

- § 63.115 Requirements for multiple barriers
  - (a) Identify those design features of the engineered barrier system, and natural features of the geologic setting, that are considered barriers important to waste isolation.
  - (b) Describe the capability of barriers, identified as important to waste isolation, to isolate waste, taking into account uncertainties in characterizing and modeling the behavior of the barriers.
  - (c) Provide the technical basis for the description of the capability of barriers

Regulatory Requirements: Individual Protection Requirements

- 10 CFR 63.311 ---- 15 mrem/yr dose limit
- 10 CFR 63.312 ---- Dose to be calculated for reasonably maximally exposed individual (RMEI)
    - Mean values of current lifestyle and diet; drinks 2 liters/day of groundwater
    - Annual water demand of 3,000 acre-feet
- 10 CFR 63.341 ---- Peak dose after 10,000 yr in EIS
- 10 CFR 63.342 ---- Need to consider features, events and processes (FEPs) more likely than 1 in 10,000 in 10,000 years

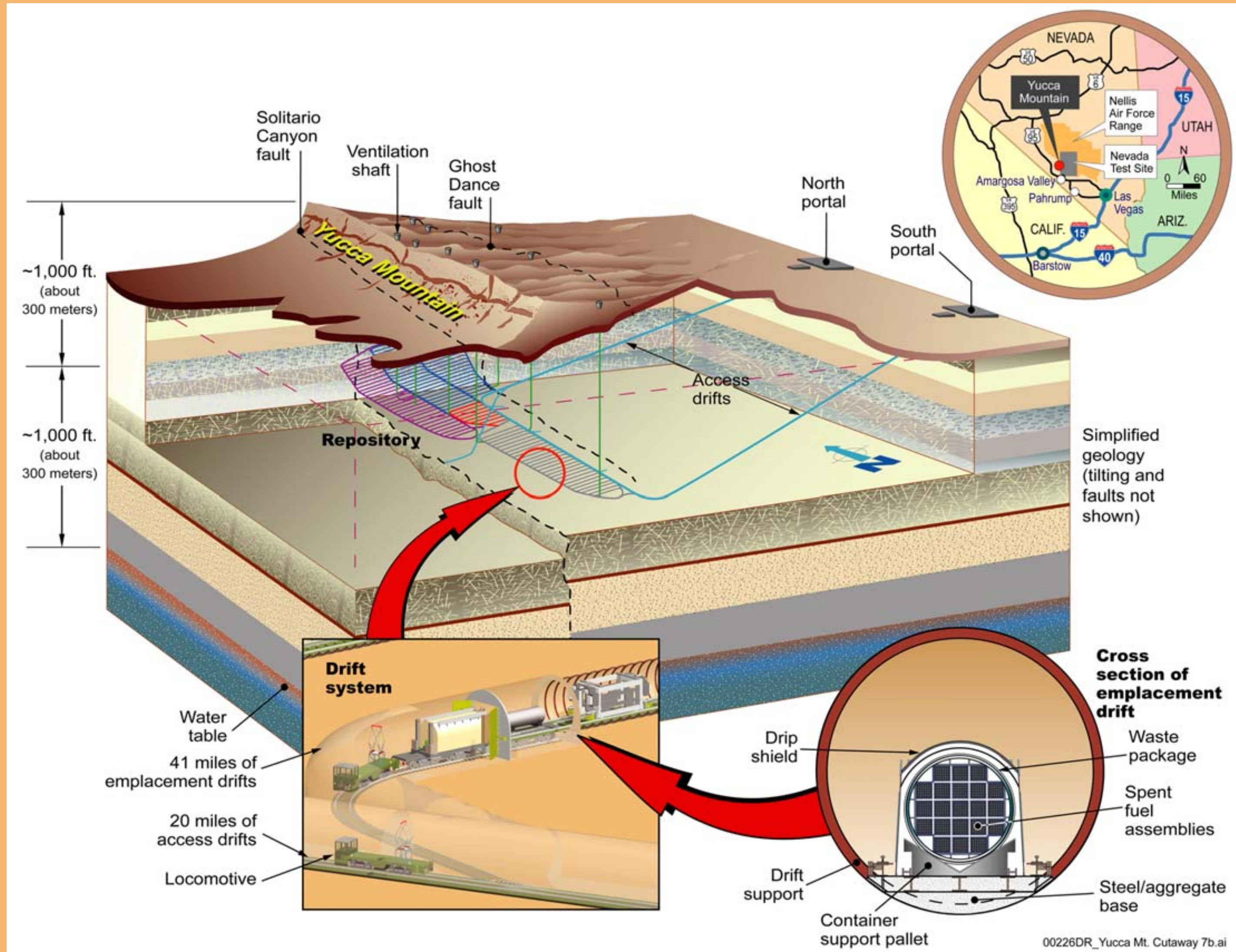
Regulatory Requirements: Groundwater Protection Standard

- **10 CFR 63.331 ---- Maximum contaminant levels for radionuclides in representative volume**
  - **Includes 4 mrem/yr dose limit for beta/gamma based on consumption of 2 liters/day**
  - **Compliance point at 18 km controlled area boundary**
- **10 CFR 63.332 ---- Representative volume is 3,000 acre-feet per year**
- **10 CFR 63.342 ---- Exclude FEPs less likely than 1 in 10 in 10,000 years**

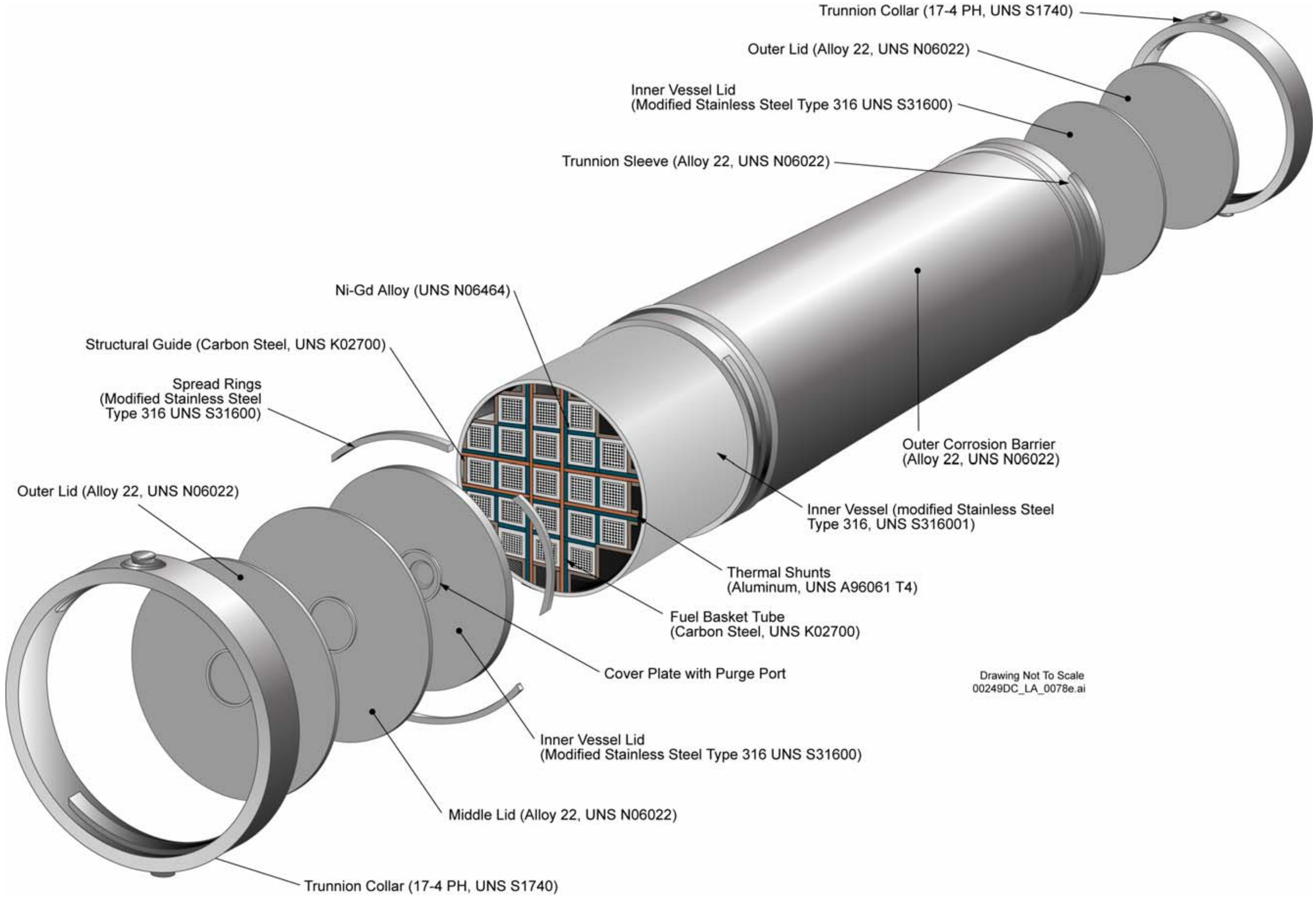
Regulatory Requirements: Human Intrusion Standard

- **10 CFR 63.321 ---- Dose limit 15 mrem/yr to RMEI at 18 km**
  - If intrusion can occur at or before 10,000 years after disposal without recognition by drillers
  - If intrusion occurs after 10,000 years, report in EIS
- **10 CFR 63.322 ---- Single event; borehole drilled through degraded waste package and into aquifer**
  - borehole not carefully sealed
- **10 CFR 63.342 ---- Exclude FEPs less likely than 1 in 10 in 10,000 years**

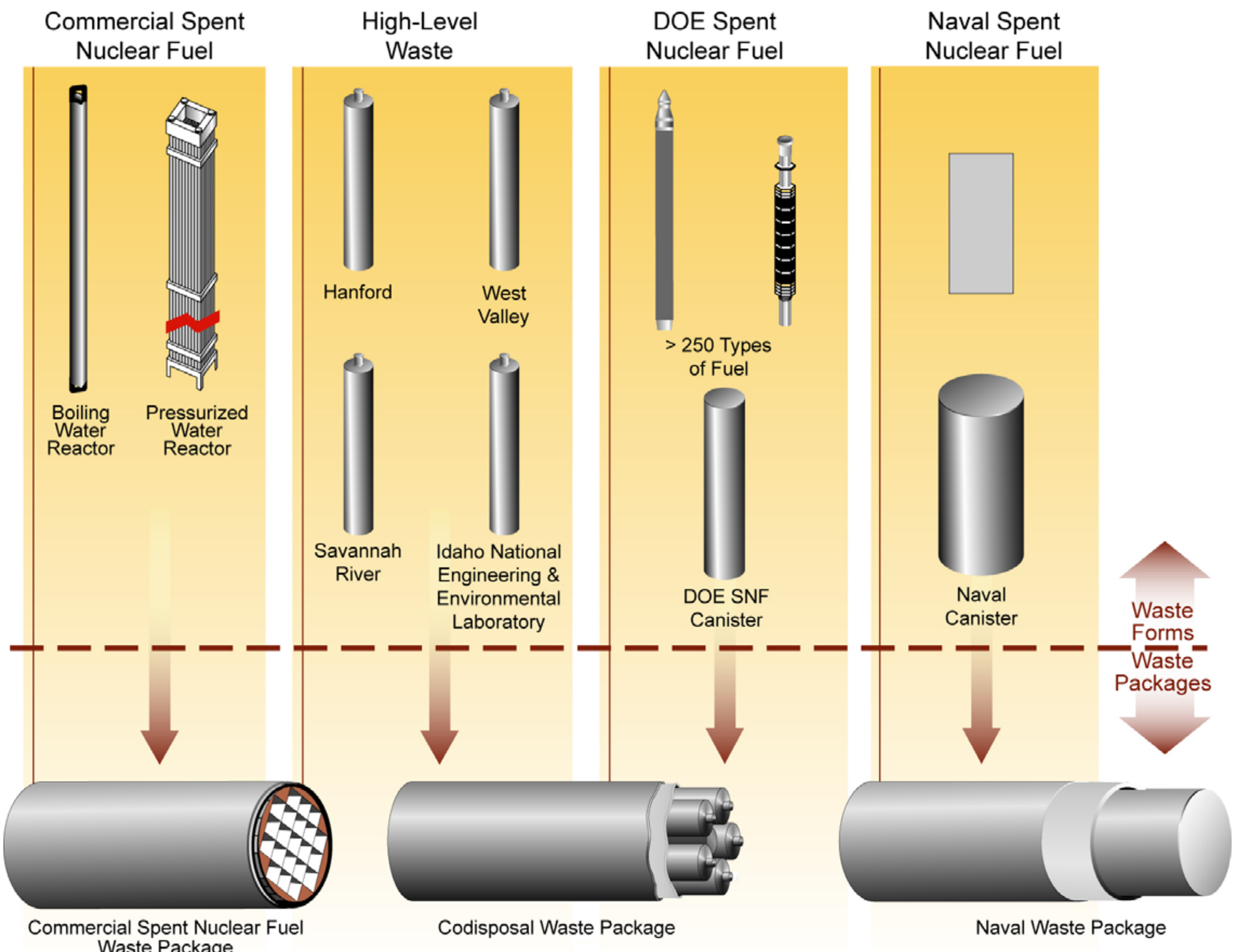
Repository Reference Design Concept



Waste Package Design



Waste Form Types



Drawing Not To Scale
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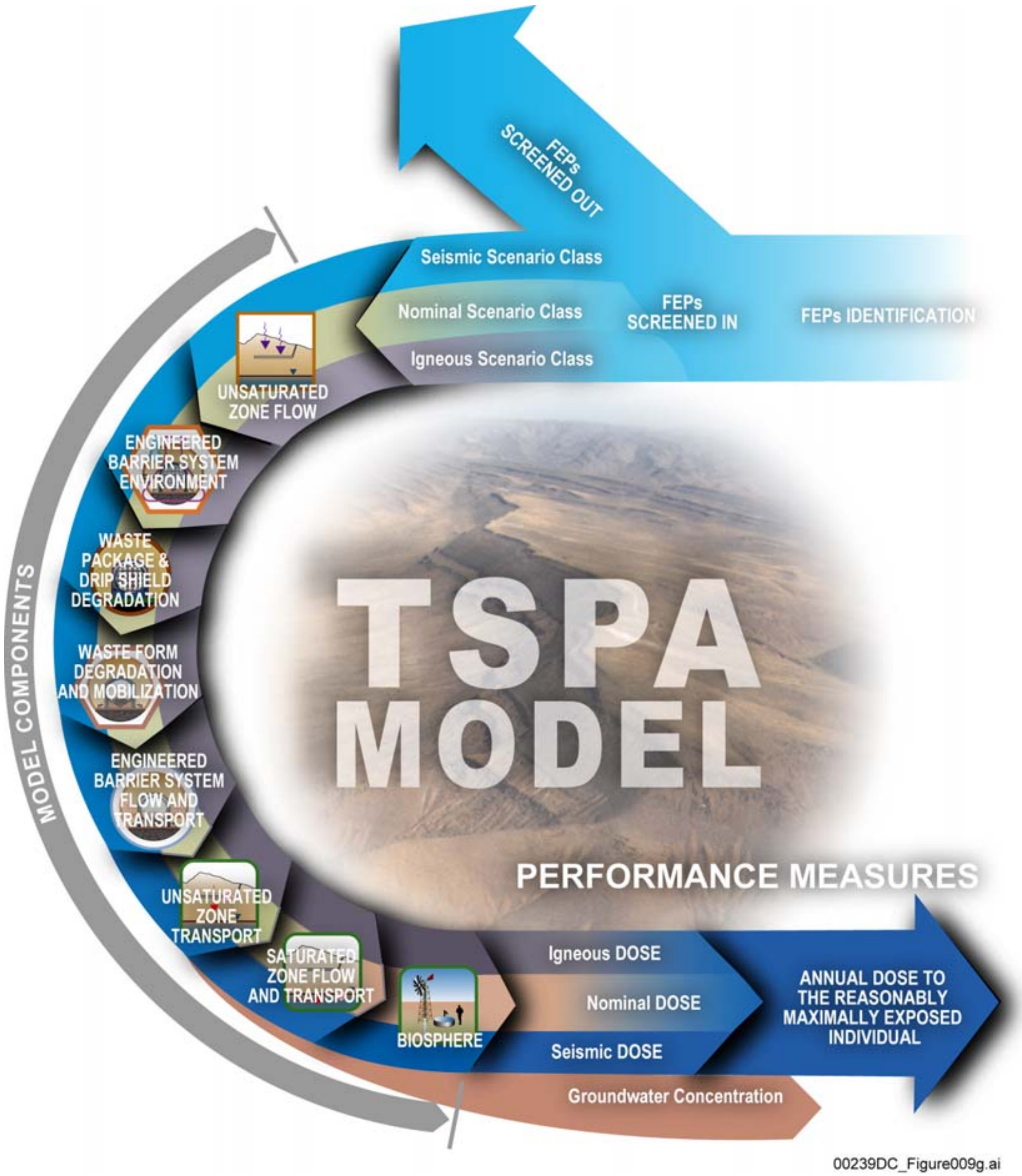
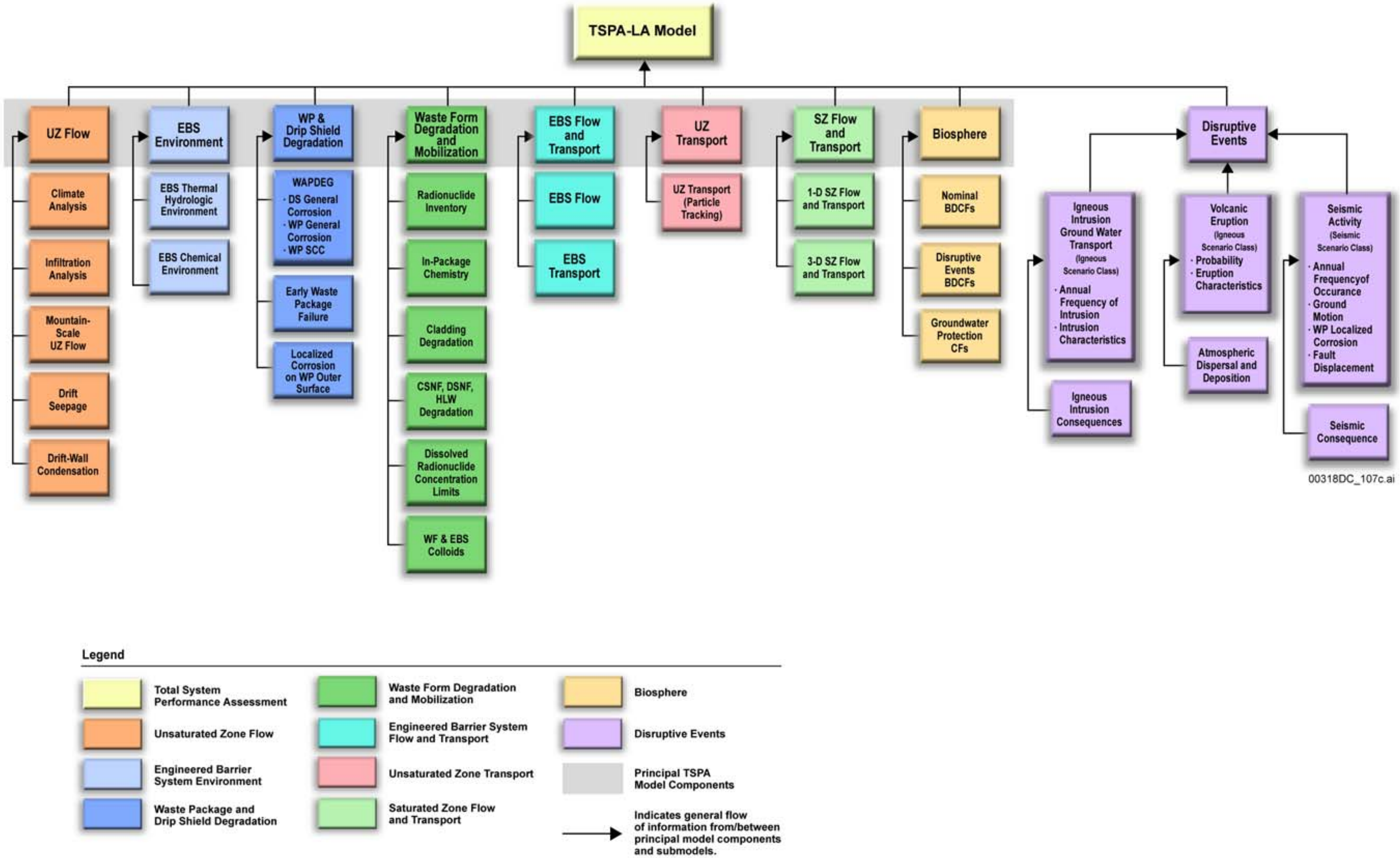
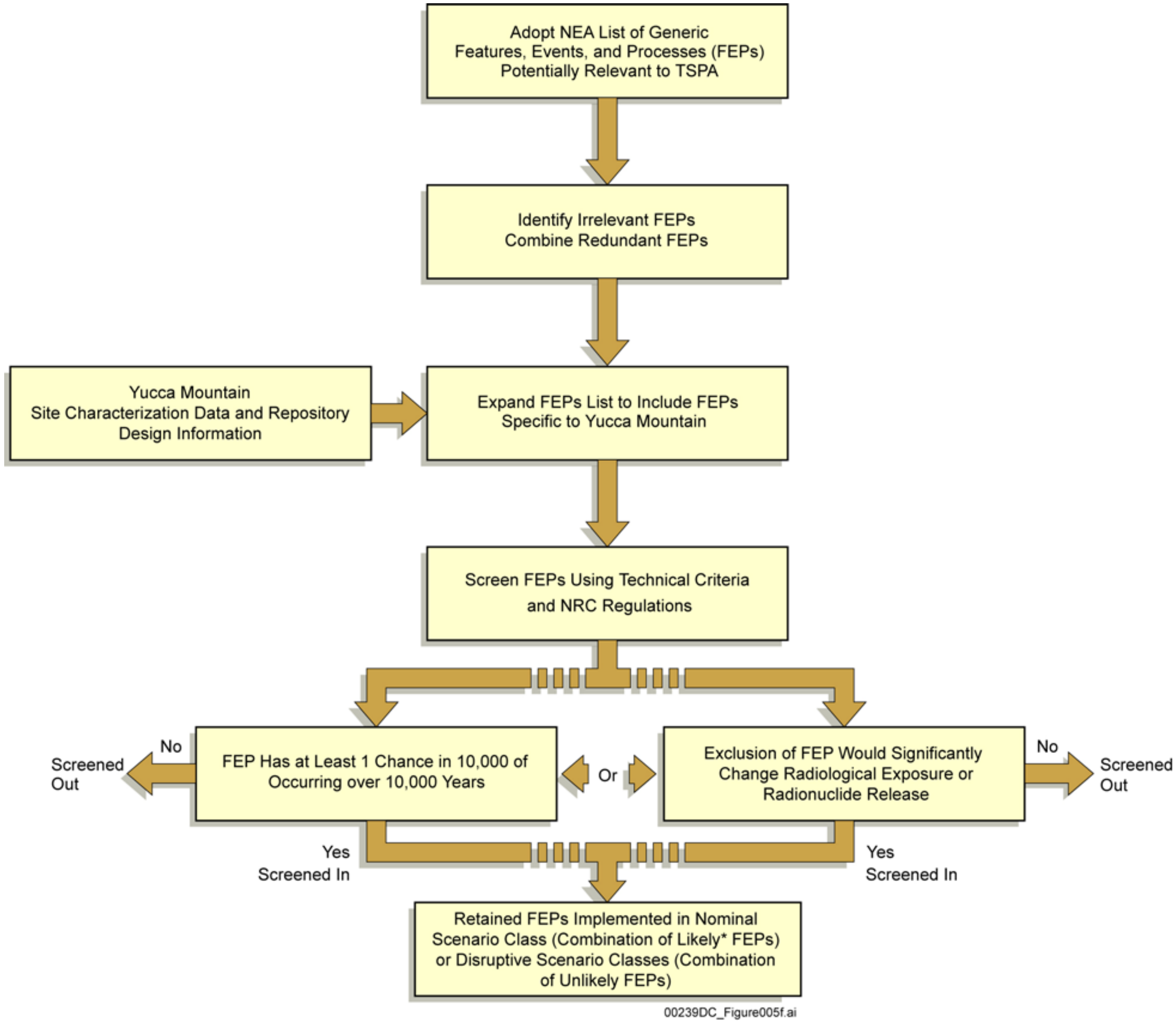
TSPA Role in Performance Assessment



Model Abstractions in TSPA



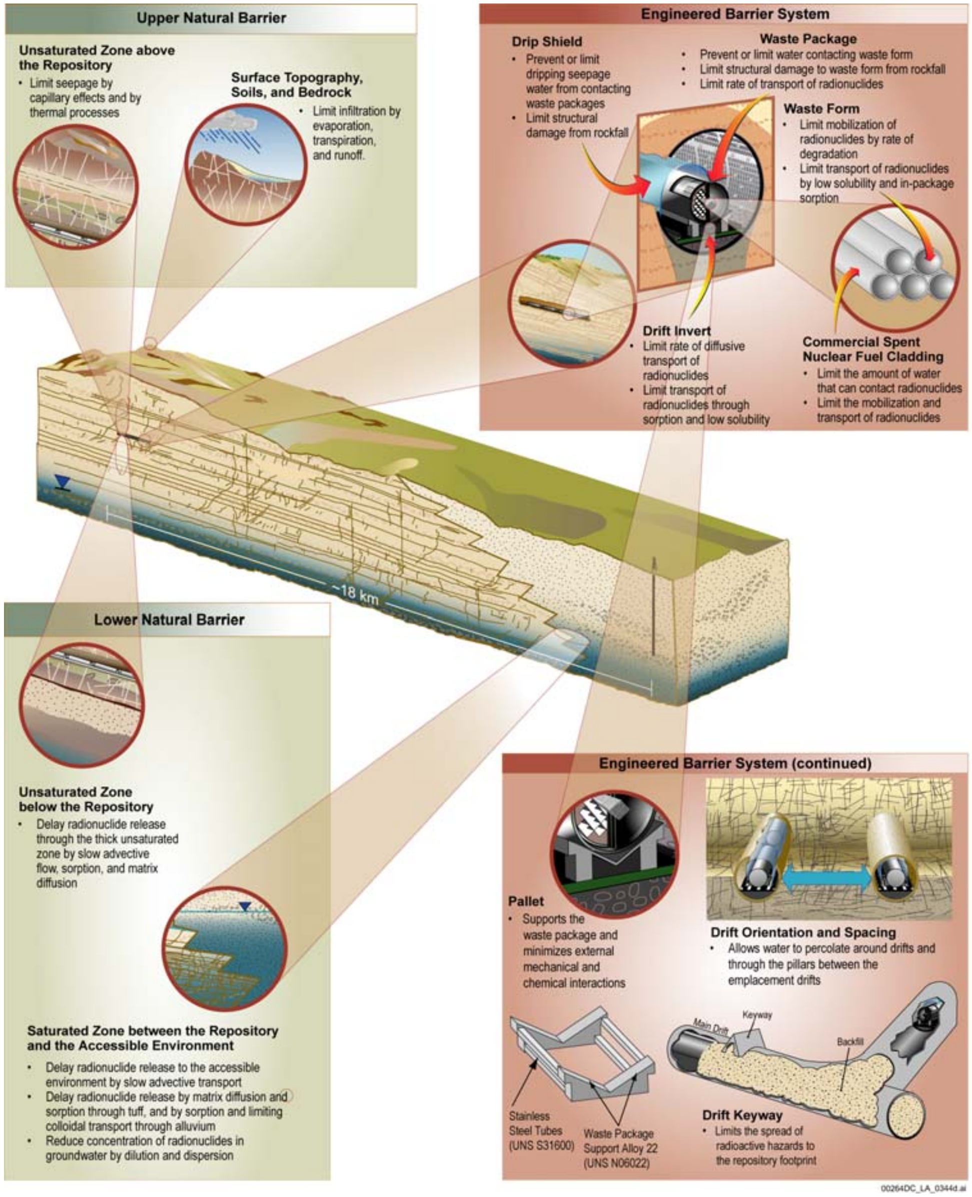
FEPs Evaluation Process



TSPA Process

- Screen features, events, and processes to determine those to be evaluated in performance assessment
- Develop models, along with their scientific basis, for each feature, event and process included in TSPA
- Evaluate uncertainty in models and parameters
- Construct integrated TSPA model using all retained features, events and processes in scenario classes
  - Nominal scenario classes contain all features, events, and processes likely to occur (including climate change)
  - Disruptive event scenario class contains unlikely events (e.g., igneous and seismic)
- Evaluate total-system performance in terms of individual protection and groundwater protection standards; incorporating uncertainty through Monte Carlo simulation

Barriers, Features, and Components in TSPA



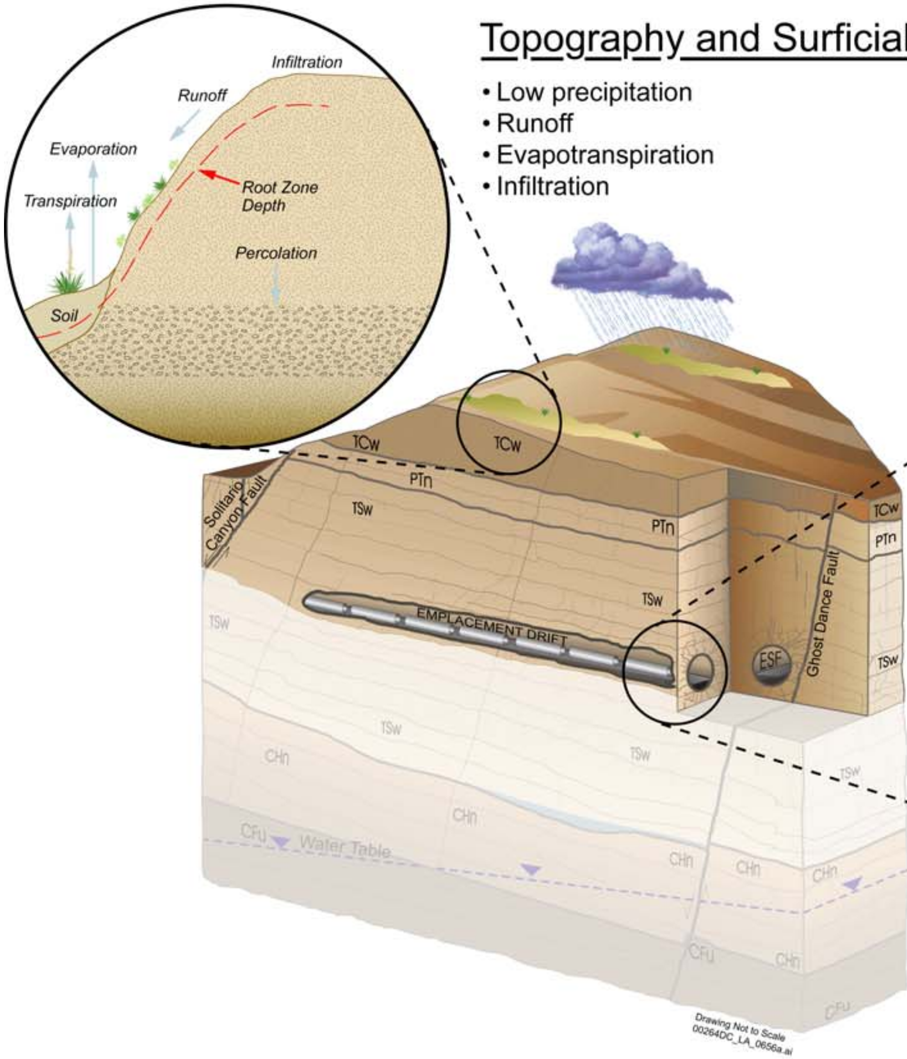
Features and Components

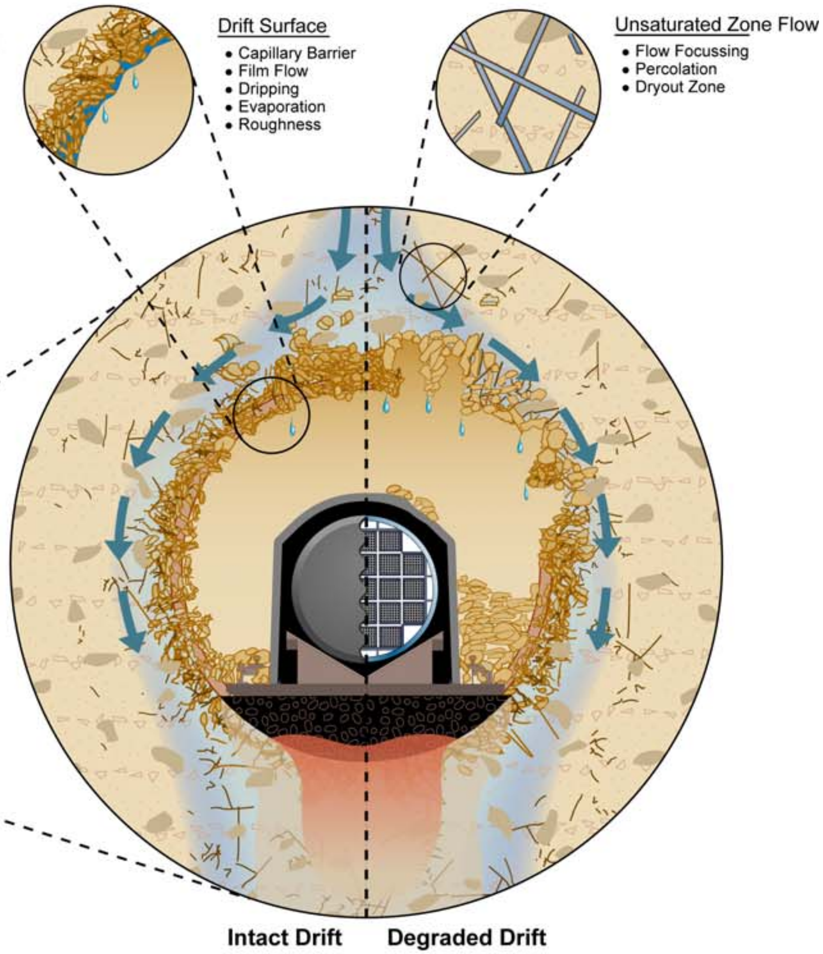
- Surface soils and topography
- Unsaturated zone above the repository
- Drip shield
- Waste package
- Cladding
- Waste form
- Invert
- Unsaturated zone below the repository
- Saturated zone

Upper Natural Barrier

Topography and Surficial Soils

- Low precipitation
- Runoff
- Evapotranspiration
- Infiltration

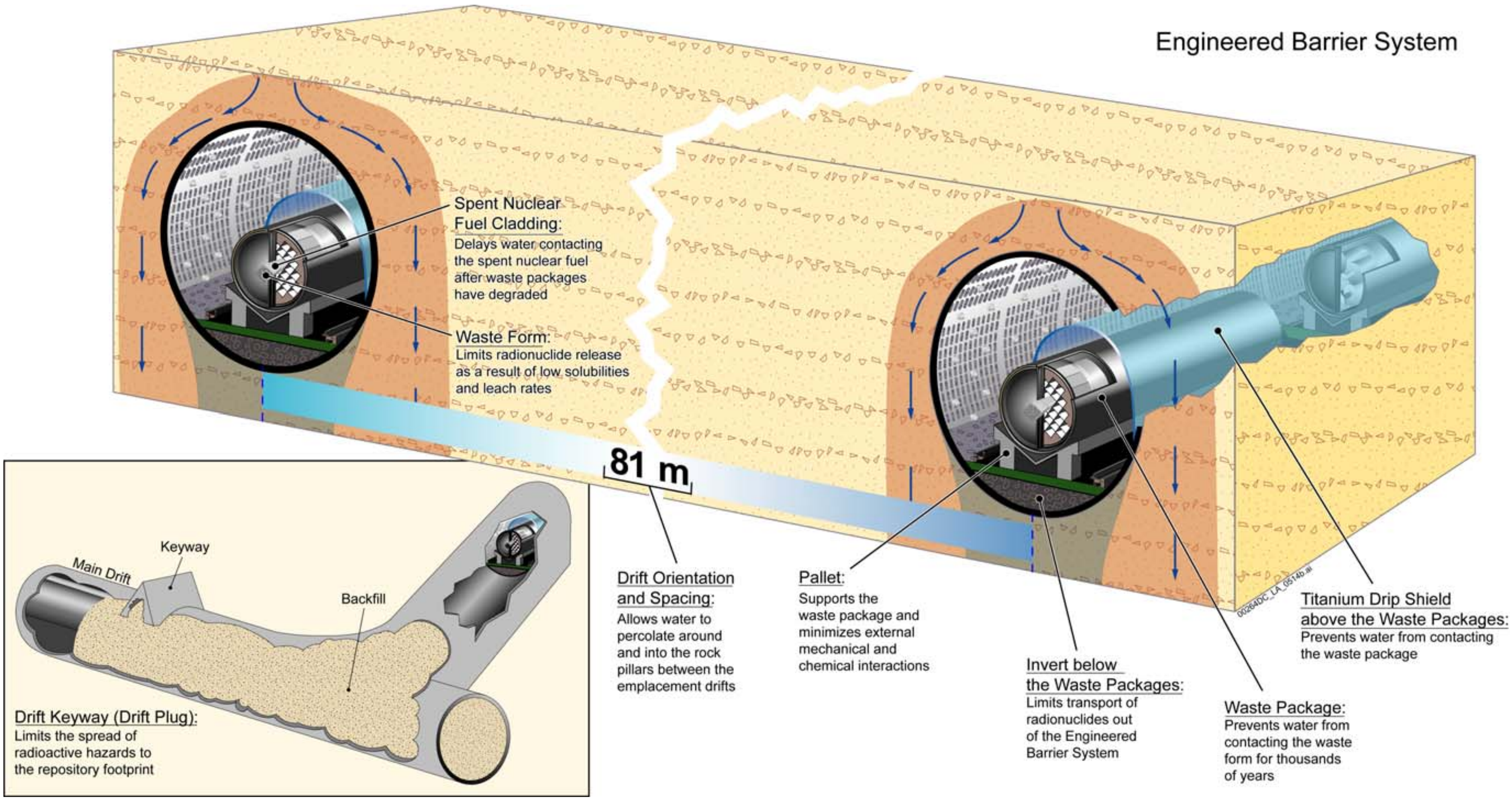




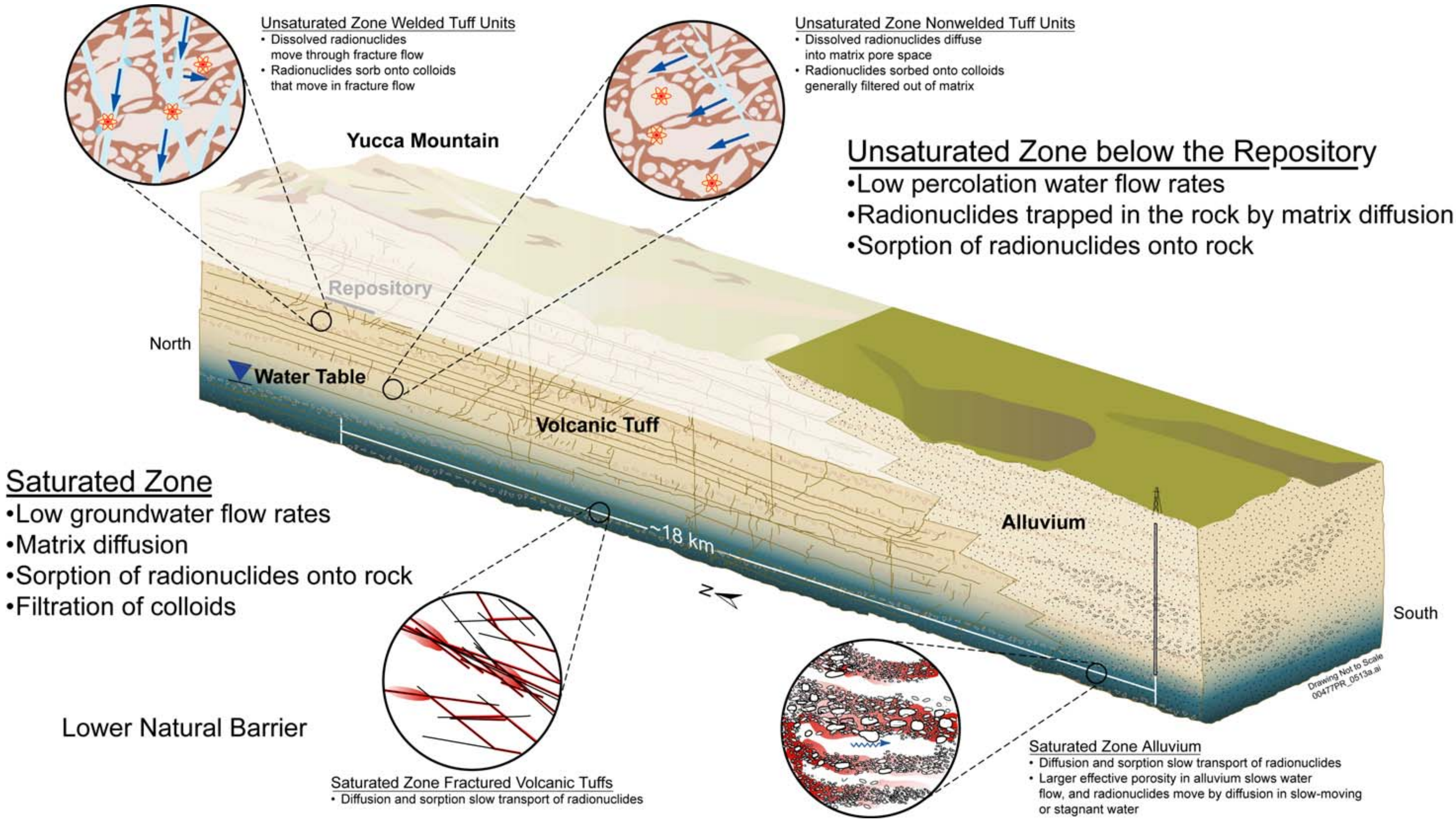
Unsaturated Zone Above Repository

- Percolation
- Capillarity
- Lateral diversion

Engineered Barrier System



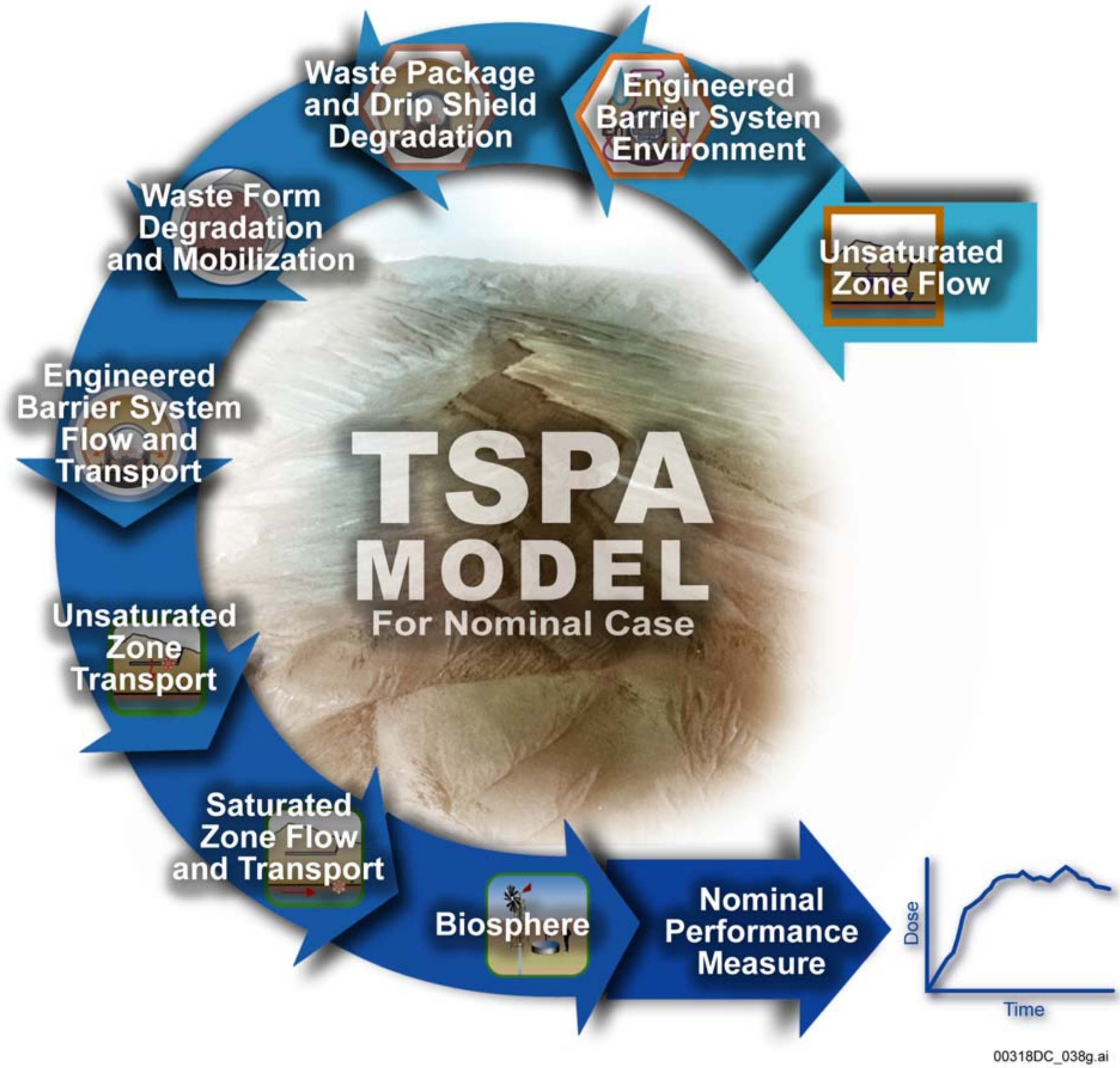
Lower Natural Barrier



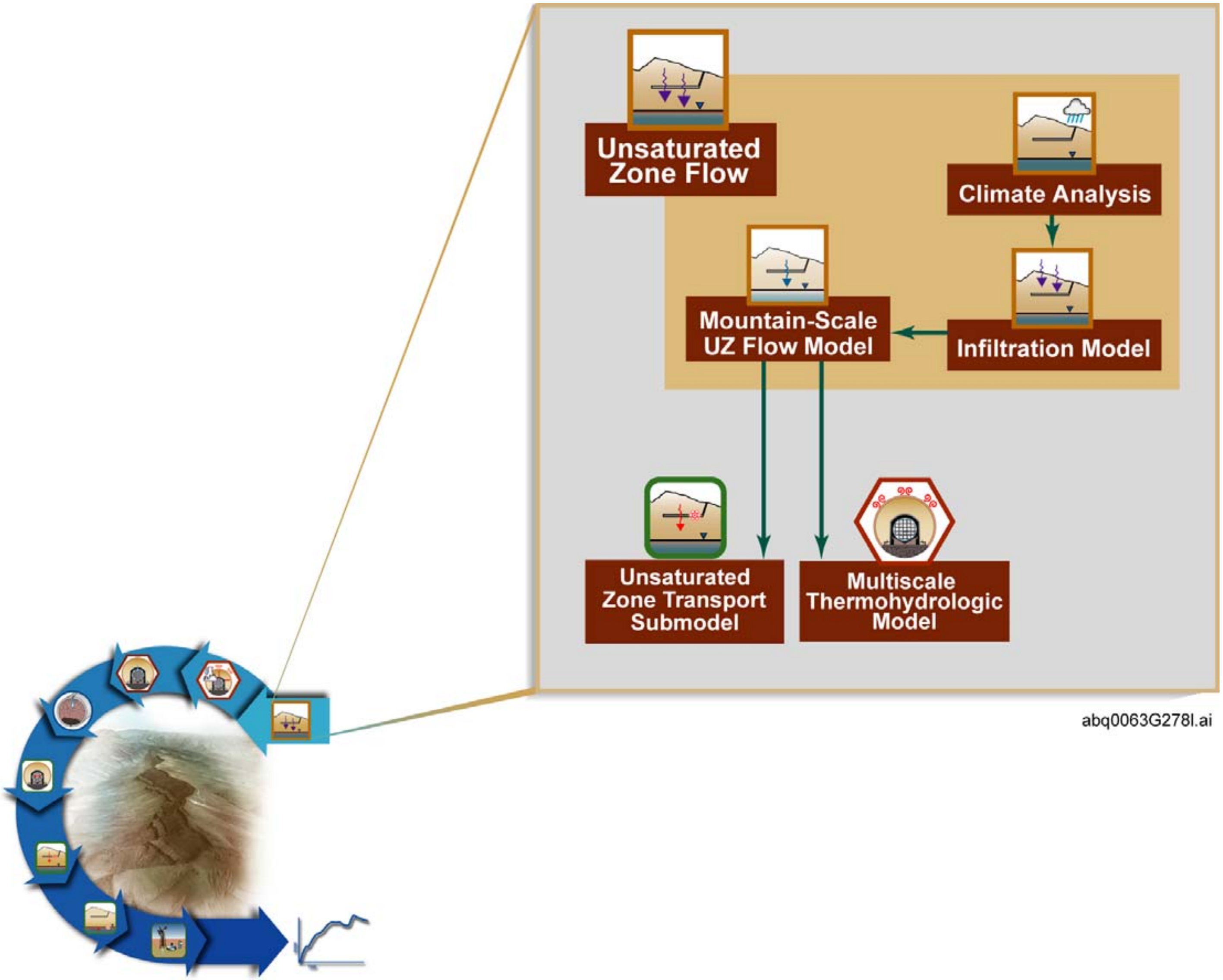
TSPA Model Architecture – Introduction

- **TSPA Models consist of three scenario classes**
  - **Nominal Scenario Class**
  - **Igneous Scenario Class**
  - **Seismic Scenario Class**
- **Each scenario class has a separate TSPA model**
- **Each model component has information flow logic diagrams**
- **Each model component has an integrated set of inputs and outputs**
- **Each model abstraction has a conceptual basis**

Nominal Scenario Class



Information Flow Diagram for Unsaturated Zone Flow



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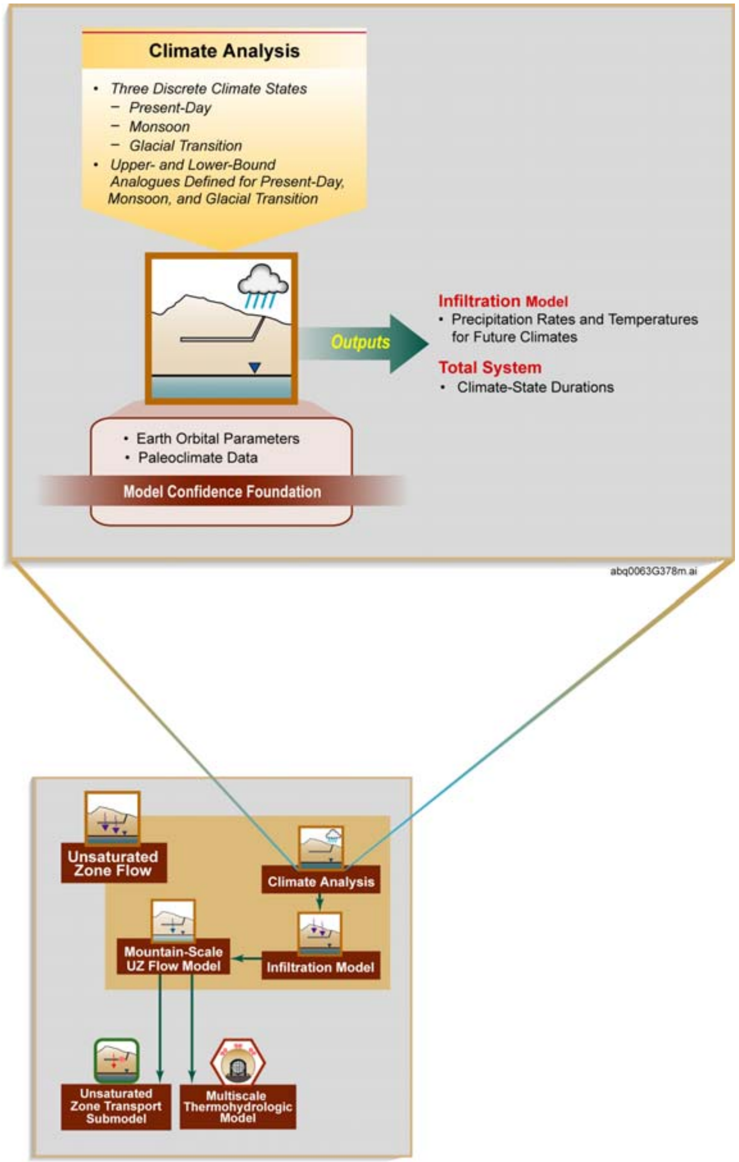
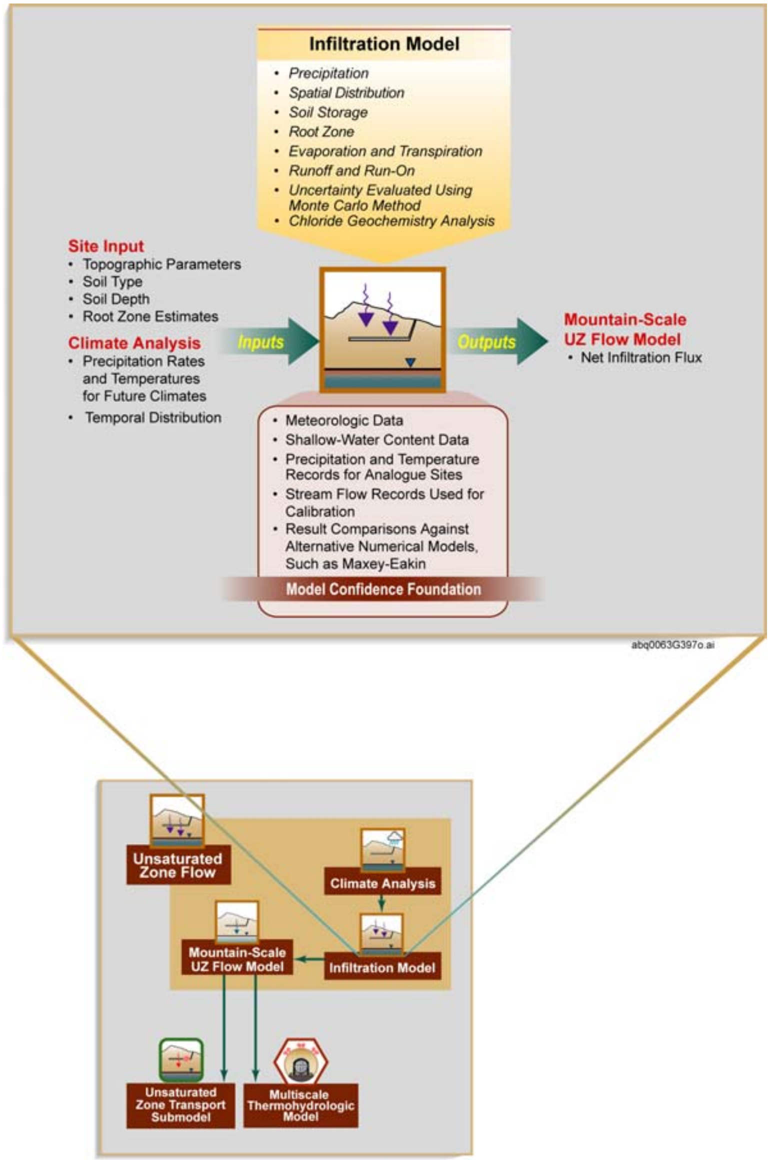
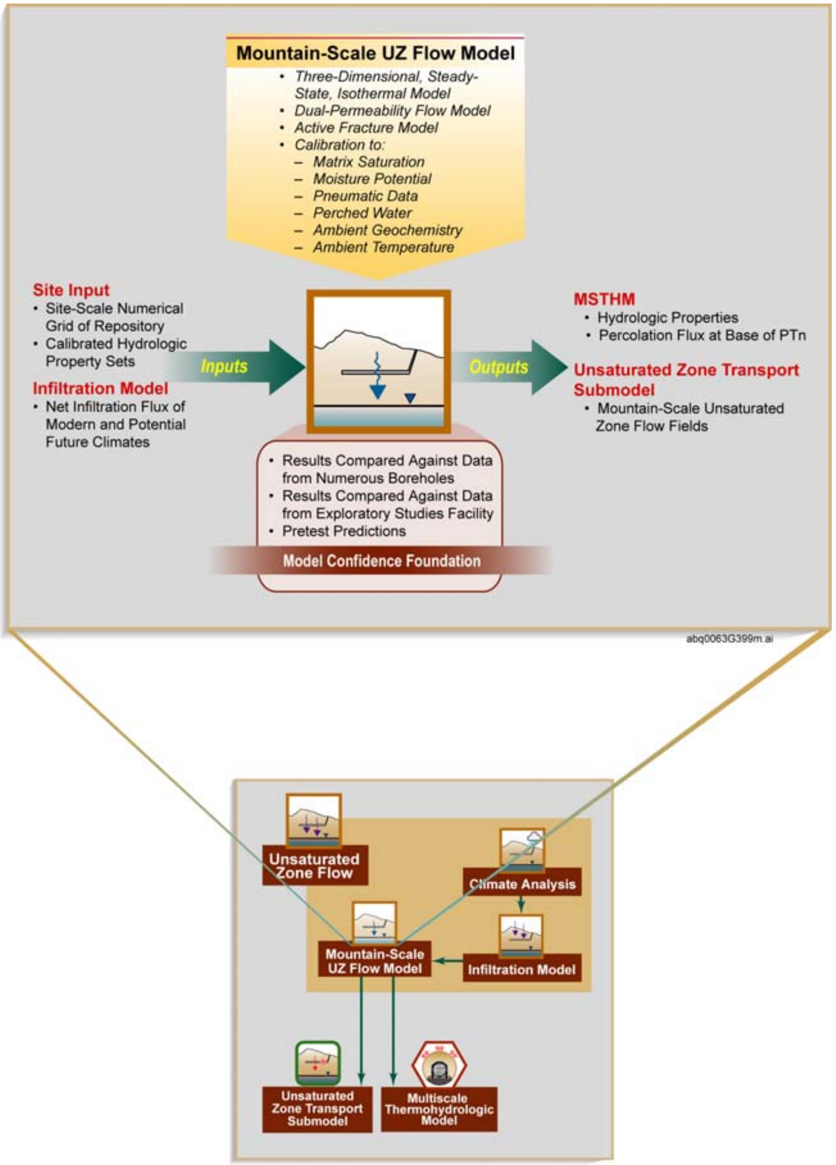
Integration Between Climate Analysis and TSPA Model



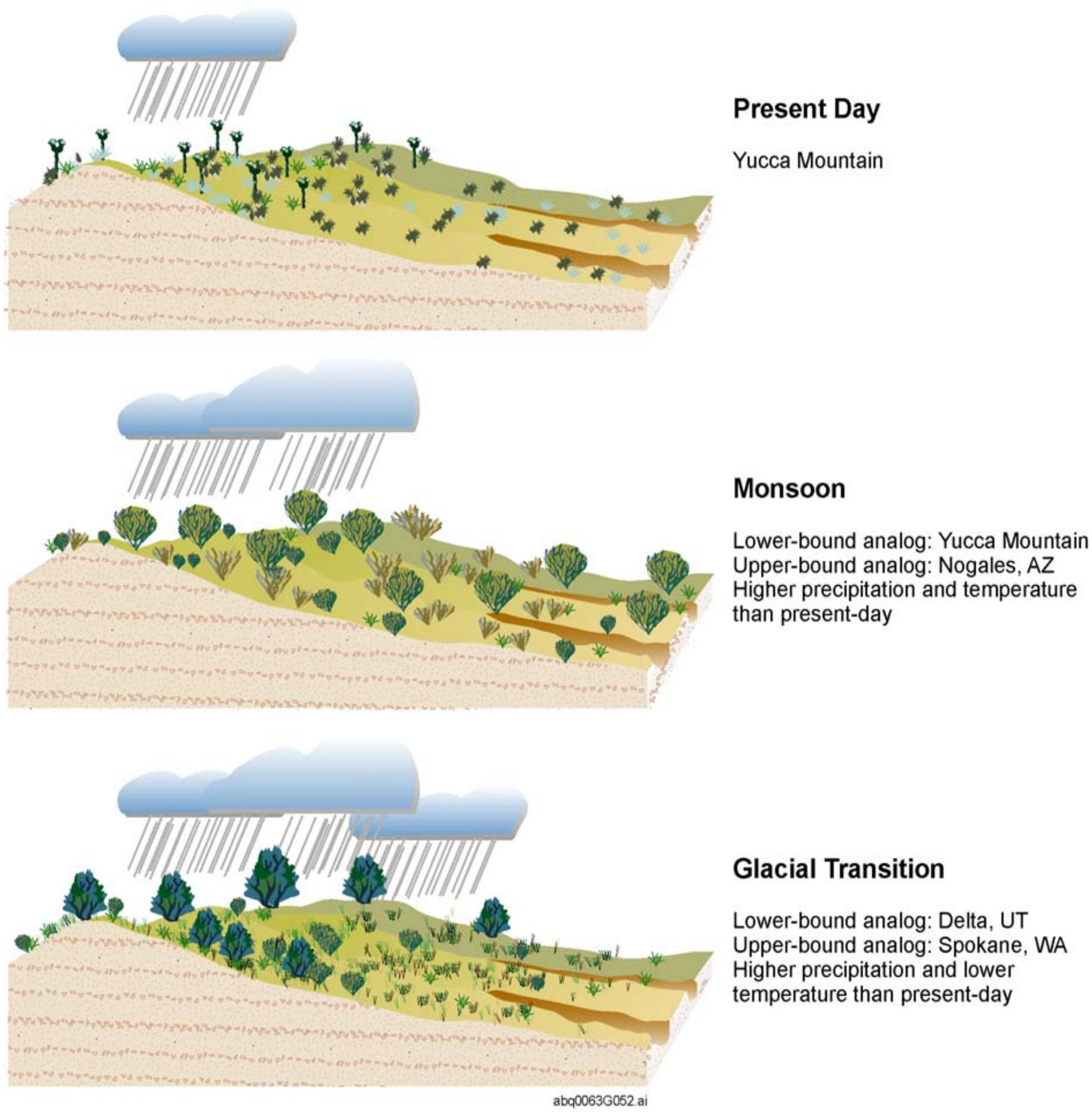
Integration Between Infiltration Model and TSPA Model



Integration Between Mountain Scale UZ Flow Model and TSPA Model

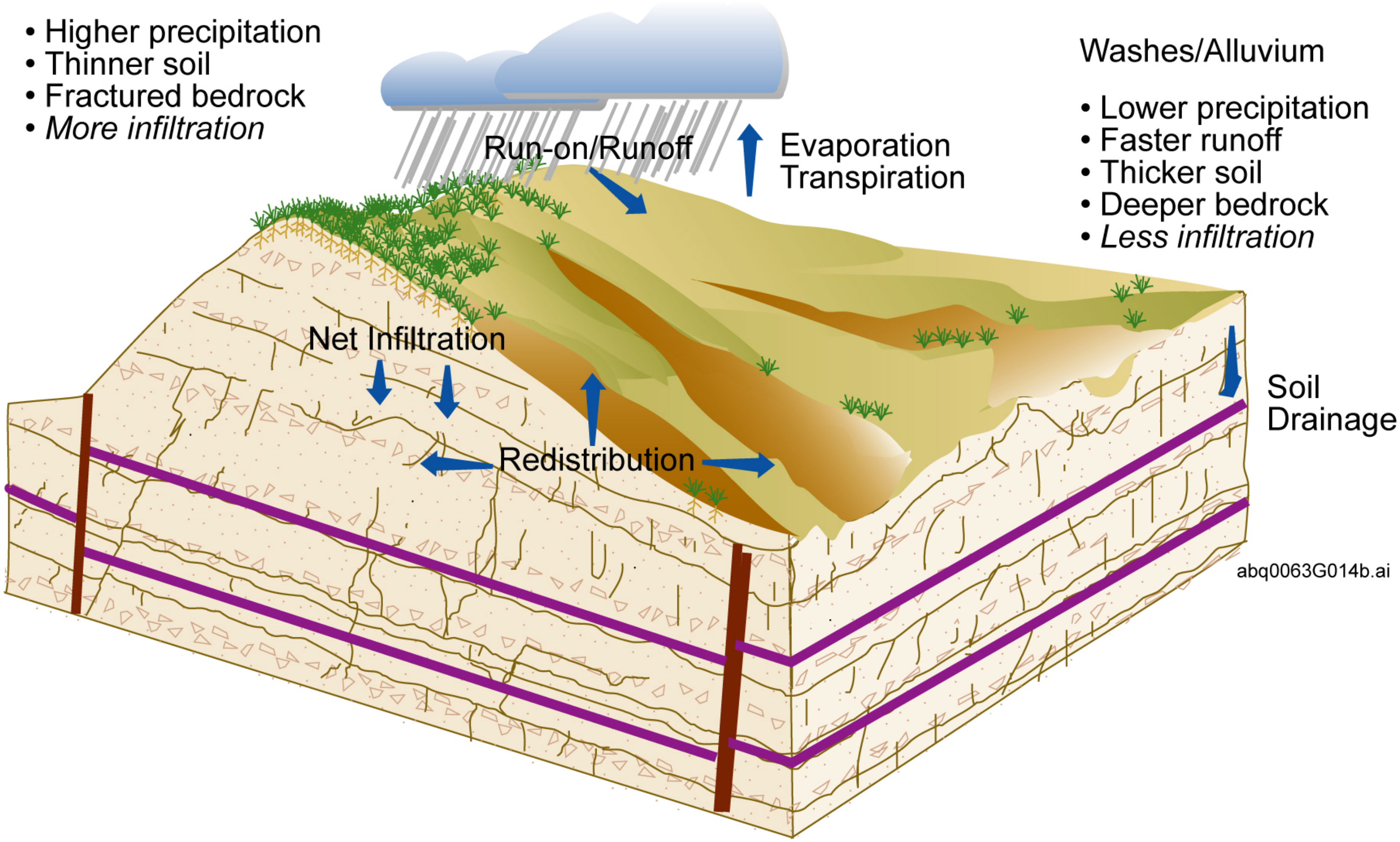


Climate



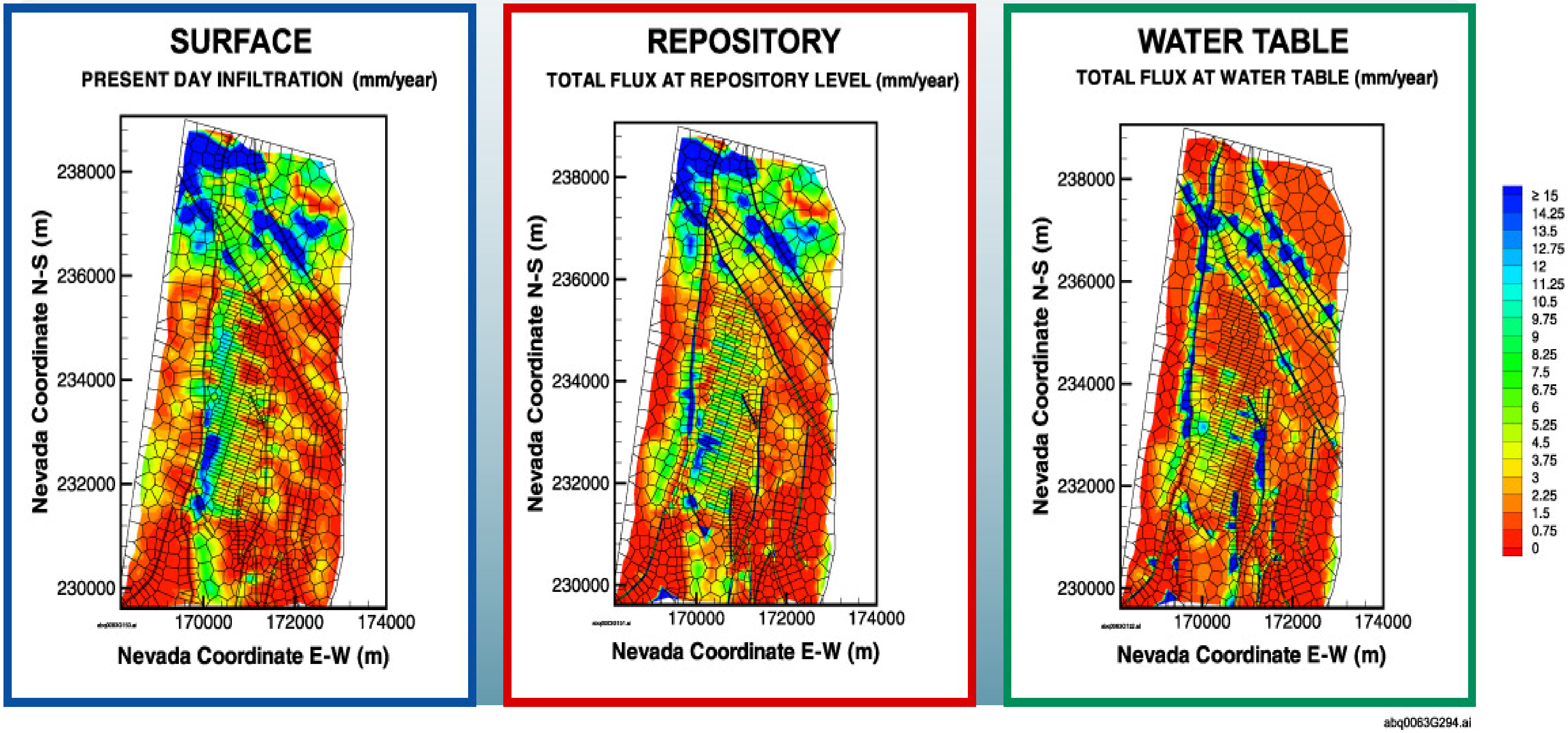
- **Present climate and two future states based on paleoclimate data and modern analogs**
- **Timing of climate changes is fixed based on evaluation of paleoclimate data**
- **Uncertainty in magnitude of changes in precipitation and temperature is included through the infiltration model**
- **Provides**
  - **Mean annual temperature and precipitation, timing of changes**
  - **Water table rise with wetter climates, shortens transport path**
  - **Increases flow rates for wetter climate states**

Infiltration



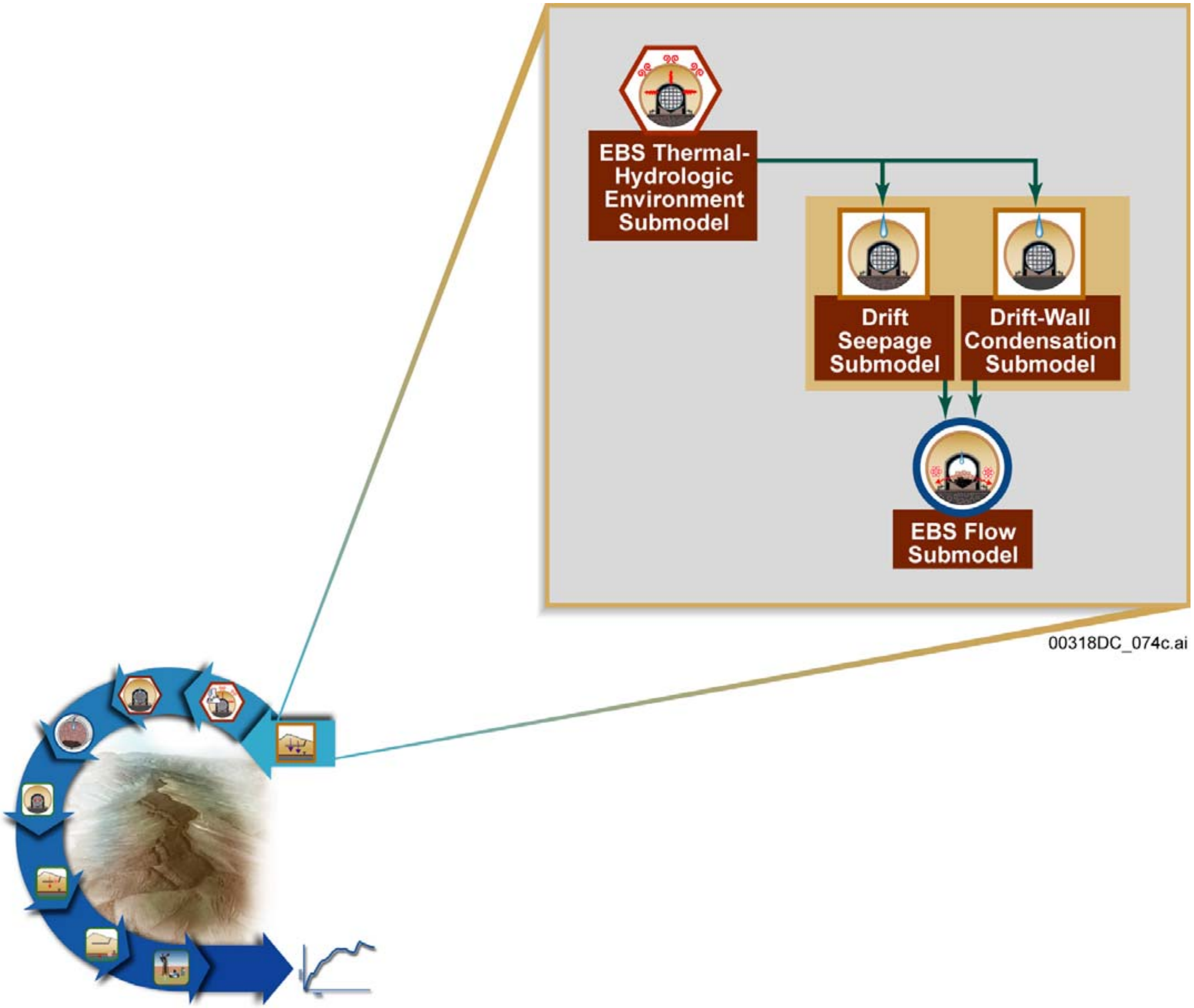
- **Infiltration is based on climate model results, site studies, and natural analog data**
- **Precipitation, temperature, evapotranspiration (evaporation and plant use), insolation (sun intensity), run-off and water pooling, and soil storage are also taken into account**

Mountain Scale Unsaturated Zone Flow

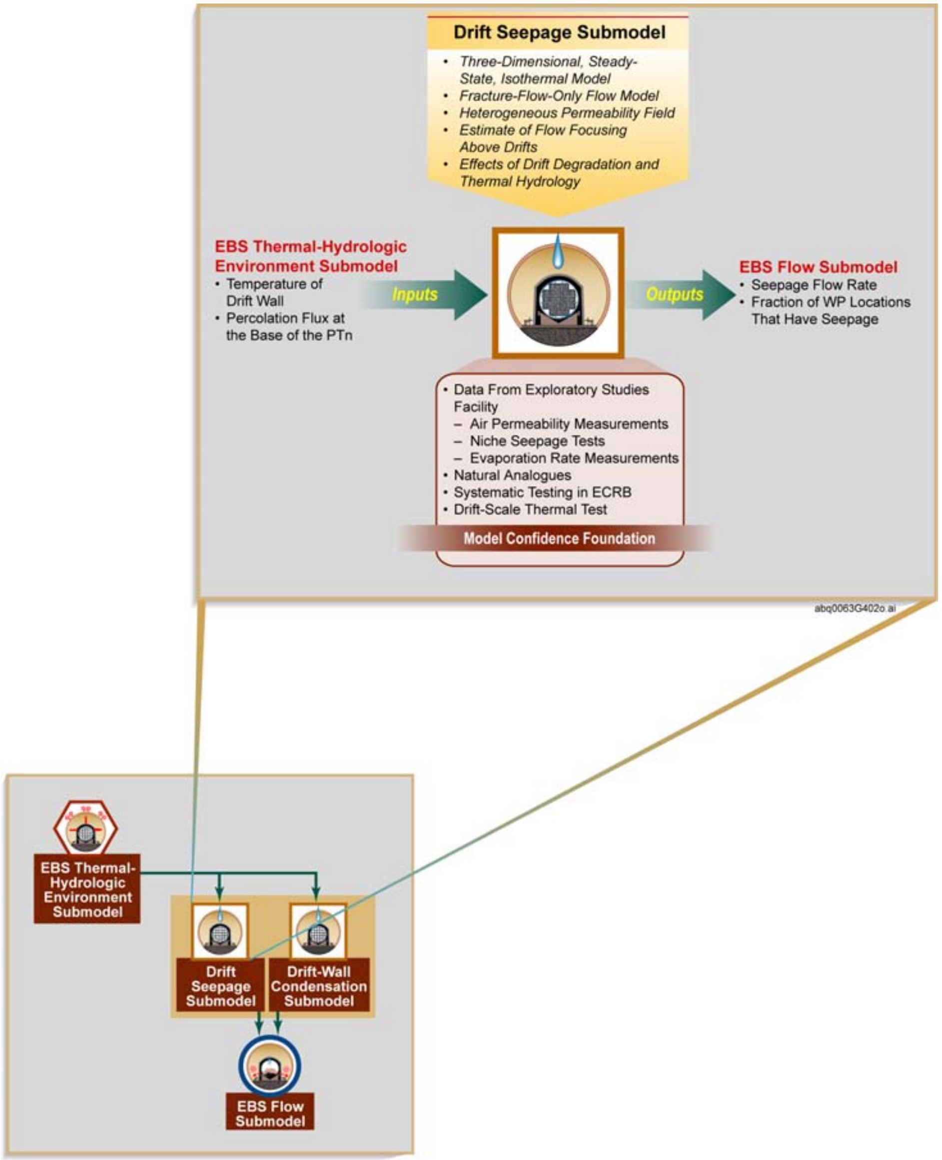


- **Site characteristics and experimental results are used to create infiltration maps**
- **Three-dimensional modeling allows estimation of water movement at repository level as well as at water table**

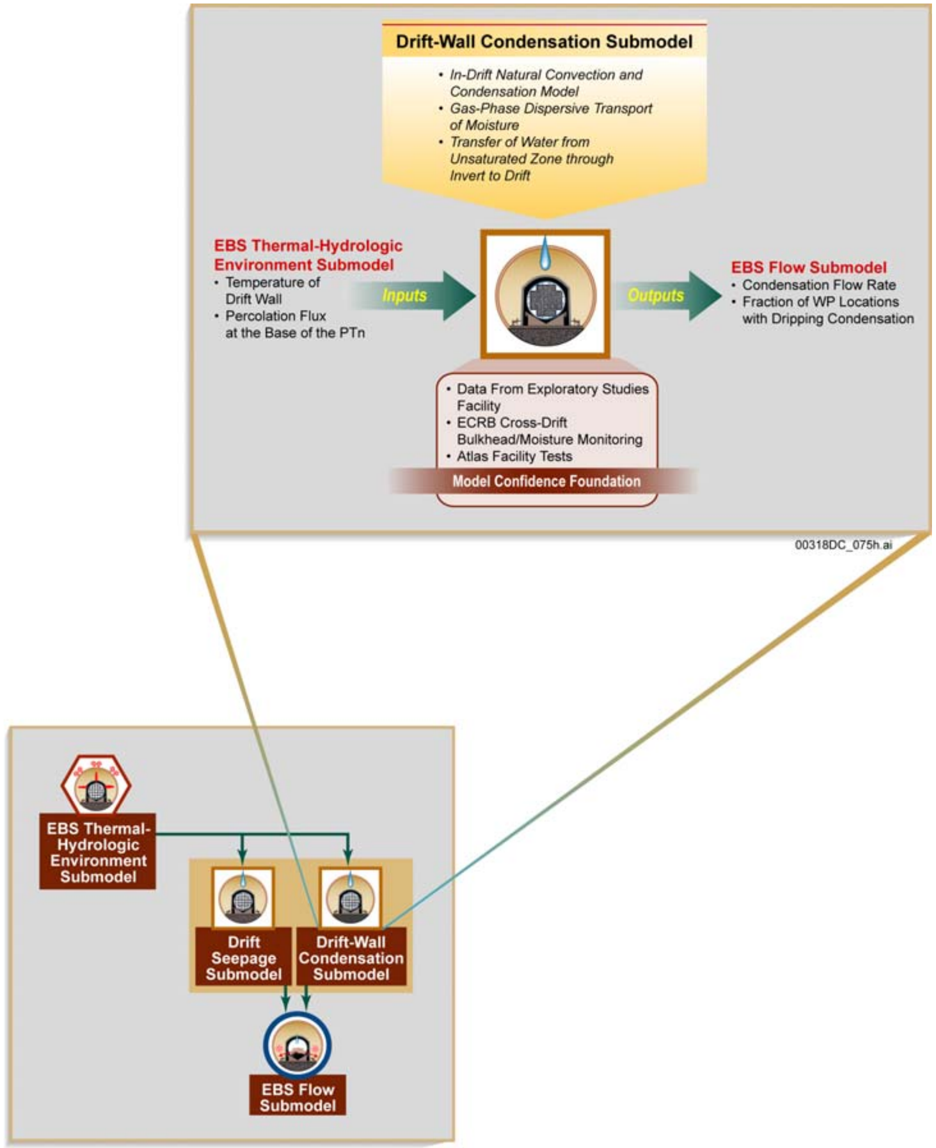
Information Flow Diagram for Drift Seepage and Drift-Wall Condensation



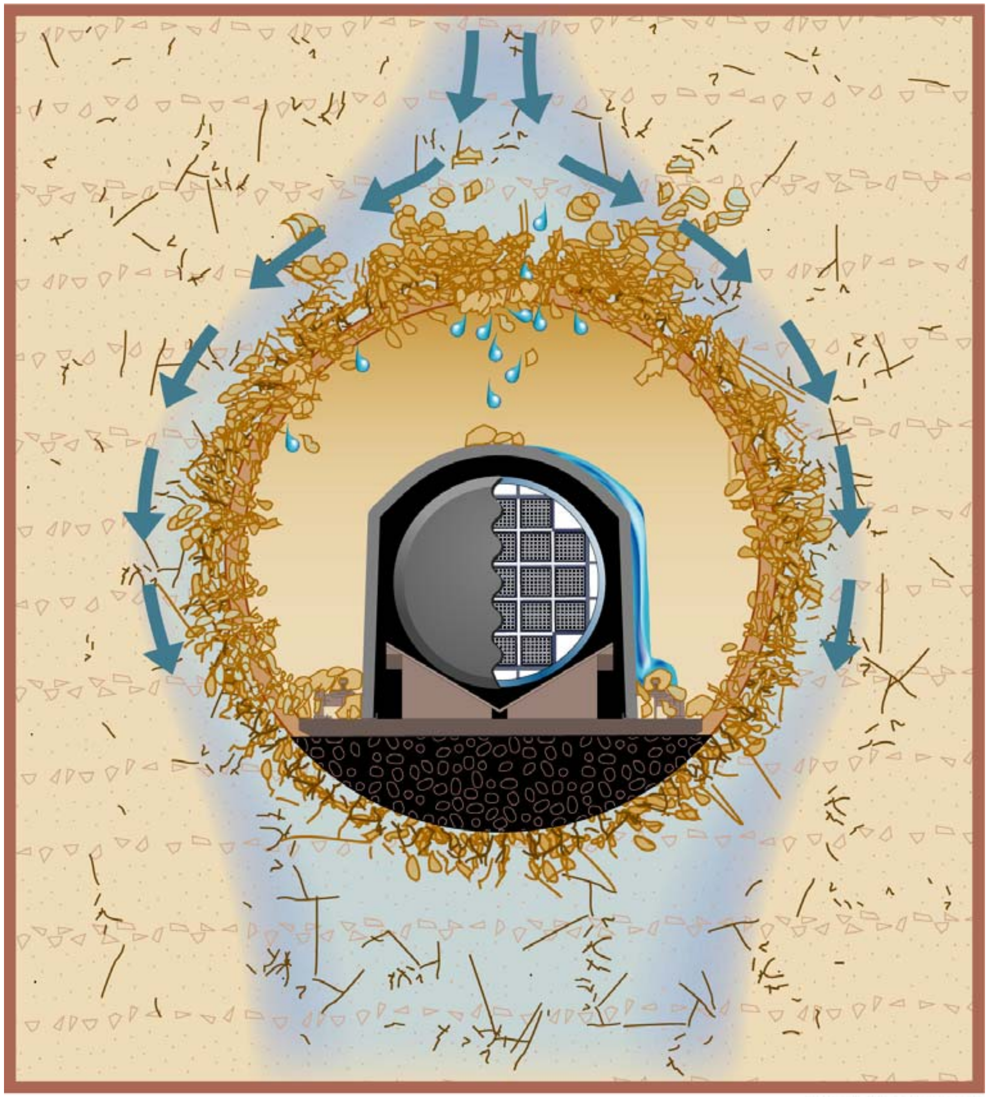
Integration Between Drift Seepage Model and TSPA Model



Integration Between Drift-Wall Condensation Model and TSPA Model



Water Seepage Into Drift



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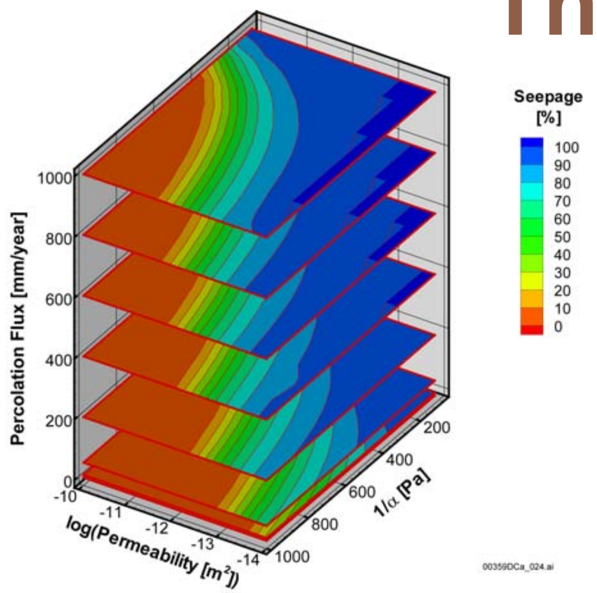
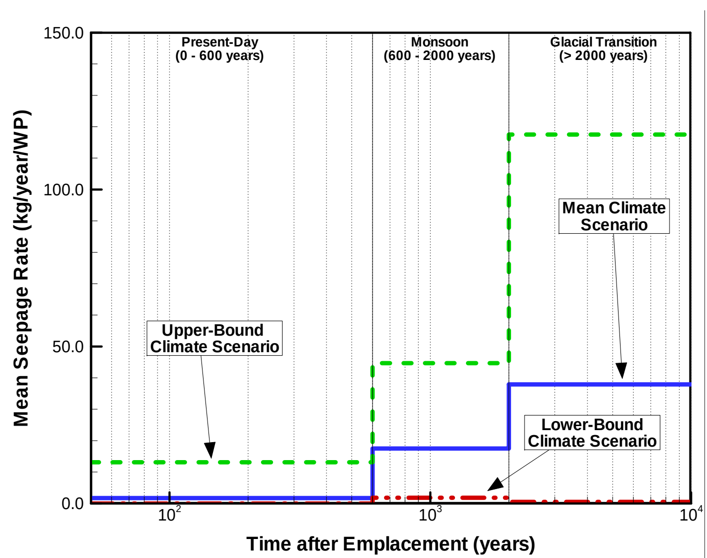
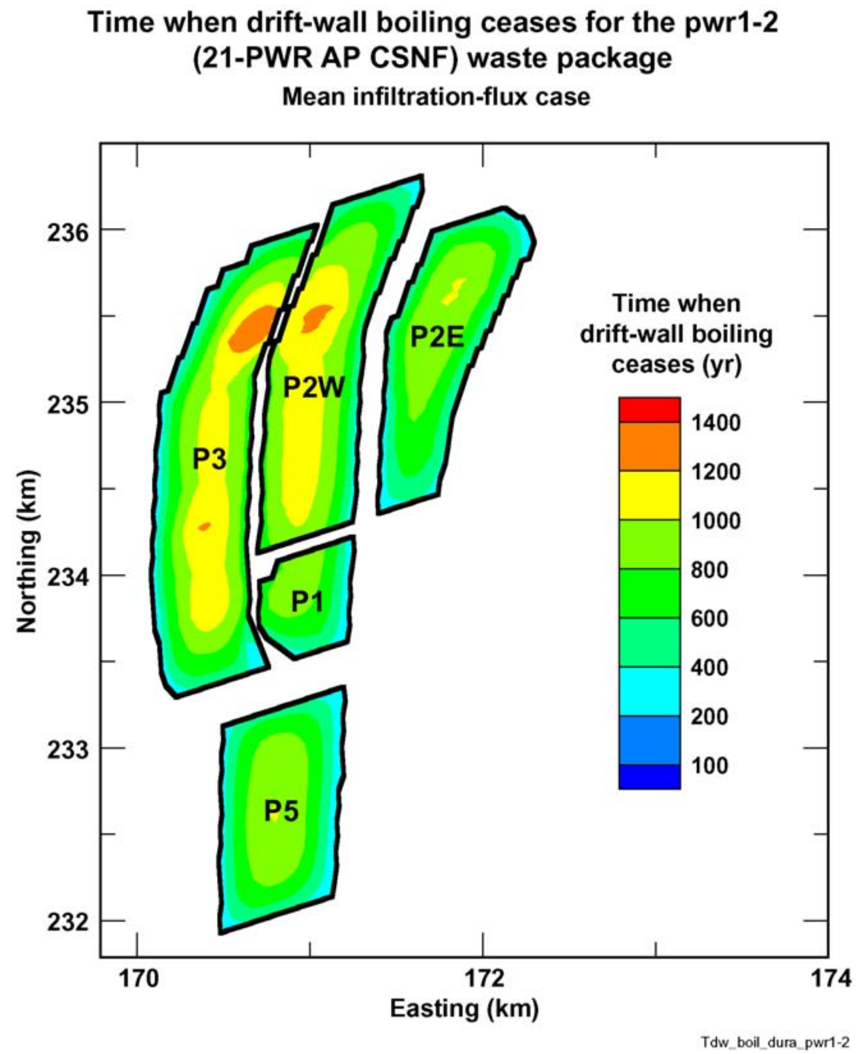
- **Water flow through fractures is calculated, including flow-focusing effects, and effects from the degrading of the drift ceiling by rock falls**
- **This modeling requires knowing thermal hydrology, drift design, and rock properties**
- **Calculations give a seepage fraction (percent of repository seeing drips) and seep rate (with uncertainty) for different regions in the repository, taking into account waste package environments and infiltration rates**

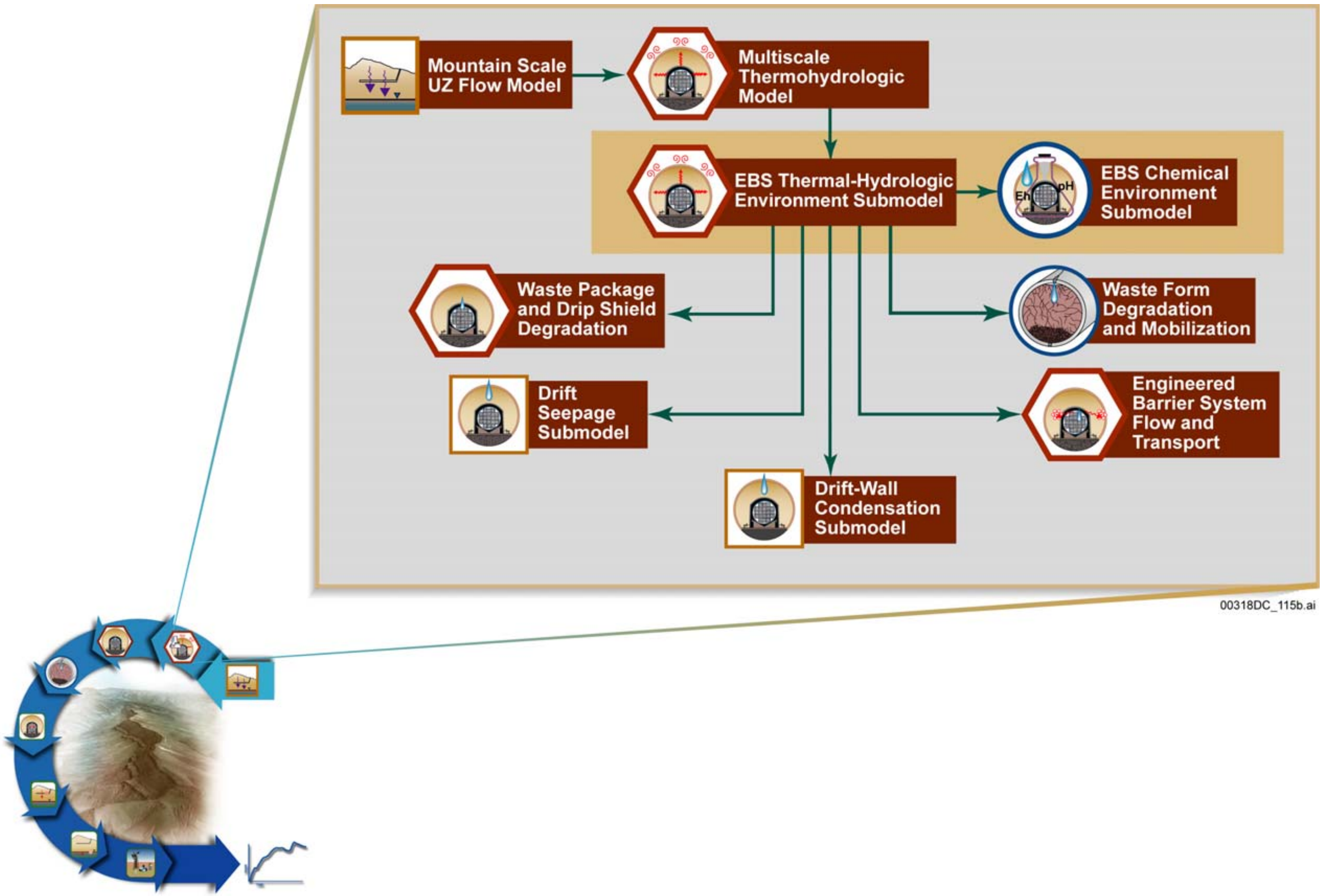
Seepage Into Drifts - During and After "Thermal Pulse"



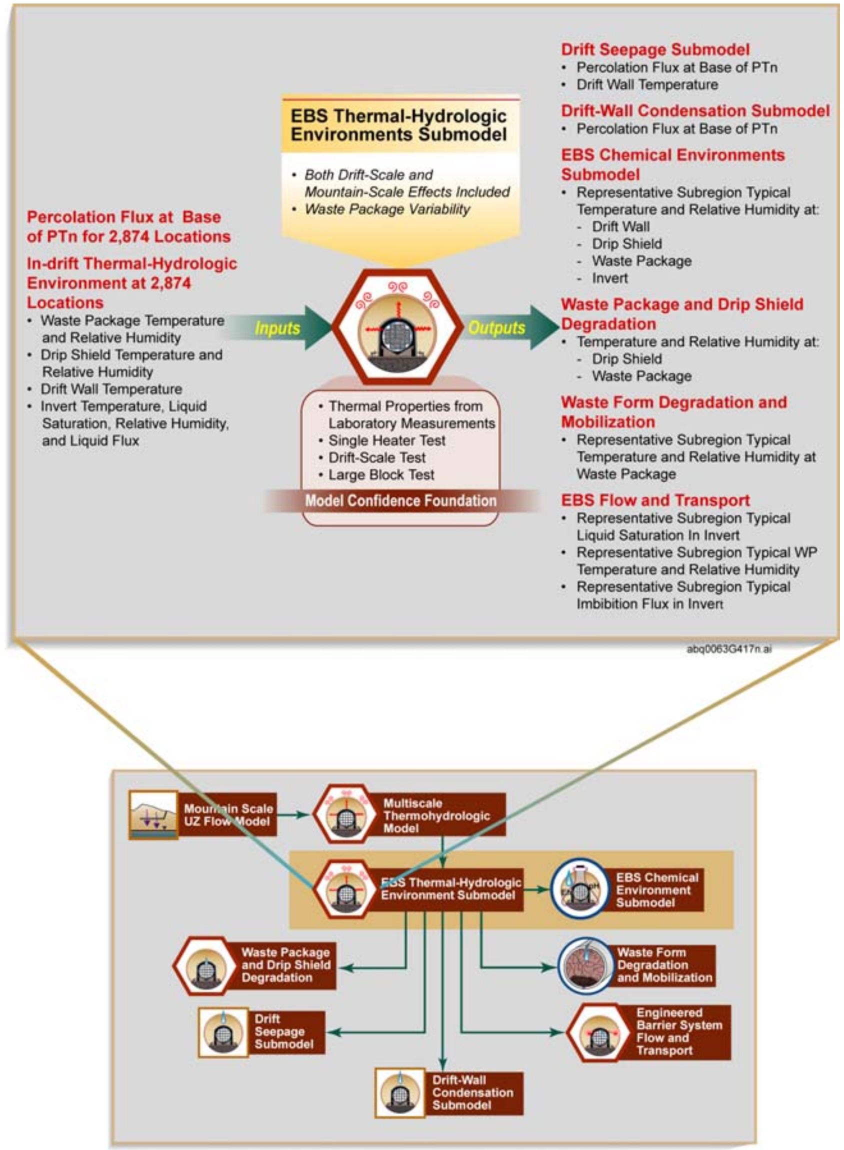




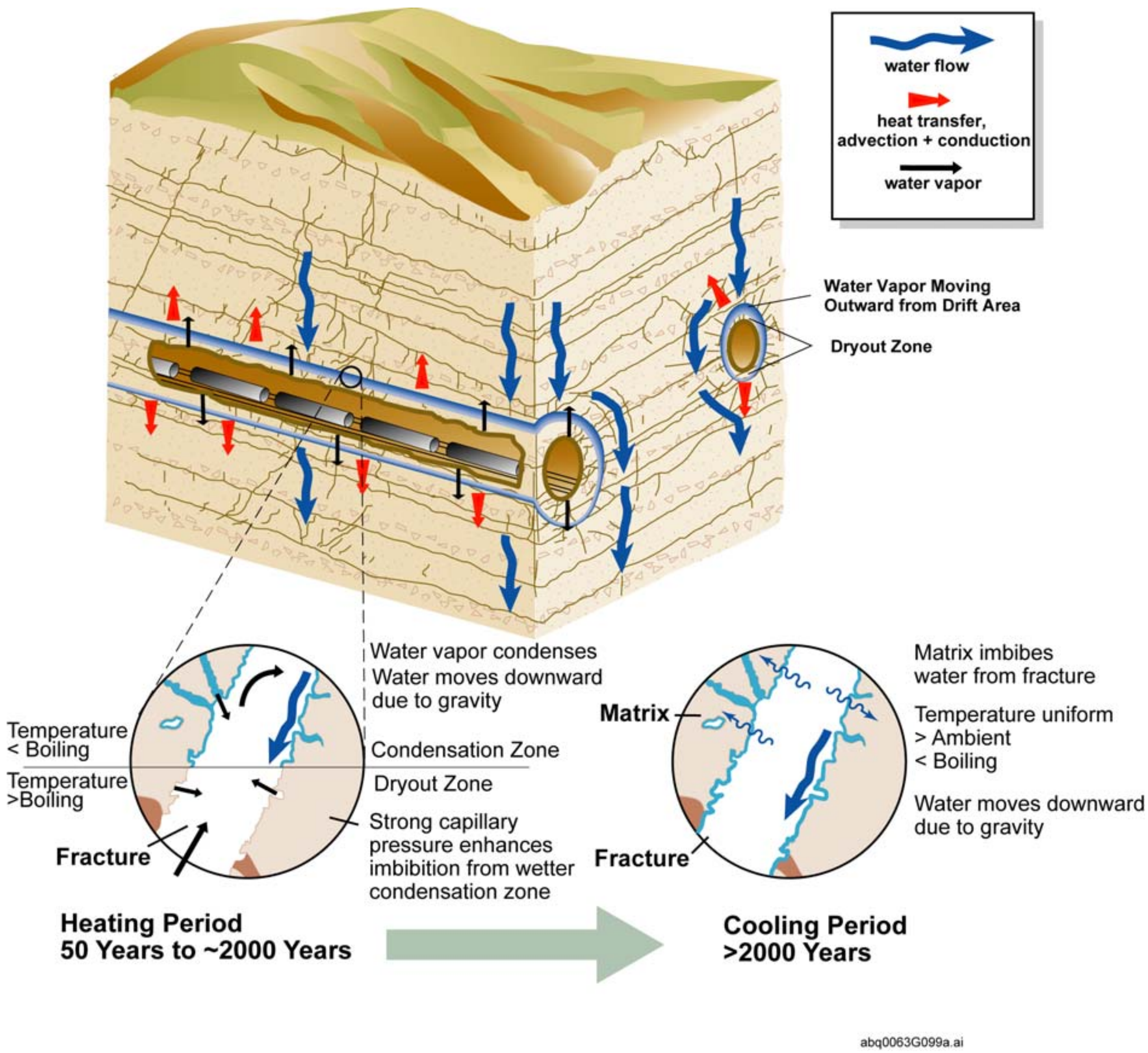
Information Flow Diagram for Engineered Barrier System Thermal-Hydrologic Environment



Integration Between EBS Thermal-Hydrologic Environment Model and TSPA Model

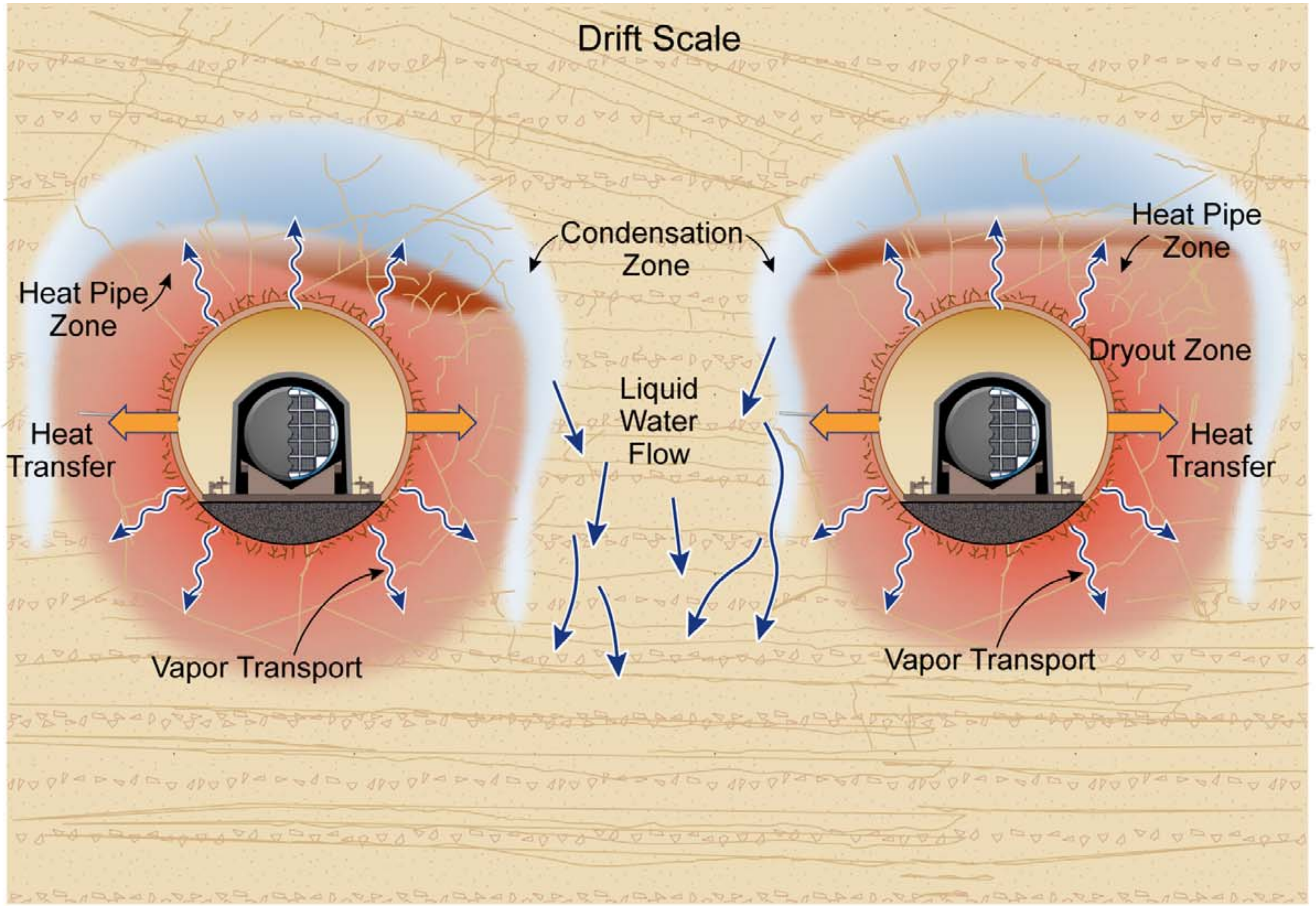


Thermal Hydrologic Environments



- **Thermal hydrology modeling evaluates water chemistry and movement changes brought about by heat from the waste packages**
- **Water evaporates and is driven away from drifts in the earlier stages when much heat is generated**
- **Water returns by gravity flow later as waste packages cool**
- **Chemistry changes occur with temperature and flow changes**

Thermal-Hydrologic Processes in the Vicinity of the Emplacement Drifts Due to Repository Heating



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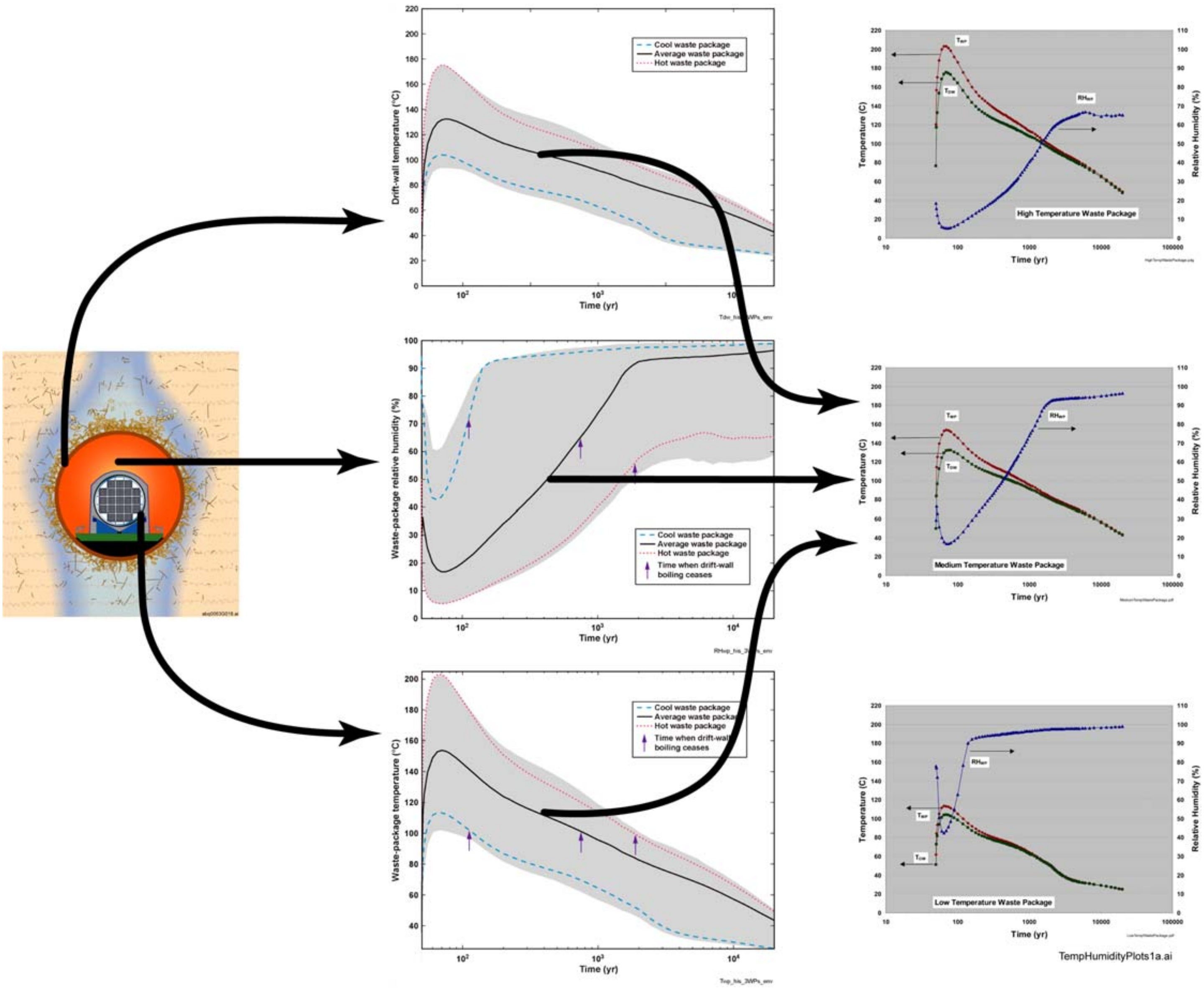
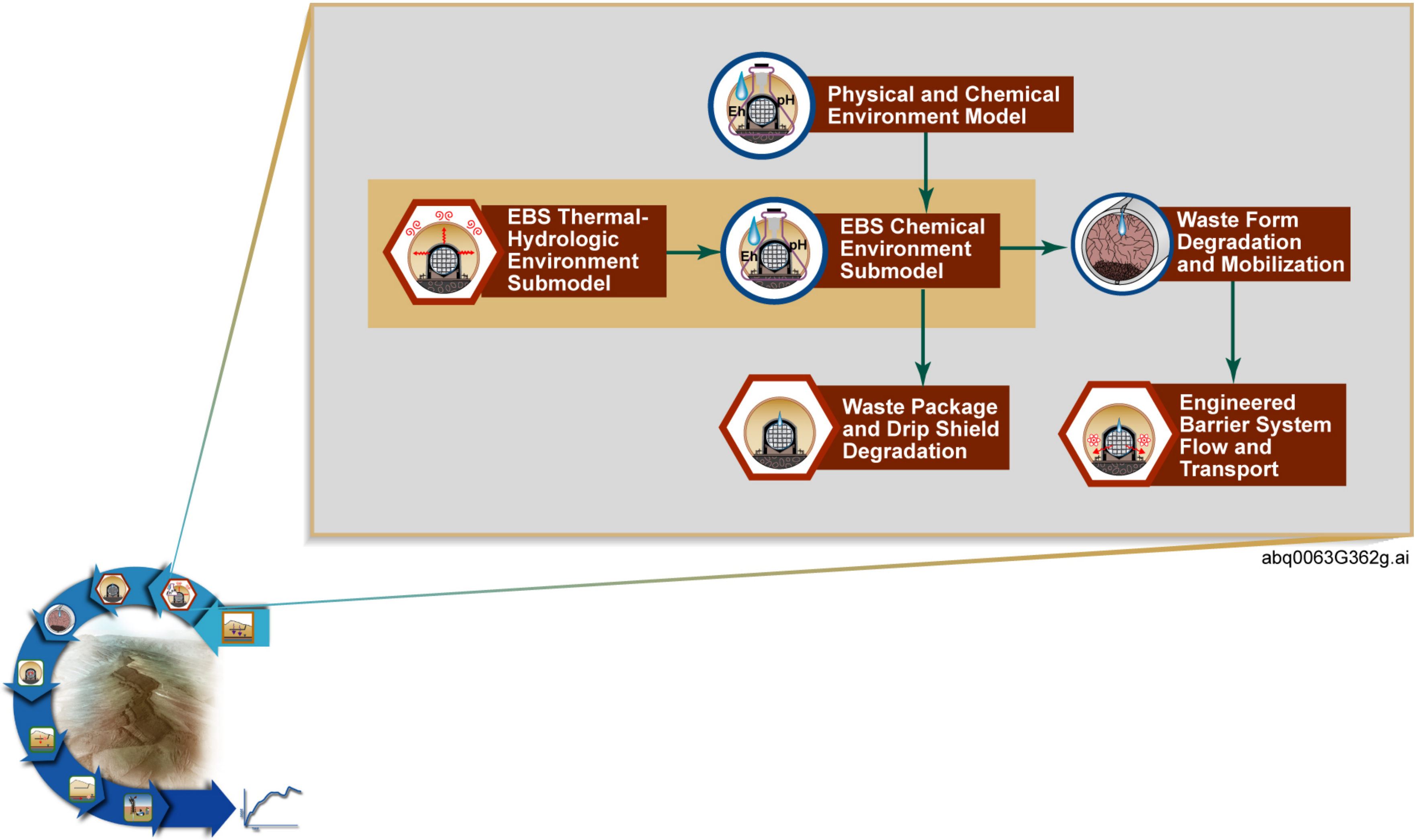
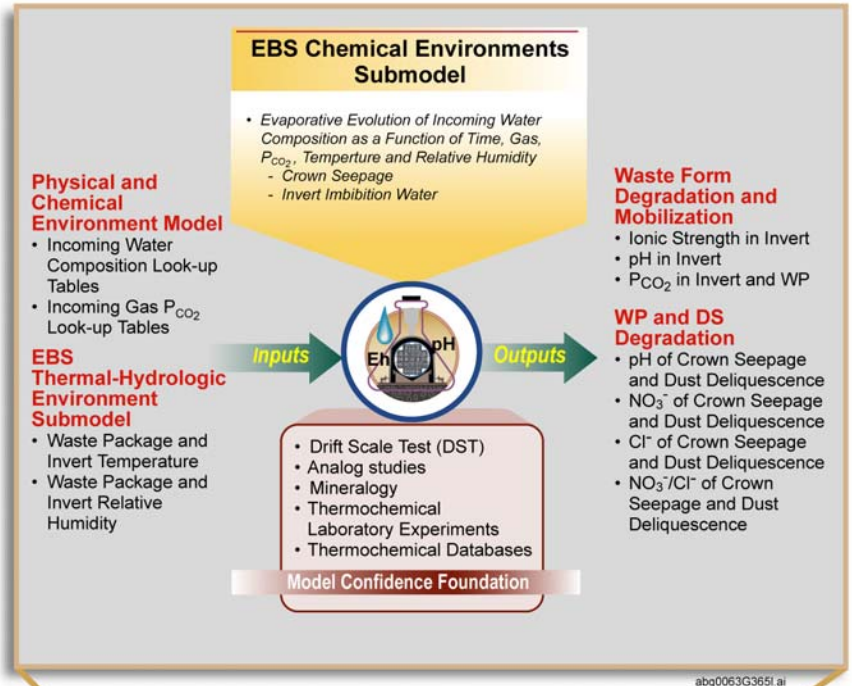
Thermal Abstraction

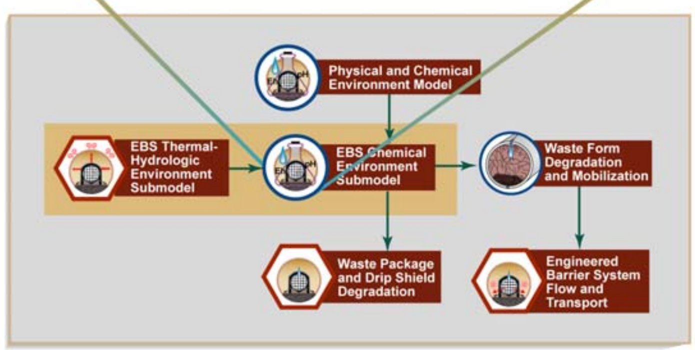


Information Flow Diagram for Engineered Barrier System Environments

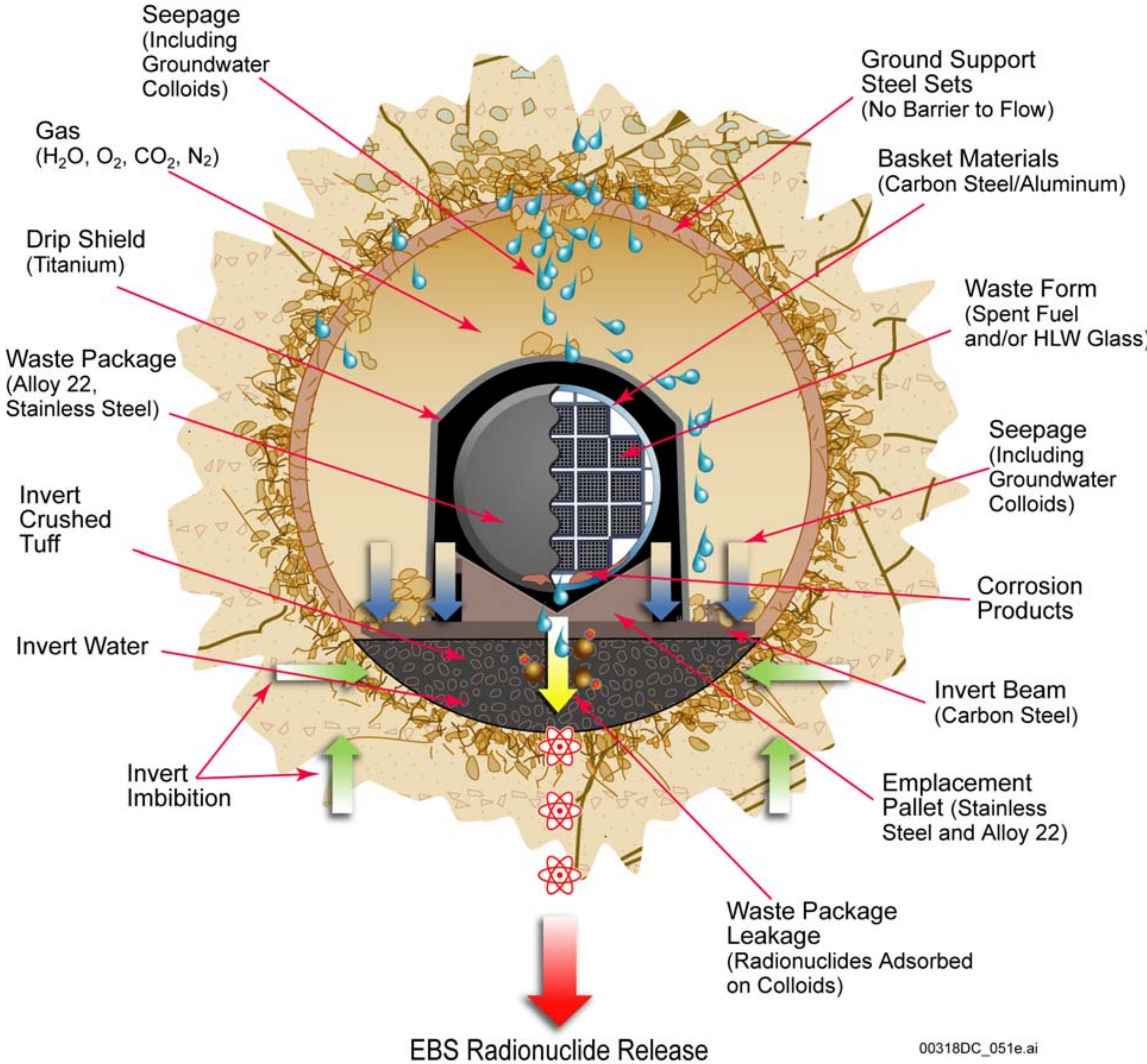


Integration Between EBS Chemical Environments Model and TSPA Model

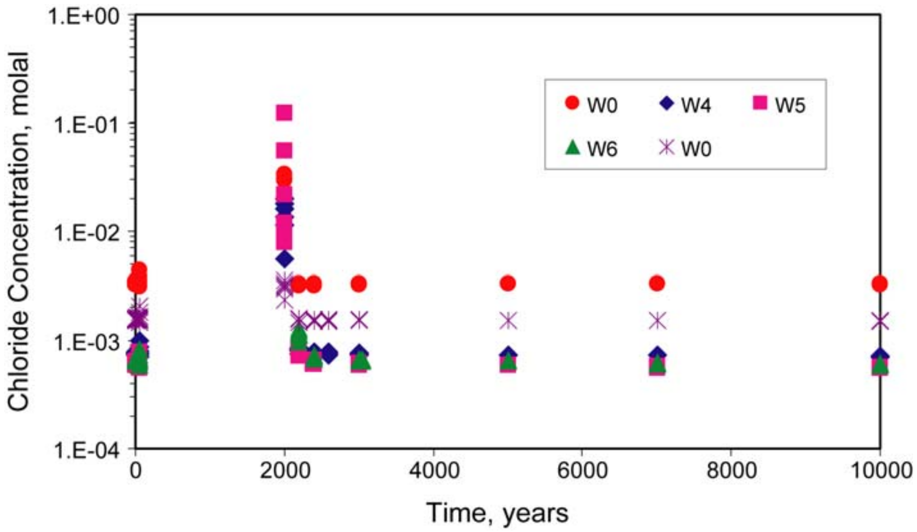


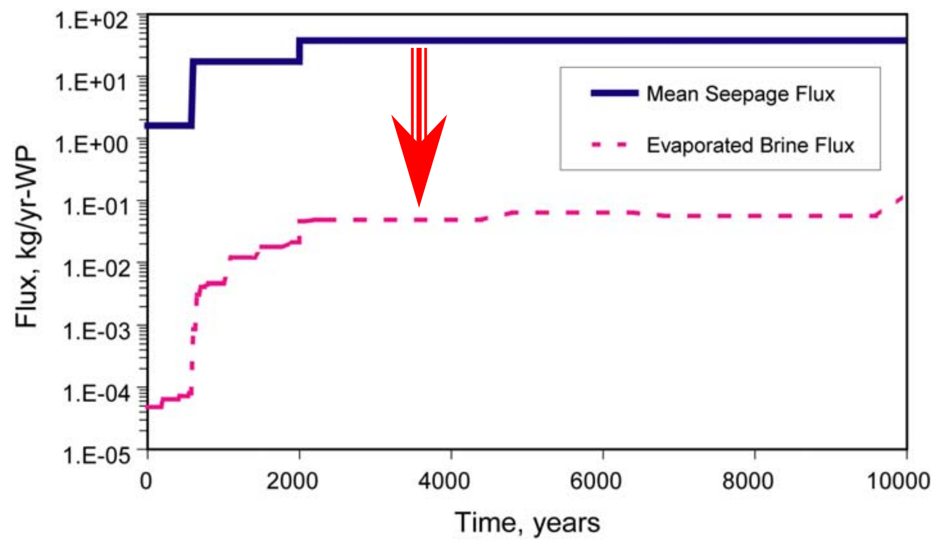


General EBS Design Features and Materials, Water Movement, and Drift Degradation



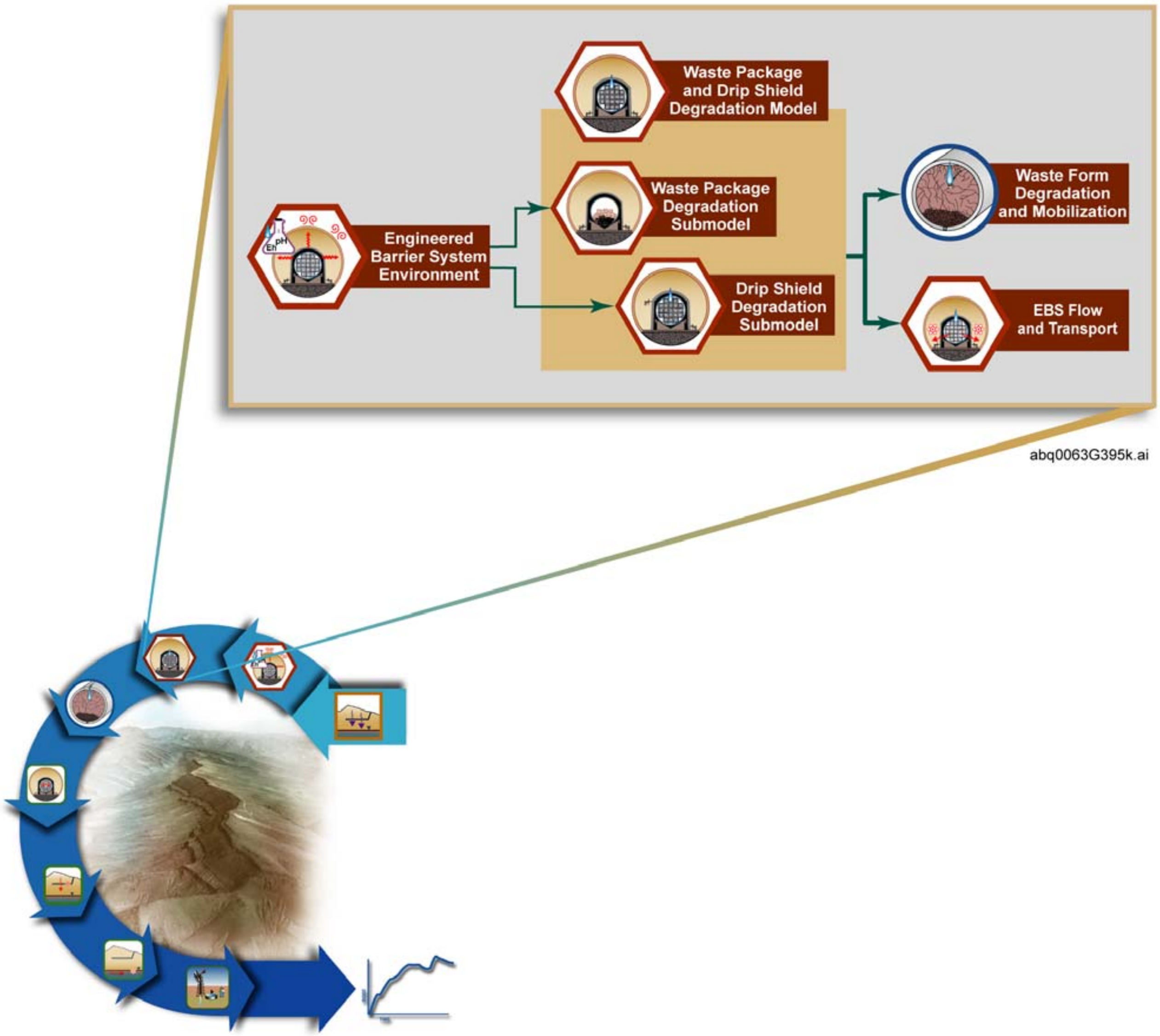
Aqueous Chemistry Evolution After the "Thermal Pulse"



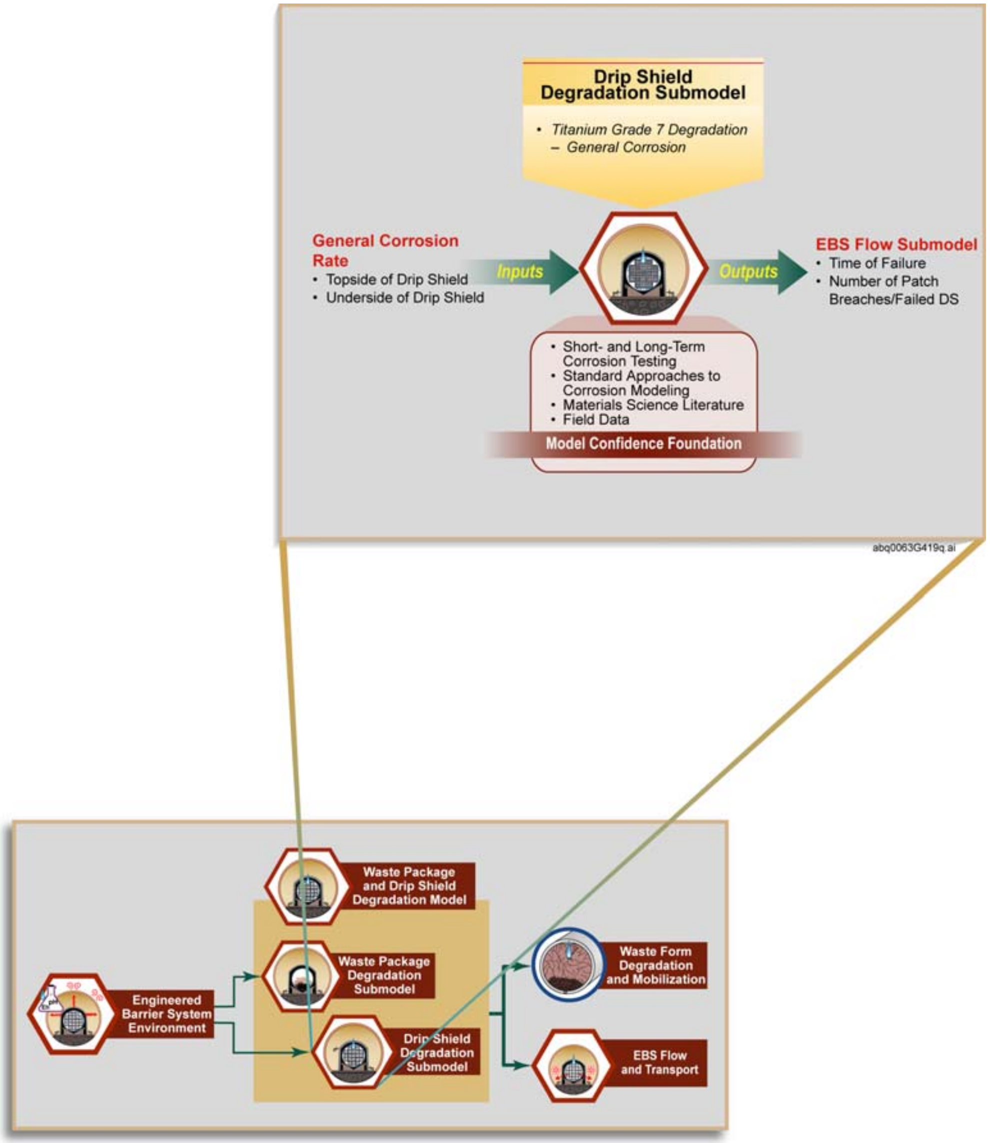


	Seepage Compositions			Brine Compositions		
Time	Cl	NO_3	NO_3/Cl	Cl	NO_3	NO_3/Cl
years	millimolal	millimolal	mole ratio	molal	molal	mole ratio
650	0.73 to 3.3	0.13 to 0.31	0.07 to 0.42	7.2	5.9	0.81
1500	0.73 to 1.3	0.13 to 0.31	0.10 to 0.42	7.0	4.1	0.59
5200	0.73 to 1.3	0.13 to 0.31	0.10 to 0.42	3.2	0.58	0.18
9200	0.60 to 3.3	0.04 to 0.10	0.03 to 0.09	2.7	0.15	0.06

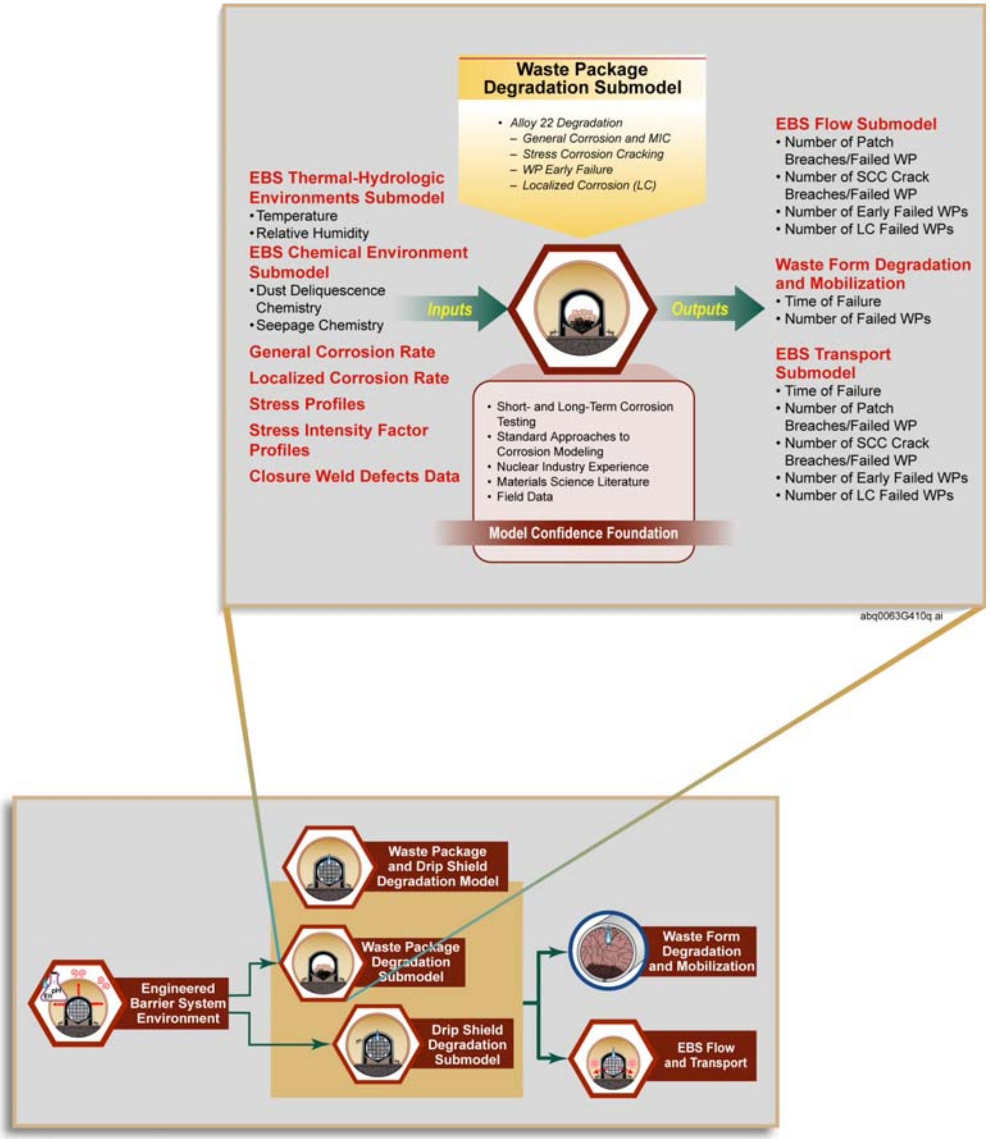
Information Flow Diagram for the Drip Shield and Waste Package Degradation Abstraction Models



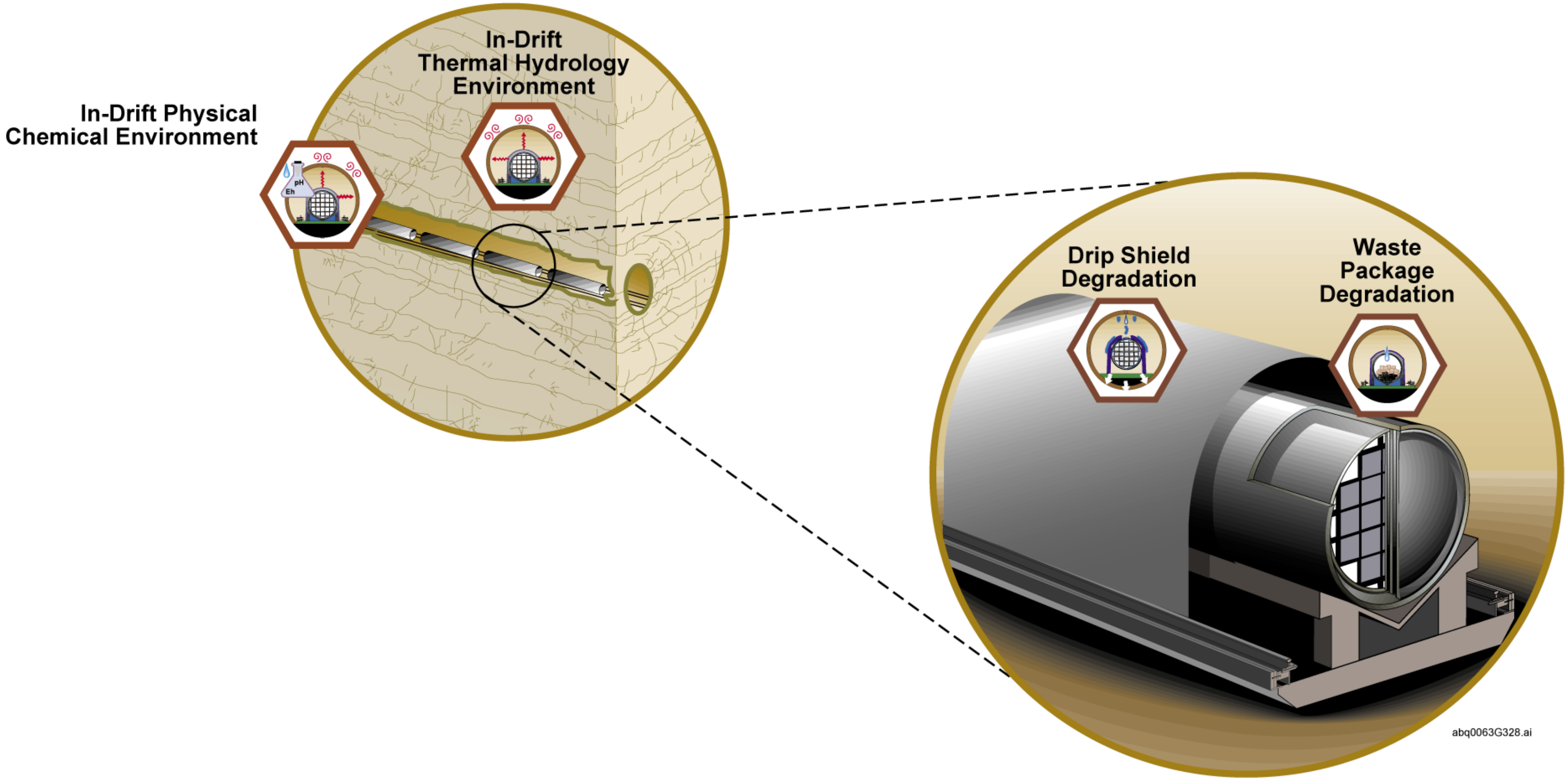
Integration of Drip Shield Degradation Model and TSPA Model



Integration of Waste Package Degradation Model and TSPA Model

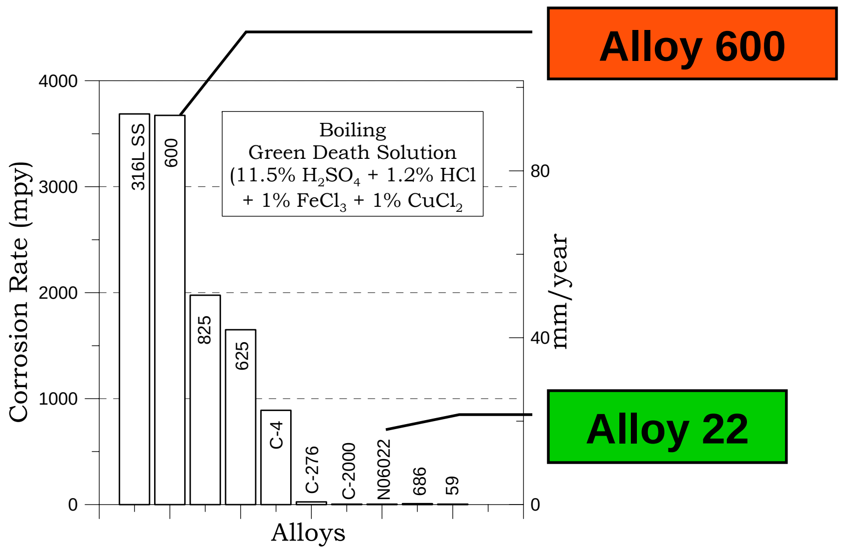


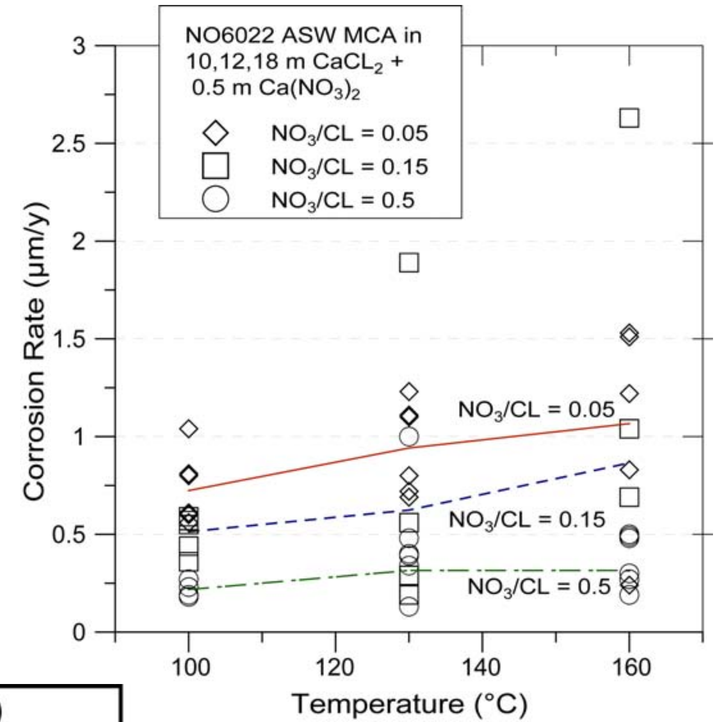
Waste Package and Drip Shield Degradation Process



- **Comprehensive testing of metals and alloys gives indication of behavior of these materials under anticipated and unanticipated conditions**

Corrosion Resistance of Alloy 22



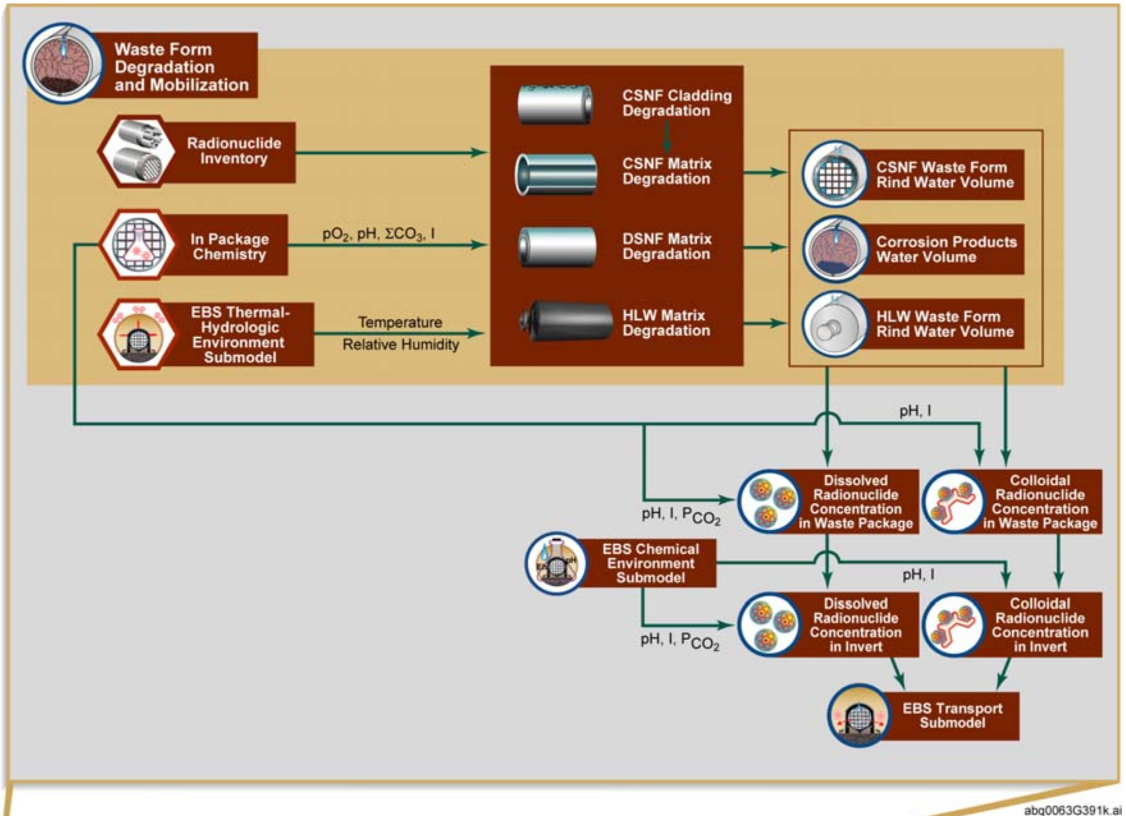


Solution		Corrosion Rate (µm/yr.)			
		Temperature °C			
NO_3/Cl	Total Molality	120	140	160	220
0.05	8.4	-	<0.02#	-	-
0.31	21.2	<0.02*	<0.02*	<0.02*	0.02#
0.5	6.7	-	0.06#	-	-
6.7	9.6	<0.02*	0.13*	0.13*	-

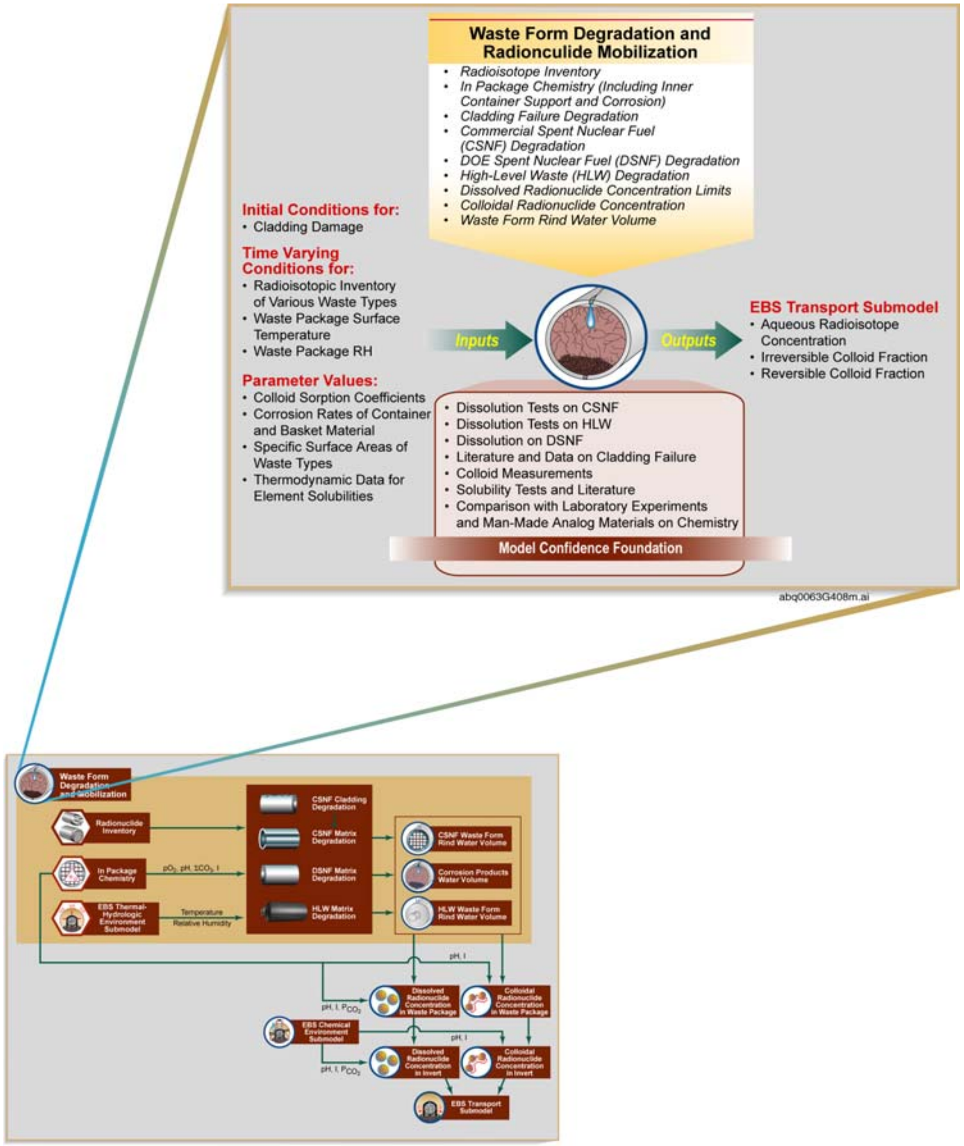
* Exposure time: 157 days
# Exposure time: 130 days

These Na and K base environments cannot exist under Yucca Mountain conditions

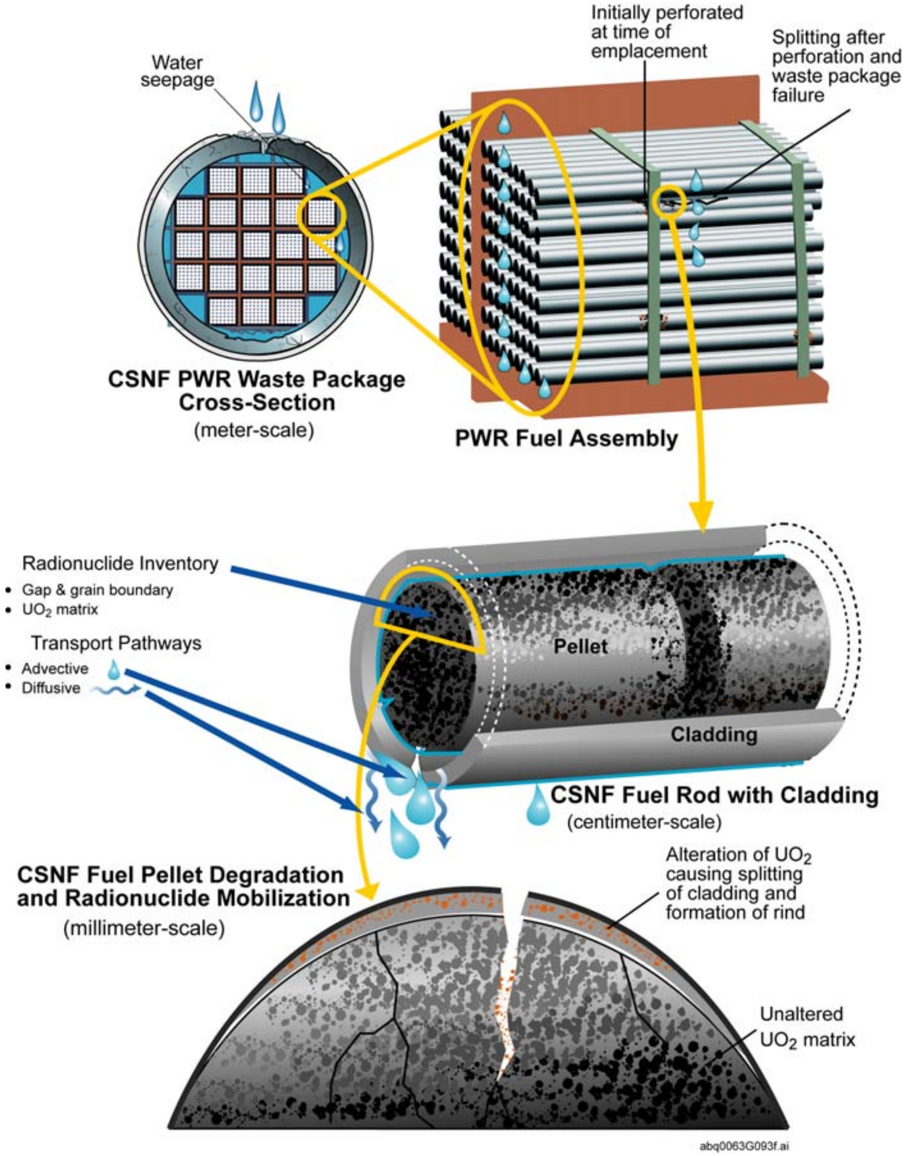
Information Flow Diagram for In-package Waste Form Degradation and Radionuclide Mobilization Models



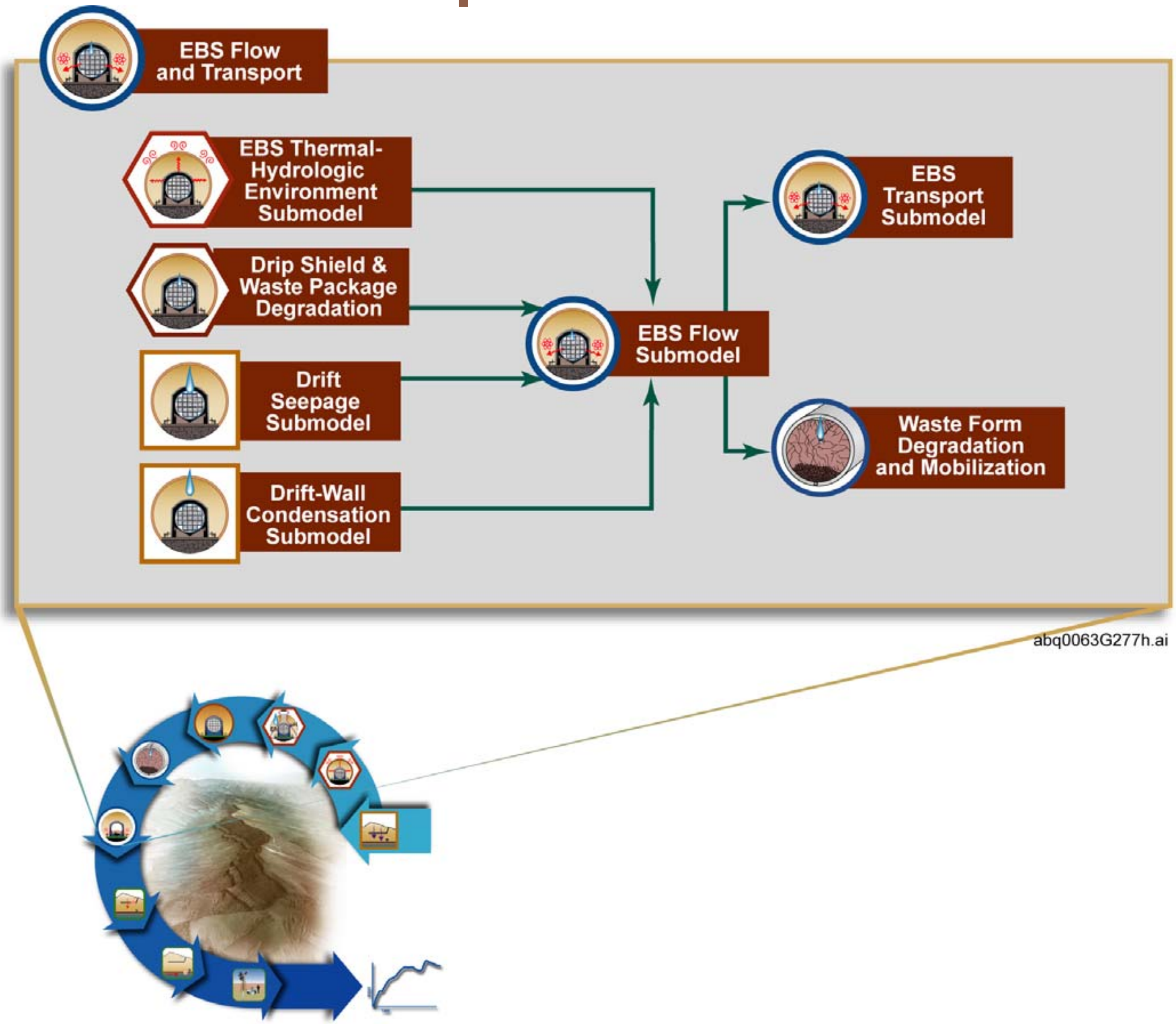
Integration Between In-Package Waste Form Degradation and Radionuclide Mobilization Model and TSPA Model



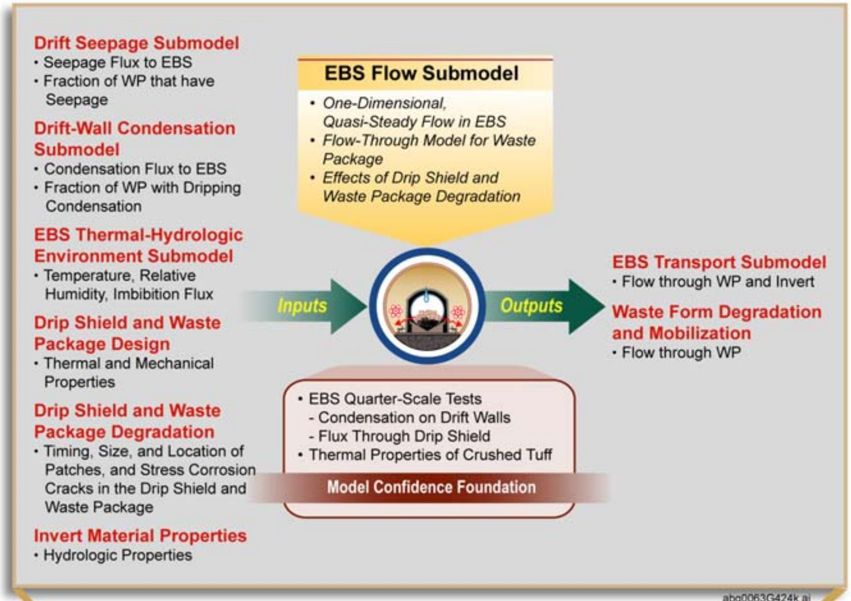
CSNF Waste Form Degradation Process at Various Scales

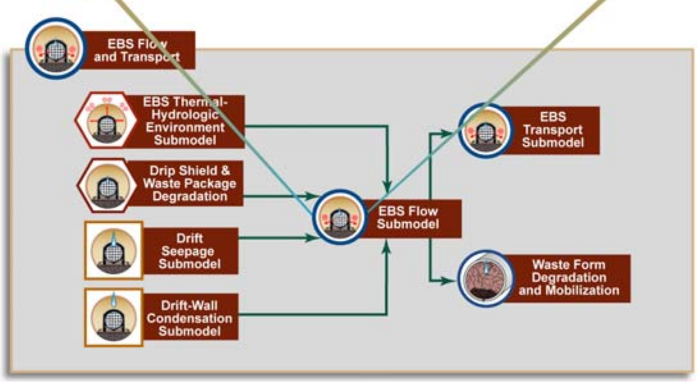


Information Flow Diagram for the EBS Flow and Transport Abstraction

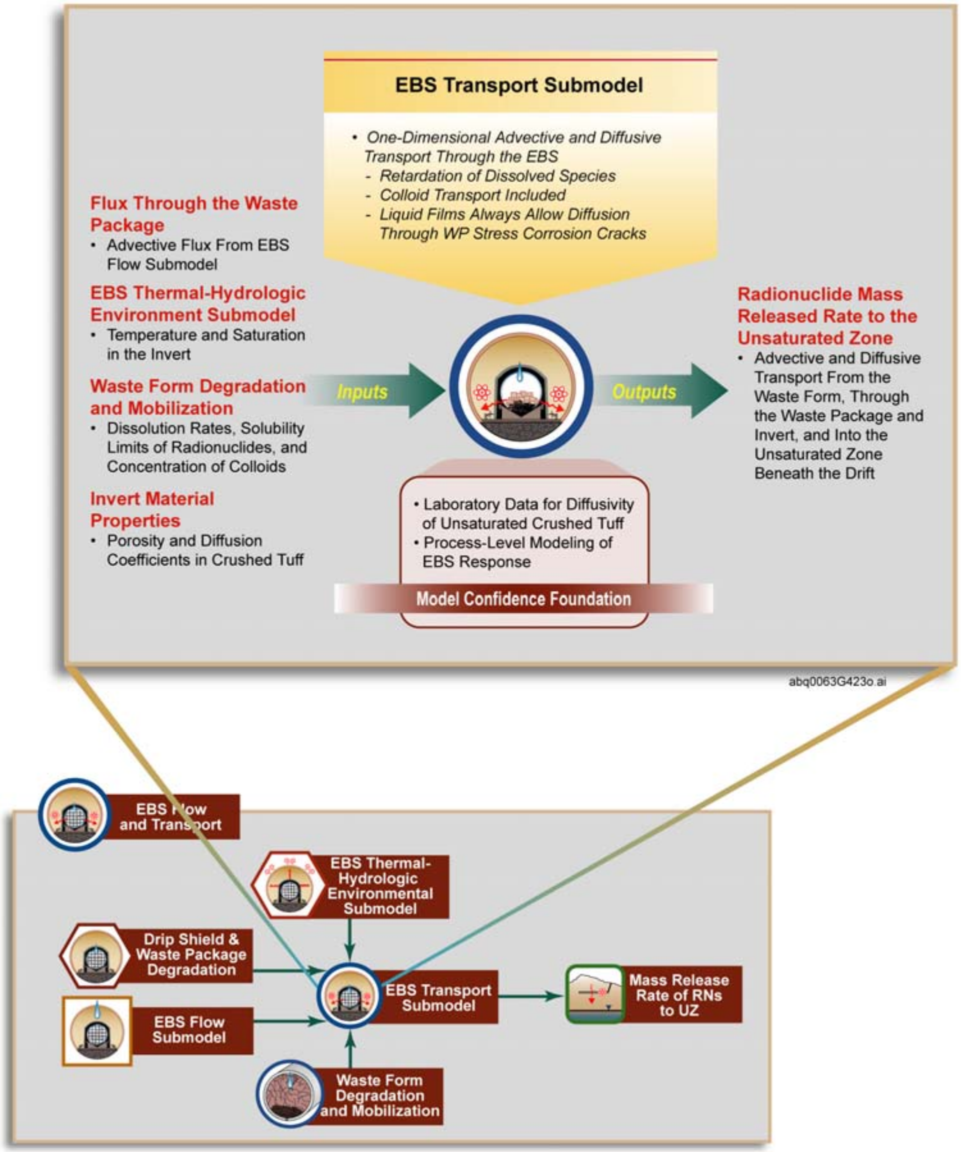


Integration Between EBS Flow Abstraction and TSPA Model

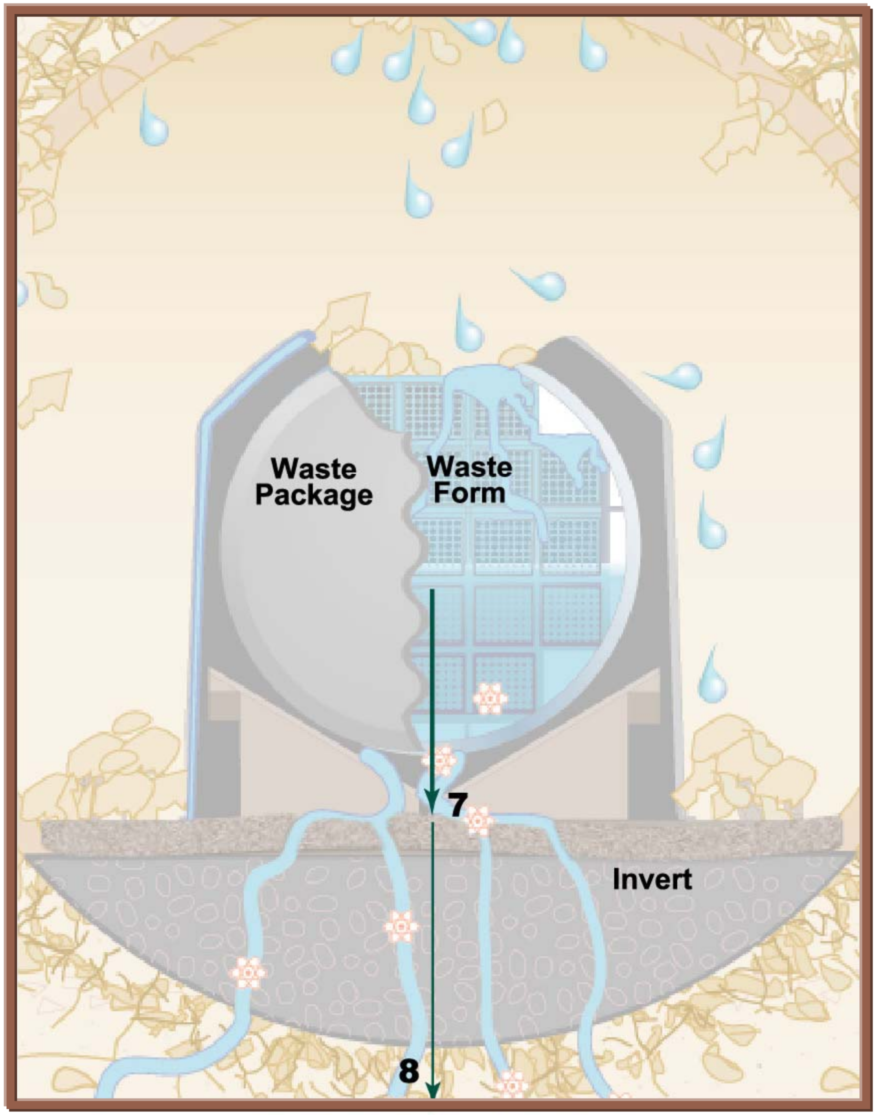




Integration Between EBS Transport Abstraction and TSPA Models



Radionuclide Transport Process in the Drift



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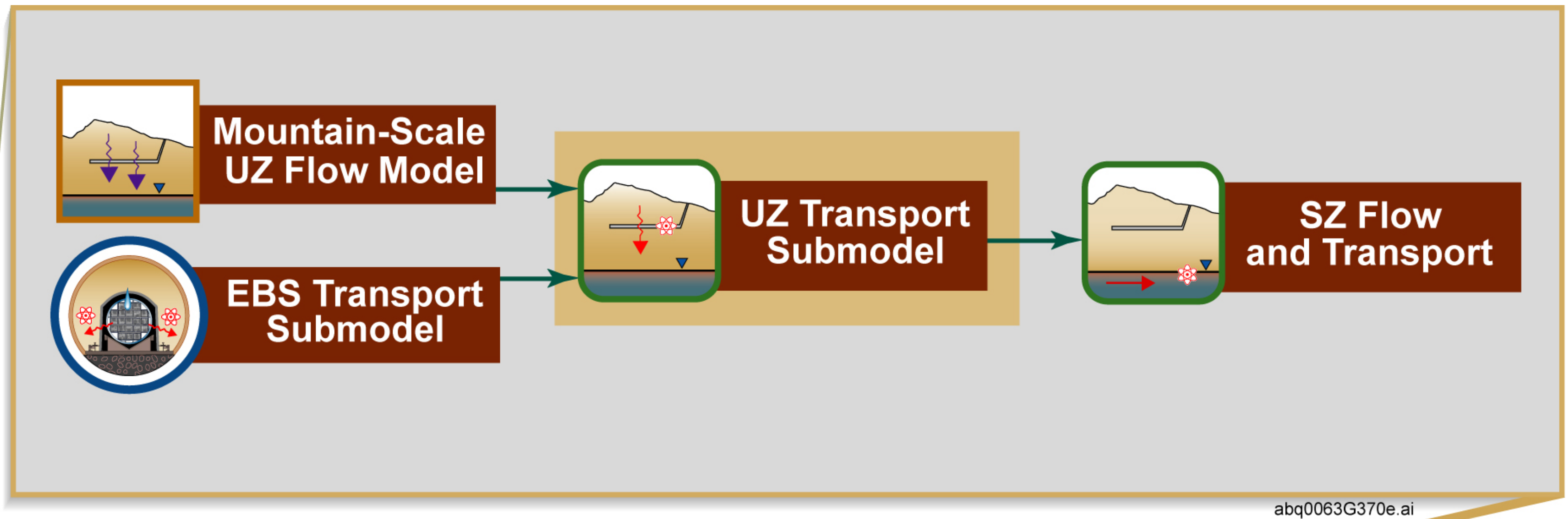
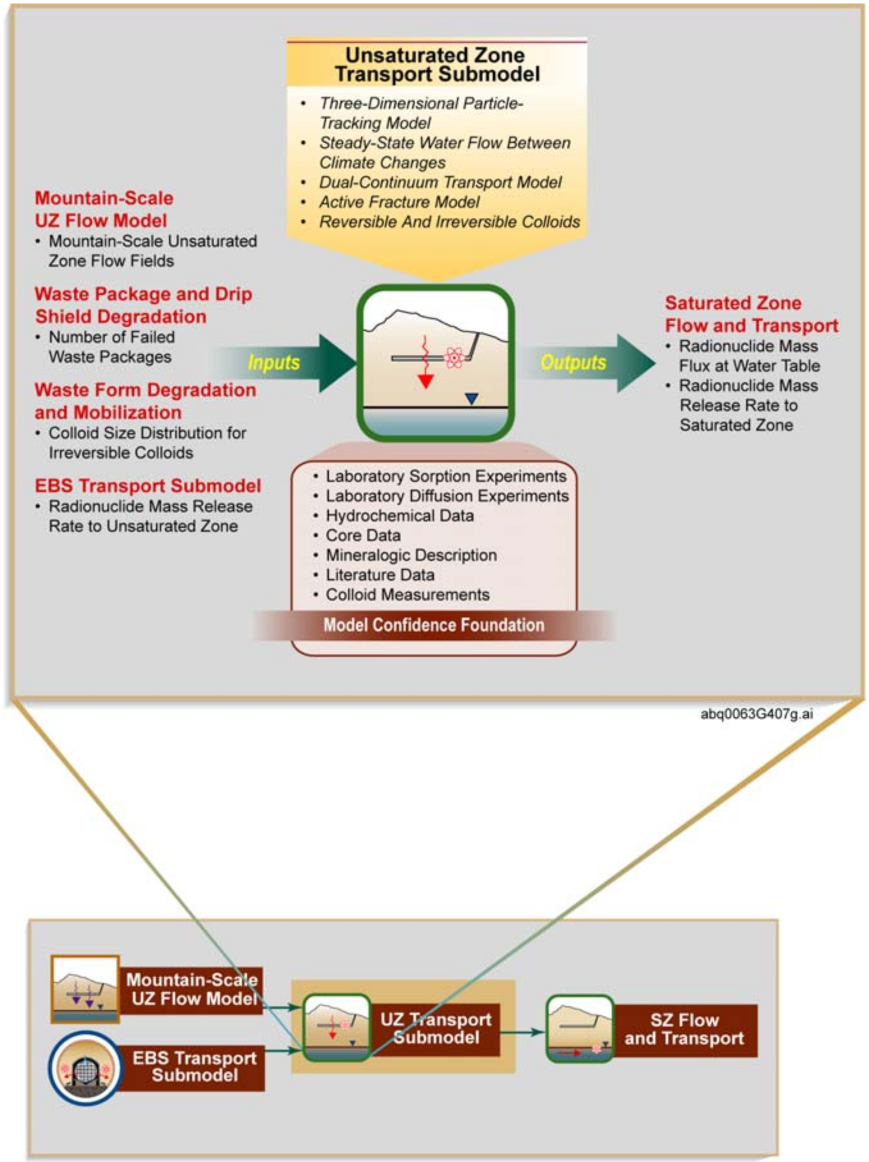
- **Engineered barrier system flow takes into account thermal hydrology, seepage, and waste package condition**
- **Engineered barrier system chemistry evaluates water chemistry, flux, and temperature**
- **Engineered barrier system transport takes into account ability of water to enter waste packages and movement of radionuclides with flowing water and by diffusion in non-flow conditions**

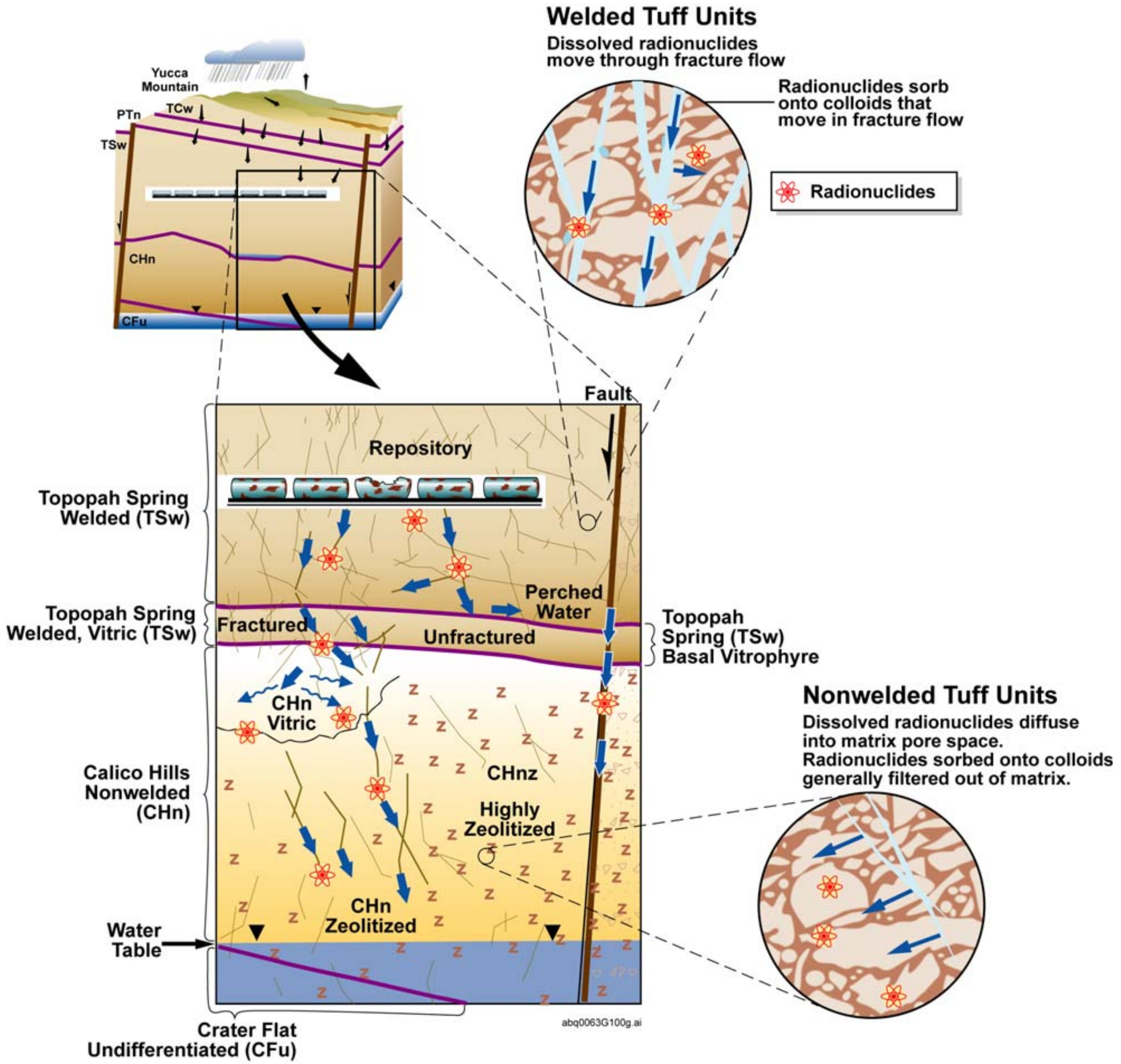
Information Flow Diagram for Unsaturated Zone Transport



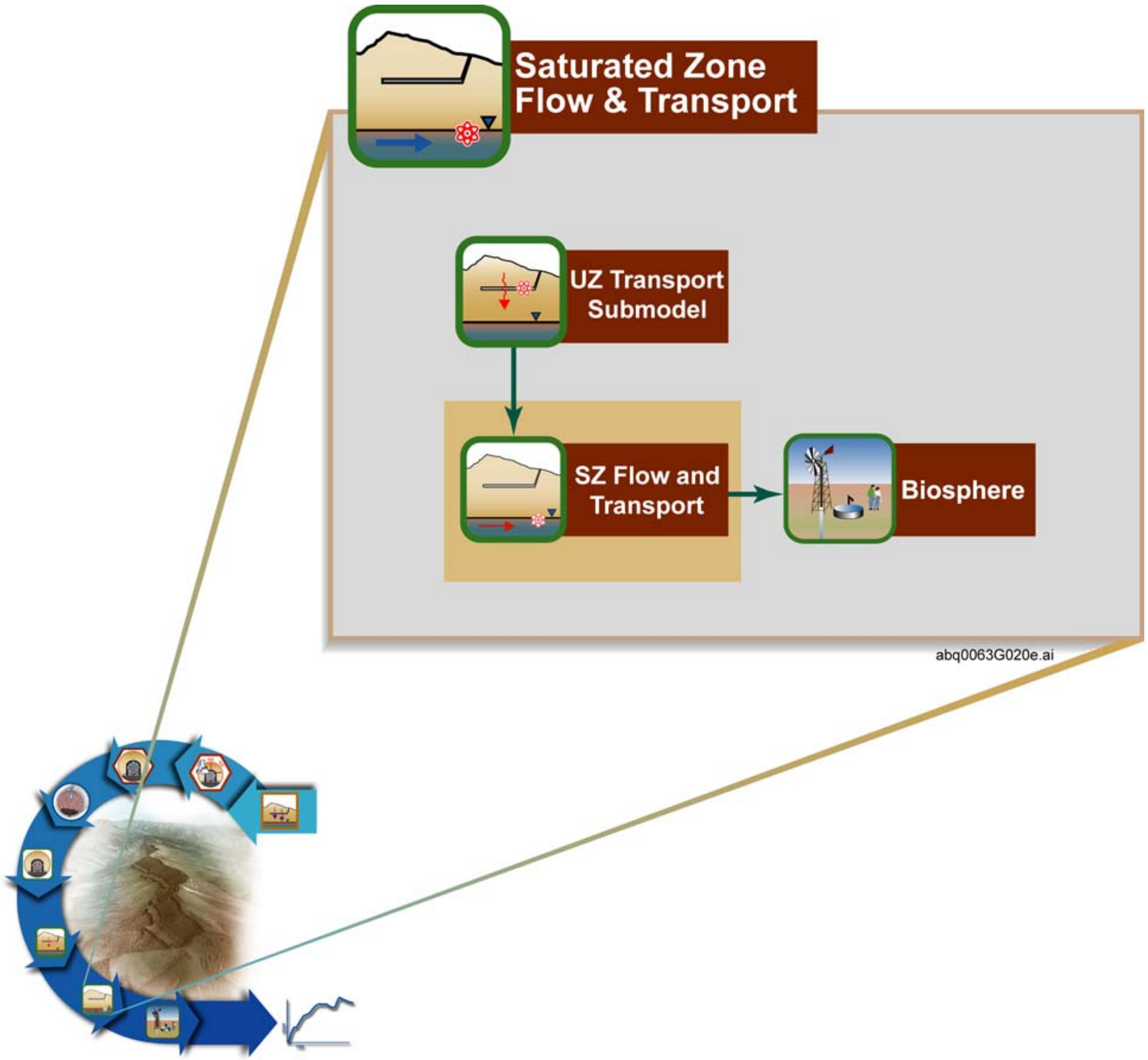
Integration Between Unsaturated Zone Transport and TSPA Model



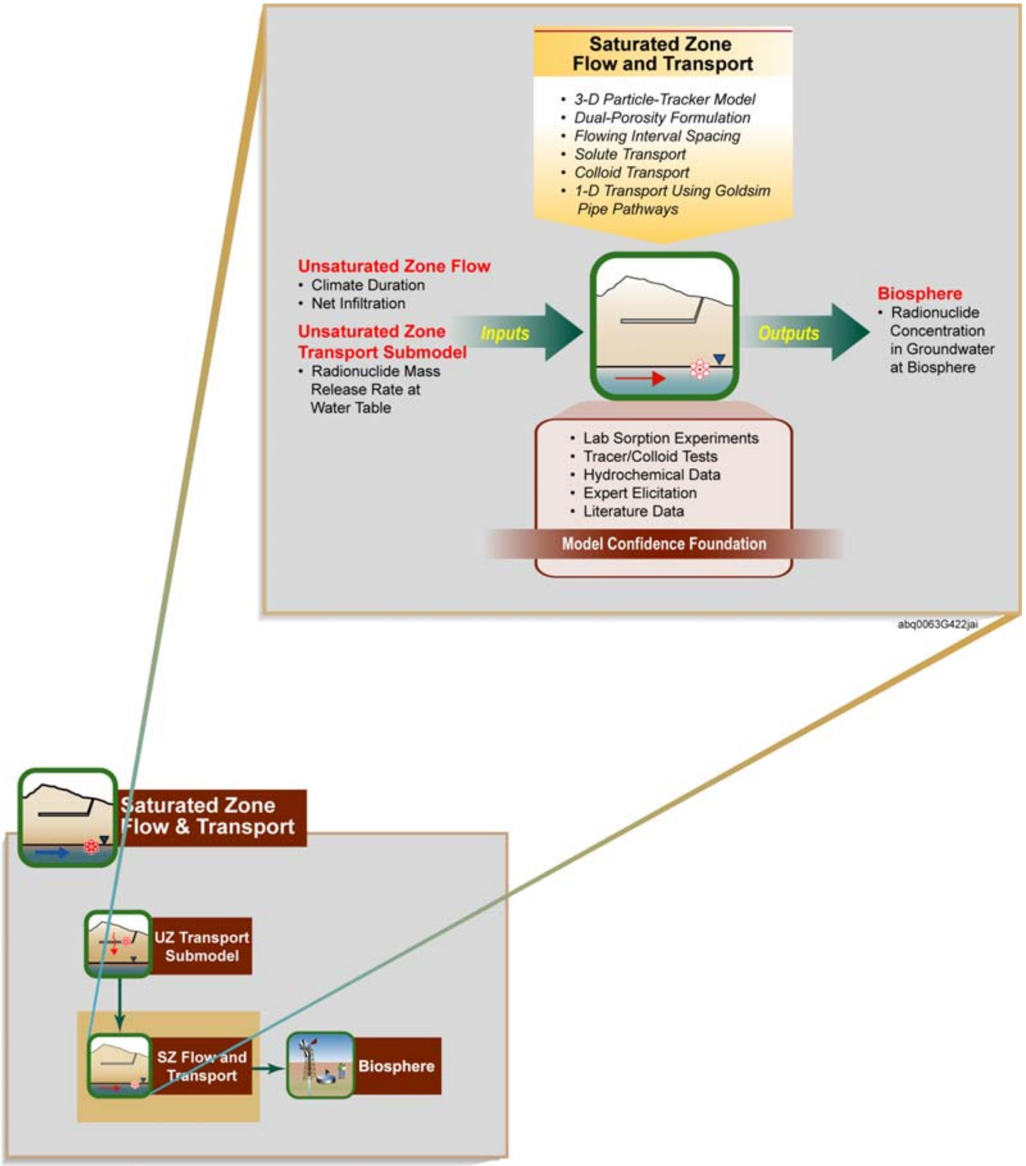
Unsaturated Zone Transport Processes



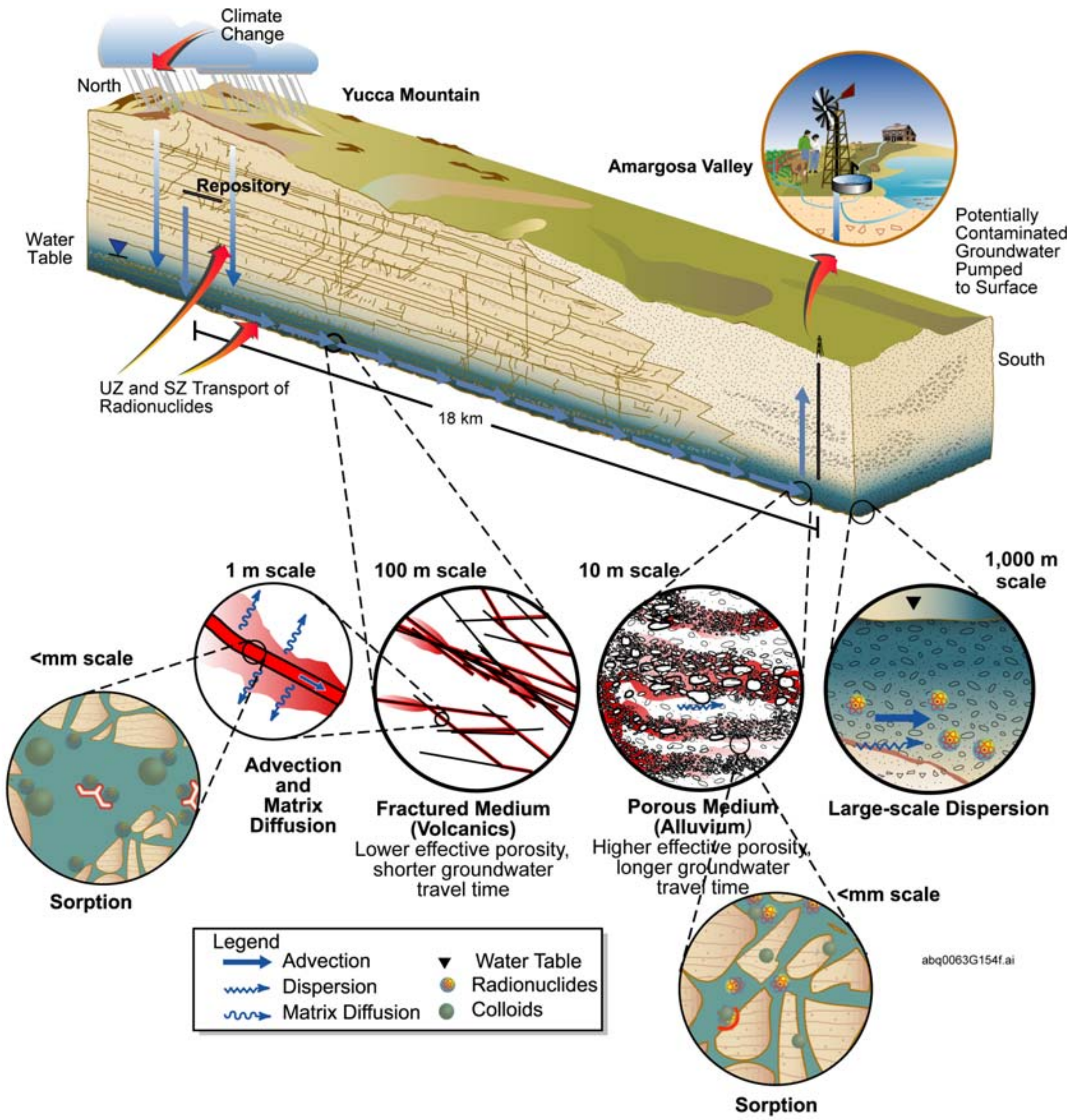
Information Flow Diagram for the Saturated Zone Flow and Transport Model



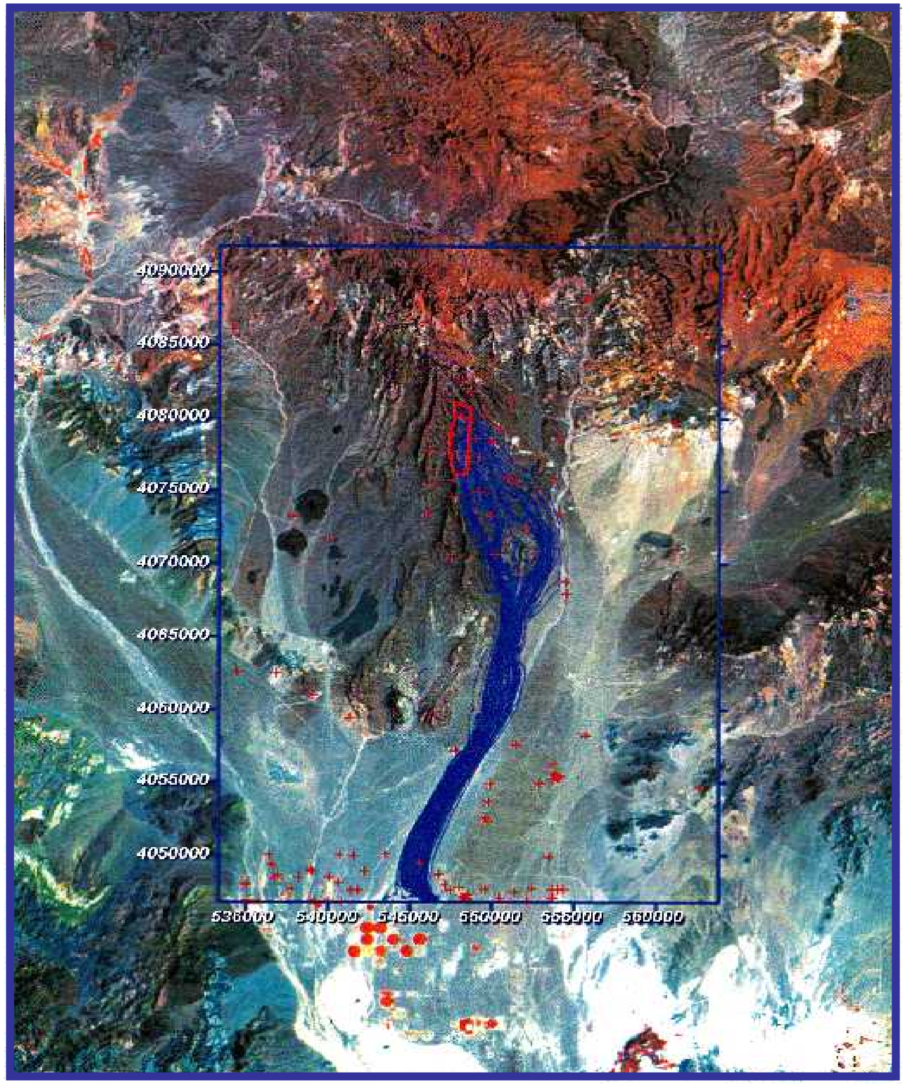
Integration Between Saturated Zone Flow and Transport and TSPA Model



Conceptualization Saturated Zone Transport Features and Processes



Saturated Zone Flow and Transport



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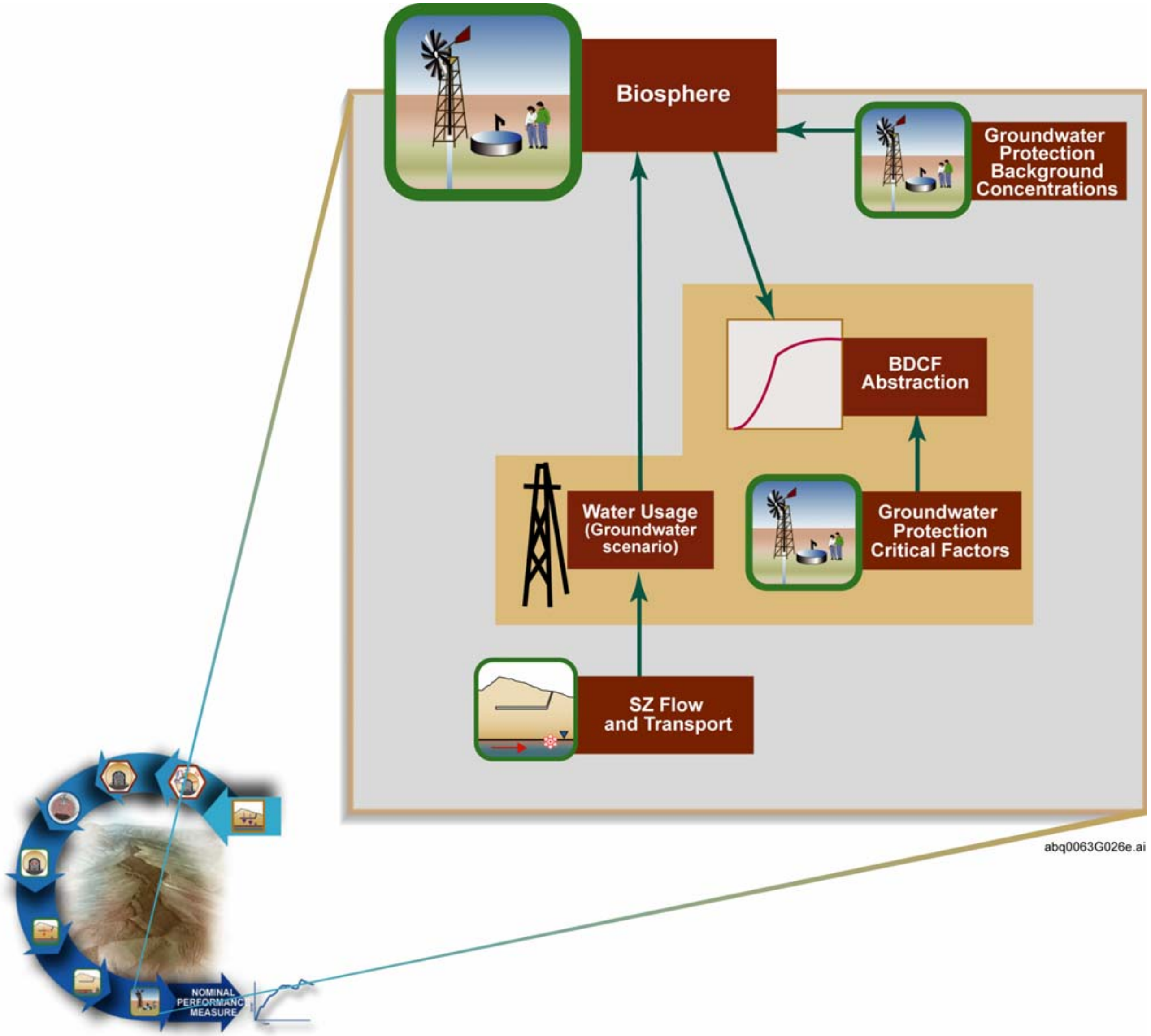
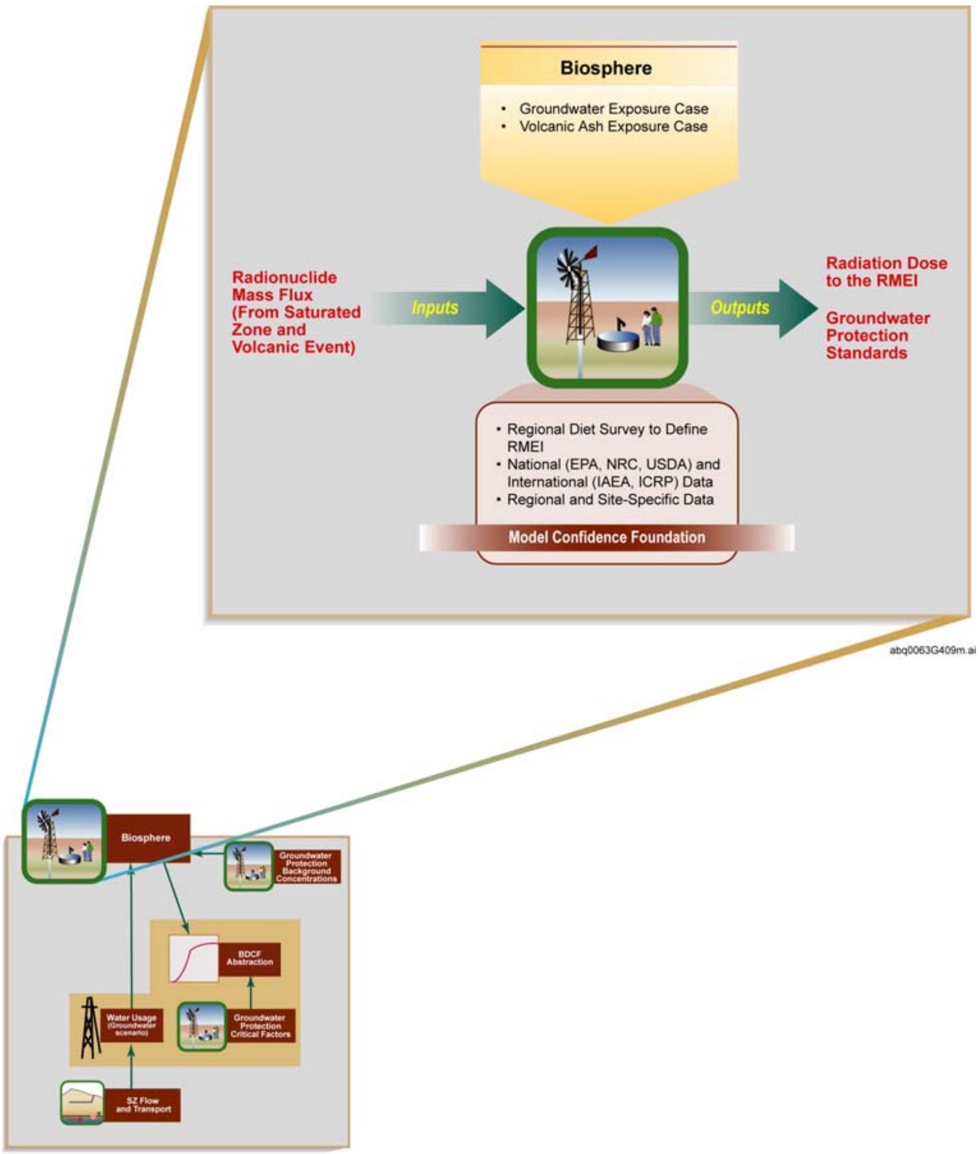
- **Process model calculates site-scale flow**
- **Transport is calculated taking into account sorption, reversible and irreversible colloids**
- **Flow and transport includes climate effects and accounts for radioactive decay and ingrowth**
- **Output to the biosphere model gives the amount of annual radionuclide mass (activity) crossing compliance boundary as a function of time**

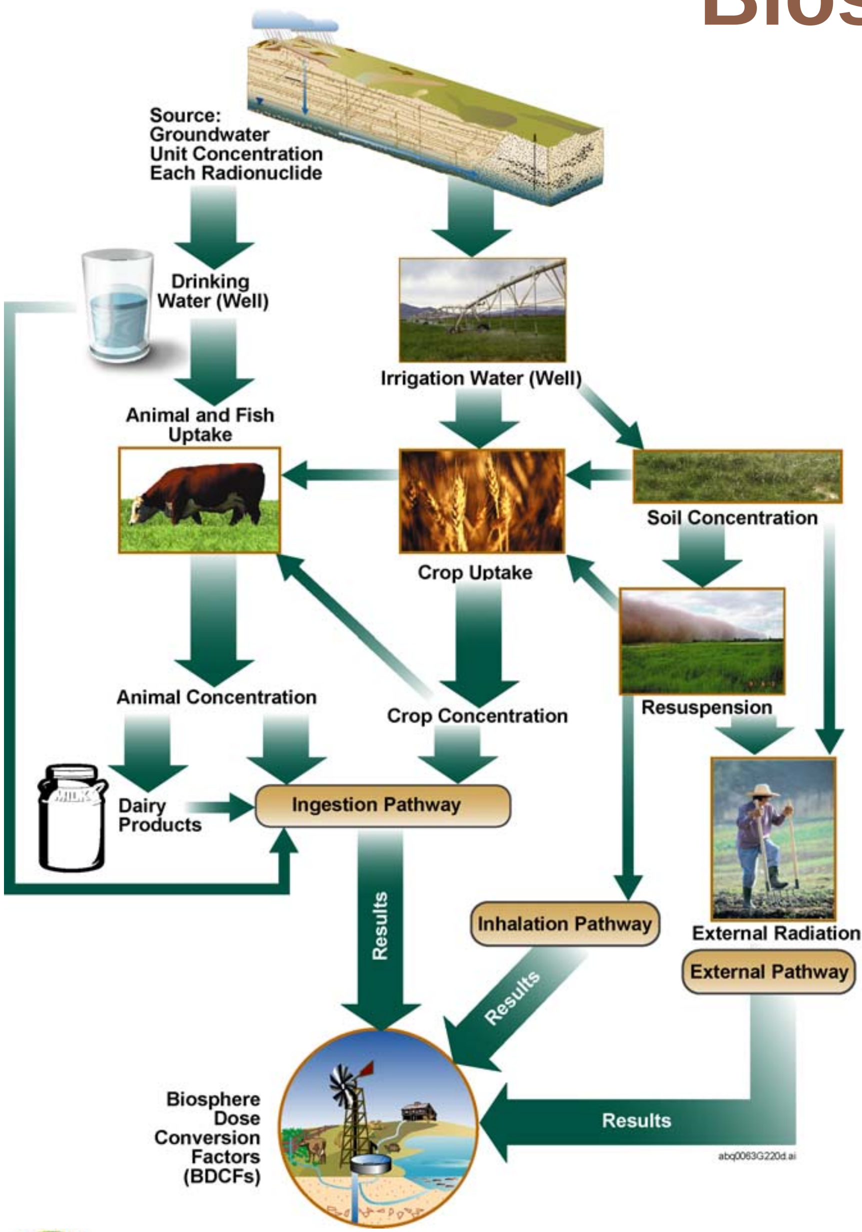
Information Flow Diagram for the Biosphere Model Component of TSPA-LA Model and TSPA-LA Model



Integration of Biosphere Model in TSPA

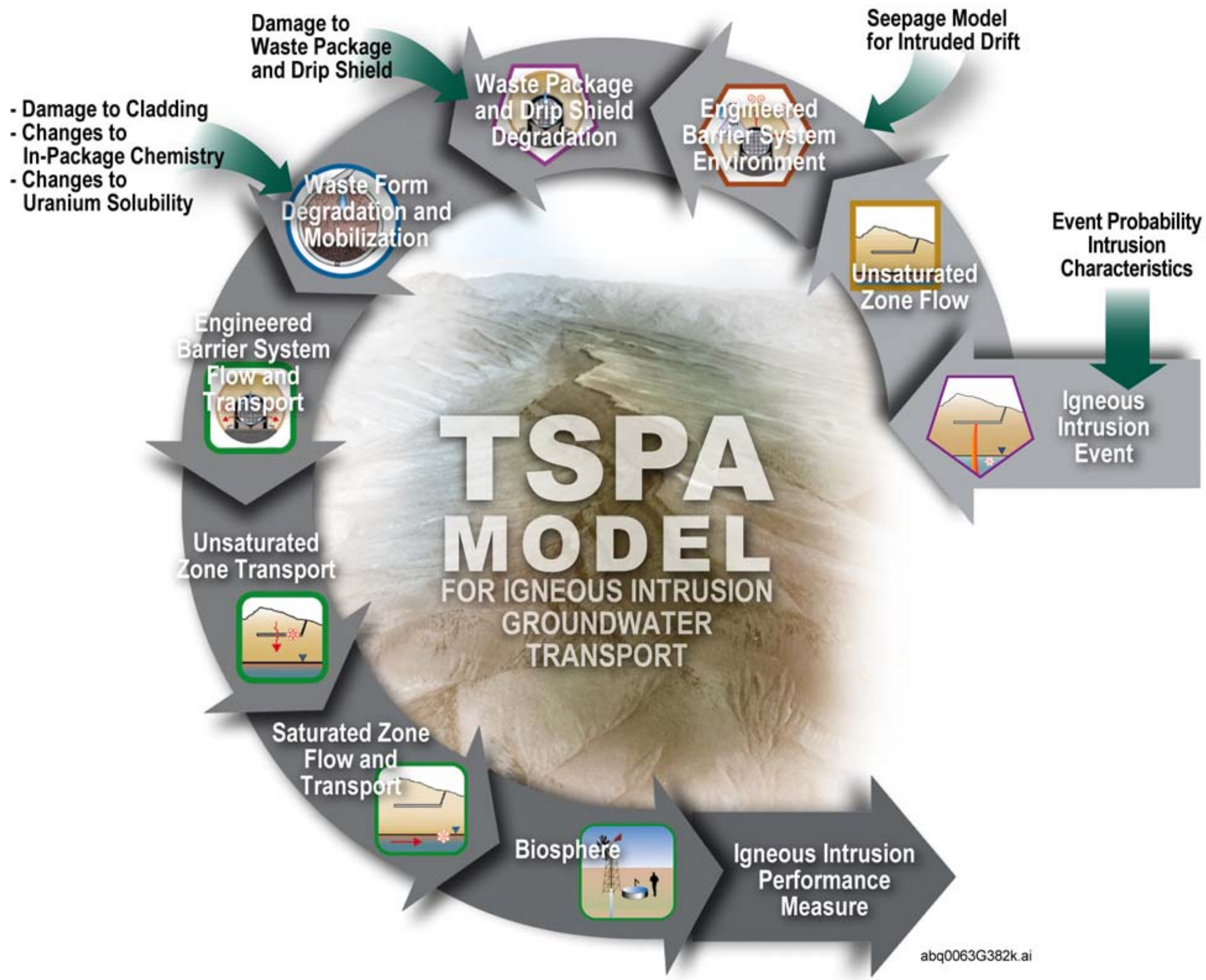


Biosphere

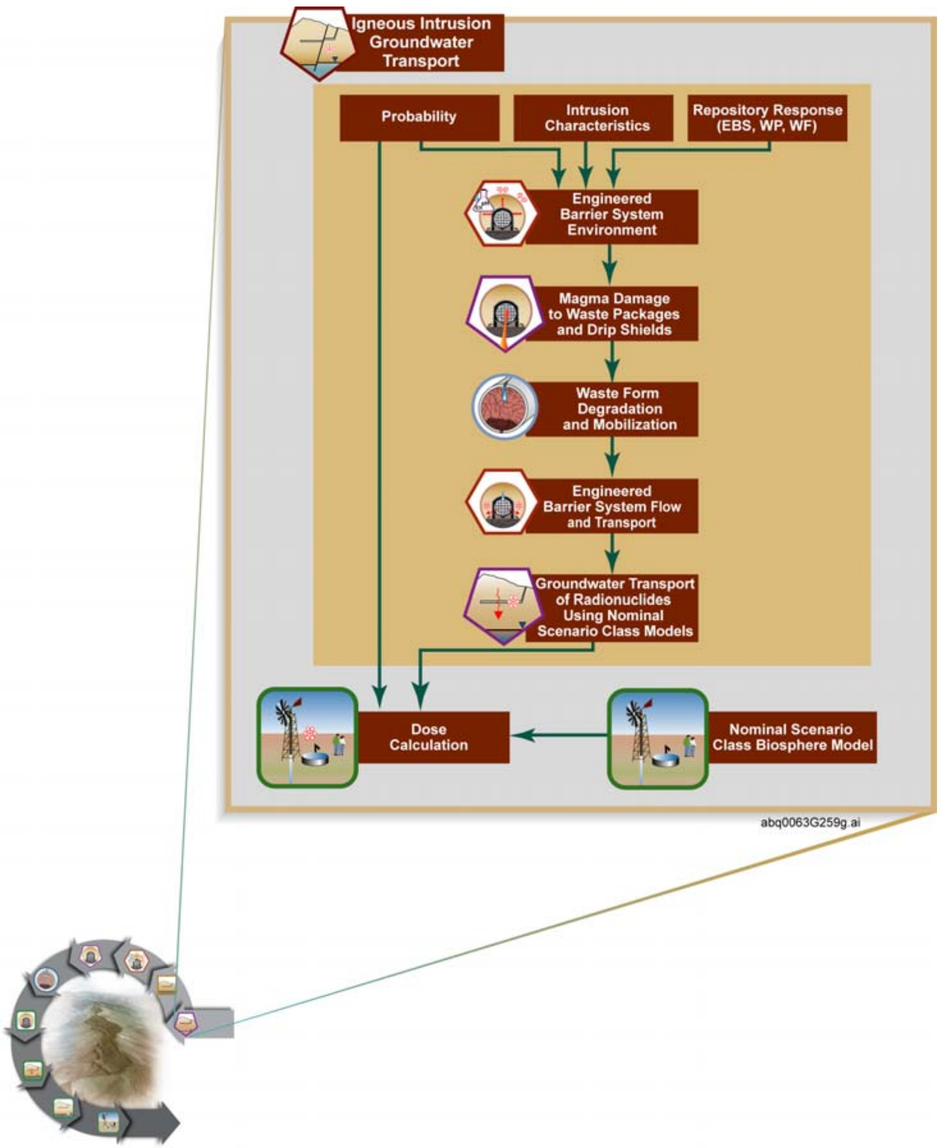


- **Exposure pathways include food and water ingestion, dust inhalation, external exposure to contaminated soil**
- **Human lifestyles consistent with regulatory requirements**
- **Dose methodology based on the International Commission on Radiological Protection standards mandated by regulation**
- **Inputs are radionuclide concentrations in groundwater, human lifestyle data**
- **Outputs to Total System Performance Assessment are biosphere dose conversion factors**

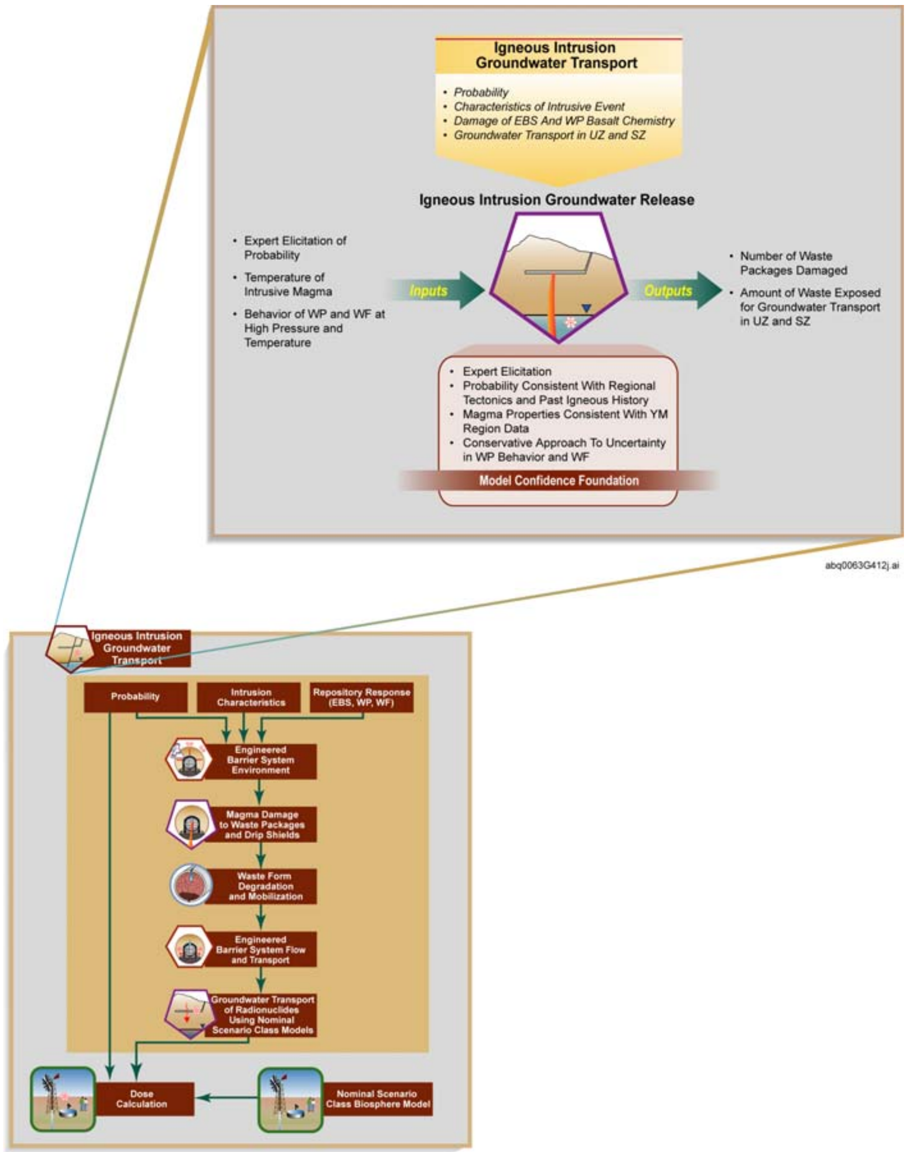
Igneous Intrusion Scenario



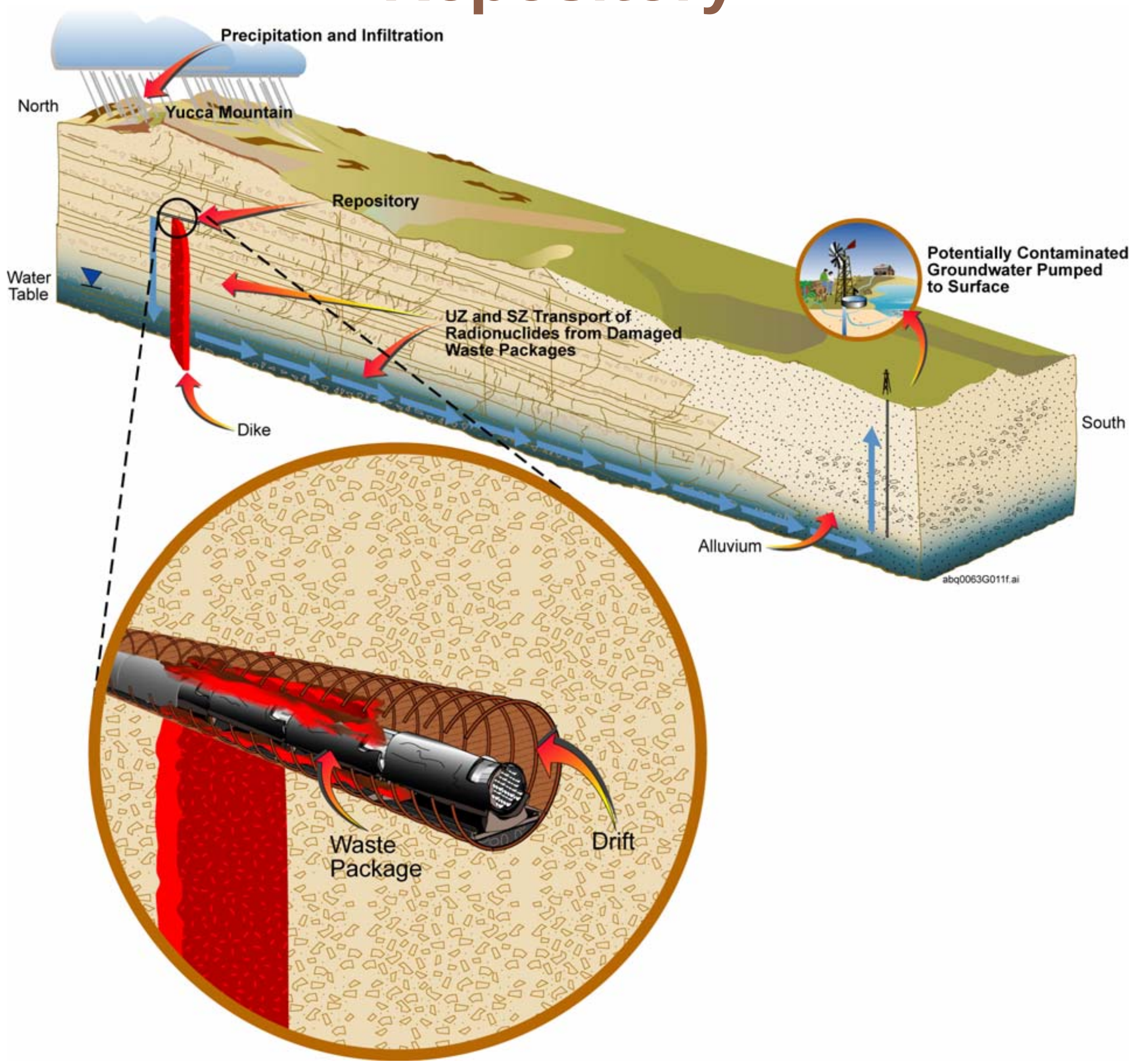
Information Flow in Igneous Intrusion Groundwater Transport Model



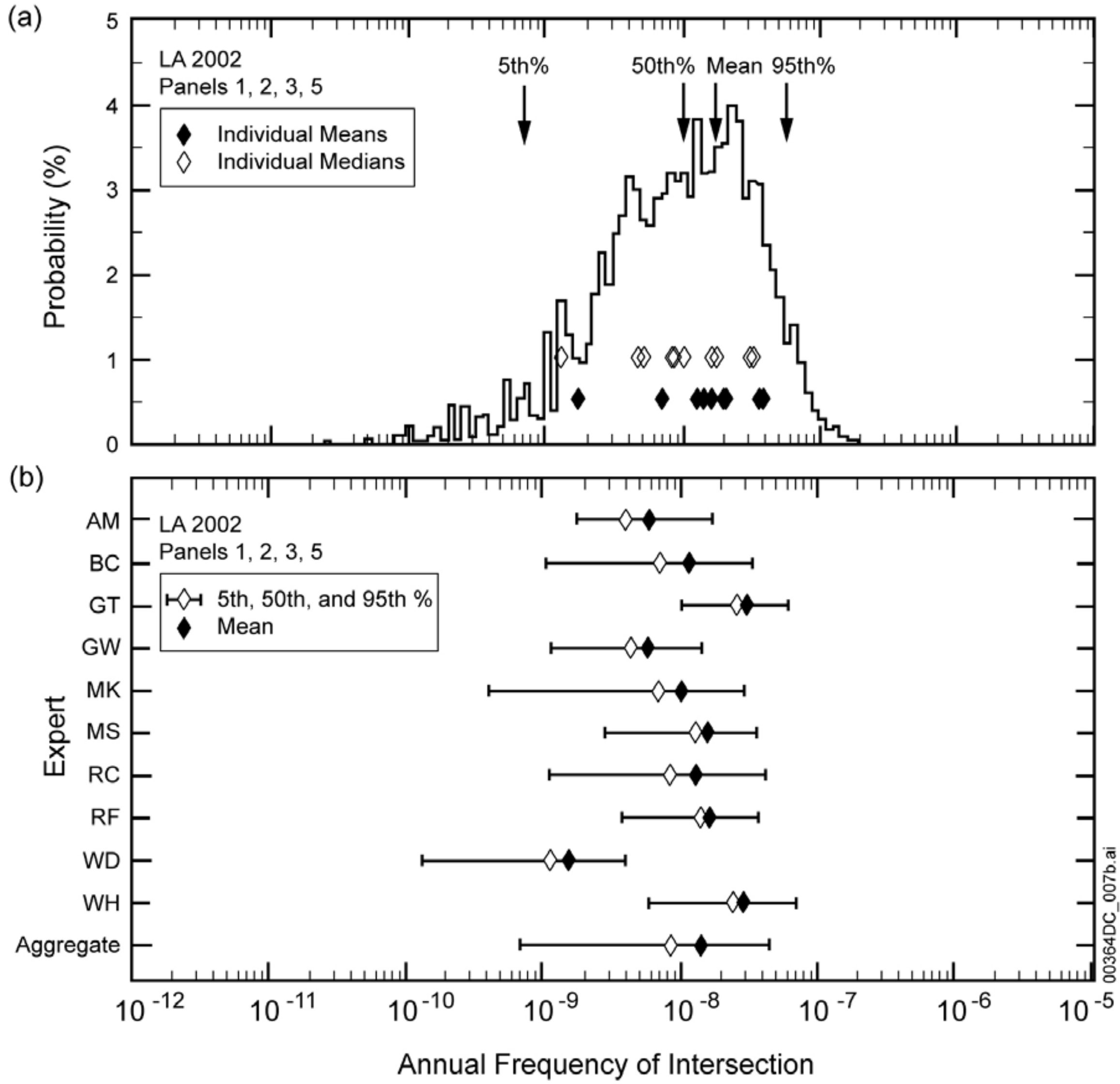
Integration of Igneous Intrusion Groundwater Transport Model in TSPA



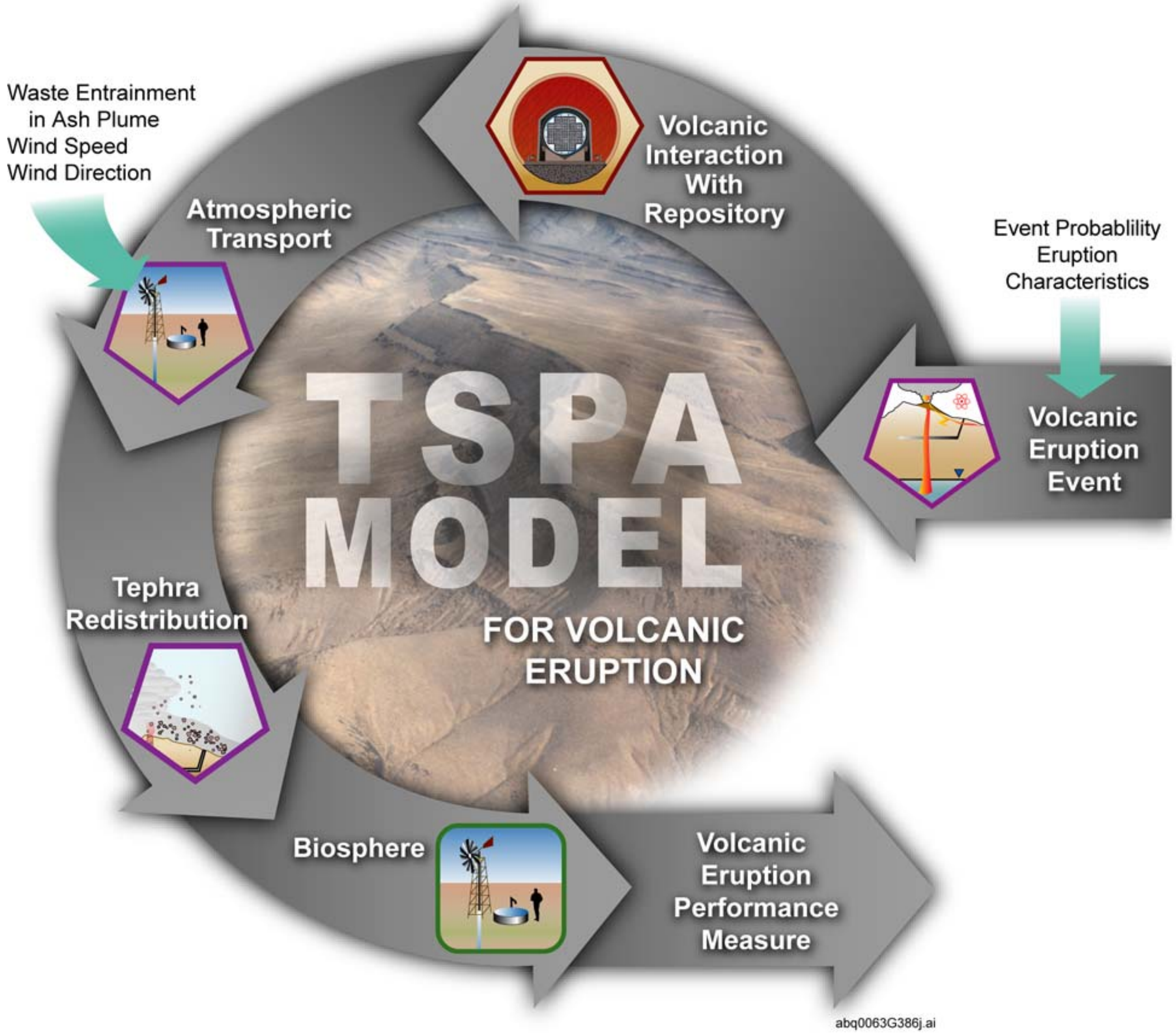
Unlikely Intersection of Igneous Dike with Repository



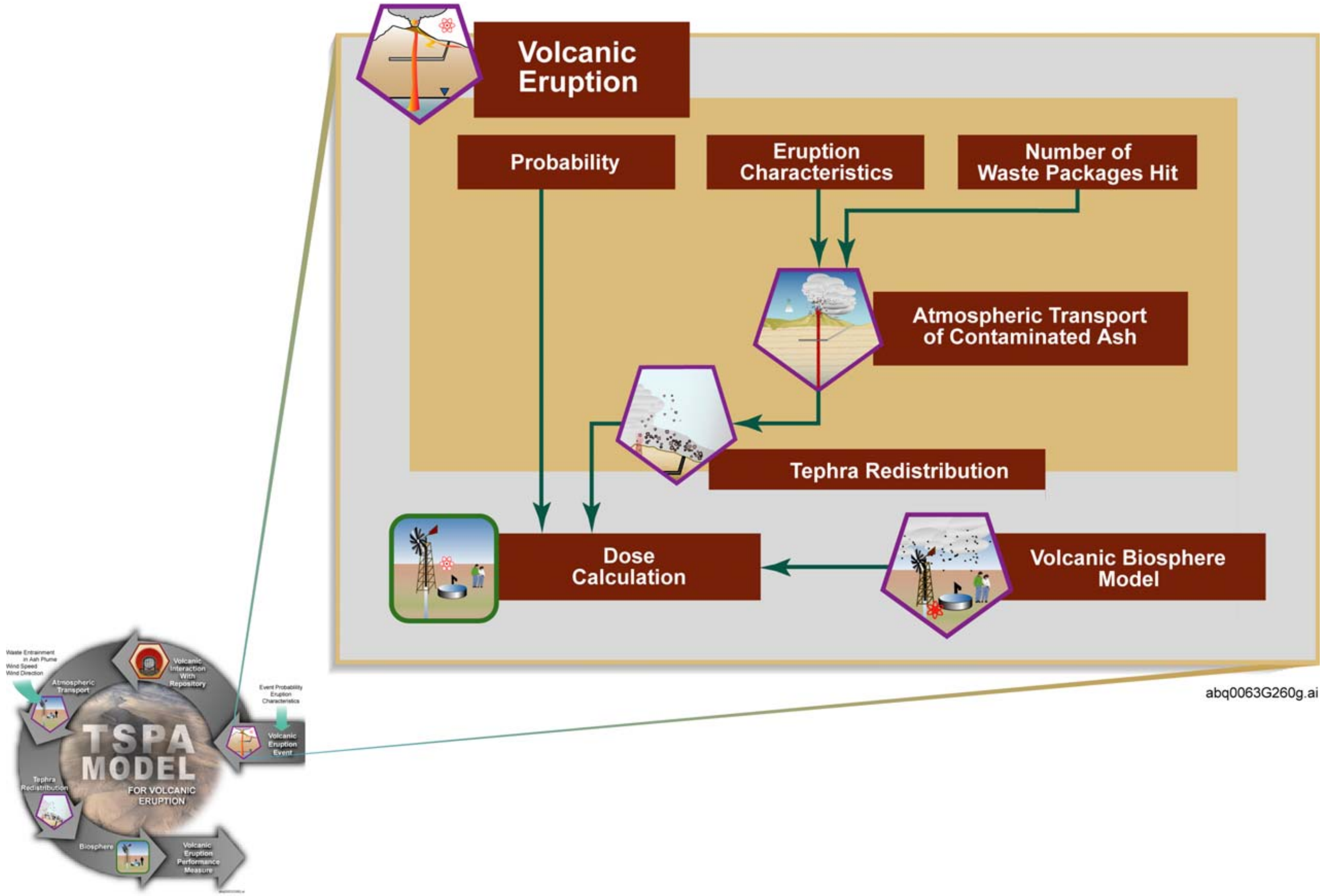
Expert Elicited Distributions of an Unlikely Igneous Dike Intersecting the Repository Footprint



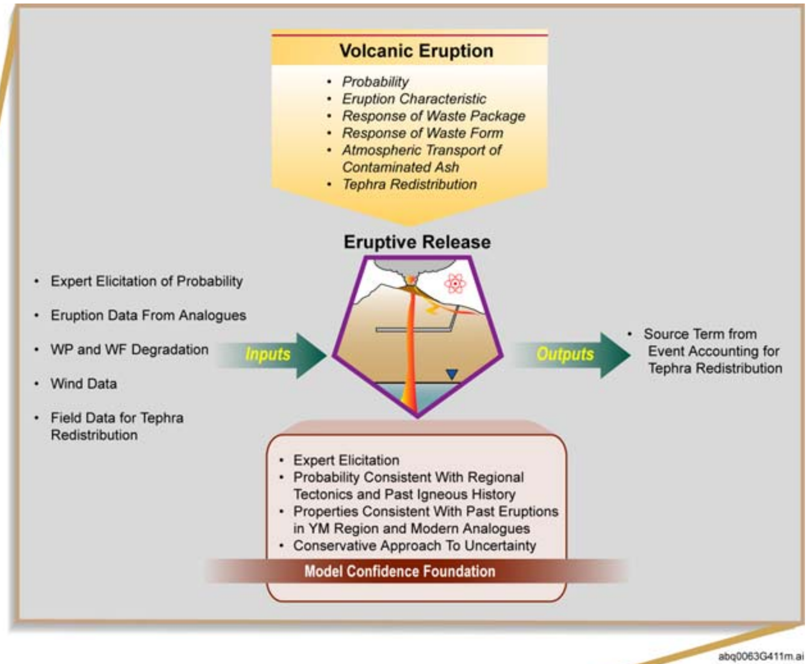
Volcanic Eruption Scenario

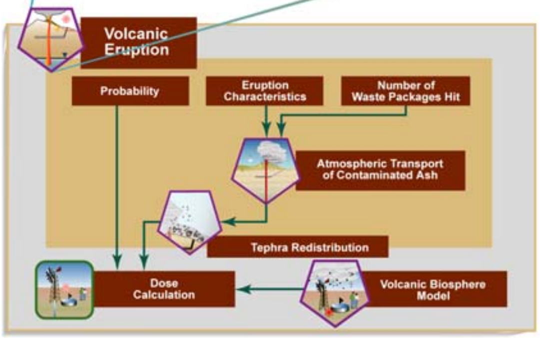


Flow of Information Within TSPA Volcanic Eruption Modeling Case

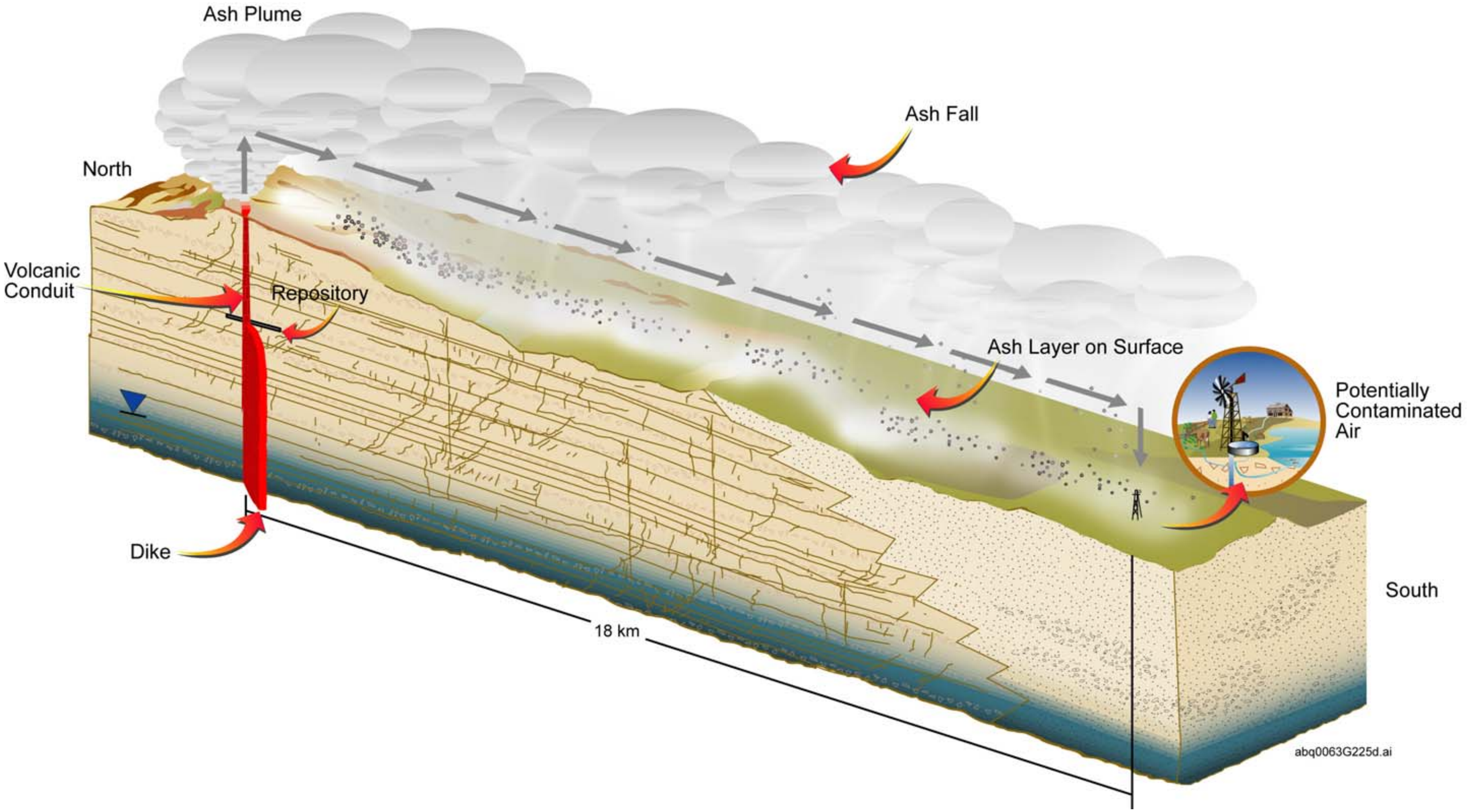


Integration of Volcanic Eruption Modeling Case in TSPA

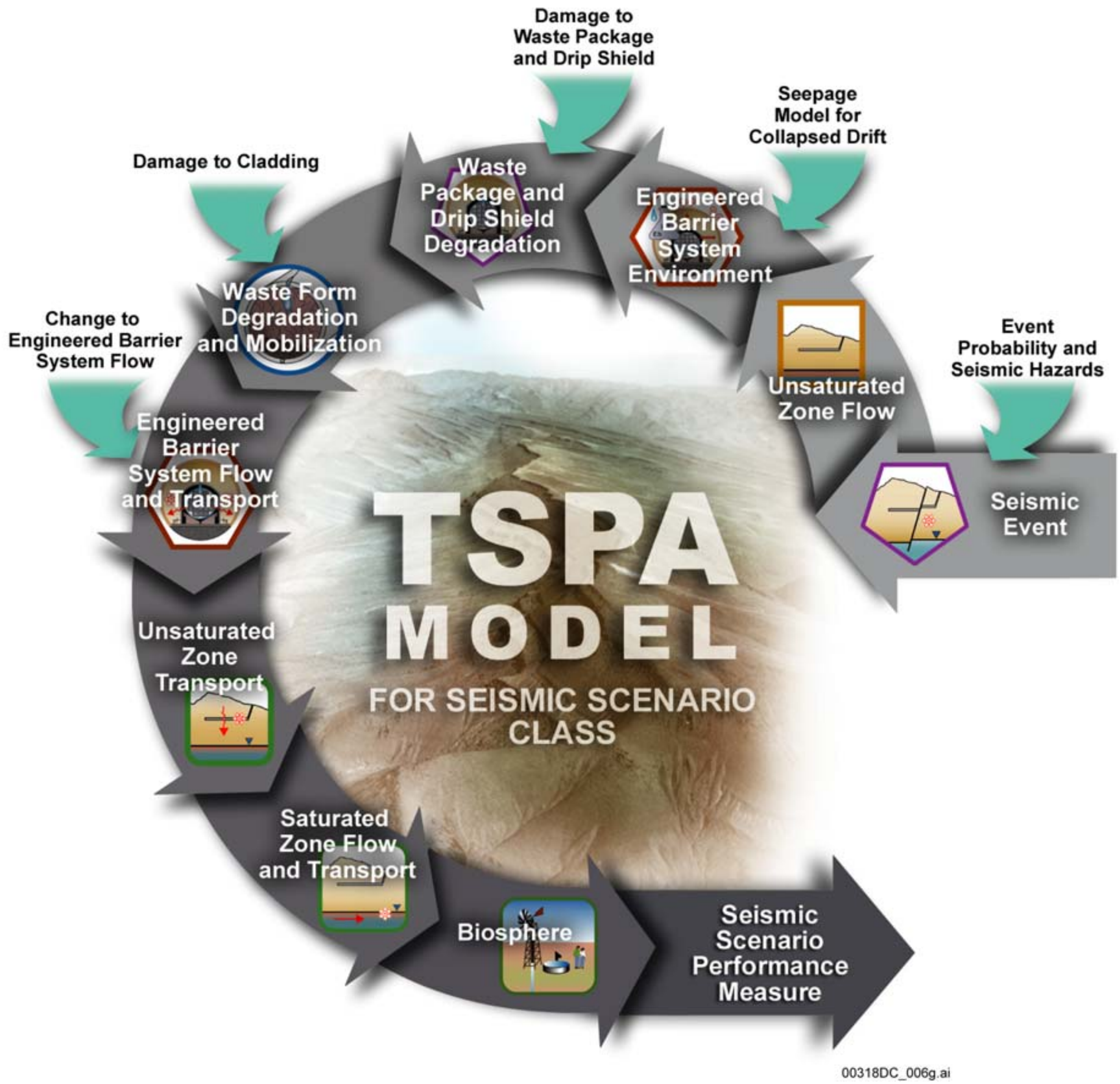




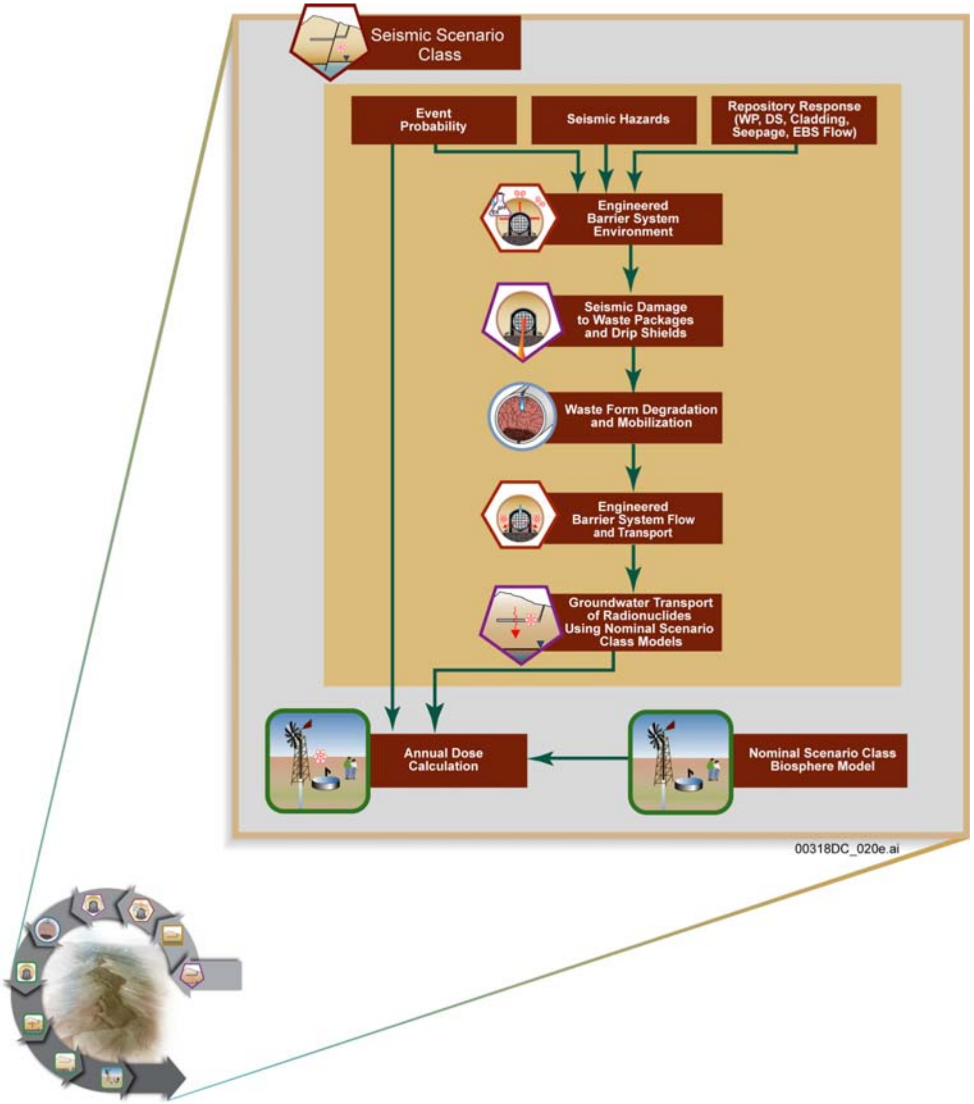
Unlikely Volcanic Eruption at Yucca Mountain,



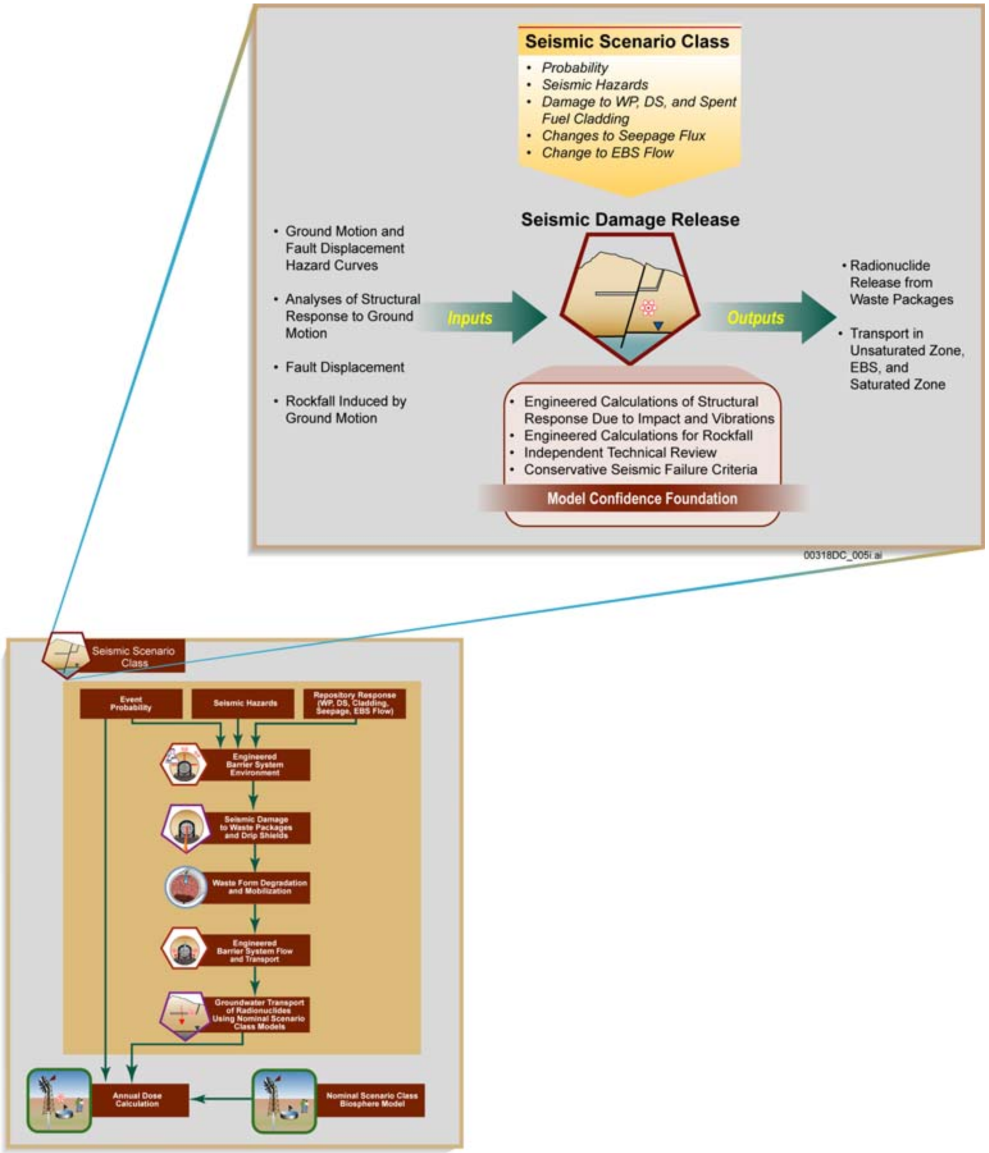
Seismic Scenario Class



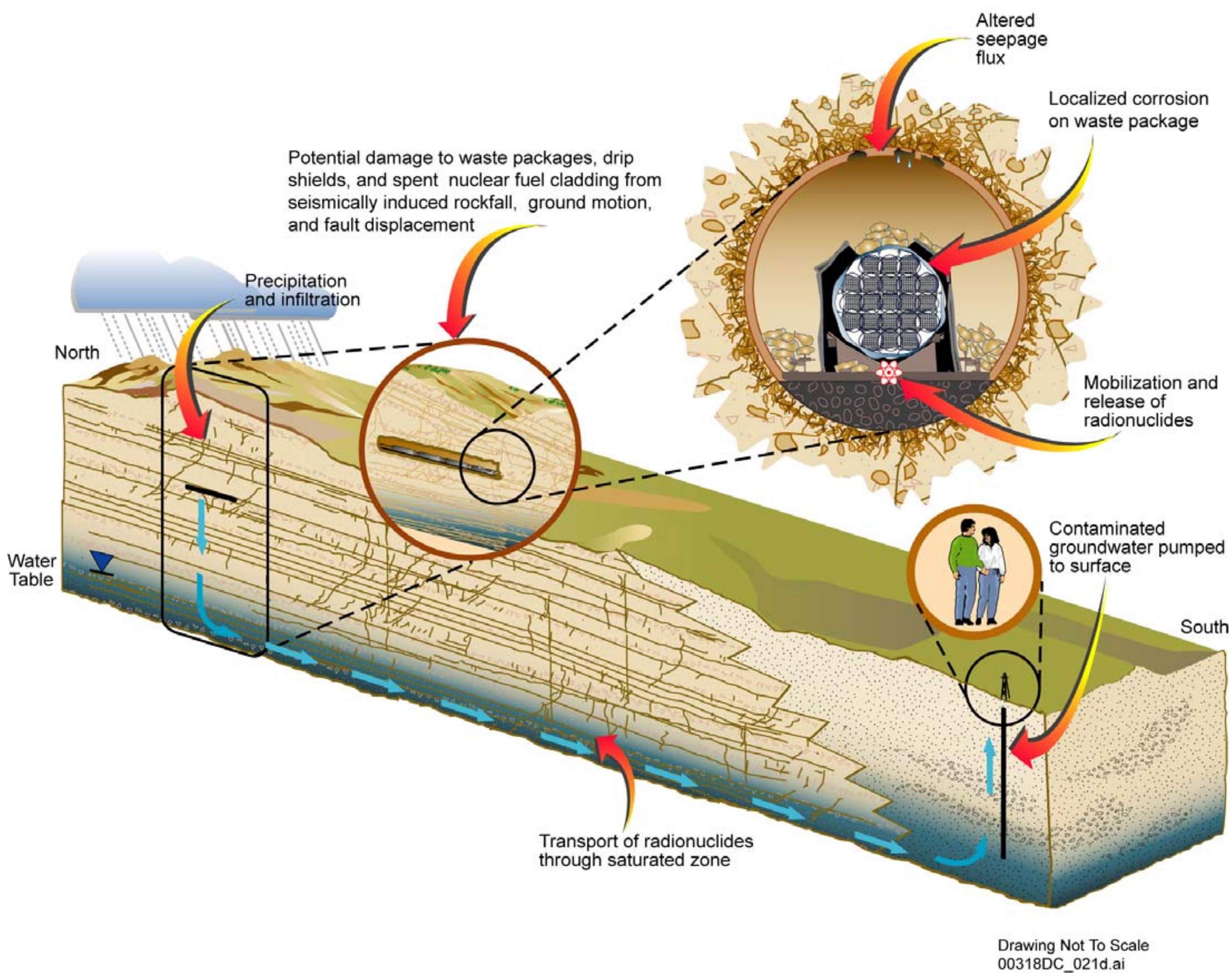
Information Flow of Seismic Scenario Class in TSPA



Integration of Seismic Scenario Class Model in TSPA



Seismic Scenario Class Model



Summary Model Changes for TSPA-LA

Model Component	Principal Change
Climate and Infiltration	• No major change
Unsaturated Zone Flow	• No major change
Seepage	• Additional test data in lower lithophysal unit • Flow focussing factor based on analyses of heterogeneous permeability • Incorporate drift collapse effects for seismic events • Incorporate above boiling vaporization barrier effect
Thermal Hydrology	• Include uncertainty in thermal conductivity • Include drift-wall condensation effects • Use full heat up and 1 year of cool down from DST for model validation • Revise based on LA repository footprint • Update hydrologic properties from UZ calibration
Thermal Chemical	• Include uncertainty in initial pore water chemistry • Use full heat up and 1 year of cool down from DST for model validation • Update chemical evolution of waters in low saturation blocks nearest drifts • Include uncertainty in in-drift thermal hydrology • Include uncertainty in deliquescent salts in dusts • Remove cementitious materials
Waste Package Corrosion	• Include 5-year weight loss data and temperature dependence • Use localized corrosion initiation model based on T, pH, NO_3, Cl and NO_3/Cl ratio based on Ecorr and Ecrit data from crevice corrosion tests • Update stress calculations due to laser peening of outer closure lid and no stress relief for middle closure lid • Revised weld flaw treatment • Update threshold stress intensity factor
In-Package Chemistry/Waste Form	• Update in-package chemistry assuming either liquid water or water vapor • Update colloid fractions • Re-evaluate actinide solubility models based on thermodynamic data including uncertainty

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Summary of Model Changes for TSPA-LA

(continued)

Model Component	Principal Change
EBS transport	• Update model for sorption onto degraded waste package and basket materials and invert
Unsaturated zone transport	• Update matrix diffusion model in FEHM particle tracker
Saturated zone transport	• No major changes
Biosphere transport	• Modify eruptive biosphere dose conversion factor model
Igneous Events	• Include uncertainty in in-drift chemistry and percolation flux for intrusive case • Modify distributions of number of waste packages intersected by eruptive and intrusive events • Revise wind distribution used in Ashplume analyses • Incorporate ash redistribution following eruptive event • Revise inhalation dose parameters • Evaluate effect of backfill in aceess mains on magma flow between drifts
Seismic Events	• Use range of peak ground velocities and accelerations from low probability initiating events • Include thermal effects following seismic-induced drift collapse • Include mechanical effects of waste package and drip shield damage • Include drift collapse possibility • Include fault displacement damage

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Summary

- **TSPA process, approach, and methodology has been well established and confirmed through multiple iterations and external reviews**
- **Model abstractions to support TSPA are based on multiple lines of evidence (data, process and alternative models, analogs) and have been through multiple external reviews**
- **TSPA analyses have been used for multiple purposes, including gaining risk insights**
- **TSPA results will be used to evaluate compliance with regulatory requirements**

Backup

Post Closure Performance Objectives

- **§ 63.113 Performance objectives for the geologic repository after permanent closure.**
  - **(a) The geologic repository must include multiple barriers, consisting of both natural barriers and an engineered barrier system.**
  - **(b) The engineered barrier system must be designed so that, working in combination with natural barriers, radiological exposures to the reasonably maximally exposed individual are within the limits specified at § 63.311 of subpart L of this part. Compliance with this paragraph must be demonstrated through a performance assessment that meets the requirements specified at § 63.114 of this subpart, and §§ 63.303, 63.305, 63.312 and 63.342 of Subpart L of this part.**
  - **(c) The engineered barrier system must be designed so that, working in combination with natural barriers, releases of radionuclides into the accessible environment are within the limits specified at § 63.331 of subpart L of this part. Compliance with this paragraph must be demonstrated through a performance assessment that meets the requirements specified at § 63.114 of this subpart and §§ 63.303, 63.332 and 63.342 of subpart L of this part.**
  - **(d) The ability of the geologic repository to limit radiological exposures to the reasonably maximally exposed individual, in the event of human intrusion into the engineered barrier system, must be demonstrated through an analysis that meets the requirements at §§ 63.321 and 63.322 of subpart L of this part. Estimating radiological exposures to the reasonably maximally exposed individual requires a performance assessment that meets the requirements specified at § 63.114 of this subpart, and §§ 63.303, 63.305, 63.312 and 63.342 of subpart L of this part.**

§ 63.114 Requirements for performance assessment

Any performance assessment used to demonstrate compliance with § 63.113 must:

- **(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.**
- **(b) Account for uncertainties and variabilities in parameter values and provide for the technical basis for parameter ranges, probability distributions, or bounding values used in the performance assessment.**
- **(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 repository.**
- **(d) Consider only events that have at least one chance in 10,000 of occurring over 10,000 years.**
- **(e) Provide the technical basis for either inclusion or exclusion of specific features, events, and processes in the performance assessment. Specific features, events, and processes must be evaluated in detail if the magnitude and time of the resulting radiological exposures to the reasonably maximally exposed individual, or radionuclide releases to the accessible environment, would be significantly changed by their omission.**

§ 63.114 Requirements for performance assessment
(continued)

Any performance assessment used to demonstrate compliance with § 63.113 must: (continued)

(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 radiological exposures to the reasonably maximally exposed individual, or radionuclide releases to the accessible environment, would be significantly changed by their omission.

(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).

§ 63.115 Requirements for multiple barriers

Demonstration of compliance with § 63.113(a) must:

(a) Identify those design features of the engineered barrier system, and natural features of the geologic setting, that are considered barriers important to waste isolation.

(b) Describe the capability of barriers, identified as important to waste isolation, to isolate waste, taking into account uncertainties in characterizing and modeling the behavior of the barriers.

(c) Provide the technical basis for the description of the capability of barriers, identified as important to waste isolation, to isolate waste. The technical basis for each barrier's capability shall be based on and consistent with the technical basis for the performance assessments used to demonstrate compliance with § 63.113(b) and (c).

§ 63.303 Implementation of Subpart L

- **DOE must demonstrate that there is a reasonable expectation of compliance with this subpart before a license may be issued. In the case of the specific numerical requirements in § 63.311 of this subpart, and if performance assessment is used to demonstrate compliance with the specific numerical requirements in §§63.321 and 63.331 of this subpart, compliance is based upon the mean of the distribution of projected doses of DOE's performance assessments which project the performance of the Yucca Mountain disposal system for 10,000 years after disposal.**

§ 63.304 Reasonable Expectation

- **Reasonable expectation means that the Commission is satisfied that compliance will be achieved based upon the full record before it. Characteristics of reasonable expectation include that it:**
  - **(1) Requires less than absolute proof because absolute proof is impossible to attain for disposal due to the uncertainty of projecting long-term performance;**
  - **(2) Accounts for the inherently greater uncertainties in making long-term projections of the performance of the Yucca Mountain disposal system;**
  - **(3) Does not exclude important parameters from assessments and analyses simply because they are difficult to precisely quantify to a high degree of confidence; and**
  - **(4) Focuses performance assessments and analyses on the full range of defensible and reasonable parameter distributions rather than only upon extreme physical situations and parameter values.**

§ 63.305 Required Characteristics of the Reference Biosphere

(a) Features, events, and processes that describe the reference biosphere must be consistent with present knowledge of the conditions in the region surrounding the Yucca Mountain site

(b) DOE should not project changes in society, the biosphere (other than climate), human biology, or increases or decreases of human knowledge or technology. In all analyses done to demonstrate compliance with this part, DOE must assume that all of those factors remain constant as they are at the time of submission of the license application.

(c) DOE must vary factors related to the geology, hydrology, and climate based upon cautious, but reasonable assumptions consistent with present knowledge of factors that could affect the Yucca Mountain disposal system over the next 10,000 years

(d) Biosphere pathways must be consistent with arid or semi-arid conditions

§ 63.311 Individual Protection Standard after Permanent Closure

- **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 dose of 0.15 mSv (15 mrem) from releases from the undisturbed Yucca Mountain disposal system. DOE's analysis must include all potential pathways of radionuclide transport and exposure.**

§ 63.312 Required Characteristics of the Reasonably Maximally Exposed Individual

The reasonably maximally exposed individual is a hypothetical person who meets the following criteria:

- **(a) Lives in the accessible environment above the highest concentration of radionuclides in the plume of contamination;**
- **(b) Has a diet and living style representative of the people who now reside in the Town of Amargosa Valley, Nevada. DOE must use projections based upon surveys of the people residing in the Town of Amargosa Valley, Nevada, to determine their current diets and living styles and use the mean values of these factors in the assessments conducted for §§ 63.311 and 63.321;**
- **(c) Uses well water with average concentrations of radionuclides based on an annual water demand of 3000 acre-feet;**
- **(d) Drinks 2 liters of water per day from wells drilled into the ground water at the location specified in paragraph (a) of this section; and**
- **(e) Is an adult with metabolic and physiological considerations consistent with present knowledge of adults.**

§ 63.331 Separate Standards for Protection of Ground Water

- **DOE must demonstrate that there is a reasonable expectation that, for 10,000 years of undisturbed performance after disposal, releases of radionuclides from waste in the Yucca Mountain disposal system into the accessible environment will not cause the level of radioactivity in the representative volume of ground water to exceed the limits in the following**

Table 1: — LIMITS ON RADIONUCLIDES IN THE REPRESENTATIVE VOLUME

Radionuclide or type of radiation emitted	Limit	Is natural background included?
Combined radium-226 and radium-228	5 picocuries per liter	Yes
Gross alpha activity (including radium-226 but excluding radon and uranium).	5 picocuries per liter	Yes
Combined beta and photon emitting radionuclides	0.04 mSv (4 mrem) per year to the whole body or any organ, based on drinking 2 liters of water per day from the representative volume.	No

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§ 63.332 Representative Volume

(a) The representative volume is the volume of ground water that would be withdrawn annually from an aquifer containing less than 10,000 milligrams of total dissolved solids per liter of water to supply a given water demand. DOE must project the concentration of radionuclides released from the Yucca Mountain disposal system that will be in the representative volume. DOE must use the projected concentrations to demonstrate a reasonable expectation that the Yucca Mountain disposal system complies with § 63.331. The DOE must make the following assumptions concerning the representative volume:

- (1) It includes the highest concentration level in the plume of contamination in the accessible environment;
- (2) Its position and dimensions in the aquifer are determined using average hydrologic characteristics which have cautious, but reasonable, values representative of the aquifers along the radionuclide migration path from the Yucca Mountain repository to the accessible environment as determined by site characterization; and
- (3) It contains 3,000 acre-feet of water
(about 3,714,450,000 liters or 977,486,000 gallons).

§ 63.341 Projections of Peak Dose

- **To complement the results of § 63.311, DOE must calculate the peak dose of the reasonably maximally exposed individual that would occur after 10,000 years following disposal but within the period of geologic stability. No regulatory standard applies to the results of this analysis; however, DOE must include the results and their bases in the environmental impact statement for Yucca Mountain as an indicator of long-term disposal system performance.**

§ 63.342 Limits on Performance Assessments

- DOE's performance assessments should not include consideration of very unlikely features, events, or processes, i.e., those that are estimated to have less than one chance in 10,000 of occurring within 10,000 years of disposal. Unlikely features, events, and processes, or sequences of events and processes shall be excluded from the assessments for the human intrusion and ground water protection standards upon prior Commission approval for the probability limit used for unlikely features, events, and processes. In addition, DOE's performance assessments need not evaluate the impacts resulting from any features, events, and processes or sequences of events and processes with a higher chance of occurrence if the results of the performance assessments would not be changed significantly.