Environmental Performance Assessment

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Introductory Comments

• What do we mean by environmental performance assessment?
• Importance of and reliance upon performance assessment with respect to decision-making for waste management and environmental restoration.
• Challenge associated with forecasting performance over time periods that exceed our experience by several orders of magnitude.
• Importance of the conceptual model(s)
• Uncertainty?
NCRP 152 (2006)

Source: Seitz (2009)

**Iterative process involving site-specific, prospective modeling evaluations** of the postclosure time phase of a waste disposal system for the purpose of

- determining whether **reasonable assurance** of compliance with regulatory performance objectives can be demonstrated, and
- identifying critical data, facility design, and model development needs for **defensible and cost-effective licensing decisions** and developing **operating limits** (waste decision criteria) for specific disposal facilities. (boldface added)
Regulatory Framework

Department of Energy
• DOE O 435.1 Radioactive Waste Management
• DOE M 435.1-1 Radioactive Waste Management Manual

Nuclear Regulatory Commission
• Licensing Requirements for Land Disposal of Radioactive Waste (10CFR61)

Environmental Protection Agency
• CERCLA (Comprehensive Environmental Response Compensation and Liability Act – “Superfund”)
• RCRA (Resource Conservation and Recovery Act)
• NEPA (National Environmental Policy Act)

Ronald Reagan NDAA Section 3116
Compliance Periods

• **RCRA** 30 years of post-closure monitoring and maintenance
• **CERCLA** 5 year reviews
• **Uranium Mill Tailings Closures** 200 to 1000 years design life
• **Low Level Waste Disposal Facilities** – 10,000 years recommended (NUREG 1573) (may be revised to 20,000 years)
• **HLW Geologic Repository** 1,000,000 years
Dose Limits

100,000 mrem – Dose leading to ~5% chance of Fatal Cancer (UNSCEAR)

10,000 mrem/yr – IAEA mandatory intervention

5,000 mrem/yr – Worker dose standard

1,000 mrem/yr – IAEA reference level for intervention for cleanup situations

360 mrem/yr – US Average dose all sources (NCRP)

100 mrem/yr – All sources limit (IAEA practices, DOE)

25 mrem/yr – NRC and DOE LLW

15 mrem/yr – EPA Radiation (40 CFR 191)

10 mrem/yr – Air (atmospheric) (40 CFR 61)

4 mrem/yr – Drinking Water (40 CFR 141)

1 mrem/yr – IAEA Exemption/Clearance

Source: Letourneau (2009)
The Performance Evaluation Process

- Performance Objectives
- Performance Assessment
- Performance Confirmation
Example EM PA and PA-like Analysis Applications

Engineered materials assessed – grout waste form and fill, concrete containers and walls, metal tanks and containers, activated metal waste, vitrified waste, tank residual solids, contaminated soils and debris, resins,…

Source: Letourneau (2009)
Historical Disposal Practices

Generic cross-sections (SDA)

Source: Sykes (2002)
Definitions Appropriate to Performance Assessment

**Model Calibration** – tuning model parameter values so that predictions match measured data

**Model Verification** – assuring that the resulting codes are correct and error free

**Model Validation** - ??? – difficult with compliance periods in the 100s to 1000s of years; maybe best approach is performance confirmation approaches to build confidence in the models and the overall performance assessment)
Modeling Approaches

Temporal
• Time independent (steady state)
• Dynamic

Spatial
• 1, 2, 3-dimensional

Level of complexity
• Simple (analytical)
• Complex (numerical)
Albert Einstein

Everything should be as simple as possible but no simpler.
The Performance Evaluation Process

- Performance Objectives
- Performance Assessment
- Performance Confirmation
Performance Assessment Components

![Diagram of Performance Assessment Components]

- Atmosphere
- Soil layers
- Cap layers
- Source
- Vadose Zone(s)
- Saturated Zone(s)
- Surface Water
- Exposure Scenarios
- Risk

Pathways:
- Airborne (diffusion)
- Waterborne (advection)
- Airborne (barometric pumping)
- Airborne (resuspension/deposition)
- Plant-induced
- Animal-induced
Conceptual Model and Scenario Issues for PA Model Components

• Cover Performance
  • Hydraulic Barrier Degradation and Increased Hydraulic Conductivity
  • Erosion and Biointrusion

• Waste Form
  • Preferred Pathways and Fracture Development
  • Radionuclide Release Processes and Scenarios

• Subsurface Fluid Flow and Radionuclide Transport
  • Fracture Flow
  • Equivalent Continuum, Discrete Fracture Networks, Stochastic Approaches
  • Radionuclide Attenuation (sorption, matrix diffusion, chemical reaction)

• Water Chemistry and Radionuclide Mobility
Major Steps in a Performance Assessment

• Select (and screen) Features, Events, and Processes (FEPs) and develop scenario classes

• Develop process models (and, perhaps, abstractions or reduced-order models) along with their scientific basis

• Evaluate parameter and model uncertainty

• Construct integrated system model with a consistent treatment of uncertainty

• Evaluate system model results, including the effects of uncertainty (conduct uncertainty/sensitivity analyses)

• Iterate

Source: Sevougian (2009)
Niels Bohr

Prediction is very difficult, especially if it's about the future.
“All models are wrong, but some are useful.”

Conceptual Site Models for Contaminated Sites

The American Society for Testing and Materials (ASTM) defines a conceptual site model as

“... a written or pictorial representation of an environmental system and the biological, physical, and chemical processes that determine the transport of contaminants from sources through environmental media to environmental receptors within the system.”
In their report on *Conceptual Models of Flow and Transport in the Fractured Vadose Zone* (NRC, 2001) the National Academies Committee on Fracture Characterization and Fluid Flow developed the following definition of a conceptual model for the purposes of their study:

“A conceptual model is an evolving hypothesis identifying the important features, events and processes controlling fluid flow and contaminant transport of consequence at a specific field site in the context of a recognized problem.”

The Committee goes on to say that

“A conceptual model is an hypothesis because it must be tested for internal consistency and for its ability to represent the real system in a meaningful way. The hypothesis evolves (is revised and refined) during testing and as new information is gathered.”
Conceptual Site Models (CSM)

- Conceptual site models link sources of contamination to potential receptors, both human and ecological, through environmental transport pathways and exposure routes.
- Conceptual site models are powerful tools for site characterization, risk assessment and the evaluation of different remediation technologies and strategies.
- Conceptual site models are depicted in different ways, using flow charts and environmental cross sections.
A conceptual site model links sources to receptors through environmental transport pathways and exposure routes
The Hydrologic Cycle
Inter-Bedded Silts and Sands in NJ Coastal Sediments
Many factors influence contaminant isolation facility performance
RCRA Subtitle ‘C’ Profile

Source: Mattson et al. (2004)
Current Approach To Cover System Design Emphasizes Prevention of Infiltration Into The Waste/Contaminated Medium
Total Systems View of a Contaminant Isolation Facility
Information Management Errors

A. Information Management Error
   - 1. Input Error
   - 2. Analysis Error
   - 3. Output Error

   1. Input Incorrect
   - 1. Lack of Resources
   - 2. Communication Error

   2. No Available Input

   1. No Output
   - 1. Communication Error
   - 2. Lack of Resources

   2. Output Incorrect

   1. No Analysis
   - 1. Lack of Resources
   - 2. Lack of Incentives

   2. Analysis Incorrect
   - 1. Lack of Integration
   - 2. Information Misinterpreted
Novel CSM – Remedial Actions

Source: Brown (2008)
Improved Conceptual Site Model (CSM)

Source: Brown, et al. (2005)
Conceptual Site Models (CSM)

• Conceptual site models link sources of contamination to potential receptors, both human and ecological, through environmental transport pathways and exposure routes.

• Conceptual site models are powerful tools for site characterization, risk assessment and the evaluation of different remediation technologies and strategies.

• Conceptual site models are depicted in different ways, using flow charts and environmental cross sections.
Elvin Jones
world class jazz drummer
(John Coltrane and others)

If you can’t find the 1 ......
forget it!
(or if the conceptual model is wrong ...
)
Factors Affecting Storage & Percolation

- Water retention characteristics of soils (loam vs. sand)
- Meteorological conditions
  - amount of precipitation
  - distribution of precipitation
  - form of precipitation
- Type of vegetation
- Layering of soils
Event Tree: Plant Community Changes Excessive Precipitation

- **Plant Community at Equilibrium**
- **Flood Stage Capacity Reached**
  - **Small Change**
    - **Mature Community**
    - **Large Change**
      - **High**
        - **Root Mortality**
        - **Low**
          - **Root System Adjustments**
          - **No Measurable Effect - Equilibrium**
          - **Potential Plant Mortality**
            - **Decreased Productivity/ New Community**
            - **Increased Productivity/ New Community**
      - **Intermed.**
        - **Partial Groundcover Death**
        - **Increased Groundwater Uptake**

Source: Mattson et al. (2004)
Event Tree: Plant Community Changes due to Drought

Plant Community at Equilibrium

- Drought Conditions Persist
  
  - Wilting Point Reached
    
    - Small Change
      
      Mature Community
    
    - Large Change
      
      - Root Mortality
        
        - High
          
          Partial Groundcover Death
        
        - Intermed.
          
          Root System Adjustments
            
            - YES
              
              Plants exploit different soil regions
            
            - NO
              
              Potential Plant Mortality
                
                - Decreased Productivity/New Community
      
      - Low
        
        Increased Productivity/New Community

No Measurable Effect - Equilibrium

Greasewood with taproot
Event Tree: Plant Community Changes due to Succession

- Plant Community Established (1yr)
  - Disturbance
    - Seral Stage Turnover
      - Mature Community
      - Large Change
        - Root Mortality
          - High
          - Low
            - Root System Adjustments
              - YES
                - New Seral Stage Develops
              - NO
                - Potential Plant Mortality
                  - Death of Vegetation/Less Groundcover
                    - Mature Community Equilibrium
                      - Increased Productivity/New Seral Stage

Greasewood with taproot
Preferred Pathways – Fast Flow Paths

• Features of a subsurface environment that enable faster transport and reduced travel times than would otherwise be anticipated
  • E.g., fractures in and zones of higher hydraulic conductivity in consolidated soils and porous media

• Preferred pathways are a typical feature in heterogeneous environments.
Transport through the subsurface invariably occurs through preferred pathways resulting in much faster travel times than would be expected in a uniform, homogeneous medium.
Transport and Fate Processes for Radionuclides Released from Waste Packages at the Proposed Yucca Mountain Repository and Migrating Through the Underlying Vadose Zone

- Advection
- Dispersion
- Matrix diffusion
- Sorption
- Colloidal transport
  - Pore size exclusion
  - Filtration/attachment
- Decay
How do we get the $K_d$ values?

In order of increasing confidence:

• from the literature
• from empirical correlations
• from laboratory tests
• from field studies
What About the Importance of the Presence of Other Chemicals?

Need to include other chemicals in the analysis especially if they have to potential to affect the mobility of the radionuclides of interest

- Complexing agents (e.g., EDTA)
- Solvents (e.g., TCE)
- Oxidizing and reducing agents
Fundamental Definitions

Uncertainty

“Lack of knowledge about specific variables, parameters, models, or other factors. Examples include limited data regarding the concentration of a contaminant in an environmental medium and lack of information on local fish consumption practices. Uncertainty may be reduced through further study.”

USEPA, 2001
Fundamental Definitions

Variability

“True heterogeneity or diversity that characterizes an exposure variable or response in a population. Further study (e.g., increasing sample size, n) will not reduce variability, but it can provide greater confidence (e.g., lower uncertainty) in quantitative characterizations of variability.”

USEPA, 2001
Areas of Uncertainty

• Scenario uncertainty
• Conceptual model uncertainty
• Parameter uncertainty
• Modeler uncertainty (Linkov and Burmistrov)
Approaches to Assessing Uncertainty

- Bounding analysis with perhaps a range of upper limit deterministic estimates (downside – often very conservative and unrealistic assumptions are made)
- More realistic deterministic estimates but with accompanying multiparameter sensitivity analysis
- Probabilistic analysis to yield a distribution of results
- “Hybrid” approach
# Evolution of PAs

<table>
<thead>
<tr>
<th>Past (Generation I)</th>
<th>Present (Generation II)</th>
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</thead>
<tbody>
<tr>
<td>Deterministic</td>
<td>Hybrid (combination of probabilistic and deterministic methods)</td>
</tr>
<tr>
<td>Reliance on conservative-bias, less</td>
<td>Balance between realism and conservative-bias (probabilistic interpretation of compliance in some cases)</td>
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<tr>
<td>consideration of engineered features</td>
<td></td>
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<tr>
<td>Conduct PA, send to regulator for review</td>
<td>Increased involvement with regulators and reviewers during development of PA (scoping)</td>
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<tr>
<td>Deterministic sensitivity analysis (One-Offs)</td>
<td>More comprehensive sensitivity and uncertainty analysis using deterministic and probabilistic methods</td>
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<tr>
<td>Minimal interaction with closure assessment</td>
<td>Increasing coordination with closure assessment modeling efforts</td>
</tr>
<tr>
<td>modeling</td>
<td></td>
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</tbody>
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Source: Letourneau (2009)
Realism and Conservative-Bias in PAs

- **Conservative Bias**
  - Proven to be efficient and appropriate in many cases
  - Provides defense-in-depth and safety margin, may be overly restrictive
  - Must defend that bias is indeed conservative

- **Realism**
  - Provides more detailed understanding and credit for specific features
  - Data and models needed, can be used as support for simplified models
  - Need to focus detailed efforts where most beneficial and defensible

Source: Letourneau (2009)
Thank You!
Backup Slides
1-D Advection Dispersion Reaction Equation

\[
D \frac{\partial^2 C}{\partial x^2} - \nu \frac{\partial C}{\partial x} - \lambda C = \frac{\partial C}{\partial t}
\]

Where:

- \( C \) = solute concentration \([\text{M L}^{-3}]\);
- \( t \) = time \([\text{T}]\);
- \( x \) = distance \([\text{L}]\);
- \( \nu \) = average groundwater velocity \([\text{L T}^{-1}]\);
- \( D \) = dispersion coefficient \([\text{L}^2 \text{T}^{-1}]\);
- \( \lambda \) = first-order decay coefficient \([\text{T}^{-1}]\);
Fundamental Processes

Advection

- Transport by which a material moves with a flowing medium (air, surface water, groundwater) at the average velocity of the medium
Dissolved Constituent Transport in The Saturated Zone

Darcy’s Law

\[ v = \frac{ik}{n} \]

where

\( v = \text{avg. gw velocity (cm/sec)} \)
\( i = \text{hydraulic gradient (dimensionless)} \)
\( k = \text{hydraulic conductivity (cm/sec)} \)
\( n = \text{effective porosity (dimensionless)} \)
Subsurface Exploration

• Soil borings, lithology
• Ground water monitoring well installation
• Pump tests and aquifer tests
• Tracer tests

(Photos courtesy of AquAeTer, Inc., Brentwood, TN)
Fundamental Processes

Diffusion

- Transport that results from a concentration gradient—material moves in the direction of decreasing concentration.

- In fractured rock, contaminants are transported from flow in fractures to the rock matrix through matrix diffusion.
  - A similar diffusive process transports contaminants from zones of relatively high mobility to zones of lower mobility in subsurface soils.
Fundamental Processes

Dispersion

• Diffusive transport plus that transport that results from velocity gradients within the flowing medium
  • Diffusion can be neglected in regions of high velocity
  • When velocities are low, diffusion becomes a very important transport process
Gaussian Atmospheric Plume Dispersion Model

\[ C(x, y, z, H) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp \left( -\frac{y^2}{2 \sigma_y^2} \right) \exp \left( -\frac{(z - H)^2}{2 \sigma_z^2} \right) \]
Atmospheric Monitoring and Modeling

Meteorological Stations for wind speed and direction data acquisition

(Photos courtesy of AquAeTer, Inc., Brentwood, TN)
Fundamental Processes

Sorption

• A reactive process by which a dissolved constituent interacts with a solid surface resulting in a retardation effect when the movement is through a solid matrix (subsurface transport).

• In atmospheric and surface water transport, sorption results in a partitioning of the material from the flowing medium to solids suspended in the medium.
Definition of the Retardation Factor, \( R \)

\[
R = 1 + (\frac{\rho}{\eta})K_d
\]

where \( \rho \) = bulk solids density (g/ml)

\( \eta \) = effective porosity

and \( K_d \), the soil water partition coefficient, is greater than or equal to zero

With this definition,

\[
R = \frac{\text{avg. groundwater velocity}}{\text{avg. velocity of the dissolved chemical}}
\]

So when \( K_d \) is greater than zero, the average velocity of the dissolved chemical is less than the average groundwater velocity, i.e., its transport is “retarded”. 
Fundamental Processes

Decay

• The transformation of a constituent into another species either through changes in the nucleus or chemical or biological transformations
Fundamental Processes

Colloidal Transport

• The movement of contaminants in the form of very small particles or attached to very small particles.

• Colloids are typically taken to be on the order of a 0.1 to 0.001 microns (micrometers).

• Colloidal transport can result in higher transport velocities and corresponding lower travel times than would be predicted otherwise.