NRC STAFF PERSPECTIVE ON TOTAL SYSTEM PERFORMANCE ASSESSMENT (TSPA)

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DOE-NRC Technical Exchange on Total System Performance Assessment
October 24, 2006

Outline

Objectives

Introduction

NRC's Use of Risk Information

NRC's Key Messages on TSPA

Summary

Objectives of Technical Exchange

- Describe the NRC perspective on the use of risk information
- Understand the DOE process for completing their performance assessment
- Identify changes implemented since last public version of the TSPA
- Identify potential changes that may be introduced prior to submittal of a license application.

Introduction

Previous TSPA Technical Exchanges

May 1999: TSPA-Site Recommendation (SR) plans

Jun 2000: TSPA-SR implementation

Jan 2001: TSPA-SR results

May and Aug 2001: Evaluation of TSPA

May 2003: Use of risk information

Introduction

Risk and Risk Assessment

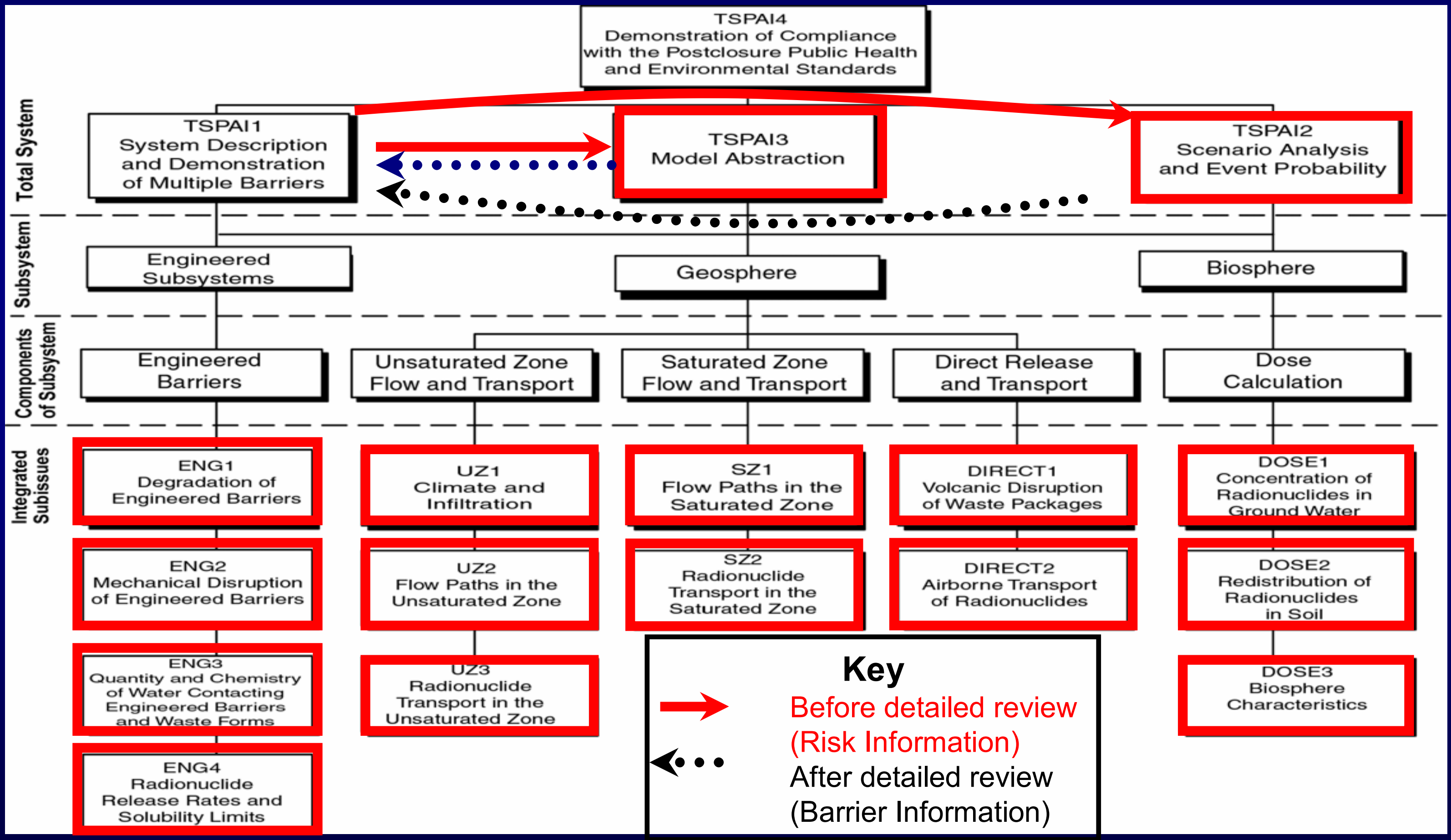
- What is the risk?
  - What can happen?
  - How likely is it?
  - What can result?
- Risk assessment
  - Systematically addresses the risk triplet
  - Risk insights inform decision-making
  - Performance assessment is a risk assessment

NRC's Use of Risk Information

- DOE's multiple barrier capabilities are used as a basis for determining where to focus NRC review of the performance assessment
- NRC's independent risk insights assist in determining focus of staff's review
- Staff review will determine whether the technical basis in DOE's performance assessment is consistent with DOE's description of barrier capability

NRC's Use of Risk Information

Timing and Flow of Information within NRC



NRC Key Messages on TSPA

Demonstration of multiple barriers

Scenario analysis

Treatment of uncertainty

Confidence in model results

Design and use of TSPA analyses

Key Messages

Demonstration of Multiple Barriers (§63.115)

The demonstrated barrier capability is an important aspect in determining which aspects of the DOE safety case are risk-significant.

- **Demonstration of multiple barriers as a source of risk information**
- **Documented barrier capability consistent with the performance assessment**

Key Messages

Demonstration of Multiple Barriers (§63.115)

Documentation of barrier capability should be adequate to describe:

- **the technical basis for the barrier capability, and**
- **how the barrier capability is consistent with the performance assessment.**

Key Messages
Scenario Analysis
(§63.114d-f)

The treatment of features, events, and processes (FEPs) offers the opportunity to enhance traceability and transparency.

A clear rationale for all screening decisions should be provided for all FEPs.

Key Messages

Treatment of Uncertainty (§63.114b-c)

A clear and appropriate treatment of uncertainty across the individual abstractions is required to ensure that the integrated analysis reflects the aggregate uncertainty in total system performance.

- **Clear treatment of uncertainty (both parameters and models)**
- **Integrated treatment of uncertainty**

Key Messages

Confidence in Model Results
(§63.141-144, §63.114g)

Confidence in a total system performance assessment is enhanced when:

- **it is developed under adequately designed and implemented quality assurance procedures, and**
- **the performance assessment is supported by comparisons with detailed process-level models, laboratory testing or field investigations, or natural analogs.**

Key Messages

Design and Use of Analyses

TSPA analyses included in a license application should clearly address a specific regulatory requirement.

The way in which a performance assessment analysis will be reviewed will be based upon the regulatory requirement that the analysis is designed to address.

Summary

- NRC will use a risk-informed and performance based approach.
- The performance assessment used by DOE to support a potential license application must be consistent with the relevant provisions of 10 CFR 63.
- Clear documentation of how these provisions will be met will be critical for the NRC review of a potential license application.

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

www.ocrwm.doe.gov

Introduction to Total System Performance Assessment (TSPA)

Presented to:
DOE/NRC Technical Exchange on TSPA for Yucca Mountain

Presented by:
Jerry A. McNeish
Sandia National Laboratories

October 24, 2006
Las Vegas, Nevada

Presentation Outline

- Description of major workscope
- Primary regulatory drivers for TSPA work
- Schedule of TSPA milestones and deliverable
- NRC key messages (October 5, 2006)
- Key things to look for

Description of TSPA Work

- **Objective of the TSPA work is to provide high-quality, procedurally compliant modeling assessment and documentation of postclosure performance of the repository**
- **Primary work scope for license application (LA) includes:**
  - **TSPA model development and validation**
  - **Software modification and documentation**
  - **TSPA parameter uncertainty development**
  - **TSPA parameter database development**
  - **Development of the TSPA model/analysis report**
  - **Support for relevant sections of supplemental environmental impact statement (EIS) and safety analysis report (SAR)**
- **Workscope is reflective of proposed EPA and NRC rule changes**
- **Previous technical exchange on TSPA was in 2000; however, TSPA methods and approach for LA is similar to approach presented in that exchange**

10 CFR 63—Performance Assessment and Postclosure Requirements

- Postclosure performance objectives
  - 63.113 Performance objectives for the geologic repository after permanent closure
- Postclosure performance assessment
  - 63.114 Requirements for performance assessment
  - 63.115 Requirements for multiple barriers
- Subpart L—Postclosure public health and environmental standards
  - 63.301 Purpose and scope
  - 63.302 Definitions for Subpart L
  - 63.303 Implementation of Subpart L
  - 63.304 Reasonable expectation
  - 63.305 Required characteristics of the reference biosphere

10 CFR 63—Performance Assessment and Postclosure Requirements

- Postclosure individual protection standard
  - 63.311 Individual protection standard after permanent closure
  - 63.312 Required characteristics of the reasonably maximally exposed individual
- Human-intrusion standard
  - 63.321 Individual protection standard for human intrusion
  - 63.322 Human intrusion scenario
- Ground water protection standards
  - 63.331 Separate standards for protection of ground water
  - 63.332 Representative volume

10 CFR 63—Performance Assessment and Postclosure Requirements

- **Additional provisions**
  - **63.341 Projections of peak dose**
  - **63.342 Limits on performance assessments**
  - **63.343 Severability of individual protection and ground-water protection standards**

Schedule for TSPA Milestones and Deliverable

- **Milestones for supporting models**
  - **Submodel form/function – December, 2006**
  - **Preliminary submodel data feed – March, 2007**
  - **Final submodel data feed and documentation – May, 2007**
- **TSPA milestones**
  - **Preliminary supplemental EIS feed – June, 2007; final – March, 2008**
  - **Preliminary SAR chapter feeds – October, 2007; final – December, 2007**
- **Key deliverable**
  - ***TSPA-LA Analysis/Model Report for the License Application* – December, 2007**

NRC Key Messages (October 5, 2006)

- **Linkage of TSPA analyses to specific regulatory requirement**
- **Barrier capability documentation consistent with TSPA, and must support risk-significant evaluation of LA**
- **Clarity of scenario analysis approach and documentation with proper level of detail and consistency in associated features, events, and processes (FEP)**
- **Appropriate treatment and analysis of uncertainty, both at submodel and TSPA level**
- **Regulatory-compliant quality assurance procedures, and clear technical basis for**

Key Points to Note in Subsequent Presentations

- Process for TSPA model development including FEPs and update to scenario classes
- Updates to specific submodels that reflect changes resulting from the requalification of infiltration data and models
- Updates to specific submodels based on design changes (e.g., transportable, aging and disposal canister), reviews of TSPA and supporting documents, and changes associated with draft rule
- Updates to enhance the defensibility of specific submodels and the characterization of uncertainty
- Software for TSPA and supporting models and how they are linked together
- Overall analysis approach including verification/validation, sensitivity and uncertainty evaluations, and multiple barrier analysis

Features, Events, and Processes (FEPs) Analysis

Presented to:
DOE/NRC Technical Exchange on Total System Performance Assessment (TSPA) for Yucca Mountain

Presented by:
Lori J. Dotson
Sandia National Laboratories

October 24, 2006
Las Vegas, Nevada

Outline

- Regulatory basis and historical background
- Current status of performance assessment (PA) FEP analysis
  - FEP identification
  - FEP screening
- Anticipated changes since TSPA for site recommendation (SR)

FEP Analysis and Scenario Development

- Purpose—*… focus the representation of the system on those features, events, and processes that most affect compliance with the overall performance objective* (Yucca Mountain Review Plan [YMRP], NUREG-1804, Section 2.2.1.2)
- Four-part process described by NRC (YMRP Section 2.2.1.2)
  – Identification of an initial list of FEPs
  – Screening of the initial list of FEPs
  – Formation of scenario classes using the reduced set of FEPs
  – Screening of scenario classes
- Overall methodology based on Cranwell et al., 1990 (NUREG/CR-1667)

Identification of Initial YMP FEP List

- Initial FEP list for the 2001 SR
  - 1261 FEPs from NEA international database
    - Canada, Sweden, Switzerland, U.K., WIPP
  - 292 site-specific FEPs from Yucca Mountain Project (YMP) literature
  - 95 additional FEPs from internal technical review
  - 8 additional FEPs from external review
    - NRC audits, Key Technical Issue meetings
- Grouped for SR into 328 “primary” FEPs
- Reorganized into 375 FEPs for the license application (LA)

Identification of YMP PA FEPs

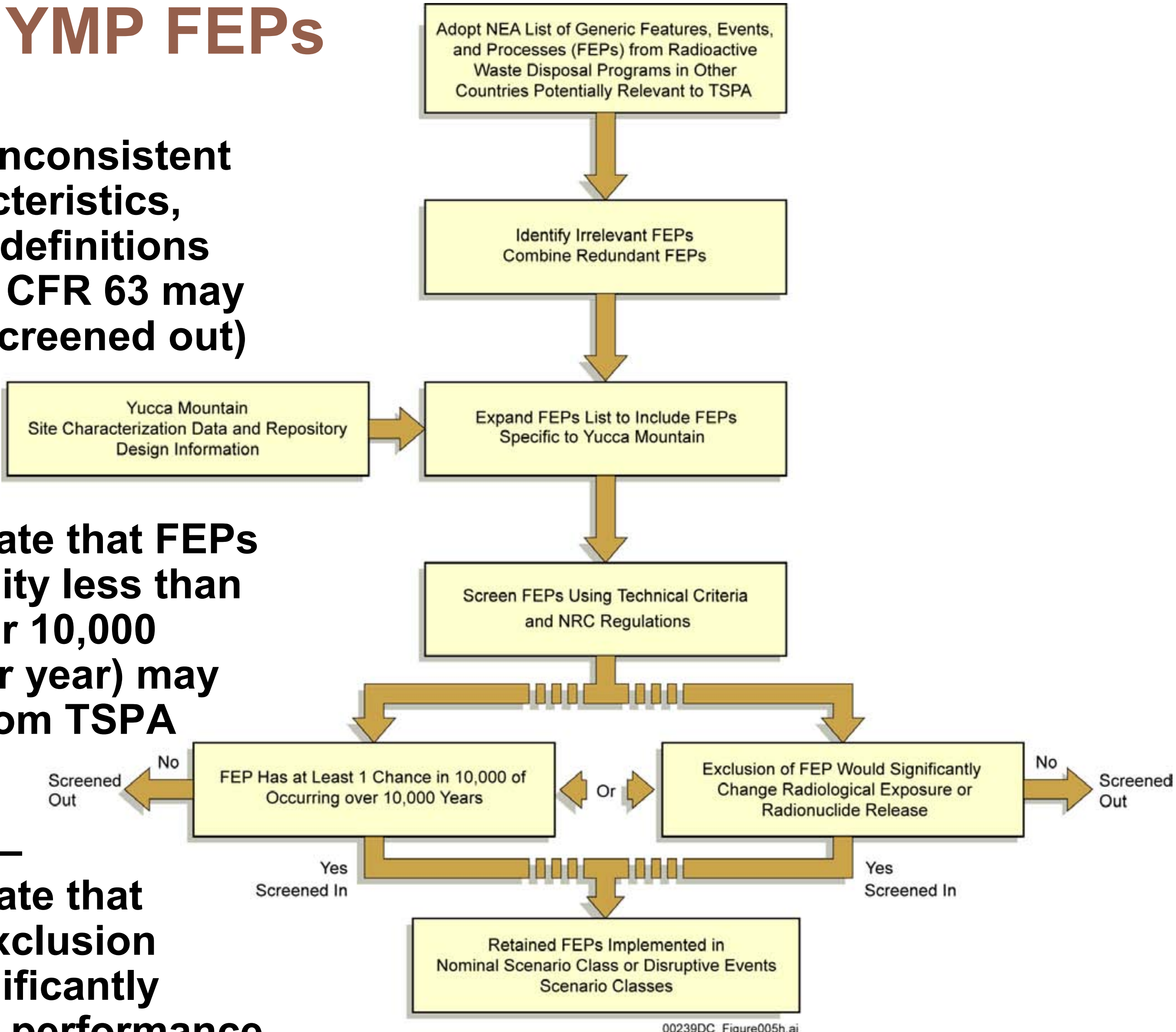
- Builds on TSPA-SR FEP list
- 375 YMP FEPs for PA
  - Each FEP encompasses a single process or event, or a few closely related or coupled processes
  - Each FEP is aggregated to the coarsest level at which a technically sound screening decision can be made while still maintaining adequate detail for analysis
  - YMP FEPs are a comprehensive list that address all issues identified from:
    - NEA international FEP database
    - Site-specific FEPs from YMP literature
    - Iterative reviews of earlier YMP FEP lists
    - Evaluation of multiple classification structures
    - Independent analysis using interaction diagrams
  - FEP configuration management process to identify and track the effect of ongoing work and design changes on FEPs

Screening of YMP FEPs

- **Regulatory—**
  FEPs that are inconsistent with the characteristics, concepts, and definitions specified in 10 CFR 63 may be excluded (screened out) from TSPA

- **Probability—**
  Regulations state that FEPs with a probability less than 1 in 10,000 over 10,000 years (~10^{-8} per year) may be excluded from TSPA

- **Consequence—**
  Regulations state that FEPs whose exclusion would not significantly change overall performance may be excluded from TSPA



FEP Screening Criteria—By Regulation

- **Regulations (10 CFR 63) may be used to support exclusion:**
  - **10 CFR 63.305—Reference biosphere and geologic setting**
  - **10 CFR 63.312—Reasonably maximally exposed individual**
  - **10 CFR 63.321 and 322—Human intrusion**
- **NUREG 1804, Section 2.2.1.2.1.3 Acceptance Criterion 2:**
  - ***An acceptable justification for excluding features, events, and processes is that either the feature, event, and process is specifically excluded by regulation; …***

FEP Screening Criteria—Low Probability

- **From 10 CFR 63.114 (d)**
  - ***Any performance assessment used to demonstrate compliance with §63.113 must:***
    - ***...Consider only events that have at least one chance in 10,000 of occurring over 10,000 years.***

FEP Screening Criteria—Low Consequence

- **From 10 CFR 63.114 (e) and (f)**
  - ***Any performance assessment used to demonstrate compliance with §63.113 must:***
    - ***...Specific features, events, and processes of the geologic setting 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.***
    - ***...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.***

PA FEP Development

- **PA FEP list revised from TSPA-SR list**
  - Eliminate mixed screen decisions
  - Eliminate secondary FEPs
  - Modified classification structure
  - More consistent level of detail
- **Iterative FEP revisions and screening**
  - FEP authors refine FEP assignment and screening decisions based on ongoing modeling and analyses
  - FEP team refines FEP list based on iterations with FEP authors and new information and/or analysis results

PA FEP Development (continued)

- **Final FEP List for PA**
  - 375 FEPs
  - FEP name, number, and description
  - Screening decision (include/exclude) and technical basis
  - Supporting documentation
  - Final list and screening information will be documented for LA

FEP Classification Scheme

- A two-dimensional FEP matrix will be prepared where on axis corresponds to the features (e.g., drip shield, saturated zone) and the other axis corresponds to the processes and events (e.g., transport, igneous) acting on the features
  - The matrix intersections represent boxes for which FEPs exist (both included and excluded FEPs)
  - All FEPs are mapped to at least one matrix box and broad FEPs (i.e., processes or events acting on multiple features) are mapped to multiple boxes
- This approach provides a top-down review of the comprehensiveness of the PA FEP analysis, which complements the bottom-up approach used in TSPA-SR
- This classification structure ensures completeness of the FEP list
- Configuration management process ensures that effect of ongoing work and design changes on FEPs are tracked and addressed accordingly

Anticipated Changes Since TSPA-SR

- **FEPs will be reorganized under new classification scheme**
- **Screening justifications will be updated/revised based on new technical information available since the SR (e.g., transportation, aging, and disposable canisters; seismic consequences; localized corrosion)**

FEP Summary

- The FEPs collectively capture all of the issues relevant to postclosure performance of the proposed Yucca Mountain repository
- Included FEPs provide the basis for TSPA scenario development
- FEPs are traceable to their origins and screening is traceable to relevant documentation
- FEP Documentation supports demonstration of comprehensiveness
  - Originated from international FEP lists
  - Augmented from site-specific literature and technical reviews
  - Evaluated under multiple classification structures
  - Supported by independent interaction diagram analysis
  - Configuration management process ensures confidence in FEP coverage

TSPA Model Development and Implementation

Presented to:
DOE/NRC Technical Exchange on Total System Performance Assessment (TSPA) for Yucca Mountain

Presented by:
S. David Sevougian
Sandia National Laboratories

October 24, 2006
Las Vegas, Nevada

Presentation Outline

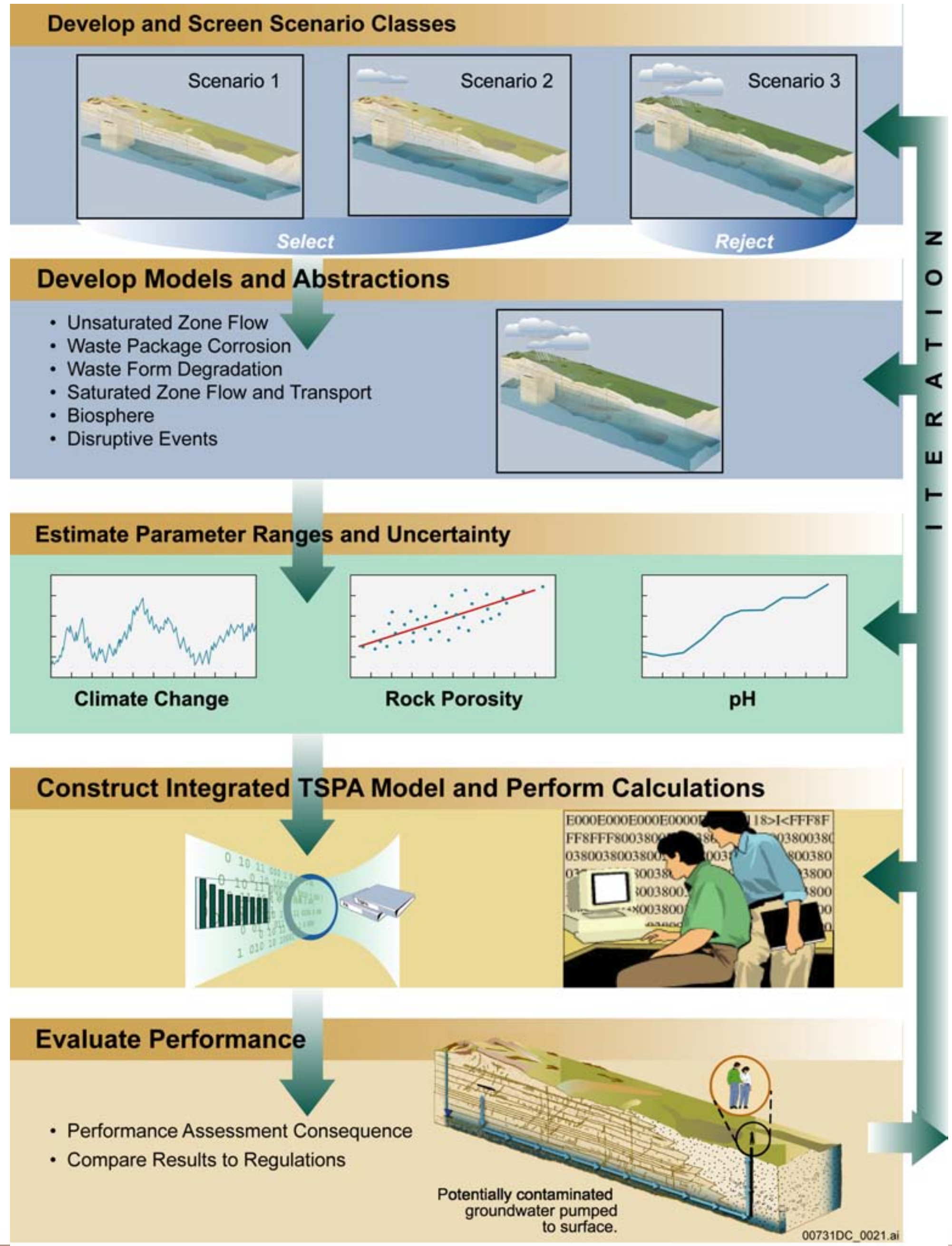
- Regulatory drivers for TSPA model development
- Major steps and structure of TSPA
- Major component models
- Information flow and wiring diagrams for component models and submodels
- Software and hardware architecture
- High-level structure of GoldSim input file (example)
- Quality Assurance (QA)
  - Procedures
  - Management control
  - Configuration control
  - Information and data control, procedures, and databases
  - Model validation and confidence building
- Anticipated changes since TSPA for site recommendation (SR)

Link to Regulations

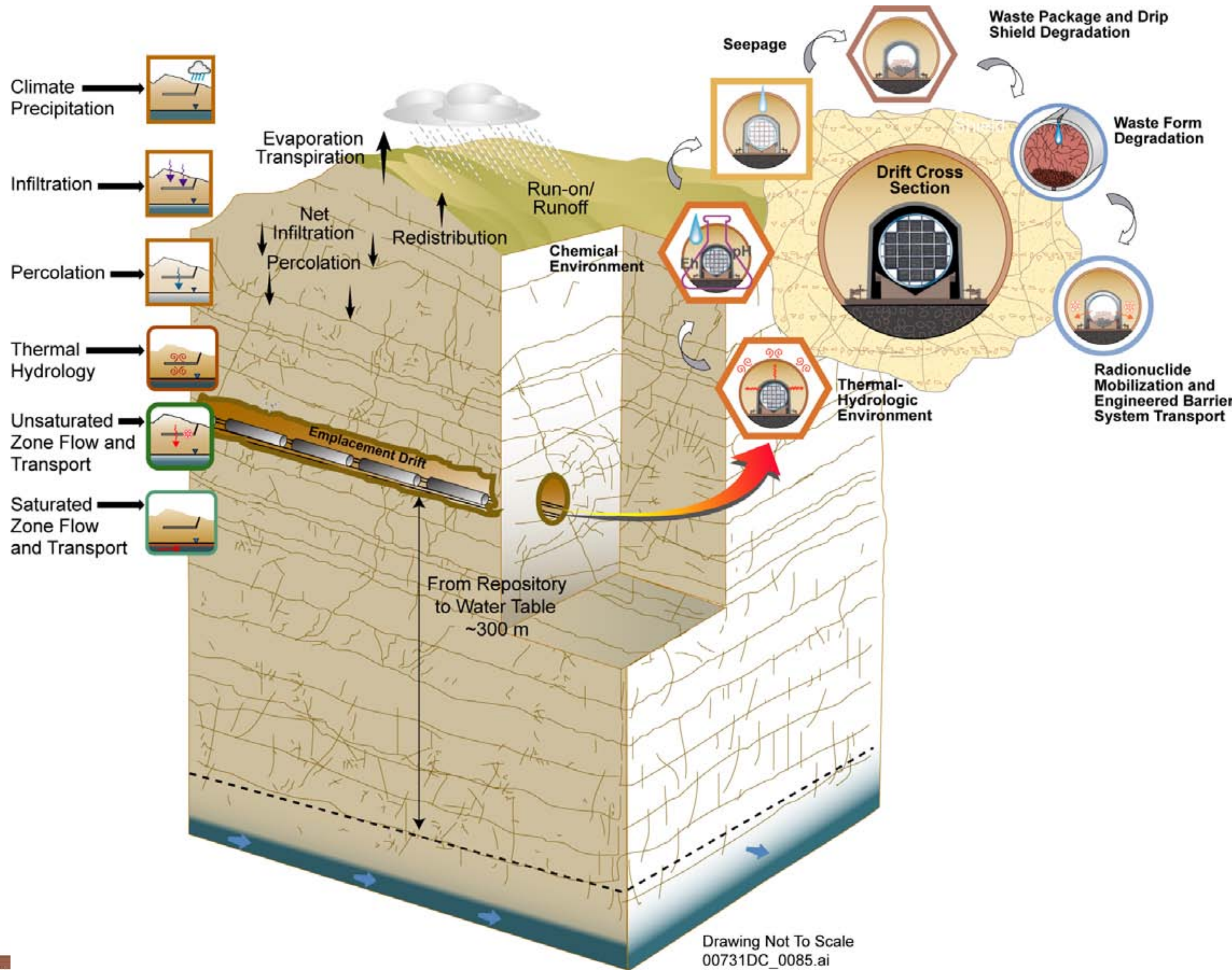
- Development and implementation of the TSPA Model is guided by specific regulatory requirements, including the ability to
  - Compute dose to the reasonably maximally exposed individual for the various standards (individual protection, human intrusion)
  - Compute groundwater concentrations at the accessible environment
  - Demonstrate capability of multiple barriers
  - Include the effect of parameter and model uncertainty on the results (Monte-Carlo-based analysis)
  - Answer the risk triplet in clear, systematic fashion
  - Provide a clearly traceable and transparent roadmap for the inclusion of specific features, events, and processes (FEPs) in the TSPA Model
  - Be transparent, traceable, and controlled under the applicable QA procedures
  - Be designed in such a way that model validation and confidence can be transparently demonstrated

Major Steps in the Iterative TSPA

- **<u>Screen FEPs</u> and develop scenario classes**
- **<u>Develop models</u> and abstractions, along with their scientific basis, for logical groupings of FEPs within scenario classes**
- **<u>Evaluate uncertainty</u> in models and parameters**
- **<u>Construct integrated TSPA model</u> using all retained FEPs and <u>perform calculations</u> for the unique scenario classes and unique "modeling cases" and scenarios within scenario classes**
- **<u>Evaluate total-system performance</u> in terms of individual protection and groundwater protection standards; incorporating uncertainty through Monte Carlo simulation**



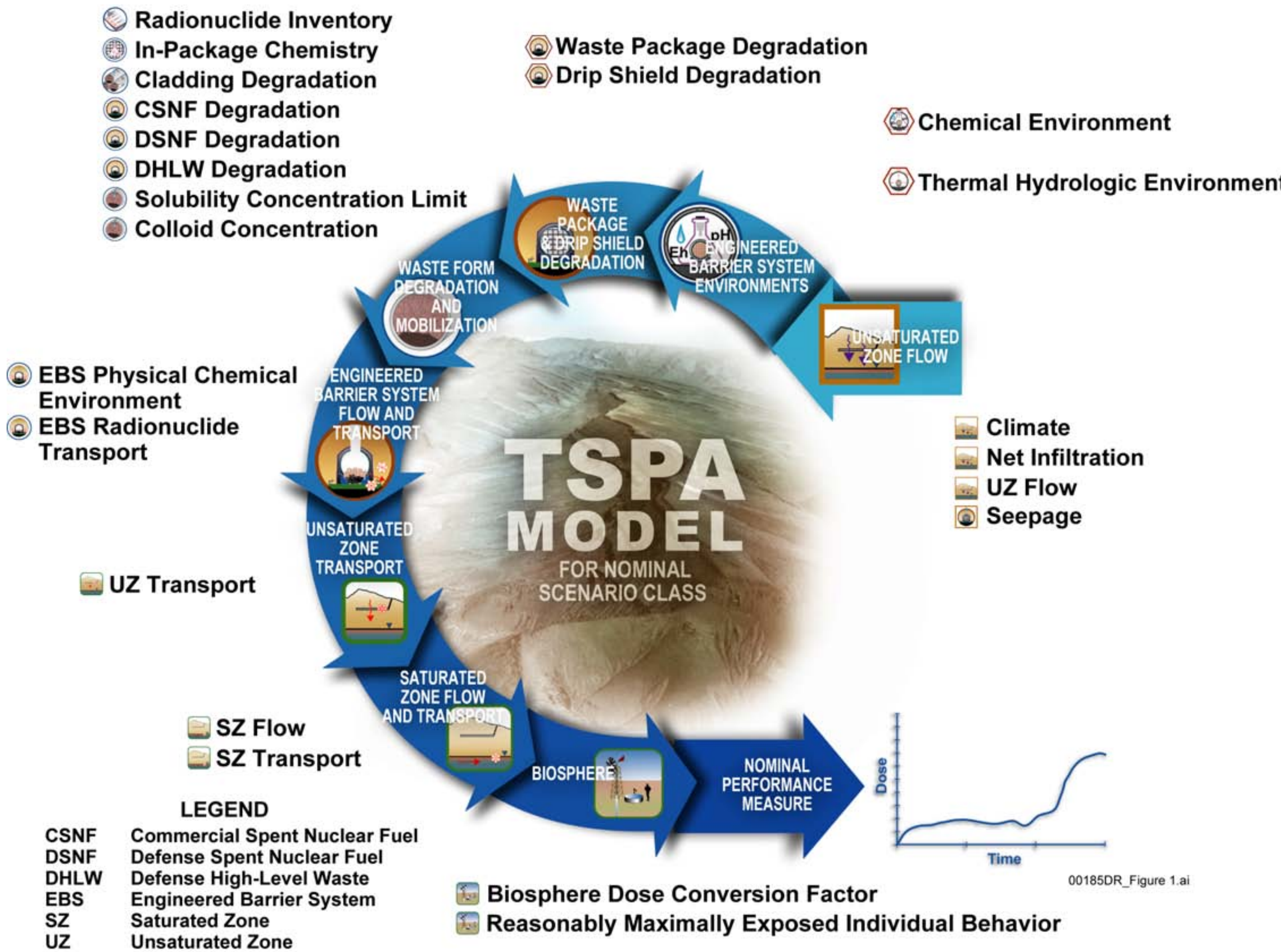
Components of Natural and Engineered Barrier Systems at Yucca Mountain



TSPA Abstractions and Submodels Information Flow and Wiring Diagrams—Various Levels of Detail

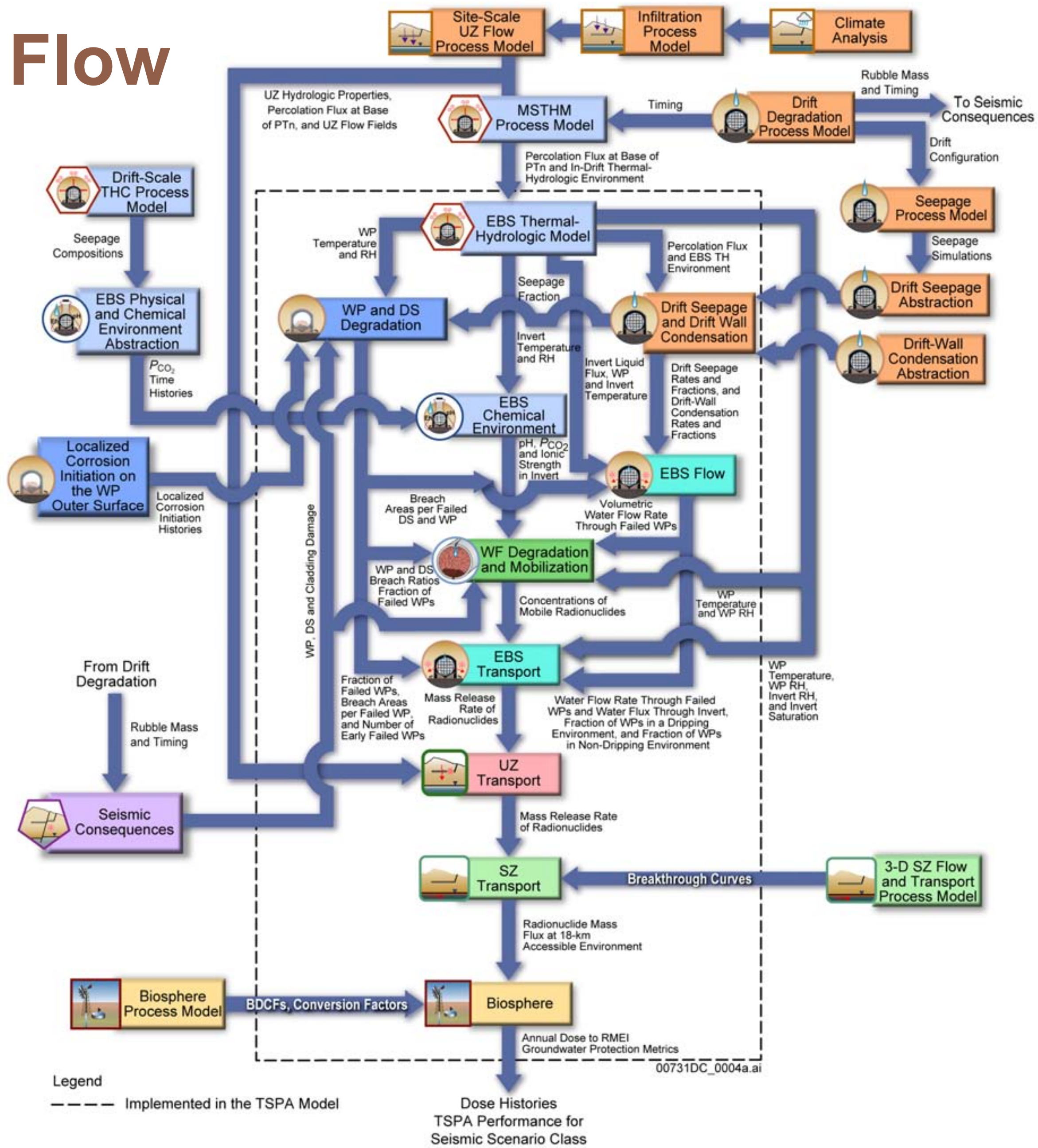
TSPA "Wheel"—Primary Component Models

- Primary couplings are one-way: in the direction of liquid and radionuclide mass flow
- Heat flow (thermal energy) drives the major couplings in the processes and models at early times
- Event-driven processes, such as seismicity, can introduce discrete changes in mass, fluid, and energy flow



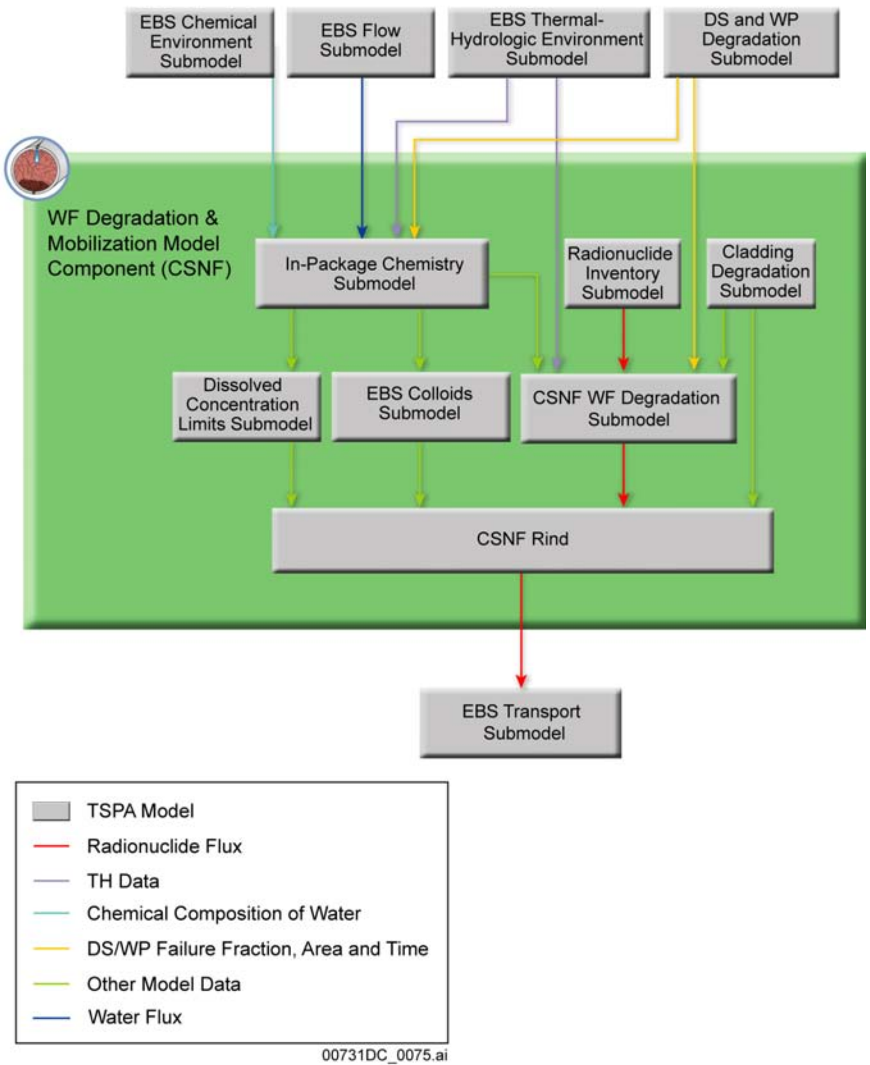
TSPA Information Flow

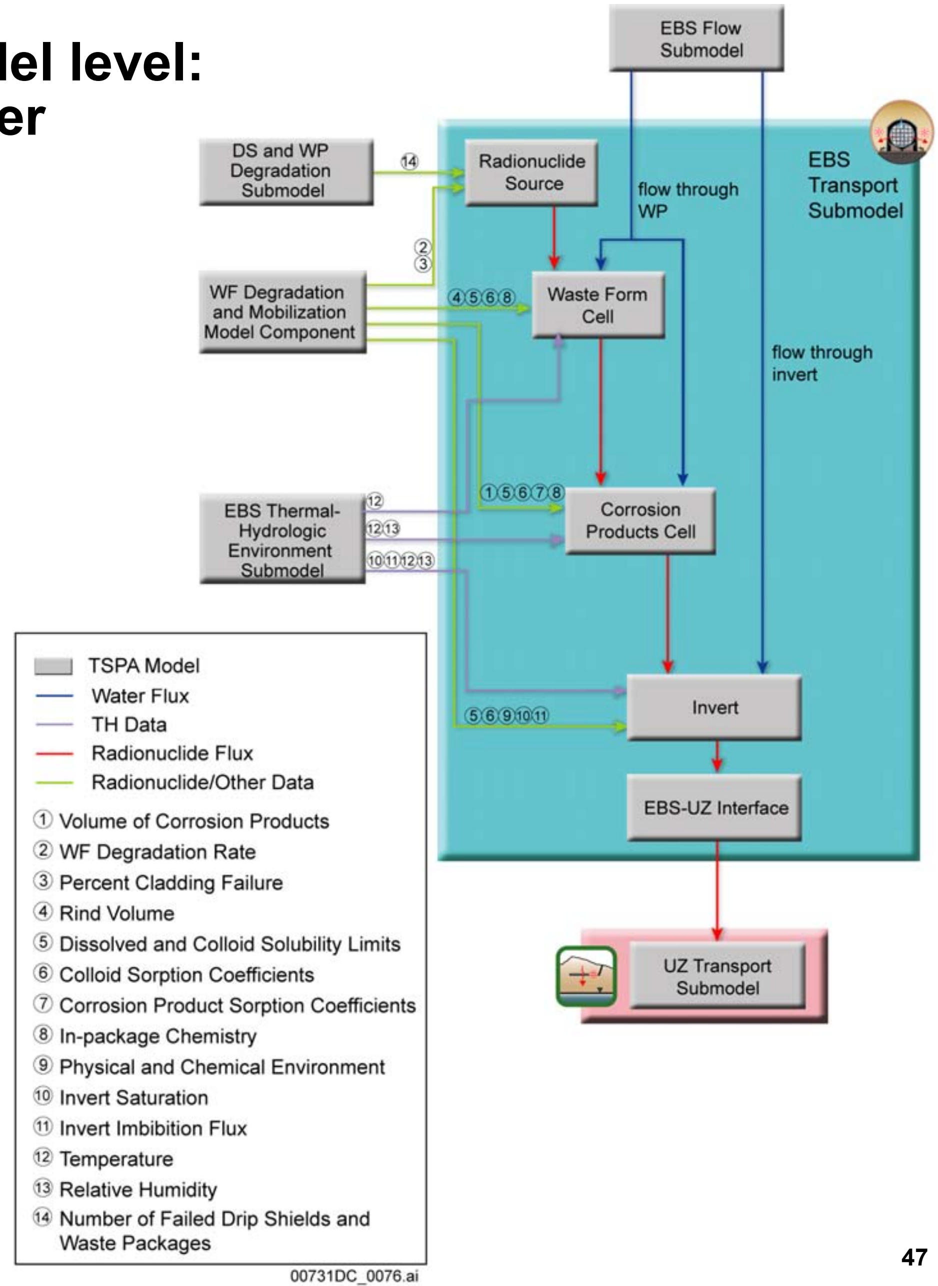
- **Seismic scenario class**
- **Shows finer division of component models into submodels/abstractions**
- **Shows primary types of information passed from process models to TSPA abstractions, and among TSPA abstractions and submodels**
- **Other diagrams are applicable to the igneous scenarios**



TSPA Information Flow (continued)

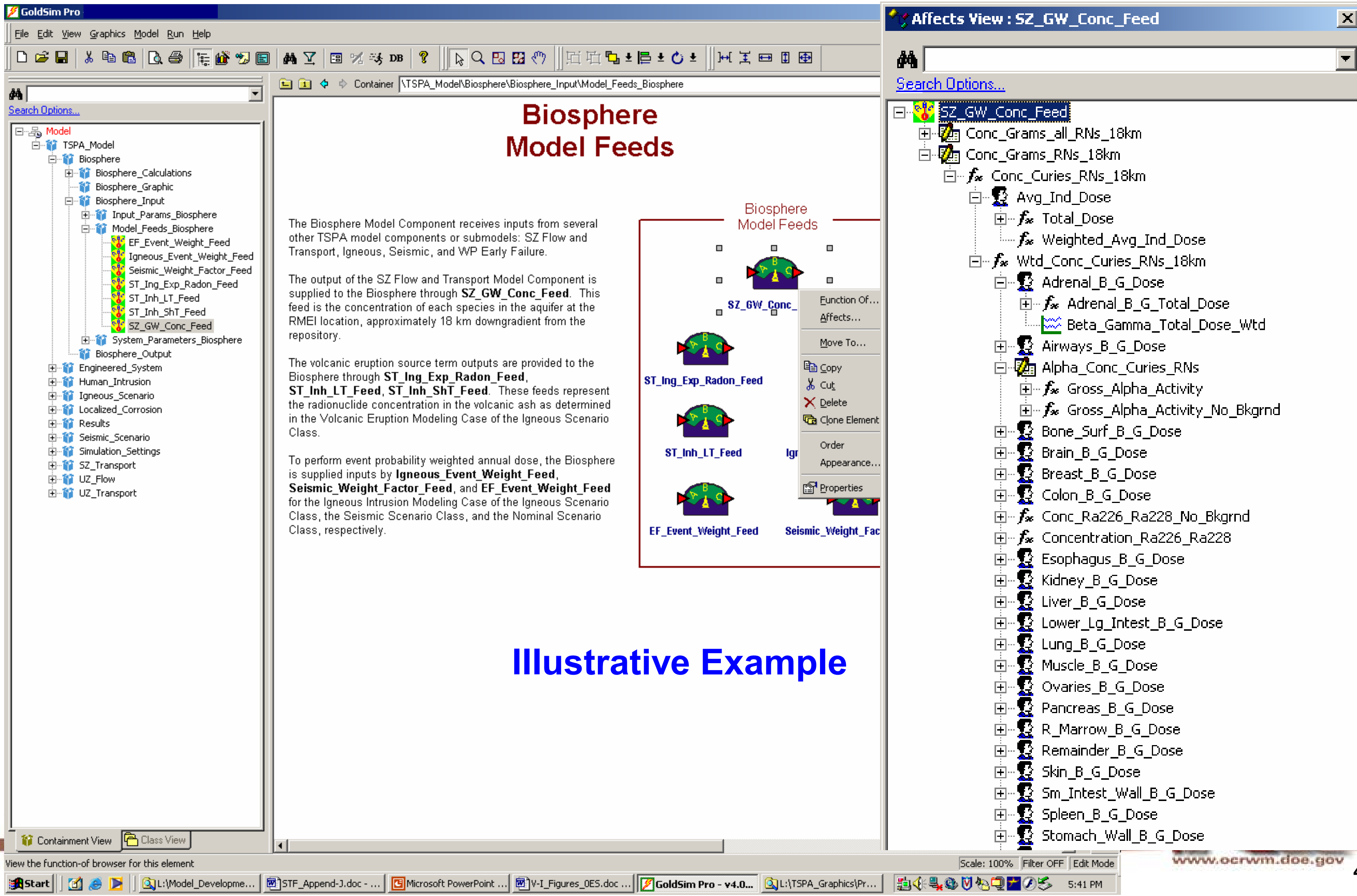
- **“Wiring” diagrams at the submodel level: waste form and Engineered Barrier System transport**





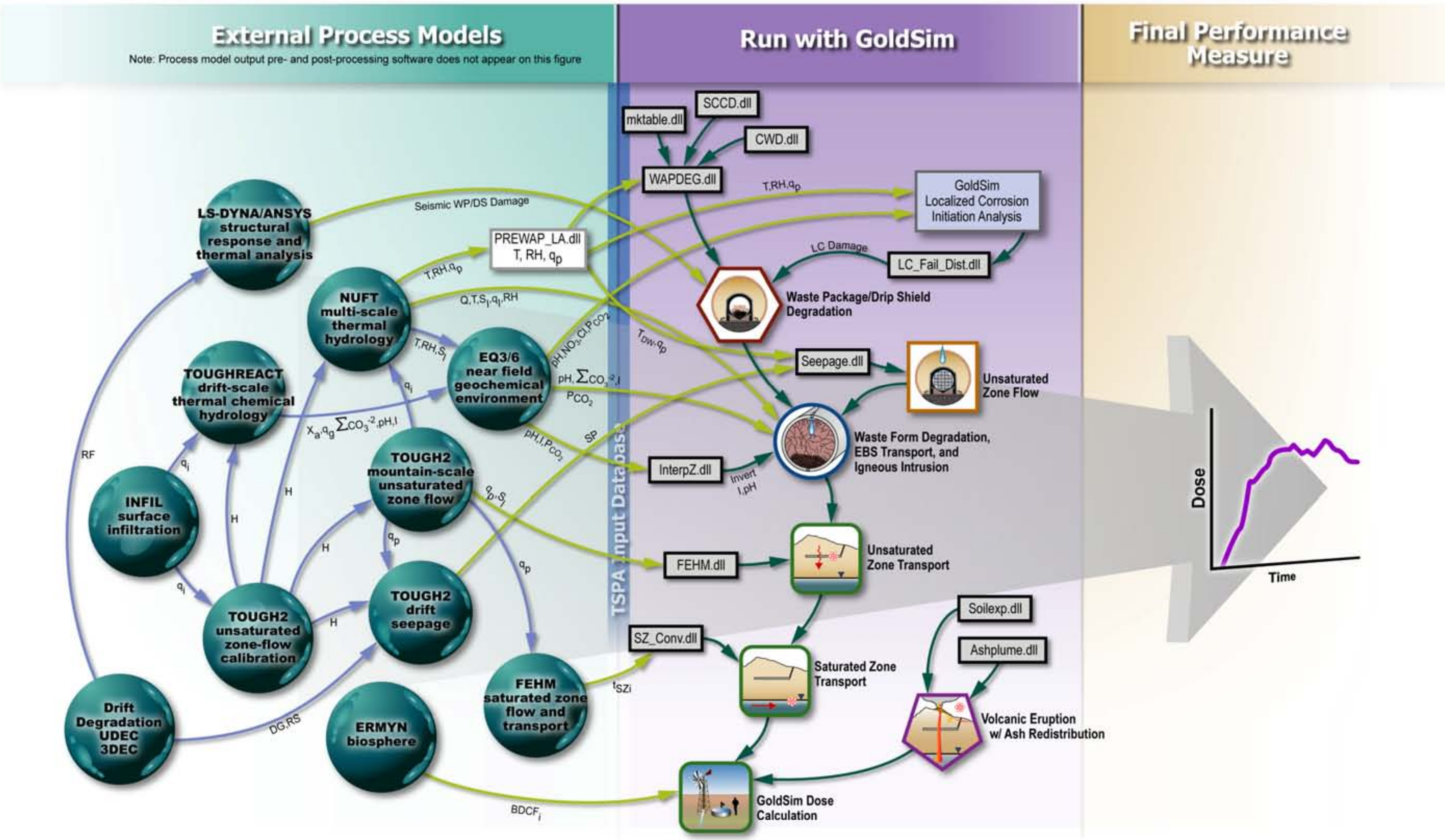
TSPA Information Flow (continued)

- The ultimate wiring diagram is the GoldSim input file itself:



TSPA Software and Hardware

TSPA Software Architecture



Output Parameters

f_S	Fraction of WPs with Seeps	q_p	Percolation Flux	q_i	Infiltration Flux	H	Hydrologic Properties
EBS	Engineered Barrier System	NO_3	Nitrate Concentration	DG	Drift Geometry	SP	Seepage Parameters
Q_S	Seep Flow Rate	T	Temperature	Cl	Chloride Concentration	RS	Rock Strength
Q	Evaporation Rate	RH	Relative Humidity	I	Ionic Strength	RF	Rock Fall Size and Number
pH	pH	S_l	Liquid Saturation	t_{SZi}	Saturated Zone Transport Time		
ΣCO_3^{-2}	Carbonate Concentration	X_a	Air Mass Fraction	$BDCF_i$	Biosphere Dose Conversion Factor		
P_{CO_2}	Partial Pressure of CO_2	q_l	Liquid Flux	q_g	Gas Flux		

Legend

- Response Surface Between Process Models
- Response Surface from Process Model to GoldSim
- Connection in GoldSim
- Preprocessor
- TSPA Model DLL

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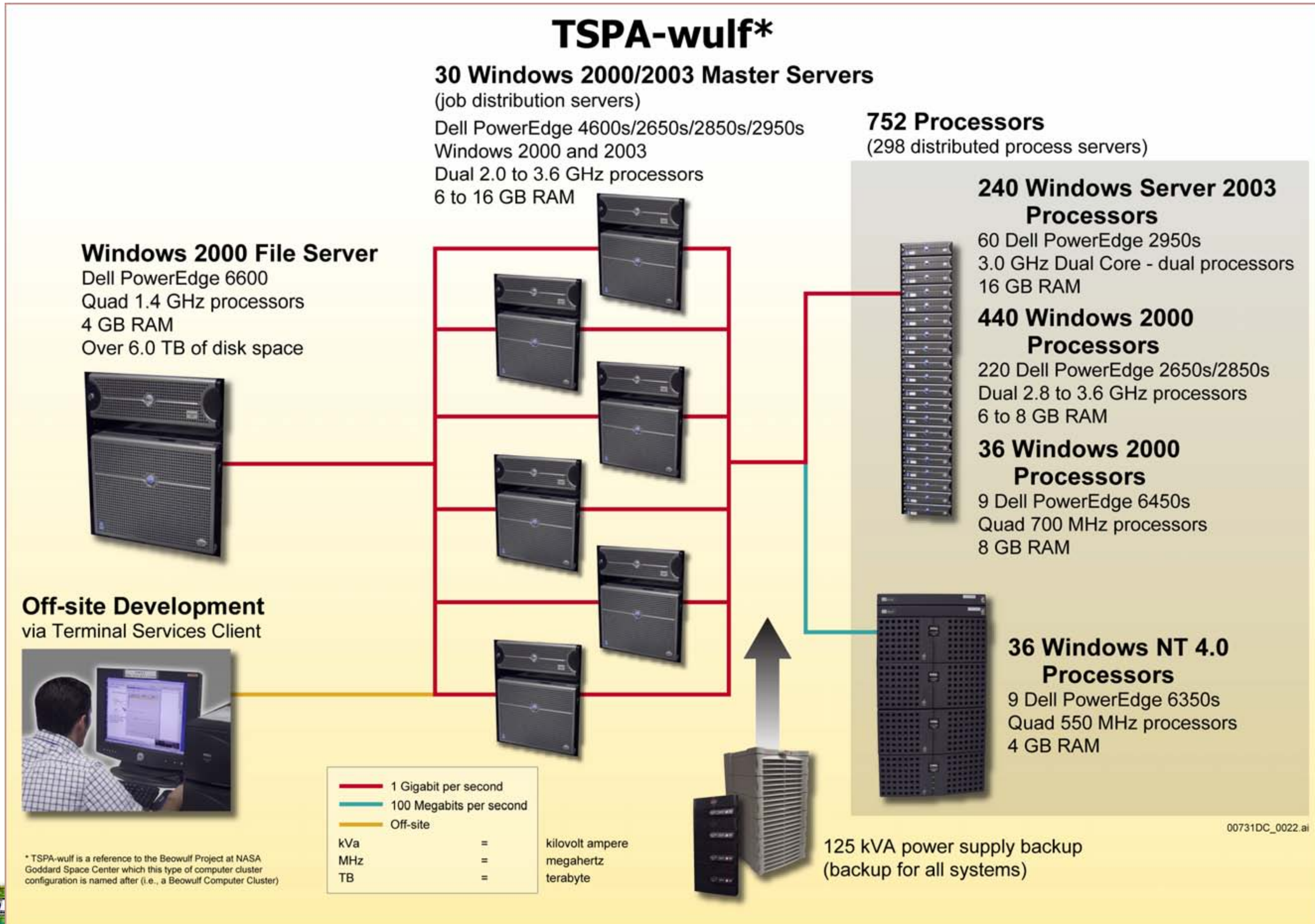
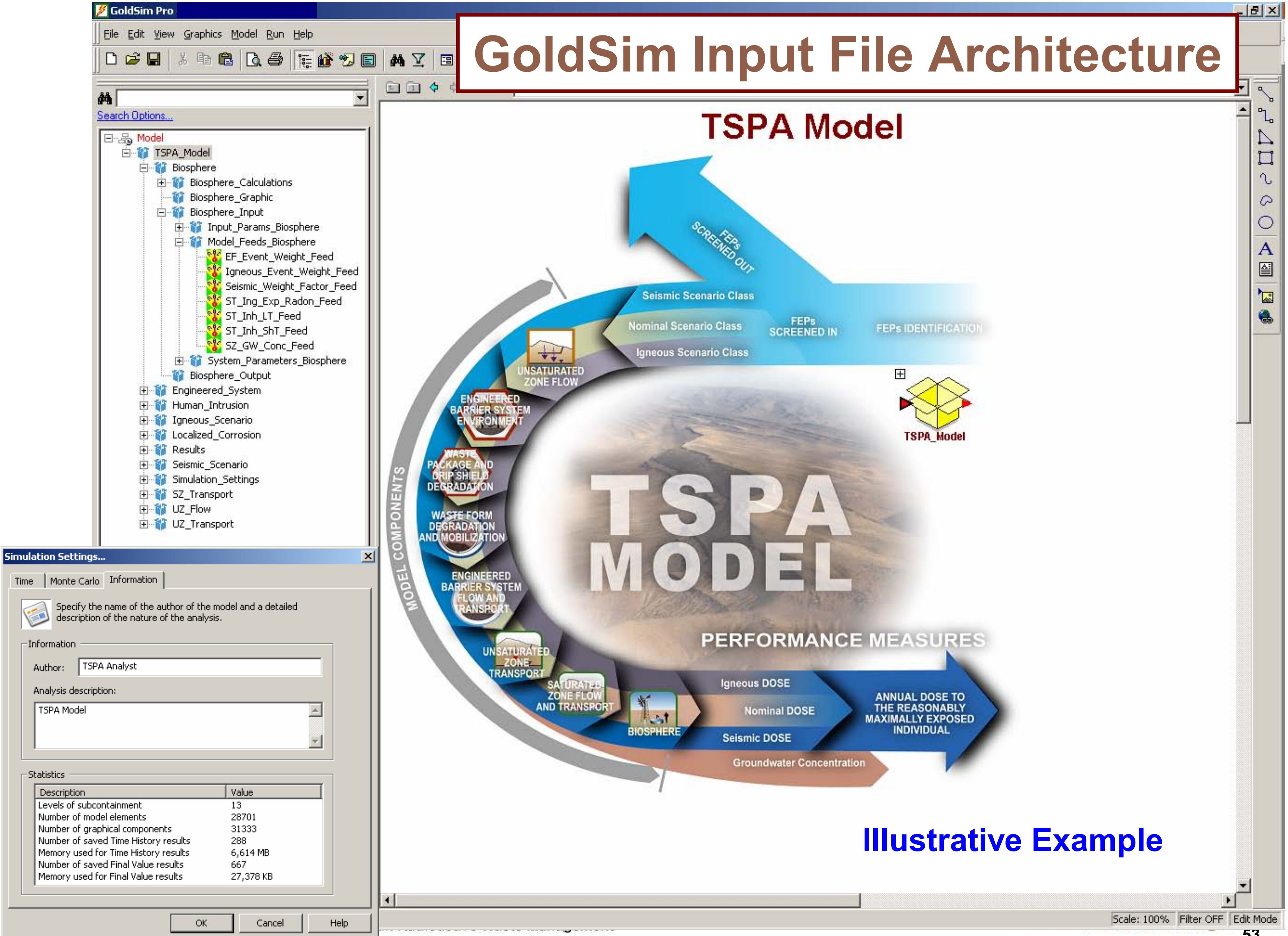
TSPA Hardware Configuration



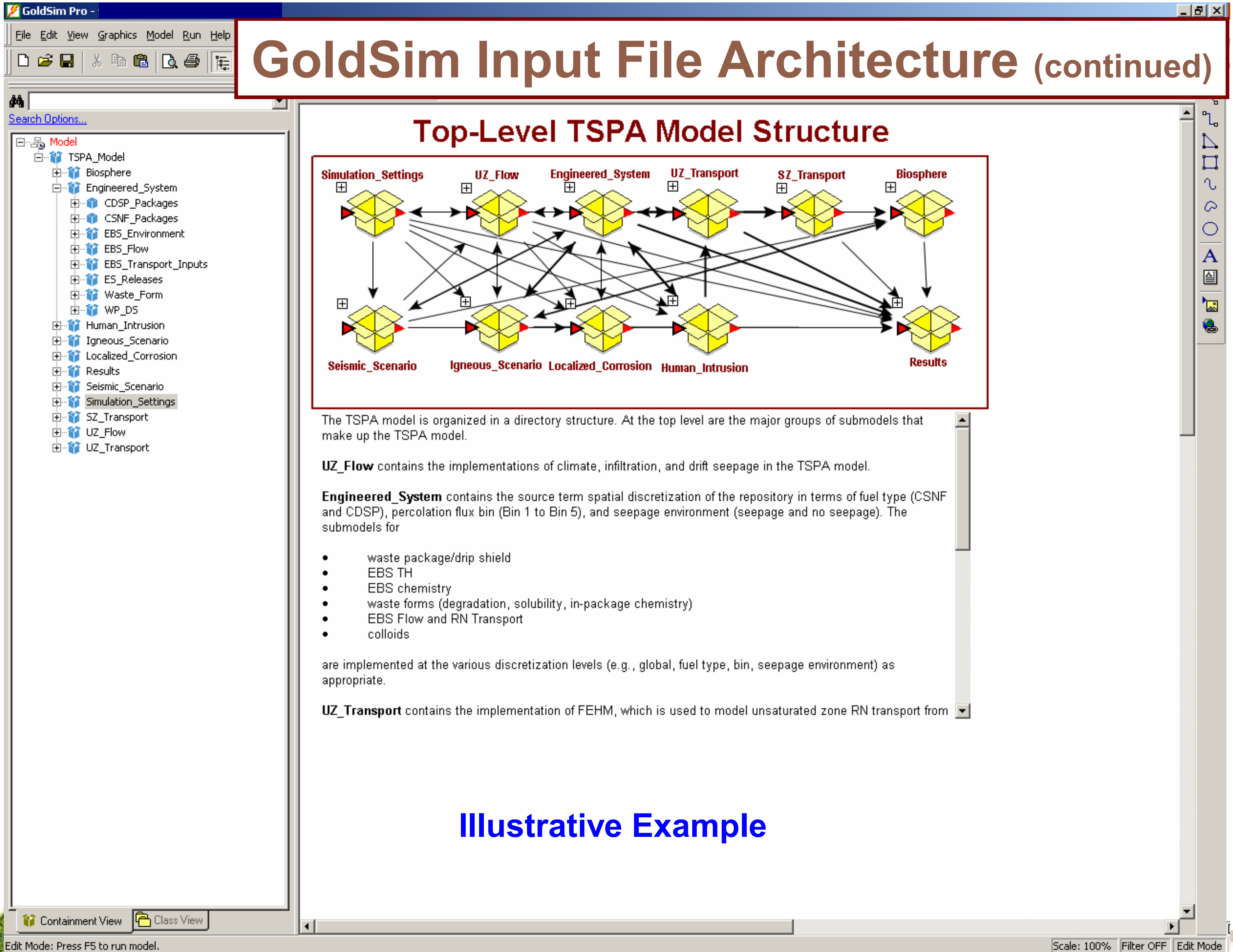
TSPA Input File Architecture in GoldSim

GoldSim Input File Architecture



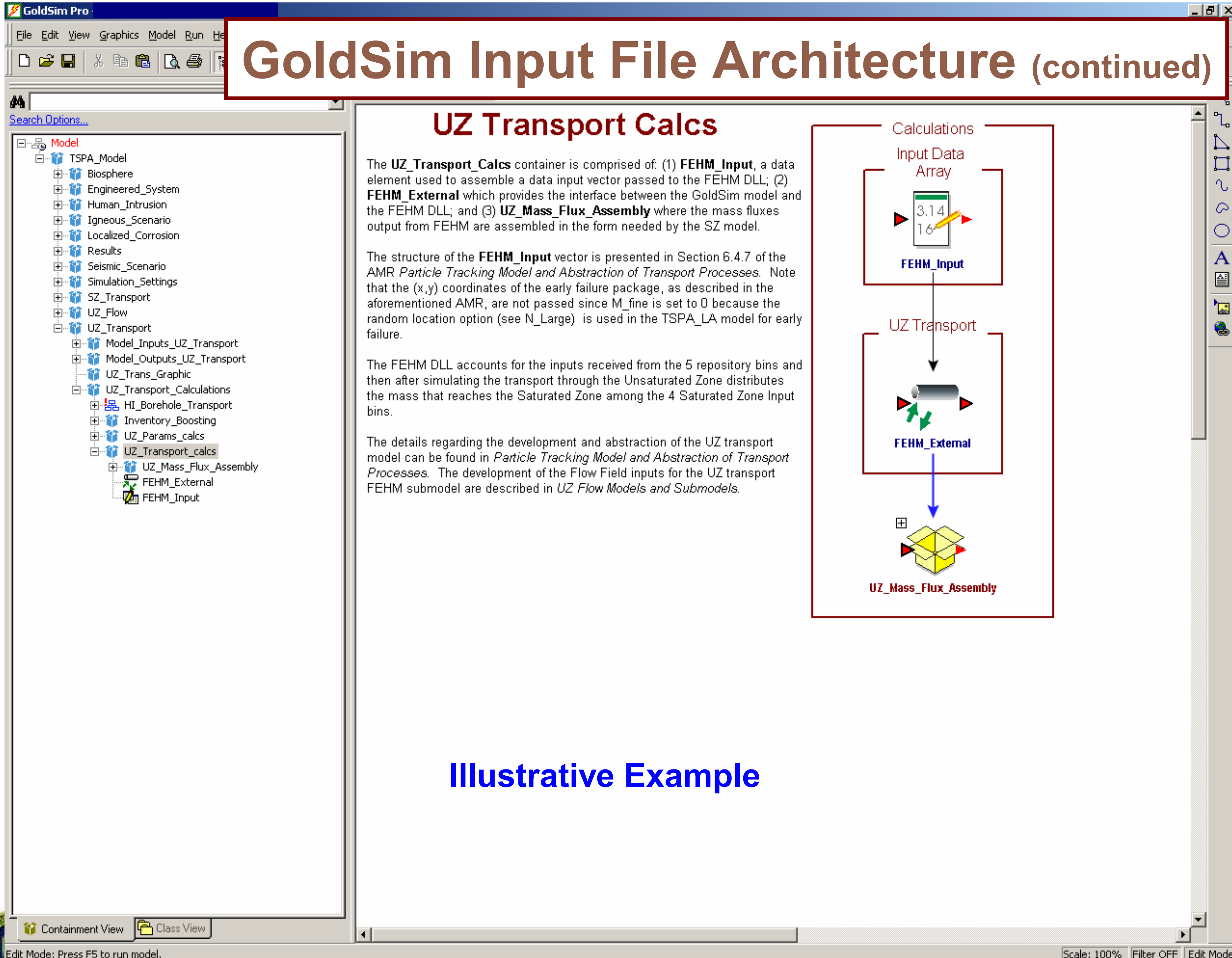
Illustrative Example

GoldSim Input File Architecture (continued)

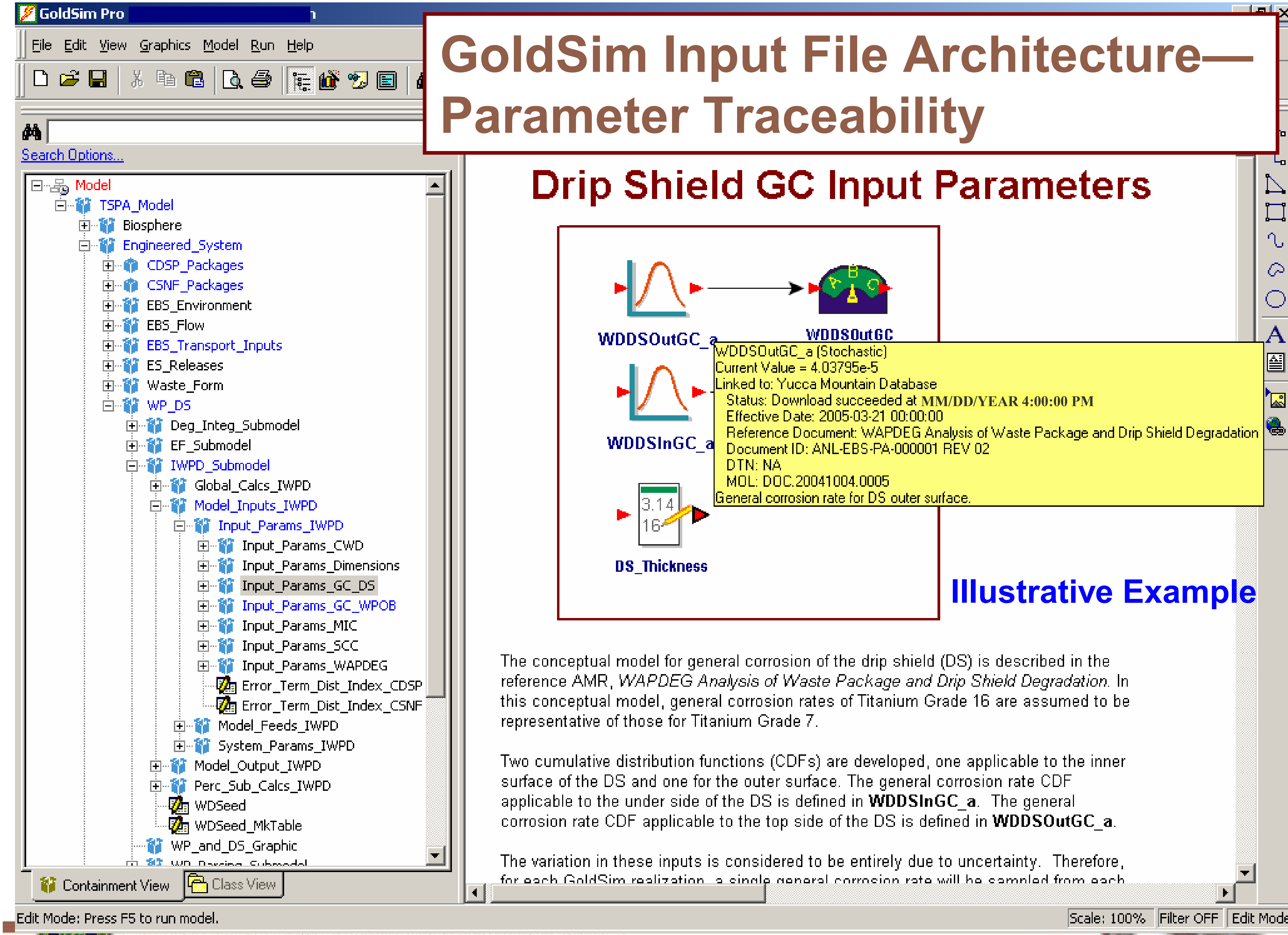


Illustrative Example

GoldSim Input File Architecture (continued)



GoldSim Input File Architecture—Parameter Traceability

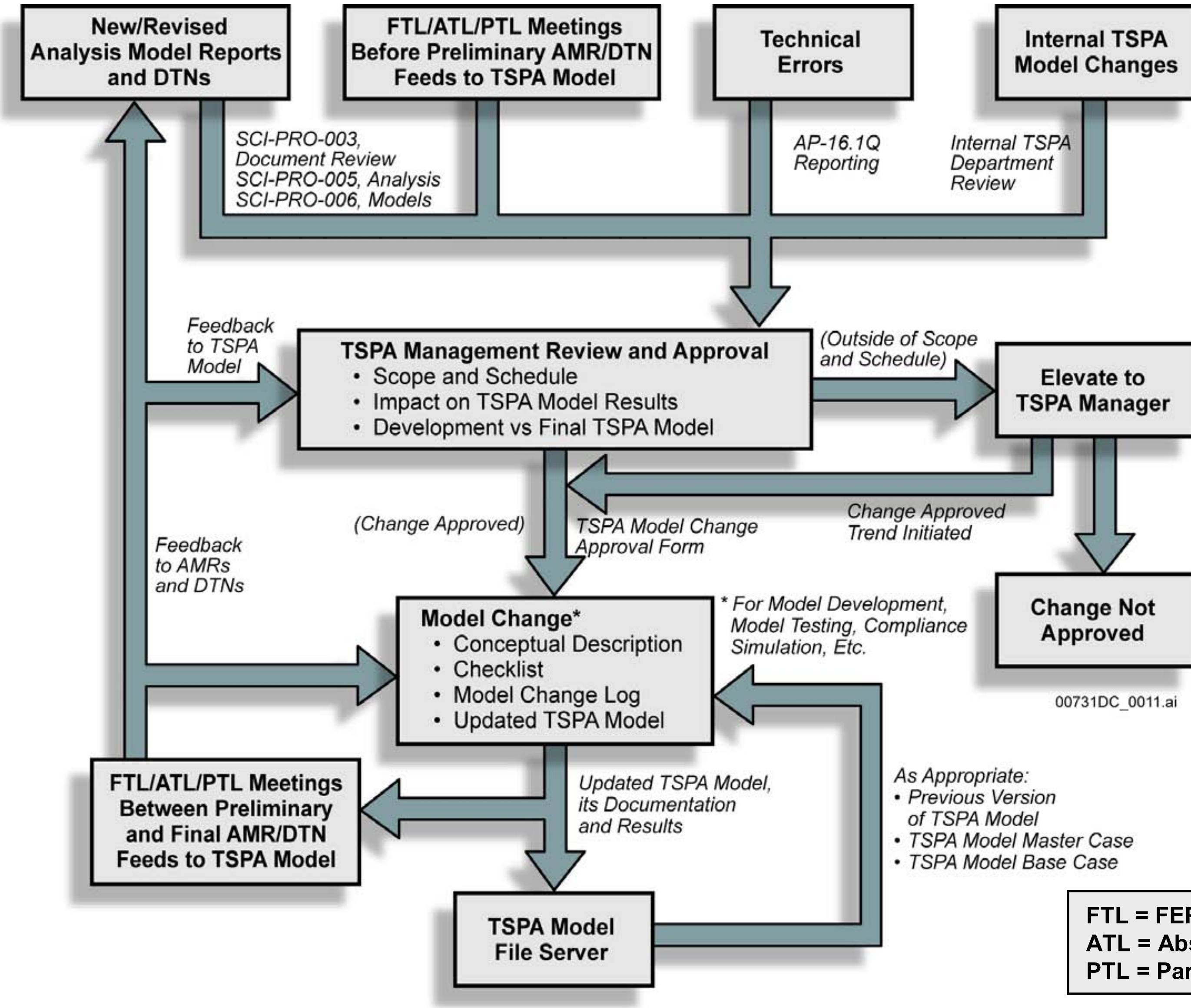


QA and Configuration Management

QA Procedures

- AP-16.1Q, Condition Reporting and Resolution
- SCI-PRO-002, Planning for Science Activities
- SCI-PRO-003, Document Review
- SCI-PRO-004, Managing Technical Product Inputs
- SCI-PRO-005, Scientific Analyses and Calculations
- SCI-PRO-006, Models
- IM-PRO-003, Software Management
- IM-PRO-004, Qualification of Software
- IM-PRO-005, Software Independent Verification and Validation
- IM-PRO-006, Independent Verification and Validation of Legacy Code
- TST-PRO-001, Submittal and Incorporation of Data to the Technical Data Management System
- TST-PRO-003, Scientific Notebooks

Management Control Process for TSPA



FTL = FEPs Team Lead
ATL = Abstraction Team Lead
PTL = Parameter Team Lead

TSPA Configuration Management Documentation

- **TSPA model is developed incrementally**
- **The documentation generated for each increment is as follows:**
  - **Change approval form signed by management**
  - **Conceptual description of change**
  - **Conceptual checklist**
  - **Change checklist—the analyst documents each area of the model that has changed**
  - **Implementation checklist**
  - **GoldSim versioning report**

Concept Checklist Example

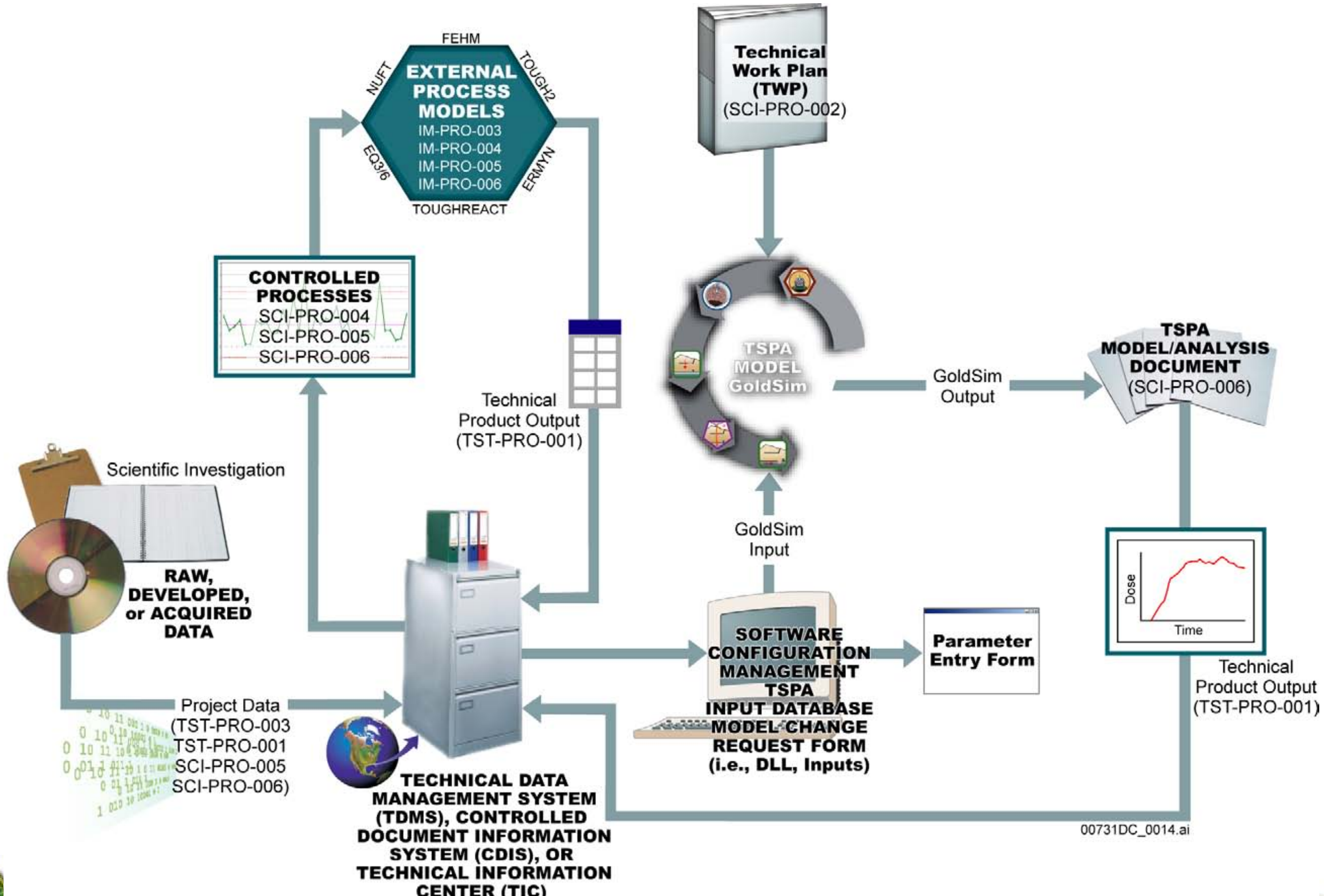
Concept Analyst Checklist for TSPA Model Version: ___________________________________

Analyst (name):
Analyst (sig): ________________ Date: ___________

Checker (name):
Checker (sig): ________________ Date___________

1.00	**Conceptual Level Check**	**Y,N, or n/a**	**Notes**	**Initials**
1.01	Is the objective adequately and clearly stated?			
	Are the conceptual descriptions sufficiently detailed to:			
1.02	Understand it's purpose?			
1.03	Explain what is intended to be done?			
1.04	Explain how it is intended to be done?			
1.05	Explain why it is being done?			
1.06	Properly designed for each relevant scenario?			
1.07	Does the implementation address the conceptual design in detail and intent for each scenario?			
1.01	Does the conceptual design, it's implementation, and analysis of results accomplish the stated purpose?			
1.09	Does the modified portion of the model respond appropriately to its inputs?			
1.10	Do the model components downstream from the modifications respond appropriately?			
1.11	Are model inputs and outputs within their specified ranges?			
1.12	Can the final dose results be explained in terms of upstream parameters (e.g., waste package/drip shield failure curves, seepage flow, pH, solubilities, EBS release rates)?			
1.13	Did the modification(s) invalidate or bring into question assumptions of an upstream or downstream conceptual model?			
1.14	Is the model implemented correctly for this scenario class?			
1.15	Are there any unintended behaviors that cannot be explained?			
1.16	Is there additional work needed or outstanding issues generated as a result of this work?			

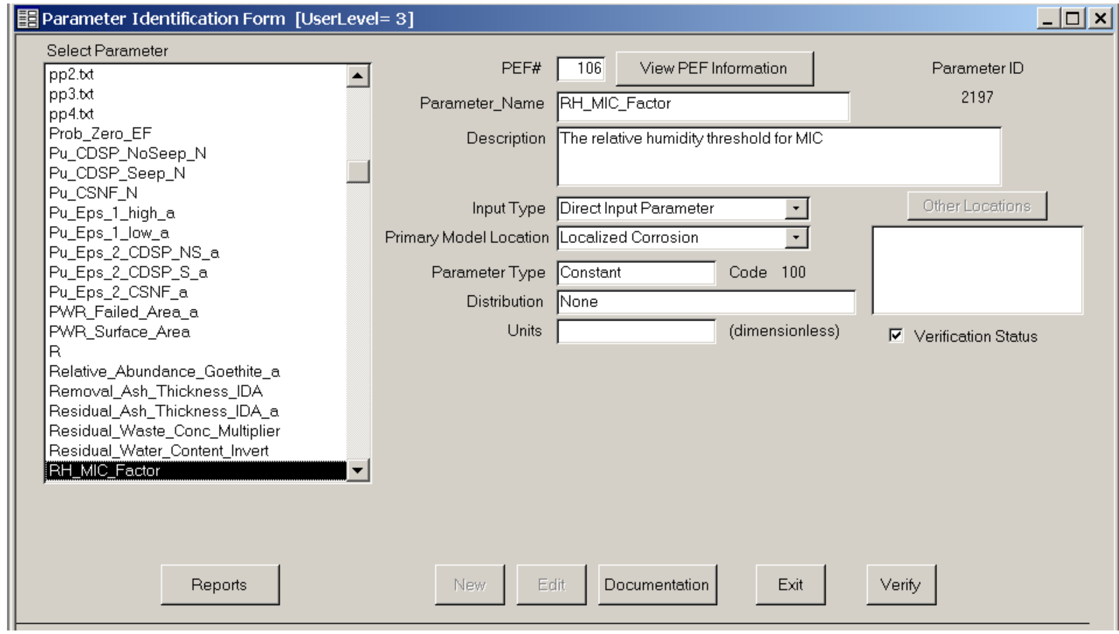
Information Control for TSPA Model Development and Analysis



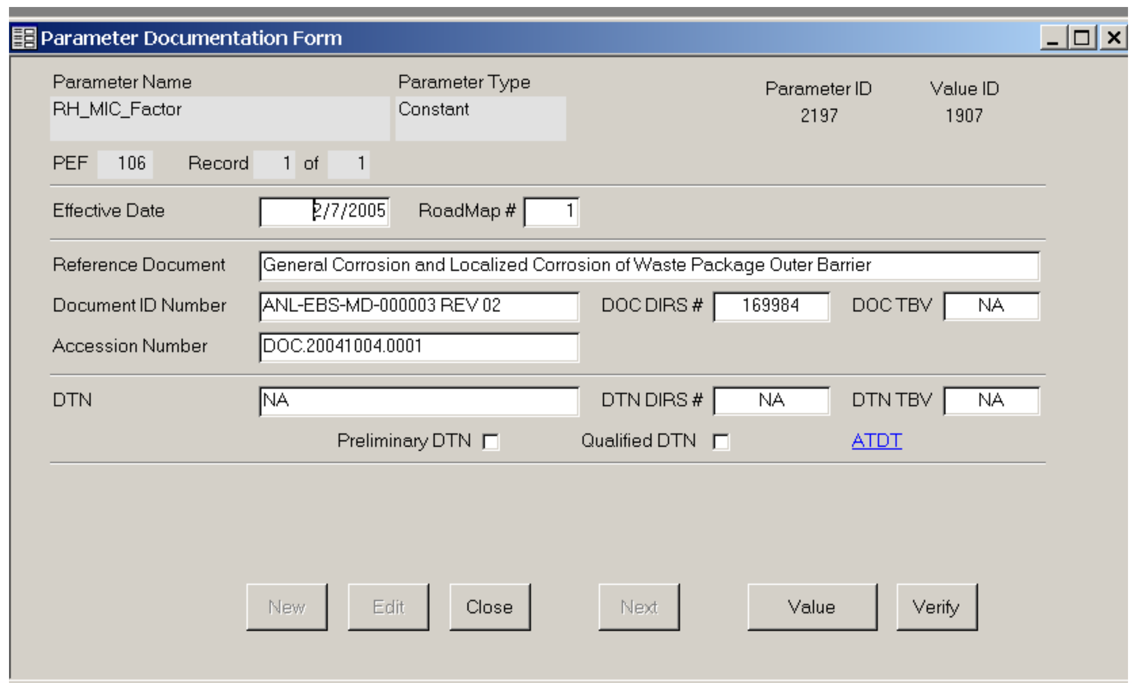
TSPA Parameter Database

- **TSPA parameter database screens**
  - Screen 1—Identifies parameter name, parameter entry form (PEF) No., primary model location, verification status
  - Screen 2—Identifies source of parameter by DTN and/or AMR; lists DIRs No., Accession No. and any TBV Nos.
  - Screen 3—Data values can been entered or reviewed; this screen is different depending on the type of parameter (e.g, Constant,1-Table)
  - Screen 4—Documents the verification of the data source and value; captures edit history
  - Screen 5—Documents where in the source of the parameter the values are located

Screen 1



Screen 2



PEF Example

TSPA Input Database Parameter Entry Form

QA: NA

PEF	*TSPA Analyst*

Road Map

PEF Revision History

Parameter Name	*ID*	***Description | Roadmap #***	***Reference Document***	**[TBV]**	***Document ID***	***DTN***	PEF **[TBV]**
					DIRS:	**DIRS:**	

Total # of Parameter Entries on Parameter Entry Form (PEF) = #Error

Parameter Team Lead (Print/Sign) ***Date***

Subject Matter Expert (Print/Sign) ***Date***

TSPA Analyst (Print/Sign) ***Date***

Database Administrator (Print/Sign) ***Date***

Wednesday, October 18, 2006 **PEF** *Page 1 of 1*

Note: 1) PEFs usually have more than one parameter; 2) Generally, parameters that come from a single source will be on the same PEF; 3) The subject matter expert (SME) signatures indicates the SME agrees with how input is used in TSPA Model.

Model Validation Approach

- **Confidence building activities during development of the TSPA model will include:**
  - **Input selection and verification**
  - **Calibration and model stability testing**
  - **Analysis of impacts of uncertainties**
- **The postdevelopment validation approach is being developed. Following methods are being considered in accordance with SCI-PRO-006, *Models*, Section 6.3.2:**
  - **Corroboration with other model results**
    - **comparisons to alternative system models**
    - **comparison of abstraction model results to process model results**
    - **analysis of subsystem results, including auxiliary analyses**
  - **Corroboration with natural analogue information (for selected submodels)**

Topics Covered in Subsequent Presentations

- **Characterization of uncertainty and variability**
  - Epistemic vs. aleatory uncertainty
  - Alternative conceptual models
  - Display of uncertainty
- **Specific scenario classes and design of TSPA analyses**
  - Computational strategy
  - Use of Monte Carlo techniques
- **Use of TSPA to characterize barrier capability**
- **Effect of transport, aging, and disposal (TAD) canisters on TSPA**

Anticipated Changes Since TSPA-SR

- **Technical basis for TSPA planned for the license application builds on the technical foundation documented for the TSPA-SR and TSPA-FEIS Models**
- **Significant changes since TSPA-SR include**
  - Seismic scenario class included (TSPA-SR excluded seismic FEPs based mainly on low consequence, except for clad damage)
  - Separation of aleatory and epistemic uncertainty
  - Additional confidence building (validation)
  - Changes to component models based on updated science
  - Additional rigor added to configuration and control processes
  - Changes to the repository design, e.g., TAD

References

- **"Total System Performance Assessment - Site Recommendation"**
  - **CRWMS M&O 2000. *Total System Performance Assessment for the Site Recommendation.* TDR-WIS-PA-000001 REV 00 ICN 01**
- **"Total System Performance Assessment - Supplemental Science and Performance Analysis"**
  - **BSC (Bechtel SAIC Company) 2001. *FY01 Supplemental Science and Performance Analyses, Volume 2: Performance Analyses.* TDR-MGR-PA-000001 REV 00**
- **"Total System Performance Assessment - Final Environmental Impact Statement"**
  - **Williams, N.H. 2001. "Contract No. DE-AC08-01RW12101 – Total System Performance Assessment – Analyses for Disposal of Commercial and DOE Waste Inventories at Yucca Mountain – Input to Final Environmental Impact Statement and Site Suitability Evaluation REV 00 ICN 02." Letter from N.H. Williams (BSC) to J.R. Summerson (DOE/YMSCO), December 11, 2001, RWA:cs-1204010670, with enclosure**
- **"One-Off Analyses"**
  - **BSC 2002. *Risk Information to Support Prioritization of Performance Assessment Models*, TDR-WIS-PA-000009 REV 01 ICN 01**
- **"One-On Analysis"**
  - **Saulnier, G. J., 2002. *Use of One-on Analysis to Evaluate Total System Performance*. ANL-WIS-PA-000004 REV 00 ICN 00**

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

www.ocrwm.doe.gov

Multiple Barriers—Identification of Barriers and Components and Characterization of Barrier Performance

Presented to:
DOE/NRC Technical Exchange on Total System Performance Assessment (TSPA) for Yucca Mountain

Presented by:
Robert J. MacKinnon
Sandia National Laboratories

October 24, 2006
Las Vegas, Nevada

Outline of Presentation

- Definition of a barrier
- Regulatory requirements
- Overview of barriers and components
- Technical basis for characterizing barrier performance
- Summary

Definition of a Barrier

- **A barrier as defined in 10 CFR 63.2 is any material, structure, or feature that includes the following functions:**
  1. **Prevents or substantially reduces the rate of movement of water or radionuclides from the repository to the accessible environment, or**
  2. **Prevents the release or substantially reduces the release rate of radionuclides from the waste**

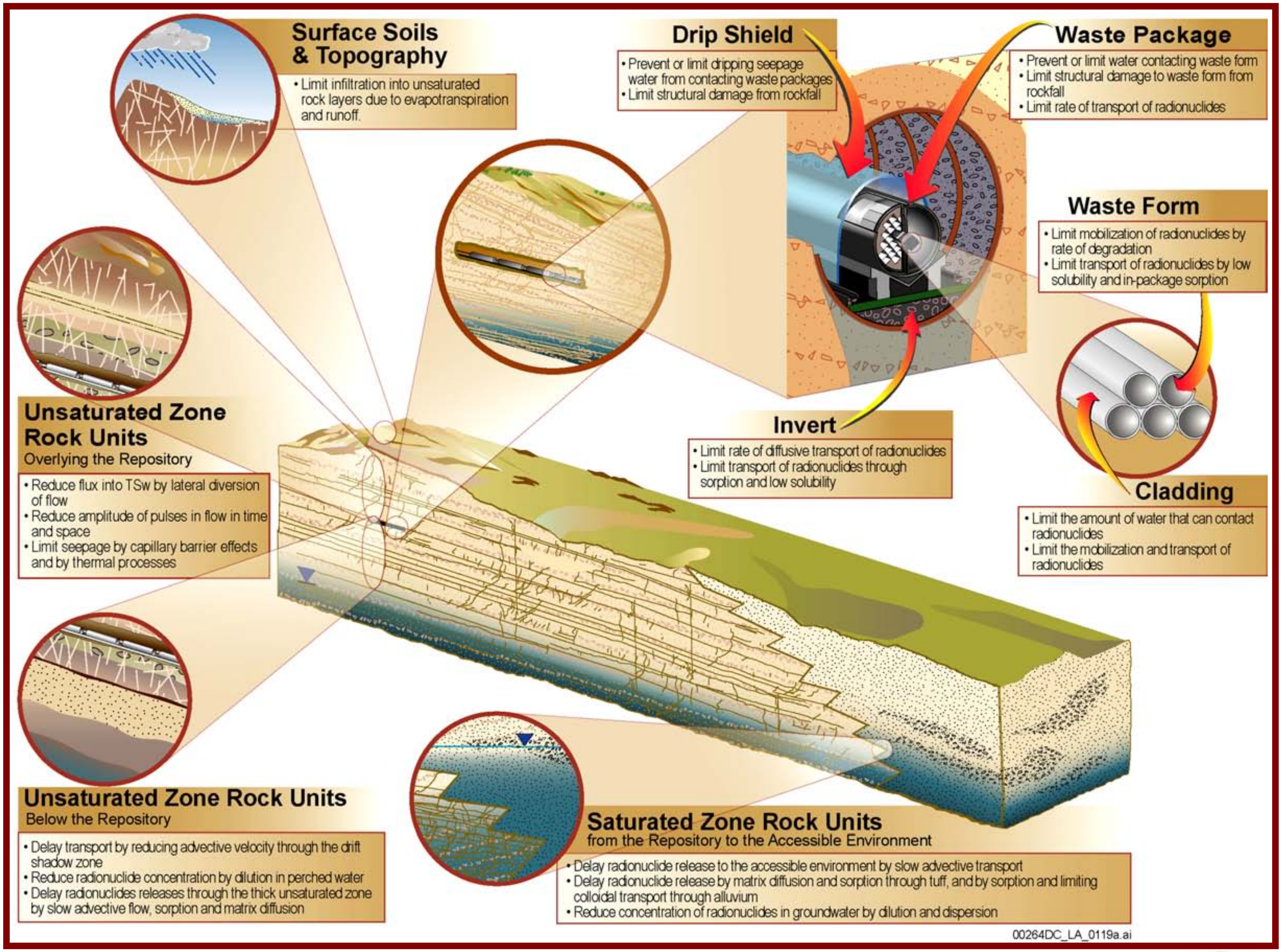
10 CFR 63.115 Requirements for Multiple Barriers

- **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**

Yucca Mountain Barriers and Components

- **Upper Natural Barrier**
  - Surface soils and topography
  - Unsaturated zone (UZ) above
- **Engineered Barrier System**
  - Drip shield
  - Waste package
  - Cladding
  - Waste form
  - Invert
- **Lower Natural Barrier**
  - UZ below
  - Saturated zone (SZ)

Yucca Mountain Component Models



Characterizing Barrier Performance

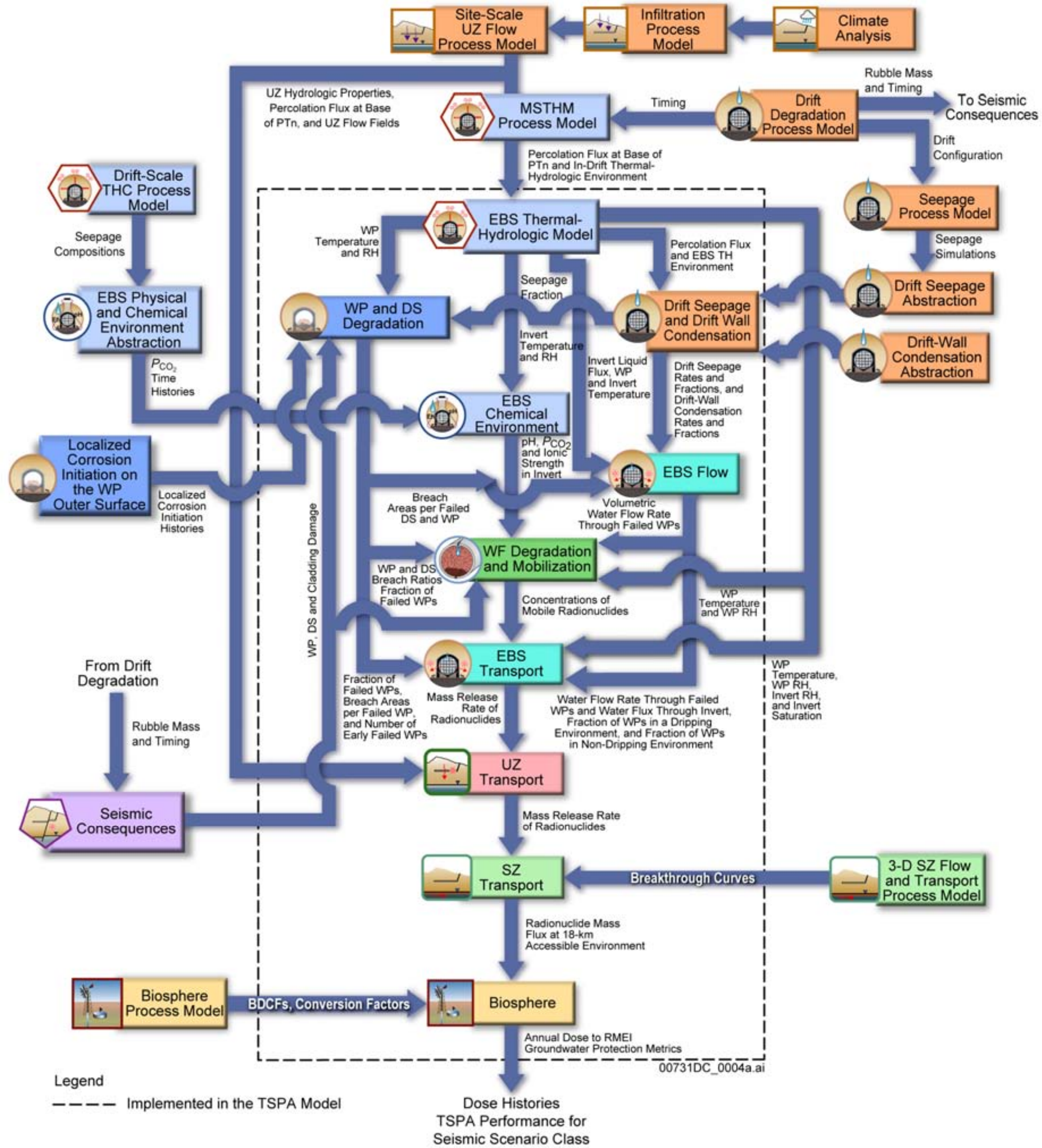
- Describe the capability of each barrier to perform its intended function and the relationship of that barrier's role to limiting radiological exposure in the context of the overall performance assessment
- Identify and describe features and processes important to barrier performance
- Identify and describe important uncertainties and their effects on barrier performance
- Use relevant output metrics to quantify performance for each barrier, for example
  - Reduction in seepage flux and water contact
  - Transport time delay and reduction in radionuclide releases for specific radionuclides
  - Radionuclide movement and retention throughout the system

Technical Basis

- **Barrier analysis approach**
  - **Examine system behavior with all components in place**
  - **Intermediate output metrics extracted from the performance assessment will be processed at component model interfaces to quantify barrier performance**
  - **Supplementary analyses as needed**

TSPA Model

Component interfaces are located where output metrics (e.g., water flow, radionuclide fluxes) from one component of the total system become the inputs to another component



Uncertainty in Parameters and Models

- **Sources of uncertainty**
  - **Incomplete data**
    - **E.g., hydrologic material properties can never be obtained for all locations**
  - **Spatial variability and scaling issues**
    - **E.g., data may be available from small volumes or discrete locations but may be used in models to represent large volumes**
  - **Measurement error**
    - **Usually only a minor contributor to total uncertainty**
  - **Lack of knowledge about the future state of the system**
    - **E.g., uncertainty about the occurrence of disruptive events**
  - **Alternative conceptual models**
- **Monte Carlo techniques used to incorporate**

Summary

- Provide qualitative and quantitative bases describing the capability of each barrier to perform its intended function and the relationship of that barrier's role to limiting radiological exposure in the context of the overall performance assessment
- Quantitative estimates will be extracted from the performance assessment of the behavior of the overall repository system
- Confidence in quantitative estimates comes from
  - Understanding components and their capabilities
  - Understanding system performance and barrier contribution to system performance
  - A clear display of uncertainty
  - An understanding of the effects of uncertainty

Treatment of Uncertainty and Variability in TSPA

Presented to:
DOE/NRC Technical Exchange on Total System Performance Assessment (TSPA) for Yucca Mountain

Presented by:
S. David Sevougian
Sandia National Laboratories

October 24, 2006
Las Vegas, Nevada

Presentation Outline

- **Sources and classification of uncertainty in performance assessment (PA) and TSPA**
- **Guidelines for characterizing parameter and model uncertainty**
- **Example from TSPA Model for combining uncertainty with varying scales of spatial variability: localized corrosion analysis**
- **Confidence-building analyses regarding the appropriateness of upscaling variability in the Engineered Barrier System (EBS) release model**
- **Potential modifications to GoldSim software architecture for the treatment of variability at the representative package scale**
- **Anticipated changes since TSPA for site recommendation (SR)**

Uncertainty in Parameters and Models

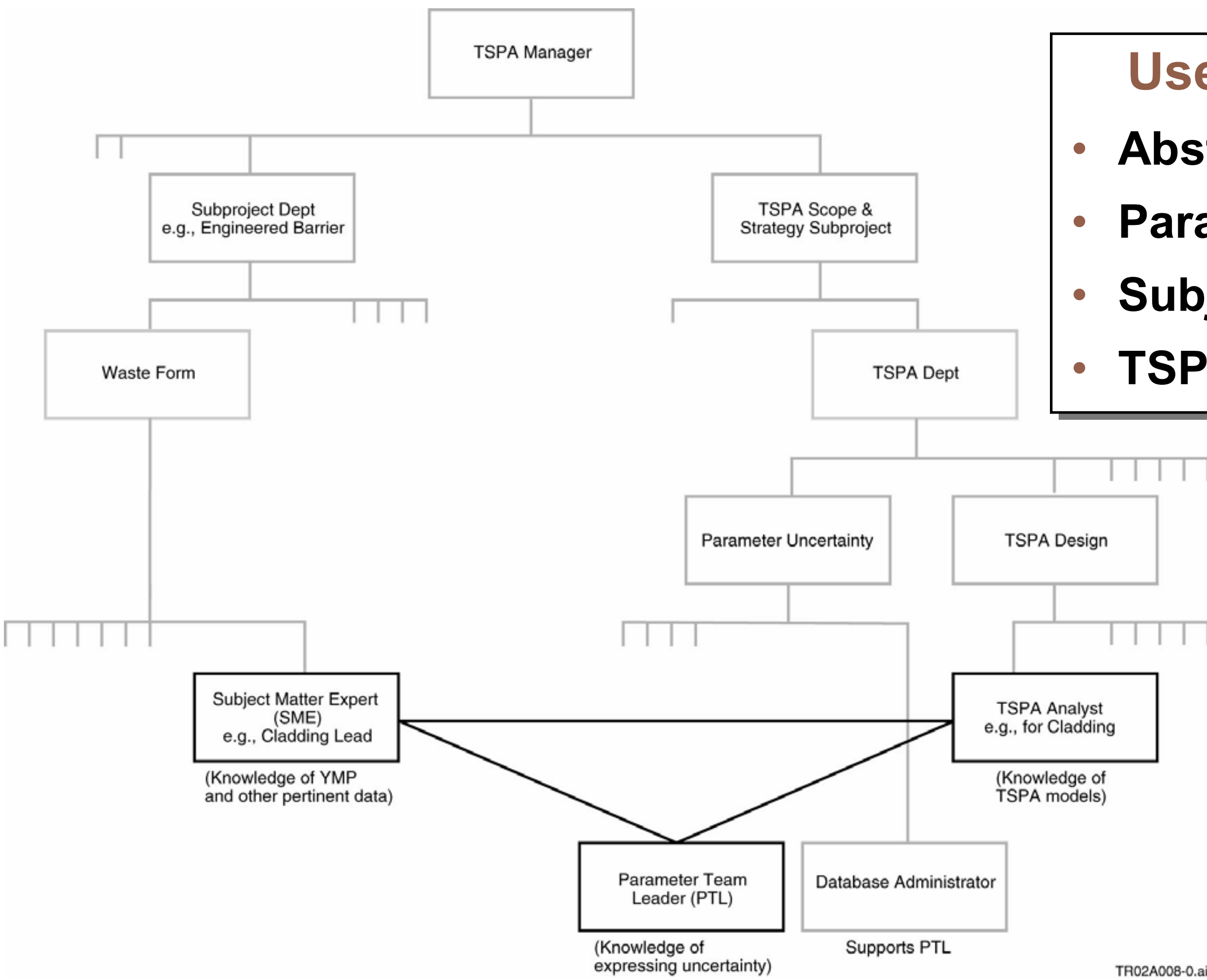
- **Sources of uncertainty**
  - **Lack of knowledge about the future state of the system (aleatory)**
    - **E.g., uncertainty about the occurrence of disruptive events**
  - **Incomplete data (epistemic)**
    - **E.g., hydrologic material properties can never be obtained for all locations**
  - **Spatial variability and scaling issues**
    - **E.g., data may be available from small volumes or discrete locations but may be used in models to represent large volumes**
  - **Measurement error**
    - **Usually only a minor contributor to total uncertainty**
  - **Alternative conceptual models**

Classification of Uncertainty in PA and TSPA for Monte Carlo Analyses

- **Aleatory uncertainty is the inherent randomness in events that could occur in the future**
  - Alternative descriptors: irreducible, stochastic, intrinsic, type A
  - Examples
    - Timing and size of an igneous event
    - Timing and size of a seismic event
- **Epistemic uncertainty is the lack of knowledge about appropriate value to use for a quantity assumed to have a fixed value**
  - Alternative descriptors: reducible, subjective, state of knowledge, type B
  - Examples
    - Permeabilities, porosities, sorption coefficients, …
    - Rates defining Poisson processes
    - Alternative conceptual models
- **Propagation of these two types of uncertainty in the TSPA analyses discussed in subsequent talk**

Guidelines for Estimation of Uncertainty

Guidelines Document: ***Guidelines for Developing and Documenting Alternative Conceptual Models, Model Abstractions, and Parameter Uncertainty in the Total System Performance Assessment for the License Application*****, TDR-WIS-PA-000008, REV 00**



Uses a Team Approach

- **Abstraction team lead (ATL)**
- **Parameter team lead (PTL)**
- **Subject matter expert (SME)**
- **TSPA analyst**

Guidelines for Estimation of Uncertainty
(continued)

- **Steps in the process**
  - TSPA analyst identifies model and TSPA parameters (consistent with abstraction)
    - Identifies fixed-value and uncertain parameters
  - SME identifies relevant data and other supporting information
  - PTL, SME, and TSPA analyst jointly review data and application of the parameter in the TSPA model
  - PTL leads SME and TSPA analyst in determining a value or construction of a distribution function for uncertain parameters
    - Joint concurrence of all three participants is documented by signature
  - PTL transmits value or function to the TSPA parameter database administrator, where it is controlled for use in TSPA analyses

Uncertainty Estimation and Characterization in FY07

- **2002 Uncertainty Guidelines Document emphasizes the process for documenting uncertainty, but not the actual mechanics of distribution fitting**
- **Re-examination of uncertainty estimation will be led by TSPA in FY07, with emphasis on processes and models that contribute most to risk**
- **Alternative conceptual models will be included in TSPA if their use better represents the full range of uncertainty and if their contribution to risk is significant**
- **Greater emphasis on consistency in uncertainty estimation across component models and abstractions**
  - **Splitting of aleatory/epistemic sampling will be emphasized**
  - **Standard statistical techniques will be emphasized for developing distributions for parameters that are well-characterized**
  - **Use accepted practices for including subjectivity and empiricism in development of epistemic parameter distributions**
- **Workshops are being held by TSPA to ensure appropriateness and consistency in the estimation of uncertainty in the abstractions**

Example Agenda—
Uncertainty Estimation Workshop

1. **Nature and Sources of Uncertainty (9:00 – 9:45)**
   a. Aleatory v/s epistemic uncertainty
   b. Problem of scale
   c. Model uncertainty

2. **Statistical foundations (9:45 – 10:30)**
   a. Univariate and bivariate statistics
   b. Empirical distributions
   c. Parametric distribution models

3. **Fitting continuous distributions (10:30 – 12:00)**
   a. Issues in distribution selection
   b. Probability plots and linear regression analysis
   c. Nonlinear least-squares analysis
   d. Distribution fitting with commercial packages

---- BREAK ----

4. **Subjective assessment of probabilities (12:30 – 1:15)**
   a. Maximum entropy distribution selection
   b. Generation of subjective probabilities
   c. Formal expert elicitation protocols

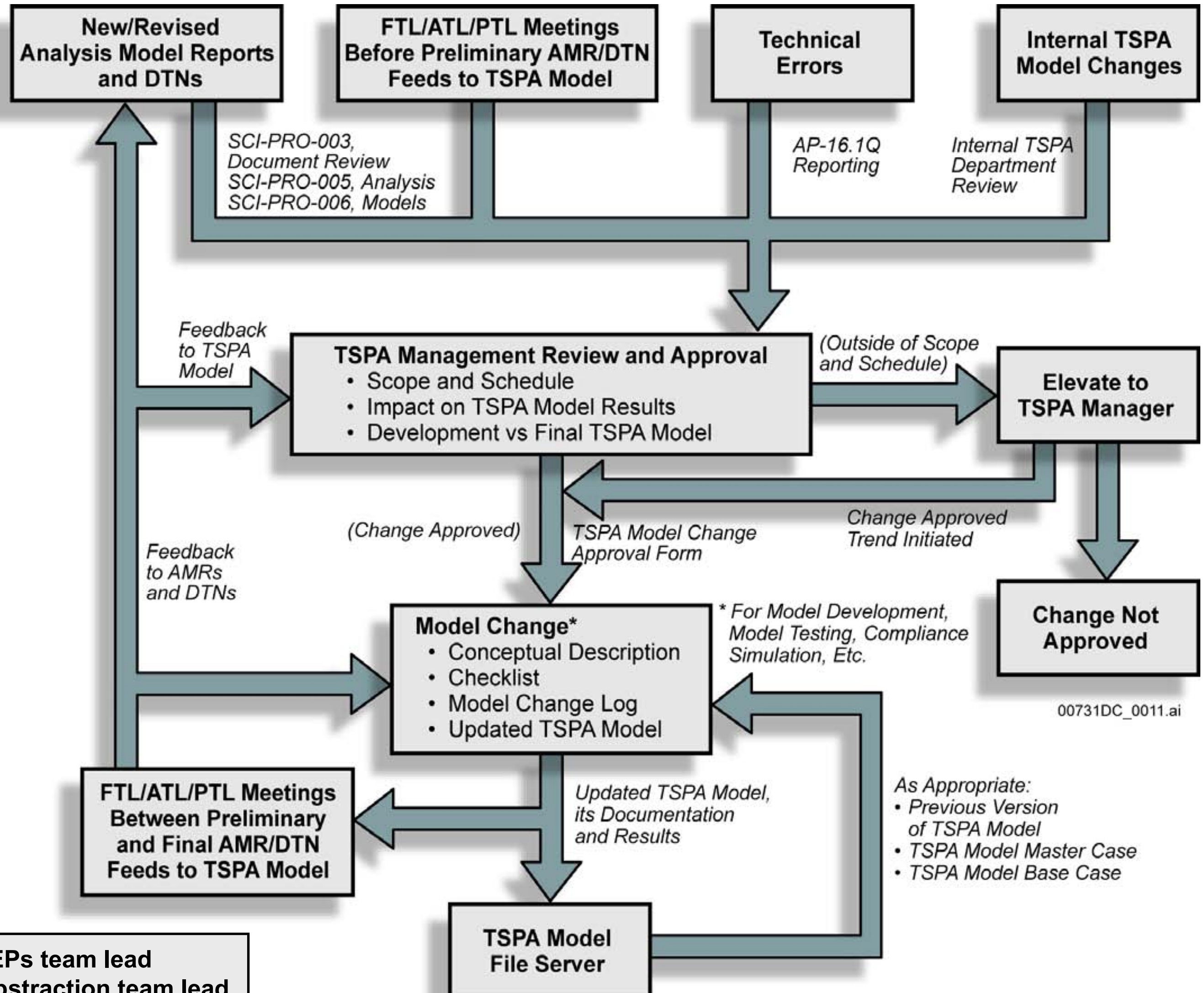
5. **Bayesian updating (1:15 – 2:00)**
   a. Bayes theorem
   b. Updating with conjugate pairs
   c. Updating using numerical approximation

6. **Regression modeling (2:00 – 3:00)**
   a. Linear regression basics
   b. Non-parametric regression overview

7. **Miscellaneous topics (3:00 – 4:00)**
   a. Data representativeness
   b. Scaling considerations
   c. Treatment of model uncertainty

8. **Wrap-up (4:00 – 4:30)**

Management Control Process for TSPA



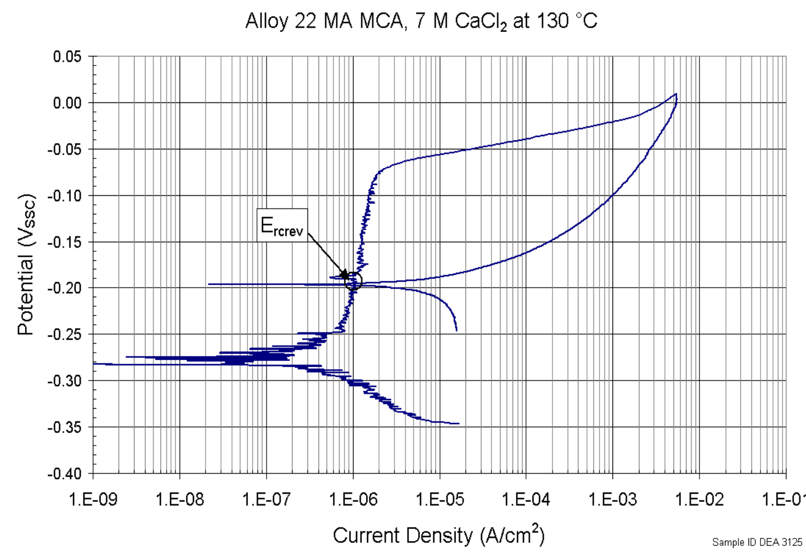
FTL = FEPs team lead
ATL = Abstraction team lead
PTL = Parameter team lead

Example of the Integration of Uncertainty and Variability in the TSPA Model—

Crown-Seepage-Induced Localized Corrosion of Alloy 22

Localized Corrosion Initiation Model

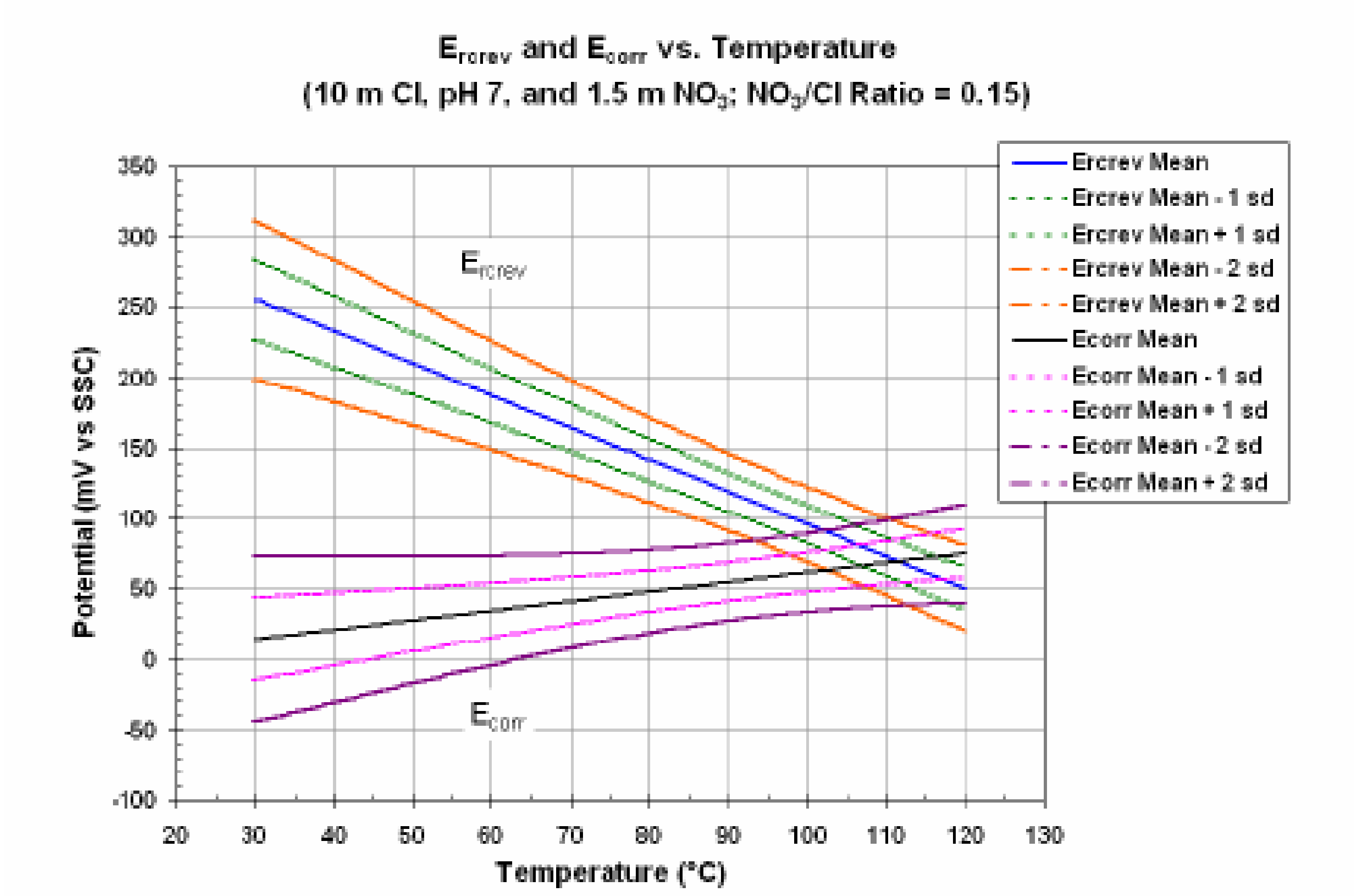
- **Localized corrosion initiation model uses empirical regression equations for corrosion potential (E_{corr}) and crevice repassivation potential (E_{rcrev}), from cyclic potentiodynamic polarization (CPP) tests**



ANL-EBS-MD-000003

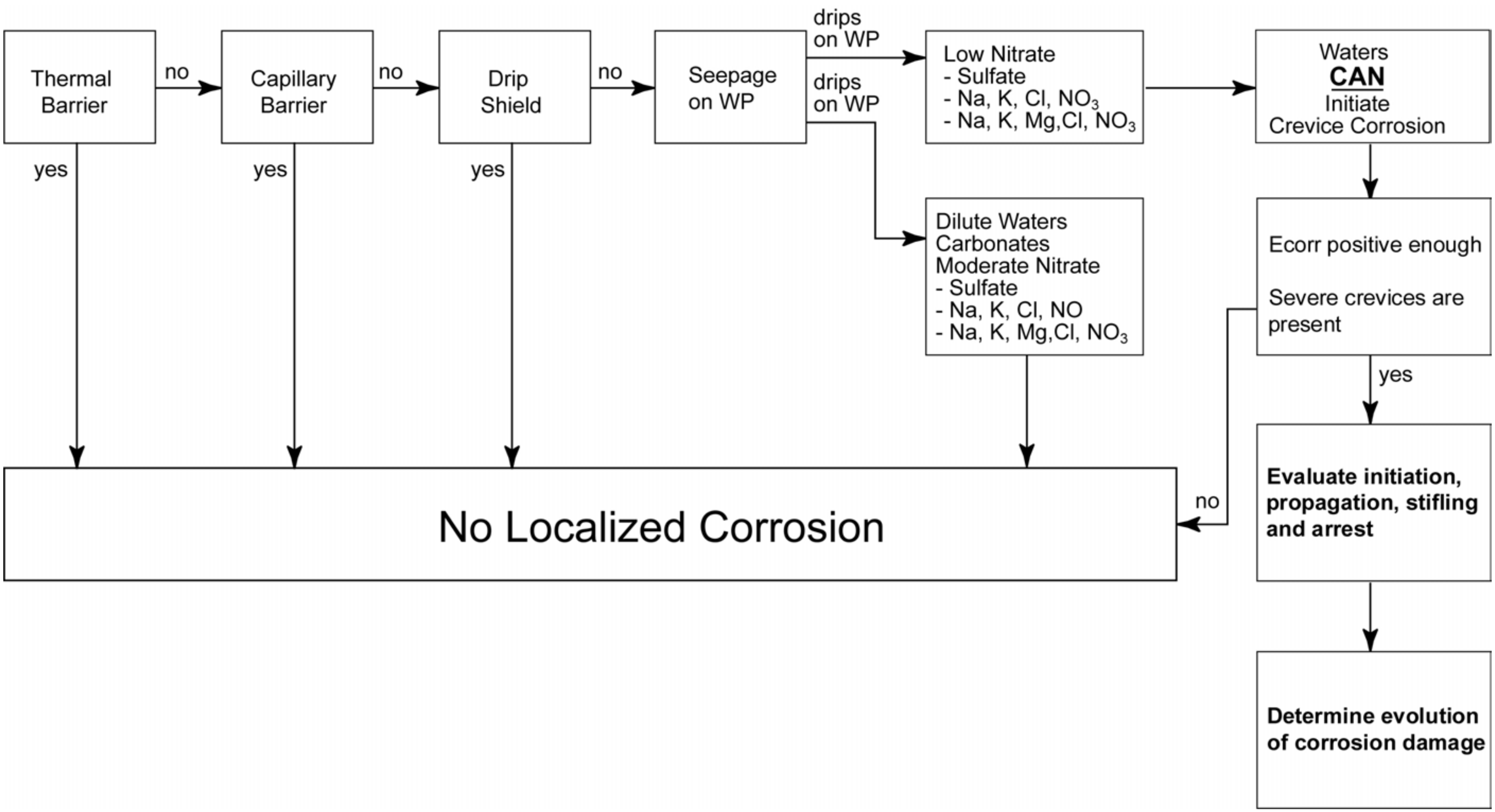
- **Regression equations include dependence on temperature, pH, chloride concentration, and nitrate concentration (with uncertainty)**
  - **Crevice repassivation potential:** $E_{rcrev} = E_{rcrev}(T, pH, Cl^-, NO_3^-, \frac{NO_3^-}{Cl^-})$
  - **Long-term corrosion potential:** $E_{corr} = E_{corr}(T, pH, Cl^-, \frac{NO_3^-}{Cl^-})$
  - **Localized corrosion initiates when:** $\Delta E = (E_{rcrev} - E_{corr}) \leq 0$

Example of LC Initiation Model Calculation



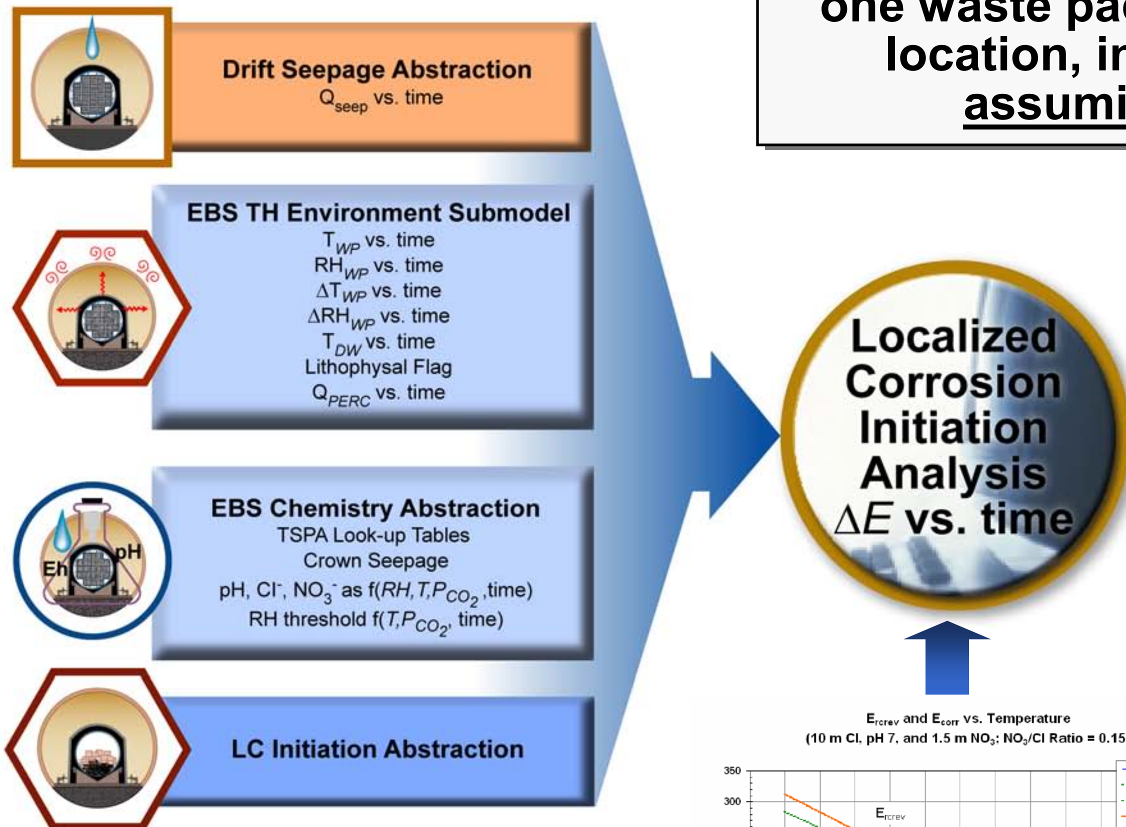
Model Results for Crevice Corrosion Susceptibility of the Waste Package Outer Barrier as a Function of Temperature for 10 *m* Chloride, pH 7, and 1.5 *m* Nitrate (NO_3/Cl Ratio of 0.15)

Crevice Corrosion Decision Tree



Coupling of EBS Localized Corrosion Initiation Model with Environmental Input Models and Abstractions

Illustration of hypothetical coupling for one waste package at one repository location, including uncertainty, assuming no drip shield



Number of Realizations →

Time ↓

Time (years)	1	2	3	4
0	0	0	0	0
100	0	0	1	0
200	0	0	1	0
500	0	0	0	0
750	0	0	0	0
1000	0	0	0	0
1250	0	0	0	0

No Localized Corrosion = 0 (in table)

Localized Corrosion Initiated = 1 (in table)

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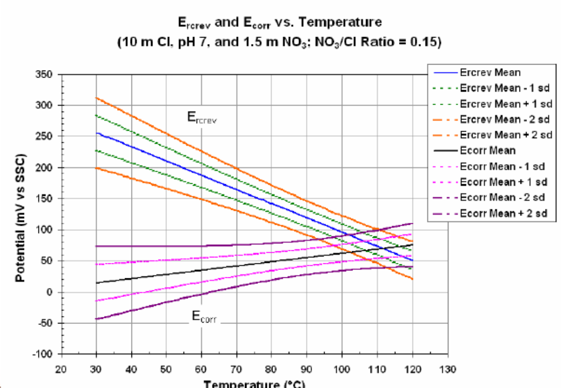
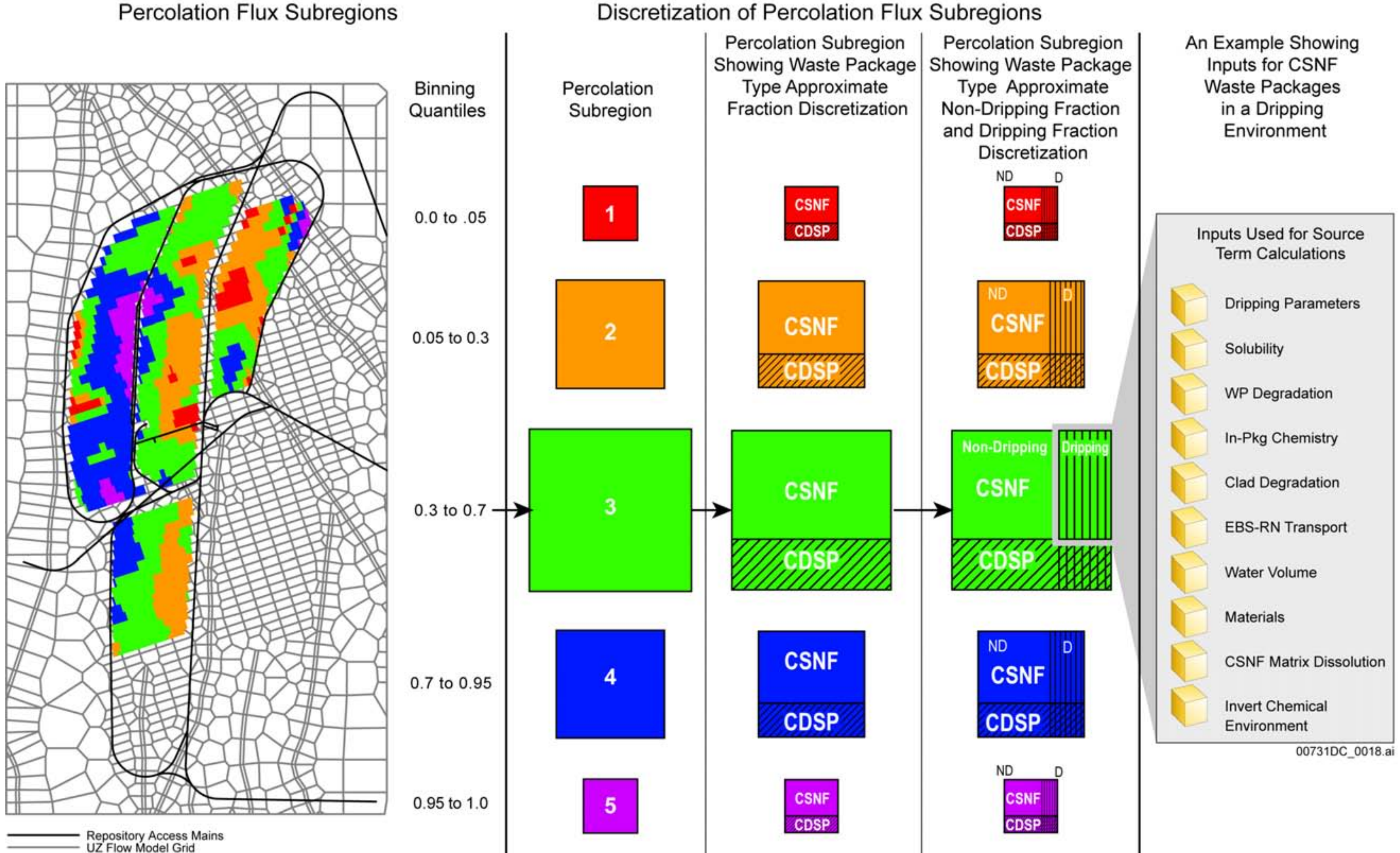


Multiple Packages—Spatial Scales and Levels of Discretization in the TSPA EBS Model Suite



Downscaling or averaging

Implementation and Connection of Localized Corrosion Initiation Model, Uncertainties, and Variabilities into EBS and TSPA Modeling

U = uncertainty

V_R = variability (representative or upscaled)

V_D = variability (detailed or fine-scale)

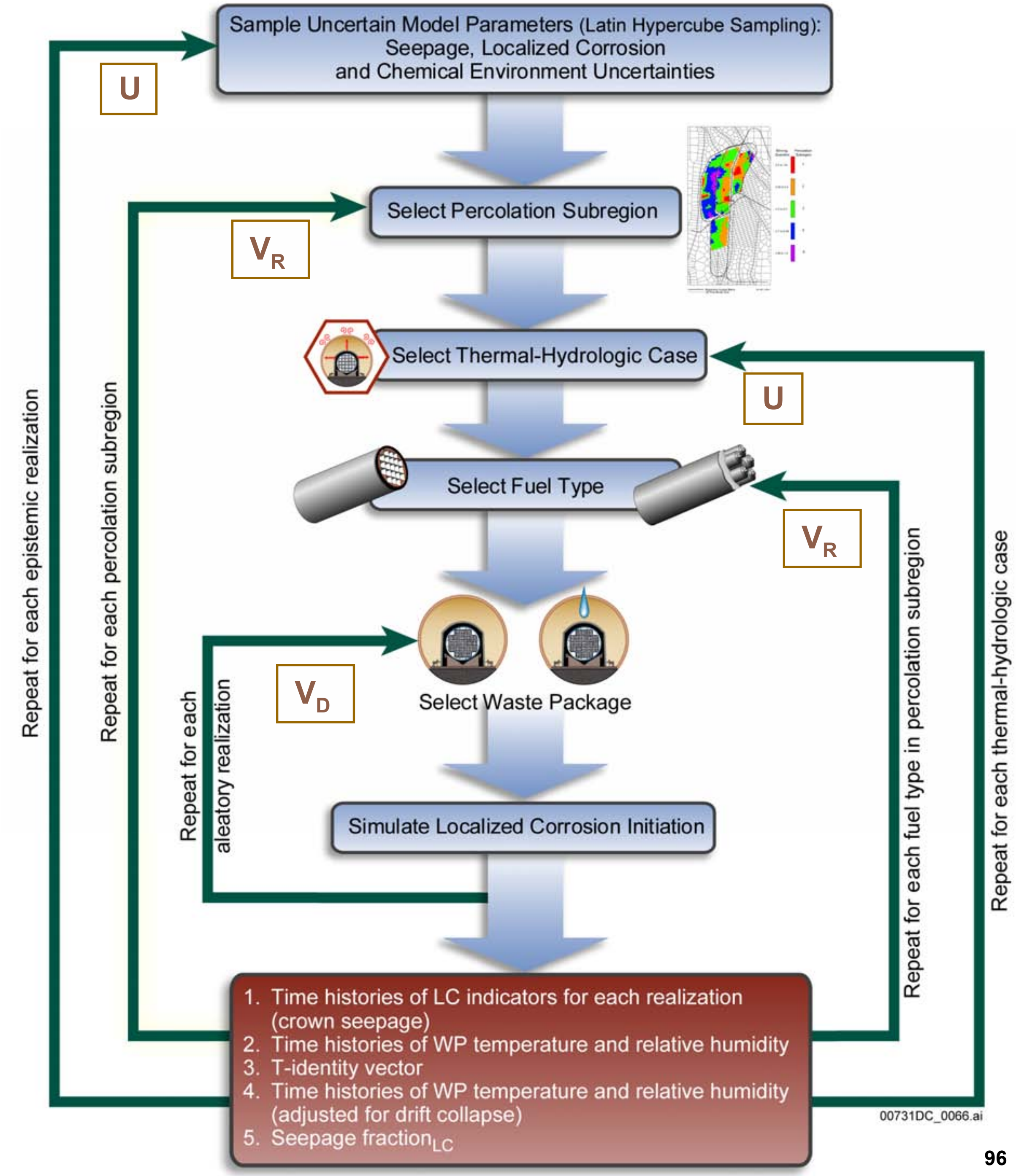
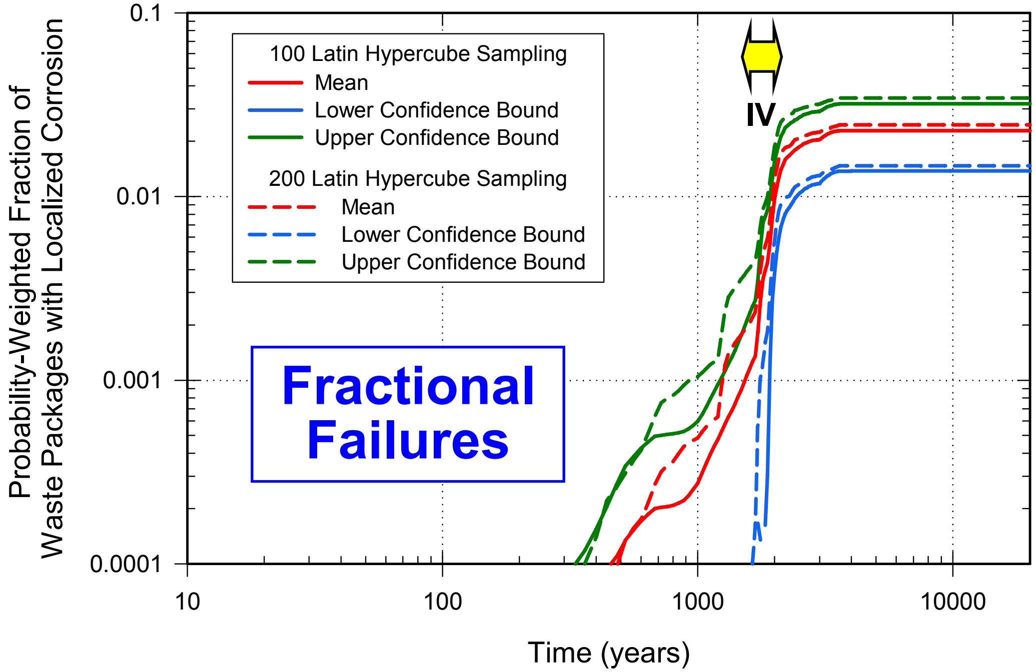
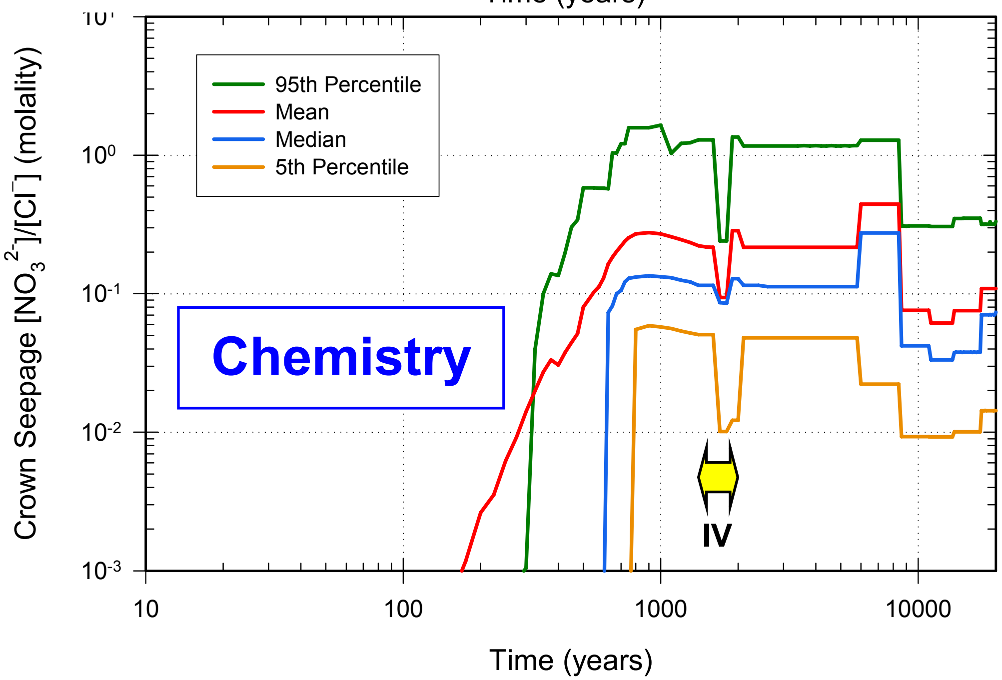
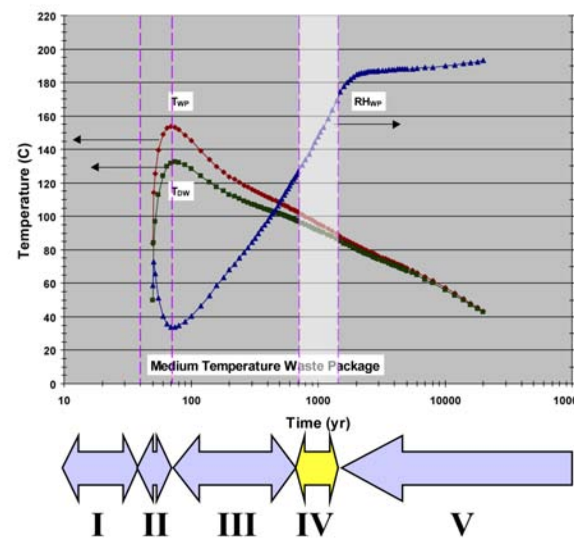


Illustration of EBS Model Testing and Verification—

Fraction of Packages Failed by Localized Corrosion (assuming no drip shield protection)







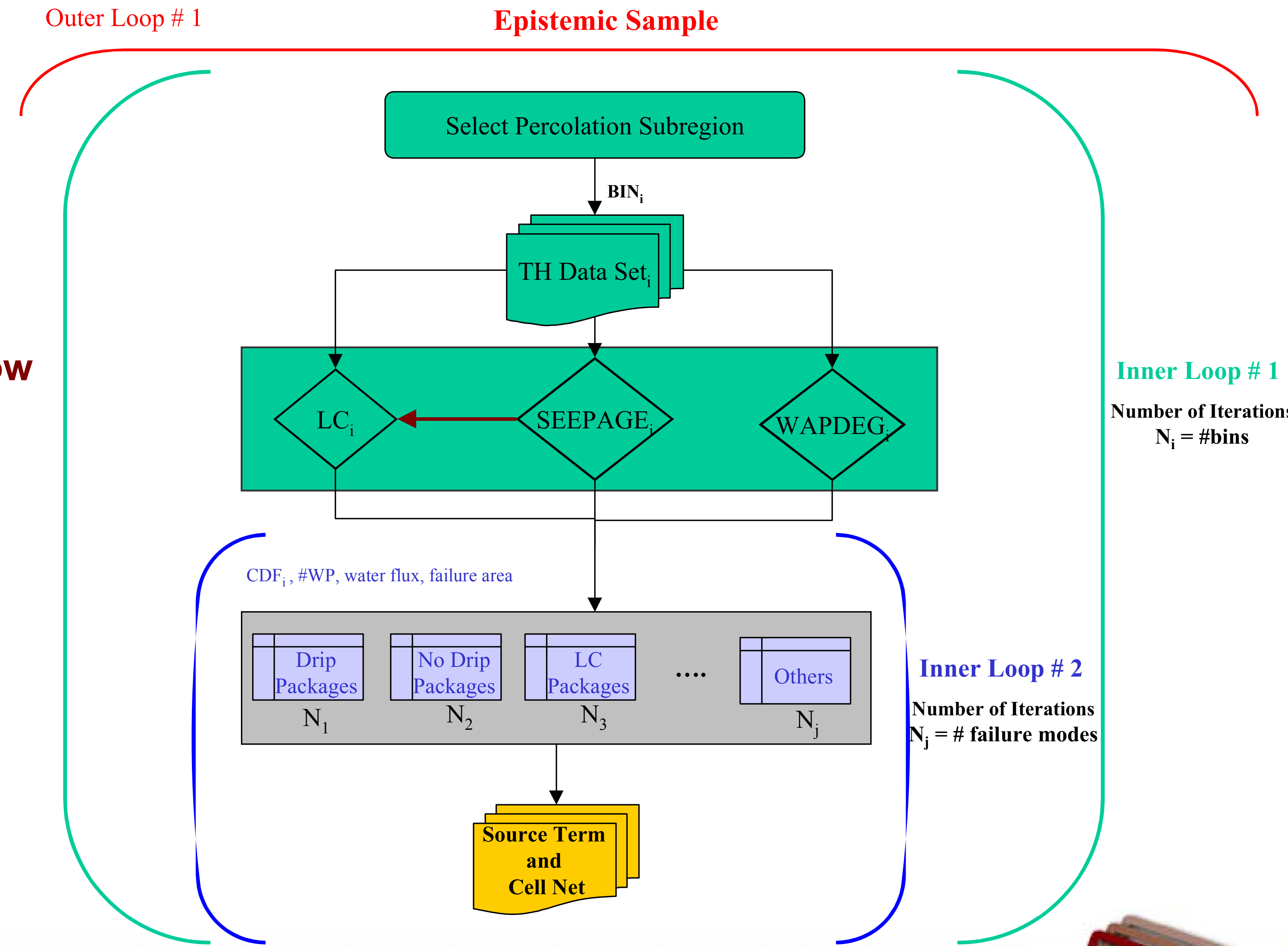
Upscaling of EBS Releases—
Basis of Percolation Subregions

Confirmation of Current Approach To Upscaling of EBS releases

- **Use a finer scale EBS-only model based on the detailed spatial scale of the thermal-hydrologic (TH) and percolation data from the Multiscale TH Model to compare to the upscaled TSPA EBS release model that uses 5 representative "packages" or percolation subregions**
  - **This methodology is being used as a confidence-building method for the TSPA model**
- **Potential changes to GoldSim architecture to accommodate looping over source term groups**
  - **Will allow more flexibility in the representation of spatial variability at the representative or "bin" level (waste form degradation and EBS releases)**
  - **Reduces the size of the GoldSim model file**

Potential GoldSim Architecture Changes

Draft Flow Diagram



Summary of Current Uncertainty/Variability Approach

- **Varying degrees of abstraction, coupling, scaling, and quantification of uncertainty and variability are being used for YMP TSPA, as appropriate to capture the primary effects of key processes, e.g.,**
  - **Detailed variability in TH processes is necessary to develop a localized corrosion fractional failure curve, and to represent seepage**
  - **Representative variability in TH processes is sufficient to capture waste form mobilization processes**

Anticipated Changes Since TSPA-SR

- Developed guidelines and management controls for characterizing uncertainty consistently across component abstractions
- Uncertainty characterization and estimation for the most important parameters and models will be re-examined in FY07
- Epistemic and aleatory uncertainty will be separated in the TSPA analyses
- Alternative conceptual models will be included when appropriate, based on contribution to risk
- Effect of uncertainty on barrier capability and performance to be included

Design and Use of Total System Performance Assessment Analyses

Presented to:
DOE/NRC Technical Exchange on Total System Performance Assessment (TSPA) for Yucca Mountain

Presented by:
Robert J. MacKinnon
Sandia National Laboratories

October 24, 2006
Las Vegas, Nevada

Presentation Outline

- Purpose of TSPA
- Defensible basis supporting performance assessment
- Epistemic and aleatory uncertainty
- Scenario classes
- Computational strategy
- Summary

Purpose of TSPA

- **Provide a defensible basis for evaluation of compliance with repository postclosure performance objectives specified in 10 CFR 63.113**
  - **Estimation of mean annual dose to the reasonably maximally exposed individual (RMEI) and groundwater concentrations for a period of 10,000 yr**
  - **Estimation of median annual dose to the RMEI after 10,000 years, but within the period of geologic stability (proposed rule)**
- **Basis includes an evaluation of the extent to which uncertainty in present understanding of the repository system affects these estimates (10 CFR 63.114, 10 CFR 63.115)**

Purpose of TSPA (continued)

- **Defensible basis will include the following analyses**
  - Total system performance analyses (10 CFR 63.113, 10 CFR 63.114, 10 CFR 63.303, 10 CFR 63.305, 10 CFR 63.312, 10 CFR 63.331, 10 CFR 63.332, 10 CFR 63.342)
  - Human intrusion analyses (10 CFR 63.321, 10 CFR 63.322)
  - Barrier performance analyses (10 CFR 63.115)
  - Uncertainty and sensitivity analyses (10 CFR 63.114, 10 CFR 63.115)

Developing the Defensible Basis

- **Q1: What can happen?**
- **Q2: How likely is it to happen?**
- **Q3: What are the consequences if it does happen?**
- **Q4: What is the uncertainty in the answers to the first three questions?**
- **Guidance from YMRP**
  - ***Risk-Informed Review Process for Performance Assessment*—***The performance assessment quantifies repository performance, as a means of demonstrating compliance with the postclosure performance objectives at 10 CFR 63.113. The U.S. Department of Energy performance assessment is a systematic analysis that answers the triplet risk questions: what can happen; how likely is it to happen; and what are the consequences.*

Uncertainty in TSPA

- **Aleatory uncertainty is the inherent randomness in events that could occur in the future**
  - Alternative descriptors: irreducible, stochastic, intrinsic, type A
  - Examples:
    - Time and size of an igneous event
    - Time and size of a seismic event
- **Epistemic uncertainty is the lack of knowledge about appropriate value to use for a quantity assumed to have a fixed value**
  - Alternative descriptors: reducible, subjective, state of knowledge, type B
  - Examples:
    - Permeabilities, porosities, sorption coefficients, …
    - Rates defining Poisson processes

Basic Elements Underlying TSPA

1. **Probabilistic characterization of what can happen in the future**
   - **Answers first two questions**
   - **Provides formal characterization of aleatory uncertainty**
   - ***E.g. assumption that igneous event occurrence is a Poisson process***
2. **Mathematical models for predicting consequences**
   - **Answers third question**
   - ***E.g. models implemented in Goldsim***
3. **Basis for answering fourth question**
   - **Provides formal characterization of epistemic uncertainty**
   - ***E.g. distribution assigned to λ (annual frequency) in Poisson process for igneous event***

Scenario Classes

- Definition and division of scenario classes is based on the type of screened-in initiating events
- Representations of possible future states of the repository
  - Igneous scenario class
    - Contains included features, events, and processes (FEPs) associated with igneous disruption
  - Seismic scenario class
    - Contains included FEPs associated with seismic disruption
  - Early failure scenario class
    - Contains included FEPs associated with early failures of waste package (WP) and drip shield (DS) failures
  - Human intrusion scenario class
    - Contains included FEPs associated with drilling intrusion
  - Nominal scenario class
    - Contains all included FEPs anticipated to occur in the absence of disruption, intrusion, and early failures of WP and DS

Modeling Cases

- TSPA modeling cases represent scenario classes
- Igneous scenario class
  - Igneous case 1—Igneous intrusion
    - Ascent of a basaltic dike, intersection of the dike with the repository, and the flow of magma into the drifts
    - Effects of magma on WPs and waste forms in the intersected drifts
    - Effects after intrusion associated with heat and changes in water chemistry, which affect mobilization of the waste by groundwater
    - Expected features and processes
    - Unlikely FEPs will be included in only the assessment of individual protection
  - Igneous case 2—Volcanic eruption
    - Eruption of a volcano through the repository and entrainment
      of waste in the eruption products
    - Airborne dispersal, deposition, and redistribution of the contaminated tephra

Modeling Cases (continued)

- **Seismic Scenario Classes**
  - Seismic case 1—Ground motion (GM)
    - Mechanical damage to the drip shield, WP, and cladding due to seismic GM and rockfall
    - Expected features and processes
    - Unlikely FEPs will be included in only the assessment of individual protection
  - Seismic case 2—Fault displacement (FD)
    - Mechanical damage to the drip shield, WP, and cladding due to FD
    - Expected features and processes
    - Unlikely FEPs will be included included in only the assessment of individual protection

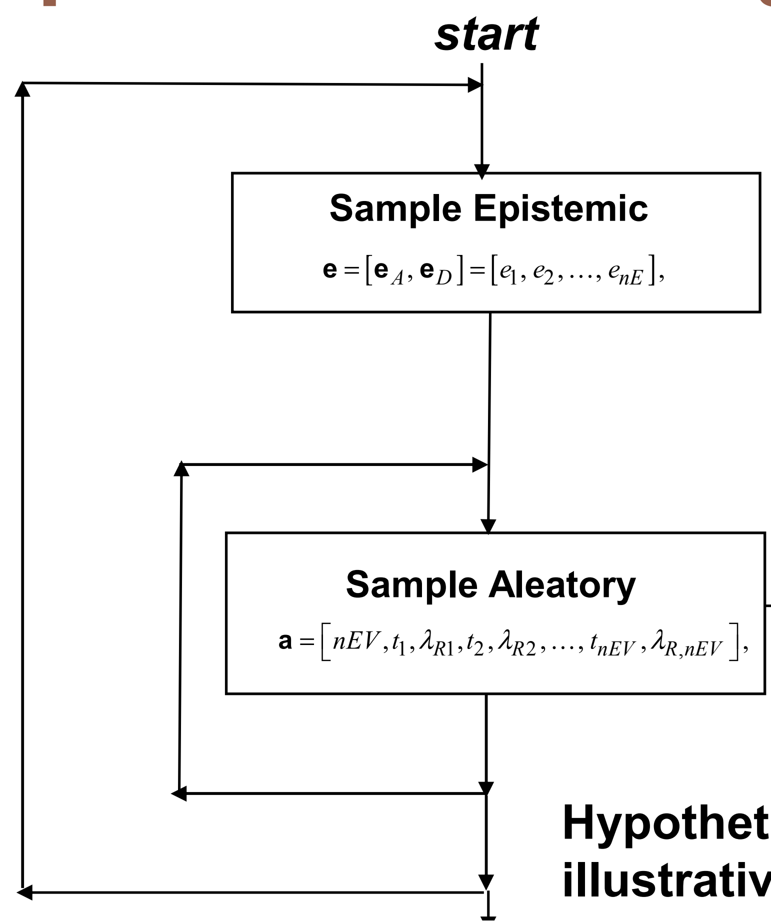
Modeling Cases (continued)

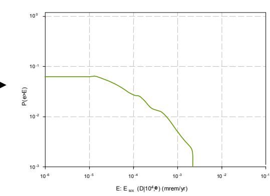
- **Early failure scenario class**
  - **Early failure case**
    - **Early failure of DS (potential being evaluated) and WPs**
    - **Expected features and processes**
- **Human intrusion scenario class**
  - **Effects of drilling intrusion on WP and waste form, transport through borehole to the saturated zone (SZ), and expected flow and transport processes**
  - **Unlikely FEPs are excluded**
- **Nominal scenario class**
  - **Nominal case**
    - **Expected features and processes**

Computational Strategy

- Maintain separation of aleatory and epistemic uncertainty
  - Epistemic uncertainty in expected dose and other quantities
  - Informative sensitivity analysis
- Processes for uncertainty propagation
  - Sampling-based (Latin hypercube sampling) for epistemic uncertainty
  - Integration-based and random sampling for aleatory uncertainty
- Produce three types of results for presentation and/or sensitivity analysis
  - Distributions over epistemic uncertainty (no aleatory events) or conditional on a specific realization of aleatory uncertainty
  - Distributions over aleatory uncertainty conditional on a specific realization of epistemic uncertainty

Computational Strategy (continued)





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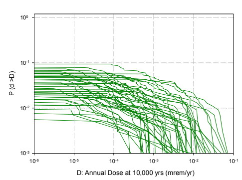
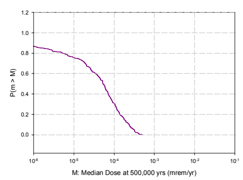
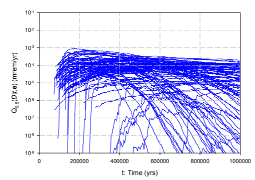
Hypothetical results from a illustrative example



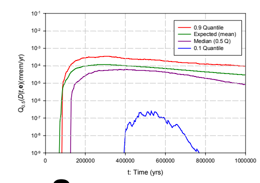
CCDFs at *t*



Dose metric at *t*



Dose metric as f(*t*)



Summary measures of uncertainty in Dose metric

Computational Strategy (continued)

- Perform sensitivity analysis
  - Investigation of mapping between uncertain TSPA inputs and TSPA results
  - Examine results and mapping at multiple interfaces, e.g., WP/Engineered Barrier System (EBS), EBS/unsaturated zone (UZ), UZ/SZ
  - Multiple time-dependent and spatially dependent results, e.g., solubilities, ionic strength, pH, temperature, release rates, integrated releases, dose, barrier performance metrics
  - Multiple radionuclides
  - Multiple scenarios, e.g., early WP and DS failure, igneous intrusive and eruptive, seismic GM and FD
  - Sensitivity analysis methods
    - Examination of scatter plots
    - Correlation and partial correlation analysis
    - Stepwise regression analysis
    - Rank transforms to linearize monotonic relationships
  - Employ sensitivity analysis to support barrier

Summary

- **Purpose of TSPA is to provide a defensible basis for evaluation of compliance with postclosure regulatory standards for the total repository system**
- **Five scenario classes represent plausible futures**
- **Computational strategy for performance assessment will maintain separation of aleatory and epistemic uncertainty**
- **Sensitivity analyses will be used to examine uncertainties and quantify the importance of parameters and models**

Impact of Transport, Aging, and Disposal Canisters on TSPA

Presented to:
DOE/NRC Technical Exchange on Total System Performance Assessment (TSPA) for Yucca Mountain

Presented by:
Robert J. MacKinnon
Sandia National Laboratories

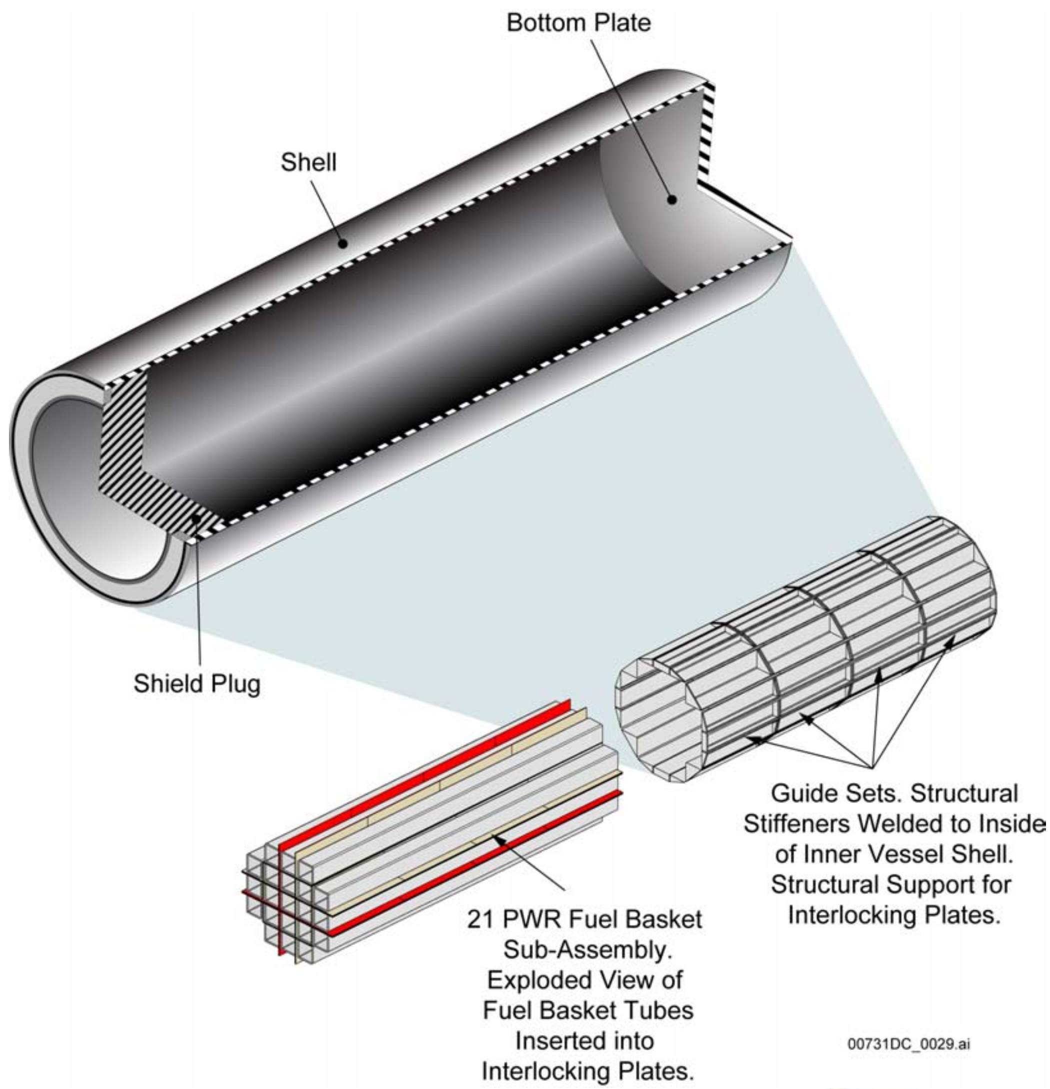
October 24, 2006
Las Vegas, Nevada

Transport, Aging, and Disposal Canister System

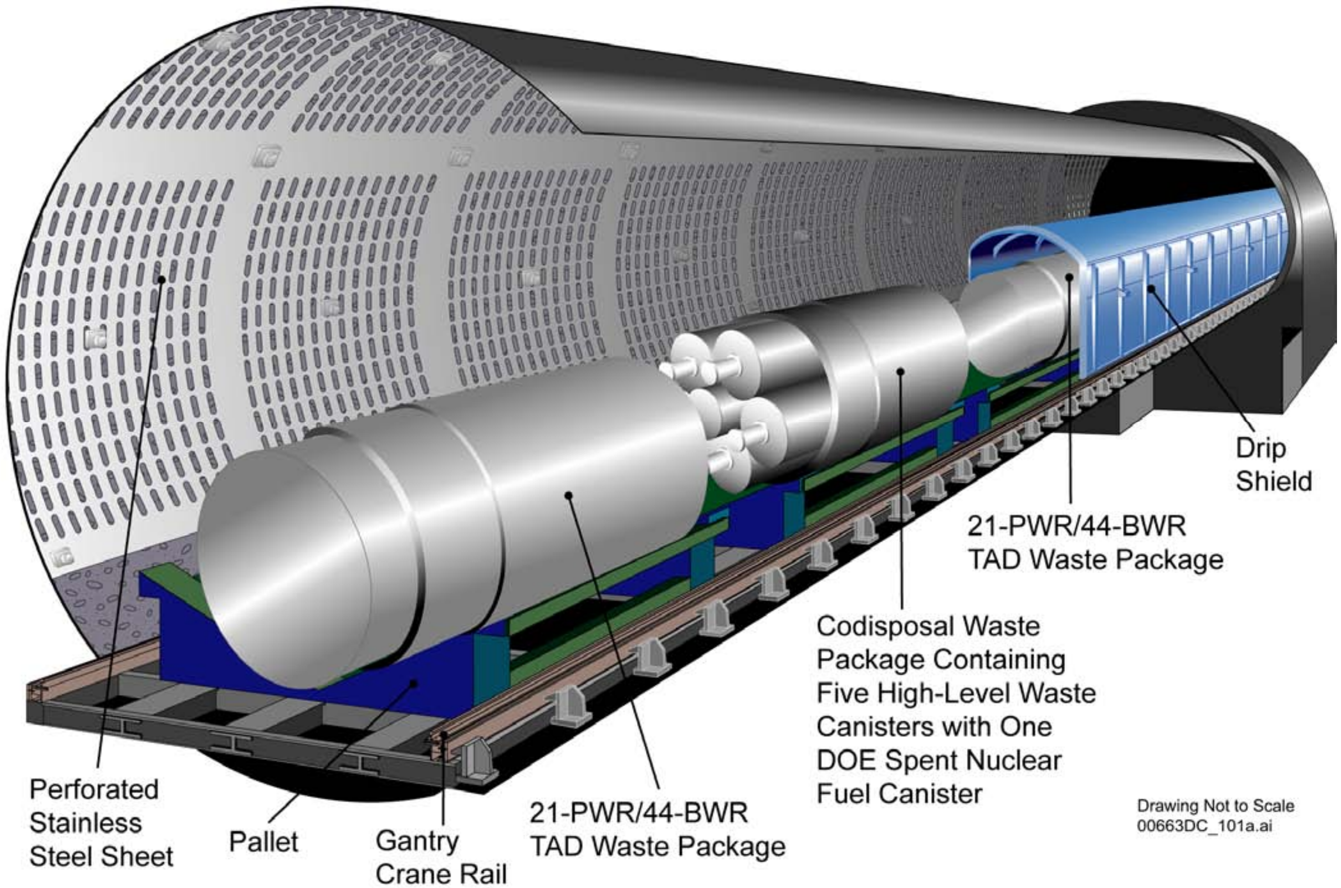
- The transport, aging, and disposal canister (TAD) system is a canister design concept that incorporates the three functions associated with its name into a single design
- In all three modes, the TAD is placed inside another vessel (overpack) that provides necessary functions such as shielding, heat dissipation, structural strength, and corrosion resistance
- The concept envisions TADs that are loaded, sealed, inerted, and tested at the nuclear utility sites
- For transportation to the repository, the overpacks for the TADs are the transportation overpacks
- At the repository, TADs are removed from the transport casks (overpacks) and placed into either shielded transfer casks for handling inside the facilities or between facilities, or to aging overpacks for crawler transport to the aging pads. Subsequent to these steps TADs will be placed and sealed into the waste packages for emplacement underground

TAD System

- **Aspects of the TADs that relate to the long-term performance assessment of the repository include**
  - **Material and dimension specifications for the TADs canister shell, internal baskets, and other canister components**
  - **Specification of the disposal overpack**



Engineered Barrier System



Summary of TADs

- **Preliminary TADs design based on the existing Naval long spent nuclear fuel canister and package**
  - **25-mm outer Alloy 22 barrier**
  - **Longer canister and package than existing 21-PWR commercial spent nuclear fuel (CSNF) due to shield plug**
  - **Very heavy shield plug at one end (~ 25-cm thick stainless steel)**
- **Major TADs factors that induce model changes**
  - **Elimination of carbon steel from CSNF packages**
  - **Shield plug changes center of mass**
  - **Thicker outer barrier may extend failure time**
  - **Longer package increases emplacement area**
  - **Shield plug also added to co-disposal packages**

Summary of Impacts on TSPA

- **In-package chemistry model impact**
  - Higher pH because of removal of carbon steel corrosion in CSNF packages
  - Probably has a limited effect on dose based on preliminary analyses
- **Seismic consequence WP damage models impact**
  - Develop new kinematic and dynamic analyses for structural damage to the WP
  - Effect is mainly due to the shield plug at one end (changed WP center of mass) and the increased WP mass
- **Thermal-hydrologic models impact**
  - Contingency drifts will be included in multiscale thermohydrologic model
  - Retain unit-cell in multiscale thermohydologic model and 1.45-kW/m line loading for thermal reference case
- **EBS transport model impact**

Nominal and Seismic Scenarios

Presented to:
DOE/NRC Technical Exchange on Total System Performance Assessment (TSPA) for Yucca Mountain

Presented by:
S. David Sevougian
Sandia National Laboratories

October 24, 2006
Las Vegas, Nevada

Presentation Outline

- Definition of nominal scenario class and anticipated changes since TSPA for site recommendation (SR)
- Definition of seismic scenario class
- Identification and linkage of abstractions for seismic processes
- Abstraction of seismic processes
  - Description of seismic scenario class
  - Input, output, and basis for model confidence
  - Assumptions
  - Conceptual model
  - Technical bases for abstraction and references
  - Treatment of uncertainty and variability
  - Implementation in TSPA model
- Anticipated changes in treatment of seismicity since TSPA-SR

Definition of Nominal Scenario Class

- Definition of scenario classes is based on the type of screened-in disruptive events identified in the features, events, and processes (FEPs) screening process
- The final set of modeled scenario classes for repository performance is still under consideration, but was generally defined in the presentation "Design and Use of TSPA Analyses"
- The nominal scenario class is defined as the set of possible futures containing no disruptive events (i.e., igneous or seismic) and no early waste package (WP) or drip shield (DS) failures
- The major changes since TSPA-SR in the nominal scenario class will be described in detail in the set of presentations on 10/25/2006 on component model abstractions in the TSPA; major changes include
  - Transport, aging, and disposal (TAD) canisters
  - Consideration of localized corrosion
  - Infiltration
  - Improved treatment of uncertainty
  - Consideration of proposed rule changes
  - Changes to component models based on updated science (Day 2 talks)

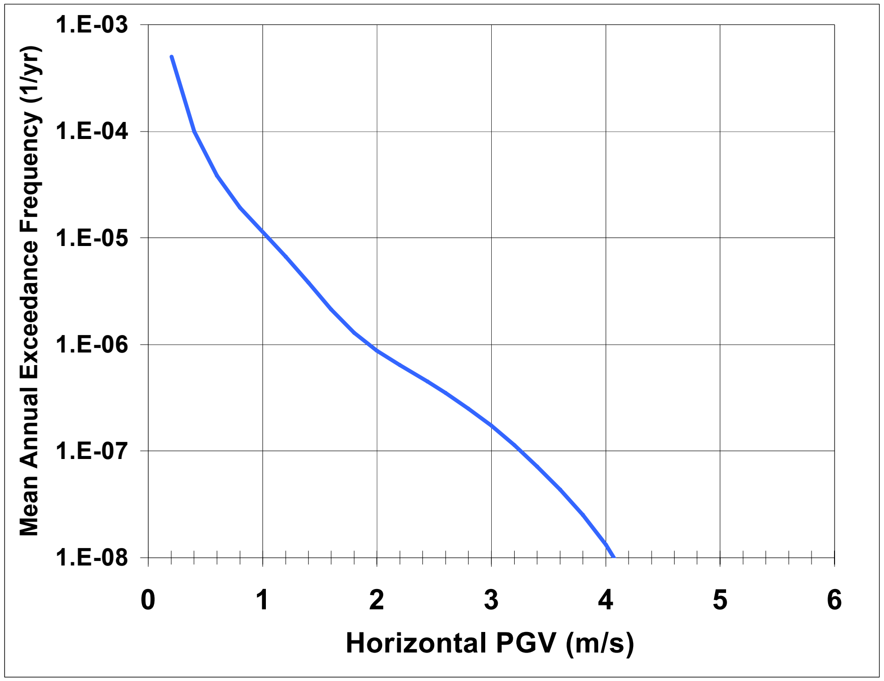
Definition of Seismic Scenario Class

- Remainder of this presentation focuses on the seismic scenario class
- The seismic scenario class is broadly defined as the set of possible futures that contain one or more seismic events but no igneous events
- The seismic scenario class includes all FEPs that are part of the nominal scenario class (all "expected" FEPs), plus FEPs associated with seismicity
- The probability of the seismic scenario class is a function of
  - The length of the future (T) being modeled (e.g., 10,000 years or 1,000,000 years)
  - The annual exceedance frequency (λ) of a "potentially damaging" seismic event, i.e., an event that causes some sort of breach in the WP

Definition of Seismic Scenario Class
(continued)

- The annual exceedance frequency (λ) of seismic events of varying magnitudes (PGV) is defined by the seismic hazard curve
- Not all events can cause Engineered Barrier System (EBS) damage; small PGVs (i.e., more frequent, but small, events) are unlikely to have a consequence
- For most events of any magnitude, damage to the WP is generally in the form of very small stress corrosion cracks

Seismic Hazard Curve



Definition of Seismic Scenario Class
(continued)

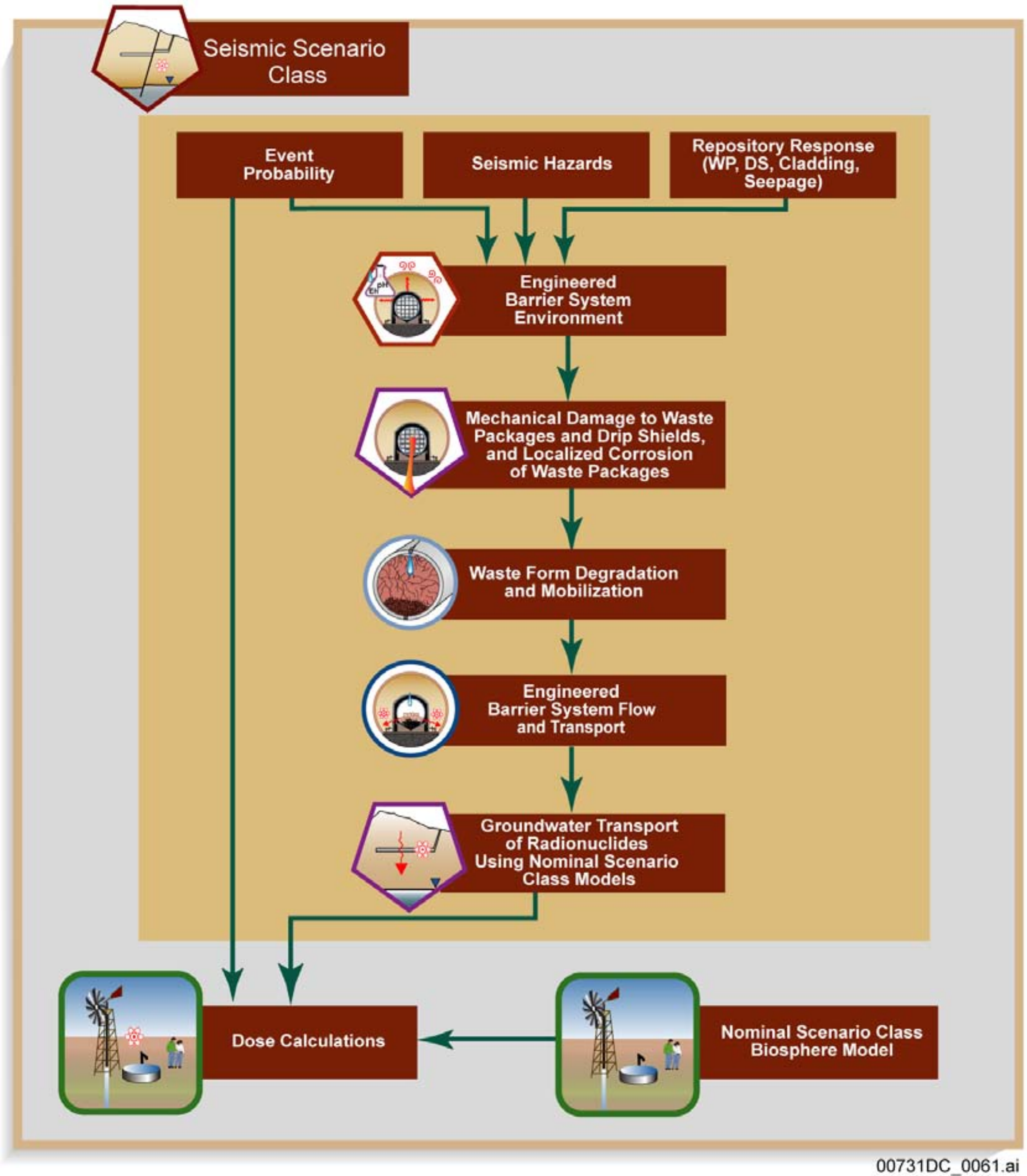
- The probability of the seismic scenario class depends on the definition of the maximum annual exceedance frequency that can result in a "potentially damaging" seismic event

- Illustration of the effect of occurrence frequency in the seismic scenario class:
  - For a Poisson process such as seismicity, the probability, P, of one or more events with an annual frequency of 1×10^{-4} per year is about 0.67 for T = 10,000 years and effectively 1.0 for T = 1,000,000 years

$$P(N(T) \geq 1) = 1 - \exp(-\lambda T)$$

where $N(T)$ = number of events in time T

Identification and Linkages of Abstractions



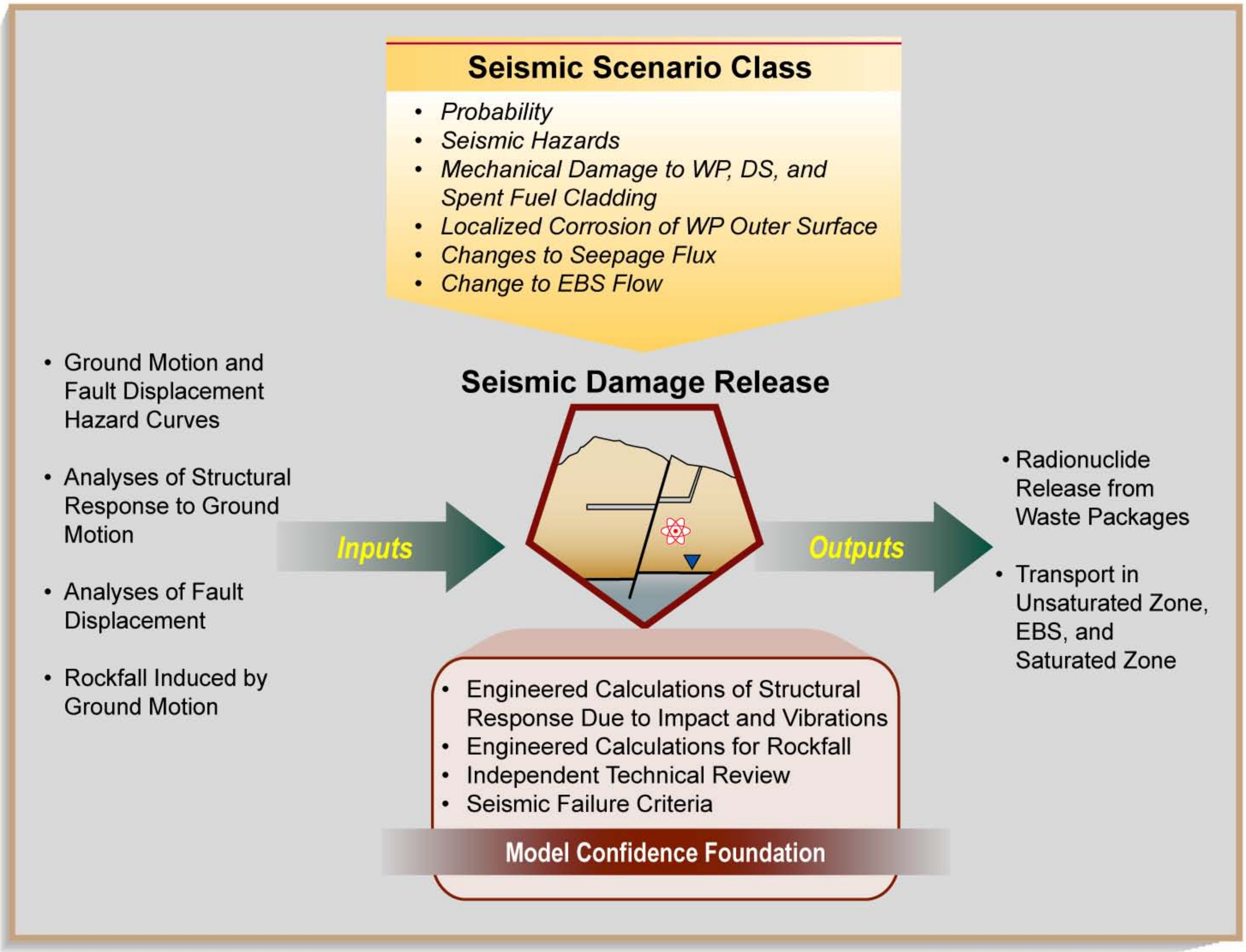
Description of Seismic Scenario Class

- Seismic scenario class includes both nominal and seismic degradation processes in the EBS
- Nominal and seismic WP degradation processes are strongly coupled through the thickness of the Alloy 22 outer barrier and the degradation or strength of the stainless steel inner vessel
- DS fragility abstraction developed based on Ti general corrosion and static and dynamic rubble loading of the DS
- General corrosion patch and stress corrosion cracking (SCC) failures in the Alloy 22 WPs occur due to nominal corrosion processes

Description of Seismic Scenario Class
(continued)

- **Seismic damage to WPs depends on the presence of the DS:**
  - **For intact DSs, crack damage to the Alloy 22 WP occurs through package-to-pallet impacts and package-to-package impacts; there is a small chance of plastic rupture damage**
  - **For failed DSs (by general corrosion and/or rubble loading), crack damage occurs from stresses induced by the surrounding rubble during strong ground motions; there is a small chance of plastic rupture**
- **Effect of fault displacement failures ($\lambda < 2\times10^{-7}$ per yr) expected to be small**
- **Cladding performance expected to be affected,**

Inputs, Outputs, Basis for Model Confidence



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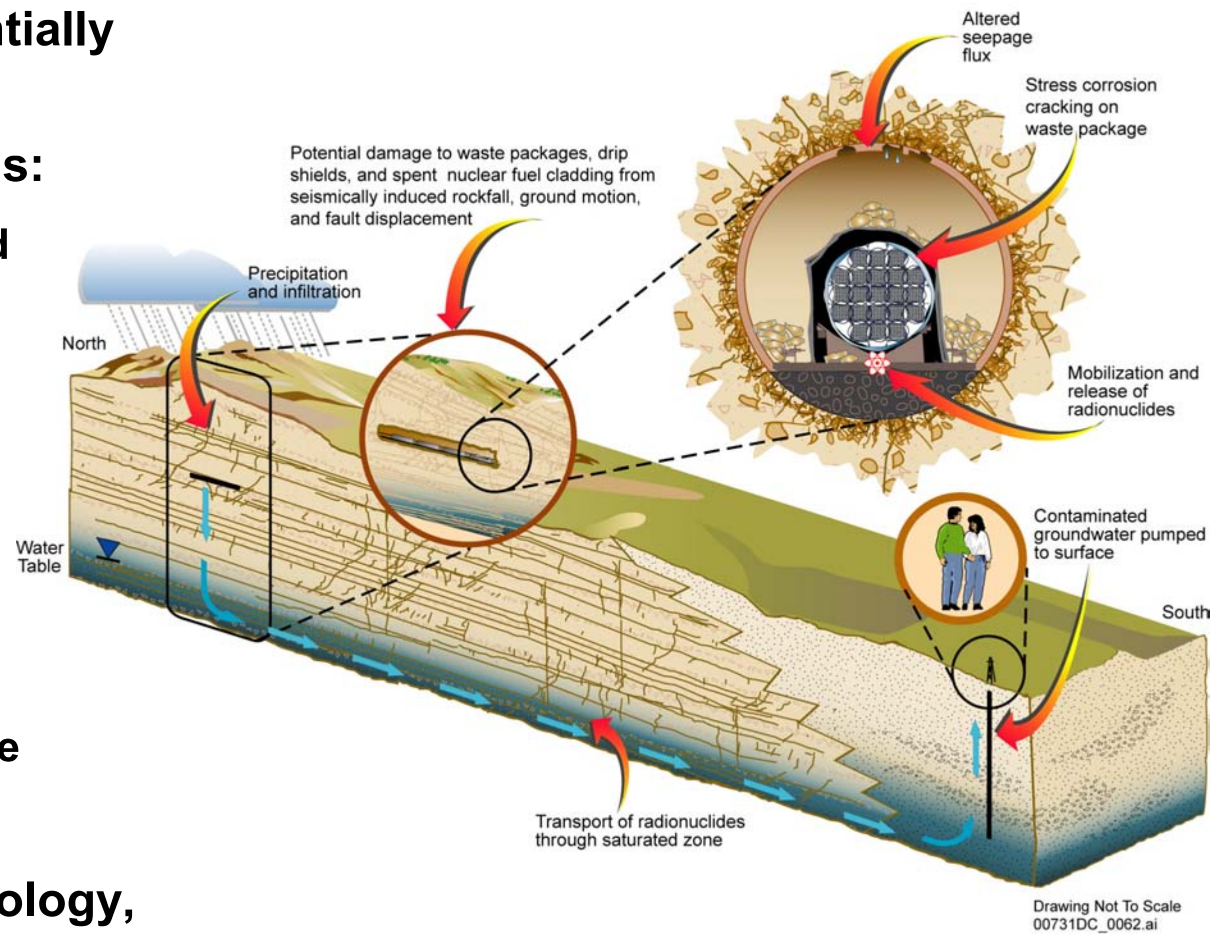
Model Assumptions

- The initial mechanical condition (or strength) of EBS components for each event is constant:
  - Previous damage does not affect the strength or configuration of the EBS components
- Total WP and DS damaged areas from multiple events is the sum of the damaged areas from the individual events
- Total rubble accumulation from multiple events is the sum of the rubble from the individual events
- Cladding damage is additive for subsequent events
- No spatial variability across WPs and DSs

Conceptual Model—Overview

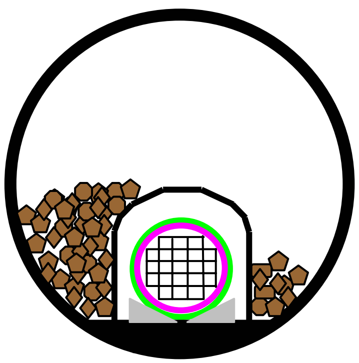
- **Source term—Ground motion time history from a potentially damaging seismic event**
- **EBS consequence models:**
  - **Rubble accumulation and loading in drift**
  - **DS damage or fragility (static and dynamic loading)**
  - **WP damage when DS is intact: cracking or rupture**
  - **WP damage after DS has failed: cracking or rupture**
  - **Cladding damage**
- **Changes to thermal hydrology, seepage, and transport**



Conceptual Model for EBS Evolution

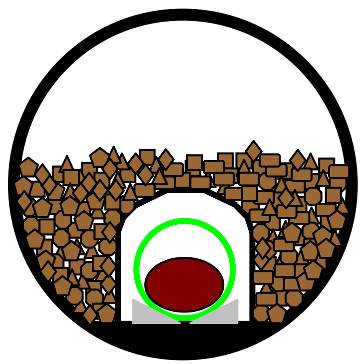
State 1

From closure until first breach of WP



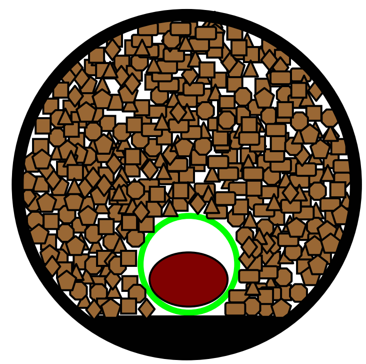
State 2

From first breach of WP until failure of DS plates



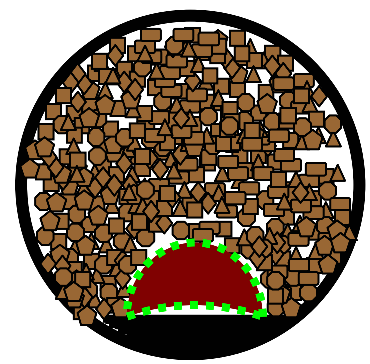
State 3

From failure of DS plates until WP collapse



State 4

After WP collapse



Kinematic analyses define damaged areas for a WP moving freely beneath the DS. Internals degrade after first breach.

DS Failure →

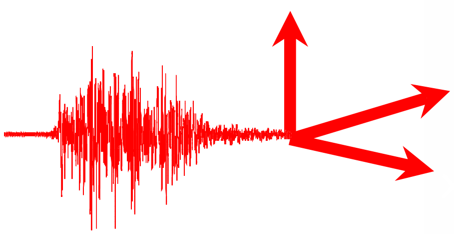
Analyses for a WP surrounded by rubble define damaged areas.

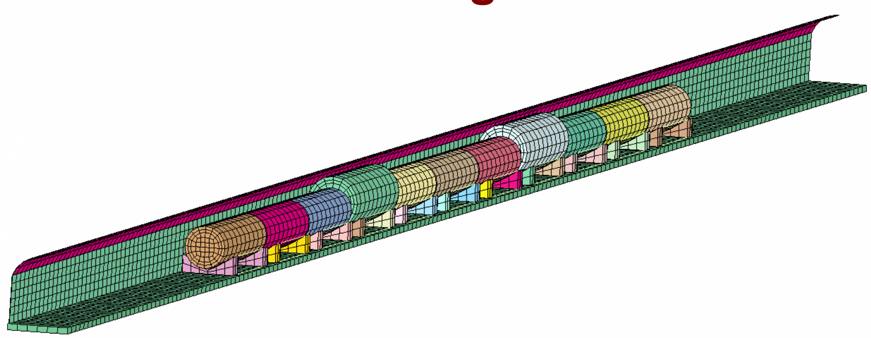
Time →

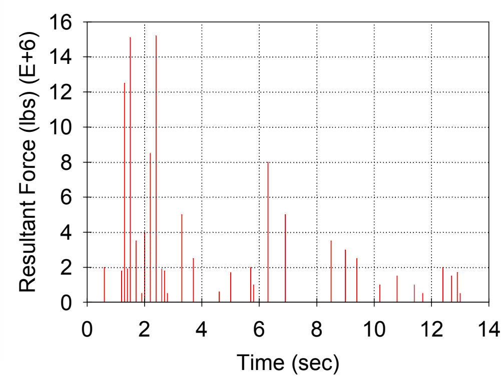
Technical Bases for Abstraction

- **Kinematic analyses, i.e., intact DS state**
  - **Planned 3D kinematic analyses will produce histories of <u>multiple</u> WP impacts for each of 17 ground motion time histories at various discrete horizontal PGV**
  - **Coarse discretization of package surface**

Schematic Ground Motion Time History → **Representative Drift Configuration** → **Ilustrative Impact Force History**



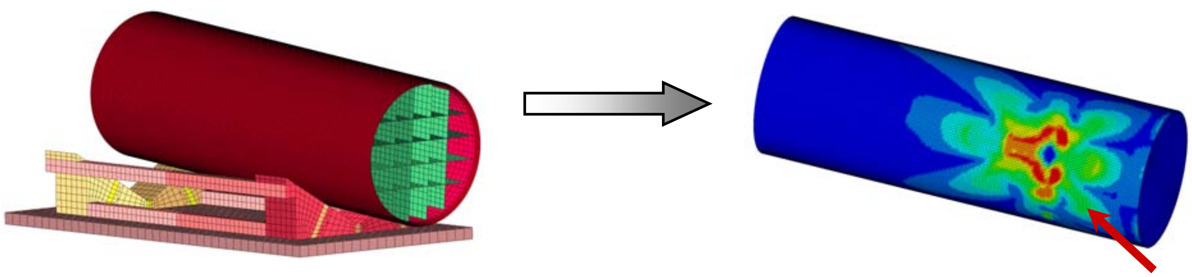




Input → **Analysis** → **Output**

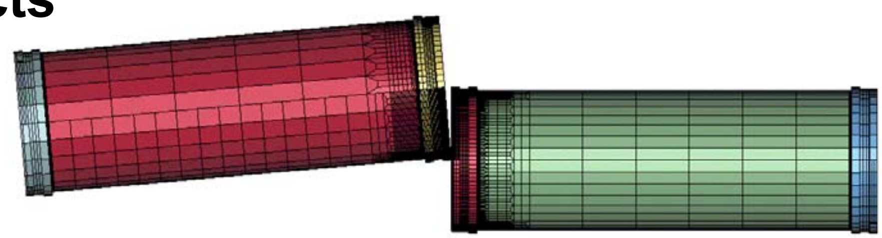
Technical Bases for Abstraction (continued)

- **Kinematic analyses, i.e., intact DS (continued)**
  - Develop catalogs for damage area and rupture condition for individual impacts in the impact force history—fine discretization of WP surface
    - Catalogs consider degraded states of WP and its internals
    - Catalogs consider various impact velocities and angles
  - WP-to-pallet impacts



Residual Stress

  - WP-to-WP impacts

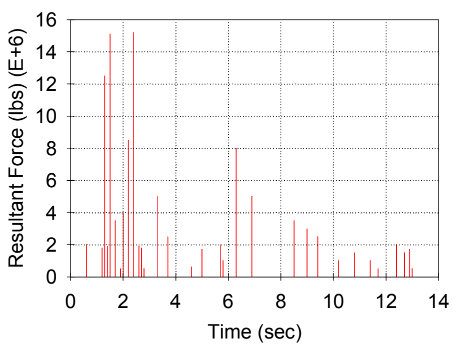


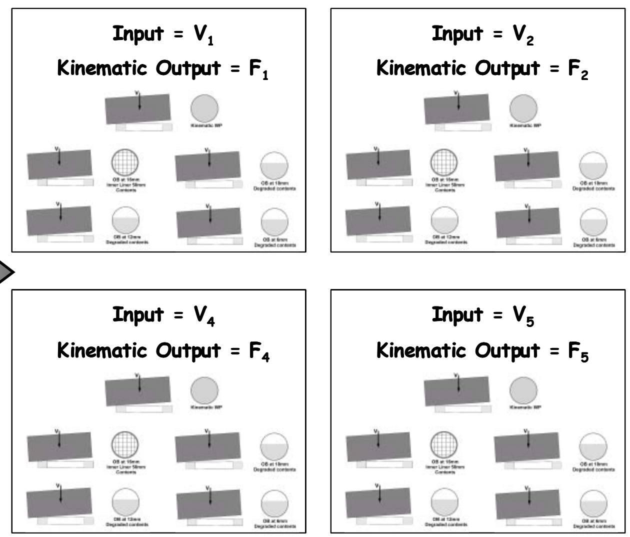
Technical Bases for Abstraction (continued)

- **Kinematic Analyses, i.e., intact DS state**
  - Combination of impact force history and damage catalogs generates potential WP damage (residual stress field and rupture condition) for a given seismic event

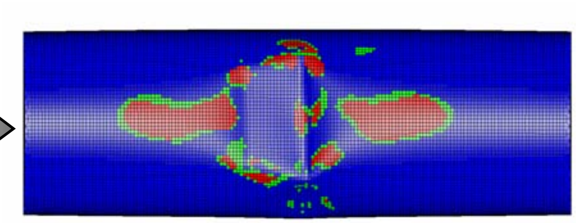
Damage Catalog

Illustrative Impact Force History





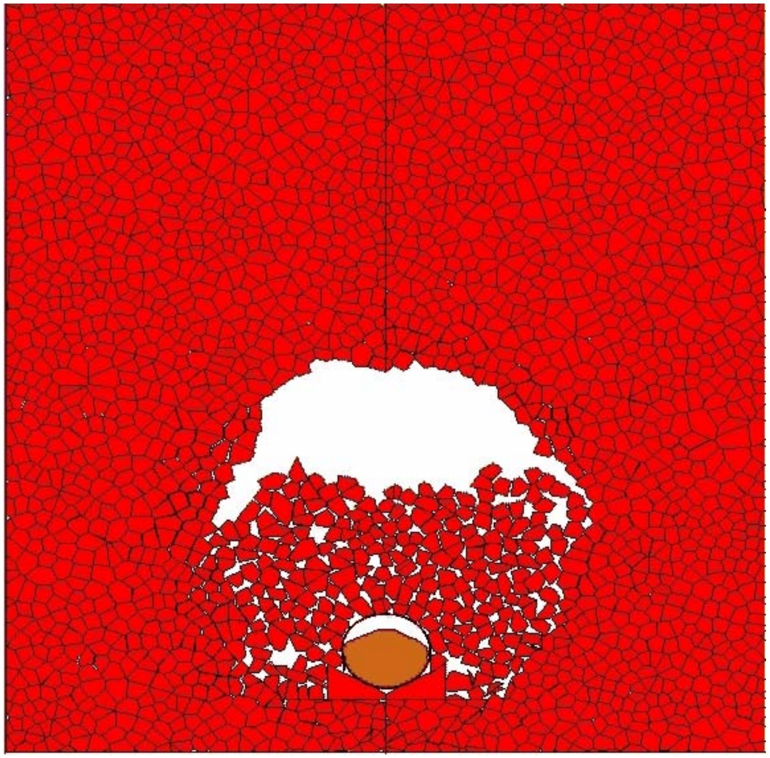
Residual Stress Field



  - Results define both the probability of rupture and the amount of damaged area as a function of the WP state and PGV level; damaged area is a network of stress corrosion cracks in the areas of residual stress above the uncertain threshold for damage (e.g., above 90% to 105% of yield stress)

Technical Bases for Abstraction (continued)

- **Damage for WP surrounded by rubble, i.e., failed DS**
  - 2D coupled structure/rockfall analyses for the lithophysal zones for 17 ground motions with random rock block patterns at various PGV levels
  - Calculations for degraded states of the outer Alloy 22 barrier and the WP internals
  - Finely discretized 2D dynamic calculations, so no need for catalogs; damage derived directly from simulations
  - Results define probability of rupture and damaged area as a function of the WP state and PGV level



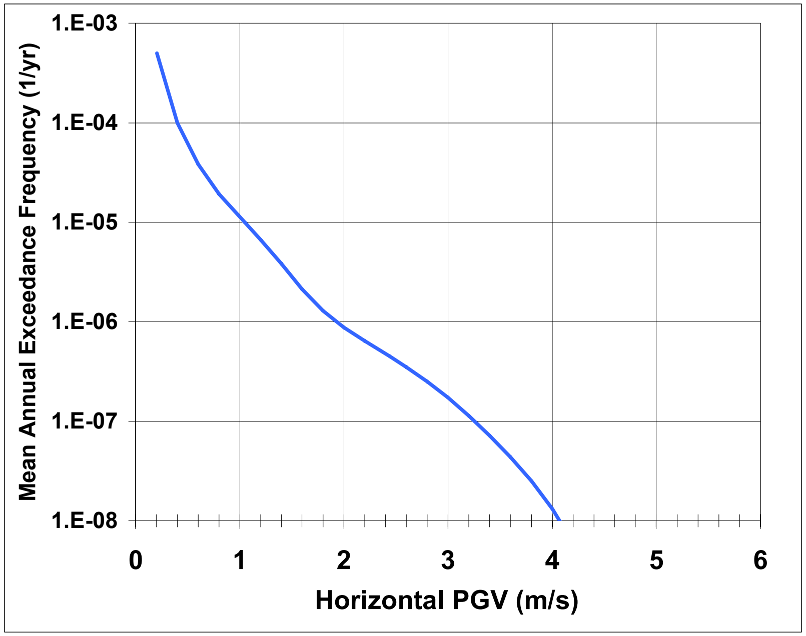
Treatment of Uncertainty and Variability

- **Treatment of uncertainties**
  - Aleatory uncertainty in the time of event, PGV of the event (seismic hazard curve), and ground motion time history for a given event
  - Epistemic uncertainty in the friction coefficient, Alloy 22 residual stress threshold to initiate stress corrosion cracking, collapsed rock block pattern, and the seismic hazard curve
- **Treatment of variabilities**
  - The potential for spatial variability of ground motions to produce spatially varying seismic damage has not been propagated into TSPA
    - All packages have equal damage
    - Long amplitude waves should have the same effect throughout the repository
  - Limited spatial variability is incorporated into TSPA for the WP corrosion rates
    - Through varying thermal-hydrologic environments in different percolation subregions

Implementation in TSPA

- **The timing of seismic events is based on a Poisson process; multiple events of varying magnitudes are possible and their timing is random**
- **The rate of the Poisson process is ($\lambda_{max} - \lambda_{min}$), where λ_{max} is the maximum annual exceedance frequency of a potentially damaging seismic event and λ_{min} is the minimum annual exceedance frequency**
  - **λ_{min} is 10^{-8}/yr for individual protection**
  - **λ_{min} is 10^{-5}/yr for groundwater protection**
- **Implementation based on hazard curve:**
  - **Sample number of events**
  - **Sample time of each event**
  - **Sample PGV for each event**

Seismic Hazard Curve



Implementation in TSPA (continued)

- **For a given seismic event, the TSPA Model determines:**
  - The amount of rubble accumulating in the drift caused by the event
  - Whether or not damage to the DSs occurs and the extent of the damage if it occurs
  - Whether or not damage to the WPs occurs and the extent of the damage if it occurs
  - Whether or not damage to the CSNF cladding occurs and the extent of the damage if it occurs
  - Event-specific uncertainty damage distributions are re-sampled for each seismic event

Implementation in TSPA
Drift Degradation, Clad Damage, and DS Damage

- **Rubble accumulation for each event is a function of PGV**
  - Rubble fill fraction is used to determine fragility of the DS
  - For multiple events, rubble area is accumulated until the drift is full
  - Rock type and strength are part of the abstraction in an average sense, but not considered to be spatially variable
- **DS fragility**
  - Probability of DS failure is a function of the DS thickness (from the general corrosion model) and the amount of rubble accumulated in the drift
  - If DSs fail, all DSs fail completely as a barrier to flow
- **Cladding damage is a function of PGV**
  - CSNF Zircaloy cladding damage can occur whether or not

Implementation in TSPA
WP Damage

- **There are six possible WP damage states and associated abstractions:**
  1. **No damage**
  2. **SCC of WP under an intact DS with WP internals intact**
  3. **SCC of WP under an intact DS with WP internals degraded**
  4. **WP rupture under an intact DS with WP internals degraded**
  5. **SCC of WP under a failed DS with WP internals degraded**
  6. **WP rupture under a failed DS with WP internals degraded**

All six abstractions are evaluated at the time of each event

Implementation in TSPA

WP Damage (continued)

- **WP and DS degradation submodel will provide the average remaining WP thickness for each percolation subregion and the average remaining DS plate thickness**
  - **Two separate calls of WAPDEG run at the beginning of each realization to determine average thickness and first corrosion breach failure fraction**
  - **DS general corrosion rates for corrosion on the top and bottom sides of the DS are used to calculate the remaining thickness of the DS**
- **Fission products (e.g., Tc) are expected to be released through cracks (via diffusion), whereas substantial actinide (e.g., Pu) releases (via advection) may require plastic rupture or general corrosion patches**

Implementation in TSPA
Other Processes

- **Seepage**
  - Drift collapse in the lithophysal zones, for seepage purposes, occurs at a time to be determined by the rubble abstraction
  - Collapsed-drift seepage fractions to be used both before and after the first event
  - Intact drift seepage flow rates to be used for the lithophysal zones before first collapse event and collapsed drift seepage flow rates to be used after that time
  - Intact drift seepage flow rate in the nonlithophysal zones
- **EBS Environment**
  - WP temperature and WP relative humidity are changed after the drift fills with rubble
- **EBS Flow and Transport**
  - The WP damage area fraction (sum of seismic damage and corrosion damage) is an input to the diffusive transport and the water flux calculations of the EBS Transport submodel

Anticipated Changes Since TSPA-SR

- **Inclusion of the seismic scenario class**
- **Detailed damage analyses developed for degraded states of the EBS components**
  - **Intact DS analyses**
  - **Failed DS analyses**
- **Conservatism removed from the upper end of the seismic hazard curve, but lower PGVs considered for their potential consequences**
- **Seismic consequence abstractions for TAD package (25-mm thick, with shield plug) are underway, including kinematics, damage catalogs, and WP surrounded by rubble**
- **Because of its probability over long time frames, the seismic scenario class (with associated nominal degradation processes) may dominate repository performance, in comparison to the igneous and human intrusion scenario classes (the purely nominal scenario class will likely have a small probability)**

Igneous Scenarios

Presented to:
DOE/NRC Technical Exchange on Total System Performance Assessment (TSPA) for Yucca Mountain

Presented by:
Greg Valentine
Los Alamos National Laboratory

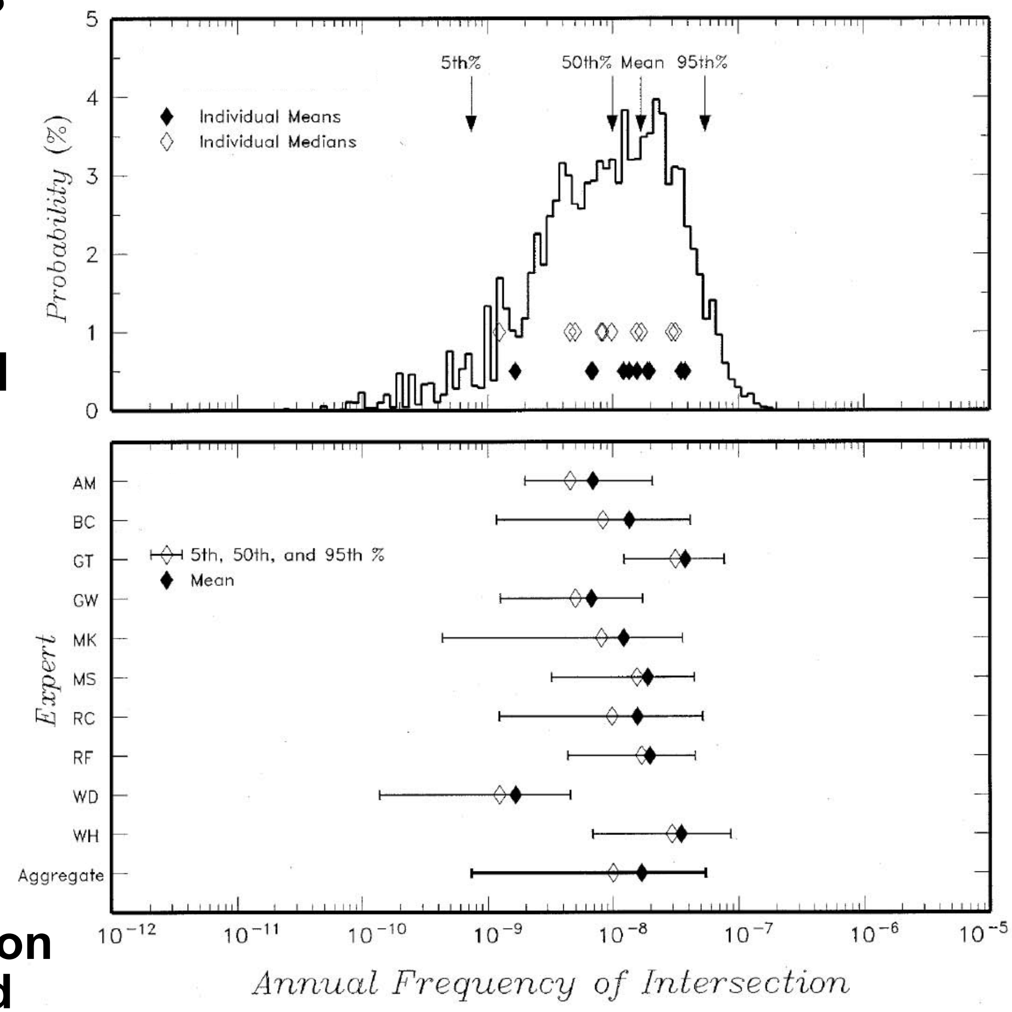
October 24, 2006
Las Vegas, Nevada

Presentation Outline

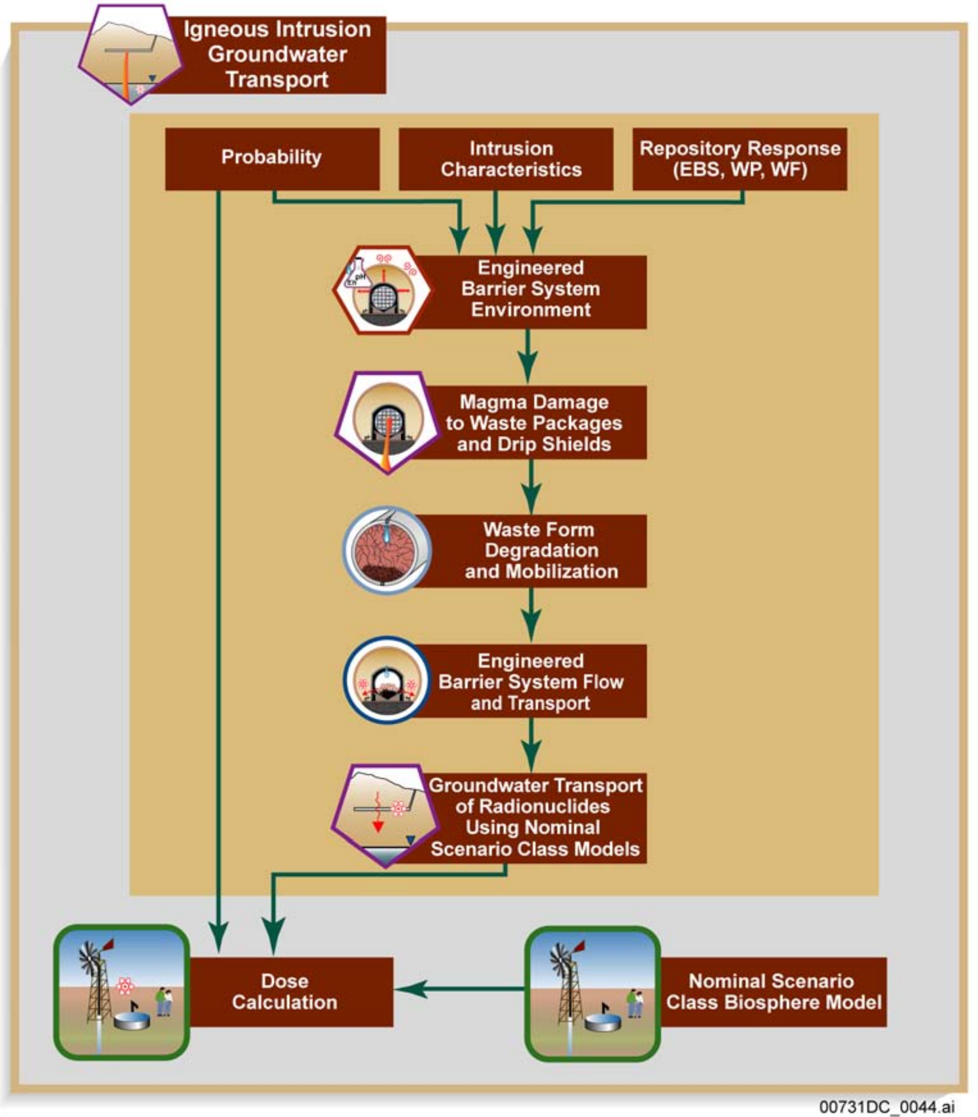
- Definition of igneous scenario class
- Identification and linkage of abstractions
- Abstraction
  - Description of igneous scenario class
  - Input, output, and basis for model confidence
  - Assumptions
  - Conceptual model
  - Technical bases for abstraction and references
  - Treatment of uncertainty and variability
  - Implementation in TSPA model
- Anticipated changes since TSPA for site recommendation (SR)

Definition of Igneous Scenario Class

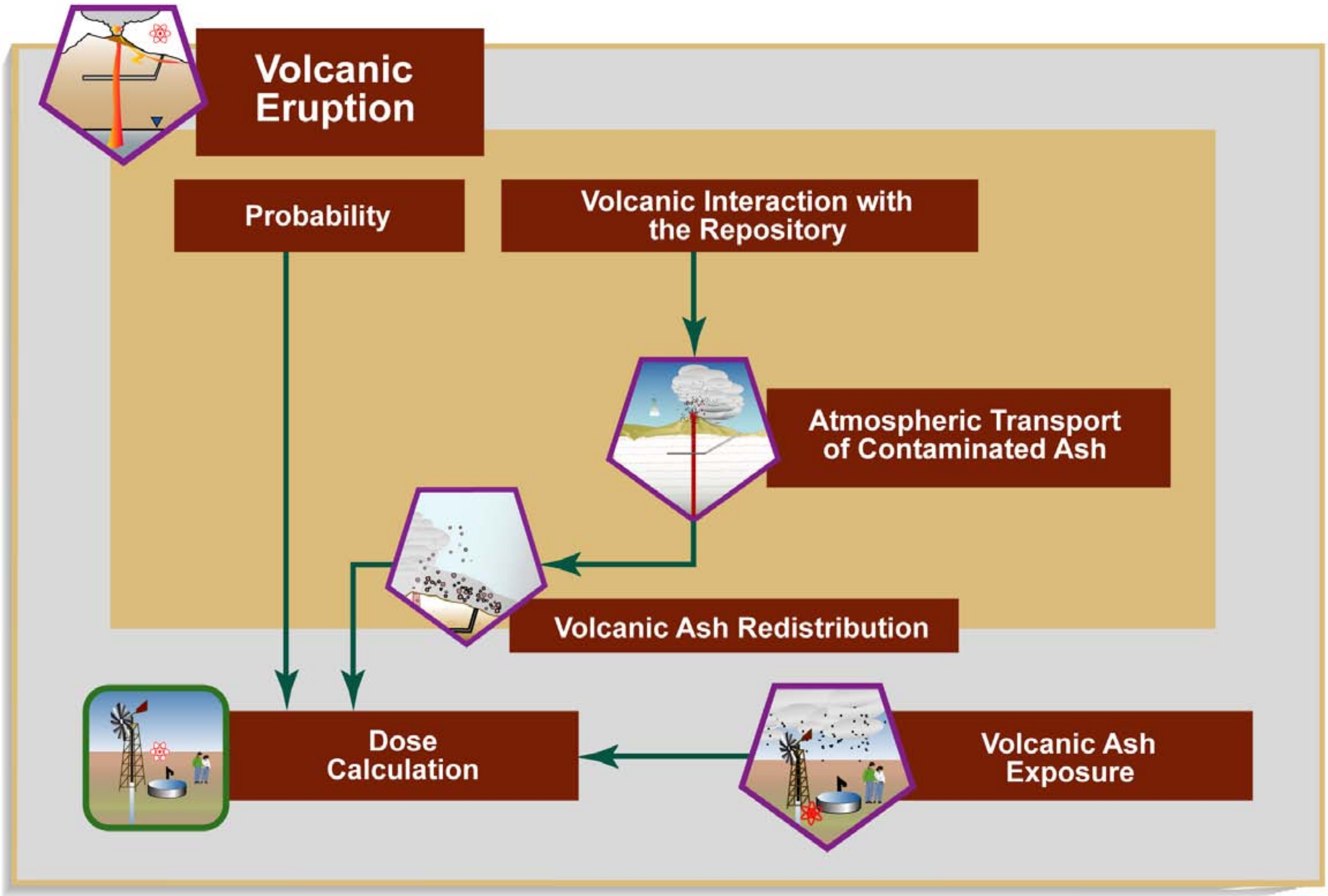
- **The igneous scenario class is the set of all possible futures that contain one or more igneous events**
- **The intersection of a volcanic dike(s) with the repository causes an intrusive event and probably an eruptive event**
- **The probability of an igneous event intersecting repository is determined as follows:**
  - **Based upon geologic record, geophysics, and geochronology of basaltic volcanoes in region**
  - **Determined by expert elicitation (Probabilistic Volcanic Hazard Analysis, 1996)**



Identification and Linkages of Abstractions—Igneous Intrusion



Identification and Linkages of Abstractions—Volcanic Eruption



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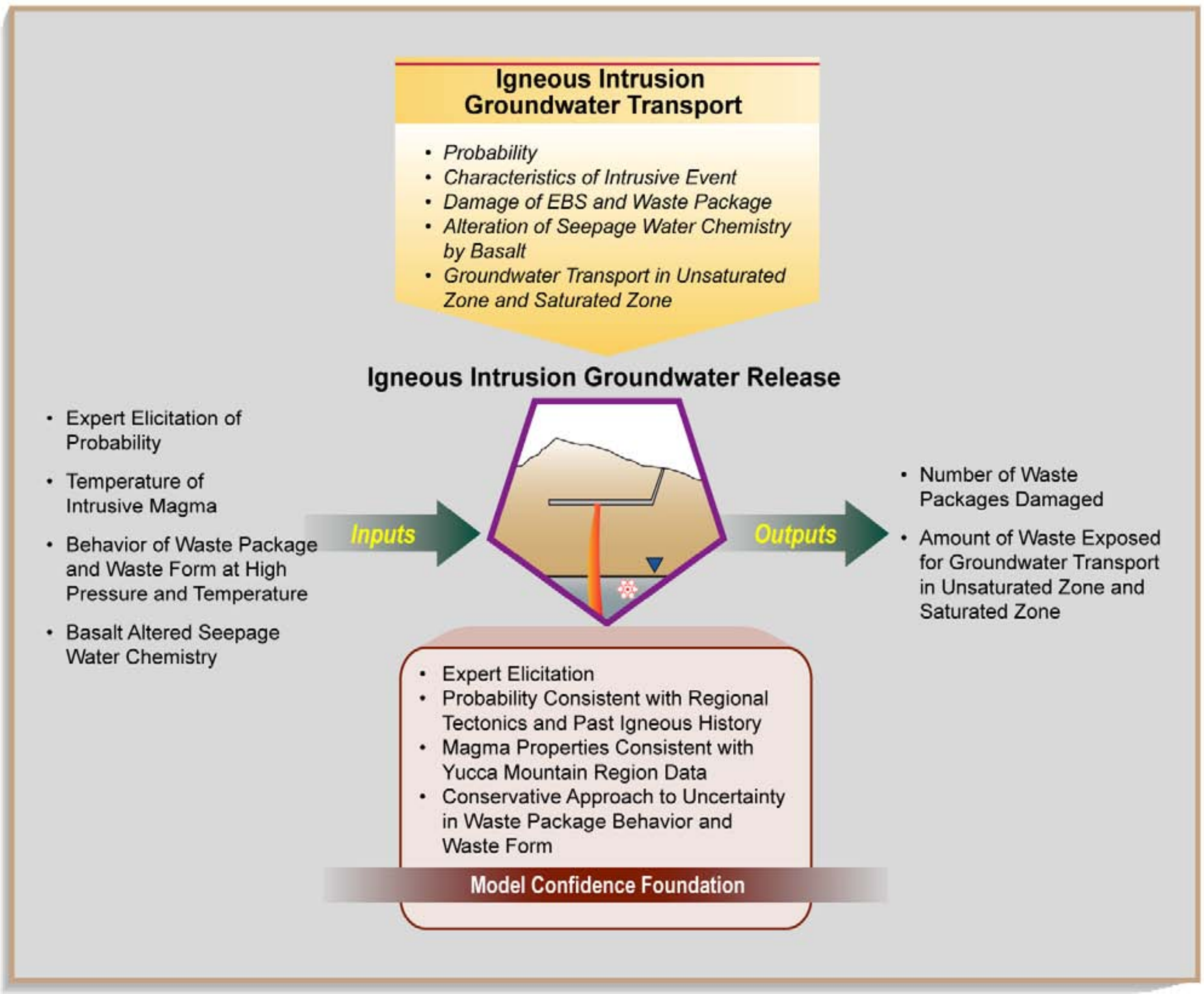
Inputs, Outputs, Basis for Model Confidence—Igneous Intrusion



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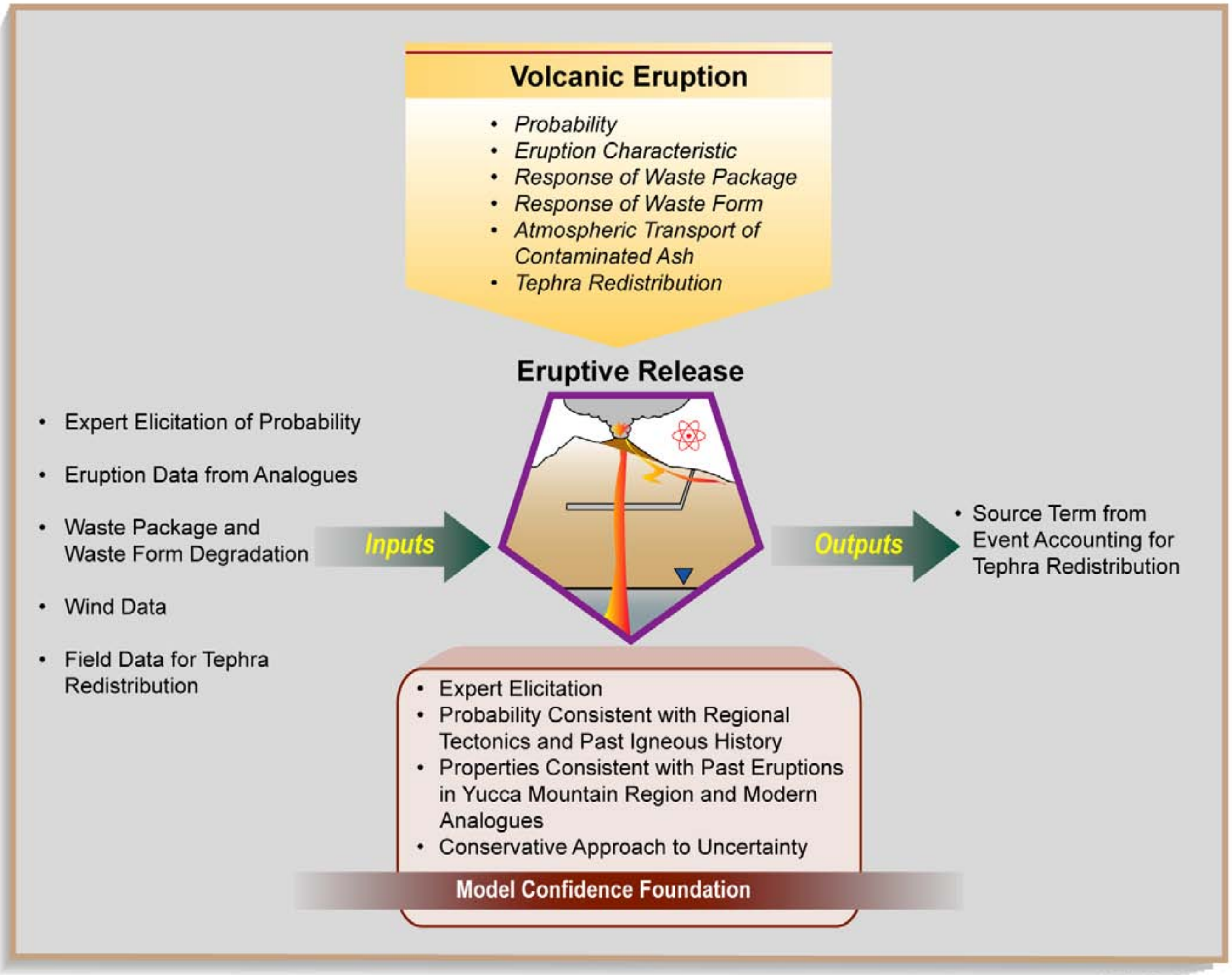
Inputs, Outputs, Basis for Model Confidence—Volcanic Eruption



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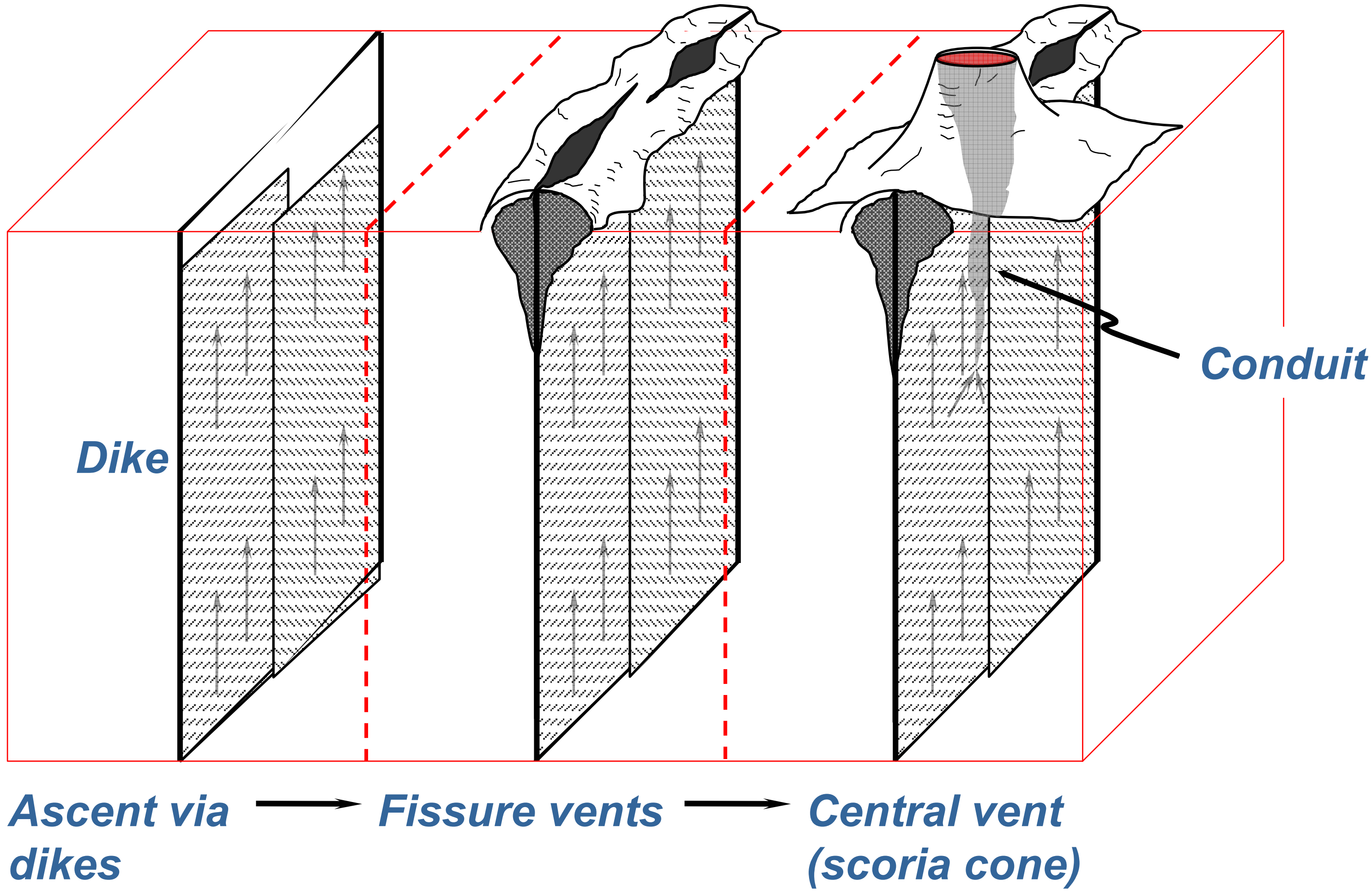
Model Assumptions—Igneous Intrusion

- Waste packages, drip shields, cladding (commercial spent nuclear fuel), and waste forms are rapidly and completely degraded in the event of an igneous intrusion
- Invert is not structurally or chemically impacted by an igneous intrusion
- Seepage flux is assumed to be re-established after magma cools to below boiling
- Fractures in cooled basalt are assumed to be consistent with the tuff host-rock fractures; basalt does not impede seepage flux

Model Assumptions—Volcanic Eruption

- Volcanic eruptions are violent Strombolian for a fraction of the duration of the eruptive phase, based upon analogue data
- Waste particles are incorporated into ash particles for transport
- Data characterizing variability in wind speed and wind direction under present climatic conditions are assumed to be acceptable to characterize future wind conditions
- Wind speed and direction are assumed to be constant during violent Strombolian event
- The mass of ash/waste that is redistributed from upstream is assumed to be deposited in the area of the reasonably maximally exposed individual (RMEI) by post-eruptive surficial processes

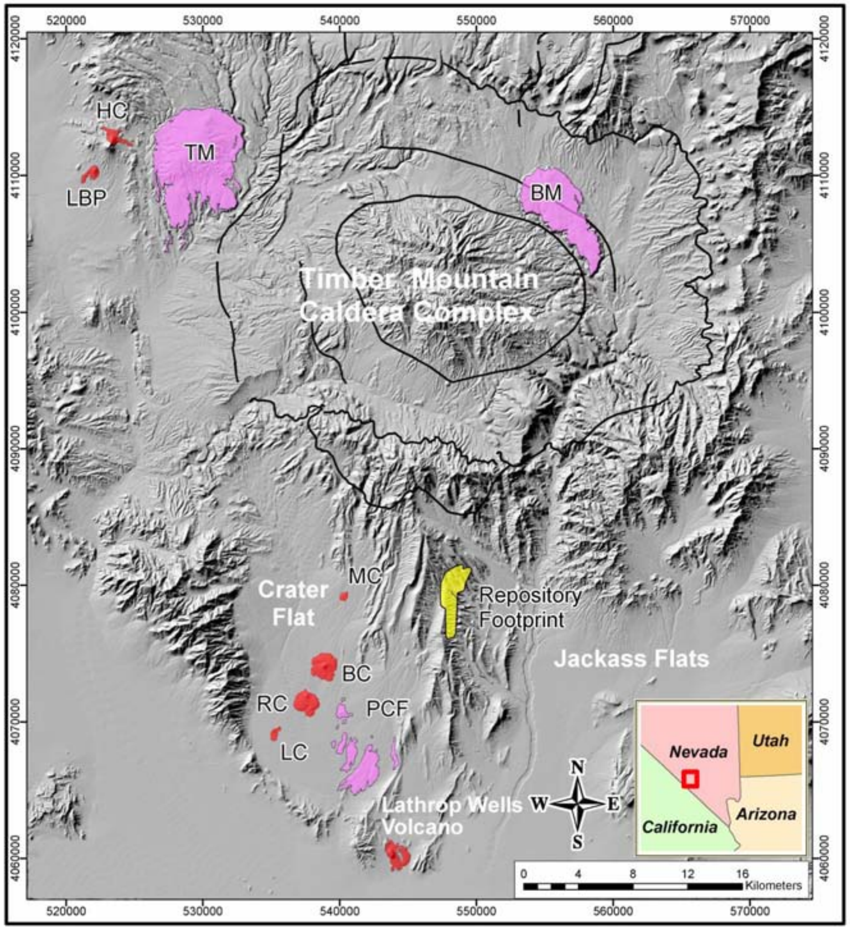
Conceptual Model for Igneous Activity



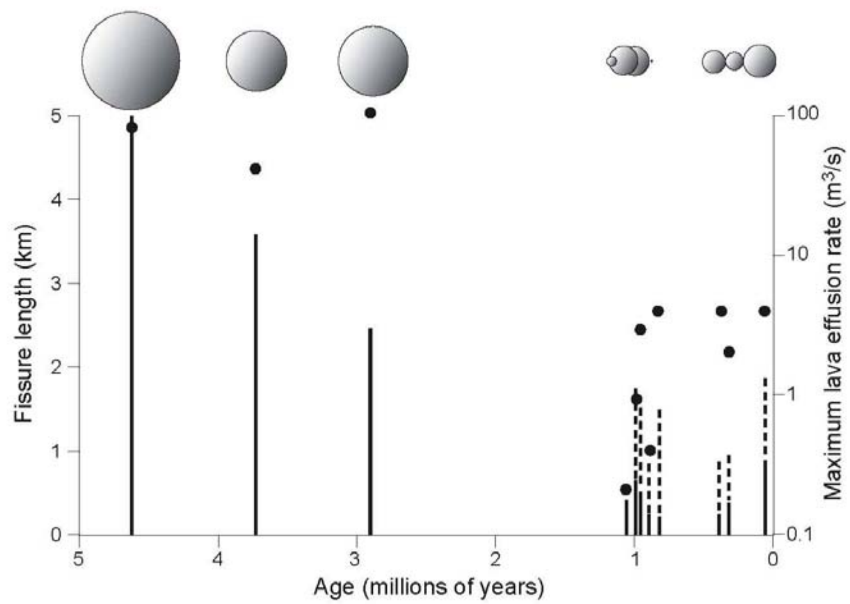
Technical Bases for Abstraction

Based upon observations in the region

Basaltic volcanoes < 5 Myr old



Volumes, lengths of fissures, and mass flux rates generally declining with time

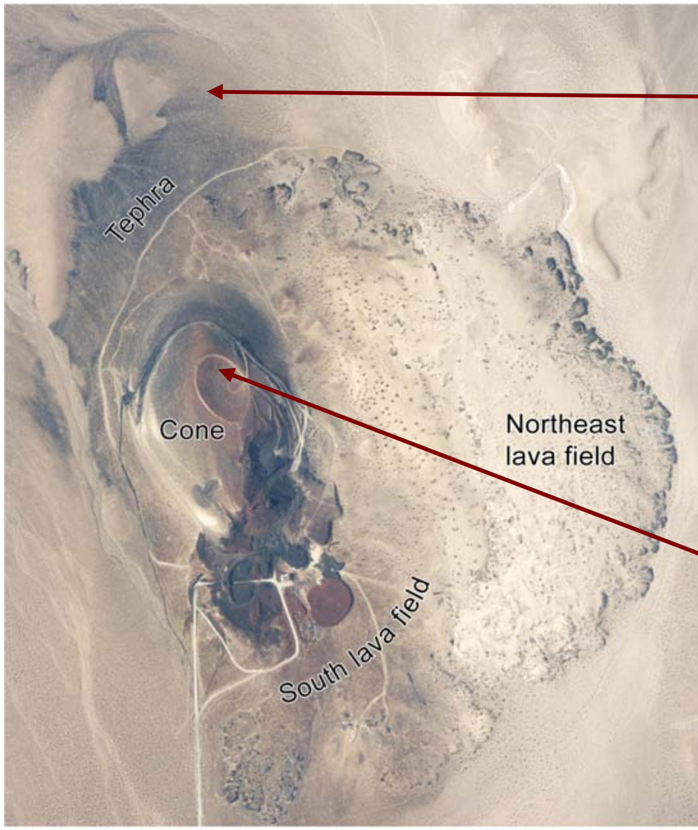


- Bars represent fissue lengths
- Points represent estimated lava effusion rates
- Circles represent erupted volume (cubed root)
- Data for volcano-exposed on surface only

Technical Bases for Abstraction (continued)

Based upon observations in the region and comparison with historic eruptions around the world

Lathrop Wells Volcano



- 80,000 yrs old
- 0.12 km^3 total volume
- 0.07 km^3 tephra fall
- 0.03 km^3 lavas
- 0.02 km^3 cone

Types of Activity

Mt. Etna (Italy), 24 July 2001

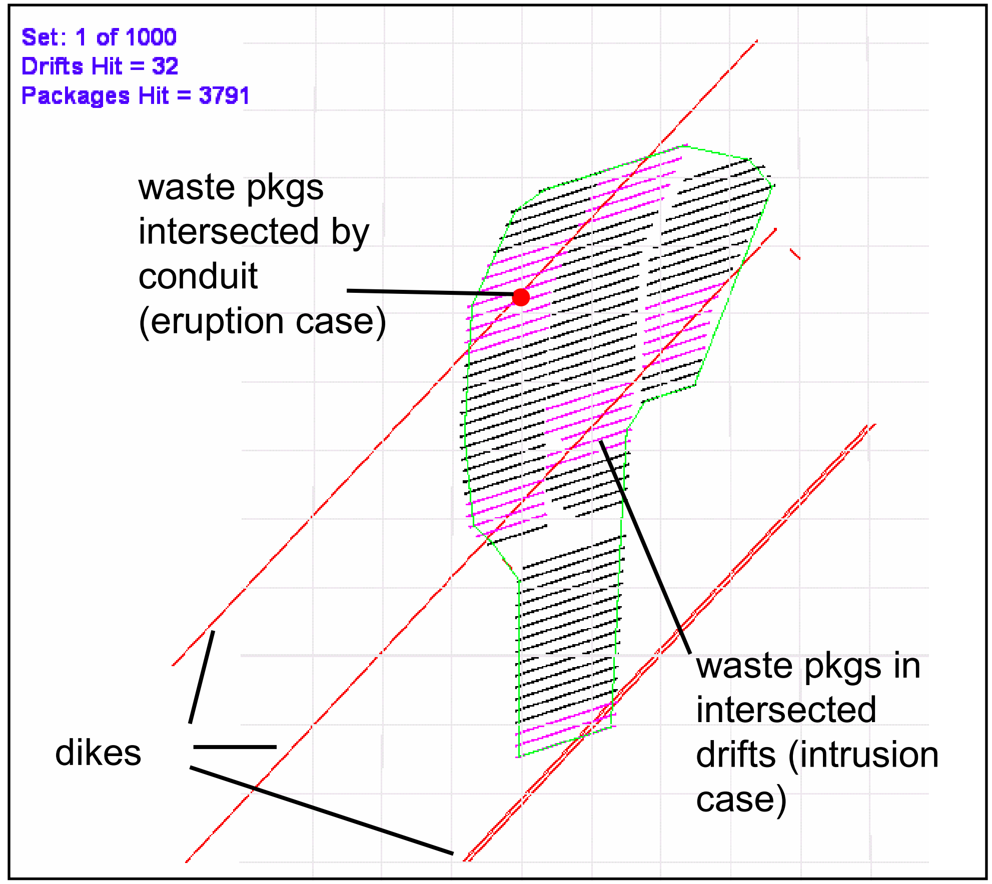
Downwind dispersal of tephra from a buoyant plume (violent Strombolian)

Stromboli volcano (Italy), date unknown

Ballistic ejecta build the cone (Strombolian)

Implementation of Conceptual Model in Abstraction

- **Waste packages hit**
  - **Inputs for intrusion scenario modeling case**
    - **Number of dikes in an event**
    - **Dike orientation**
    - **Dike length**
    - **Dike spacing**
  - **Additional inputs for eruption scenario modeling case**
    - **Conduit diameter**
    - **Number of conduits**



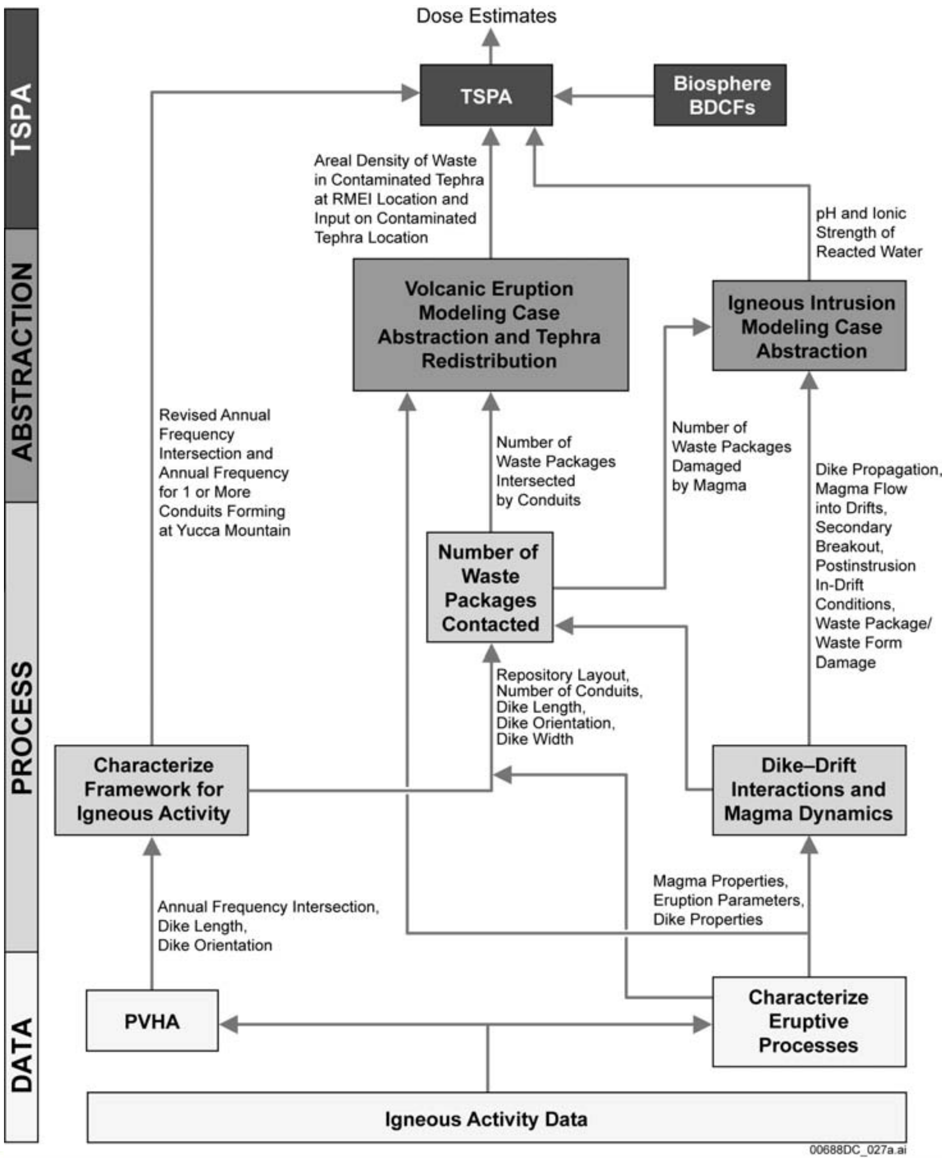
Parameterization and Treatment of Uncertainty—Intrusion Case

- Event probability
  - Parameterized based upon expert elicitation
  - Event probability treated as a probability distribution function (PDF) to capture uncertainty
- Parameters based upon analog data
  - Field data for each parameter forms the basis for a PDF that captures uncertainty
  - Uncertainty is propagated by Monte Carlo sampling of PDFs of each parameter (e.g., in waste-packages-hit analysis)
- Intrusion modeling case
  - Post-emplacement magma cooling and gas flow parameter distributions
  - pH and ionic strength of waters in contact with basalt captured by analog data (literature) and geochemical modeling and are presented to TSPA as ranges of values
  - Revised distribution for number of waste packages hit

Parameterization and Treatment of Uncertainty—Eruption Case

- **Eruption modeling case**
  - 1000 Ashplume model runs
  - Each model run samples PDFs of eruption plume height (based upon analog data) and wind field (meteorological data) to estimate tephra depth and waste areal density at each grid point
  - Revised distribution of number of waste packages hit
  - Tephra redistribution calculated for each realization of Ashplume

Implementation in TSPA



Focus on upper half of diagram

- **Intrusion modeling case**
  - Number of waste packages damaged by contact with magma (waste-packages-hit analysis)
  - pH and ionic strength of groundwater that has reacted with cooled basalt (dike-drift interactions)
- **Eruption modeling case**
  - Number of waste packages intersected by conduits (waste-packages-hit analysis)
  - Areal density of waste in contaminated tephra (ashplume model)
  - Concentration of contaminated tephra in channel sediments following redistribution (FAR model)

Implementation in TSPA (continued)

- **Intrusion modeling case**
  - Waste packages contacted by magma fail and expose waste to interactions with seepage waters after magma cools
  - Aqueous geochemistry (pH and ionic strength) in basalt-filled drift determines radionuclide solubility
  - Nominal case flow fields for unsaturated and saturated zones are re-established after igneous event for transport to RMEI

Implementation in TSPA (continued)

- **Eruption modeling case**
  - Waste packages within eruptive conduit assumed to provide no protection for waste
  - Exposed waste form breaks down to sub-mm sizes, incorporated onto/into volcanic particles
  - Tephra plume rises to altitude proportional to mass flux
  - Tephra dispersed downwind by diffusion-advection and fall out according to particle size (ASHPLUME)
  - Surface transport of contaminated tephra to RMEI modeled with landscape/fluvial transport code (FAR)
    - Contaminated tephra diluted by mixing process as it is transported to the location of the RMEI
    - Dose calculated based on concentration of radionuclides in tephra at the surface

Summary of Anticipated Changes Since TSPA-SR

- **Updated models for magma flow in drifts and magma cooling**
- **Updated analyses for number of waste packages hit**
- **New parameter values based upon analog data**
  - Dike length, width, orientation, and number of dikes
  - Conduit size, and number and locations of conduits
  - Fraction of eruptive material in tephra, cone, and lavas
- **New parameter values for pH and ionic strength of waters in contact with basalt**
- **New model for tephra redistribution by surficial processes**

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

www.ocrwm.doe.gov

Unsaturated Zone Flow

Presented to:
DOE/NRC Technical Exchange on Total System Performance Assessment (TSPA) for Yucca Mountain

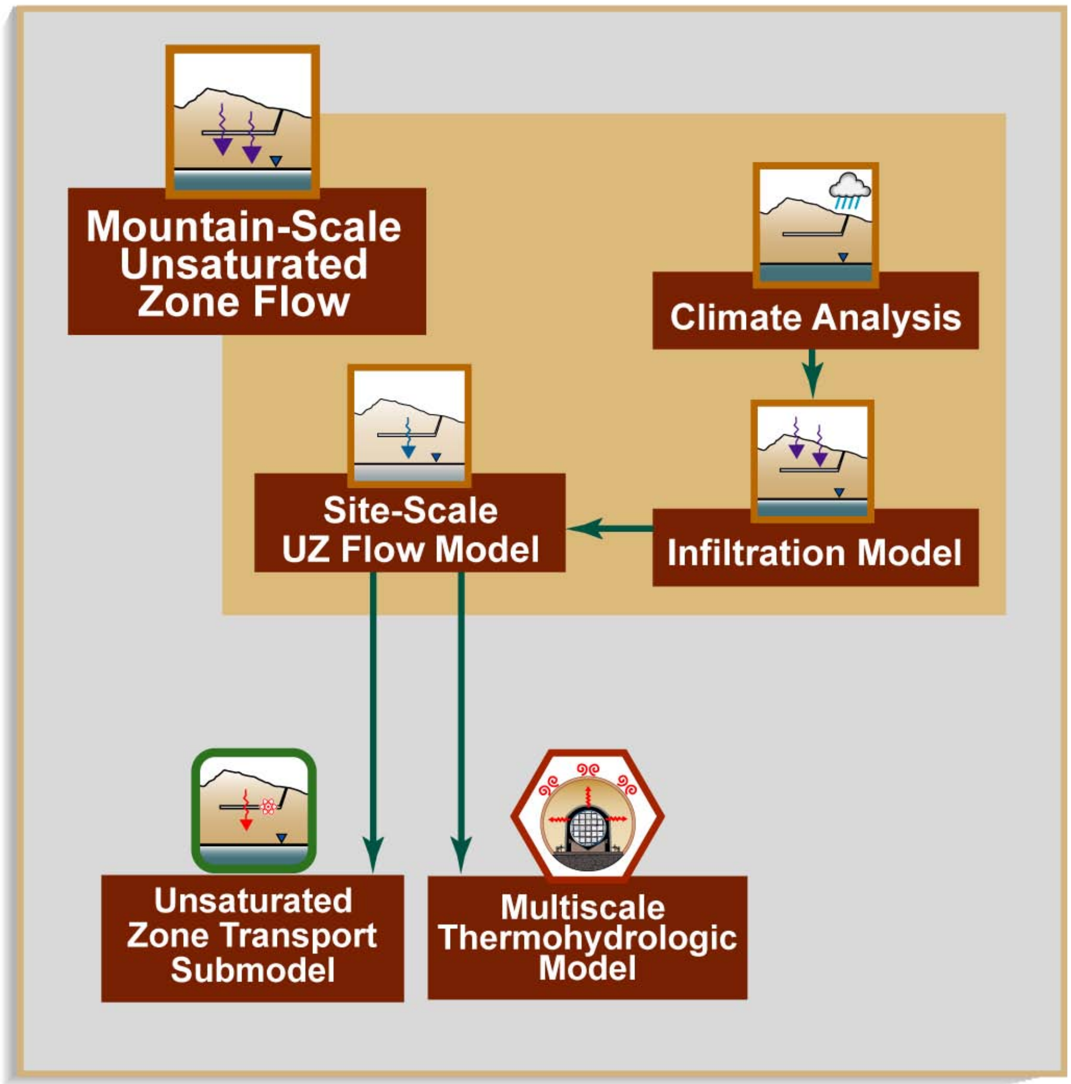
Presented by:
Clifford K. Ho
Sandia National Laboratories

October 25, 2006
Las Vegas, Nevada

Presentation Outline

- **Identification and linkage of abstractions**
- **Abstraction**
  - **Objectives**
  - **Input, output, and basis for model confidence**
  - **Assumptions**
  - **Conceptual model**
  - **Treatment of uncertainty and variability**
  - **Technical bases for abstraction and references**
  - **Implementation in TSPA model**
- **Anticipated changes since TSPA for site recommendation (SR)**

Identification and Linkages of Abstractions



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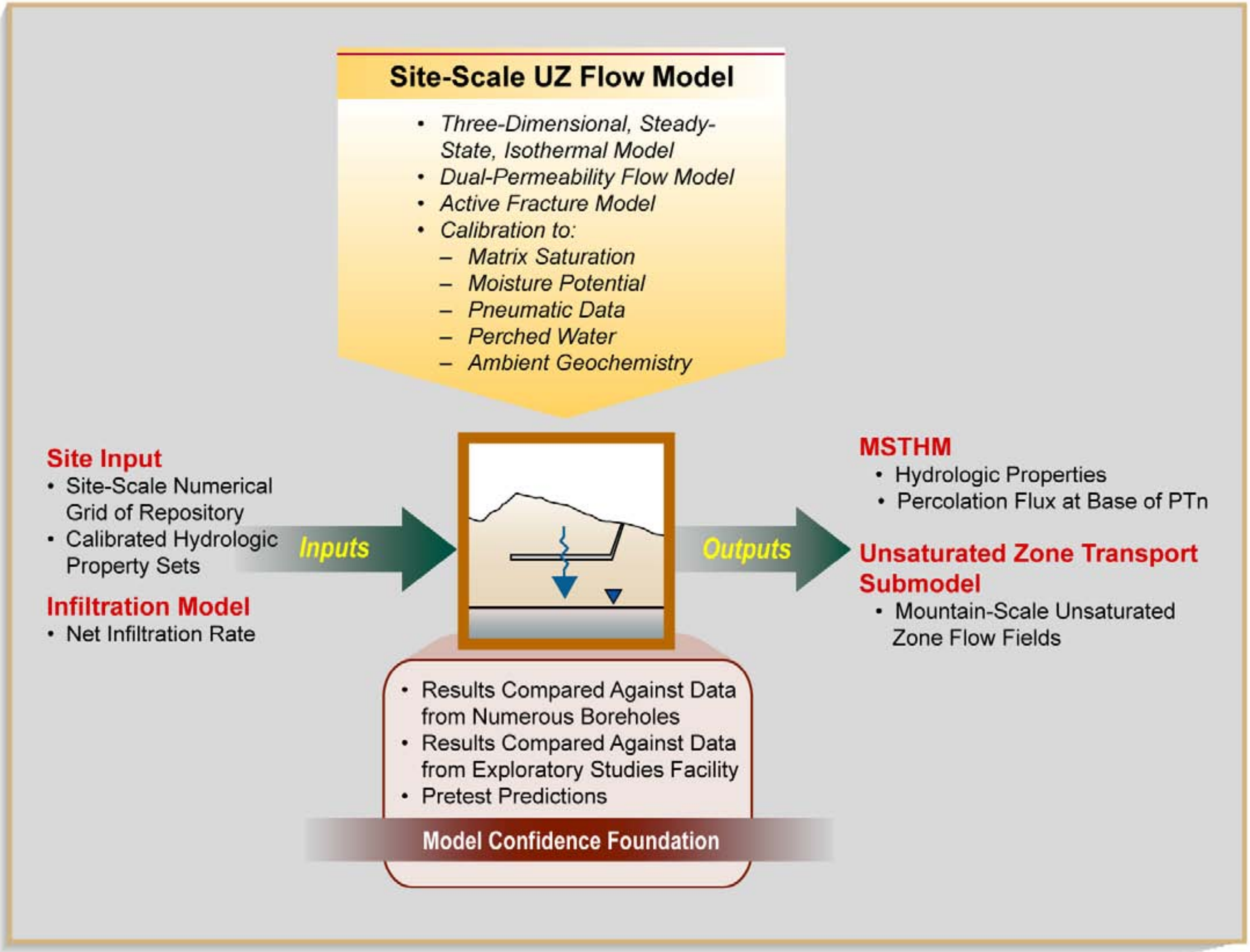
Objective of Unsaturated Zone Flow Abstraction

- **Provides flow fields for use in estimating seepage into the repository and migration of radionuclides through the unsaturated zone (UZ) below the repository**

- **Flow fields are abstracted using the 3D site-scale UZ flow process model with input parameters based on the calibrated property sets**

Inputs, Outputs, Basis for Model Confidence



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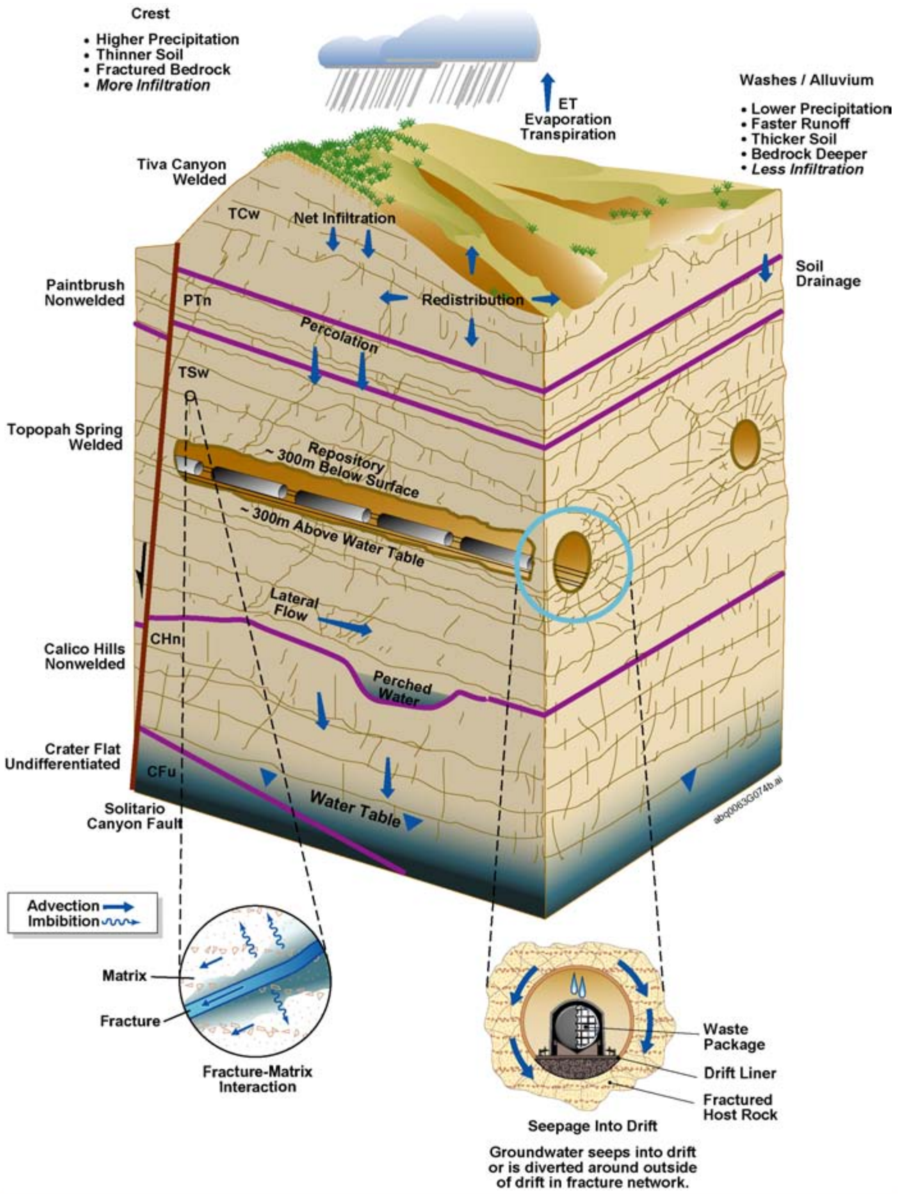
MSTHM = multiscale thermohydrologic model

Model Assumptions

- **Water percolation in the unsaturated zone is adequately represented by steady-state conditions**
- **Climate changes affect the flow fields instantaneously**
- **No evaporation of water occurs in the Tiva Canyon welded (TCw) unit**
- **Faults**
  - **Either vertical or inclined 30-m-wide zones**
  - **Crosses the entire UZ thickness from the surface to the water table**
- **Average surface temperature**
  - **Linear function of surface elevation**
  - **Used only for ambient model validation, i.e., this**

UZ Flow Conceptual Model



- **3D, steady-state flow model**
- **Dual-permeability model of fracture/matrix flow and interaction**

Treatment of Uncertainty and Variability

- **Treatment of uncertainties**
  - **Upper boundary condition (infiltration maps)**
    - **Propagates uncertainty in precipitation and surface hydrologic parameters for different climate states**
  - **Subsurface hydrologic properties**
    - **Calibrated to UZ site data over a set of discrete infiltration maps representing the range of infiltration uncertainty**
- **Treatment of variability**
  - **Infiltration maps are spatially variable**
  - **3D UZ flow model has spatial variability in features and processes**
    - **Stratigraphy, faults, hydrologic properties (inter-layer), perched water, lateral flow**

Technical Bases for Abstraction

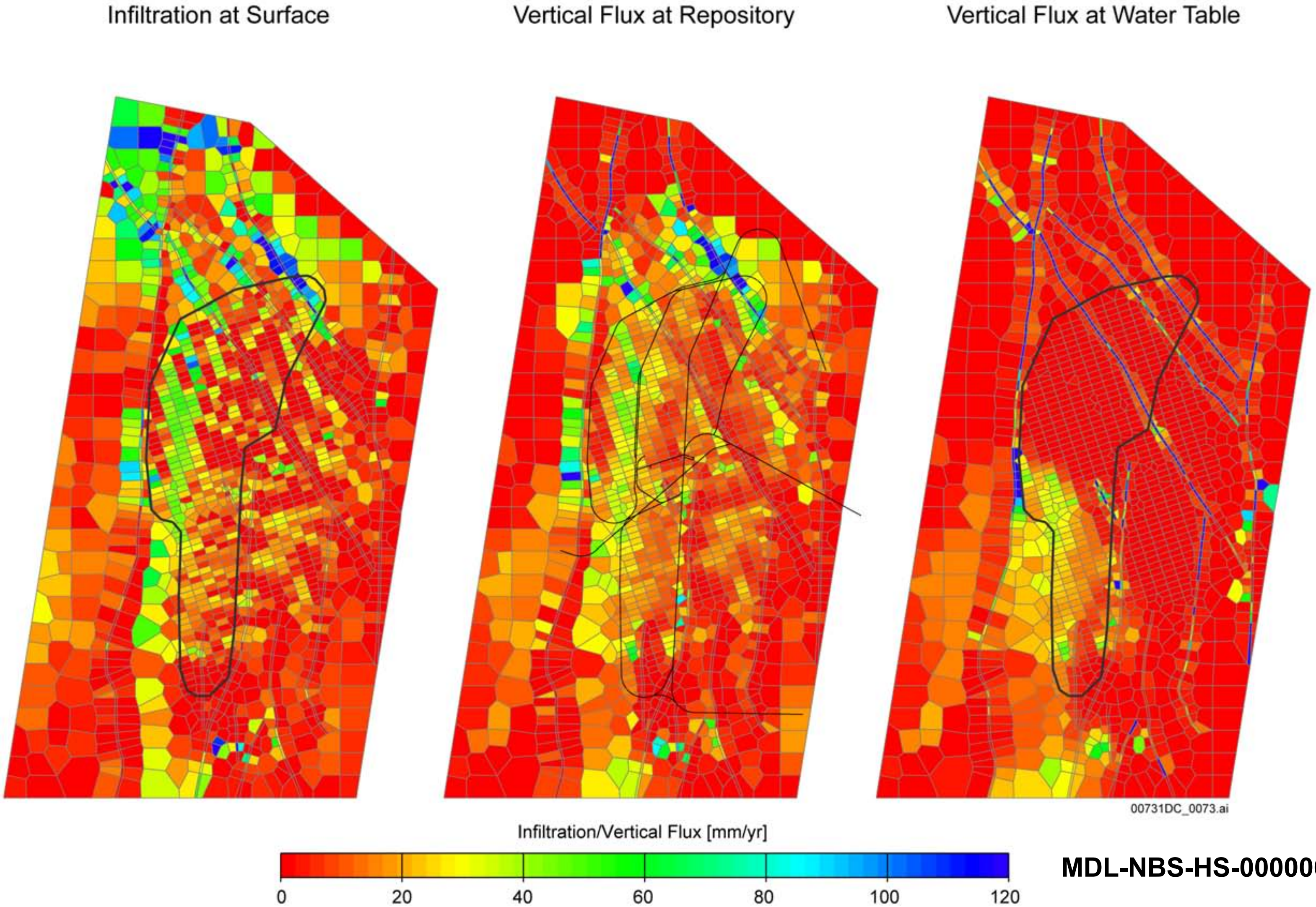
- **Calibration**
  - Hydrologic properties calibrated to moisture content, water potential, pneumatic data, chloride data, perched water
- **Validation**
  - 3D model is validated against site data (temperature, chloride, water potential, perched water, strontium, pneumatic, calcite)
- **References**
  - UZ Flow Models and Submodels, MDL-NBS-HS-000006 REV 02
  - Calibrated Properties Model, MDL-NBS-HS-000003 REV 02
  - Future Climate Analysis, ANL-NBS-GS-000008 REV 01
  - Simulation of Net Infiltration for Present and Potential Future Climates, MDL-NBS-HS-000023 REV 00
  - Analysis of Infiltration Uncertainty, ANL-NBS-HS-000027 REV 01

UZ Flow—Implementation

- Steady-state UZ flow fields are generated
  - Climate
    - Present, monsoon, glacial transition
  - Infiltration maps
    - Maps will be selected to represent range of infiltration uncertainty for each climate
  - Weights will be assigned to resulting flow fields
- Resulting flow fields used directly by TSPA
  - Flow fields formatted for Finite Element Heat and Mass (FEHM) particle tracking

Implementation—Simulated Percolation Flux

Mean, Glacial Transition



MDL-NBS-HS-000006 REV 02

Anticipated Changes Since TSPA-SR

- **Model validation cases have been developed**
  - Carbon-14 data, Alcove 8–Niche 3 test results, ambient thermal data, chloride data, calcite deposition data, and strontium chemical and isotopic data
- **Stronger basis for models**
  - Damping of flow transients/spatial homogenization of flow in the Paintbrush Tuff nonwelded (PTn) unit
  - Evaluation of fast flow and transport associated with chlorine-36 data
  - Justification of parameter sets used for modeling future climates
  - Evaluation of flow and transport sensitivity to hydrologic parameters
- **Broader range of infiltration maps**
  - Based on enhanced treatment of uncertainties in input parameters
- **Use geochemical and temperature data to help constrain weights for flow fields**

Engineered Barrier System (EBS) Environment—Thermal Hydrology and In-Drift Chemistry

Presented to:
DOE/NRC Technical Exchange on Total System Performance Assessment (TSPA) for Yucca Mountain

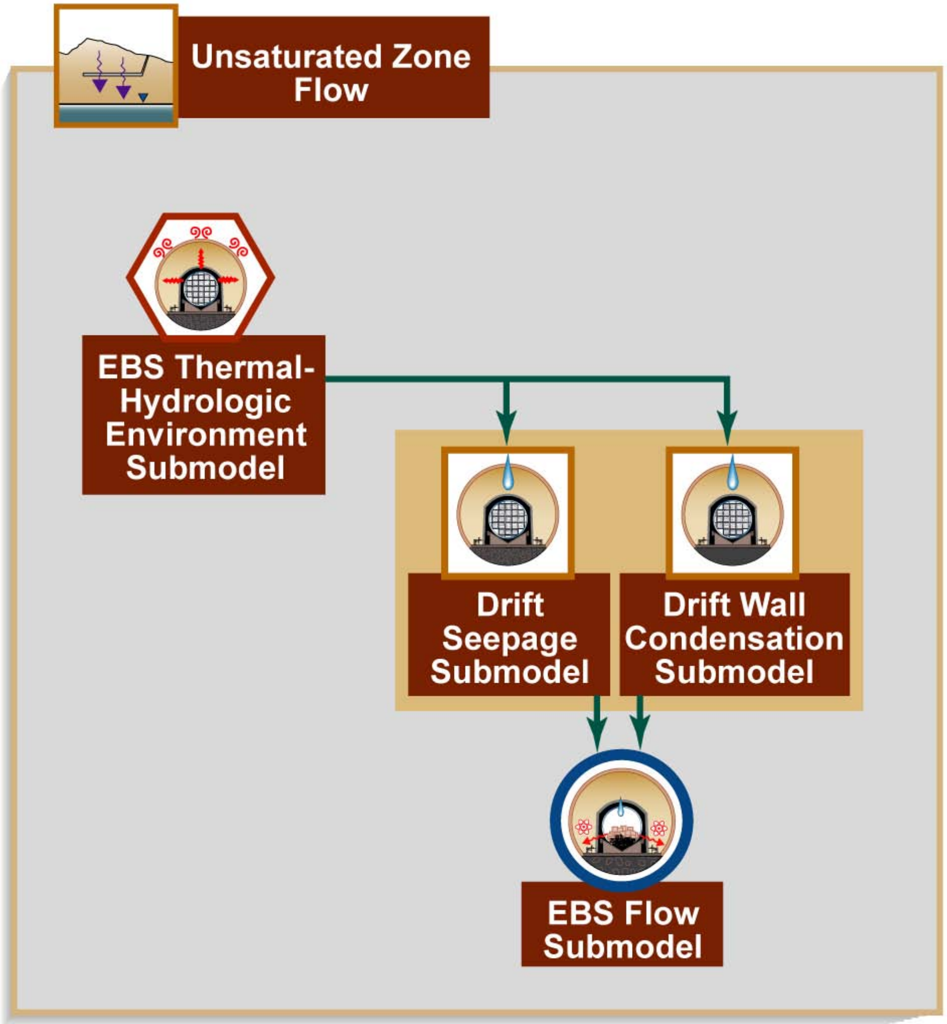
Presented by:
Ernest Hardin
Sandia National Laboratories

October 25, 2006
Las Vegas, Nevada

Presentation Outline

- Identification and linkage of abstractions
- Abstraction
  - Objectives
  - Input, output, and basis for model confidence
  - Assumptions
  - Conceptual model
  - Treatment of uncertainty and variability
  - Technical bases for abstraction and references
  - Implementation in TSPA model
- Anticipated changes since TSPA for site recommendation (SR)
- Modeling areas
  - Ambient seepage/thermal seepage
  - Thermal hydrology
  - Near-field/in-drift chemistry

Identification and Linkages of Abstractions
Ambient Seepage / Thermal Seepage



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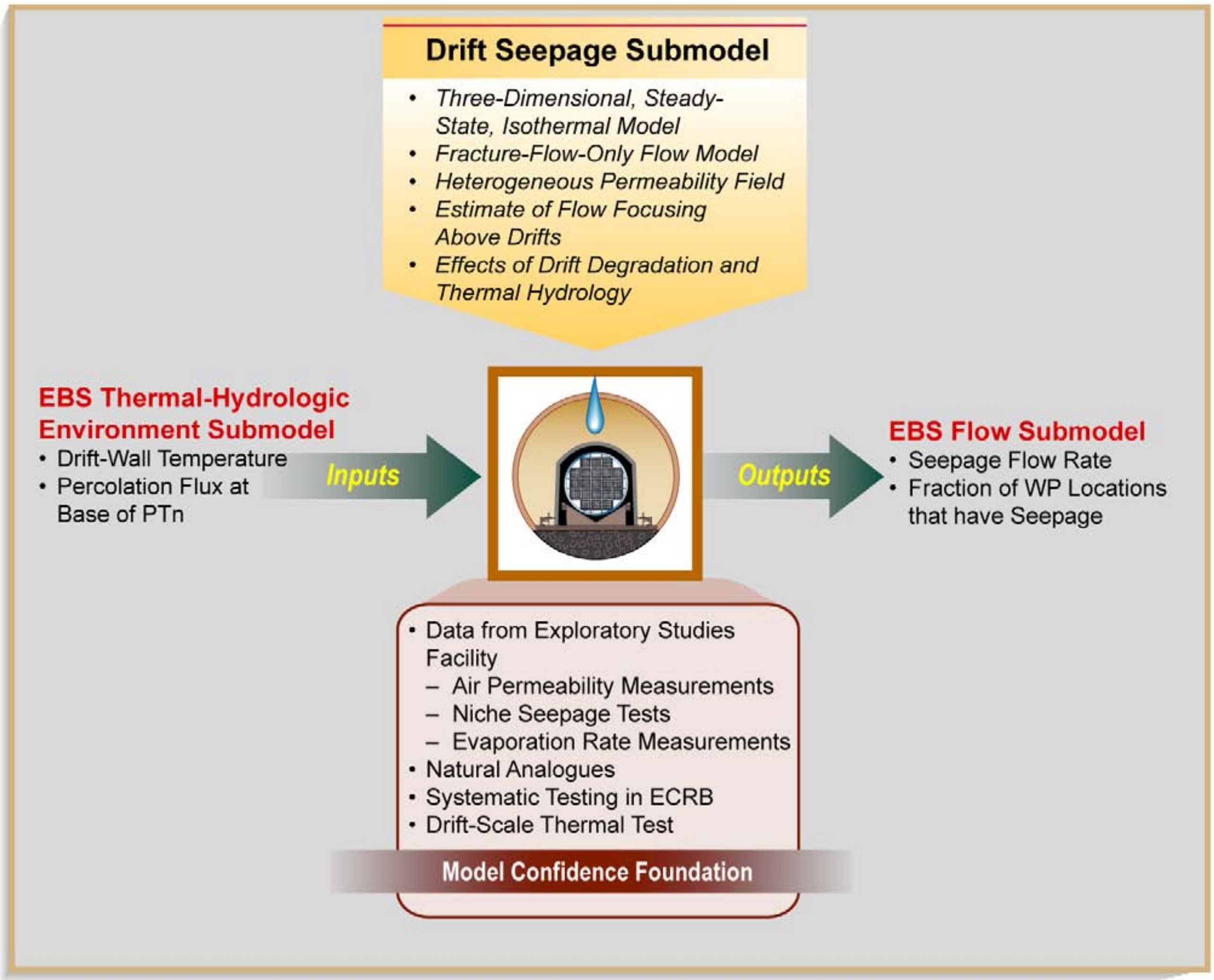
- Note: Drift-wall condensation is abstracted from process model simulations, and added to seepage flux diverted by drip shield.

Objectives for Abstractions

Ambient Seepage / Thermal Seepage

- **Determines seepage into the repository and liquid flux in the EBS to represent**
  - Corrosion environment
  - Advective transport of radionuclides in the EBS
- **Determines threshold temperature for seepage into emplacement drifts**

Inputs, Outputs, Basis for Model Confidence
Ambient Seepage / Thermal Seepage



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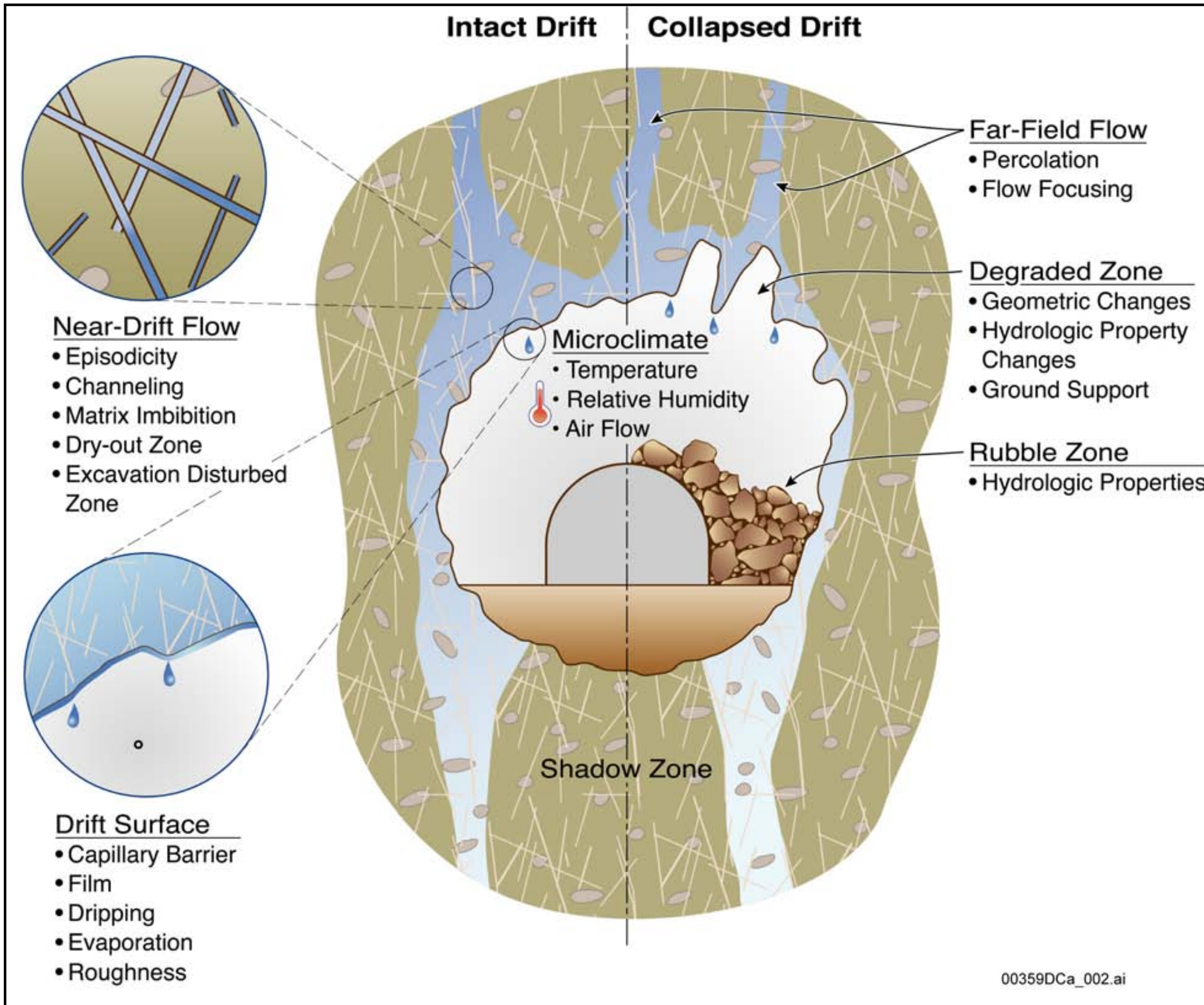
Model Assumptions
Ambient Seepage / Thermal Seepage

- Capillary strength parameter distribution applies to all host rock units; includes film flow, evaporation, etc. at the drift wall
- Permeability distributions for lithophysal and nonlithophysal host-rock units
- Temperature threshold (100°C vs. 96°C) ensures the boiling isotherm is contained within the rock when seepage resumes

Conceptual Model
Ambient Seepage / Thermal Seepage



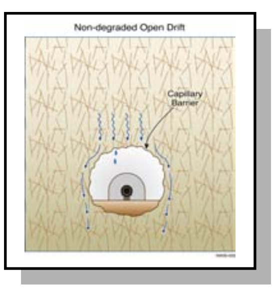
- **Liquid-release tests (~100)**
- **Drift-scale heterogeneous fracture-continuum model**
- **Inverse modeling to estimate seepage parameters**
- **Validation and abstraction**

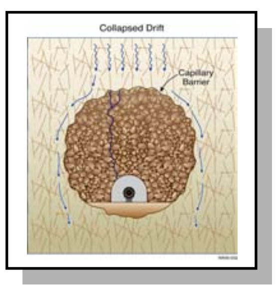
Treatment of Uncertainty and Variability
Ambient Seepage / Thermal Seepage

- **Treatment of uncertainty**
  - Bulk permeability and capillary strength (uncertainty distributions on mean values)
  - Seepage response (standard deviation response surface)
  - Drift collapse effect (increased opening size)
  - Rockfall effect (multiplier on seepage percentage)
- **Treatment of variability**
  - Propagates variability of percolation flux and hydrostratigraphy
  - Flow focusing represents intermediate-scale variability in unsaturated zone flow

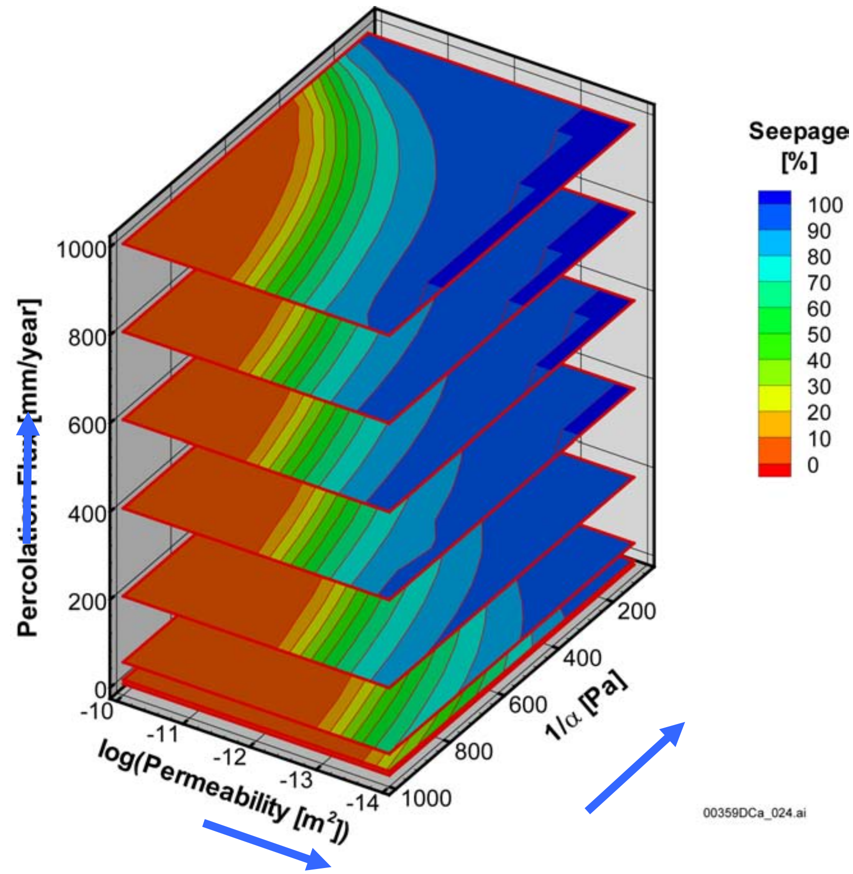
Implementation in TSPA
Ambient Seepage Prediction Model

- **Same conceptual framework as calibration model**
- **Systematic seepage predictions varying the three key parameters for seepage**
- **Look-up table of seepage rates (and uncertainty) for TSPA**
- **Separate look-up tables for intact (including moderate degradation) and fully collapsed drifts**





Seepage Look-up Table

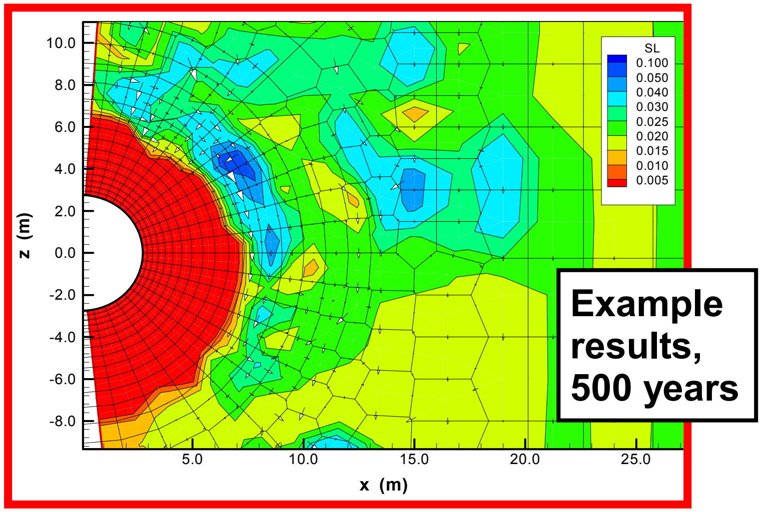


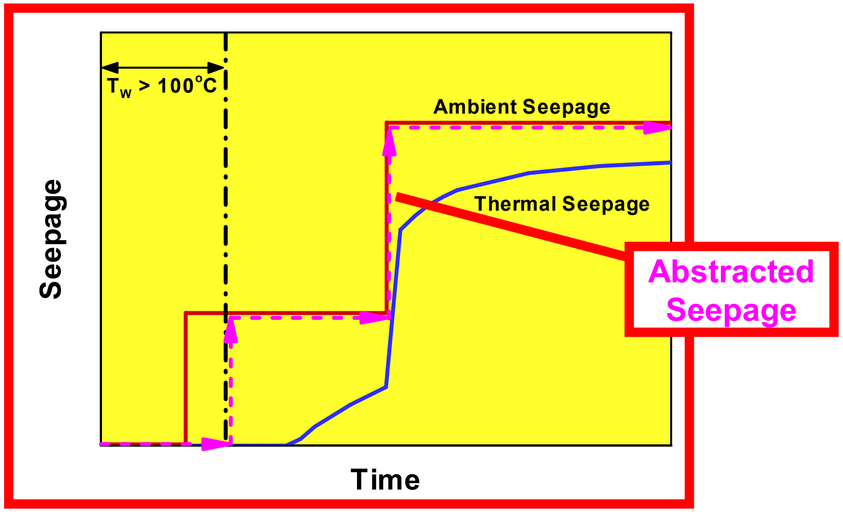
blue arrow: increasing seepage

MDL-NBS-HS-000002 REV 03 Figure 6-8

Implementation in TSPA
Thermal Seepage

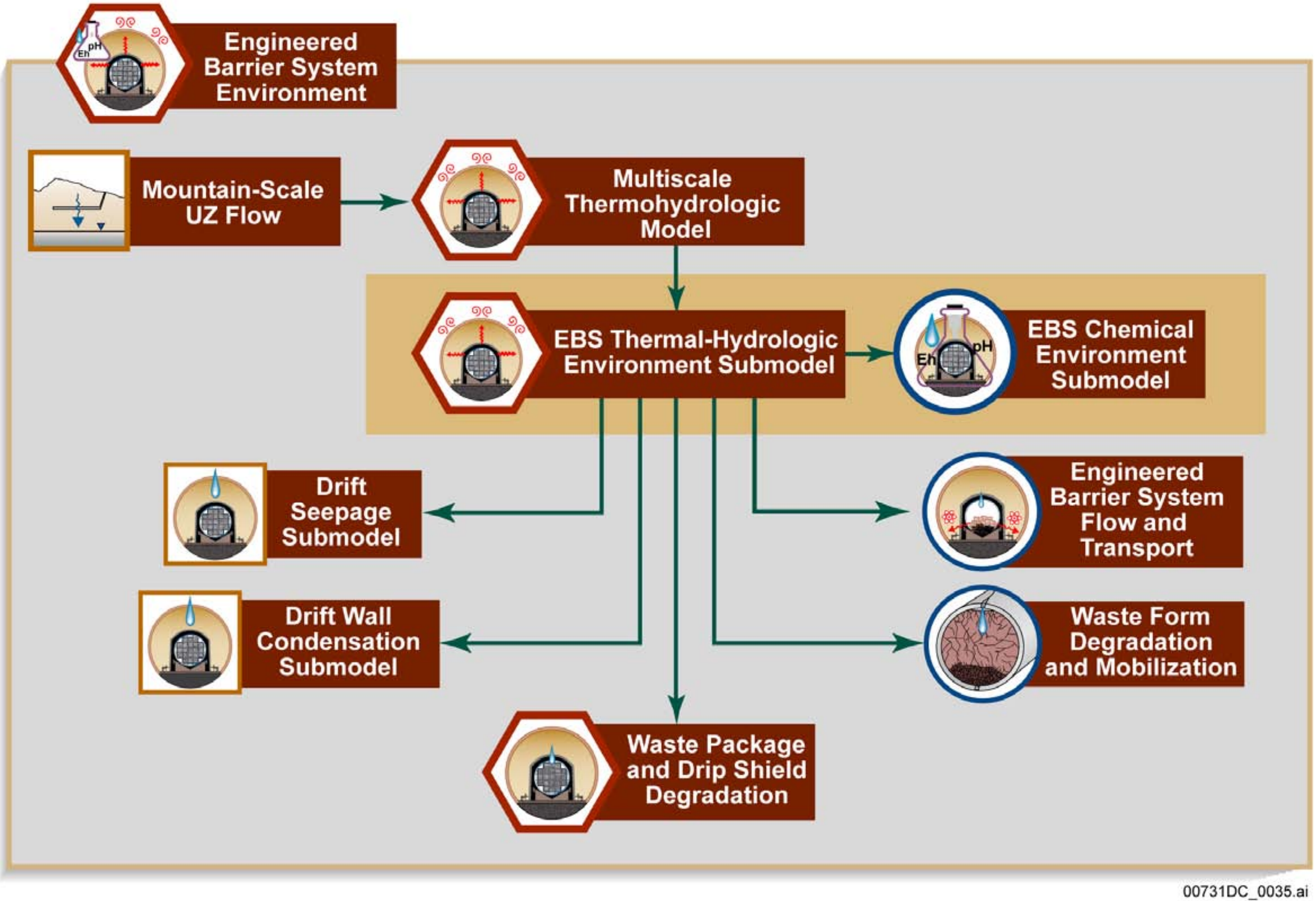
- **Based on numerical simulation, validated by comparison to an alternative model**
- **Vaporization is effective for above-boiling conditions**
- **Thermal seepage is always less than ambient seepage**
- **Resaturation delays seepage conditions**
- **Sensitivity analyses ⇒ consistent results for wide ranges of relevant parameters and conditions**





MDL-NBS-HS-000015 REV 01
Figures 6.2.2.2-3 and 6.2.4.1-1

Identification and Linkages of Abstractions
Thermal Hydrology / Multiscale Model

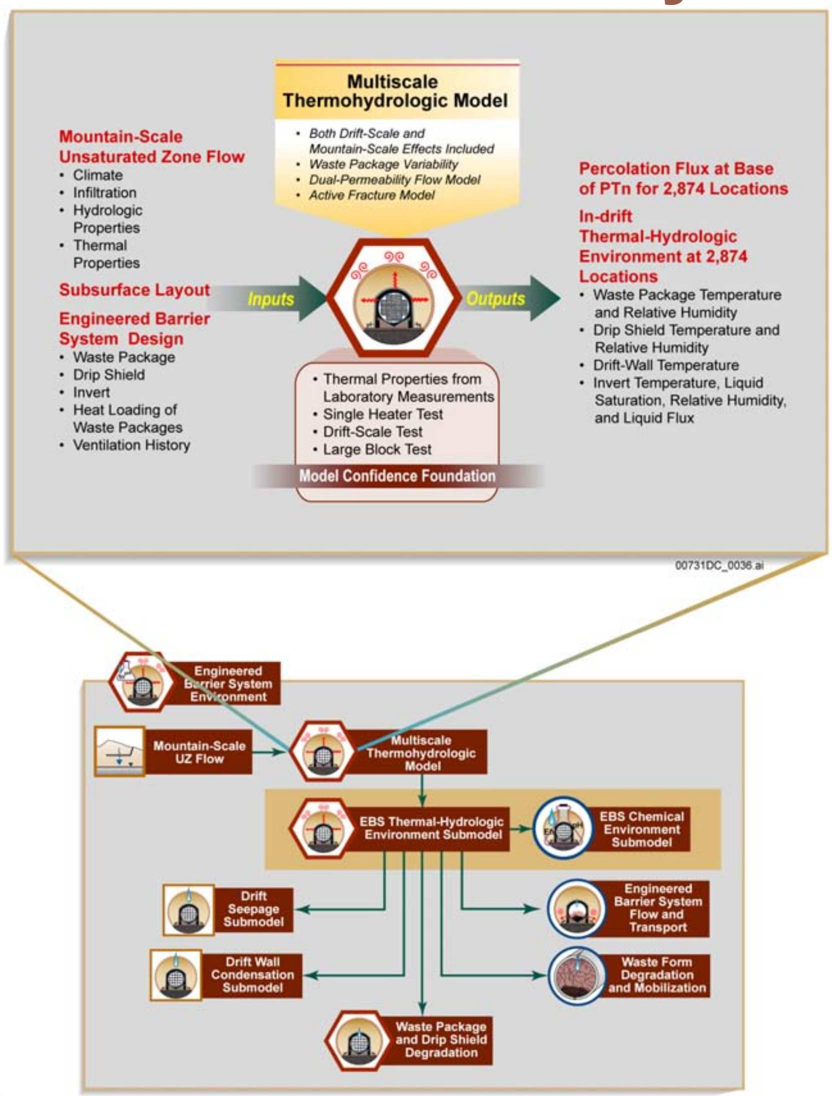


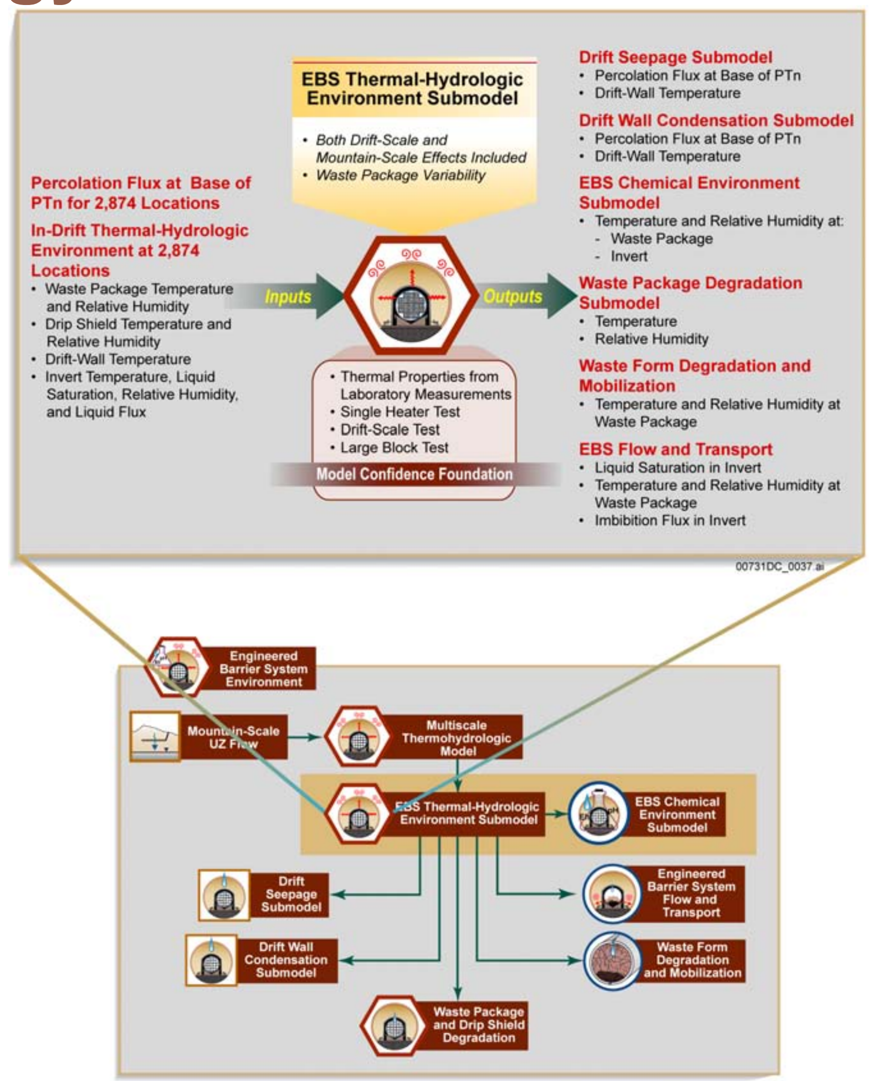
Objectives for Abstraction

EBS Thermal Hydrology / Multiscale Model

- **Determine in-drift temperature and relative humidity histories affecting**
  - Corrosion environment
  - In-package degradation processes
  - Transport of radionuclides in the EBS
- **Organize information on waste package-specific variability**
- **Select representative waste packages for TSPA**

Inputs, Outputs, Basis for Model Confidence
EBS Thermal Hydrology / Multiscale Model





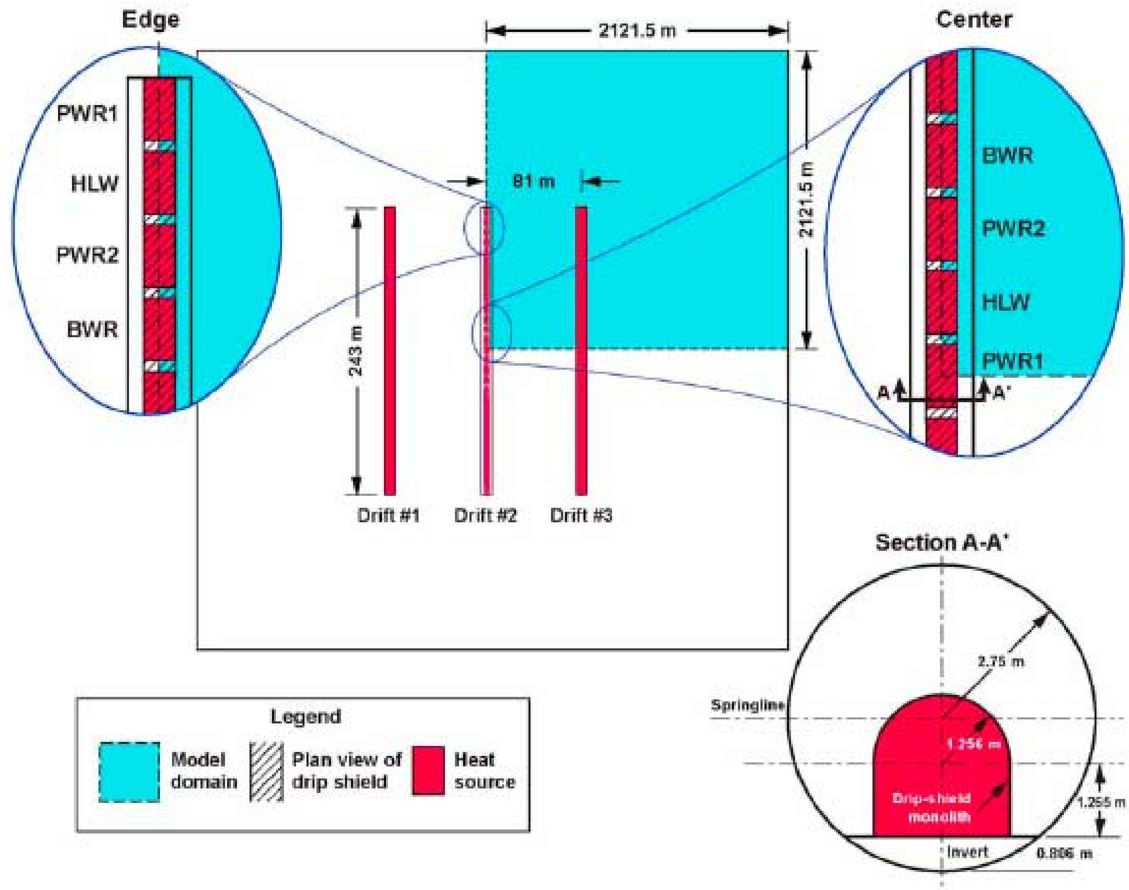
Model Assumptions
Thermal Hydrology / Multiscale Model

- Porous medium, dual-permeability
- Conduction-dominated heat flow
- Predicted climate changes occur at 600 and 2,000 yr
- Future water table rise effect is insignificant
- All waste packages are emplaced at time = 0, followed by 50 years of ventilation
- Axial transport of water vapor in the drift is a minor effect

Conceptual Model

Implemented in 3D Thermal-Hydrologic Process Model

- **3-drift repository process-level validation case**
- **Developed to validate multiscale abstraction methodology**
- **4 waste package types (BWR, PWR2, HLW, PWR1)**
- **Includes axial gas-phase moisture transport**



NOTE: To the upper left is the plan view of the three-drift repository test case; highlighted in blue is the zone of symmetry. To the upper right is a close-up of the Drift #2 waste package sequencing. To the bottom right is the vertical cross-section of the modeled drift with the drip shield and waste package lumped together as a heat source.

ANL-EBS-MD-000049 REV 03 Figure 7.5-1

Treatment of Uncertainty
Thermal Hydrology / Multiscale Model

- **Suites of thermal-hydrologic (TH) histories calculated for key parameter uncertainties**
  - Percolation flux state (lower, mean, upper)
  - Host rock thermal conductivity (mean ±1σ)

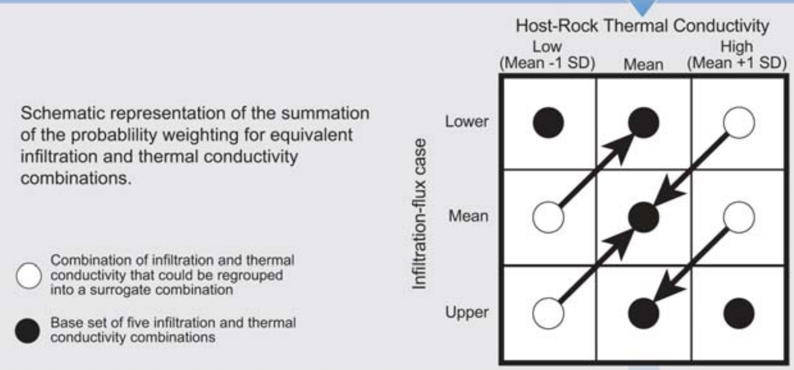
    (9 possible represented by 5 weighted suites)
- **Representative waste packages are selected for TSPA**
  - Representative commercial spent nuclear fuel and co-disposal packages are selected from each percolation subregion (e.g., 2 x 5 = 10)
  - Repeat for each suite of TH histories (e.g., 5 x 10 = 50)

Weighting of Nine Combinations

Probability weighting of the nine combinations of infiltration scenario and host-rock thermal conductivity.

Infiltration-Flux Case	Probability			
	Host-Rock Thermal-Conductivity Case			
	All	Low	Mean	High
All	1.0000	0.33333	0.33333	0.33333
Lower	0.2400	0.08000	0.08000	0.08000
Mean	0.4100	0.13667	0.13667	0.13667
Upper	0.3500	0.11666	0.11666	0.11666

Equivalent Combination Mapping



Weighting of Five Aggregate Combinations

Probability weighting of the five MSTHM data sets used by the TSPA-LA Model.

Infiltration-Flux Case	Probability			
	Host-Rock Thermal-Conductivity Case			
	All	Low	Mean	High
All	1.0000	0.33333	0.33333	0.33333
Lower	0.2400	0.08000	0.21667	
Mean	0.4100		0.33333	
Upper	0.3500		0.25334	0.11666

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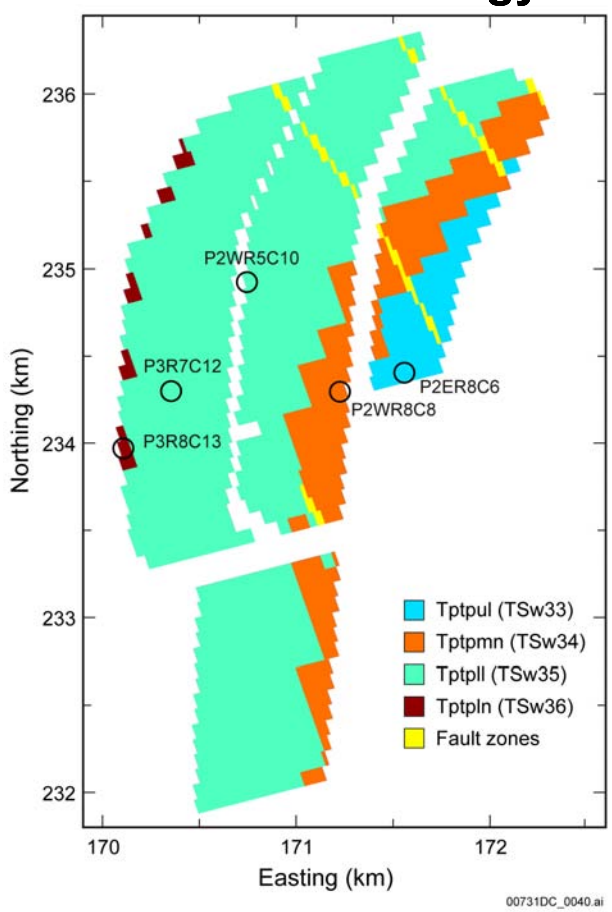
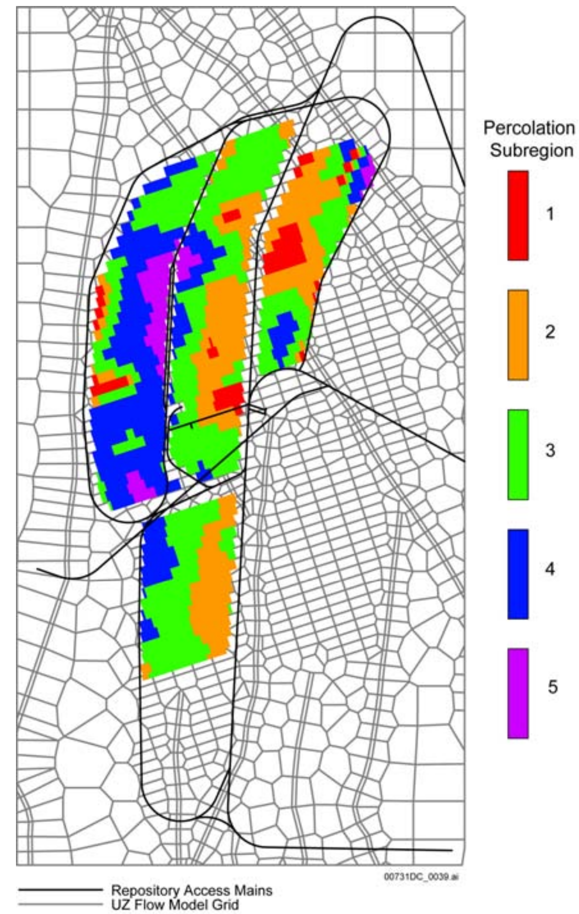
Treatment of Variability

Thermal Hydrology/ Multiscale Model

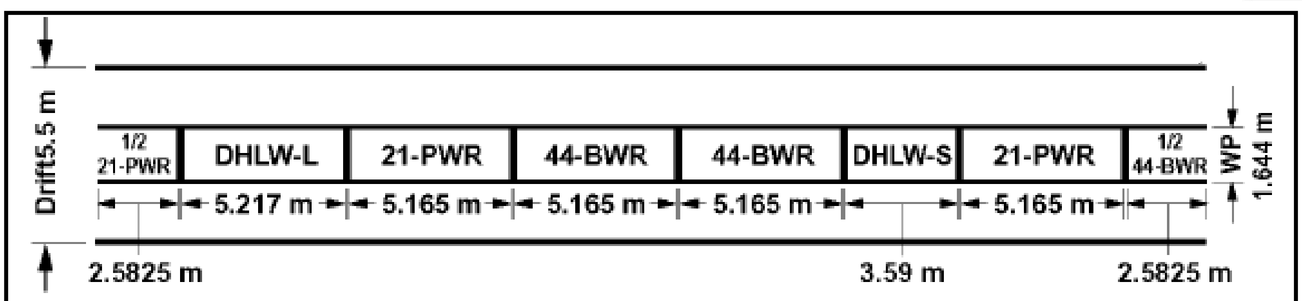
Host Rock Lithology



Percolation Subregions



Waste Package Types (preliminary, does not incorporate dimensions of transportation, aging, and disposal canister)

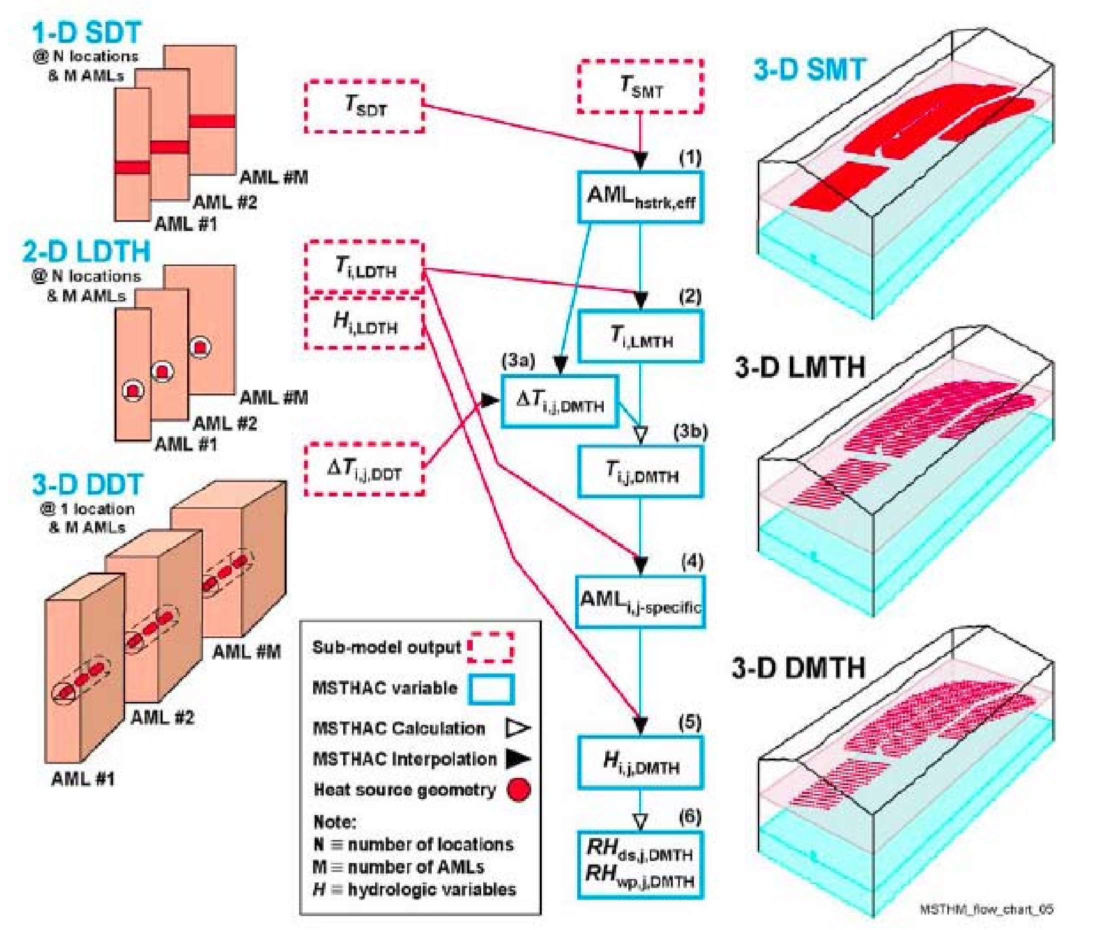


ANL-EBS-MD-000049 REV 03
Figure s 6.2-2 and 6.3-1

Implementation in TSPA

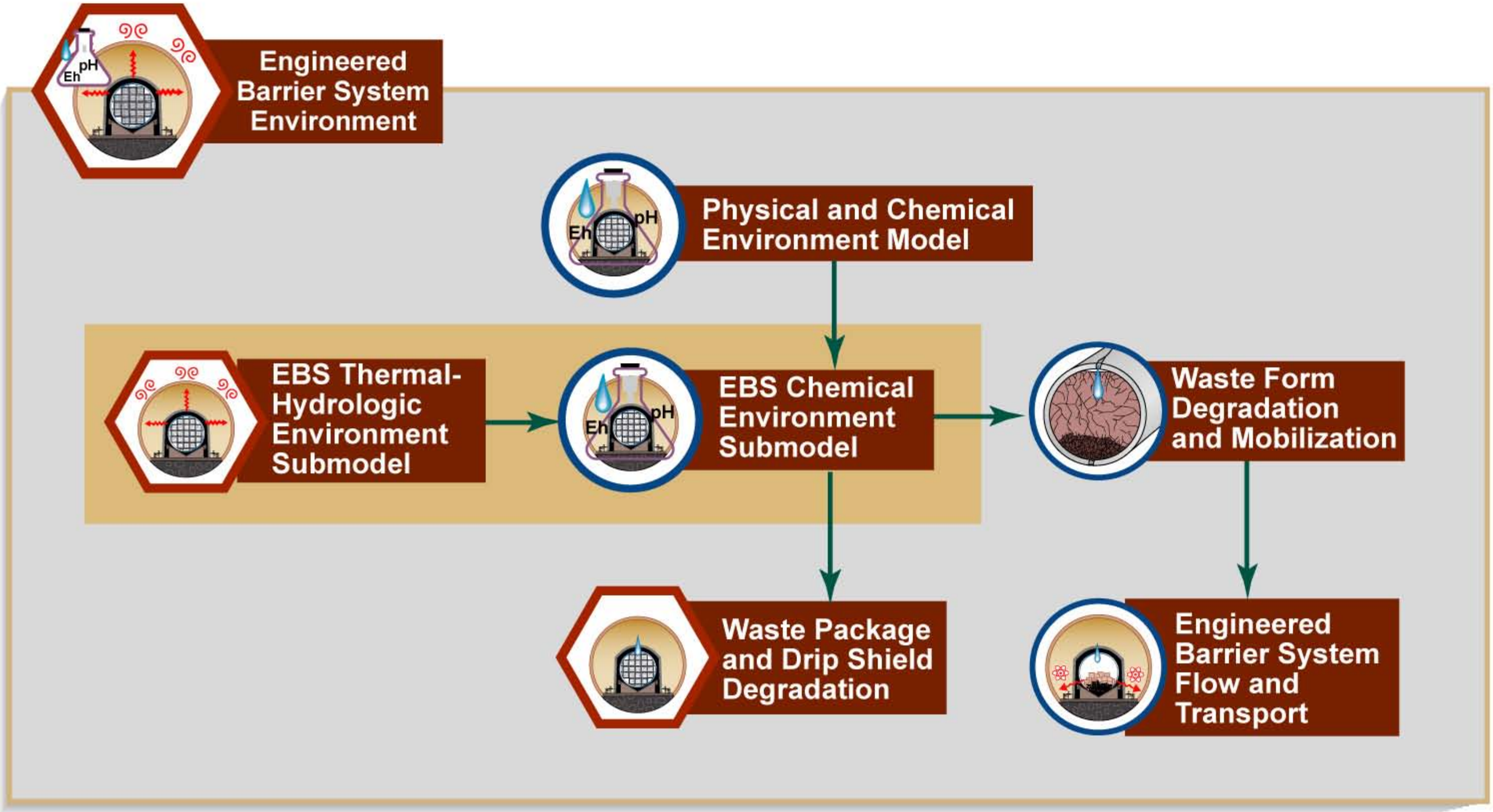
Thermal Hydrology / Multiscale Methodology

- Uses superposition principles
- Mountain-scale heat flow (SMT)
- Discriminate 3D heat-flow effects from 1D vertical (SDT)
- Package-package temperature variability (DDT)
- Hydrology implemented in 2D submodels (LDTH)



ANL-EBS-MD-000049 REV 03 Figure 1-1

Identification and Linkages of Abstractions
Near-Field/In-Drift Chemistry



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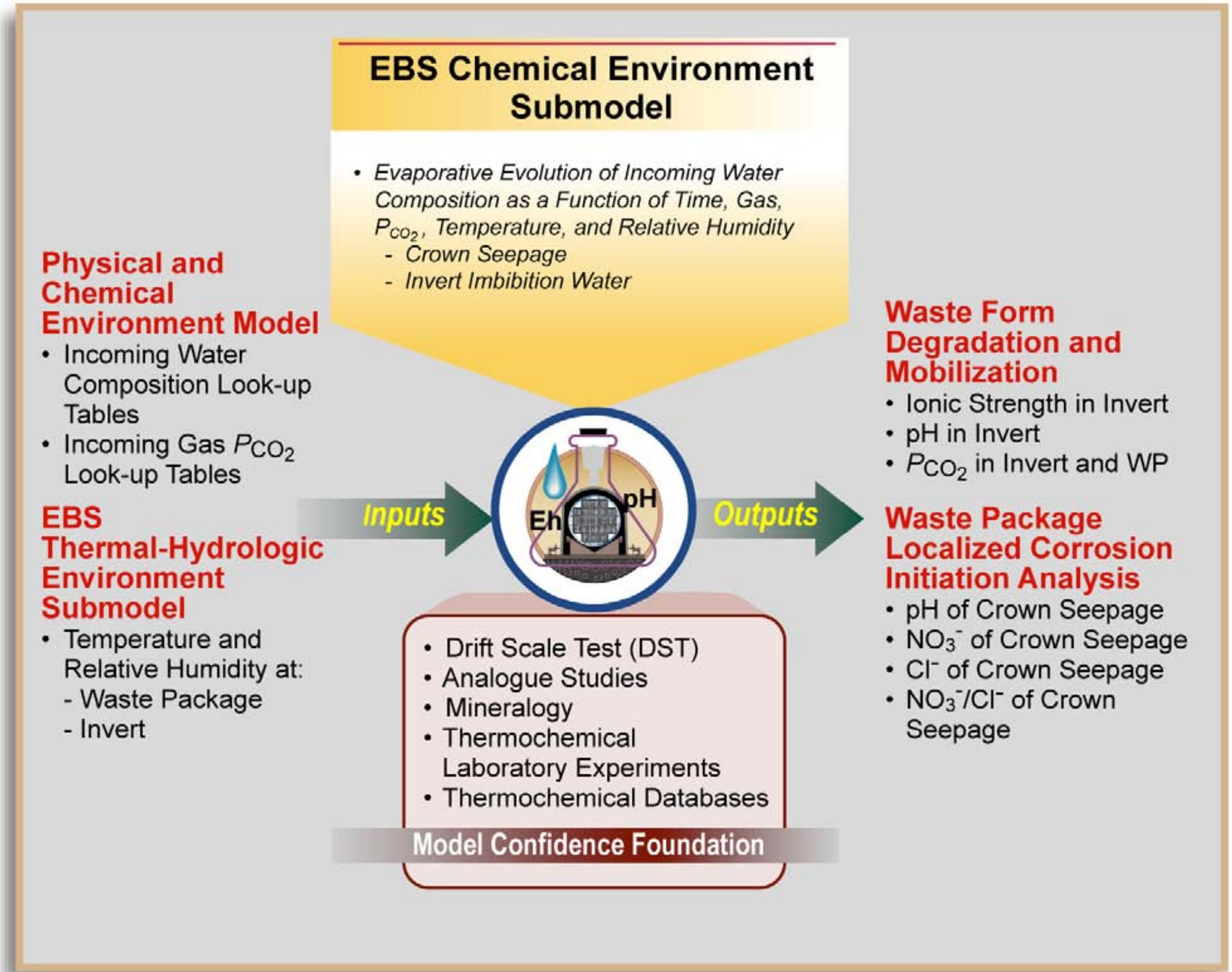
Objectives for Abstractions

Near-Field/In-Drift Chemistry

- **Determine chemical composition of seepage and invert porewater, affecting**
  - **Corrosion environment**
  - **Radionuclide solubility**
  - **Transport of radionuclides in the EBS**
- **Determine P_{CO2} in the drift environment for representing water composition**

Inputs, Outputs, Basis for Model Confidence
Near-Field/In-Drift Chemistry



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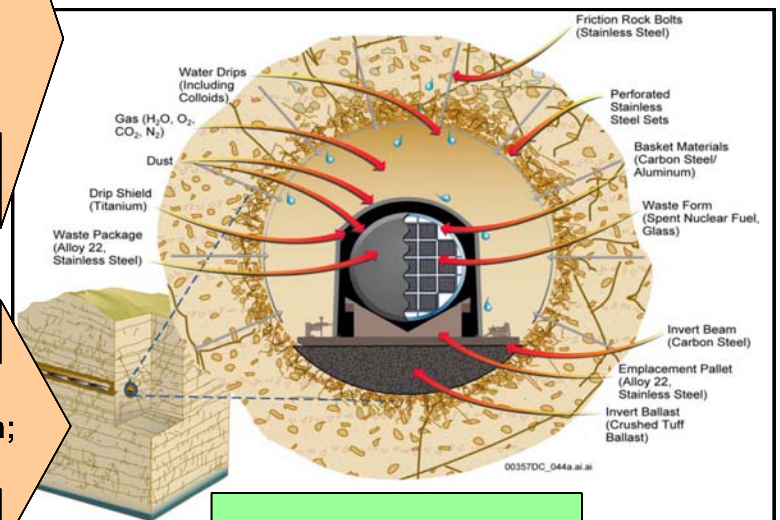
Model Assumptions
Near-Field / In-Drift Chemistry

- **Thermal-hydrologic-chemical (THC) seepage model constitutive relations**
- **Initial/boundary (“starting”) water compositions represent uncertainty in THC seepage model**
- **Thermodynamic equilibrium for in-drift evolution**
- **Local in-drift environmental conditions (T, RH) controlled by thermal hydrology**

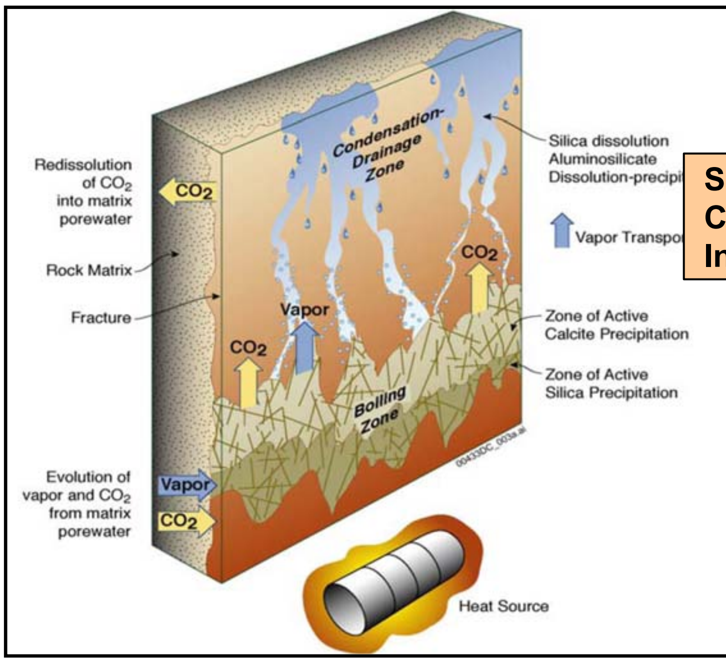
Conceptual Model
Near-Field / In-Drift Chemistry

Equilibrium Thermodynamic (Pitzer) Model for Evaporative Evolution

Physical & Chemical Environment Model



THC Seepage Model



Seepage Composition; In-Drift P_{CO2}

To TSPA:

Composition of Evaporated Seepage Water $f(T, P_{CO2}, RH)$

pH, I, [Cl], (NO_3^-/Cl^-)

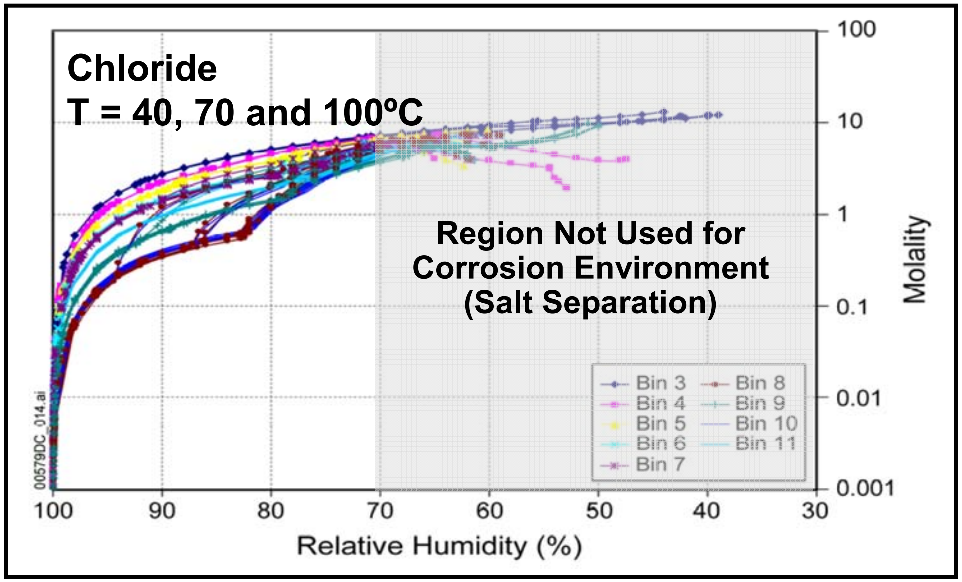
MDL-NBS-HS-000001 REV 04 Figure 6.2-2 and ANL-EBS-MD-000033 REV 05 Figure 6.4-1

Treatment of Uncertainty and Variability
Near-Field/In-Drift Chemistry

- **Treatment of uncertainty**
  - Range of measured in situ ("starting") porewaters
  - Predictive Pitzer model uncertainty
  - Binning uncertainty
- **Treatment of variability**
  - Crown seepage and invert porewater compositions
  - In-drift water chemistry abstraction approach propagates variability (T, RH) from EBS thermal hydrology
  - Repository-center THC results with mean percolation flux apply to all waste packages

Implementation in TSPA
Near-Field/In-Drift Chemistry

- **Select THC realization ("starting" water)**
  - P_{CO2} time series
  - Bin history
- **Seepage and invert porewater evaporation**
  - Interpolate lookup tables for pH, Ionic Strength, Cl^-, and NO_3^- (functions of T, RH, P_{CO2})
  - Apply uncertainties
- **Salt separation**
  - Halite precipitates if seepage contacts waste package for RH < ~ 70%
  - Chloride may then separate from NO_3^- ⇒ very low nitrate, halite-saturated conditions



ANL-EBS-MD-000033 REV 05 Figure 6.13-18

EBS Environment
Summary of Anticipated Changes Since TSPA-SR

- **Updated infiltration/percolation flux distributions**
- **Thermal hydrology**
  - Multiscale methodology will interpolate flux and stratigraphic effects from a library of TH calculations
  - Expanded 3D panel-scale process-level validation model
- **Near-field/in-drift chemistry**
  - Selection of starting waters from expanded available data
  - THC process model has normative dryout procedure; revised software
  - Develop reaction-path model for seepage composition, to be used as the abstraction, eliminating binning

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

www.ocrwm.doe.gov

Abstraction of Waste Package and Drip Shield Degradation

Presented to:
DOE/NRC Technical Exchange on Total System Performance Assessment (TSPA) for Yucca Mountain

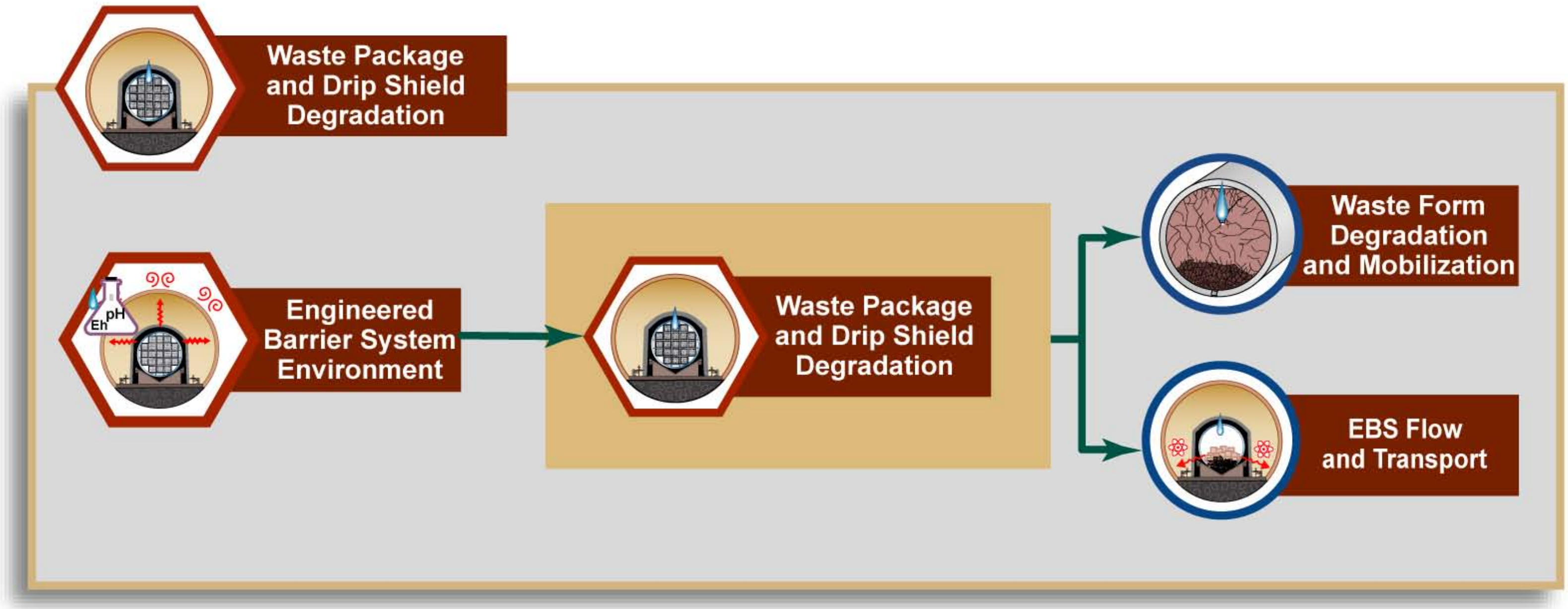
Presented by:
David Stahl
ISSi

October 25, 2006
Las Vegas, Nevada

Presentation Outline

- Identification and linkages of abstractions
- Abstraction
  - Objectives
  - Input, output, and basis for model confidence
  - Assumptions
  - Conceptual model
  - Treatment of uncertainty and variability
  - Technical bases for abstraction and references
  - Implementation in TSPA model
    - General corrosion (GC), microbially influenced corrosion (MIC) localized corrosion (LC), stress corrosion cracking (SCC), early failure (EF)
- Anticipated changes since TSPA for site recommendation (SR)

Identification and Linkages of Abstractions



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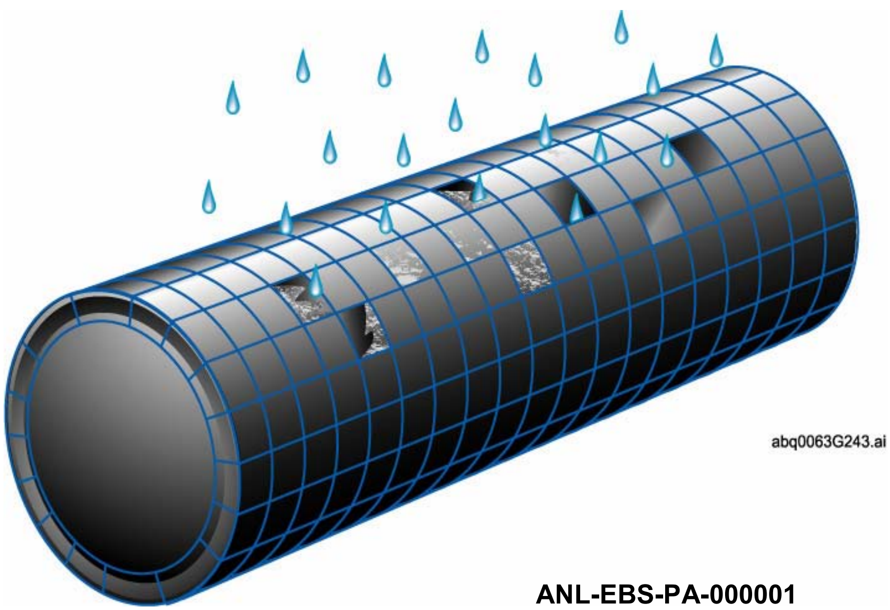
EBS = Engineered Barrier System

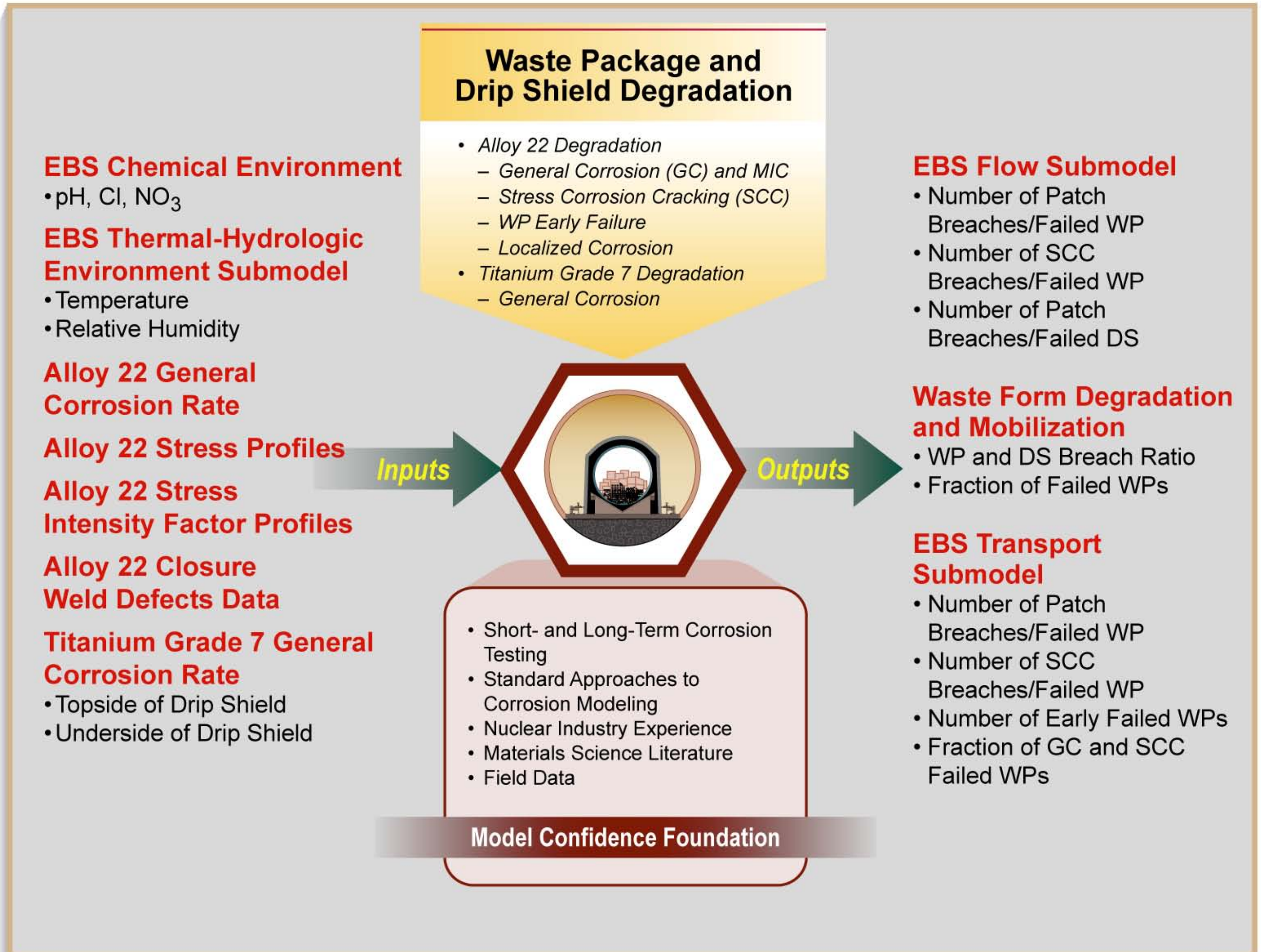
Objectives of Waste Package and Drip Shield Degradation Abstraction

- **Provide EBS flow and transport model and waste form degradation and mobilization model the**
  - **Number of patch and crack breaches per failed waste package (WP)**
  - **Number of patch breaches per failed drip shield (DS)**
  - **Number of early failed WPs and DSs**



ANL-EBS-PA-000001

Inputs, Outputs, Basis for Model Confidence



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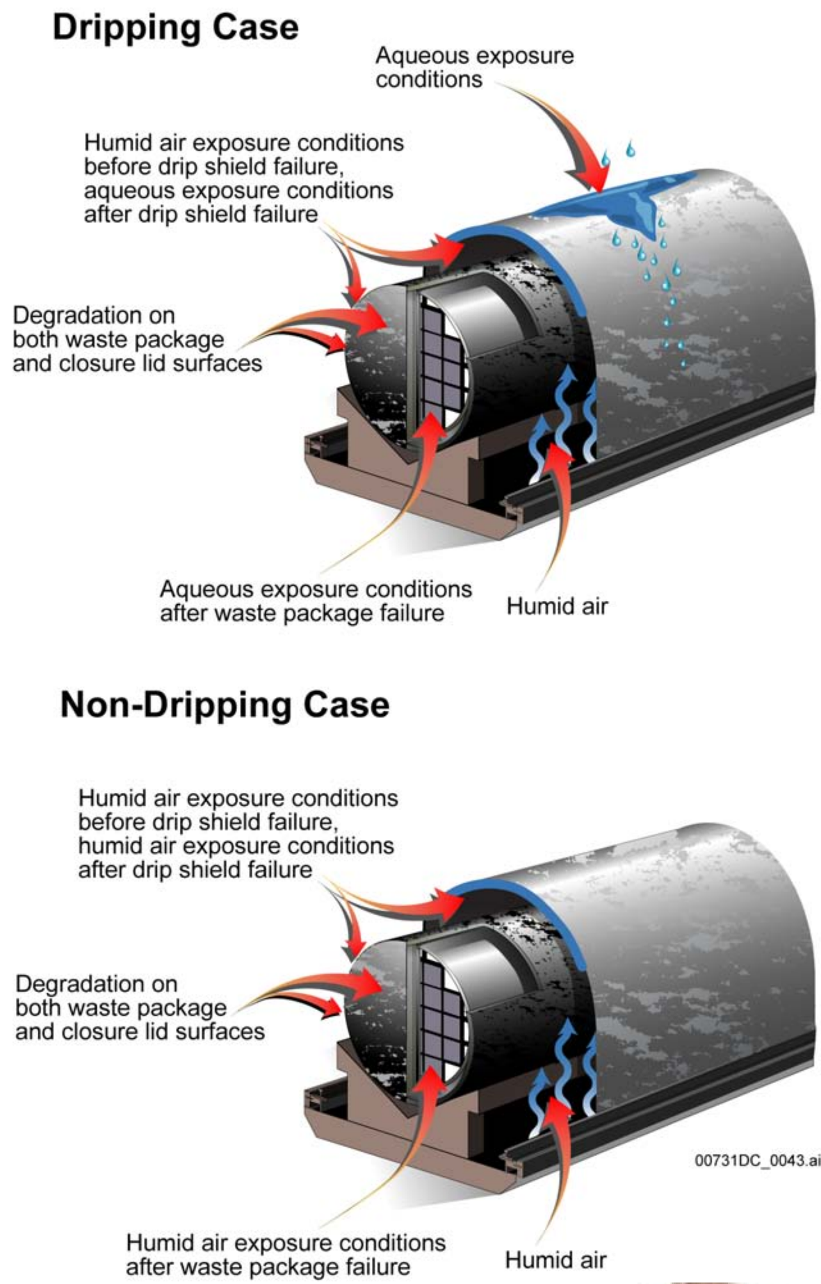
Model Assumptions

- Alloy 22 WP outer barrier
  - GC occurs at all times
  - GC rates time independent
  - LC is represented by crevice corrosion
  - LC rates time independent
  - SCC occurs regardless of exposure environment
  - MIC treated as GC rate multiplier
- Titanium grade 7 DS plates
  - GC occurs at all times
  - GC rates time independent

WP and DS Degradation Conceptual Model

- **DS degradation (GC) not dependent on seepage contact**
- **WP GC and SCC not dependent on seepage water contact**
- **WP LC can initiate only if seepage contacts the WP surface**
  - **After DS failure**



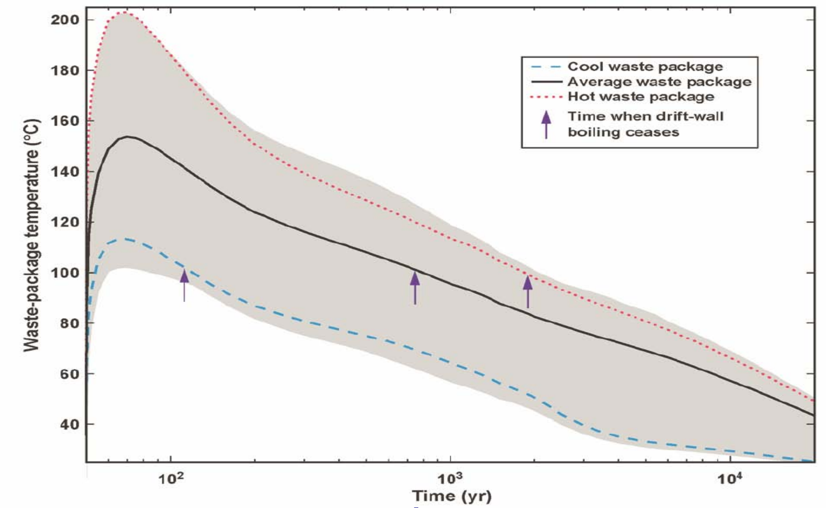
Treatment of Uncertainty and Variability

- **Treatment of uncertainty**
  - WP GC temperature dependence
  - WP LC initiation model parameters
  - WP SCC stress and stress intensity factor profiles
  - WP SCC growth model parameters
  - WP MIC GC rate multiplier
  - DS GC rate
- **Treatment of variability**
  - WP GC/LC temperature/chemical inputs
  - WP GC pre-exponent term
  - WP SCC stress and stress intensity factor profiles
  - WP SCC closure weld flaw size/number

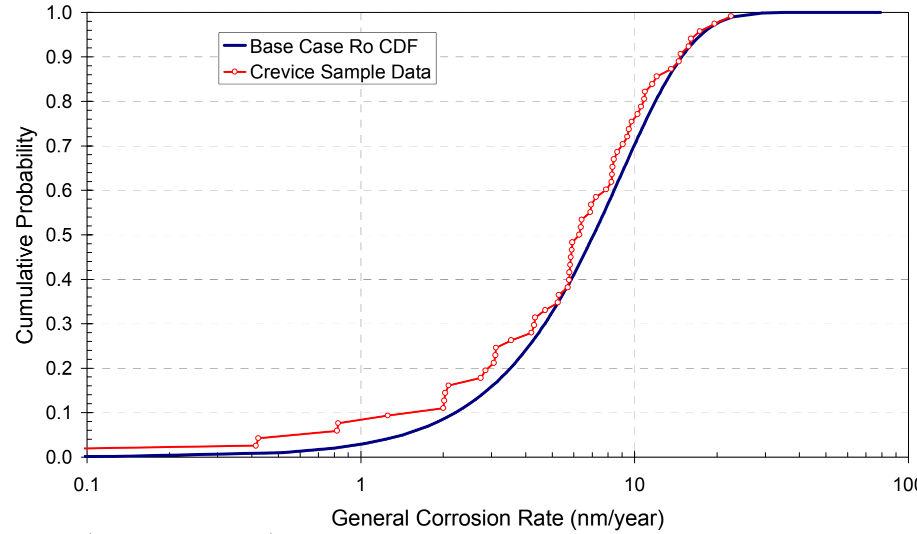
Technical Basis for Abstraction

- **Short and Long-term experimental data**
  - Up to 5-year weight-loss measurements
  - Up to 3-year corrosion potential (E_{corr}) measurements
  - WP mock-ups
- **Validation / confidence evaluation**
  - Comparison to literature data
  - Alternative conceptual models
- **References**
  - General Corrosion and Localized Corrosion of Waste Package Outer Barrier, ANL-EBS-MD-000003 Rev 02, ICN 00
  - General Corrosion and Localized Corrosion of the Drip Shield, ANL-EBS-MD-000004 Rev 02, ICN 00
  - Stress Corrosion Cracking of the Drip Shield and Waste Package Outer Barrier, ANL-EBS-MD-000005 Rev 02, ICN 00
  - Analysis of Mechanisms for Early Waste Package/Drip Shield Failure, CAL-EBS-MD-000030 REV00C, ECN 02

Implementation—WP GC



ANL-EBS-MD-000049

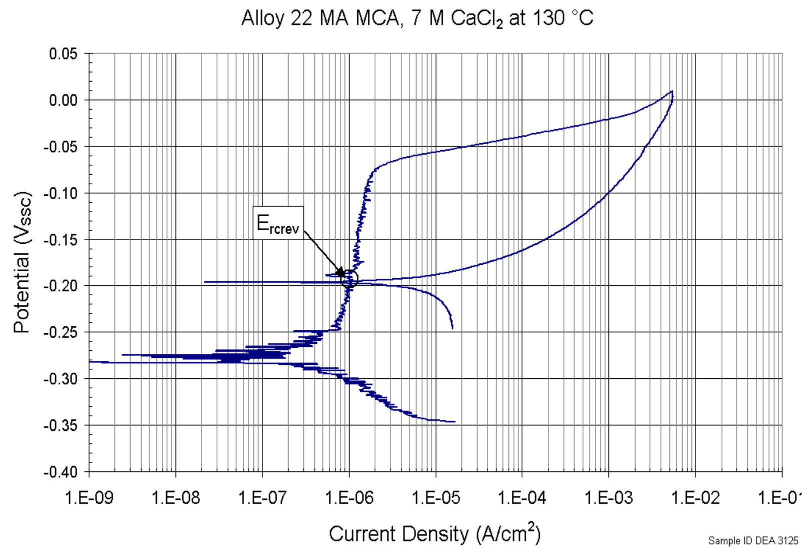


ANL-EBS-MD-000003

$$\text{Rate} = f_{MIC} \exp\left(C_o - \frac{C_1}{T}\right)$$

- **Temperature profiles**
  - **Spatial variability (WP-to-WP)**
- **C_o, pre-exponent, based on Weibull distribution fit to weight-loss data**
  - **Spatial variability (patch-to-patch)**
- **C_1, temperature dependence, based on normal distribution from polarization data**
  - **Epistemic uncertainty**
- **f_{MIC}, MIC multiplier**
  - **Epistemic uncertainty**

Implementation—WP LC

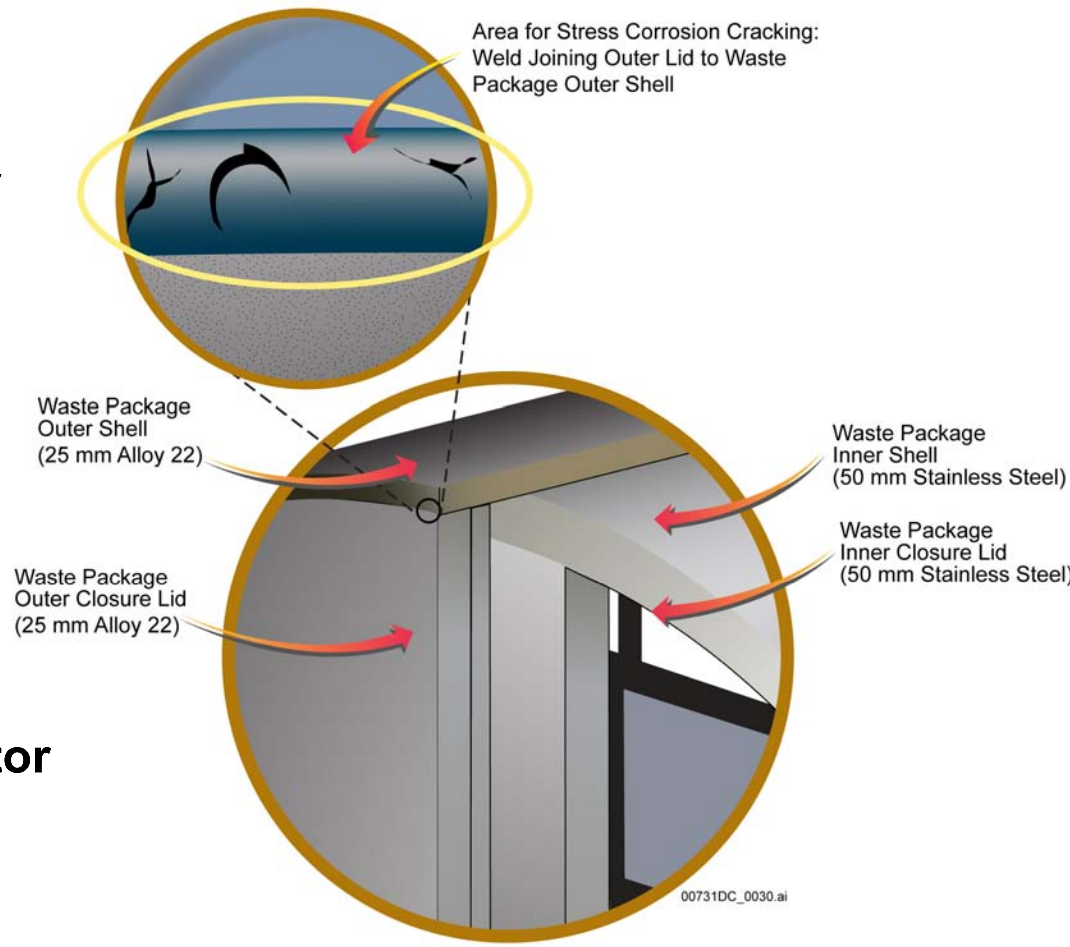


ANL-EBS-MD-000003

- **Waste package areas contacted by seepage may be subject to LC**
- **If seepage occurs at RH < ~70% then model initiates LC**
  - **Potential for salt separation**
- **If seepage occurs at RH > ~70%**
  - **Compare**
    - **E_{corr}, long-term corrosion potential, to**
    - **E_{rcrev}, crevice repassivation potential**
  - **If $E_{corr} \geq E_{rcrev}$ model initiates LC**
    - **E_{corr} and E_{rcrev} are functions of T, pH, [Cl $^-$], and [NO_3^-]**
      - » **Epistemic uncertainty in fitting parameters**
      - » **Spatial variability from thermal and chemical variations**

Implementation—WP SCC

- Only in closure weld regions (in absence of seismicity)
  - Weld region plasticity burnished
  - Initiates at incipient defects or weld flaws
- Growth by Slip Dissolution Model
  - Rate of crack growth a function of
    - Stress intensity factor
      - Mainly epistemic uncertainty
    - Repassivation rate
      - Epistemic uncertainty

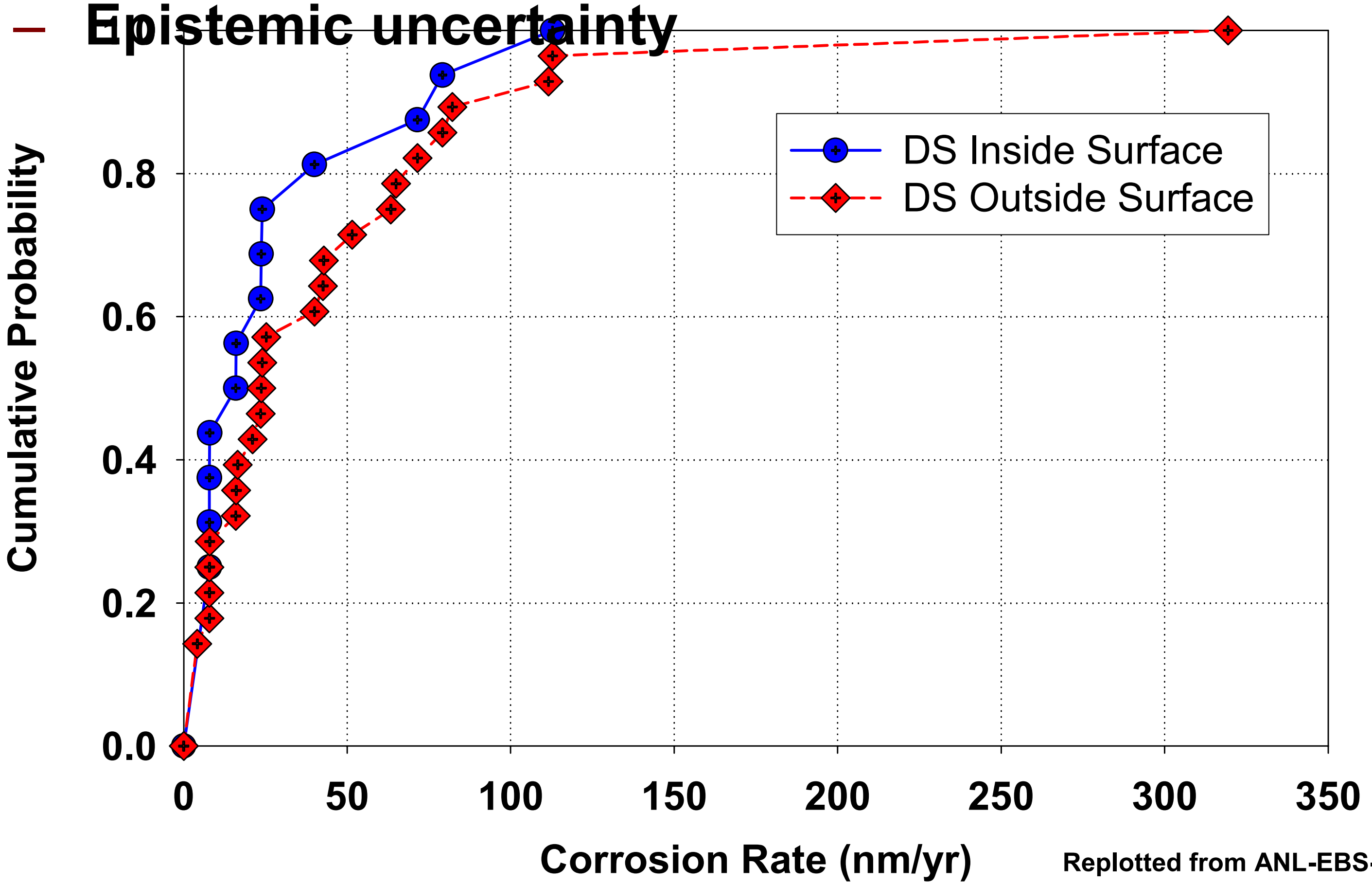


Sources of WP/DS EF

- **Analyses under evaluation for WP and DS**
- **Considers the probability of processes occurring and not being detected such as**
  - Base metal and weld flaws
  - Use of improper material
  - Improper heat treatment
  - Contaminants
  - Mislocated or missing welds
  - Handling damage
  - Administrative/operational error
- **Strict fabrication controls will be used to minimize their occurrence**

Implementation—DS GC

- **Titanium grade 7 drip shield plates**
  - **Empirical distributions for inside and outside surfaces**
  - **Epistemic uncertainty**

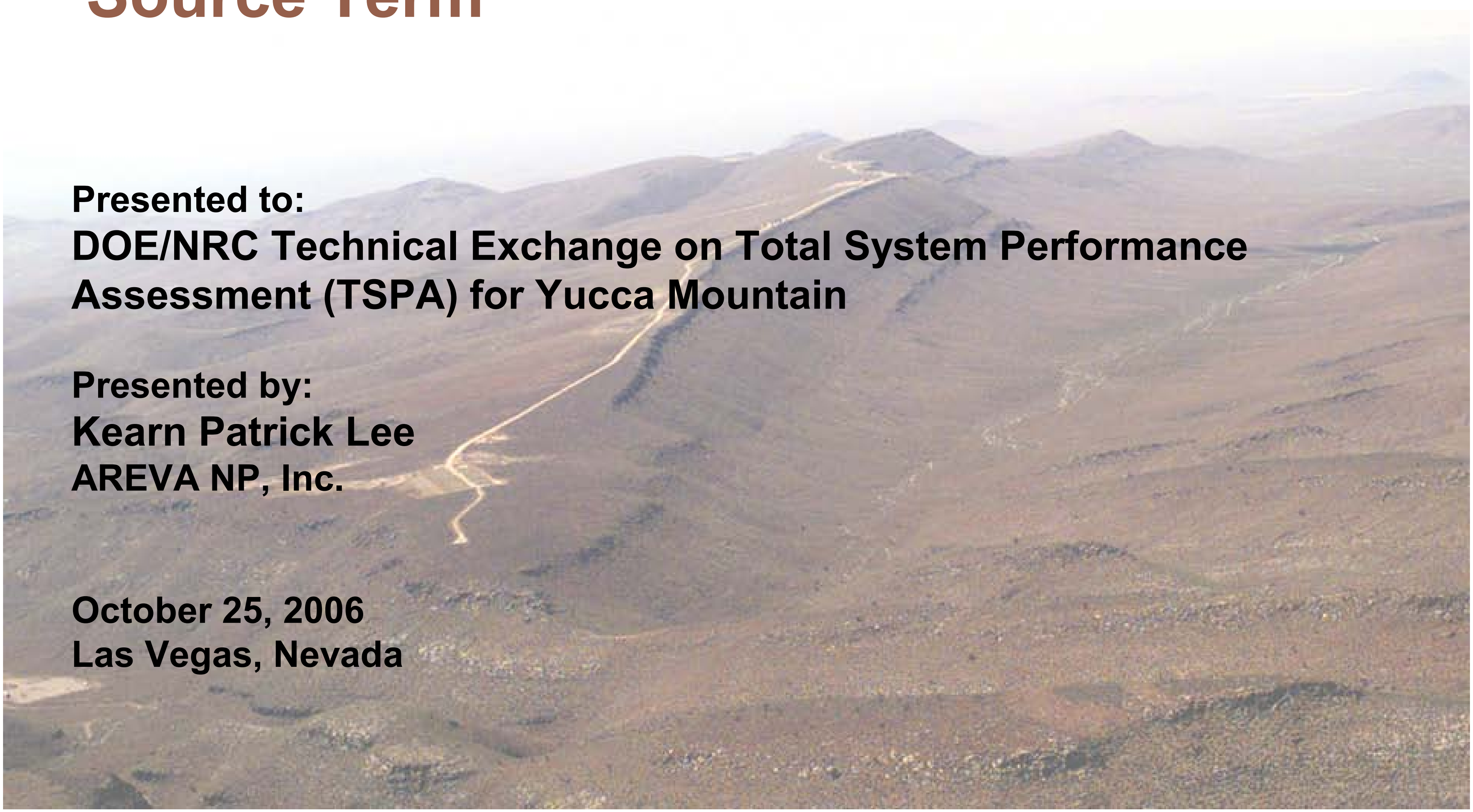


Replotted from ANL-EBS-MD-000004

Anticipated Changes Since TSPA-SR

- **WP outer barrier GC**
  - Temperature dependence added
  - Longer-term data available
  - Changes in uncertainty treatment
- **WP outer barrier LC**
  - Change in functional forms used
  - More data available
- **WP outer barrier SCC**
  - Changes in stress/stress intensity factor profiles
  - Small changes in uncertainty treatments
- **DS GC**
  - Change in uncertainty treatment
- **WP and DS early failure**
  - Under evaluation

Source Term



Presented to:
DOE/NRC Technical Exchange on Total System Performance Assessment (TSPA) for Yucca Mountain

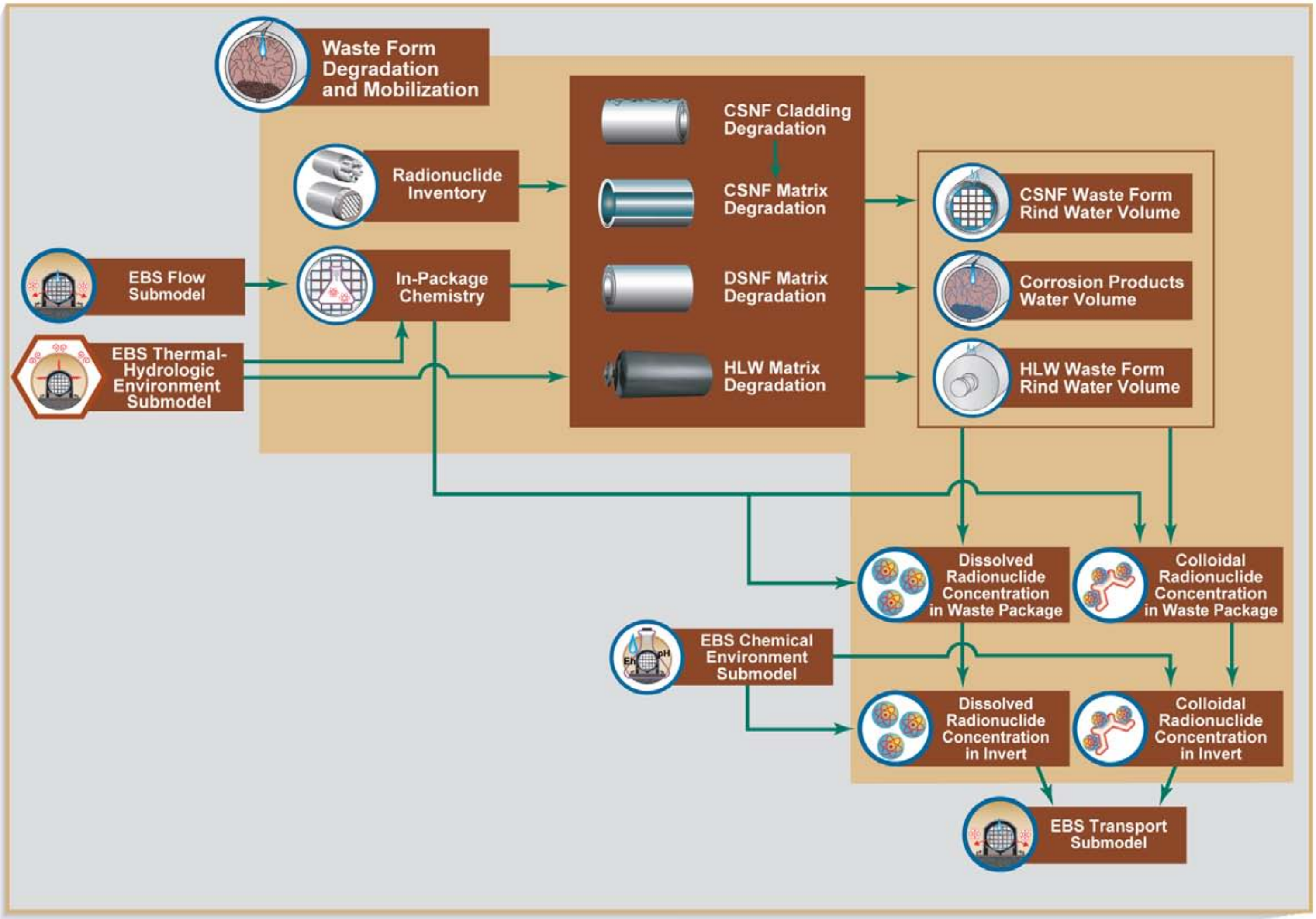
Presented by:
Kearn Patrick Lee
AREVA NP, Inc.

October 25, 2006
Las Vegas, Nevada

Presentation Outline

- **Identification and linkage of abstractions**
- **Abstraction**
  - Objectives
  - Input, output, and basis for model confidence
  - Assumptions
  - Conceptual model
  - Treatment of uncertainty and variability
  - Technical bases for abstraction and references
  - Implementation in TSPA model
- **Anticipated changes since TSPA for site recommendation (SR)**

Identification and Linkages of Abstractions



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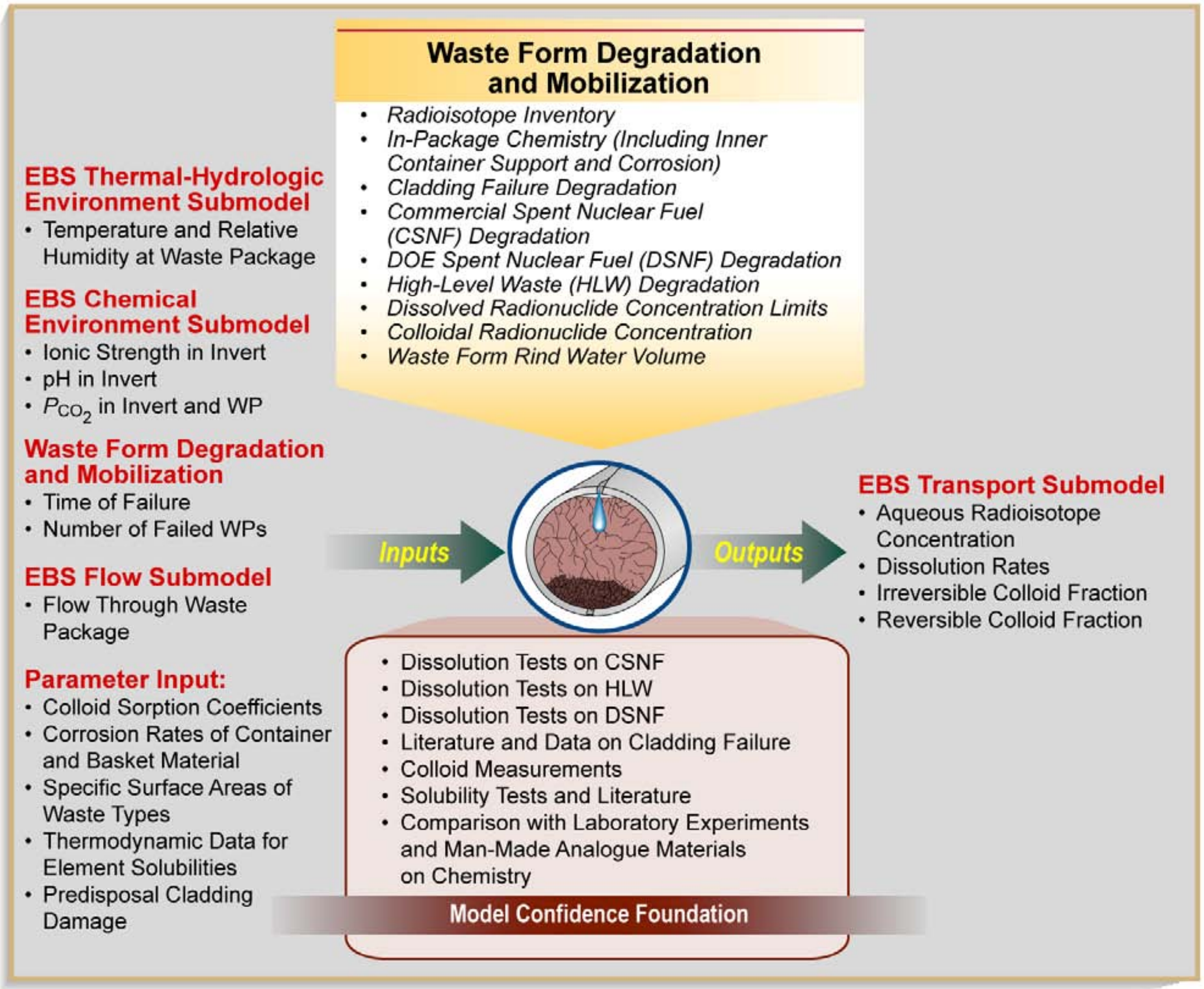
Objective of Source Term Abstractions

- **Account for physical and chemical processes that occur inside a failed waste package (WP) and affect the availability of radionuclides to be transported through and out of the failed WPs**

Inputs, Outputs, Basis for Model Confidence



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Model Assumptions

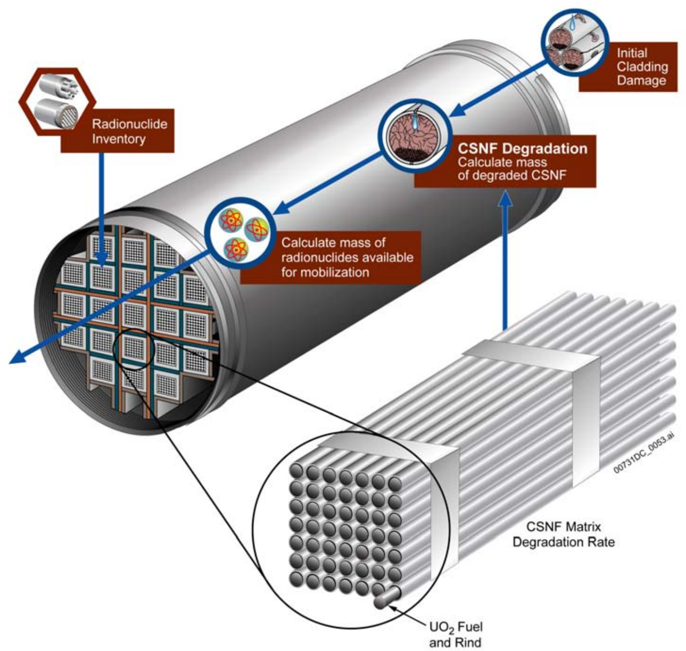
- The repository is in an oxidizing condition and oxygen fugacity equals 0.2 bar
- In-package oxygen and carbon dioxide maintain equilibrium with the ambient atmosphere outside of the WP
- Zircaloy cladding is assumed to split instantly along the length of a fuel rod when perforated by disruptive event
- No credit taken for stainless steel cladding
- All radionuclides are transported in the aqueous phase between the repository and the accessible environment

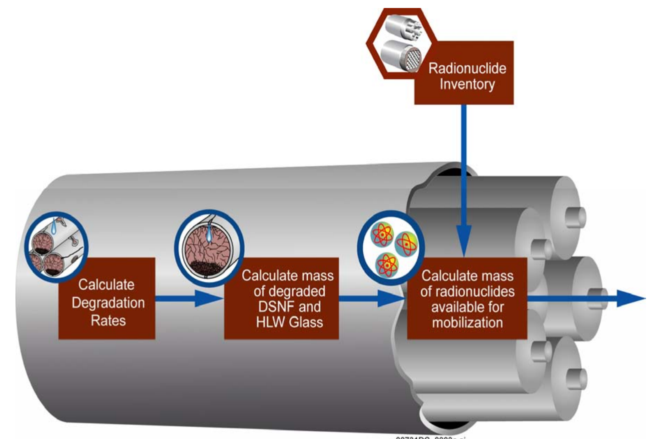
Model Assumptions (continued)

- Bulk water chemistry calculated by a well mixed batch reactor model is applicable to thin films of water
- Thermodynamic database for dilute solutions is used in the in-package chemistry calculations

Source Term Conceptual Model

- The chemistry inside a breached WP is abstracted from process models performed using geochemical equilbrium codes
- In a breached WP:
  - Inventory is available only after the cladding, if any, is breached
  - Unbound inventory is immediately available
  - Bound inventory is available once the fuel matrix begins to degrade
- The amount of inventory available for transport is constrained by the release rate from the waste form (WF) and the solubility of the radioelements in the available water within the WP





Treatment of Uncertainty and Variability

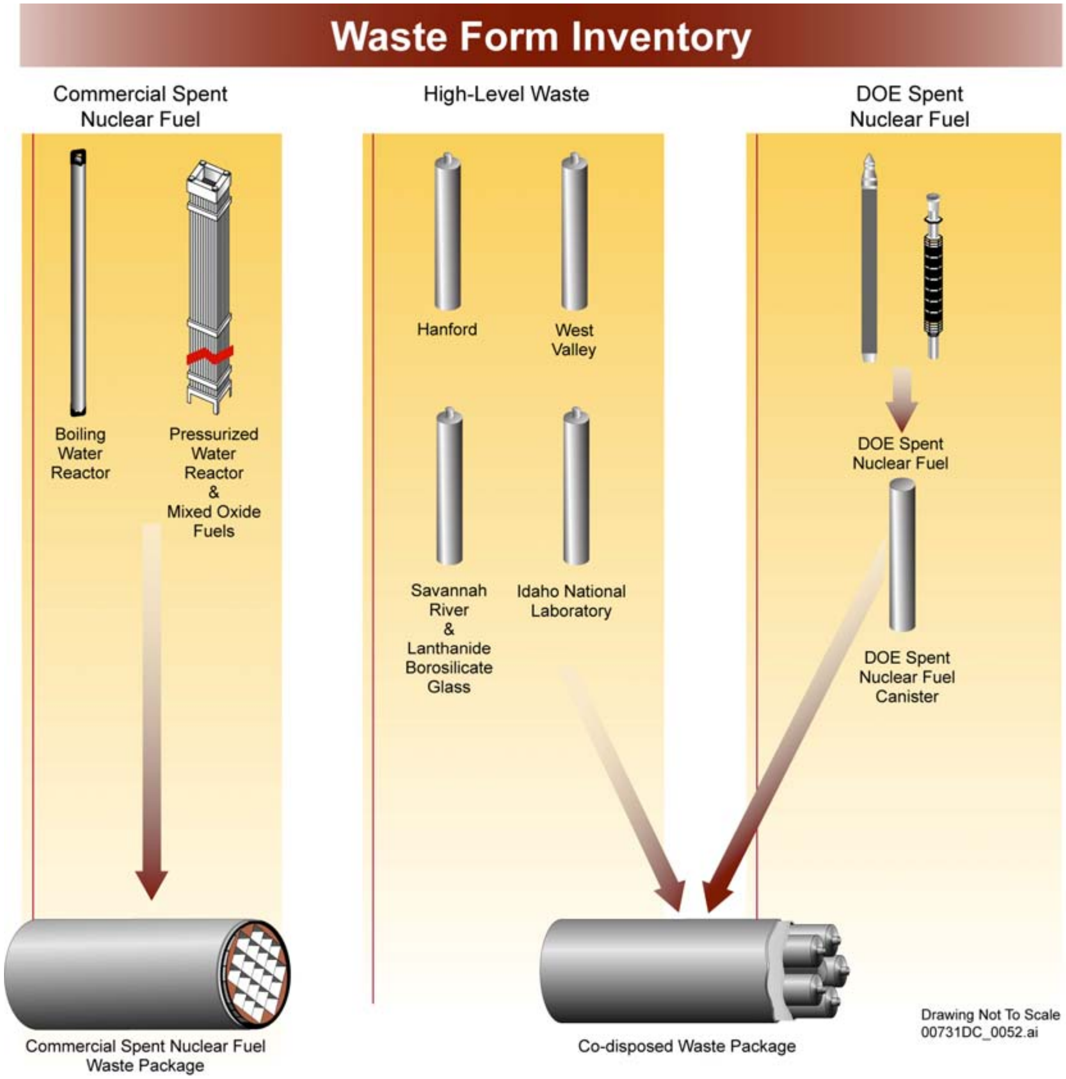
- **Treatment of uncertainties**
  - **Initially failed cladding and unbound inventory**
    - **Propagates uncertainty in the amount of commercial spent nuclear (CSNF) initially available for transport**
  - **In-package chemistry**
    - **Uncertainty in the pH and ionic strength affects WF degradation rates, colloid stability, and radioelement solubility**
  - **WF degradation rates**
    - **Propagates uncertainty in the rate that the CSNF fuel and high-level radioactive waste (HLW) glass release radionuclides from the fuel matrix**
  - **Solubility**
    - **Propagates uncertainty in the the amount of inventory that can dissolve within the in-package water**
- **Treatment of variability**

Technical Bases for Abstractions

- **Cladding failure derived from available data on failures during reactor operation**
- **WF degradation rate models derived from available literature and experimental data**
  - **CSNF matrix oxidation and oxidative dissolution processes**
  - **HLW glass dissolution**
- **Chemistry and solubility modeled using chemical equilibrium codes, EQ3/6 and PHREEQC, and a qualified thermodynamic database**

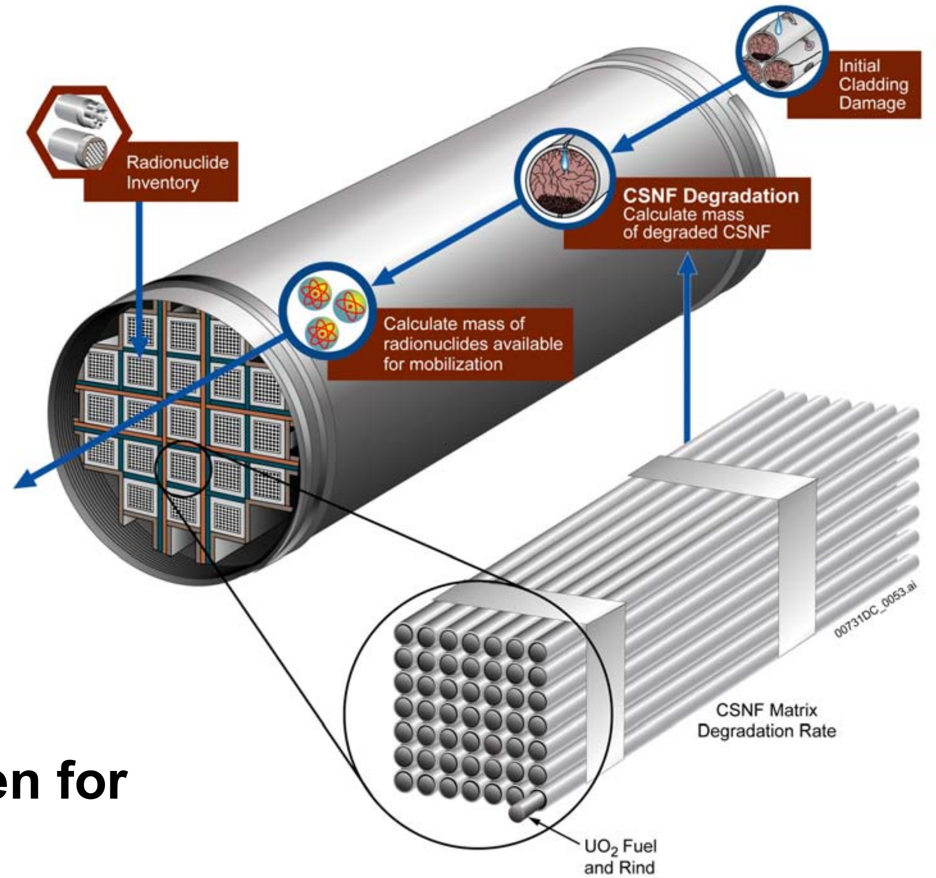
Inventory—Implementation

- **Inventory averaged over WP types**
  - **Year 2060 inventory**
- **CSNF WP contains:**
  - **PWR, BWR, MOX fuel**
  - **Zircaloy and stainless steel clad fuel**
- **Co-disposal WP contains:**
  - **Defense spent nuclear fuel (DSNF)**
  - **HLW, lanthanide borosilicate glass (LaBS)**



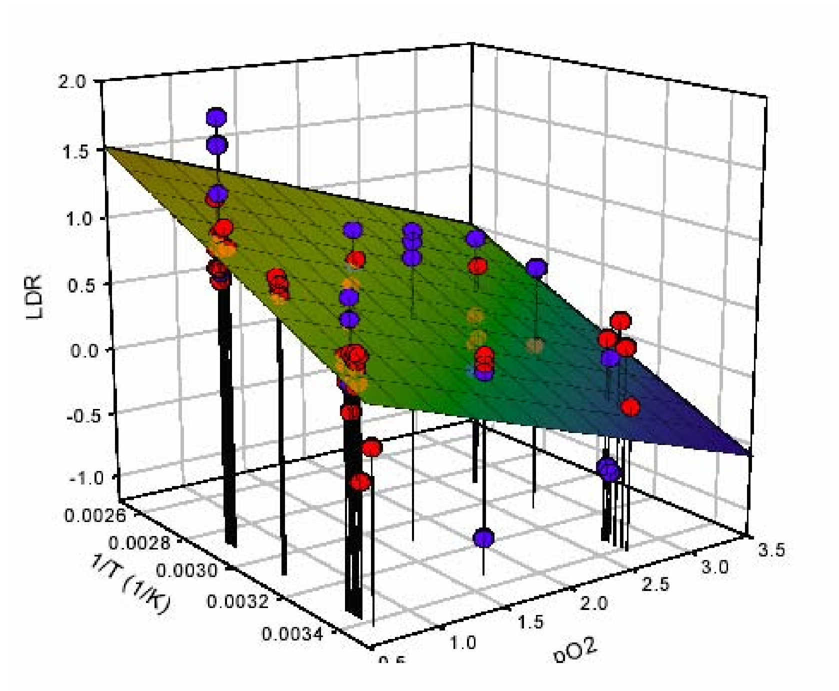
Cladding—Implementation

- **Stainless steel cladding**
  - **~1% of the CSNF fuel**
  - **No performance credit**
- **Zircaloy cladding**
  - **0.01% – 1% as-received failures**
  - **Performance credit is taken for intact cladding**
- **Mechanical damage from disruptive events**



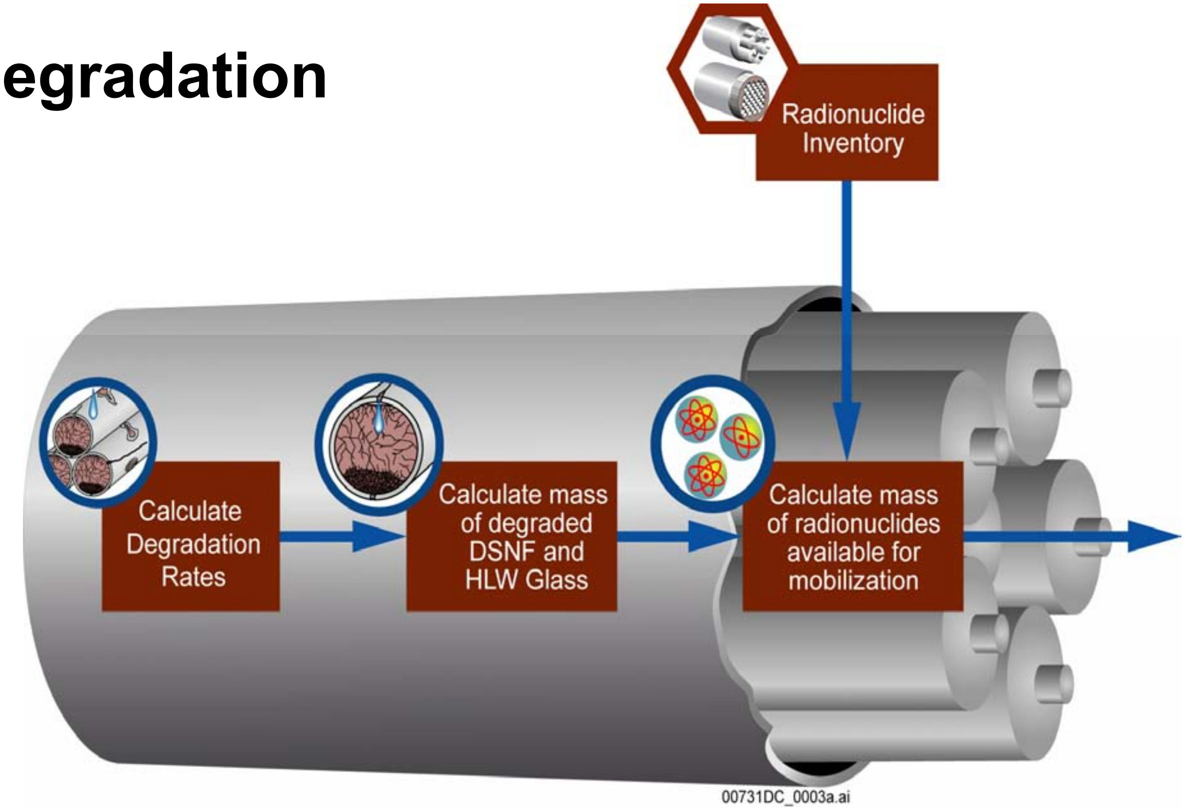
CSNF WF Degradation—Implementation

- **WF degradation begins when the cladding fails**
- **Instantaneous release of hardware inventory (C) and the gap and grain boundary inventory (Cs, Tc, Sr, I)**
  - **Range 0.01% – 26%**
- **Fractional degradation rate for CSNF**
  - **Function of T, pH, P_{O2}, CO_3 concentration**
  - **Coefficients in the regression equation include epistemic uncertainty**



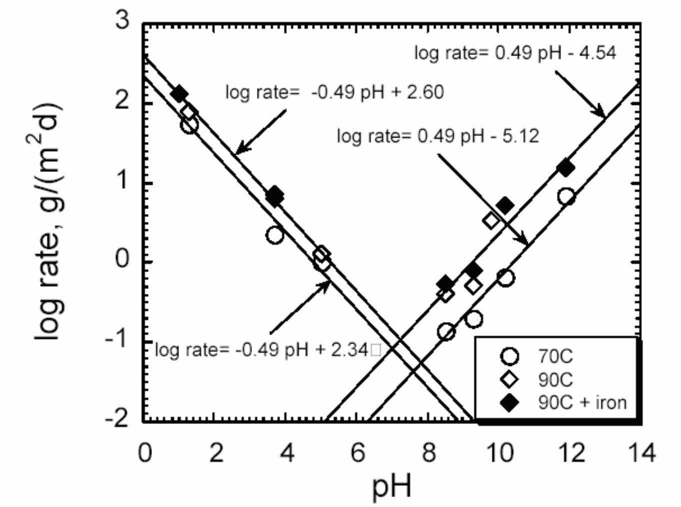
DSNF WF Degradation—Implementation

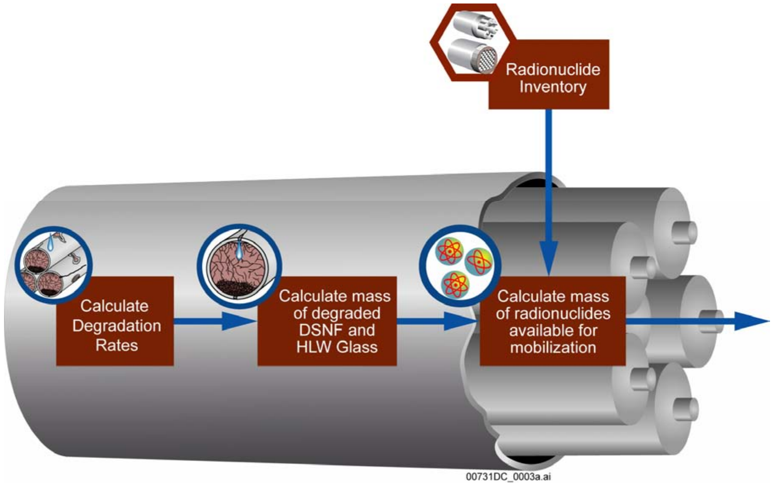
- **TSPA model uses one surrogate for ten DSNF groups**
- **Instantaneous degradation of DSNF**



HLW Glass Degradation—Implementation

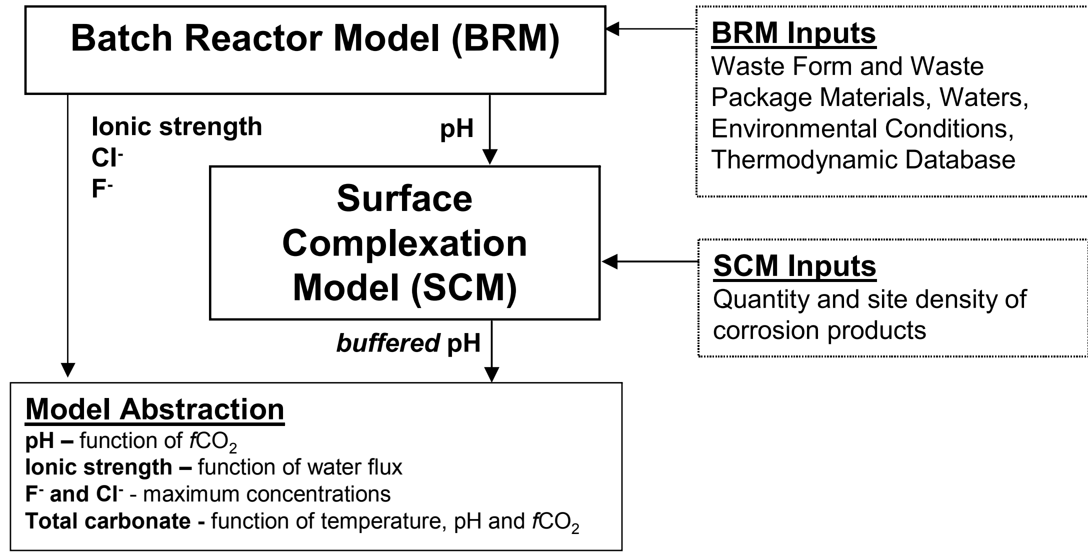
- One surrogate to represent full range of disposed glass degrading in humid air, dripping or immersion conditions
- Fractional degradation rate for HLW glass
  - RH < 44%: Rate = 0 yr^{-1}
  - Function of T, pH
  - Coefficients in the regression equation include epistemic uncertainty





In-Package Chemistry—Implementation

- P_{CO2} and P_{O2} are in equilibrium with the drift
- pH (range 4.5 – 8.5)
  - Fuel type
  - Dripping conditions
  - P_{CO2}
  - Exposure time



- Ionic strength (range 1×10^{-3} molal to 4 molal)
  - Fuel type
  - Dripping conditions
- Total carbonate *f* (pH, T, P_{CO2})

Solubility—Implementation

- Solubility Models for Ac, Am, Np, Pa, Pu, Ra, Se, Sn, Th, and U
  – Solubilities are functions of pH and P_{CO2} presented as look-up tables for the solubility controlling phase(s)
  – Uncertainty associated with thermodynamic properties is included
  – Uncertainty associated with variations in water chemistry is included
- No solubility limit for other radioelements
- Solubility controlling phase(s)
  – PuO_2 (hyd, aged)
  – NpO_2 within the WPs (currently)
  – Np_2O_5 within the invert
  – Schoepite + Na-boltwoodite (U phases) within co-disposal WPs and invert, within CSNF WPs for igneous scenario

Anticipated Changes Since TSPA-SR

- **Fraction of initially failed cladding**
- **Treatment of uncertainty and degradation rate model coefficients**
- **In-package chemistry functionality and range**
- **Solubility model**

Engineered Barrier System (EBS) Radionuclide Transport

Presented to:
DOE/NRC Technical Exchange on Total System Performance Assessment (TSPA) for Yucca Mountain

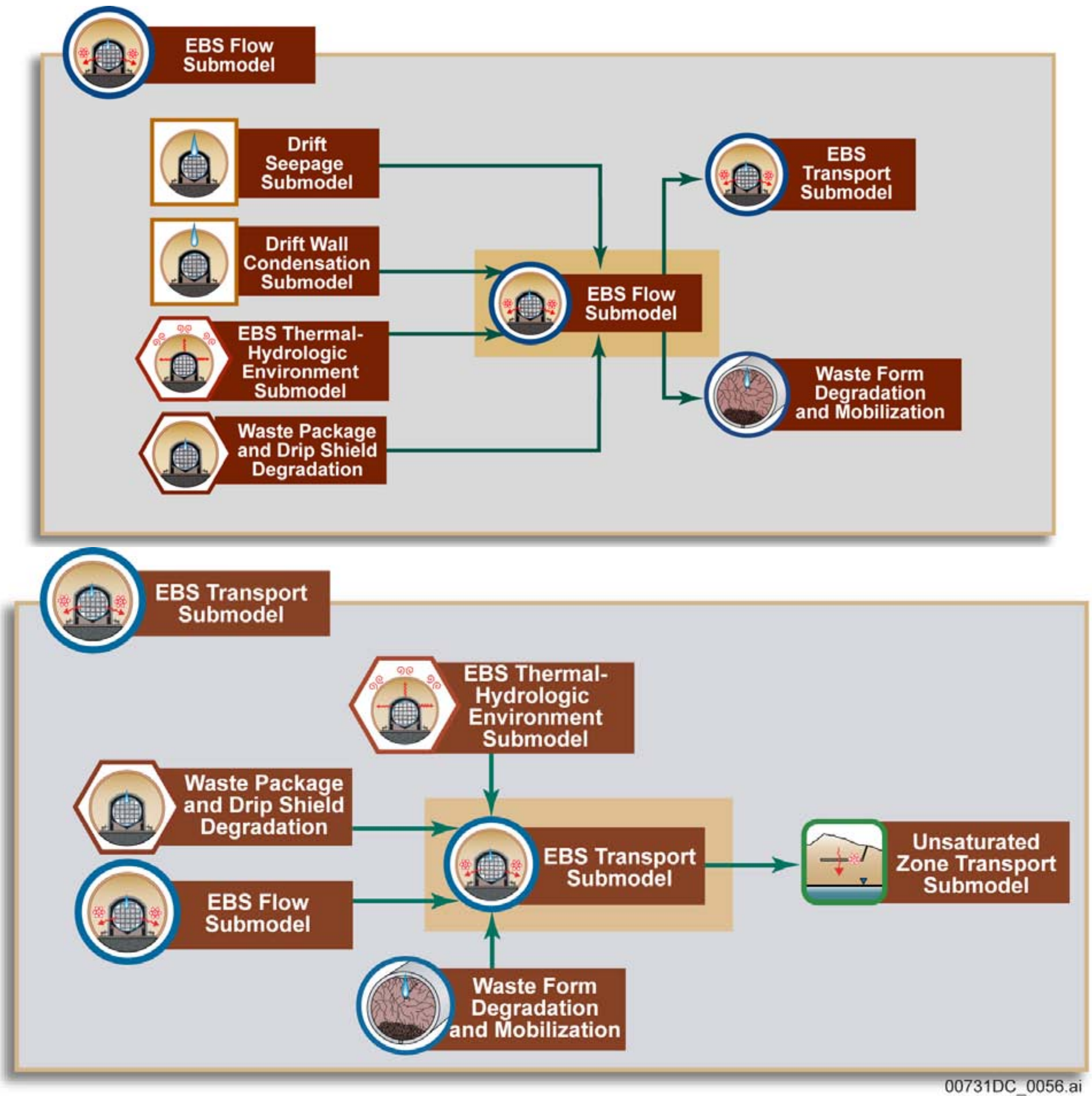
Presented by:
Sunil Mehta
Intera Inc.

October 25, 2006
Las Vegas, Nevada

Presentation Outline

- Identification and linkage of abstractions
- Abstraction
  – Objectives
  – Input, output, and basis for model confidence
  – Assumptions
  – Conceptual model
  – Treatment of uncertainty and variability
  – Technical bases for abstraction and references
  – Implementation in TSPA model
- Anticipated changes since TSPA for site recommendation (SR)

Identification and Linkages of Abstractions



Objective of EBS Transport Abstraction

- **Computes the advective and diffusive radionuclide mass flux through various components of the EBS once the waste form is degraded**
- **Provides time-dependent radionuclide mass flux from EBS to the fracture and matrix nodes of the unsaturated zone (UZ) transport model**

Inputs, Outputs, Basis for Model Confidence

EBS Thermal-Hydrologic Environment Submodel
- Liquid Saturation in Invert
- Temperature and Relative Humidity at Waste Package
- Imbibition Flux in Invert

Waste Package and Drip Shield Degradation
- Time of Failure
- Number of Patch Breaches/Failed WP
- Number of SCC Breaches/Failed WP
- Number of Early Failed WPs
- Number of LC Failed WPs
- Number of GC and SCC Failed WPs

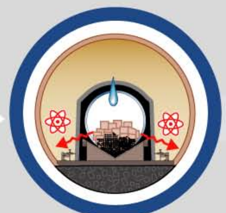
EBS Flow Submodel
- Flow Through the Waste Package and Invert

Waste Form Degradation and Mobilization
- Dissolved Concentration Limits
- Dissolution Rates
- Irreversibly Sorbed Radionuclide Mass on Colloid
- Reversibly Sorbed Radionuclide Mass on Colloid

Invert Material Properties
- Porosity and Diffusion Coefficients in Crushed Tuff

EBS Transport Submodel
- *One-Dimensional Advective and Diffusive Transport Through the EBS*
  - *Retardation of Dissolved Species*
  - *Colloid Transport Included*
  - *Liquid Films Always Allow Diffusion Through WP Stress Corrosion Cracks*

Inputs



Outputs

Unsaturated Zone Transport Submodel
- Radionuclide Mass Release Rate to the Unsaturated Zone

- Laboratory Data for Diffusivity of Unsaturated Crushed Tuff
- Process-Level Modeling of EBS Response

Model Confidence Foundation

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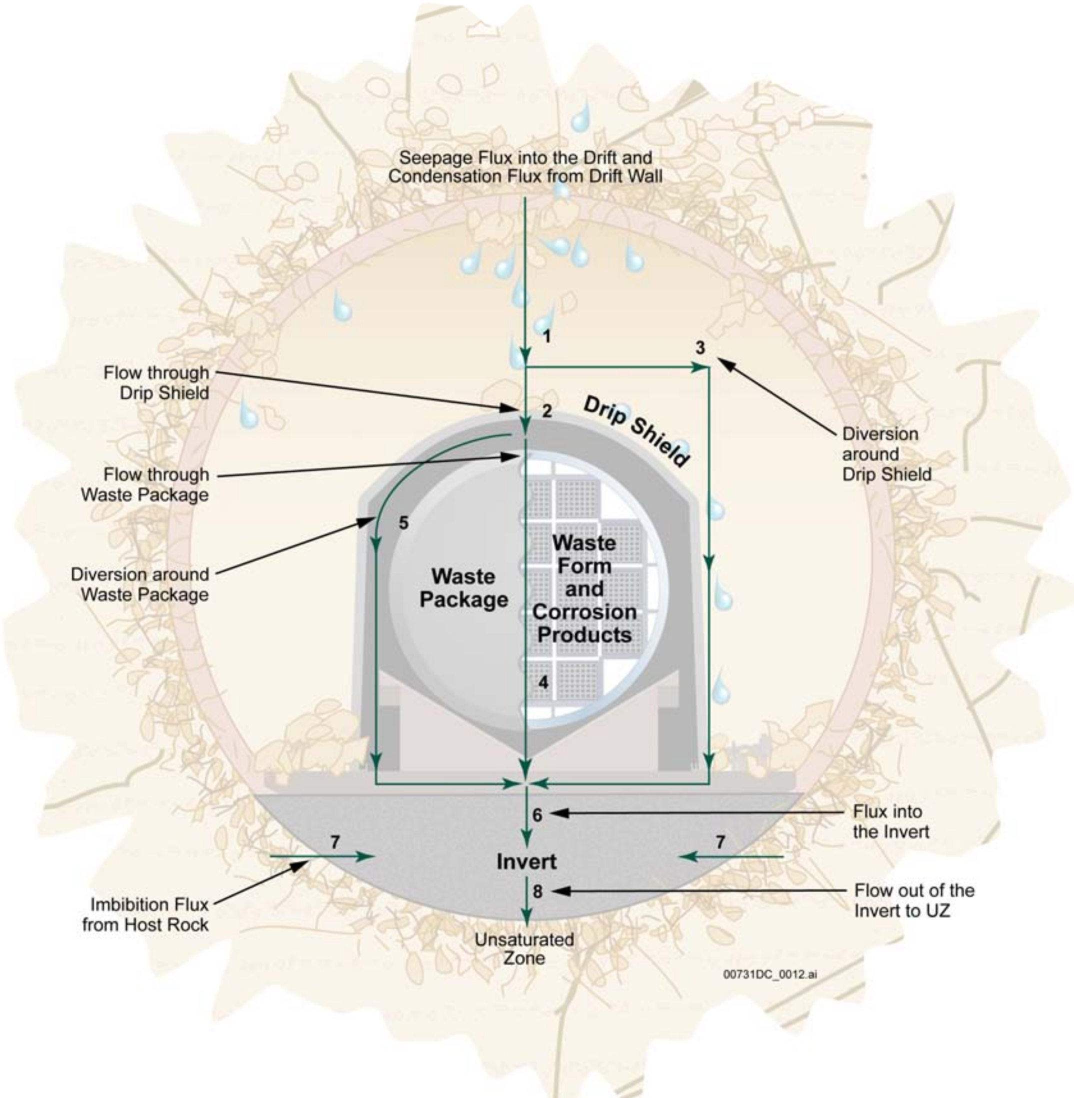
Model Assumptions

- No radionuclide transport when temperatures are above 100°C
- Presence of continuous thin films on the internals of the waste package (WP) and waste form (WF) (after WP breach and WP Temp <100°C)
  - For diffusive transport under no water flow conditions
- WP is assumed to be in contact with the invert
  - Continuous thin water film assumed between WP and invert for diffusive transport under no water flow conditions
- All drift-seepage falls onto drip shield (DS) (and WP)

EBS Flow Conceptual Model

- **EBS flow model describes the mass balance of water within various EBS components**
- **8 flow paths are considered**



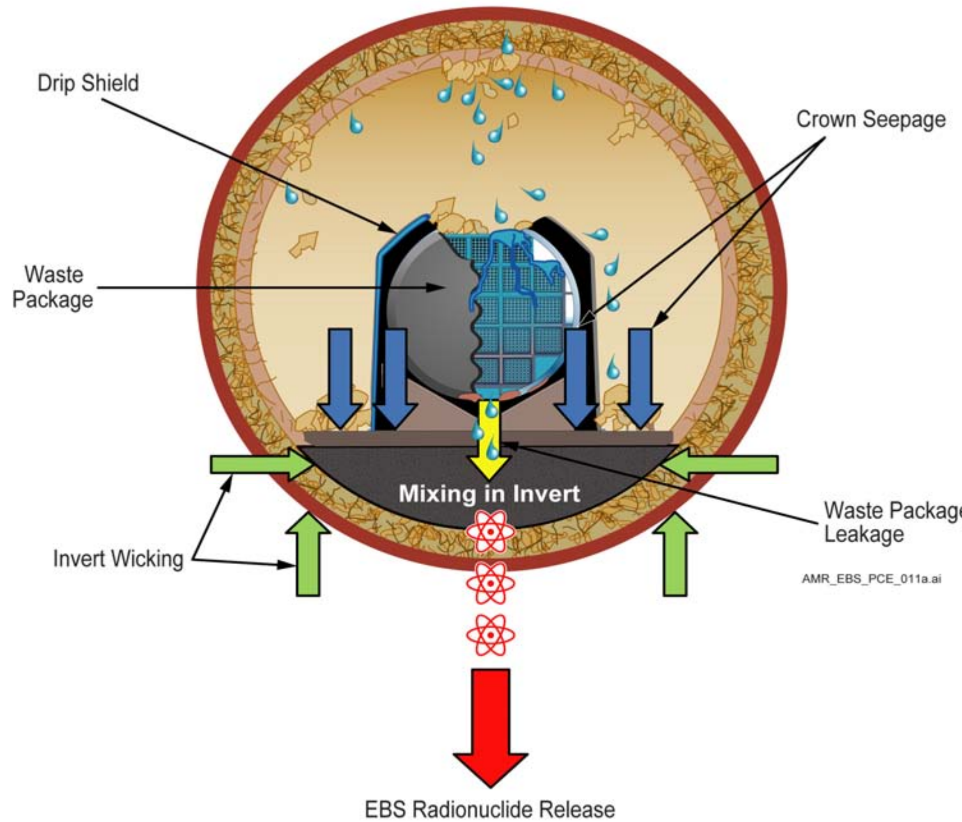
Modified from ANL-WIS-PA-000001 REV 02

EBS Flow Conceptual Model (continued)

- Flow through drip shield and waste package breaches (patches) represented by flux splitting model with uncertainty due to:
  - Patch location with respect to drip location and crown location
  - Splatter distribution, rivulet spread
  - Patch interference, variable patch size
- Flow through stress corrosion cracks is screened out (for WP and DS)
- Flow through the invert is based on the dual continuum representation of invert: intergranular and intragranular continuum
- Imbibition flux (from host rock), drift seepage flux, and drift wall condensation flux combined in the invert

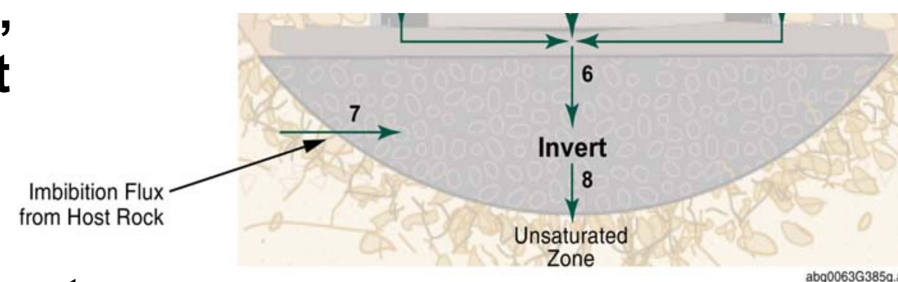
EBS Transport Conceptual Model

- **Once the waste form starts degrading the mass is released through the breached WP into the invert and to the UZ**
- **1D and 2D advective and diffusive transport model that includes sorption and radioactive decay**
- **Both dissolved and colloid facilitated transport considered**
- **Affect of continued degradation of WP internals included**
- **Chemical conditions inside the WP and invert (for solubility and colloid stability calculations) determined separately**



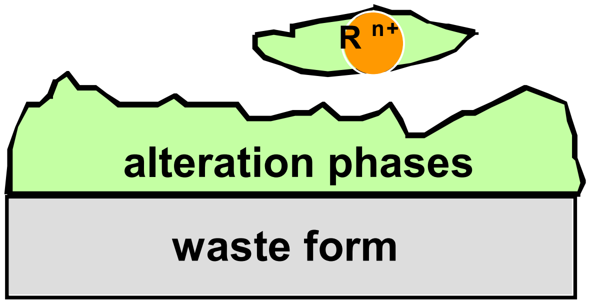
EBS Transport Conceptual Model (continued)

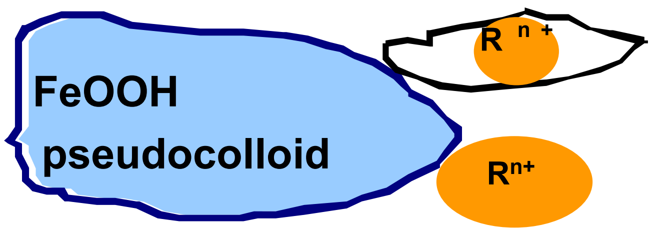
- Transport modeled to occur through porous medium in the WP
- Invert considered to be single continuum for transport calculations
- Part of UZ domain (near and below invert) is modeled as a dual continuum (fracture and matrix), consistent with the UZ transport model
- It is used to apply boundary condition for diffusion out of invert and to determine the fracture/matrix mass flux split

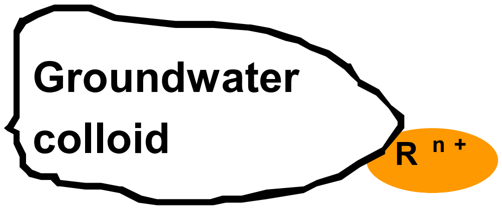


EBS Transport Conceptual Model (continued)

- **Colloid-facilitated transport in EBS: three types of colloids modeled**
  - Waste form colloids
    - Smectite and U-oxide mineralogy
  - Iron oxyhydroxide (corrosion product) colloids
    - Ferrihydrite, goethite, hematite mineralogy
  - Groundwater (seepage water) colloids
    - Smectite mineralogy

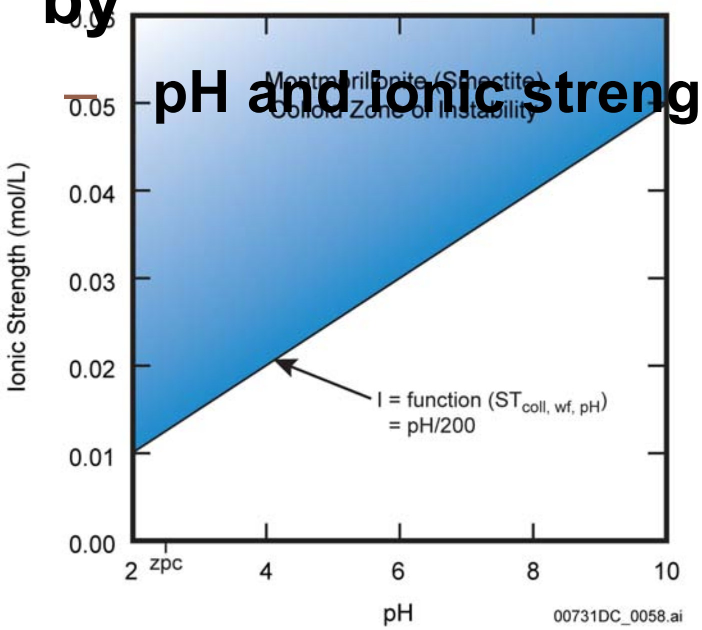


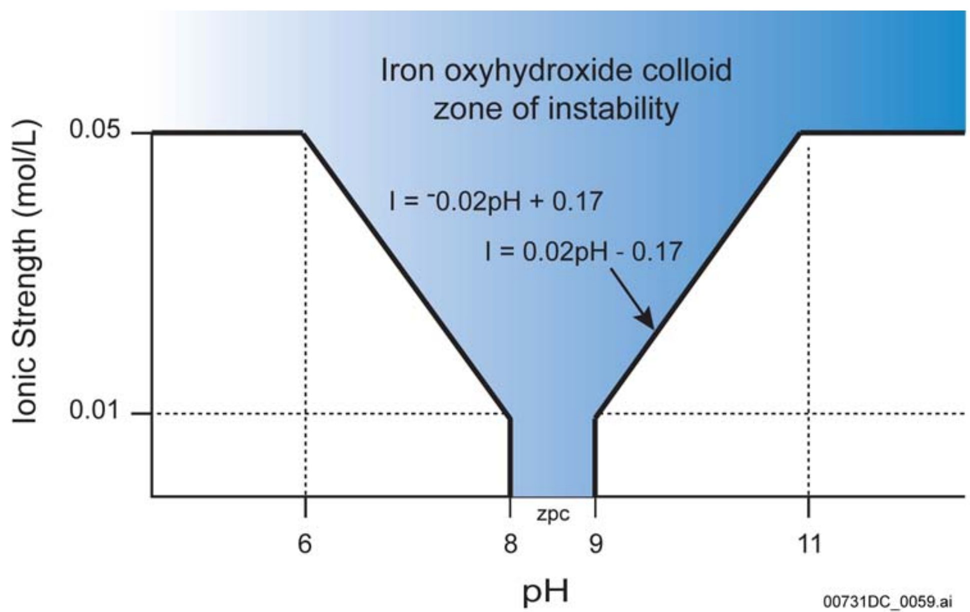




EBS Transport Conceptual Model (continued)

- **Colloid concentration distributions are derived based on**
  - **Laboratory experiments**
  - **Field data**
- **Colloid stability inside WP and invert is controlled by**
  - **pH and ionic strength**





Source: Modified from *Waste Form and In-Drift Colloids-Associated Radionuclide Concentrations: Abstraction and Summary*, MDL-EBS-PA-000004 REV 02

EBS Transport Conceptual Model (continued)

- Three different radionuclide sorption processes considered on colloids
  - Equilibrium (reversible) sorption on all three colloid types
    - Currently Pu, Am, Pa, Th, and Cs
  - Embedded (irreversible) mass sorption on waste form colloids
    - Pu and Am embedded inside the waste form glass
  - Kinetic sorption on iron oxyhydroxide colloids
    - First-order rate law
    - Currently applied towards sorption of Pu and Am

Treatment of Uncertainty and Variability

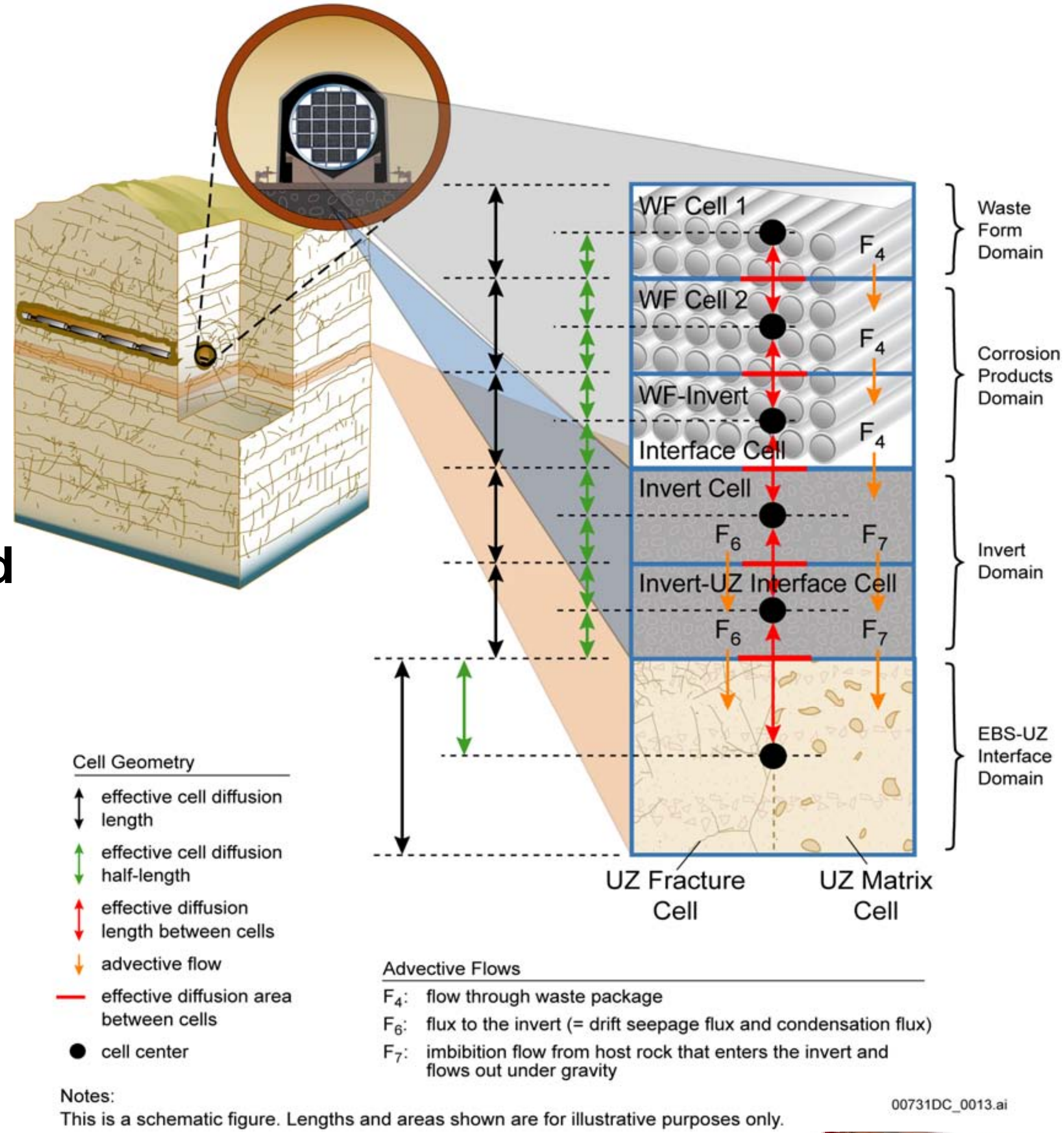
- **Treatment of uncertainties**
  - Diffusion coefficient (invert); diffusive length (WP)
  - Steel corrosion rates inside the WP
  - Equilibrium and kinetic rate constants for sorption
  - Hydrologic properties (near field UZ)
  - Colloid concentrations
  - Uncertainty in flow through breached DS and WP
- **Treatment of variability**
  - Percolation subregions considered are spatially variable
  - Each percolation subregion further divided into dripping and nondripping environments

Technical Bases for Abstraction

- **Transport parameters**
  - Sorption parameters based on lab and field measurements
  - Colloid concentrations and stability ranges based on lab measurements and literature
  - Diffusion coefficient for invert is based on lab measurements
  - Hydrologic properties calibrated to moisture content, water potential, pneumatic data, and perched water
- **Validation**
  - Coupled flow and transport model validated by peer-review, by comparison to process-level model results, and by comparison to mock-up experiments
- **References**
  - EBS Radionuclide Transport Abstraction, ANL-WIS-PA-000001 REV 02
  - Waste Form and In-Drift Colloids-Associated Radionuclide Concentrations: Abstraction and Summary, MDL-EBS-PA-000004 REV 02

EBS Transport—Implementation

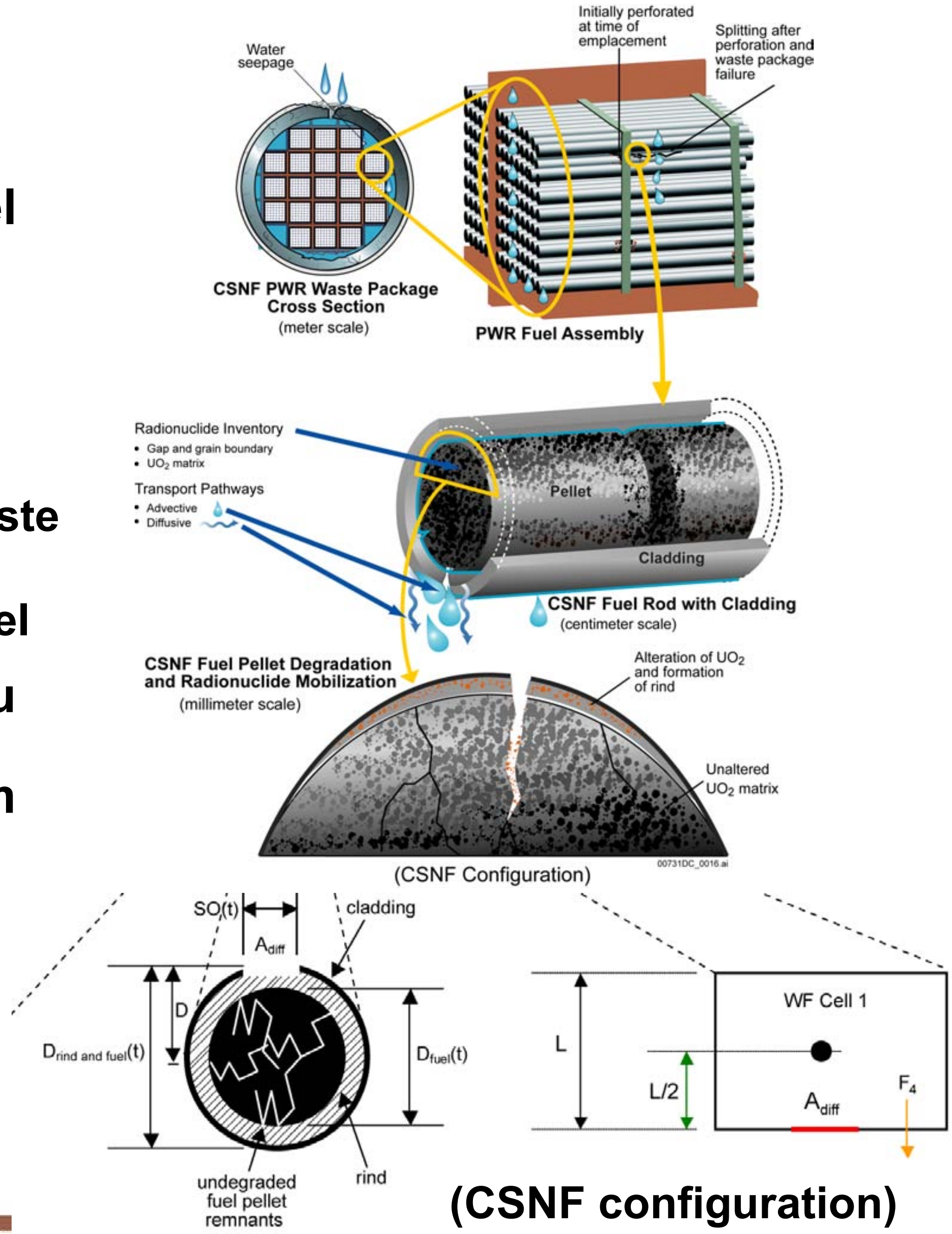
- **Implemented using Cell pathway capability of GoldSim**
- **Solved as a coupled system of equations in a cell-net (finite difference network)**
- **Each decay-family solved separately**
- **Model discretized into four transport domains**



WF Domain—Implementation

- **Commercial spent nuclear fuel (CSNF)—single waste form domain; represents fuel rods**
- **Co-disposal—two WF sub-domains**
  - **High-level radioactive waste (glass logs)**
  - **Defense spent nuclear fuel**
- **WF colloids are generated. Pu and Am are embedded (irreversibly) in the waste form glass colloids (currently)**
- **Diffusive length and area is based on the fuel alteration and formation of rind**
- **Diffusion coefficient**

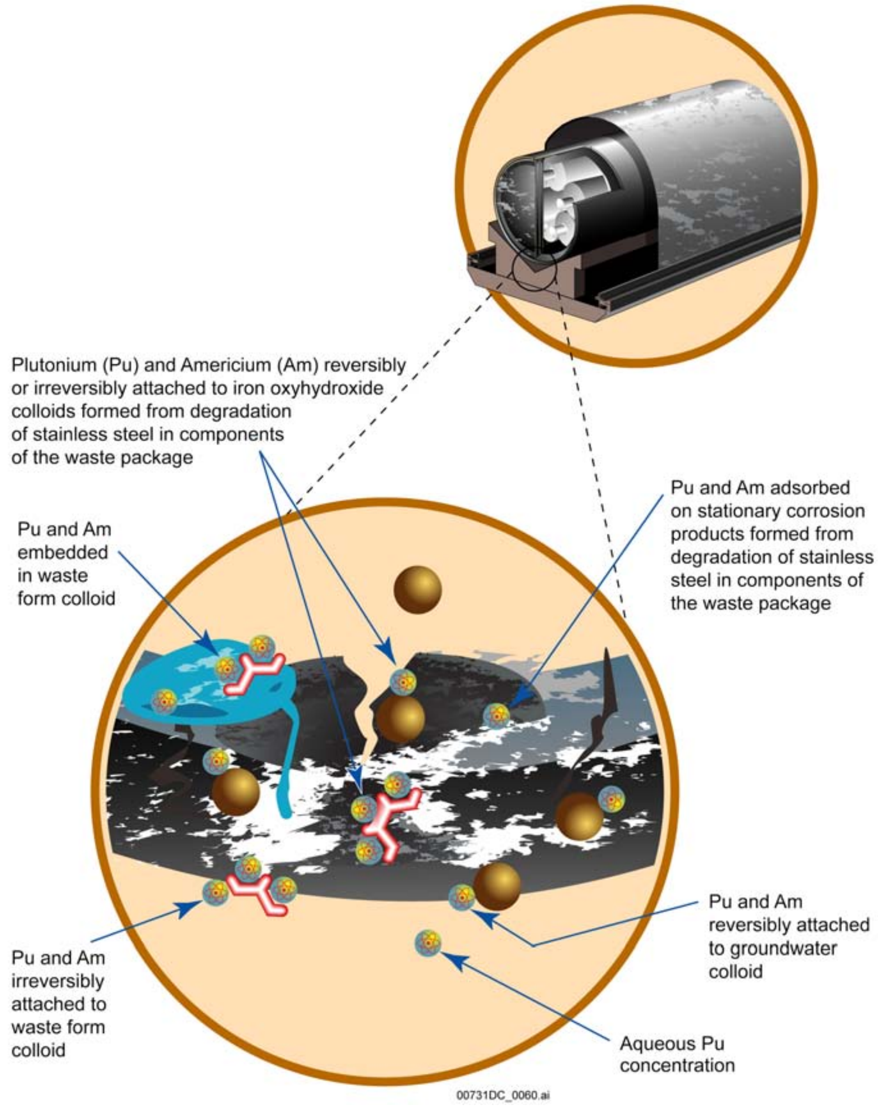
$$D_{WF} = \phi^{1.3} S_w^{\ 2} D_0$$



(CSNF configuration)

Corrosion Product Domain—Implementation

- Represents steel corrosion products (iron oxyhydroxides) from degradation of basket material and other support structure inside the WP
- Iron oxyhydroxide colloids are formed here
- Equilibrium and kinetic sorption modeled on the stationary corrosion products and iron oxyhydroxide colloids
- For CSNF (with no water flux through WP) saturation is based on adsorption isotherm of iron oxides as a function of RH
- $D_{CP} = \phi_{CP}^{1.3} S_w^{2} D_0$
- Diffusive area is the WP breached area; Diffusive length is sampled



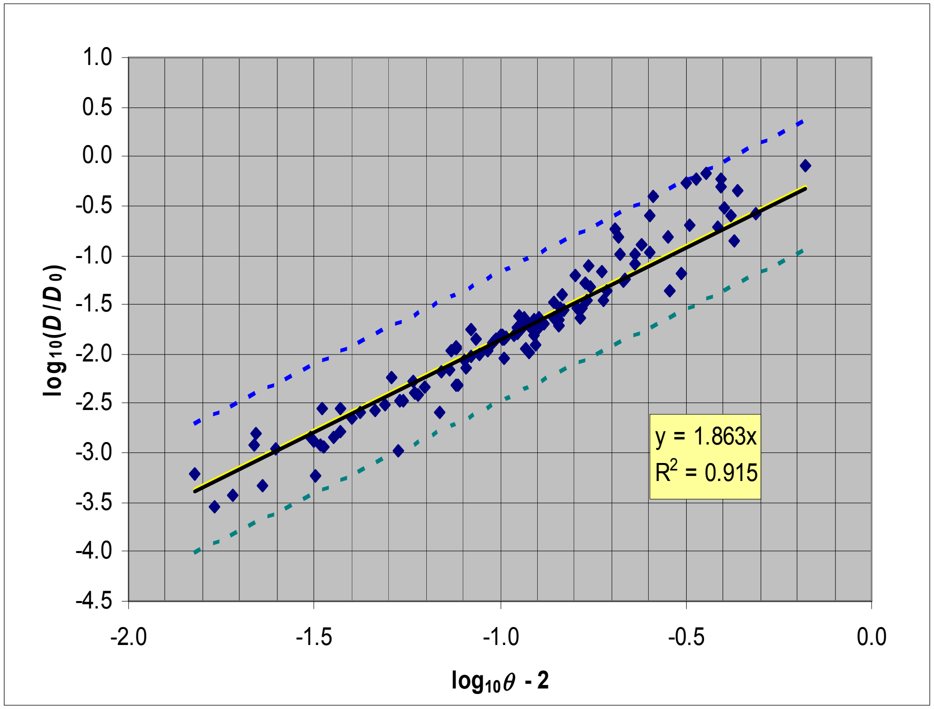
Invert Domain—Implementation

- **Assumes rectangular geometry using an average thickness (fixed diffusive length and area)**
- **Reversible sorption on the crushed tuff modeled**
- **Iron oxyhydroxide and groundwater colloids can occur**
- **Water volume of invert is based on computing the bulk water content from dual continuum representation of invert: intergranular and intragranular continuum**
- **Diffusion Coefficient:**

  (based on experimental data)

$$D = D_0 \phi^{1.863} S_w^{1.863} 10^{ND(\mu=0.033,\sigma=0.218)}$$

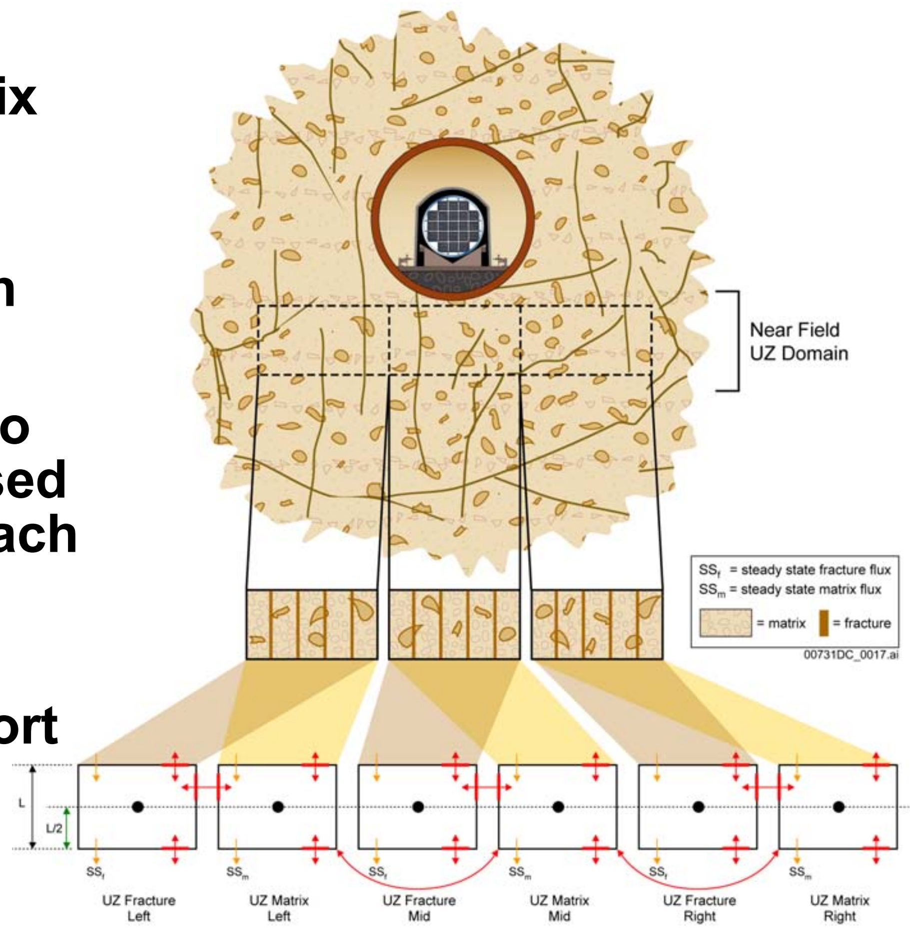
ND = Normal Distribution



Based on dataset in ANL-WIS-PA-000001 REV 02

EBS-UZ Interface Model Domain—Implementation

- **2D dual continuum UZ domain (fracture and matrix continua)**
- **Reversible sorption in the UZ matrix continuum**
- **Hydrologic properties and percolation flux are consistent with the 3D UZ model**
- **Mass flux (g/yr) going from invert to UZ domain is intercepted and passed to UZ transport model (FEHM) at each time step for each radionuclide**
- **Mass flux introduced into fracture and matrix nodes of the UZ transport model (FEHM) is based on the advective and diffusive mass flux going into the fracture and matrix cells of the EBS-UZ domain**



Colloid-Facilitated Transport—
Implementation Treatment at EBS-UZ Interface

- **The reversibly transported radionuclide mass is combined with the dissolved mass at the EBS-UZ boundary**
  - **The total mass is repartitioned in the UZ and SZ on one type of colloid particle (groundwater colloids) based on the Kc approach**
- **The irreversibly transported radionuclide mass (currently Pu and Am) is combined and transported as two types of colloid particles in the UZ and SZ, namely:**
  - **Fast irreversible fraction (virtually unretarded; small fraction)**
  - **Slow irreversible fraction (variably retarded; predominant fraction)**

Anticipated Changes Since TSPA-SR

- Add near-field UZ cells to better represent diffusion boundary condition in EBS and to partition the mass release to fracture and matrix nodes of the UZ transport model
- Add corrosion products domain for better discretization of the transport through the WP
- Add kinetic sorption of Pu and Am on iron oxyhydroxide colloids and stationary corrosion products (in corrosion products domain), and equilibrium sorption of other actinides
- Add TADs related changes to the mass of corrosion products (affects amount of sorption)
- Add water flux splitting model for flow through breached DS and WP
- Add water adsorption isotherm to compute water volume in the corrosion products domain
- Invert saturation based on dual continuum representation

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Unsaturated Zone (UZ) Radionuclide Transport

Presented to:
DOE/NRC Technical Exchange on Total System Performance Assessment (TSPA) for Yucca Mountain

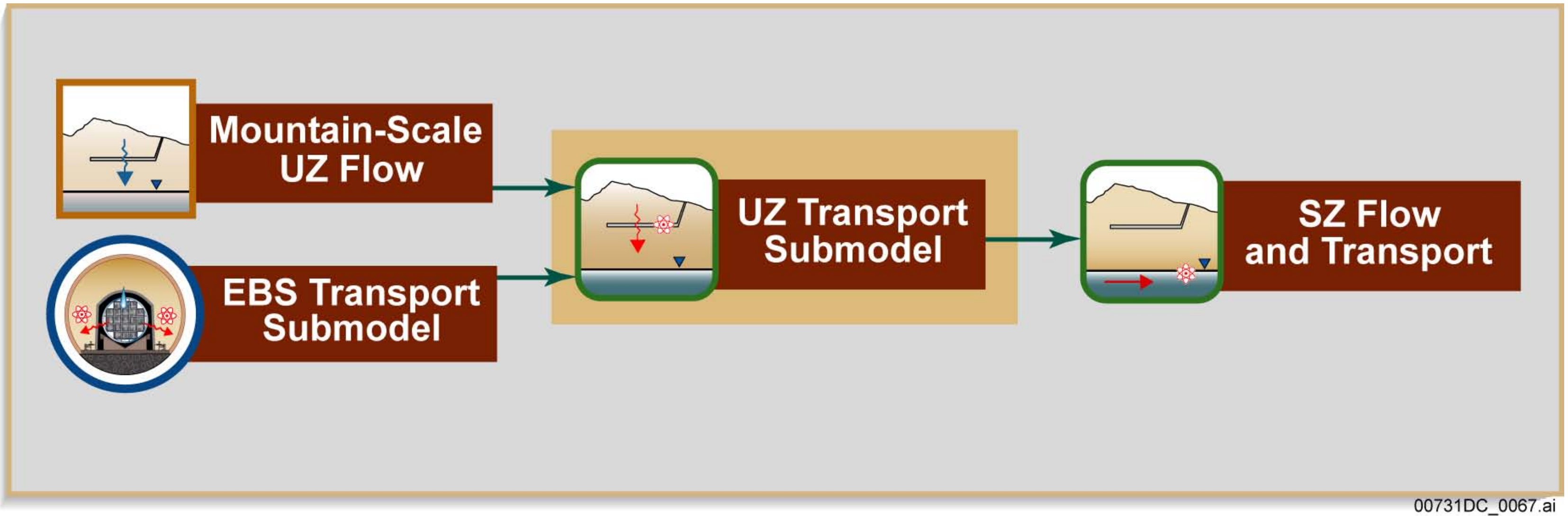
Presented by:
James Houseworth
Lawrence Berkeley National Laboratory

October 25, 2006
Las Vegas, Nevada

Presentation Outline

- **Identification and linkage of abstractions**
- **Abstraction**
  - **Objectives**
  - **Inputs, outputs, basis for model confidence**
  - **Assumptions**
  - **Conceptual model**
  - **Treatment of uncertainty and variability**
  - **Technical bases for abstraction and references**
  - **Implementation in TSPA model**
- **Anticipated changes since TSPA for site recommendation (SR)**

Identification and Linkages of Abstractions



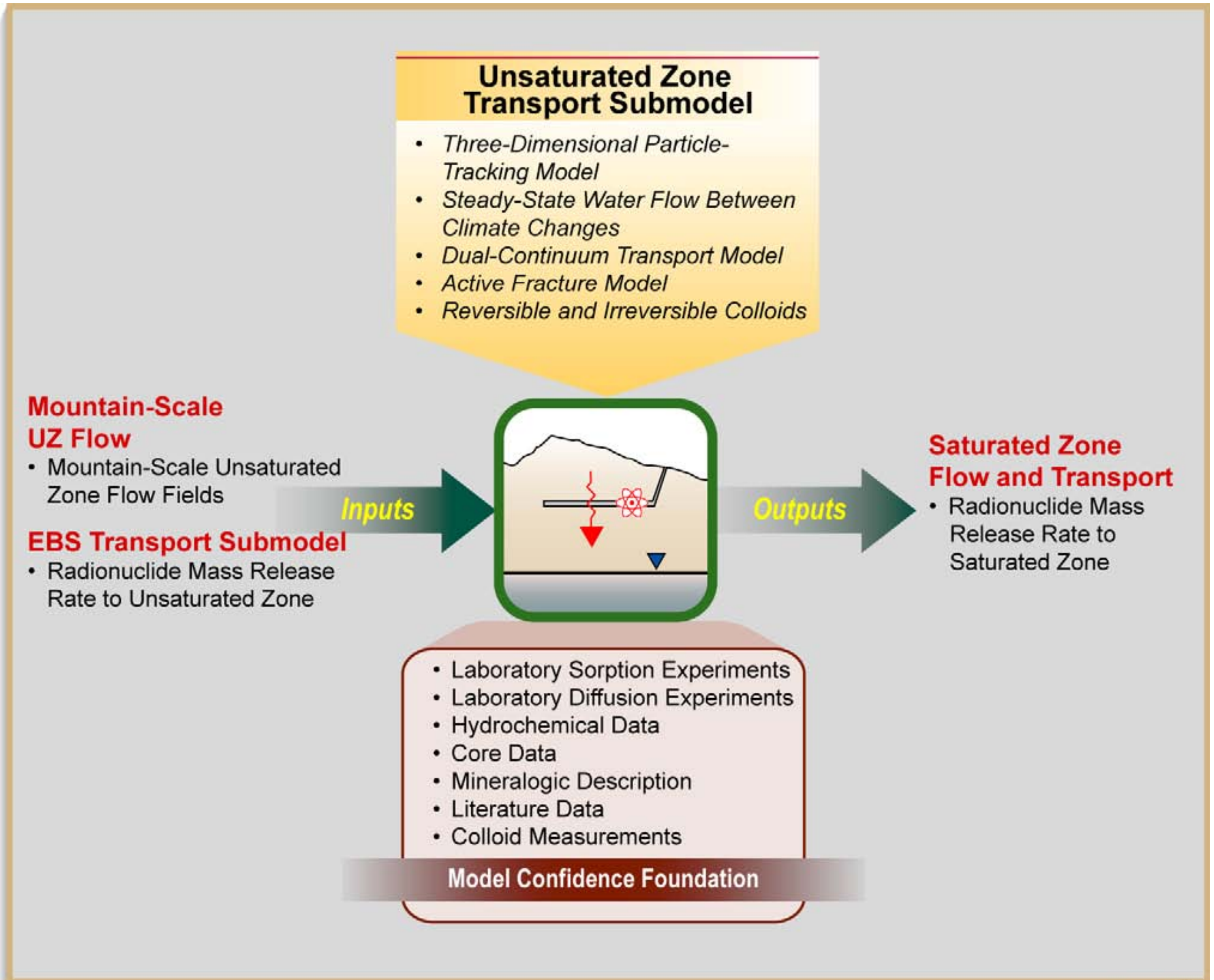
EBS = Engineered Barrier System

SZ = saturated zone

Objective of UZ Transport Abstraction

- **Provide radionuclide mass flux at the water table as a function of location and time for performing radionuclide transport calculations in the SZ**
- **The model output also distinguishes aqueous radionuclide mass flux and radionuclide mass flux irreversibly attached to colloids**

Inputs, Outputs, Basis for Model Confidence



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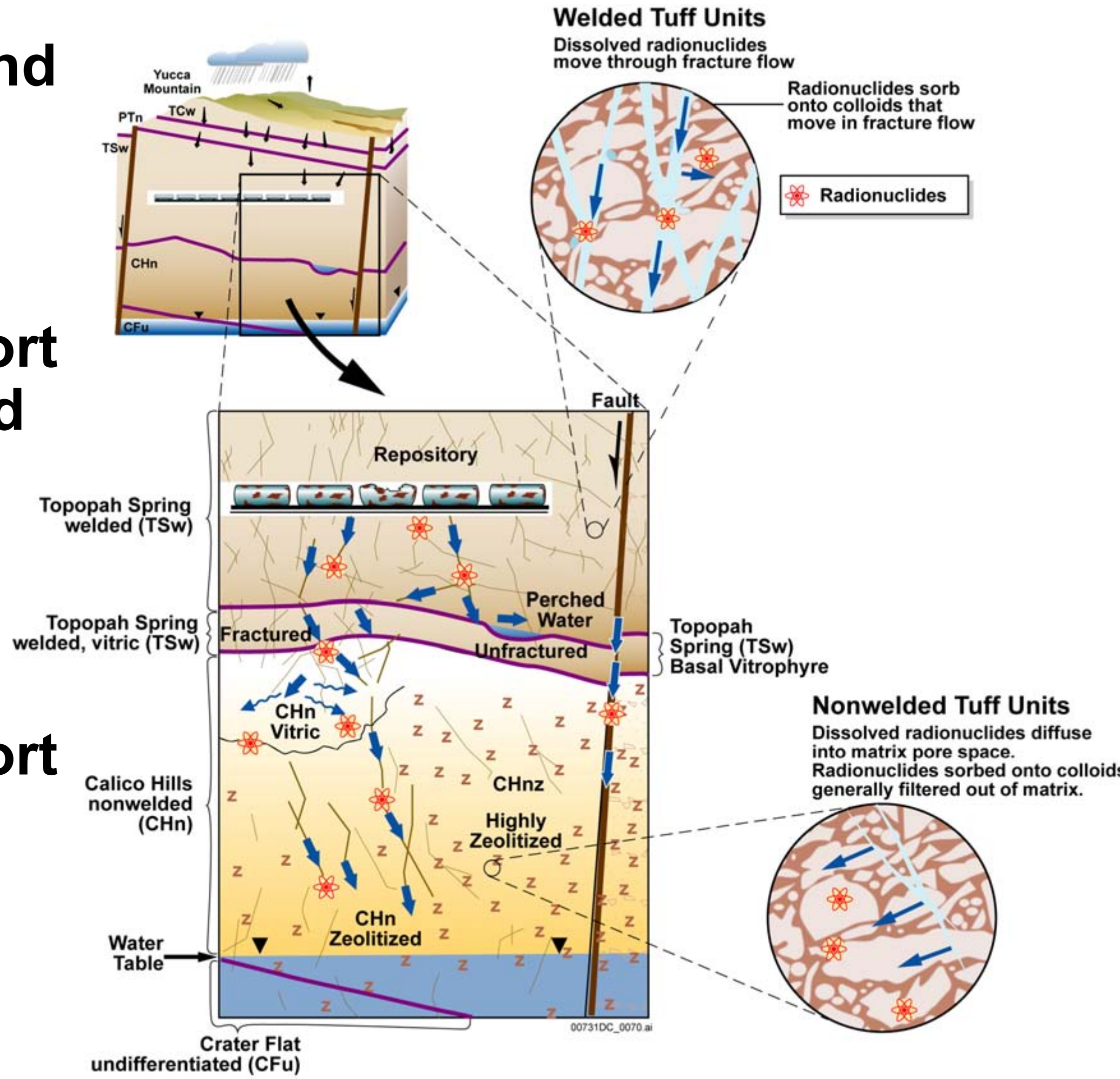
Model Assumptions

- Steady state, calibrated flow fields under ambient thermal conditions can be used to simulate radionuclide transport
- Climate-induced changes to UZ flow occur instantaneously
- Sorption occurs reversibly, subject to a linear, equilibrium (K_d) sorption model

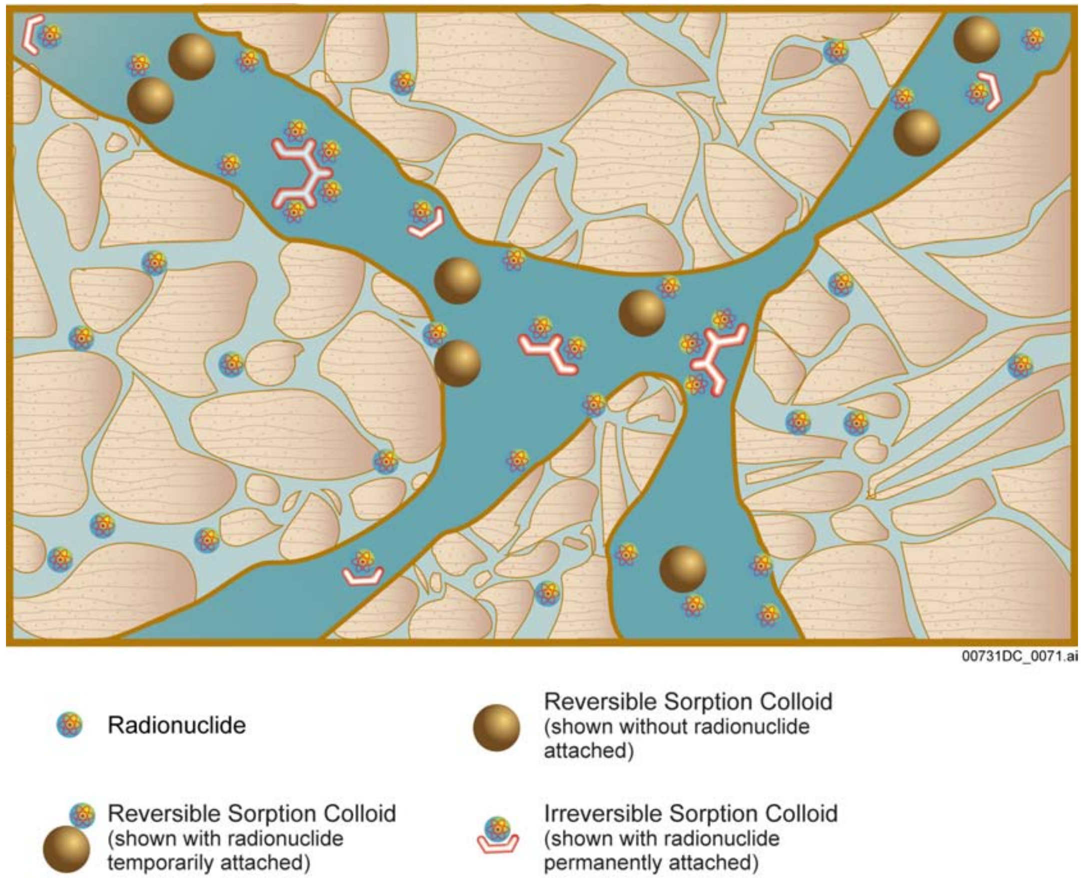
Overview—Conceptual Model

- Combined fracture and matrix flow: dual-continuum model formulation
- Radionuclide transport through fractures and matrix: advection, diffusion, sorption, colloid-facilitated transport
- Radionuclide transport is simulated using ambient flow fields
- Releases to both fractures and matrix



Overview—Conceptual Model
Colloid Transport

- **Reversible sorption type colloid**
  - Colloid partitioning coefficient (K_c) describes the relative amount of radionuclide on colloids versus that in the aqueous phase
  - Retardation via reversible filtration within the fracture continuum
- **Irreversible sorption type colloid**
  - Advective transport without diffusion into the rock matrix
  - Size exclusion model to prevent transport from fractures into some matrix units
  - Retardation via reversible filtration within the fracture continuum. Utilize a range of retardation factors in colloid diversity model
  - A small fraction of the colloid inventory transports unretarded (the “fast fraction”)



Note that for both colloid types, there is no diffusion or retardation of colloids in the rock matrix.

Treatment of Uncertainty and Variability

- Epistemic parameter uncertainty
  - Sampled during TSPA execution
    - Fracture geometric parameters
    - Sorption K_d values
    - Diffusion coefficients
    - Flow field index
    - Colloid transport parameters
  - Flow model parameter uncertainties (sensitivity analyses at the submodel level)
- Model uncertainty
  - Alternative conceptual models for fracture-matrix interaction will be evaluated in TSPA
- Spatial variability
  - Spatial variability in radionuclide source, flow fields, and transport properties are represented explicitly in the abstraction model

Technical Bases for Abstraction and References

- Laboratory measurements
  - Diffusion
  - Sorption
- Core data
  - Matrix porosity
  - Mineralogical composition
- Field data
  - Fracture porosity
  - Fracture spacing
- Validation with UZ transport process model
  - UZ transport process model validated against Alcove 8–Niche 3 and Busted Butte field test data

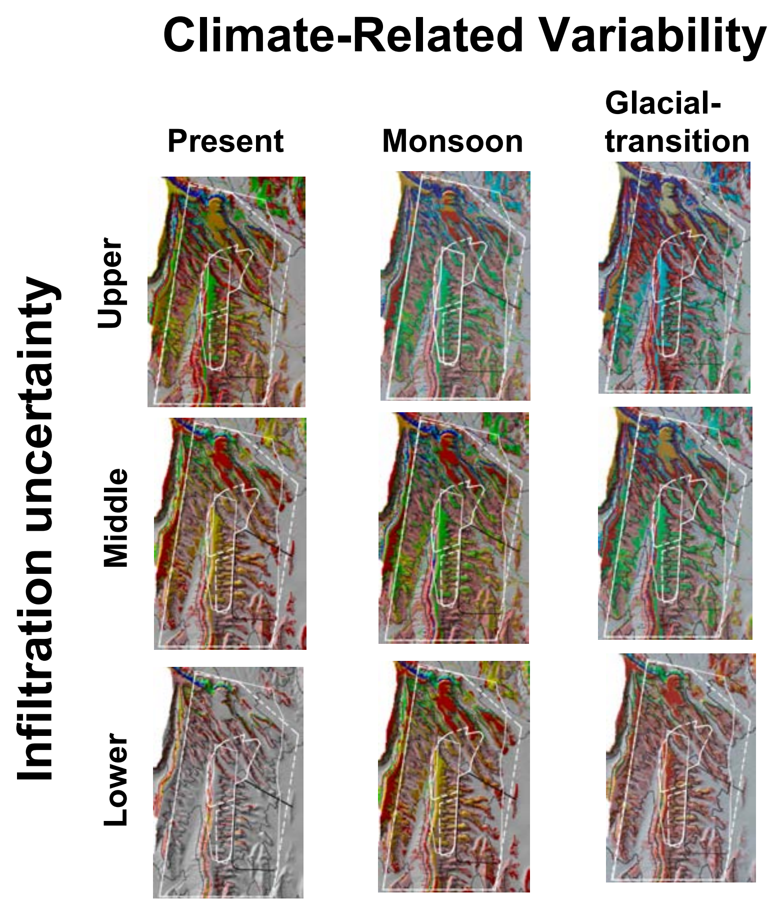
- References
  - *UZ Flow Models and Submodels,* MDL-NBS-HS-000006 REV 02
  - *Radionuclide Transport Models Under Ambient Conditions,* MDL-NBS-HS-000008 REV 02
  - *Particle Tracking Model and Abstraction of Transport Processes,* MDL-NBS-HS-000020 REV 02

Implementation—Overview

- 3D particle tracking model that directly implements UZ flow field results and simulates transport processes
- Multiple radionuclides are tracked, with decay and ingrowth included
- Incorporates time-varying and spatially varying radionuclide source inputs
- Produces time-varying and spatially varying radionuclide mass flux at the water table

Implementation—UZ Flow

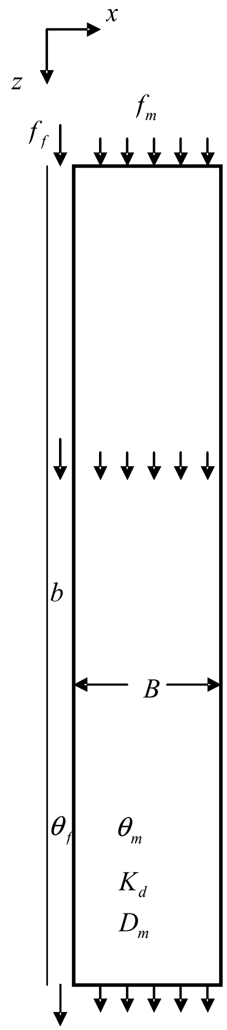
- **3D, steady state, dual-continuum flow fields from UZ flow model**
- **Instantaneous transition of flow field from one climate state to another**
- **Water table rise for future, wetter climate states**
- **Uncertainty from infiltration model is propagated through the UZ transport model**



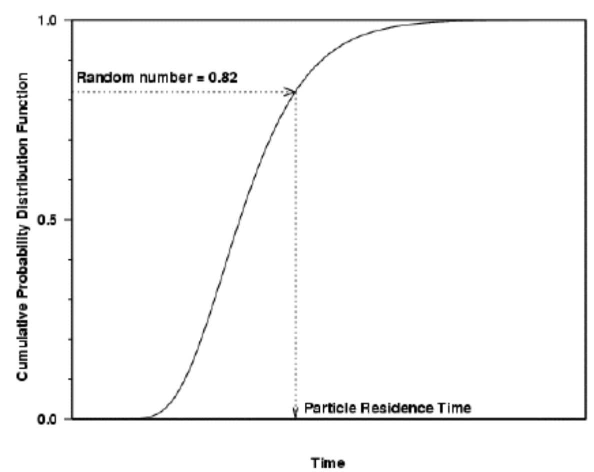
MDL-NBS-HS-000023 Rev 00

Implementation—Transport Processes and Residence Time Distributions

- **Submodel for a given grid cell is an idealized fracture/matrix system with the following processes:**
  - **Advection in fractures, matrix, and interflow**
  - **Matrix diffusion between fractures and matrix**
  - **Sorption in matrix**
  - **Colloid filtration and size exclusion and sorption to colloids**

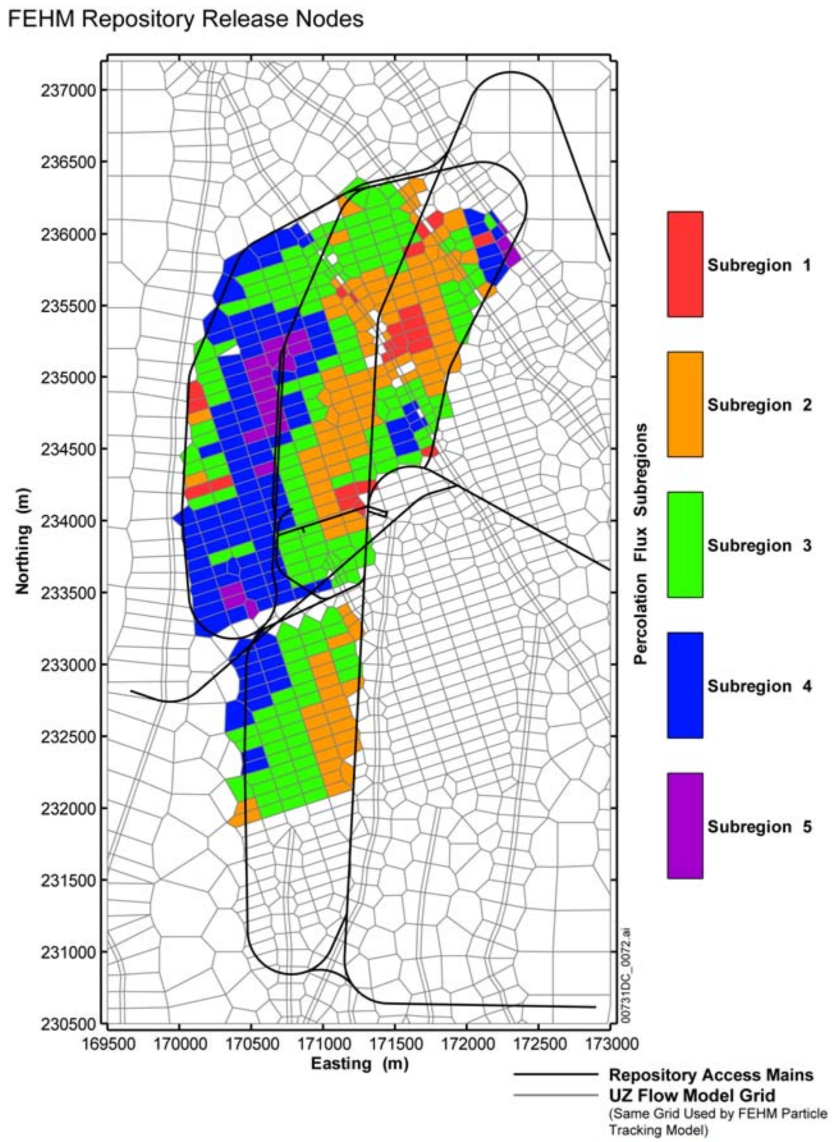


- **Submodel output is in the form of residence time distributions**



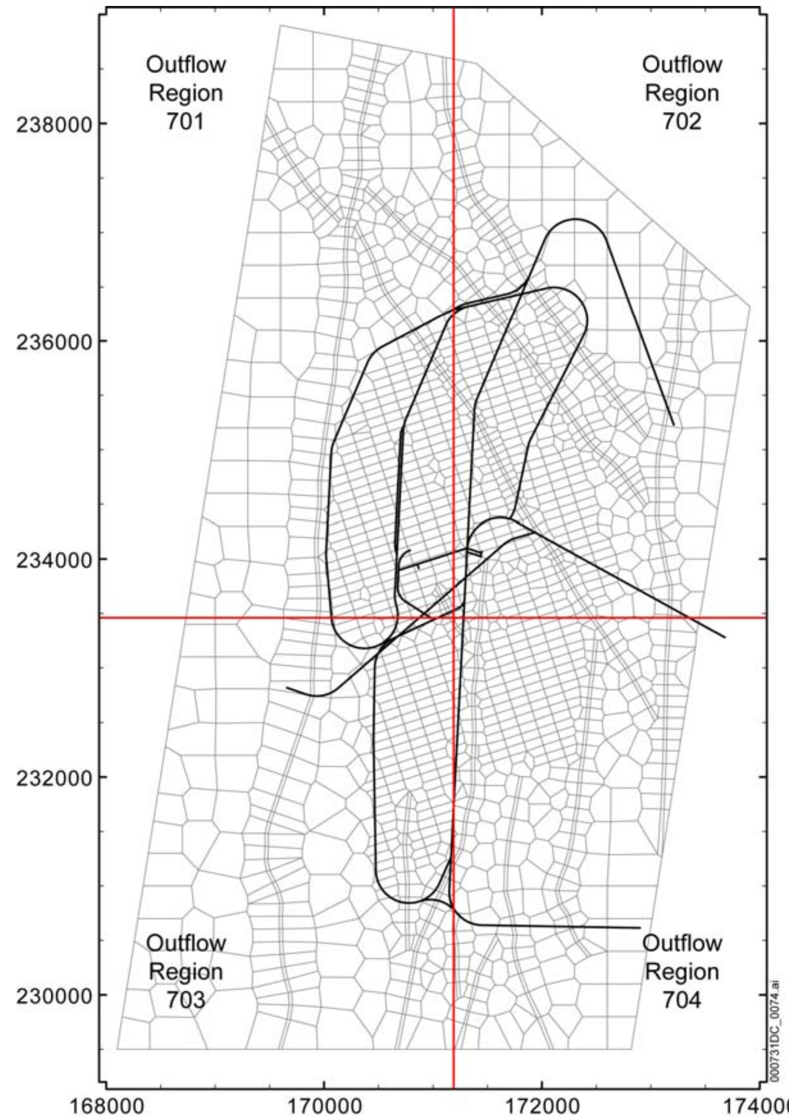
Implementation—Input from EBS

- Repository domain is segregated into subregions of different percolation flux
- Radionuclides enter the UZ from grid cells within same subregion as release location from EBS
- Radionuclides enter the UZ in both fracture and matrix continua



Implementation—Output to SZ Model

- Particle location is recorded at the water table
- Outflow region is identified based on particle location
- This radionuclide mass is added to the appropriate pathway of the SZ transport abstraction model



Anticipated Changes Since TSPA-SR

- **Fracture-matrix submodel has been revised to more accurately reflect transport in a dual-continuum system**
- **Colloid transport may feature a diverse population of transport properties, rather than single values**
- **Releases from the EBS transport model will occur in both the fractures and matrix, rather than assuming that all releases are into the fractures**
- **Updated analyses of sorption and diffusion parameters**
- **Water table rise under future climatic conditions is implemented as an uncertain parameter, subject to a distribution**

Saturated Zone (SZ) Flow and Transport

Presented to:
DOE/NRC Technical Exchange on Total System Performance Assessment (TSPA) for Yucca Mountain

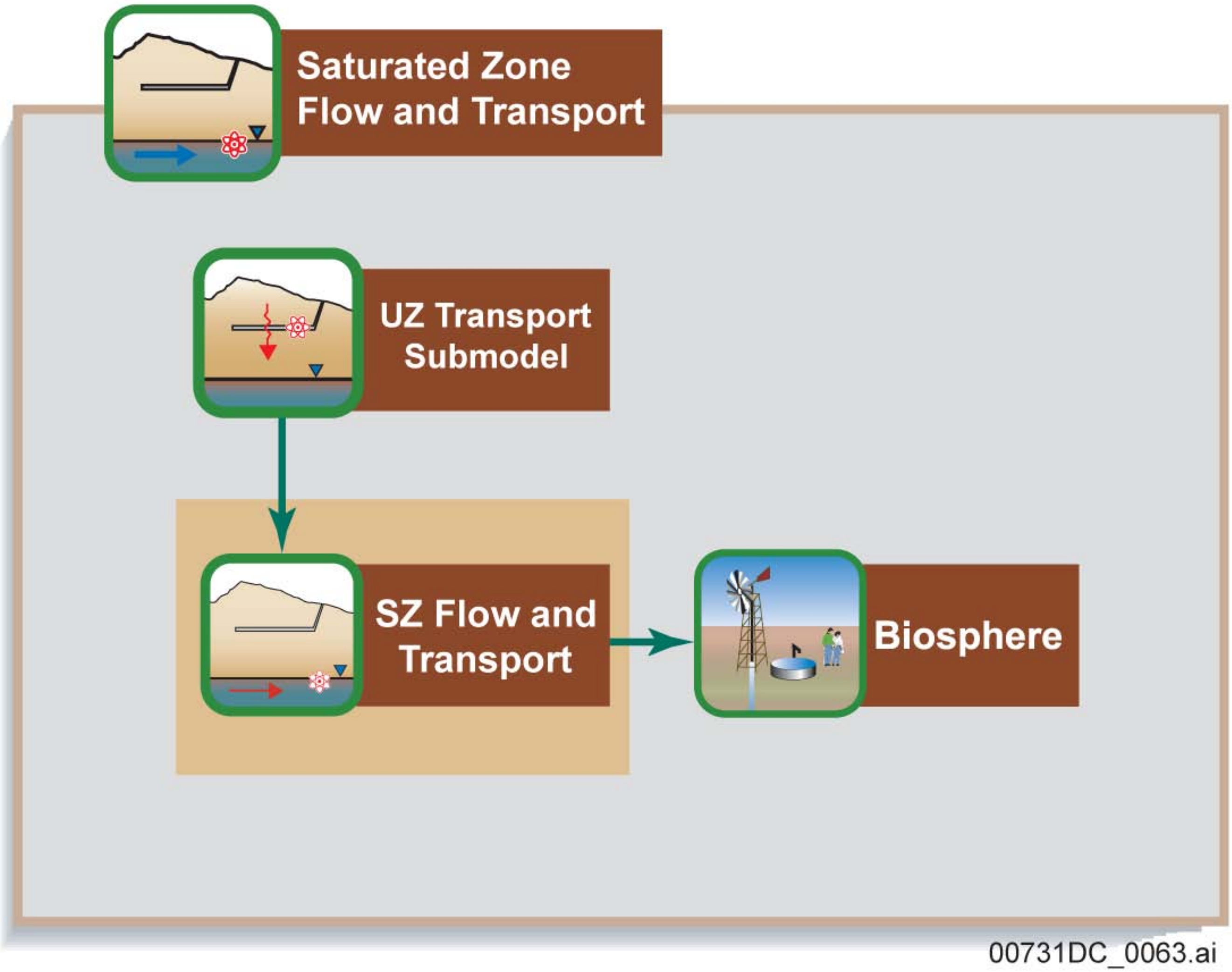
Presented by:
Kenneth Rehfeldt
Los Alamos National Laboratory

October 25, 2006
Las Vegas, Nevada

Presentation Outline

- Identification and linkage of abstractions
- Abstraction
  - Objectives
  - Input, output, and basis for model confidence
  - Assumptions
  - Conceptual model
  - Treatment of uncertainty and variability
  - Technical bases for abstraction and references
  - Implementation in TSPA model
- Anticipated changes since TSPA for site recommendation (SR)

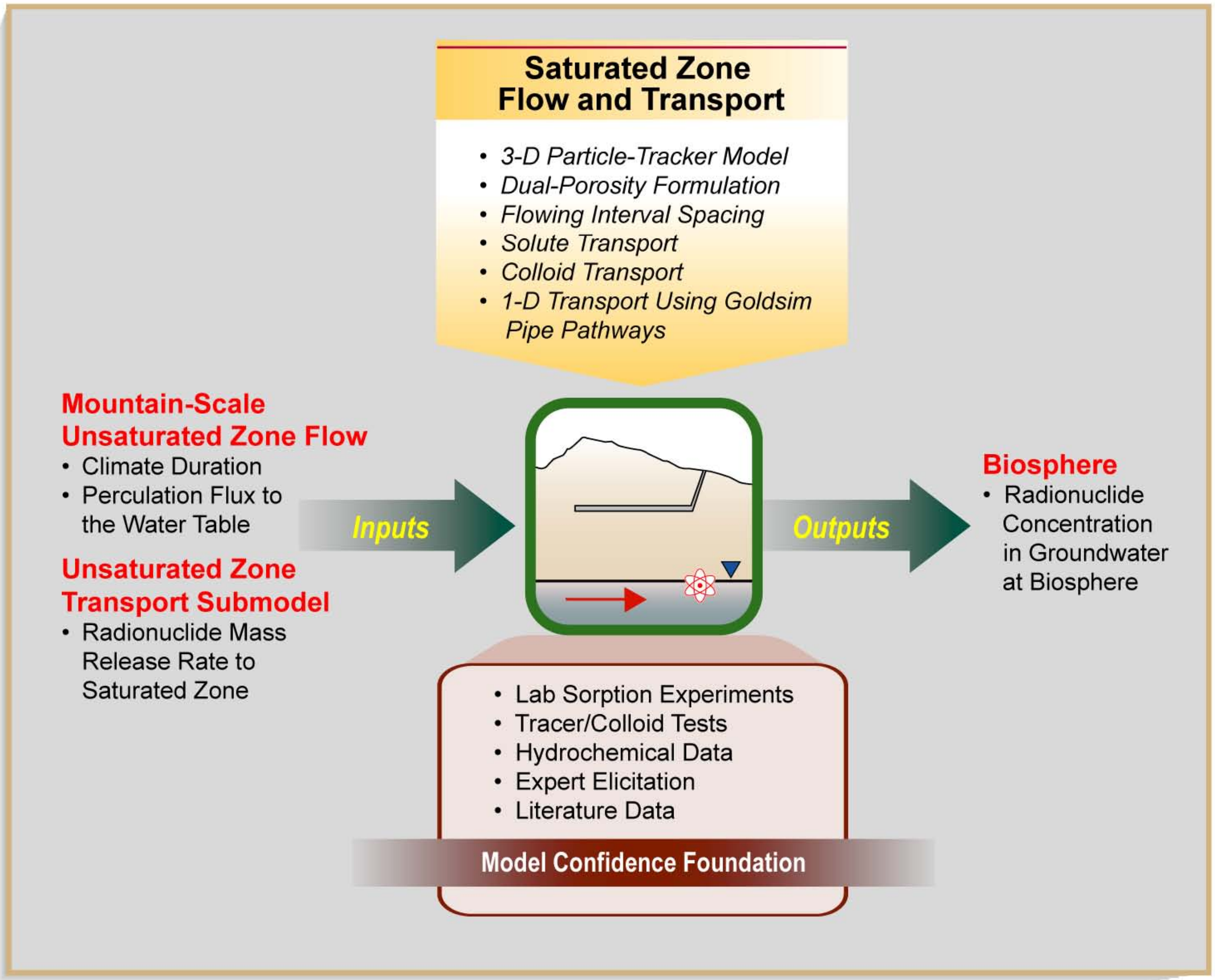
Identification and Linkages of Abstractions



Objective of SZ Flow and Transport Abstraction

- **Provides groundwater flow fields in the SZ for the area surrounding Yucca Mountain**
- **Simulates radionuclide transport in the SZ from the water table beneath the proposed repository to the boundary of the accessible environment**
- **Incorporates uncertainty in SZ flow and transport parameters into the TSPA analyses**

Inputs, Outputs, Basis for Model Confidence



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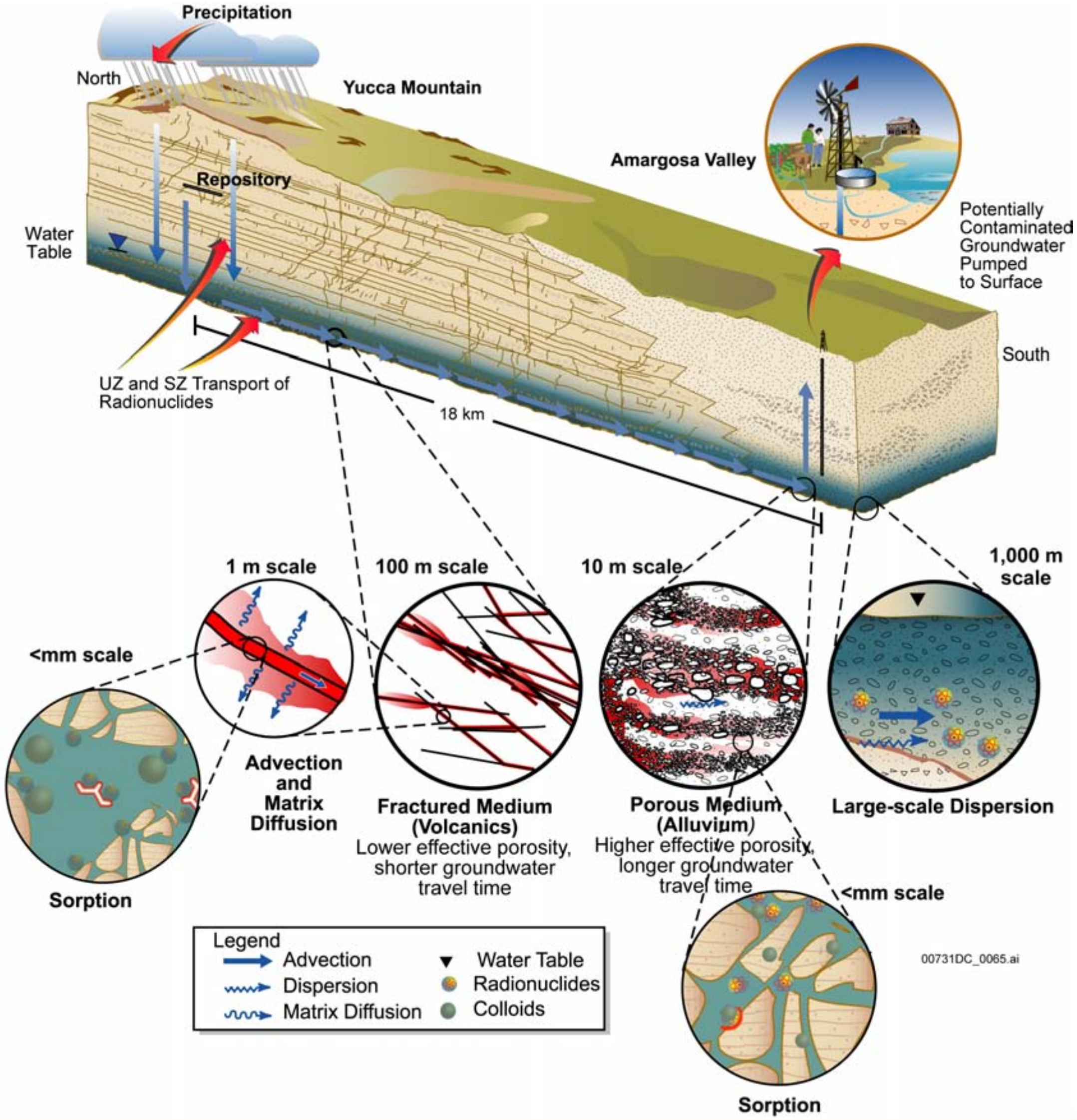
Model Assumptions

- Steady-state groundwater flow simulated in the SZ
- Instantaneous change in SZ groundwater flux with climate change; no change in flow paths
- Matrix diffusion from uniformly spaced, parallel fractures in the fractured volcanic units, as implemented in the Sudicky and Frind (1982) analytical solution
- Equilibrium, linear sorption occurs in tuff matrix and alluvium
- No sorption of solutes on fracture surfaces/coatings

Model Assumptions (continued)

- **Oxidizing conditions are assumed in the SZ with regard to sorption coefficients and solubility limits of redox-sensitive radionuclides such as ^{99}Tc and ^{237}Np**
- **For transport of radionuclides reversibly attached to colloids, local equilibrium is assumed among the colloids, the aqueous phase, and the aquifer material**
- **For radionuclides irreversibly attached to colloids, it is assumed there will be no desorption of radionuclides from the colloids**
- **Irreversible colloids are subject to attachment and detachment from the mineral grains, as governed by distributions of retardation factors**

SZ Flow and Transport Conceptual Model



Treatment of Uncertainty and Variability

- Groundwater flow and geological uncertainty
  - Groundwater specific discharge
  - Horizontal anisotropy in permeability (fractured tuff)
  - Alluvium – tuff contact in the subsurface
- Radionuclide transport uncertainty
  - Matrix diffusion in fractured tuff
    - Flowing interval spacing
    - Effective diffusion coefficient in tuff matrix
    - Flow porosity in tuff
  - Sorption coefficients (tuff matrix and alluvium)
  - Dispersivity (longitudinal, transverse horizontal and vertical)
  - Effective porosity of alluvium
  - Source location
  - Colloid retardation factor distributions (tuff and alluvium)
  - Sorption coefficients onto colloids
  - Groundwater colloid concentration

Technical Bases for Abstraction

- **Site-scale SZ flow model calibration constrained by or validated with:**
  - Subsurface hydrogeological unit geometry and fault locations (MDL-NBS-HS-000024 REV 00)
  - Water-level measurements in wells (ANL-NBS-HS-000034 REV 02)
  - Estimates of groundwater flow rates from the regional-scale flow model and the unsaturated zone (UZ) site-scale flow model (ANL-NBS-MD-000010 REV 01)
  - Estimates of permeability and anisotropy from pumping tests (ANL-NBS-HS-000039 REV 01 and MDL-NBS-HS-000011 REV 02)
  - Delineation of groundwater flow paths inferred from hydrochemical data (MDL-NBS-HS-000011 REV 02)
  - Observed values of horizontal and vertical hydraulic gradient (MDL-NBS-HS-000011 REV 02)
  - Estimates of specific discharge along the flow path from beneath the proposed repository (ANL-NBS-HS-000039 REV 01)

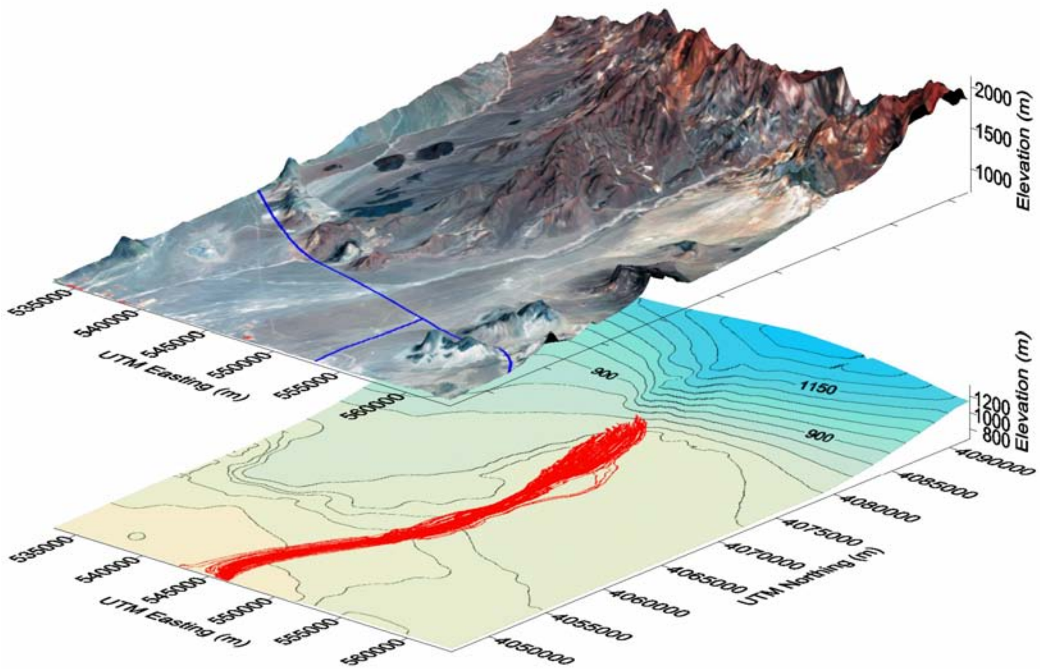
Technical Bases for Abstraction (continued)

- **Site-scale SZ transport model is informed by or validated with:**
  – **Field- and laboratory-scale testing of matrix diffusion, sorption, and dispersivity in fractured tuff (ANL-NBS-HS-000039 REV 01)**
  – **Field-scale estimates of dispersivity and effective porosity in alluvium (ANL-NBS-HS-000039 REV 01)**
  – **Field-scale estimates for retardation of colloids in tuff and alluvium (ANL-NBS-HS-000031 REV 02 and ANL-NBS-HS-000039 REV 01)**
  – **Extensive database of laboratory testing of sorption in tuff and alluvium (MDL-NBS-HS-000010 REV 02)**
  – **Delineation of groundwater flow paths and transport times through the SZ system inferred from hydrochemical data (MDL-NBS-HS-000010 REV 02 and MDL-NBS-HS-000011 REV 02)**

SZ Flow and Transport—Implementation

- **3D SZ site-scale flow and transport models used to simulate radionuclide mass transport to the accessible environment from a point mass source (4 source regions below the repository)**
- **Convolution integral method used to couple radionuclide source term from the UZ with the SZ transport in the TSPA calculations**
- **Radionuclide concentration in groundwater source to the biosphere calculated by dividing radionuclide mass crossing the boundary of the accessible environment by the representative groundwater volume of 3000 acre-ft/year**
- **Climate change incorporated by scaling radionuclide mass breakthrough curves in proportion to SZ groundwater flux changes**
- **Abstracted 1D transport model used for radioactive decay chains**

Implementation—SZ Particle Tracking



- **Particle tracking method includes radionuclide transport processes of advection, dispersion, matrix diffusion in fractured volcanic units, colloids and sorption**
- **Simulated flow paths from the repository occur in the upper few hundred meters of the SZ**

Anticipated Changes Since TSPA-SR

- Updated hydrogeologic framework model (HFM) incorporating new Nye County drilling data and updated USGS regional model

- Updated and recalibrated site-scale SZ flow model
  - Incorporation of updated HFM
  - Water-level measurements in new Nye County wells
  - Updated estimates of groundwater flux at lateral boundaries from USGS regional-scale flow model
  - Incorporation of new hydrochemical data in flow model validation analysis

Anticipated Changes Since TSPA-SR
(continued)

- Updated site-scale SZ transport model
  - Incorporation of updated site-scale SZ flow model
  - For colloids with irreversibly attached radionuclides, transport may feature a diverse population of retardation factors rather than single values
  - Possible addition of reducing zones
- Updated SZ flow and transport abstraction model
  - Reevaluate parameter uncertainty distributions considering any new information
  - Potential deterministic representation of the tuff-alluvium contact
  - For colloids with irreversibly attached radionuclides, transport may feature a diverse population of retardation factors, rather than single values, in the SZ 1D transport model

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Biosphere

Presented to:
DOE/NRC Technical Exchange on Total System Performance Assessment (TSPA) for Yucca Mountain

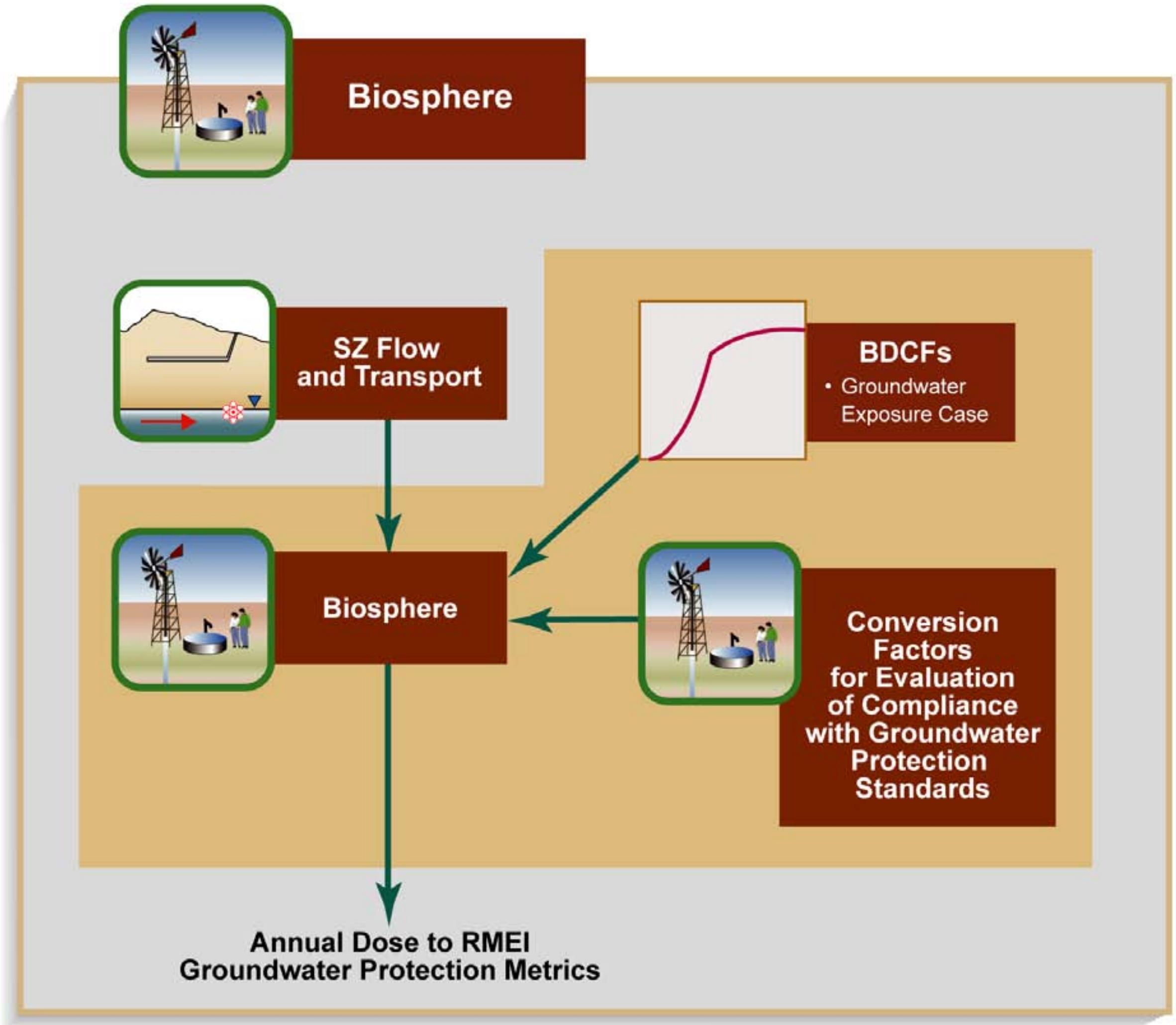
Presented by:
Maryla A. Wasiolek
Sandia National Laboratories

October 25, 2006
Las Vegas, Nevada

Presentation Outline

- **Identification and linkage of abstractions**
- **Abstraction**
  - **Objectives—Biosphere input to TSPA**
  - **Input, output, and basis for model confidence**
  - **Biosphere exposure scenarios**
    - **Assumptions**
    - **Conceptual model and model implementation**
    - **Treatment of uncertainty and variability**
    - **Technical bases for abstraction and references**
  - **Implementation in TSPA model**
- **Anticipated changes since TSPA for site recommendation (SR)**

Identification and Linkage of Abstractions



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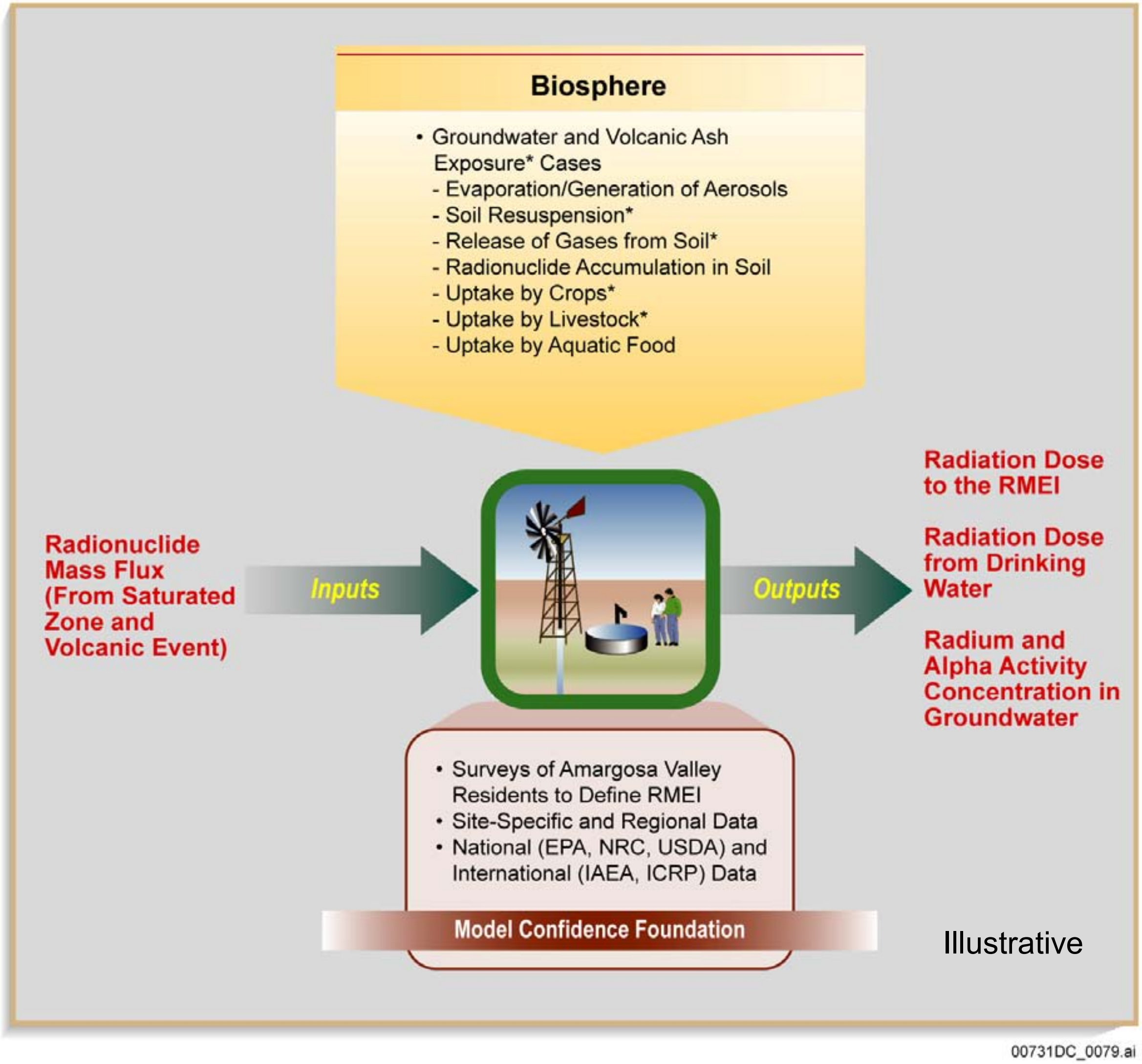
Biosphere Input to TSPA—Objective

- **Biosphere dose conversion factors (BDCFs)—used in calculations of dose to the reasonably maximally exposed individual (RMEI) from radionuclide concentrations in groundwater and in volcanic ash/soil (source media)**
  - **BDCFs for groundwater exposure scenario**
  - **BDCFs for volcanic ash exposure scenario (different from groundwater BDCFs in format and values)**
  - **In the TSPA biosphere model component, BDCFs are multiplied by radionuclide concentrations in source media to calculate annual dose to the RMEI**
- **Conversion factors and methods supporting evaluation of compliance with Groundwater Protection Standards**

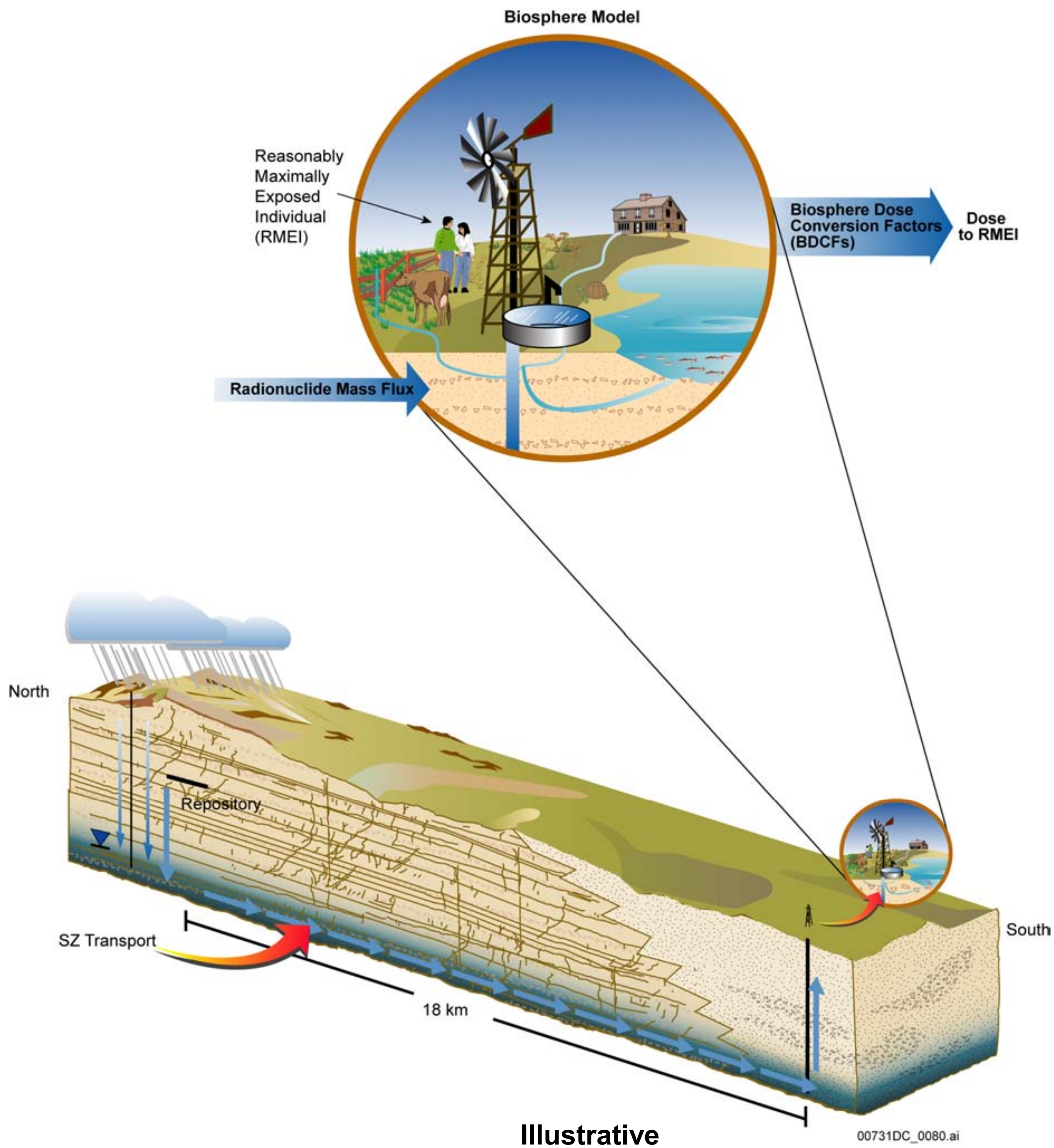
Inputs, Outputs, and Basis for Model Confidence



Biosphere Exposure Scenarios

- **Biosphere model for two exposure scenarios (cases)**
- **Groundwater exposure scenario**
  - **Applies to the TSPA modeling scenarios/cases that consider groundwater release of radionuclides**
  - **Three sets of BDCFs for three climate states: present-day, monsoon, and glacial transition**
- **Volcanic ash exposure scenario**
  - **Applies to igneous scenario class; radionuclide release in volcanic ash**
  - **One set of BDCFs developed for all climates (insignificant differences between climates)**

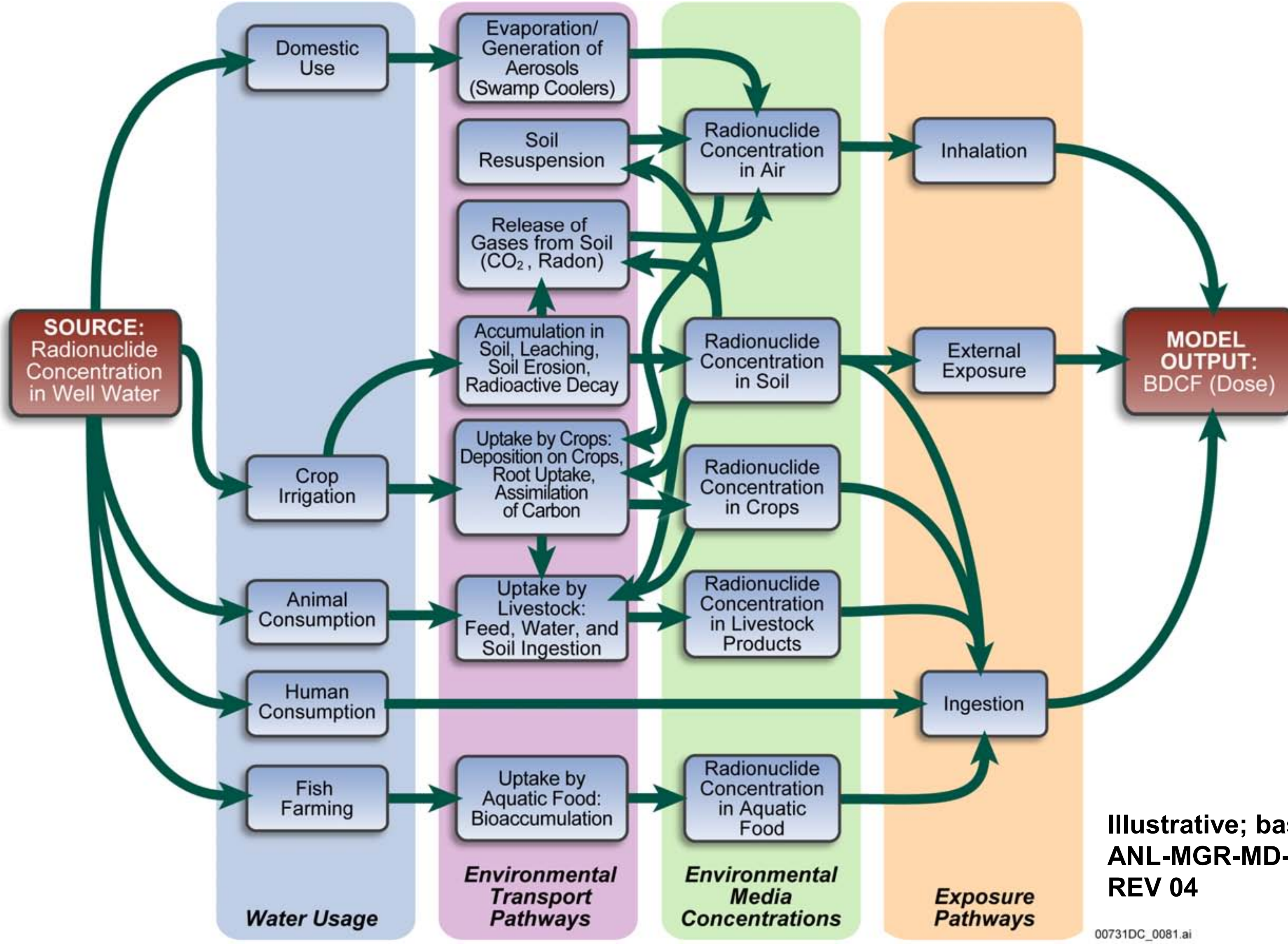
Groundwater Transport of Radionuclides from the Repository and Release to the Biosphere



Biosphere Model for Groundwater Release Assumptions

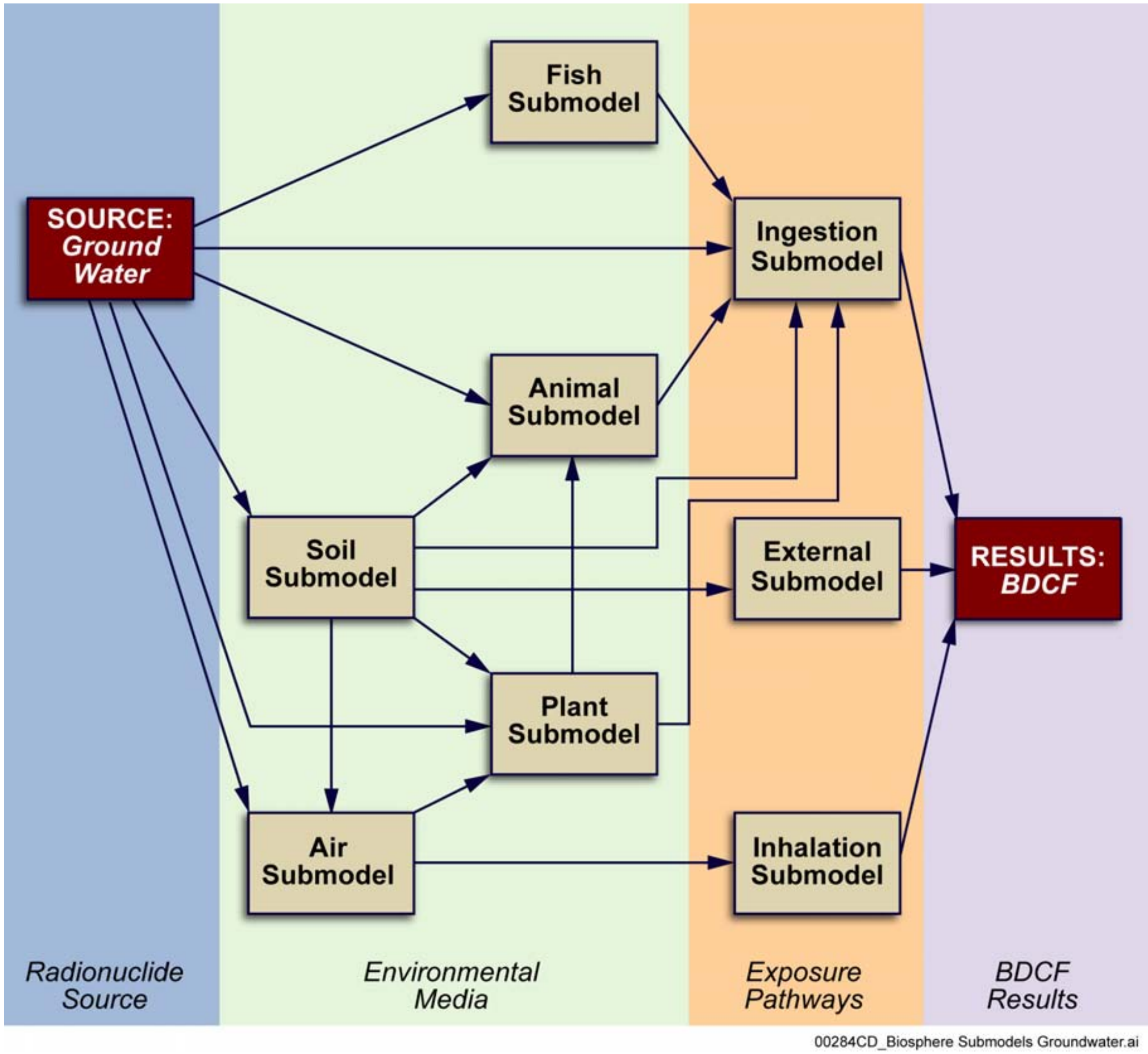
- For BDCF calculation, radionuclide concentrations in groundwater assumed constant through time
- Long-term irrigation and land use
  - Radionuclide buildup in surface soil
- Inhalation and external exposures accrued at all times while in contaminated area
- For evaluation of inhalation and external exposures, contaminated area divided into microenvironments

Conceptual Model—Groundwater Release



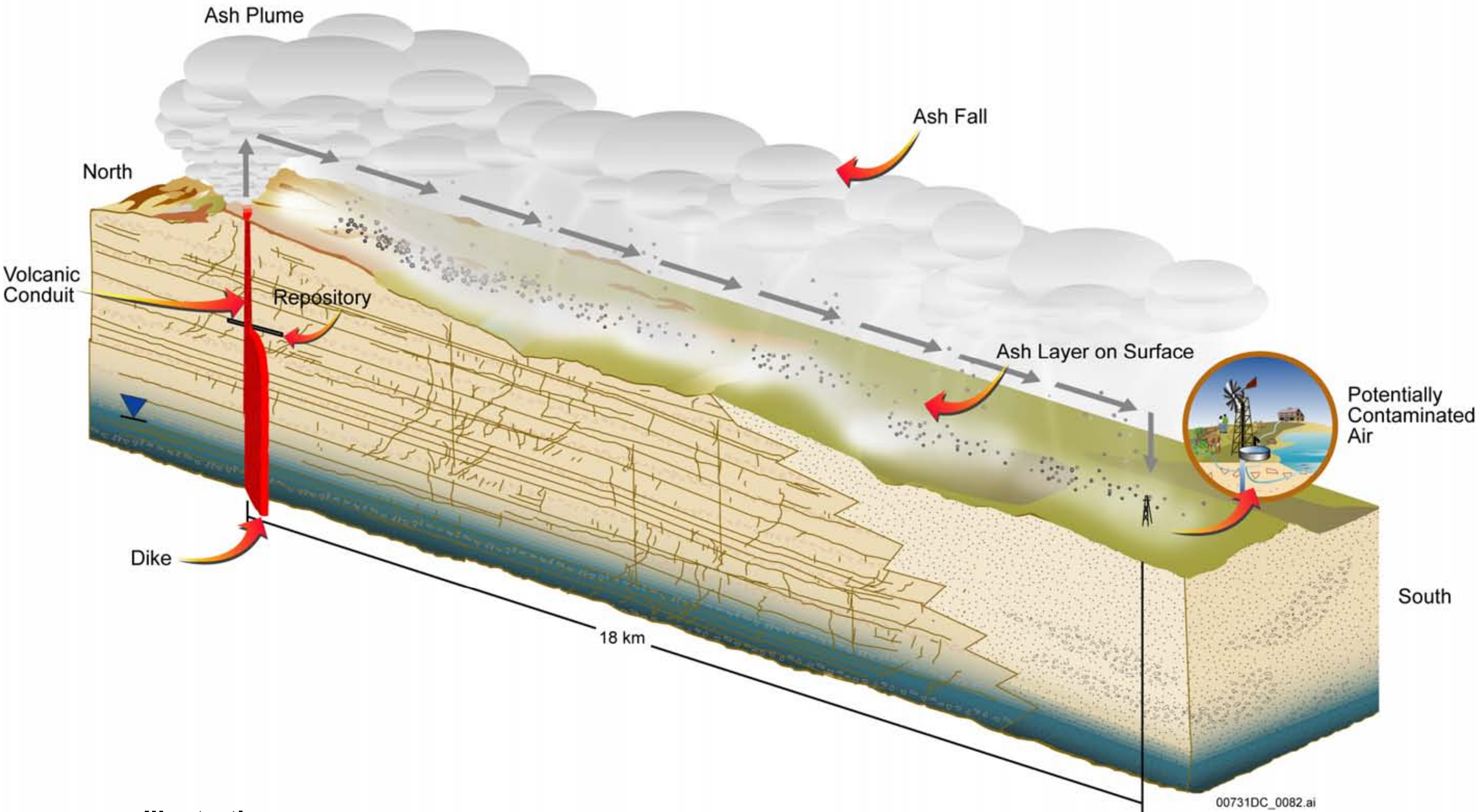
Illustrative; based on ANL-MGR-MD-000009 REV 04

Model Implementation—Groundwater Release



Source: MDL-MGR-MD-000001 REV 01

Radionuclide Release in Volcanic Ash

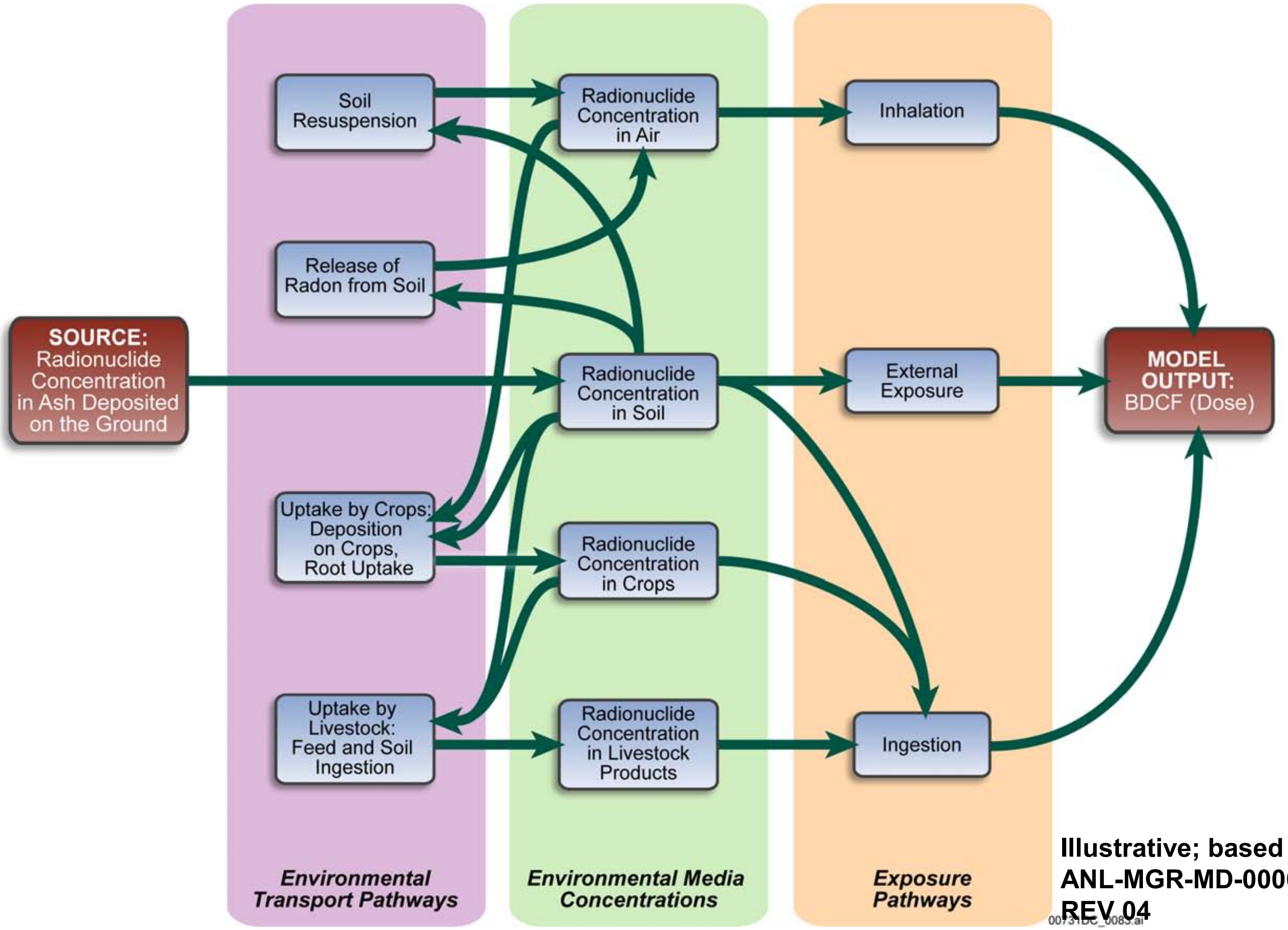


Illustrative

Biosphere Model for Volcanic Release Assumptions

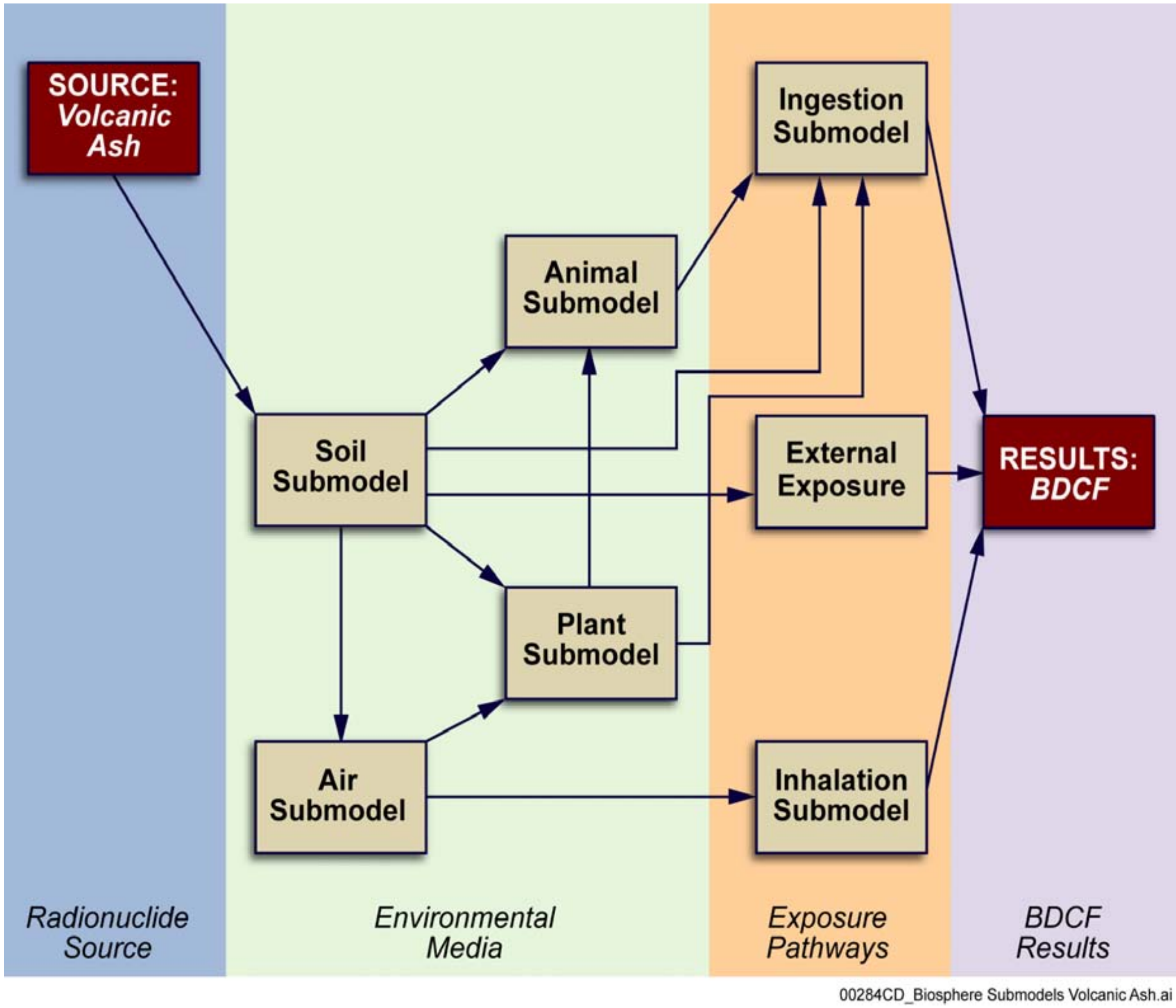
- **Volcanic ash source**
  - Cultivated lands (contaminated ash tilled into surface soil)
  - Non-cultivated lands (contaminated ash assumed to remain at the soil surface)
- **Ash resuspension**
  - Cultivated lands (deposition on crops)
  - Non-cultivated lands (inhalation)
- **Time-dependent mass loading**

Conceptual Model—Volcanic Release



Illustrative; based on ANL-MGR-MD-000003 REV 04

Model Implementation—Volcanic Release



Source: MDL-MGR-MD-000001 REV 01

Treatment of Uncertainty and Variability—Biosphere Model

- **Model uncertainty**
  - Decisions regarding applicability of alternative conceptual models and the inclusion or exclusion of potential pathways in the conceptual model
  - Conceptual and mathematical representation of environmental transport and receptor exposure pathways in the model
- **Data uncertainty**
  - Reference biosphere—full range of reasonable variation and uncertainty in environmental parameters
  - Dietary and lifestyle characteristics of the RMEI—range of reasonable variation and uncertainty about the average of parameters

Treatment of Uncertainty and Variability—Biosphere Input to TSPA

- The set of 1,000 BDCF row vectors sampled randomly within TSPA to propagate uncertainty from the biosphere model into the TSPA dose calculations
- The results of the process-level biosphere model incorporated into the TSPA without further abstraction
- The uncertainty attributed to input parameters has a direct effect on prediction of dose to the RMEI; model uncertainty is not propagated into TSPA
- Linear relationship between the dose from individual radionuclides and BDCFs for these

Technical Bases for Biosphere Model

- **Model confidence foundation**
  - Surveys of Amargosa Valley residents to define RMEI
  - Site-specific and regional data
  - National (EPA, NRC, USDA) and international (ICRP, IAEA) data
- **Model validation**
  - Biosphere model was validated by comparing the computational methods to the methods of five published biosphere and radiological assessment models
  - Methods and calculations used in each submodel were compared to the analogous methods and calculations in the validation models
- **References**

– Biosphere Model Report, MDL-MGR-MD-000001 REV 01

Anticipated Changes Since TSPA-SR

- **New model requirements**
  - Receptor—RMEI
  - Incorporation of additional pathways
  - More comprehensive treatment of uncertainty
- **GoldSim-based model (GENII-S used in TSPA-SR)**
- **Additional model improvements**
  - Ability to define distributions for and stochastically sample all parameters
    - Over 230 variable input parameters for the volcanic ash exposure scenario
    - Over 270 variable input parameters for the groundwater exposure scenario
  - No limitation on number of model realizations