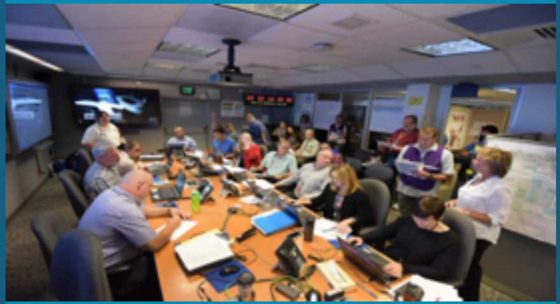
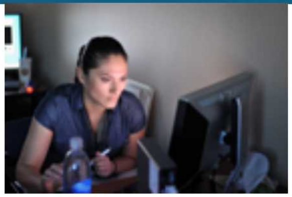
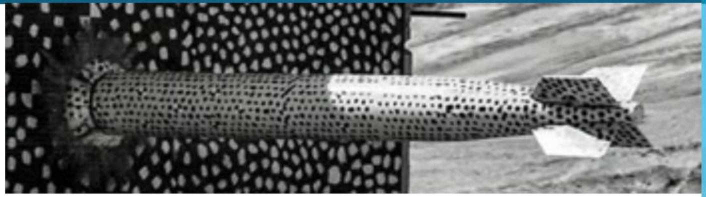
SAND2019-5253PE

L10: Safety Assessment and Optimization of the EBS







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Ed ward N. Matteo

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Safety Case and Safety Assessment

Safety Case (*Definition from Outcomes of the NEA MeSA Initiative, OECD 2012*)

"A safety case is the synthesis of evidence, analyses and arguments that quantify and substantiate a claim that the repository will be safe after closure and beyond the time when active control of the facility can be relied on."

Post-Closure Safety Assessment (or Performance Assessment)

A quantitative assessment of repository performance that predicts the long-term behavior of a repository, including the ability of the repository barriers to perform their safety functions, and plays a key role in substantiating that a repository will be safe and comply with regulatory safety requirements.

Geologic Repository Safety Case Development

- **International experience *should* lessen the technical challenges**

- NEA (2004). Post-closure safety cases for geological repositories. Nature and purpose. *OECD/NEA report 3679*. Paris.
- **Yucca Mountain Repository License Application: Safety Analysis Report, 2008**
- http://www.nrc.gov/waste/hlw-disposal/yucca-lic-app/yucca-lic-app-safety-report.html
- NEA (2009a). Considering timescales in the post-closure safety of geological disposal of radioactive waste. *OECD/NEA report 6424*. Paris.
- NEA (2009b). International experiences in safety cases for geological repositories (INTESC). Outcomes of the INTESC project. *OECD/NEA report 6251*. Paris.
- IAEA (2011). Disposal of radioactive waste*. Specific Safety Requirements SSR-5.* IAEA, Vienna.
- THE POST-CLOSURE RADIOLOGICAL SAFETY CASE FOR A SPENT FUEL REPOSITORY IN SWEDEN An international peer review of the SKB license - application study of March 2011 (Final report)
- Posiva (2012c). Safety case for the disposal of spent nuclear fuel at Olkiluoto—synthesis, 2012. *POSIVA report 2012-12.* Posiva Oy, Eurajoki.
- The Safety Case for Deep Geological Disposal of Radioactive Waste: 2013 State of the Art Symposium Proceedings, 7-9 October 2013, Paris, France
- Posiva (2013a). Safety case for the disposal of spent nuclear fuel at Olkiluoto—performance assessment 2012. *POSIVA report 2012-04.* Posiva Oy, Eurajoki.
- Posiva (2013b). Safety case for the disposal of spent nuclear fuel at Olkiluoto—assessment of radionuclide release scenarios for the repository system 2012. *POSIVA report 2012-09.* Posiva Oy, Eurajoki.

What is a deep geologic repository?

An engineered facility for safe handling and disposal of nuclear waste that includes disposal rooms or tunnels excavated sufficiently deep beneath the surface to ensure <u>isolation</u> of the waste from external changes or events. The underground facility typically comprises engineered and geologic barriers that act together to <u>contain</u> the waste within the facility and to <u>limit and delay</u> the release of radionuclides to the surrounding geosphere subsequent to loss of containment. Typical engineered barrier systems include the following components - waste form (and inventory), waste package, buffer/backfill, and engineered seals.

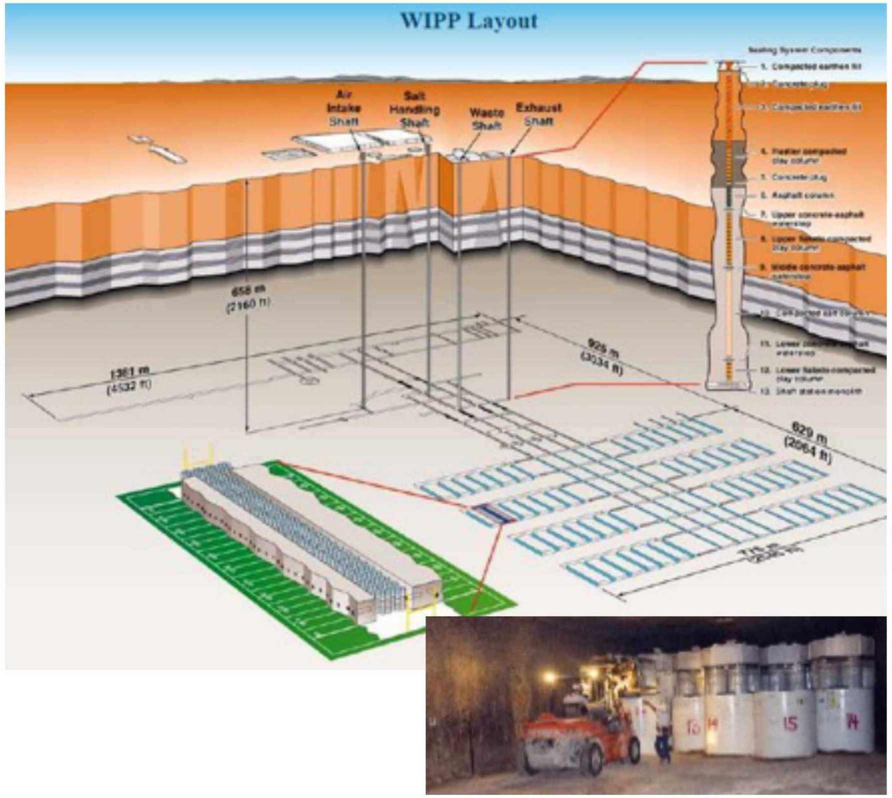
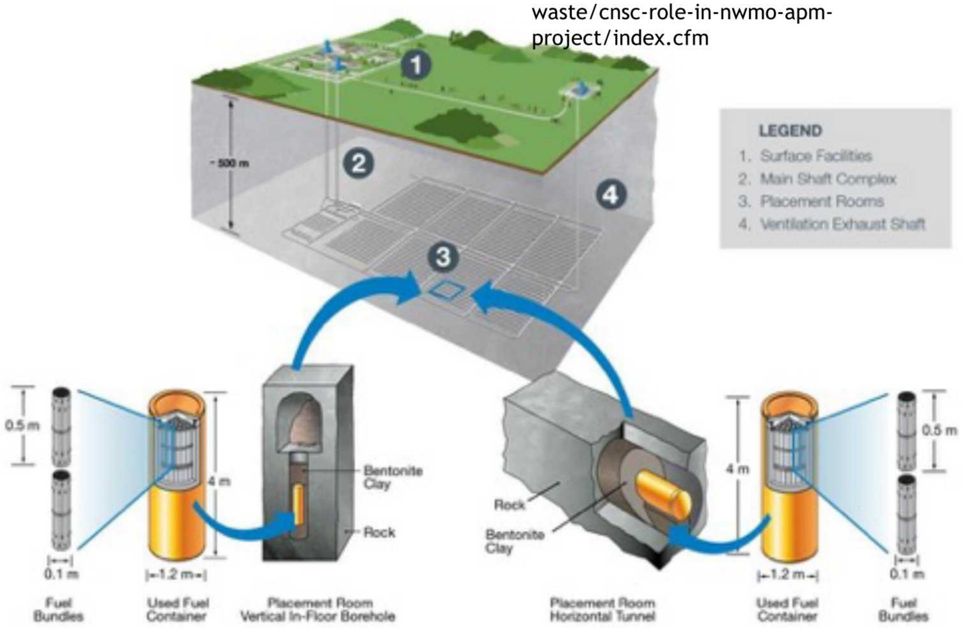
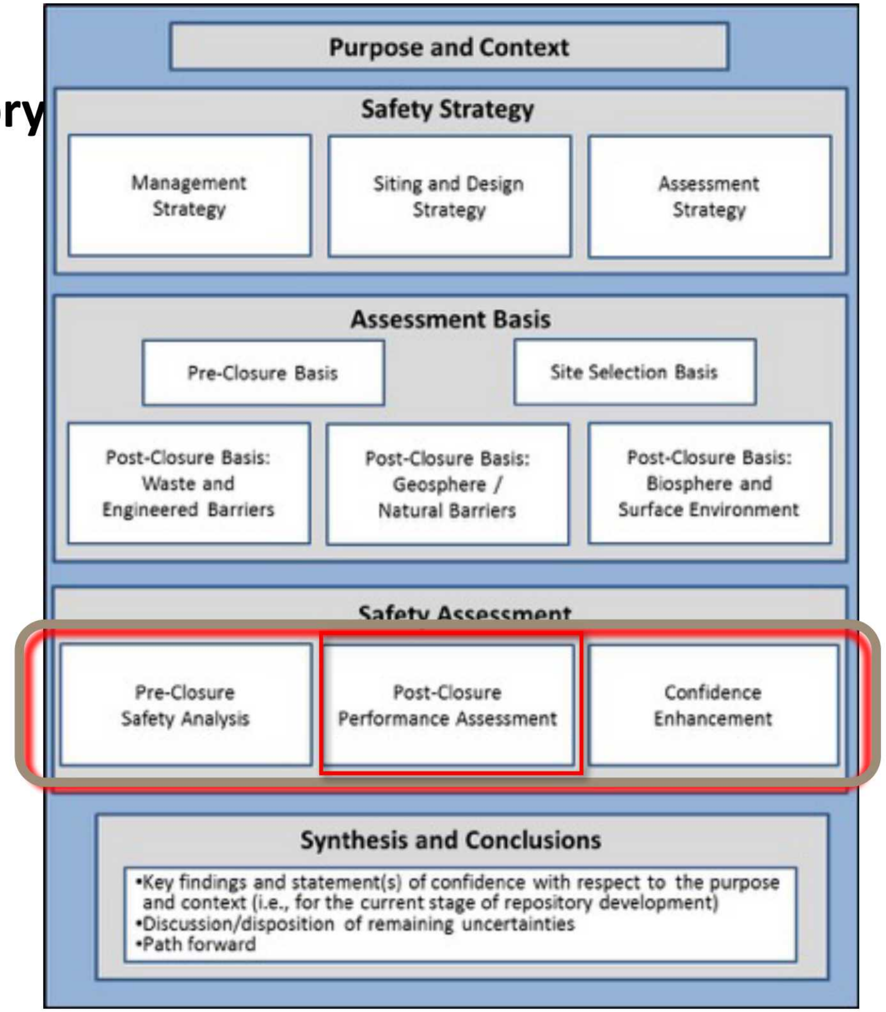


Figure Source: https://www.cnsc-ccsn.gc.ca/eng/waste/high-level-waste/cnsc-role-in-nwmo-apm-project/index.cfm



Disposal System Evaluation

- **Preclosure Safety Analysis**
  - Worker/public exposure from repository operations accidents
  - Include transportation and packaging/ handling safety analyses
  - Current knowledge base includes U.S. experience with WIPP and German experience with Asse and Morsleben
- **Postclosure Safety Assessment**
  - Quantitative comparison to system safety standards (dose or risk)
  - Quantitative/qualitative analysis of barrier capability or subsystem safety functions
  - Uncertainty/sensitivity analyses
- **Confidence-Building Activities**



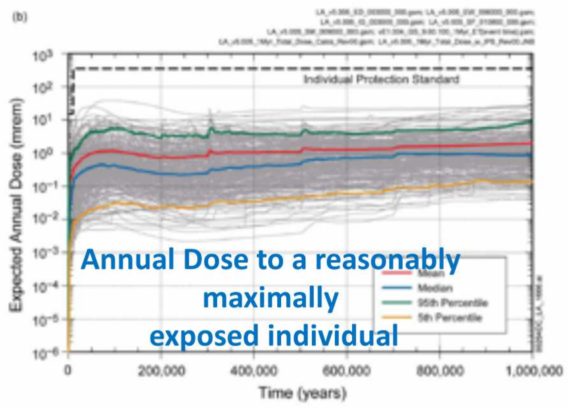
Long-Term Performance

Biosphere
- Dilution
- Irrigation
- Water Consumption
- Dose Conversion Factors

Repository Design
- Location and layout
- No. and type of WPs
- EBS and Seals
- Thermal Loading and Ventilation

Near Field (EBS + DRZ)
- EBS Evolution
- DRZ Evolution
- Chemical Interactions
- Thermal Effects
- Mechanical Effects
- Flow and Transport

Performance Goal



Annual Dose to a reasonably maximally exposed individual

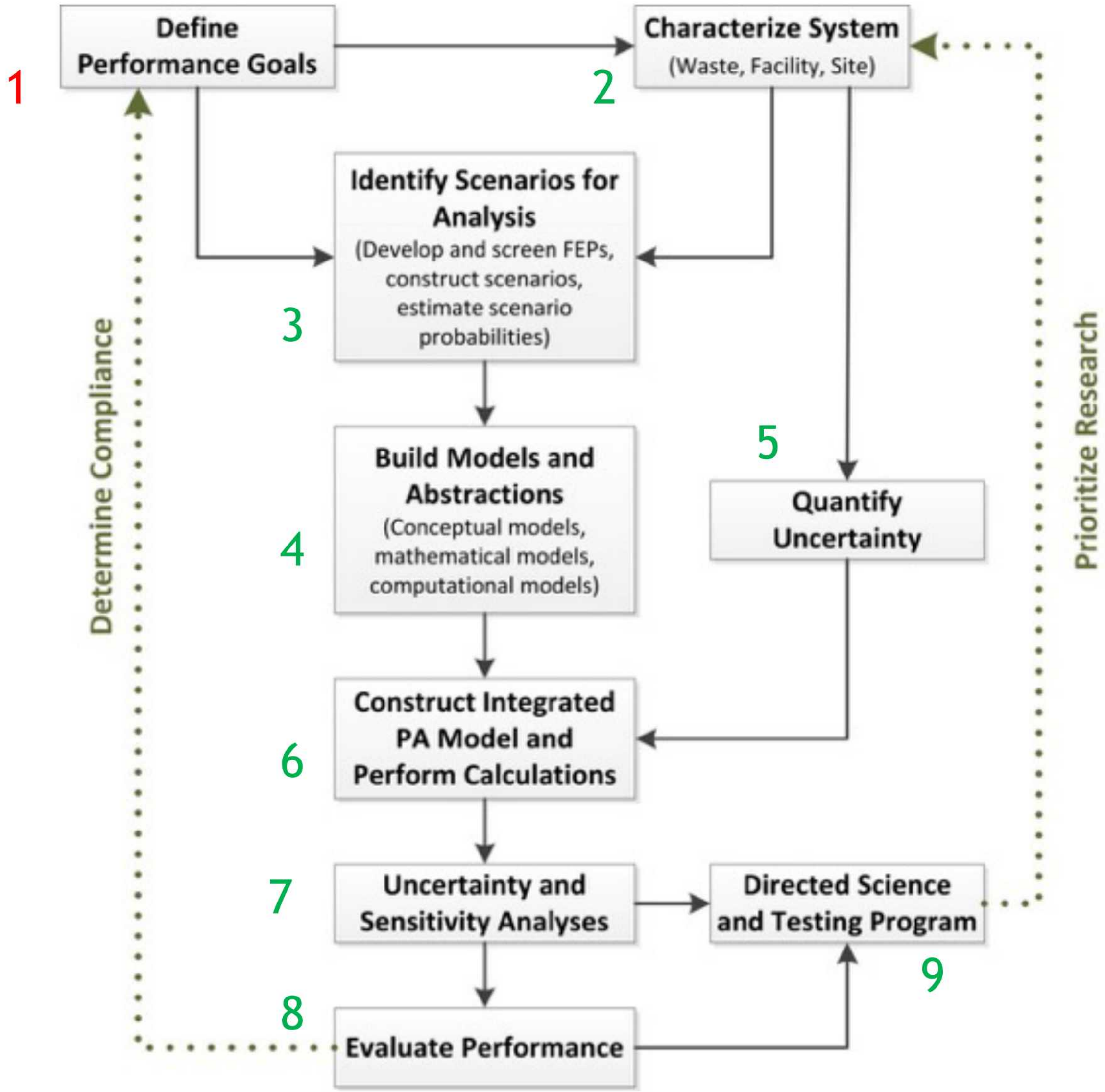
Source Term
- RN Inventory
- WF Degradation
- WP Degradation
- Gas Generation
- RN Release

Far Field
- Flow and Transport
- Sorption
- RN Decay and Ingrowth

Natural System
- Climate
- Stratigraphy
- Hydrogeology
- Geochemistry
- Material properties
- Disruptive events

Engineered Barrier System (EBS)
Radionuclide (RN)
Waste Form (WF)
Waste Package (WP)
Disturbed Rock Zone (DRZ)

Performance Assessment (PA) Methodology



Performance Goals

Performance goals are typically defined up front because they determine the design of the performance assessment and have considerable influence on scenario construction, model development, and research programs

Ideally, performance goals are taken directly from legal regulations governing the repository

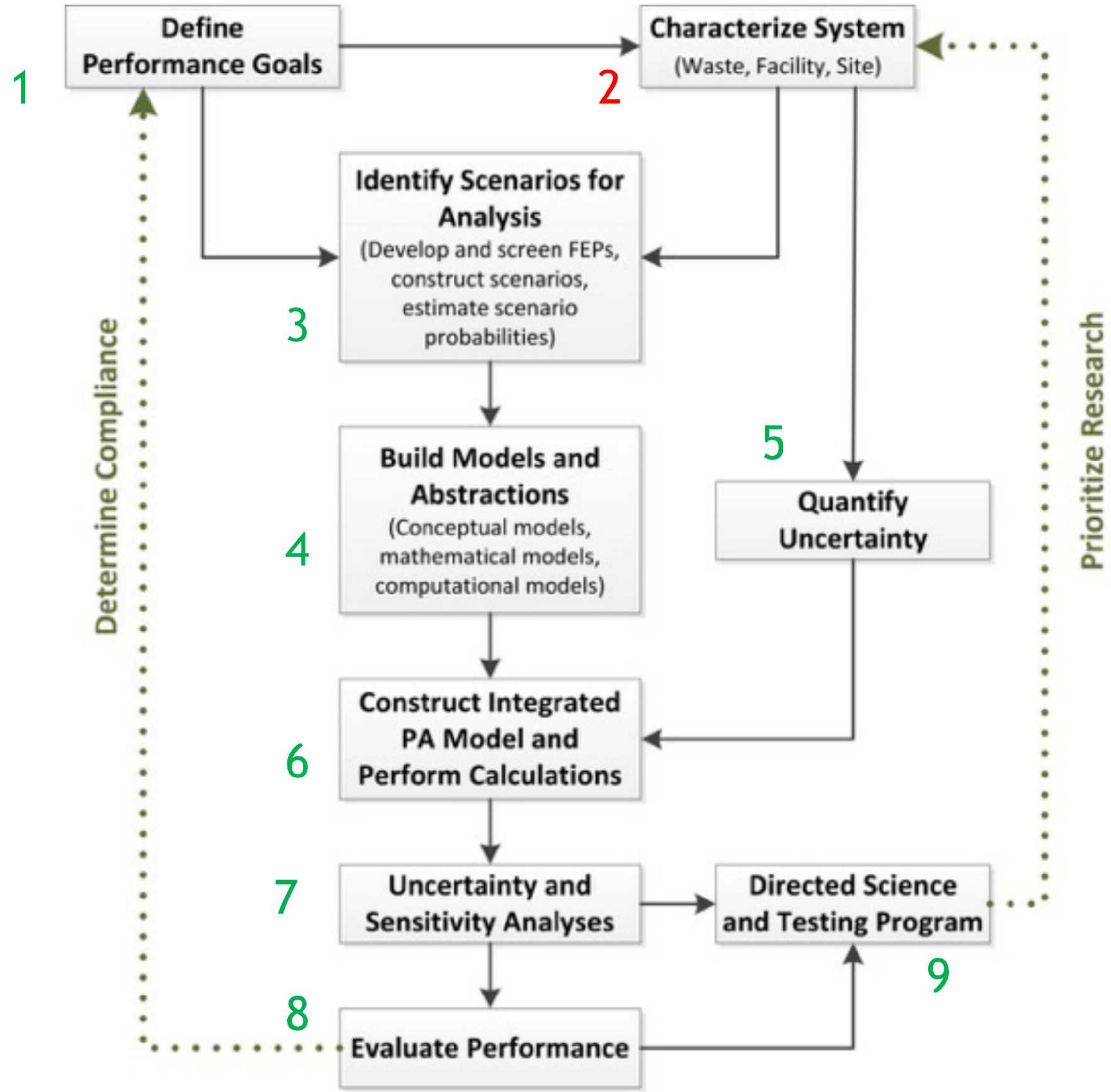
For early iterations of the performance assessment methodology, final regulatory performance measures may not yet be promulgated, and assumptions about possible standards need to be made

Performance Goals cont.

The performance assessment group designs the analyses to simulate the quantities specified in the regulations (e.g., radiological dose to the receptor group or maximum groundwater concentrations)

The performance assessment group should analyze total system and subsystem performance indicators (e.g., temperature in backfill, transport time in the saturated zone) and perform sensitivity analyses to provide input to design, site characterization, and post-closure technical basis

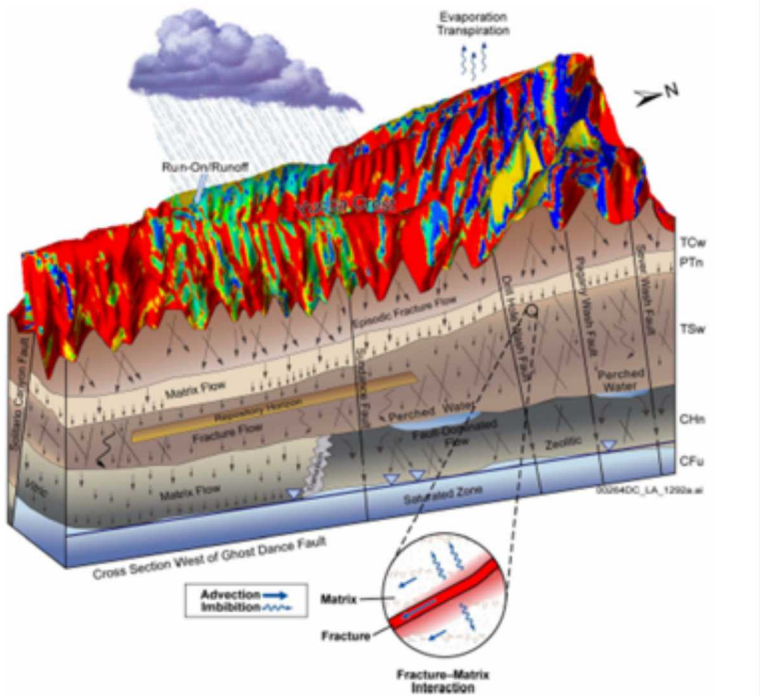
PA Methodology



Characterize System

A system description includes the characteristics of the waste (e.g., radionuclide inventory, decay chains, half-lives), the facility (e.g., layout, thermal loading from emplaced waste, design and properties of engineered barriers), and the site (e.g., geology, hydrogeology, geochemistry).

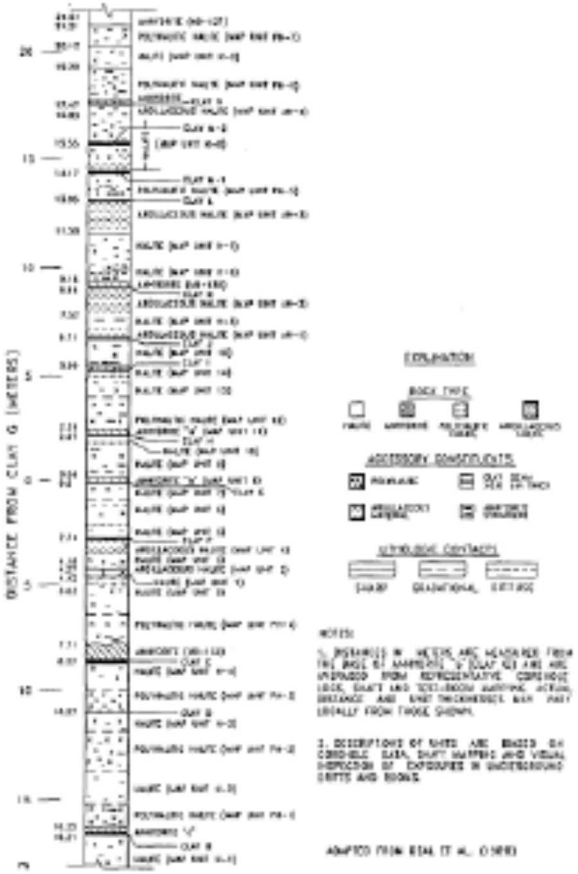
System information is derived from laboratory and field tests, published literature, natural analogues, and/or expert judgment.



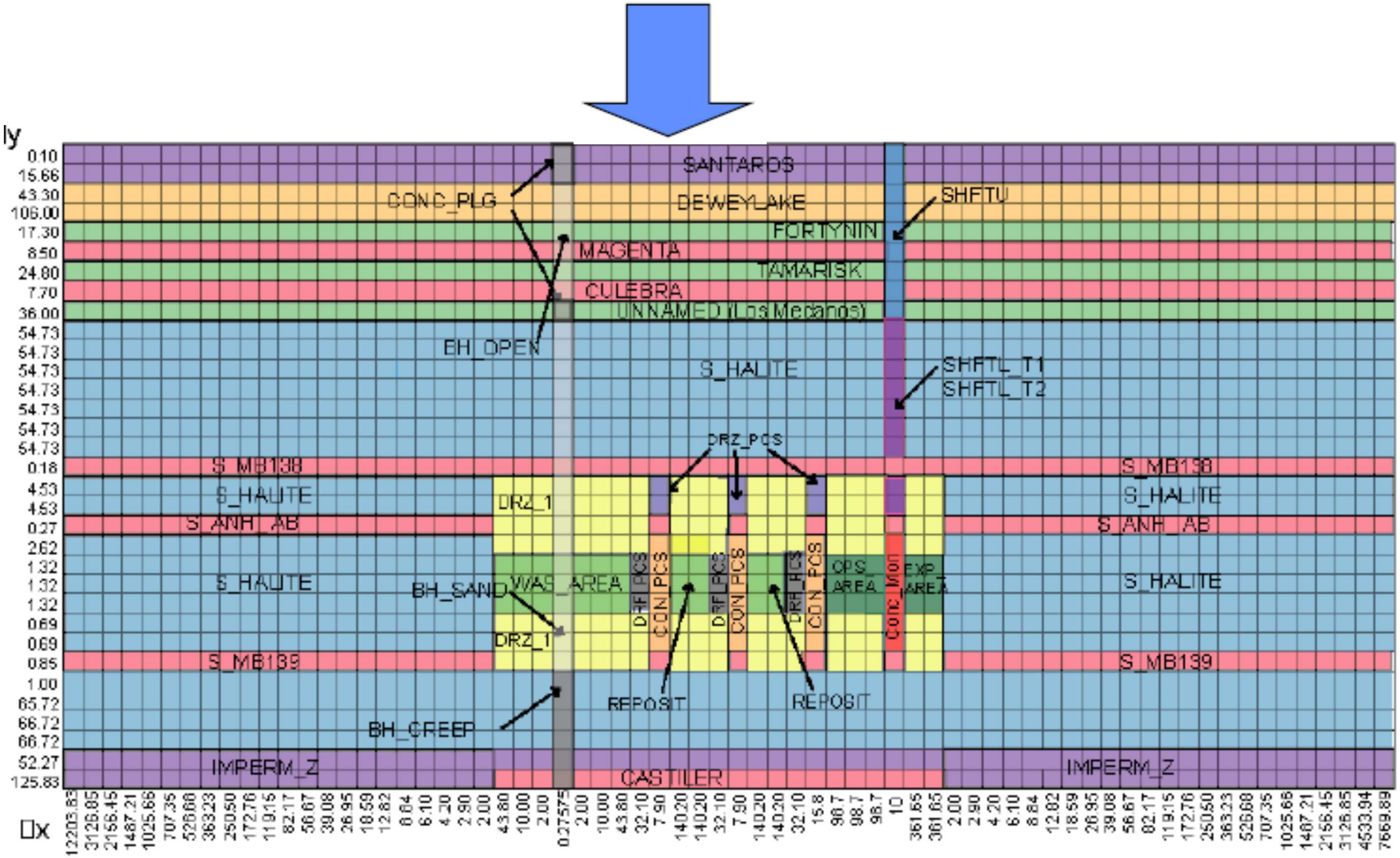
Overall Conceptualized Water Flow Behavior in the Unsaturated Zone at Yucca Mountain

Integration of Site Characterization Data

Example: Stratigraphy



Integration of Site Characterization Data



Characterize System Cont.

Preliminary phase

- Scope of data collection is broad because something needs to be known about almost everything to support the feasibility analysis
- Literature studies are used to build preliminary conceptual models and identify uncertainties that warrant direct experimental study
- PAs begin (at least qualitatively) with the first system level conceptual models, and guide system characterization toward uncertainties that matter
- Data collection focuses on any data specifically called out by regulation or agreements, on literature data, and on sufficient experimental and field information, to confirm the absence of unacceptable features and to characterize uncertainty in conceptual models of site performance

Characterize System Cont.

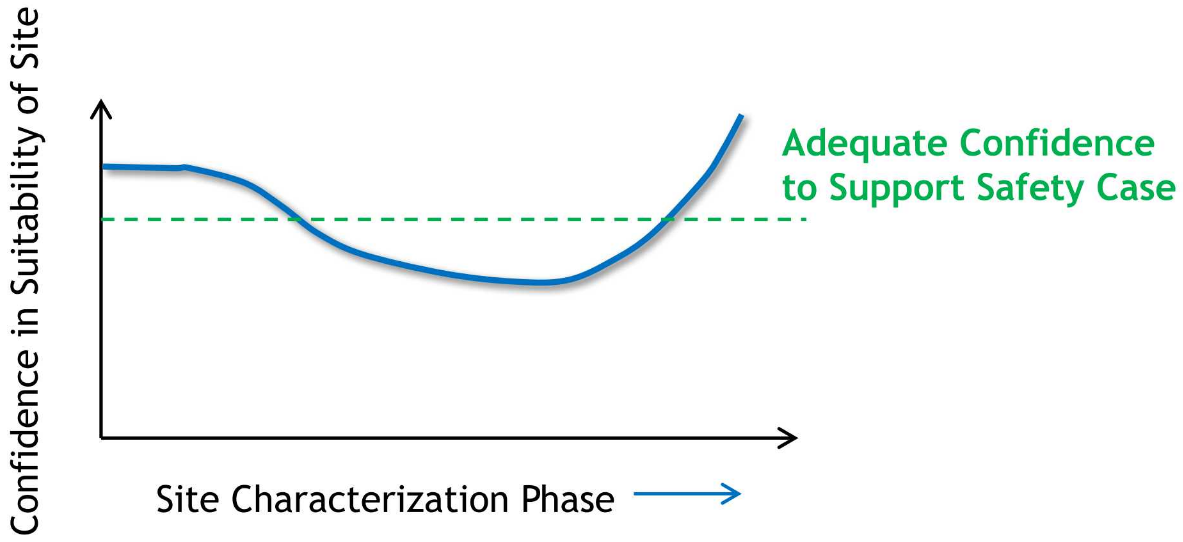
As system understanding matures, PA provides evidence that total system performance satisfies applicable safety standards

- Site-specific data are collected to support preliminary quantitative estimates of uncertainty in overall performance
- Models are sufficiently developed to allow assessment of the relative importance of specific features, events, and processes (FEPs) potentially relevant to performance
- A formal FEP screening process is implemented to identify those FEPs that are sufficiently unlikely or inconsequential to be set aside with no further data collection
- Data collection is focused on conceptual and data uncertainties that matter, with a focus on increasing realism in model depictions
- PAs are conducted iteratively with feedback from characterization program to identify areas where data uncertainties have the potential to impact licensing

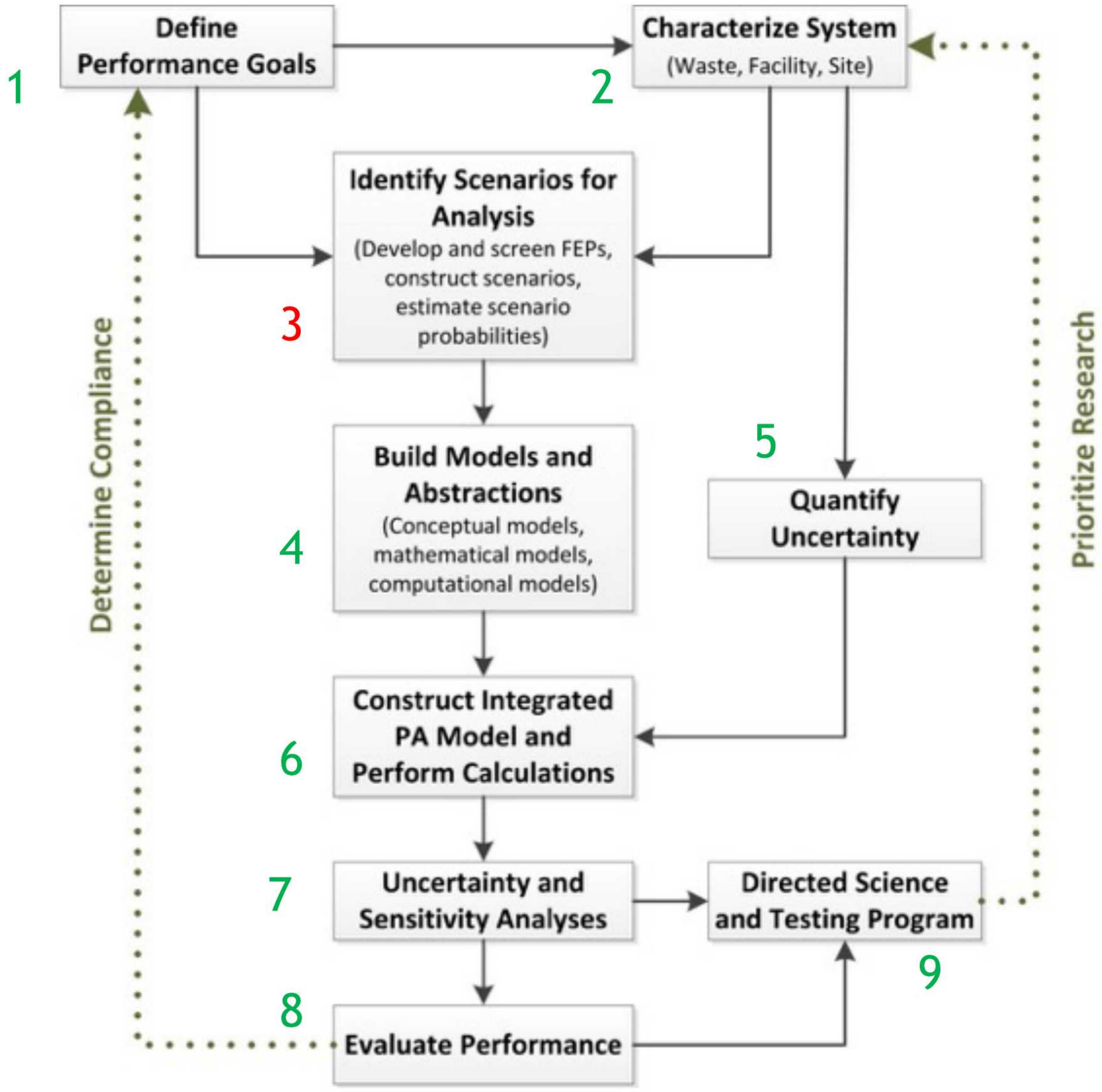
Characterize System Cont.

The final phase confirms the safety of the disposal system

- Data collection focuses intensively on those areas needed either to support the safety assessment and safety case or required explicitly by other regulatory drivers
- Data collection activities include any data specifically called out by regulation, data specifically requested by the regulator, data required to support parts of the license application determined to be incomplete or inadequate, and data required for operations-phase monitoring or confirmation activities



PA Methodology



Identify Scenarios for Analysis

Features, events, and processes (FEPs) may be naturally occurring, induced by the disposal system, or related to human activity.

- **Features—Features are physical, chemical, or thermal characteristics of the site or repository system**
- **Events—Events are occurrences that have a specific starting time and, usually, a duration shorter than the time being simulated in a model**
- **Processes—Processes are phenomena and activities that have gradual, continuous interactions with the system being modeled**

Identify Scenarios for Analysis

Scenario development is the identification and specification of potential futures "paths" relevant to safety assessment of radioactive waste repositories

A typical approach to scenario development is to create an "expected" or nominal scenario and one or more "disturbed" scenarios

A comprehensive set of "scenarios" are developed by combining FEPs that remain after screening

The first step of the FEPs analysis is to compile a comprehensive list of FEPs for the repository system

FEPs are screened on the basis of several factors:

- Physical reasonableness
- Probability of occurrence
- Consequence

Identify Scenarios for Analysis

An important goal in identifying the FEPs potentially relevant to long-term performance is the demonstration of completeness (i.e., nothing is too insignificant or improbable to be considered as potentially relevant)

- **NEA FEP list is the basis for many SNF/HLW FEP lists**
  - **Comprehensive NEA FEP list from NEA FEP database (NEA 2006) contains ~2000 FEPs from 10 international programs in 6 countries**
- **Yucca Mountain Project (YMP) list = 374 FEPs (SNL 2008)**
  - **~400 site- and design-specific phenomena considered in addition to ~2000 NEA FEPs**
- **Preliminary UFD SNF/HLW list = 208 FEPs (Freeze et al. 2010, 2011)**

Treatment of Aleatory Uncertainty: Defining scenarios based on unlikely events

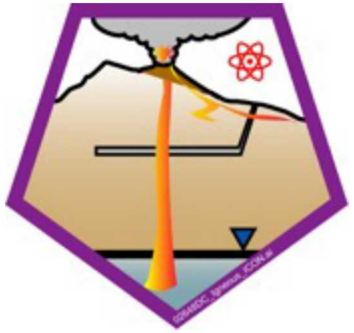
Four scenario classes divided into seven modeling cases

Nominal Scenario Class

- **Nominal Modeling Case (included with Seismic Ground Motion for 1,000,000-yr analyses)**

Igneous Scenario Class

- **Intrusion Modeling Case**
- **Eruption Modeling Case**

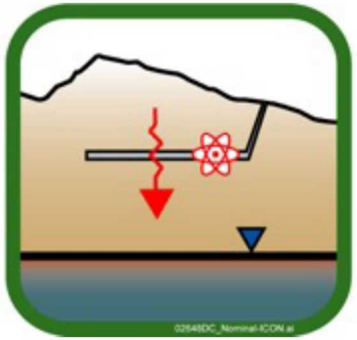


Early Failure Scenario Class

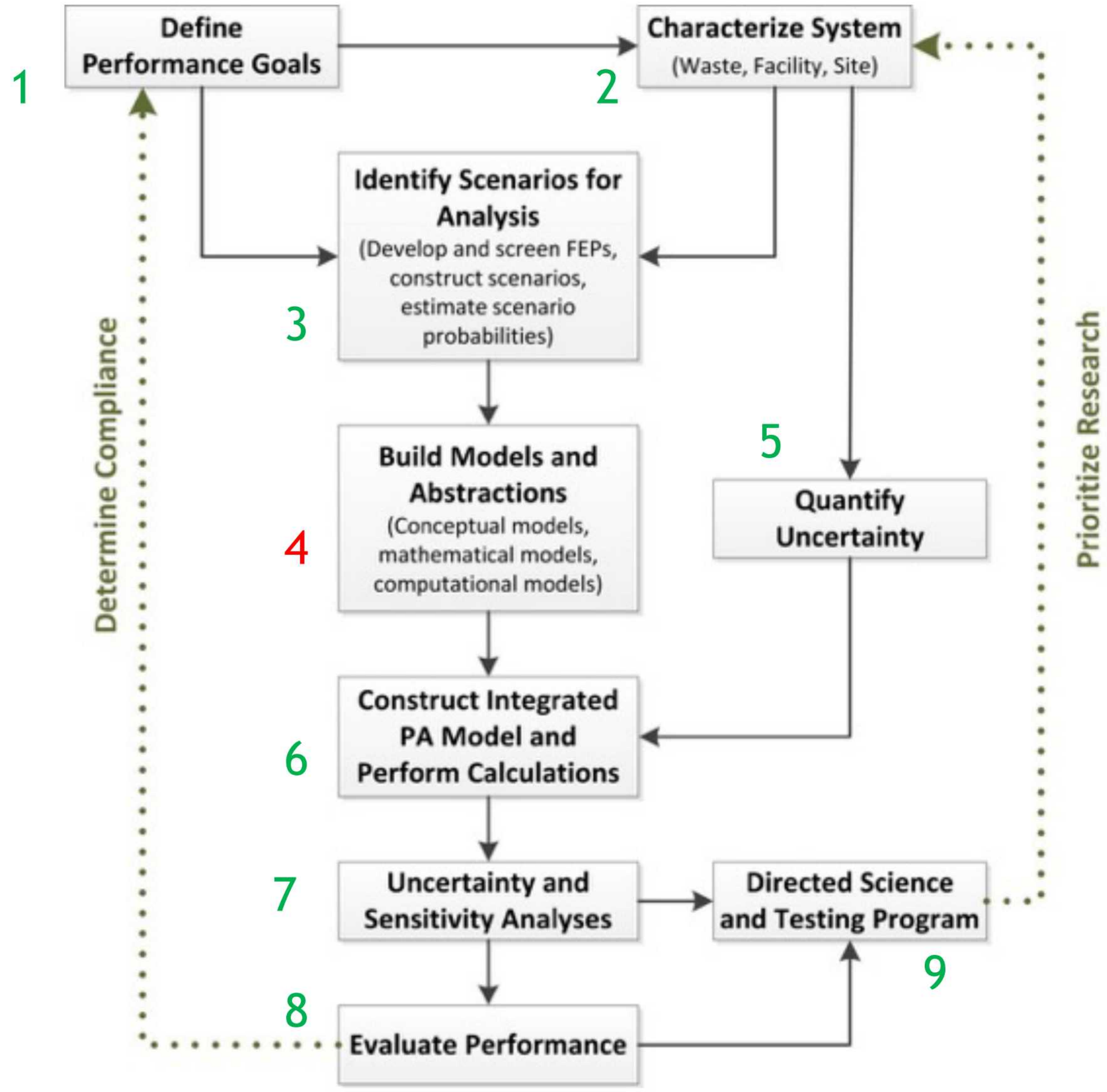
- **Waste Package Modeling Case**
- **Drip Shield Modeling Case**

Seismic Scenario Class

- **Ground Motion Modeling Case**
- **Fault Displacement Modeling Case**



PA Methodology



Build Models and Abstractions

FEPs and scenarios retained after the screening process are represented in the PA through conceptual models, mathematical models, and computational (numerical) models

A conceptual model is a description of the physical system and processes (THMBC), dimensionality, and assumptions, consistent with available information, that formalizes the understanding of how a system behaves

A mathematical model translates the conceptual model into a set of governing mathematical equations or expressions and initial and boundary conditions

A computational model provides numerical (or analytical) solutions to the mathematical models

Build Models and Abstractions

Development of computational models may occur at different levels:

- **Testing interpretation models (site characterization)**
- **Process Models (e.g., corrosion, thermal, flow and transport)**
- **Sub-system models (e.g., EBS, Geosphere)**
- **Total system performance assessment models (PA)**

Abstraction/simplification of sub-system models <u>may be necessary</u> for incorporation into the TSPA model.

Abstractions may include reduction in dimensionality, simplified processes, look-up tables, etc.

Build Models and Abstractions

The total system performance assessment model consists of sets of data and information, assumptions, and computational models that together describe the essential processes of the repository system and its long-term performance

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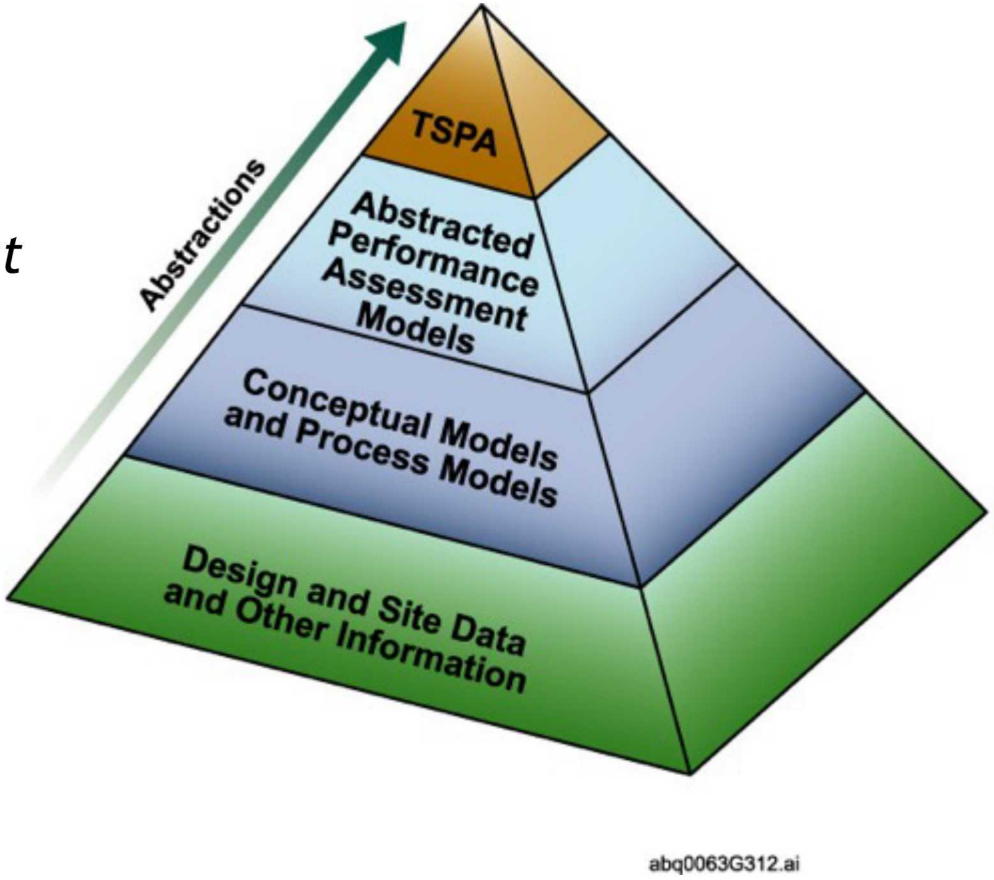


Simulation Tools (Codes)

FEHM - Zyvoloski, A. George (2007). FEHM: A control volume finite element code for simulating subsurface multi-phase multi-fluid heat and mass transfer (Report). Los Alamos Unclassified Report LA-UR-07-3359

TOUGH2 – MP - Keni Zhang, Yu-Shu Wu, and Karsten Pruess: User's Guide for TOUGH2-MP A Massively Parallel Version of the TOUGH2 Code, Earth Sciences Division Lawrence Berkeley National Laboratory, May 2008

TOUGH - Karsten Pruess, Curt Oldenburg, George Moridis: Tough2 User's Guide, Version 2, LBNL-43134 , 1999.

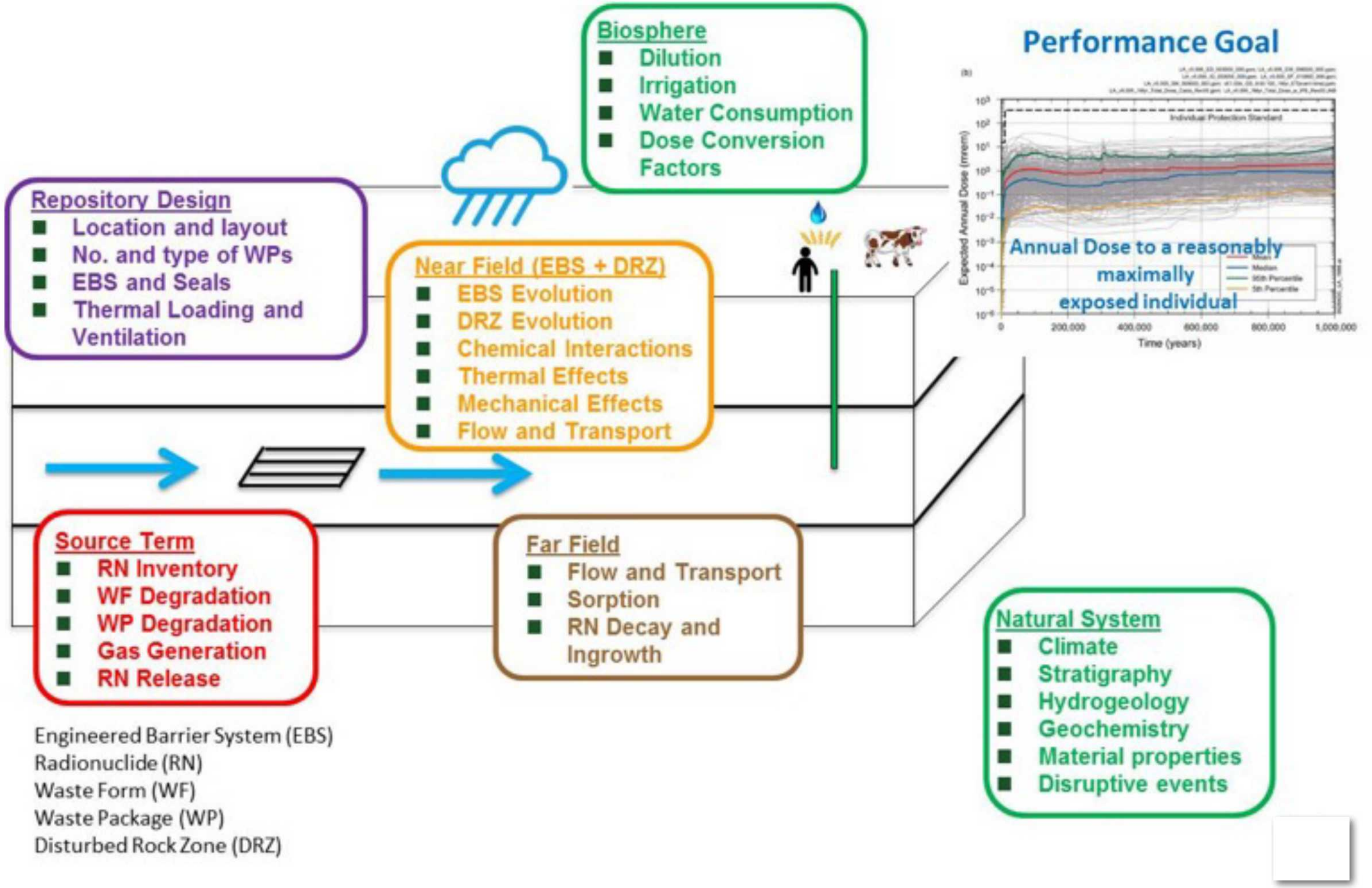
PFLOTRAN - http://www.pflotran.org/

- *PFLOTRAN is an open source, state-of-the-art massively parallel subsurface flow and reactive transport code. PFLOTRAN solves a system of generally nonlinear partial differential equations describing multiphase, multicomponent and multiscale reactive flow and transport in porous materials.*

Dakota - https://dakota.sandia.gov/

- *The Dakota toolkit provides a flexible, extensible interface between analysis codes and iterative systems analysis methods. Dakota contains algorithms for:*
- *optimization with gradient and nongradient-based methods;*
- *uncertainty quantification with sampling, reliability, stochastic expansion, and epistemic methods;*
- *parameter estimation with nonlinear least squares methods; and*
- *sensitivity/variance analysis with design of experiments and parameter study methods.*
- *Stepwise linear regression – most statistical software packages, MATLAB*

Long-Term Performance



Engineered Barrier System (EBS)
Radionuclide (RN)
Waste Form (WF)
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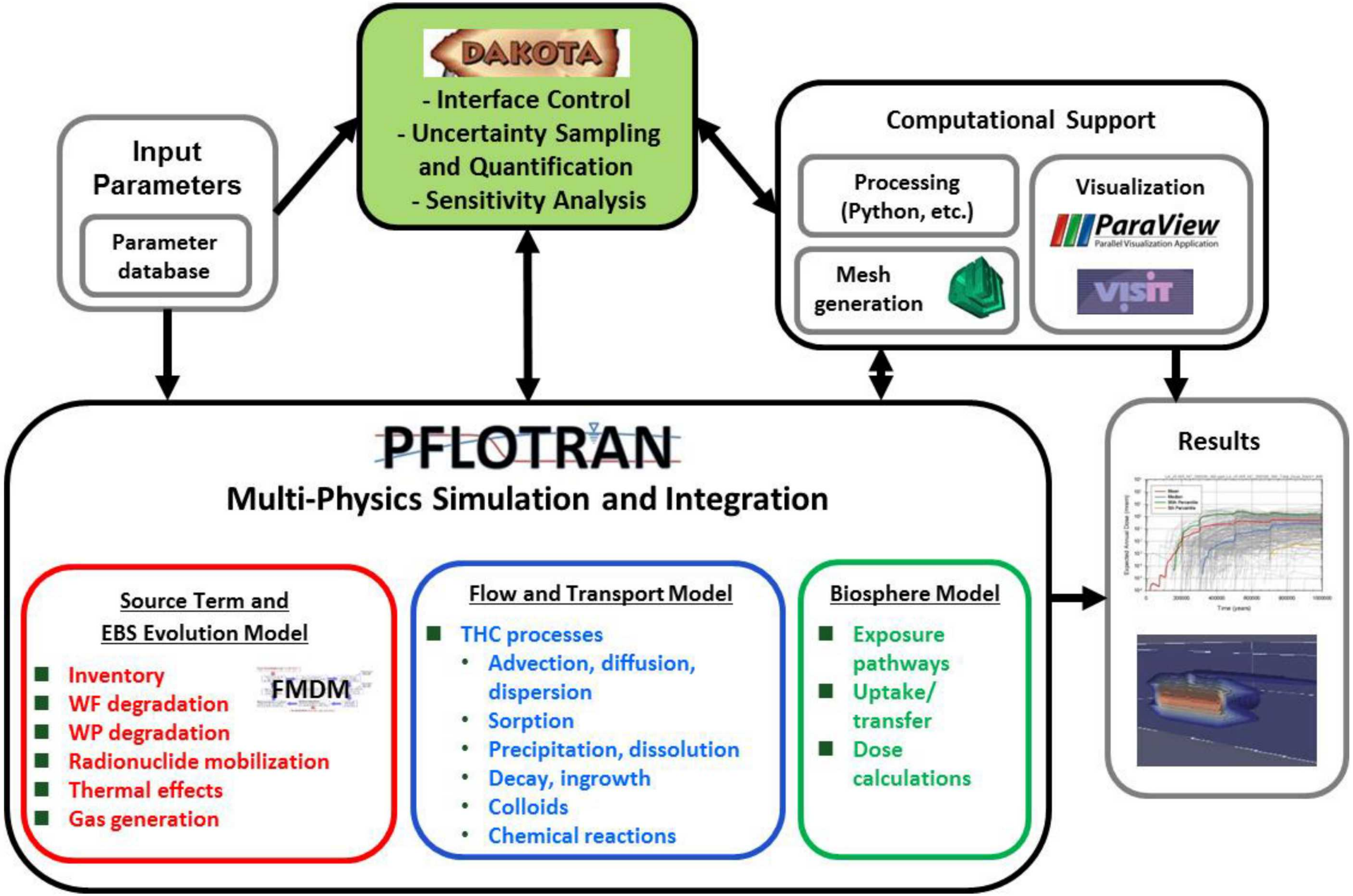
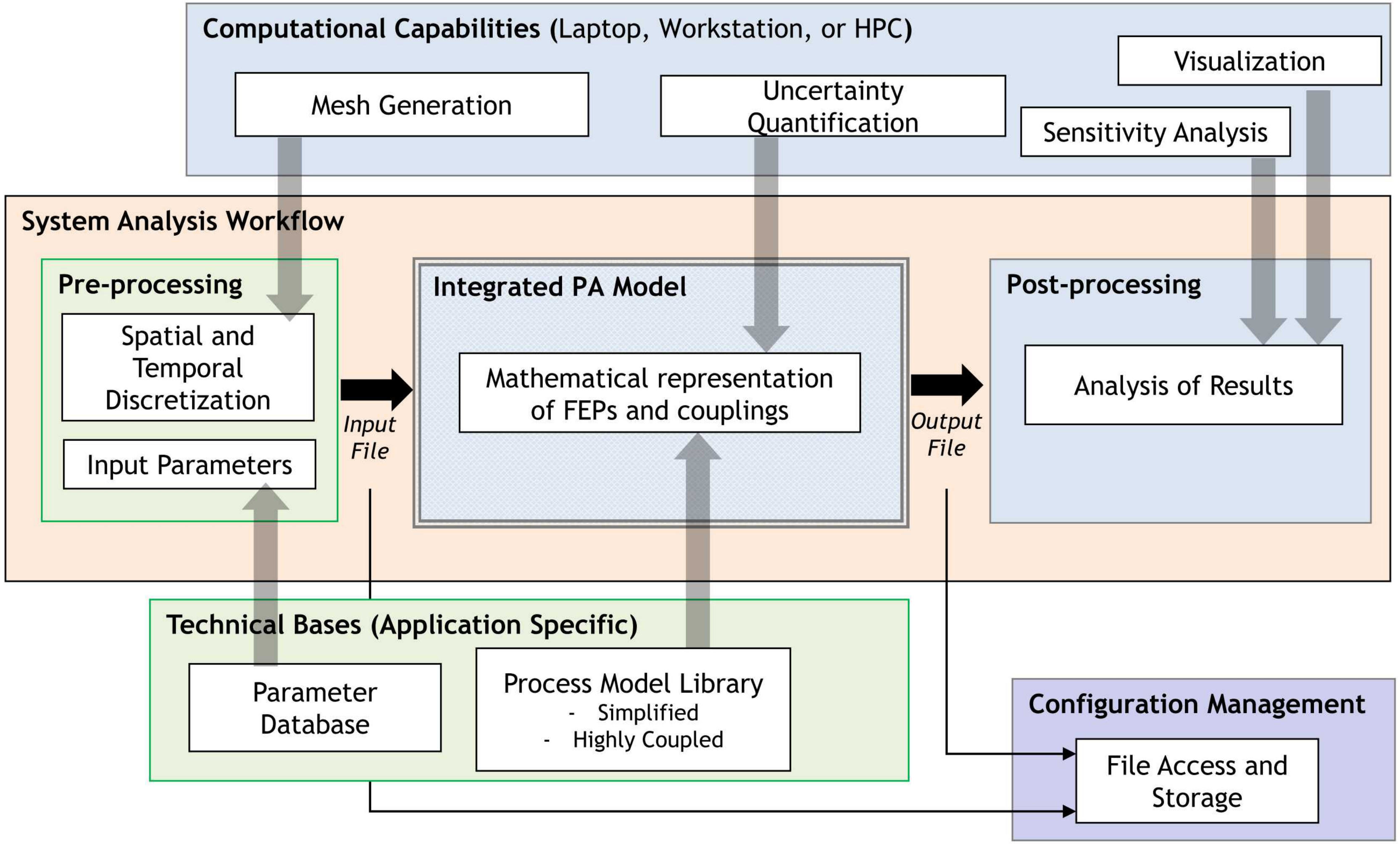
Disturbed Rock Zone (DRZ)

Enhanced PA Computational Model Architecture



Generic PA – Computational Framework



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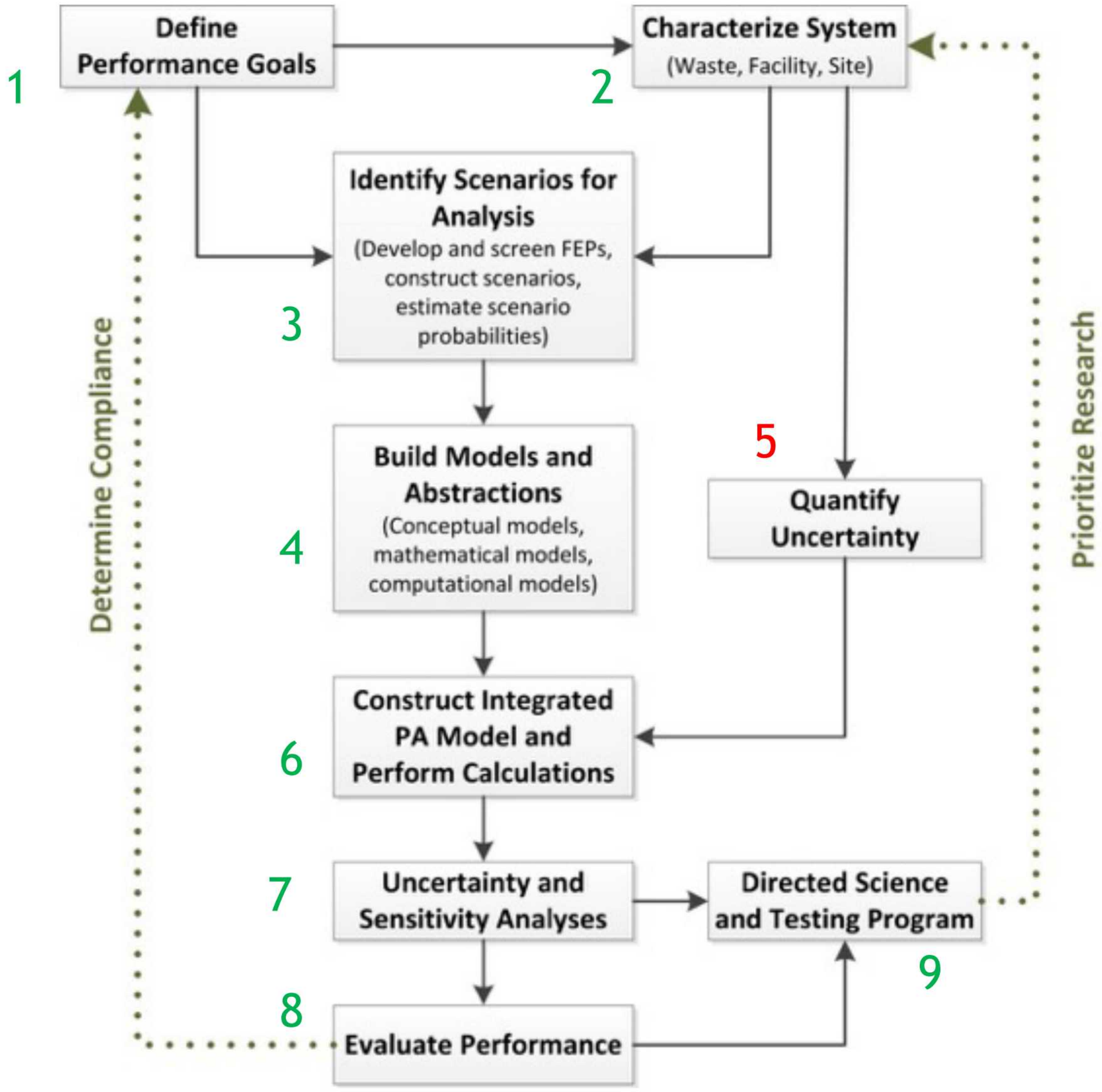
PA Methodology



Quantify Uncertainty

Uncertainties are inherent in projections of long-term performance of geologic repositories

An essential element of the performance assessment is to account for these these uncertainties and quantify their impact on future outcomes

Two main types of uncertainty, Aleatory and Epistemic

Quantify Uncertainty

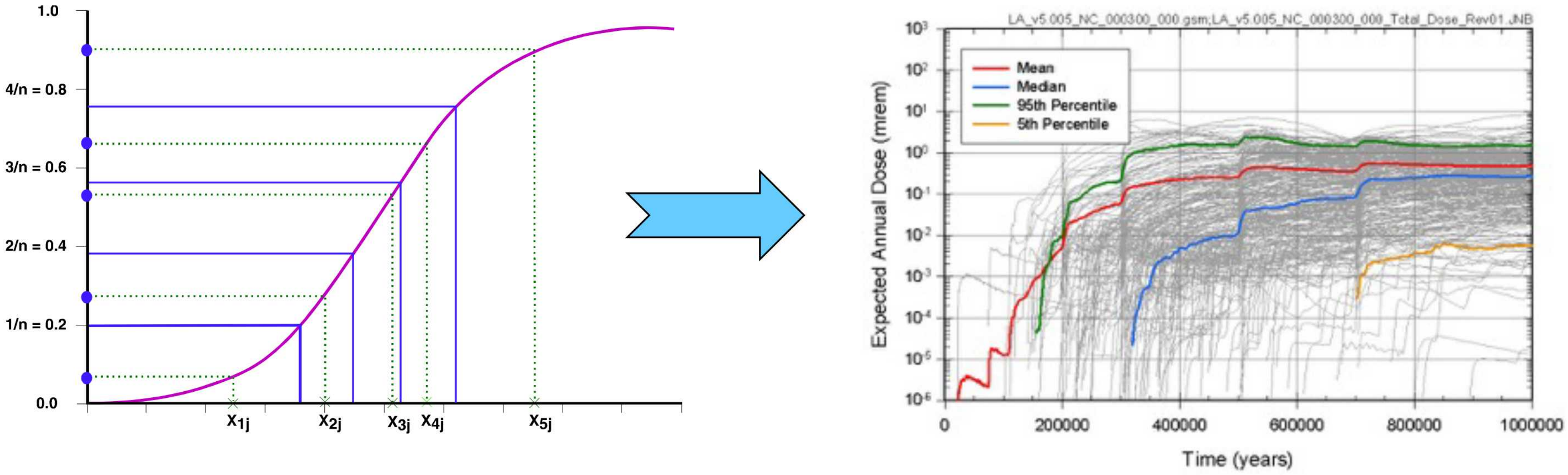
Three major sources of uncertainty should be considered in a performance assessment:

- Uncertainty in the future state of the system (aleatory uncertainty)
  - Example: time and size of a seismic event
- Data and parameter uncertainty (aleatory and epistemic uncertainty)
  - Examples: permeabilities, porosities, sorption coefficients, corrosion rates
- Model uncertainty (usually epistemic, but in general both aleatory and epistemic)
  - Example: dual porosity vs dual permeability

Data and Parameter Uncertainty

Epistemic uncertainty incorporated through Latin hypercube sampling of cumulative distribution functions and Monte Carlo simulation with multiple realizations

Approx. 400 uncertain epistemic parameters incorporated directly in Yucca Mountain TSPA-LA



Techniques for constructing PDF for uncertain parameters

If sufficient measurements exist, construct an empirical distribution function or

Fit analytical distributions (e.g., Normal, Log normal, Student-t, Uniform, Log-uniform, Triangle, etc)

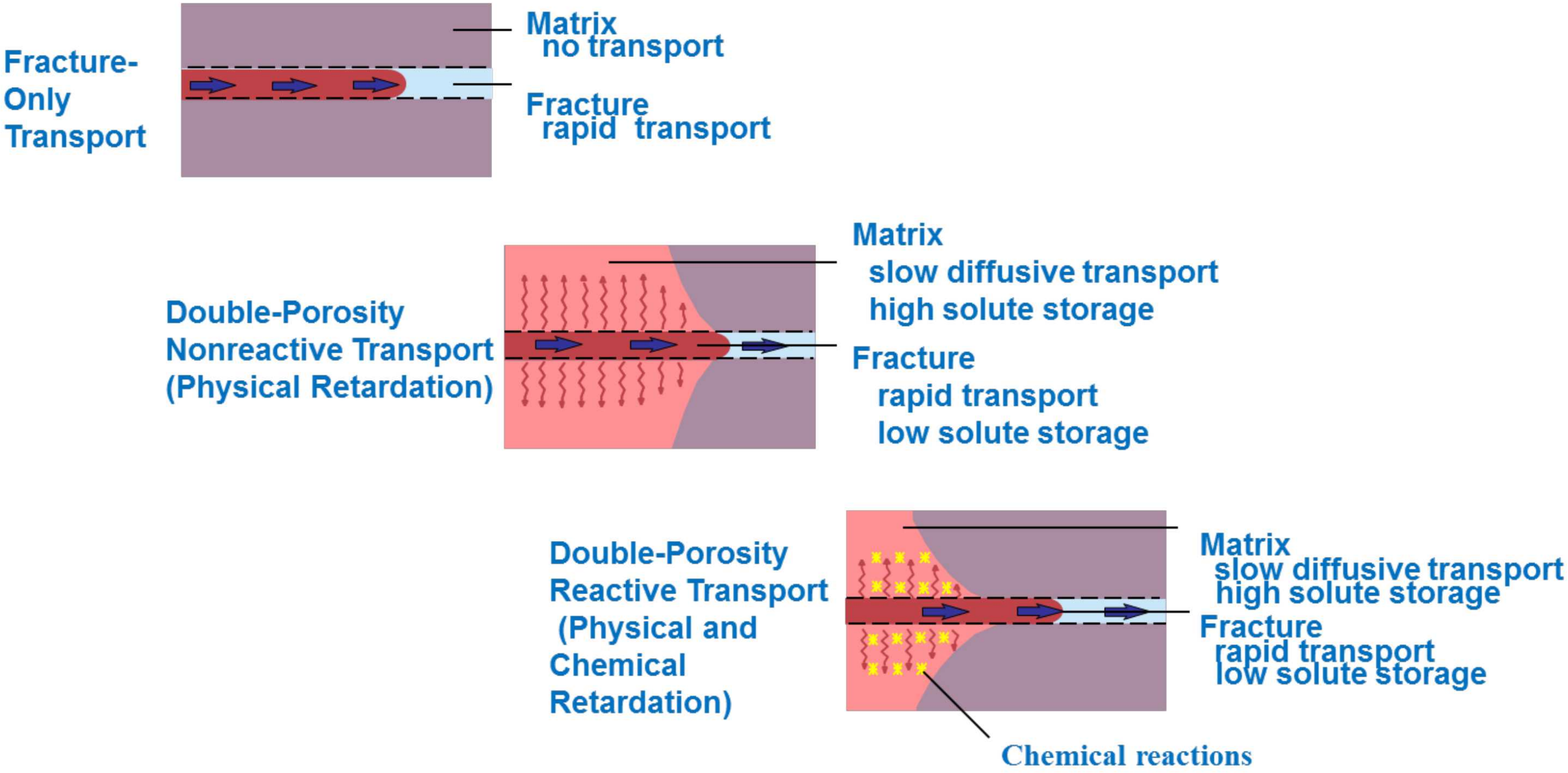
If few or no measurements exist, use elicitation processes:

- Informal request for professional judgement
- Formal elicitation of expert opinion

Goodness of fit statistics

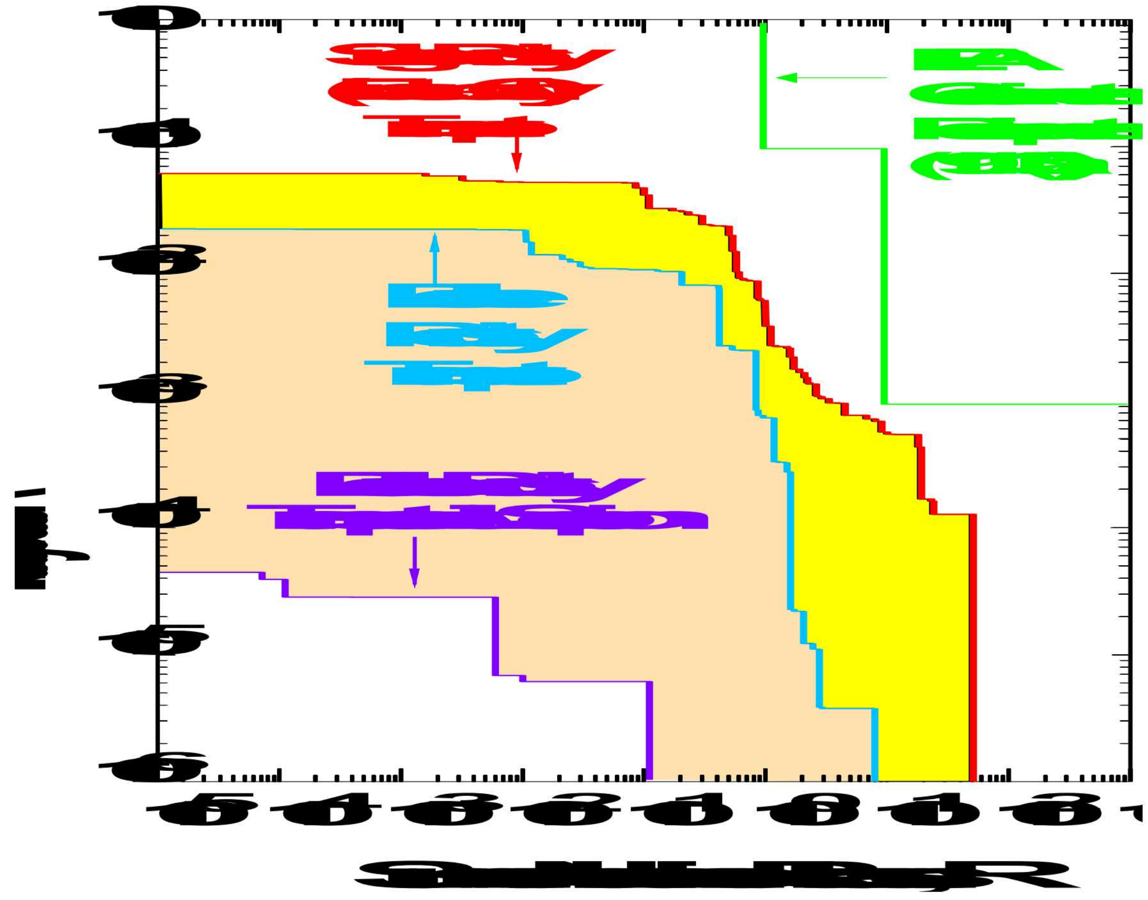
- Chi-Squared; Kolmogorov-Smirnoff; and Anderson-Darling

Alternative Conceptual Models

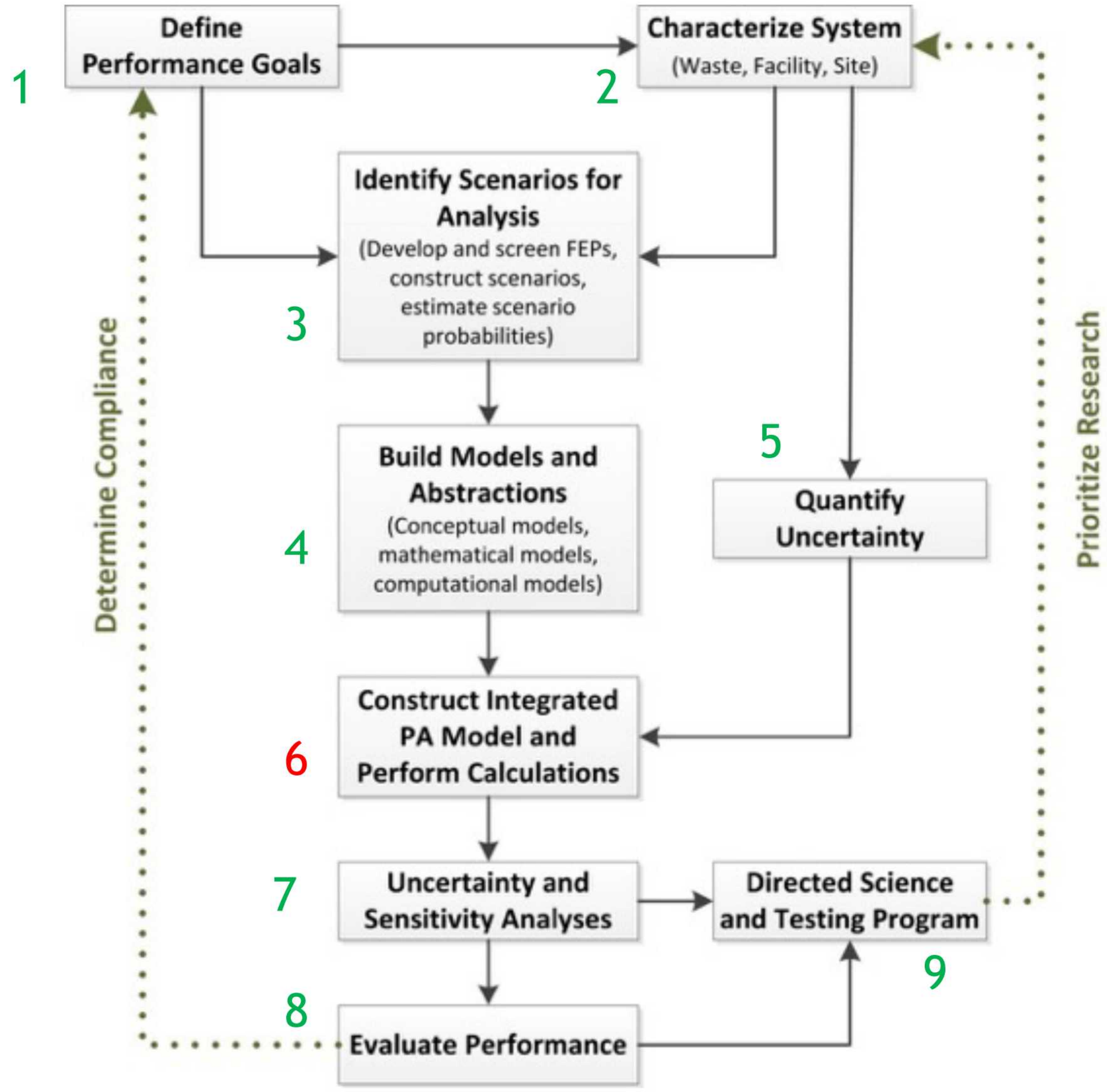


WIPP Alternative Conceptual Models

Conceptual model of fracture transport within the Culebra Dolomite has a strong influence on WIPP PA results.

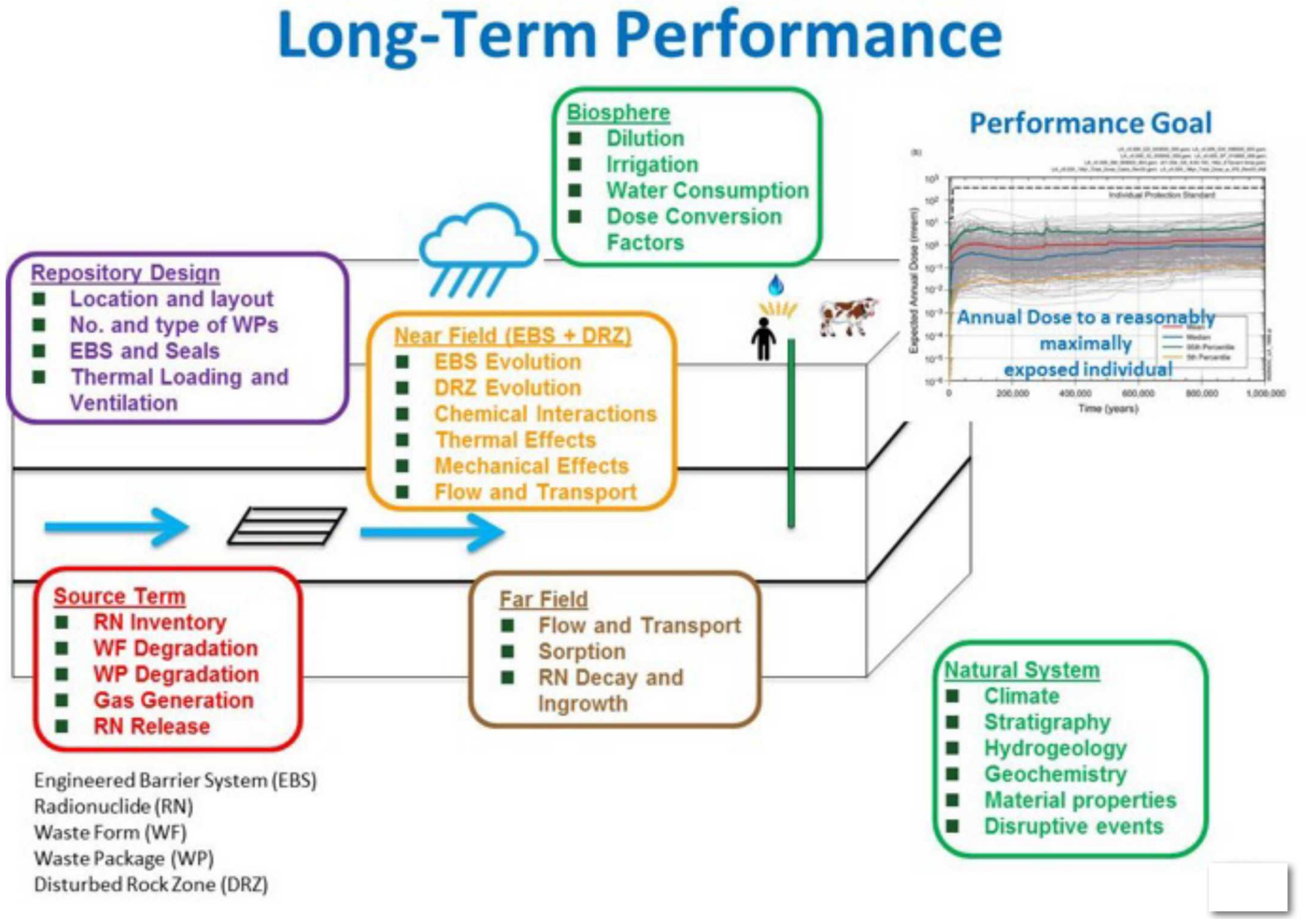


PA Methodology



Construct Integrated PA Model and Perform Calculations

The integrated PA model is constructed by coupling the sets of scenario sub-models together to calculate overall system performance



Construct Integrated PA Model and Perform Calculations

Uncertainty in the input parameters can be treated using deterministic or probabilistic methods

In a deterministic simulation of a specific scenario, each input parameter is assigned a single value, typically representative of best estimate or conservative conditions

- The PA model is then used to calculate a corresponding value(s) for the system performance measure(s)
- Bounding analyses involve parameter values selected such that the performance of the system is "worst case".
- Defining what the worst case is can be a challenge, however, it is typically easy to defend if all agree that the performance could not be worse than that calculated

Construct Integrated PA Model and Perform Calculations

In a probabilistic simulation, parameter values are sampled and propagated through the coupled set of models to generate a distribution of potential outcomes.

- Parameter uncertainty is propagated into the PA by conducting multiple calculations for each scenario using values sampled from the distributions of possible values (e.g., Monte Carlo simulation).
- Each individual calculation uses a different set of sampled input values and produces a different value(s) for the system performance measure(s).

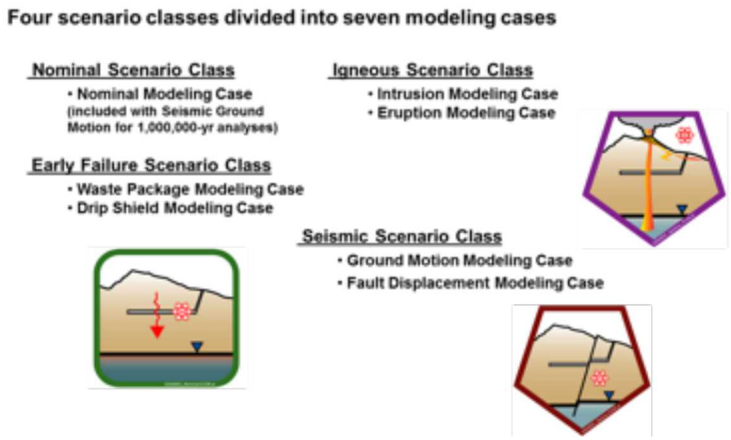
*Fig. 1: J.C. Helton et al. / Reliability Engineering and System Safety 122 (2014) 267–271.

Construct Integrated PA Model and Perform Calculations

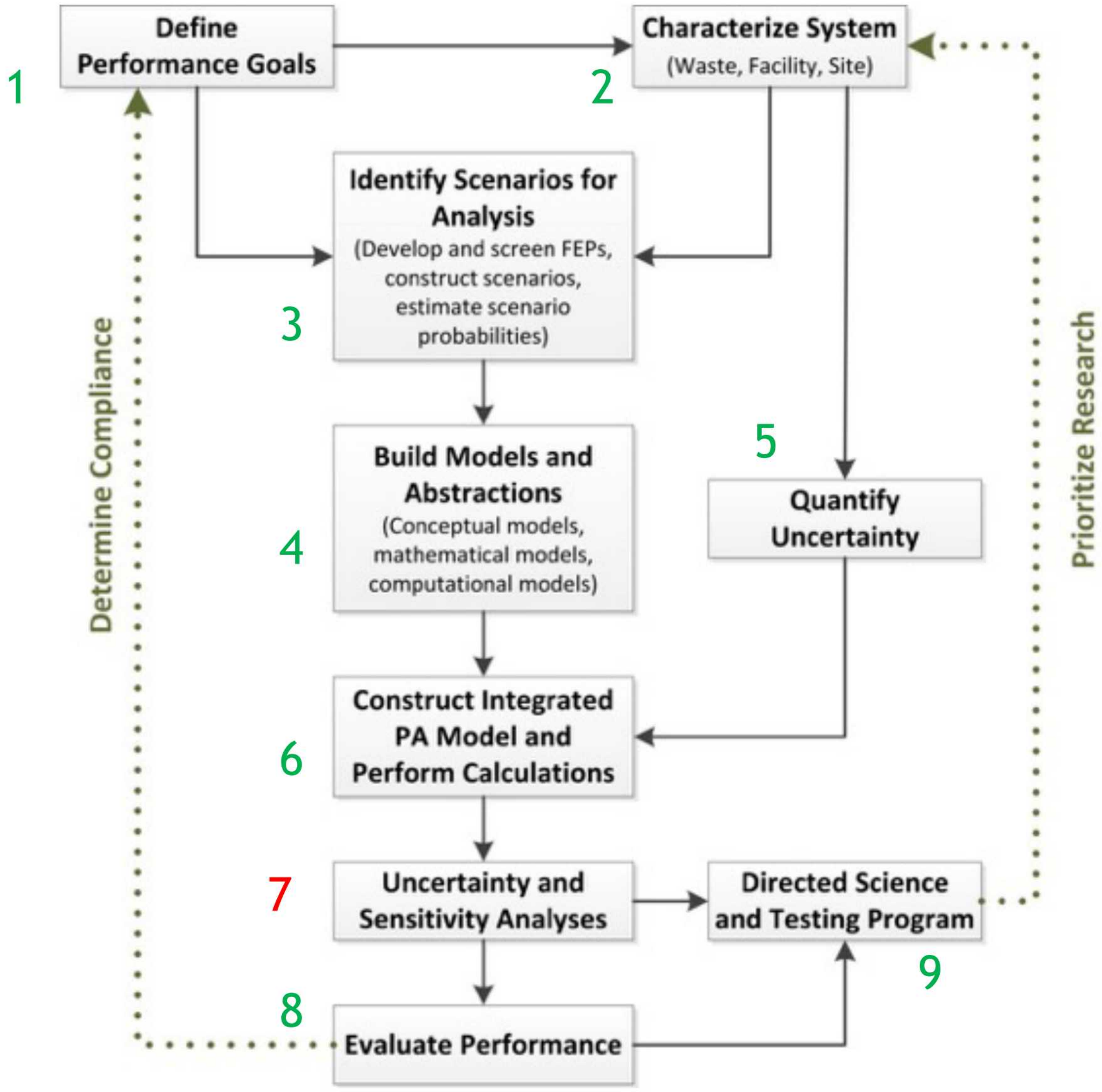
The result of each individual calculation represents a different possible realization of the future overall performance of the system, consistent with the uncertainty in the input parameters

Overall system performance for a specific scenario is then quantified by some measure of the distribution of results from all realizations, such as the mean or median of the system performance measure(s)

Uncertainty associated with the probability of occurrence of each scenario is included in the PA by conducting separate analyses for each scenario and then probability weighting the results to estimate an overall system consequence



PA Methodology



Perform Uncertainty and Sensitivity Analyses

Uncertainty and Sensitivity analyses are used to quantify the spread of performance projections and identify those factors that "drive" the spread in the performance projections.

Sensitivity analyses are valuable for understanding the processes of the repository system, for improving analyses in the next iterative cycle, and for PA quality assurance.

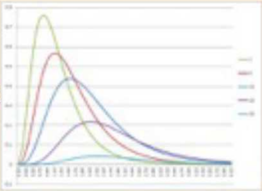
Interpretation of sensitivity analyses plays an important role in integration between site characterization, repository design, and performance assessment

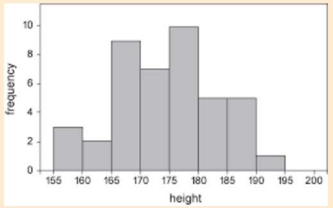
Perform Uncertainty and Sensitivity Analyses

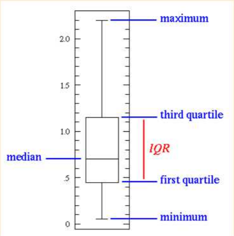
Uncertainty analysis

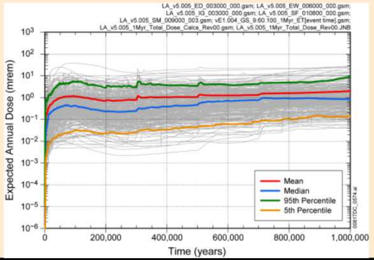
Determination of the uncertainty in analysis outcomes that results from uncertainty in analysis inputs

- Distributions
- Histograms
- Box plots





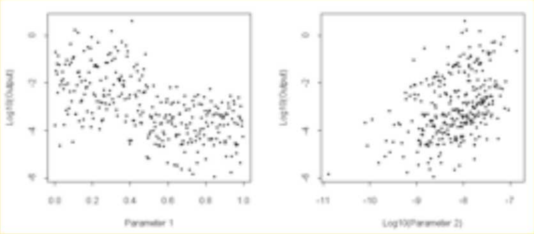


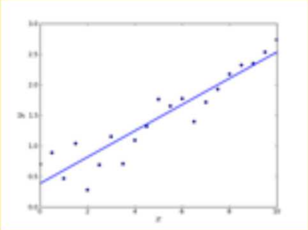


Sensitivity analysis

Determination of the effect of uncertainty in individual analysis inputs on analysis outcomes

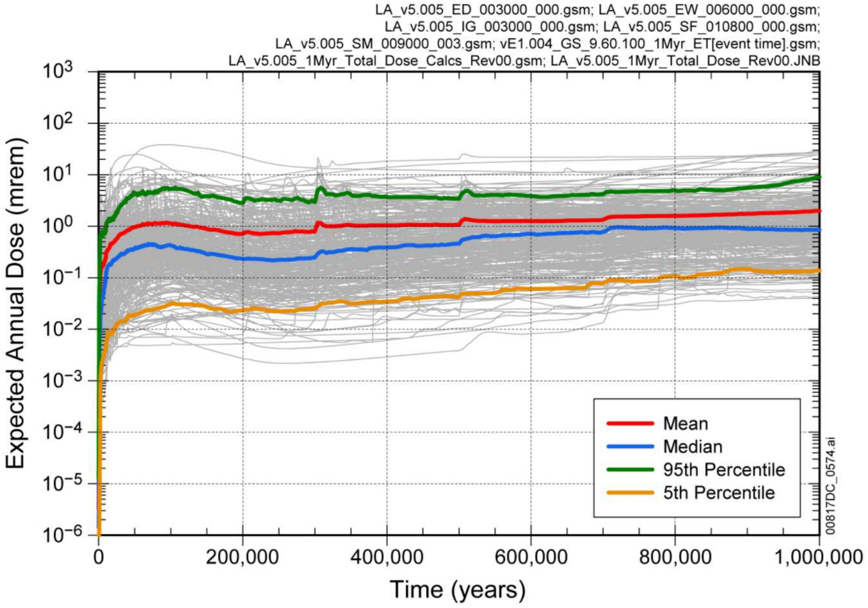
- Scatterplots
- Stepwise regression
- Partial Correlation

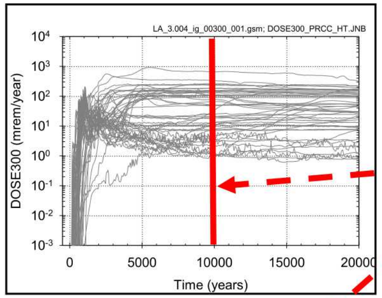




Perform Uncertainty and Sensitivity Analyses

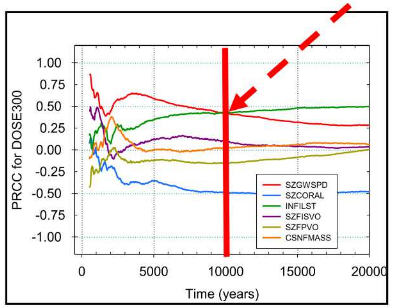
Monte Carlo estimates of overall performance
(Example dose histories from Yucca Mountain Total System Performance Assessment for the License Application, total expected dose from all scenarios)

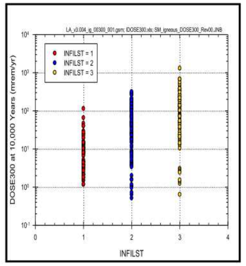


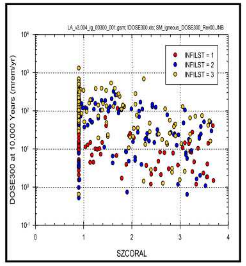


DOSE300: 10,000 yr

Variable	R^2	SRRC
INFILST	0.28	0.53
SZCORAL	0.40	-0.36
SZGWSPD	0.53	0.36
GTCPU239	0.61	0.27
IGPH	0.63	0.15
SZHAVO	0.64	0.09
EP1LOWU	0.65	0.10
EPSLOWPU	0.66	0.09
SZNVF7	0.66	0.08



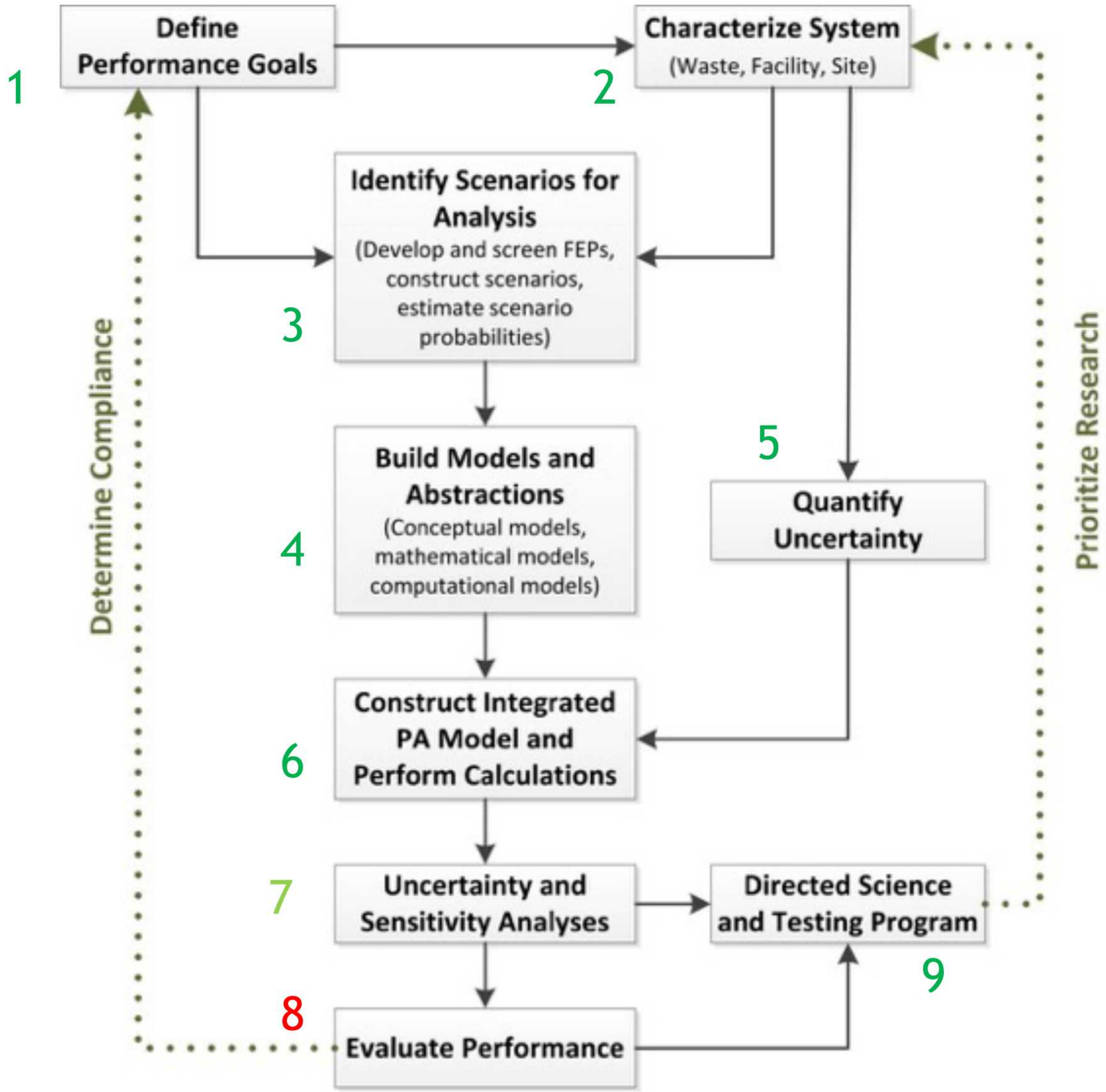




Sensitivity and Uncertainty Analyses
Identify model inputs important to uncertainty in performance estimates

See - Total System Performance Assessment Model/Analysis for the License Application, MDL-WIS-PA-000005, 2008

PA Methodology



Evaluate Performance

Quantitative PA results provide indications of subsystem and overall system performance

When combined with sensitivity analyses, PA results can be used to identify the models and parameters that have the greatest effect on the behavior of the system

Identification of the uncertainties that are most important in preliminary PAs can help guide site characterization, repository design, and model development through a directed science and testing program

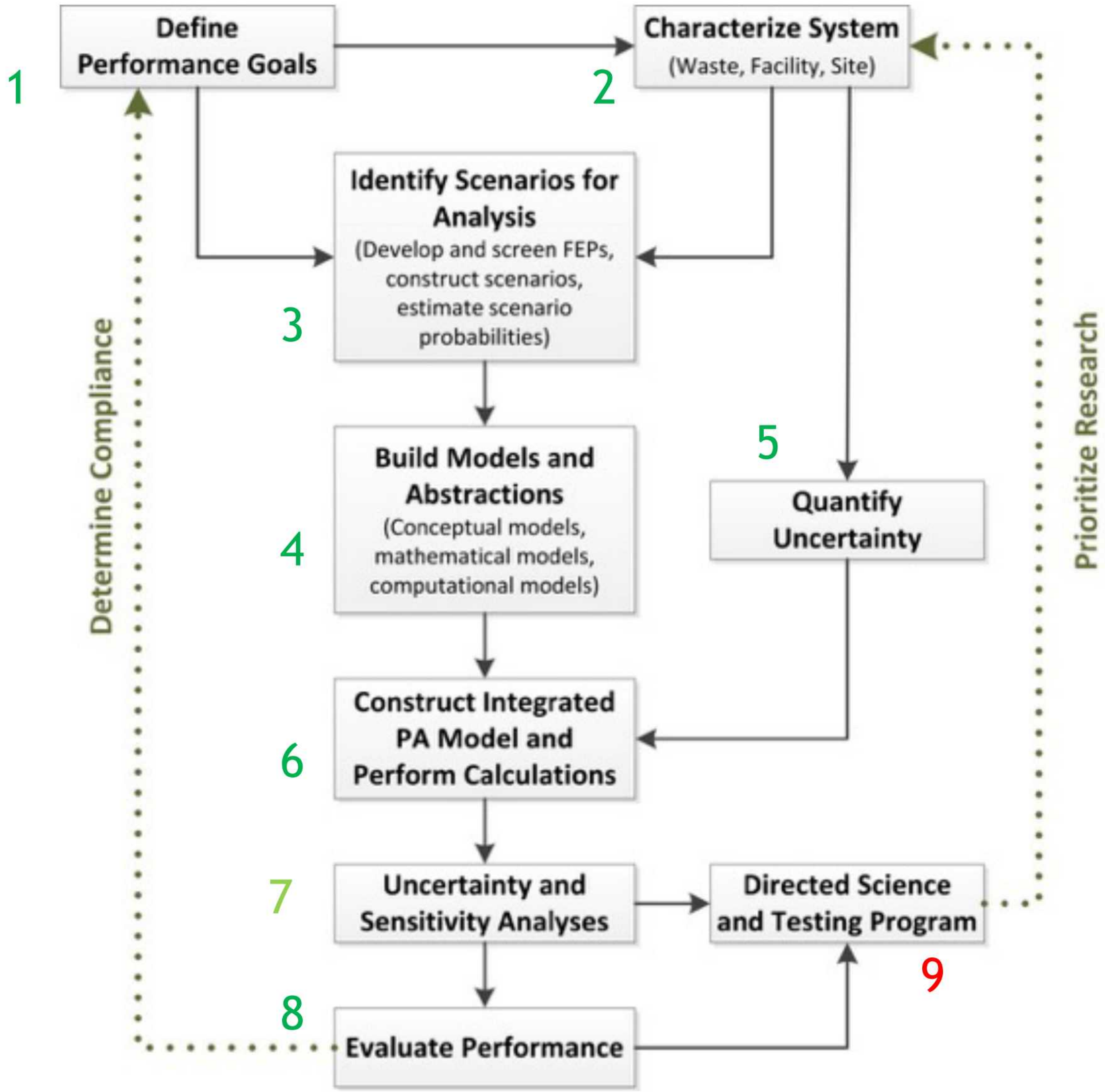
The steps in the PA process are repeated, as needed, until a final decision is reached

Evaluate Performance cont.

A decision in favor of regulatory acceptability of the repository would only be made at a mature stage of a repository program when PA models are sufficiently well developed and documented to support regulatory decisions.

A favorable decision of acceptability requires not only quantitative determination from the PA model, but also requires support from the site characterization and repository design groups and a rigorous Safety Case.

PA Methodology



Directed Science and Testing Program, 1/2

Information from the overall performance evaluation and uncertainty and sensitivity analyses serves to identify important parameters and systems for further investigation.

This may include identifying systems whose performance can be improved by modifications to the design, or parameters with uncertainties that, if reduced through further site or laboratory investigations, would significantly increase confidence in the overall safety assessment results.

The safety assessment process can help inform programmatic decision-making regarding the testing and scientific investigations that will most effectively improve the accuracy and confidence in safety assessment results and toward design decisions most likely to improve real system performance.

Directed Science and Testing Program, 2/2

Factors other than the quantitative sensitivity of the TSPA model may be important to consider in the prioritization of data collection and analyses

Public and political confidence in the repository system may require a minimum level of understanding for certain aspects of the system, regardless of the expected quantitative impact on performance

Some data collection tasks that have a high technical priority may also require long time frames, placing them in conflict with project schedule goals

Summary

The iterative application of the performance assessment methodology through the lifetime of a deep geologic disposal project supports a defensible:

- **Evaluation of subsystem and total system performance with respect to specific criteria or requirements**
- **Consideration of expected and disturbed scenarios**
- **Evaluation of design options/alternatives**
- **Development of the models used to simulate the important FEPs and scenarios**
- **Determination and representation of significant sources of aleatory, epistemic, and model uncertainty**
- **Incorporation of information from laboratory and field tests, published literature, natural analogues, and expert judgment**
- **Prioritization of research and testing needs**

Sources of Information

IAEA Safety Standards: No. SSR-5 “Disposal of Radioactive Waste”

OECD Radioactive Waste Management Document: “Post-Closure Safety”

Case For Geological Repositories: Nature And Purpose”

National Academy of Sciences: “One Step at a Time: The Staged Development of Geologic Repositories for High-Level Radioactive Waste”

Nuclear Energy Agency: “Confidence in the Long-term Safety of Deep Geological Repositories: Its Development and Communication”

Yucca Mountain Repository Safety Analysis Report

WIPP Certification and Recertification Reports

Examples from various international programs and personal experience

Geological Disposal: An overview of the generic Disposal System Safety Case, UK, NDA

International Atomic Energy Agency (IAEA), IAEA Safety Glossary: Terminology Used in Nuclear Safety and Radiation Protection, Vienna. Publication STI/PUB/1290, 2007

FEP References

Freeze, G., Mariner, P., Houseworth, J.E., and Cunnane, J.C. 2010. Used Fuel Disposition Campaign Features, Events, and Processes (FEPs): FY10 Progress Report. SAND2010 -5902, Sandia National Laboratories, Albuquerque, New Mexico.

Freeze, G., Mariner, P., Blink, J.A., Caporuscio, F.A., Houseworth, J.E., and Cunnane, J.C. 2011. Disposal System Features, Events, and Processes (FEPs): FY11 Progress Report. SAND2011- 6059P, Sandia National Laboratories, Albuquerque, New Mexico.

NEA (Nuclear Energy Agency) 2006. The NEA International FEP Database: Version 2.1. Paris, France: Nuclear Energy Agency.

SNL (Sandia National Laboratories) 2008. Features, Events, and Processes for the Total System Performance Assessment: Analysis. ANL-WIS-MD-000027 REV 01. Las Vegas, Nevada: Sandia National Laboratories.

Additional Slides

Four Questions Underlying PA

Q1: *What can happen?*

Q2: *How likely is it to happen?*

Q3: *What are the consequences if it does happen?*

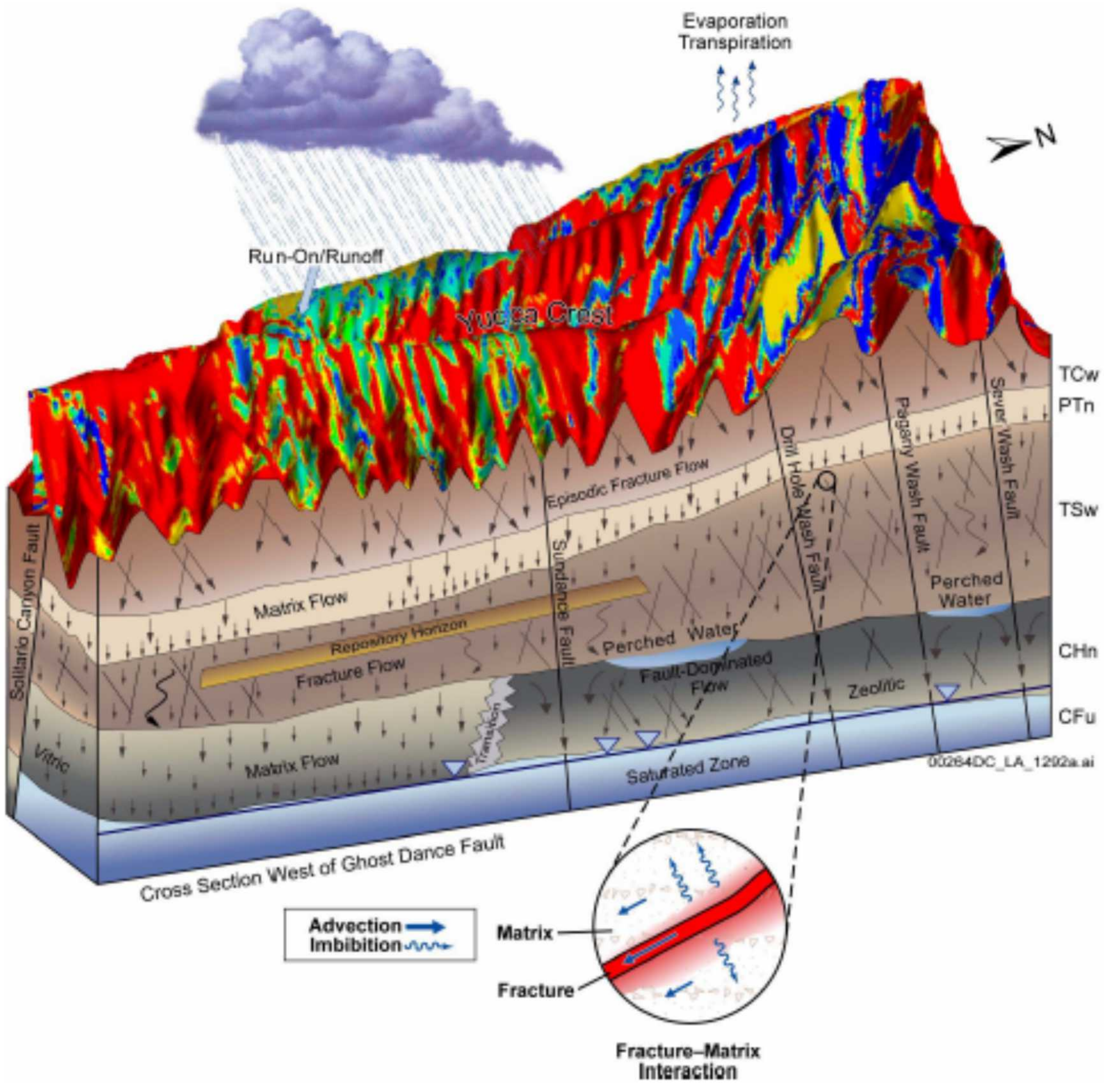
Q4: *What is the uncertainty in the answers to the first three questions?*

Role of PA in the Case for Safety

Performance Assessment (PA) is performed iteratively throughout the development of the repository assessment bases

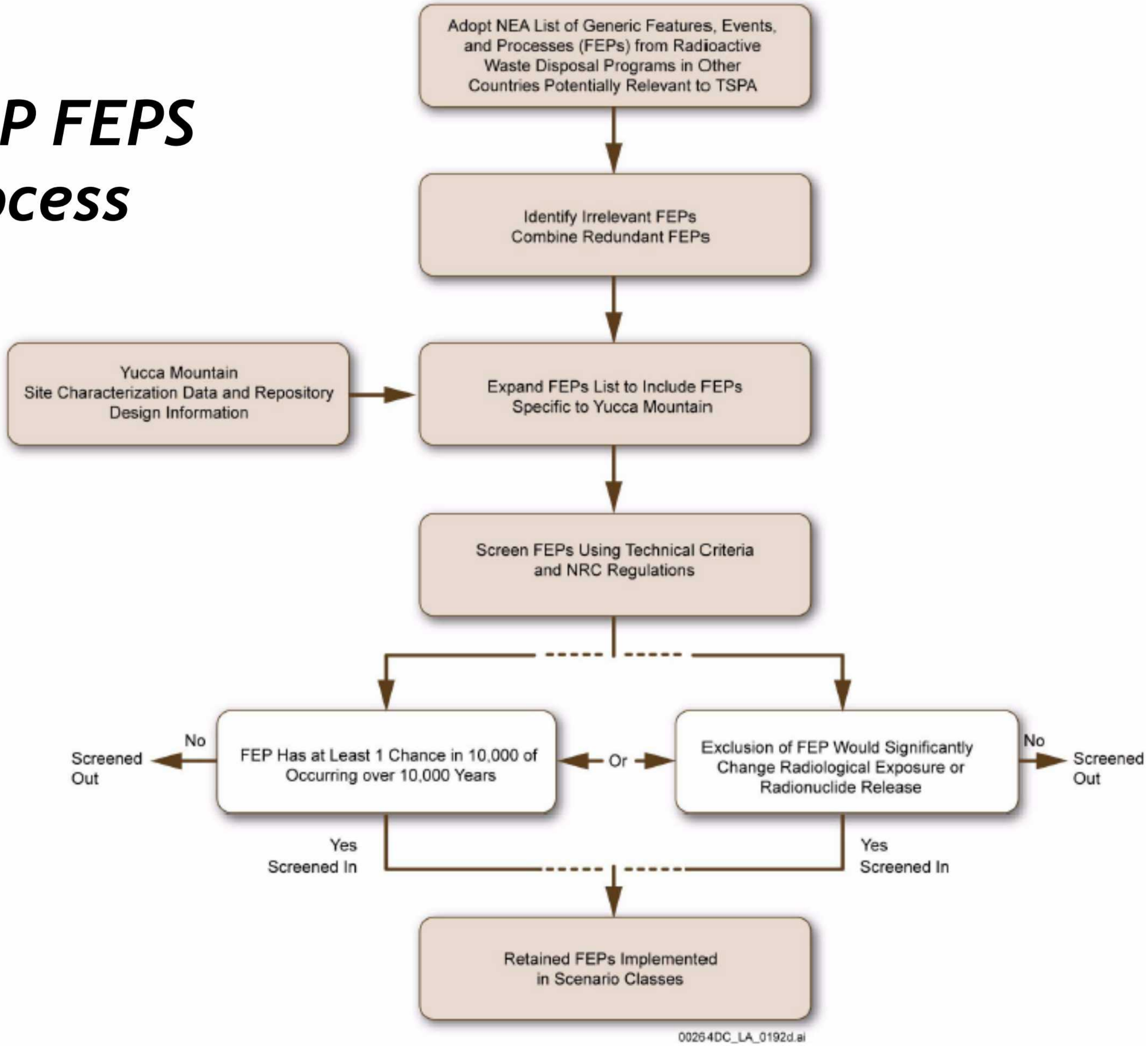
- Evaluate and synthesize the current scientific understanding and data for the given design concept or possible repository at a site
- Understand and forecast long-term performance of the repository and identify factors that are most important to that performance
- Identify factors and processes for which improved understanding or data are needed
- Identify possible repository design modifications to improve performance or to reduce uncertainties
- Demonstrate that the repository concept meets attendant regulatory requirements and will remain safe over the required timescale
- **Provide the framework around which integration among repository design, site characterization, and PA groups can be organized**

Characterize System: Conceptual Models

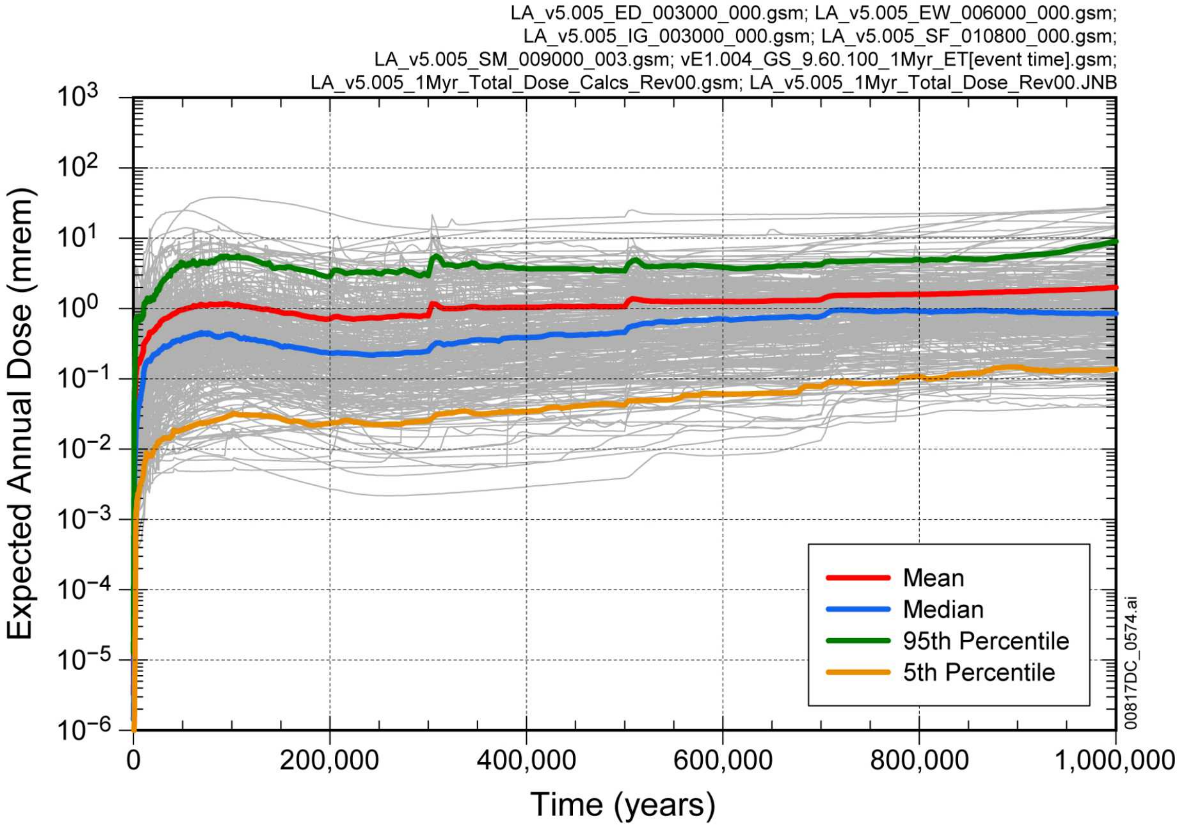


Overall Conceptualized Water Flow Behavior in the Unsaturated Zone at Yucca Mountain

YMP FEPS Process



Perform Uncertainty and Sensitivity Analyses



Quantify Uncertainty

Uncertainty in the future state of the system

- Aleatory uncertainty is typically addressed in a performance assessment model through scenario construction and screening, where each retained scenario represents a possible future state of the disposal system.
- Scenario probabilities are used to weight the consequences of each scenario according to its probability of occurrence.

Data and parameter uncertainty

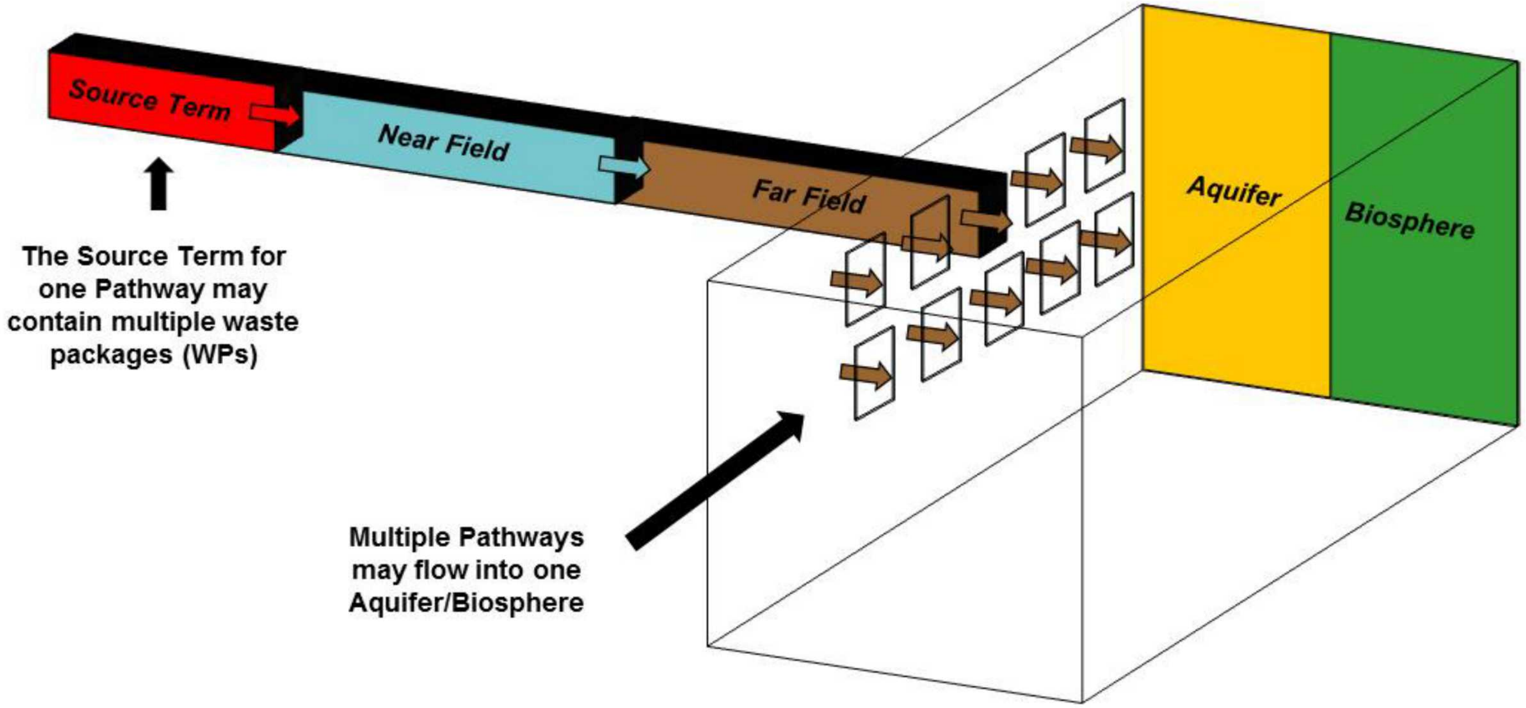
- Accounted for by developing a distributions of values for each uncertain parameter, each distribution describes a range of values within which the true value is believed to fall, with an expected value that corresponds to the best estimate of the true value

Model uncertainty

- **Alternative conceptual models must be considered when more than one valid interpretation of system behavior is possible from the existing data**

Application of Simplified PA Models

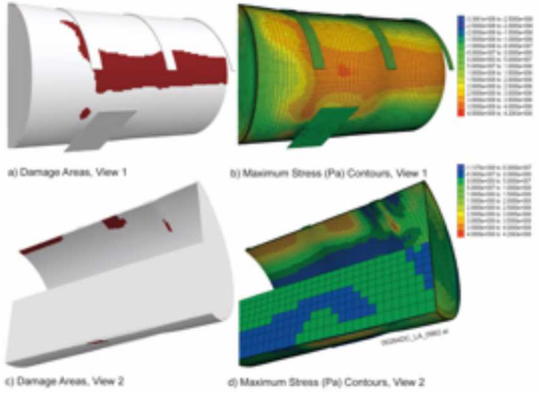
- **GoldSim framework**
  - Single associated 1D flow and transport pathway (streamtube)
    - Assumes multiple WPs and pathways all converge at receptor
      - *No spatial variability in source term or transport*
      - *No temporal variability in WF degradation or WP failure*
      - *No thermal effects (except flow rate abstraction for deep borehole)*



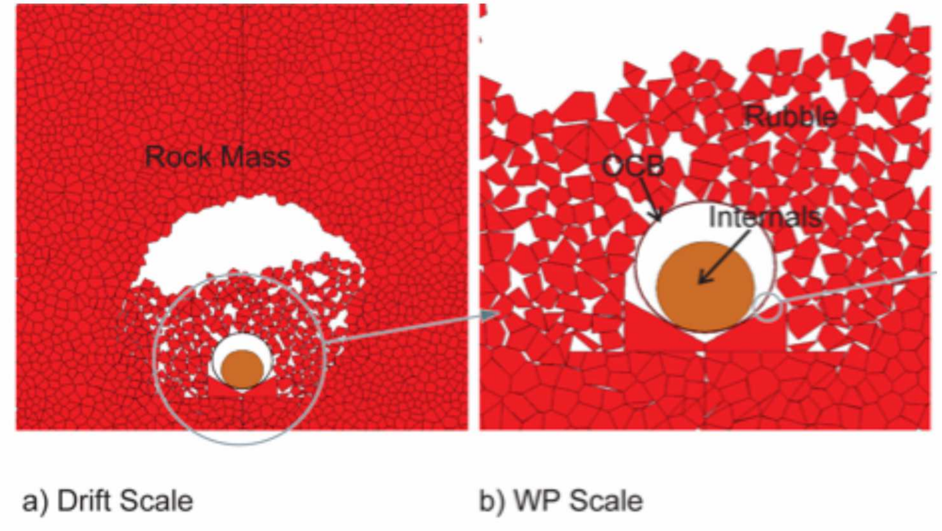
Consequence Models for Seismic Disruption at Yucca Mountain

- Two Release Scenarios
  - Direct fault displacement ruptures waste packages
    - Minor contributor due to low probability of new fault formation
  - Ground motion damages packages through
    - Vibratory motion and impact
    - Rockfall impact
    - Accumulated loading of rockfall
- Waste package damage is a function of:
  - Event magnitude
  - Type of waste package
  - Time-dependent package degradation

Right
Modeled Waste Package Damage and Stress Contours following vertical loading (DOE/RW-0573 Rev. 1, Figure 2.3.4-91)



Below
Model for Rubble-Waste Package Interactions (DOE/RW-0573 Rev. 1, Figure 2.3.4-88)



Perform Uncertainty and Sensitivity Analyses

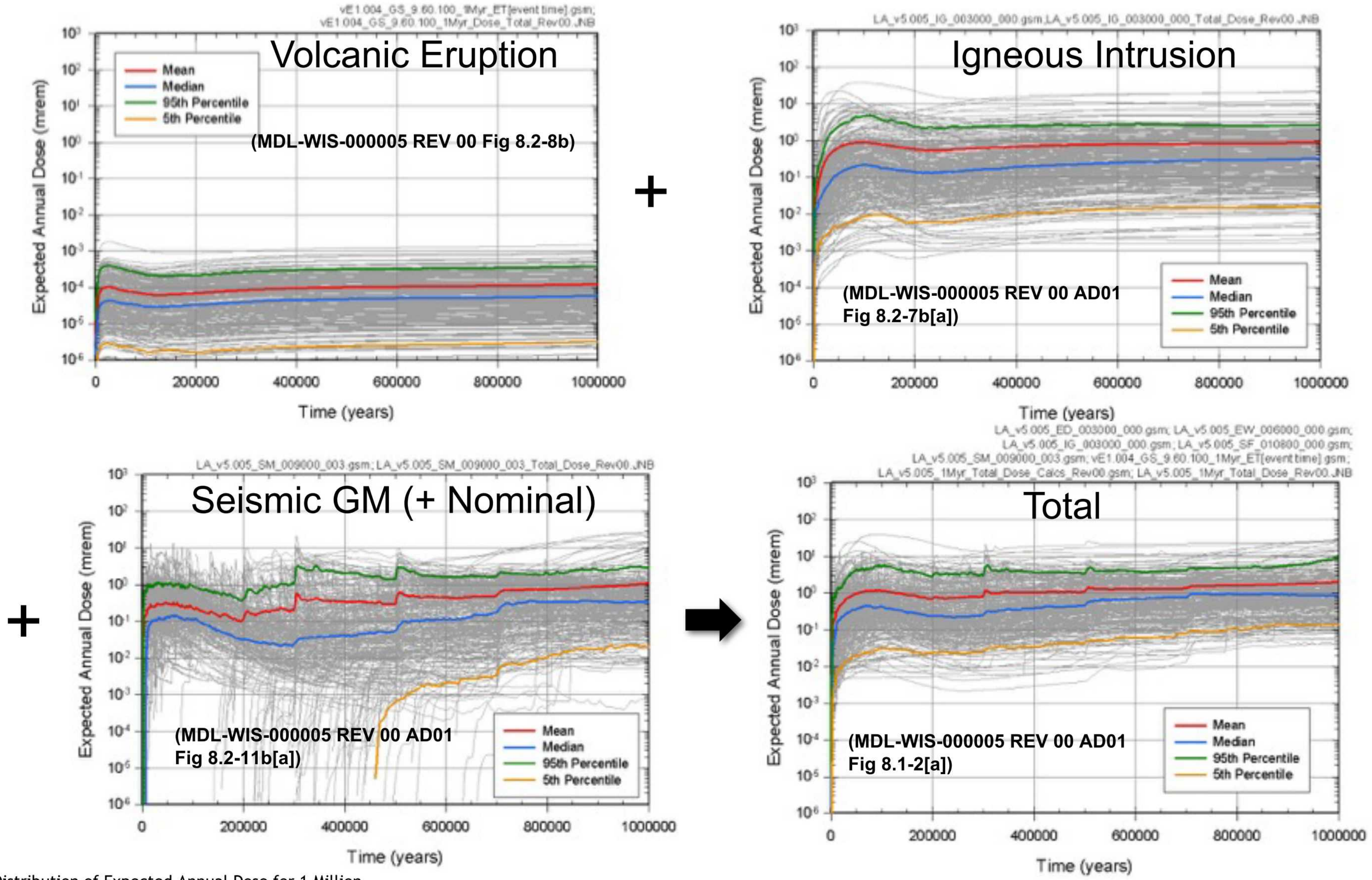
Build a sequence of multivariate linear rank regression models between output and inputs

At each step, admit the variable which accounts for the largest amount of unexplained variance until no more regression coefficients pass statistical significance tests

Importance ranking metrics

- Partial correlation => correlation between output and input after removing linear influence of all other inputs
- *R*2-loss => loss in explanatory power of current model if a variable is excluded from regression model

Construct Integrated PA Model and Perform Calculations: Construction of Total Dose



Distribution of Expected Annual Dose for 1 Million
Years after Repository Closure, YMP SAR 2.4, 2008

Perform Uncertainty and Sensitivity Analyses

Sensitivity Analysis Techniques

Scatter plot analysis

- **Visual measure of relationship between model output and uncertain inputs**

Regression analysis

- **Quantitative input-output model built via rank regression to determine most important contributors to output variance (spread)**

Perform Uncertainty and Sensitivity Analyses

Scatter Plot Analysis - Example