An aerial photograph of a desert landscape, likely the Yucca Mountain region. The foreground shows dark, rippled sand dunes. A winding road or path cuts through the dunes, leading towards the horizon. The background features more distant, hazy mountains under a cloudy sky.

Uncertainty Underground: Yucca Mountain and the Nation's High-Level Nuclear Waste

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Uncertainty Underground

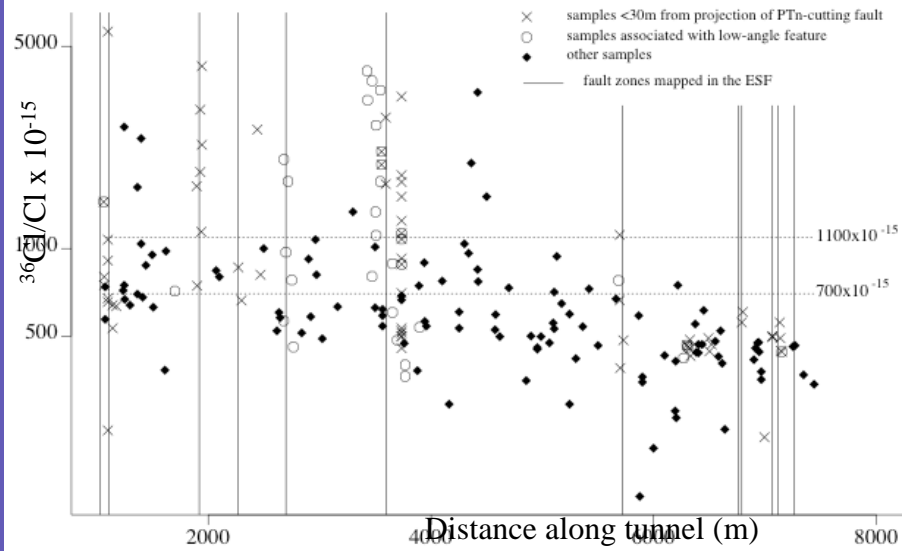
- Purpose of book
 - rectify lack of geologic input into nuclear waste policy decision-making
 - Shed light on uncertainties in technical issues at Yucca Mt
- Chapter authors
 - Wide variety of views
 - Wide variety of institutions



Surface Infiltration

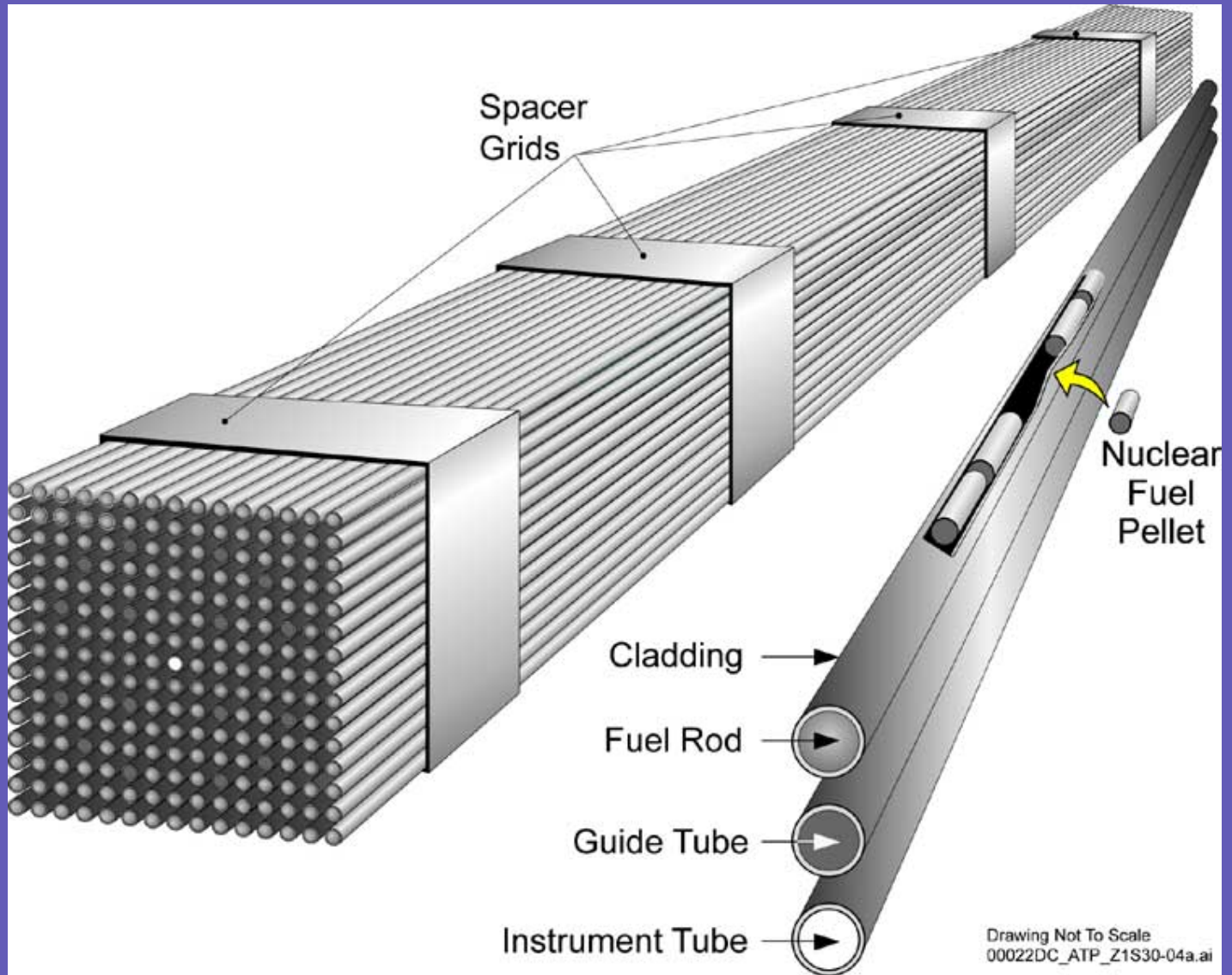
- Assumptions about future infiltration based on predicted climate change at YM
- Looked at last 400,000 years (last 4 interglacial-glacial cycles) to predict wettest conditions to be experienced over the next 10,000 years (up to 5-fold increase in infiltration)
- DOE may be underestimating climate effects:
 - Atmospheric CO₂ levels in Pleistocene: 200 ppm-280 ppm
 - Now: 380 ppm
 - 2100: 500 ppm - 1200 ppm
 - Last time CO₂ levels in the 1000's of ppm: 50 Ma (Eocene)
 - Implies a greater than 5-fold increase in infiltration

(a) $^{36}\text{Cl}/\text{Cl}$ ratios and selected structural features



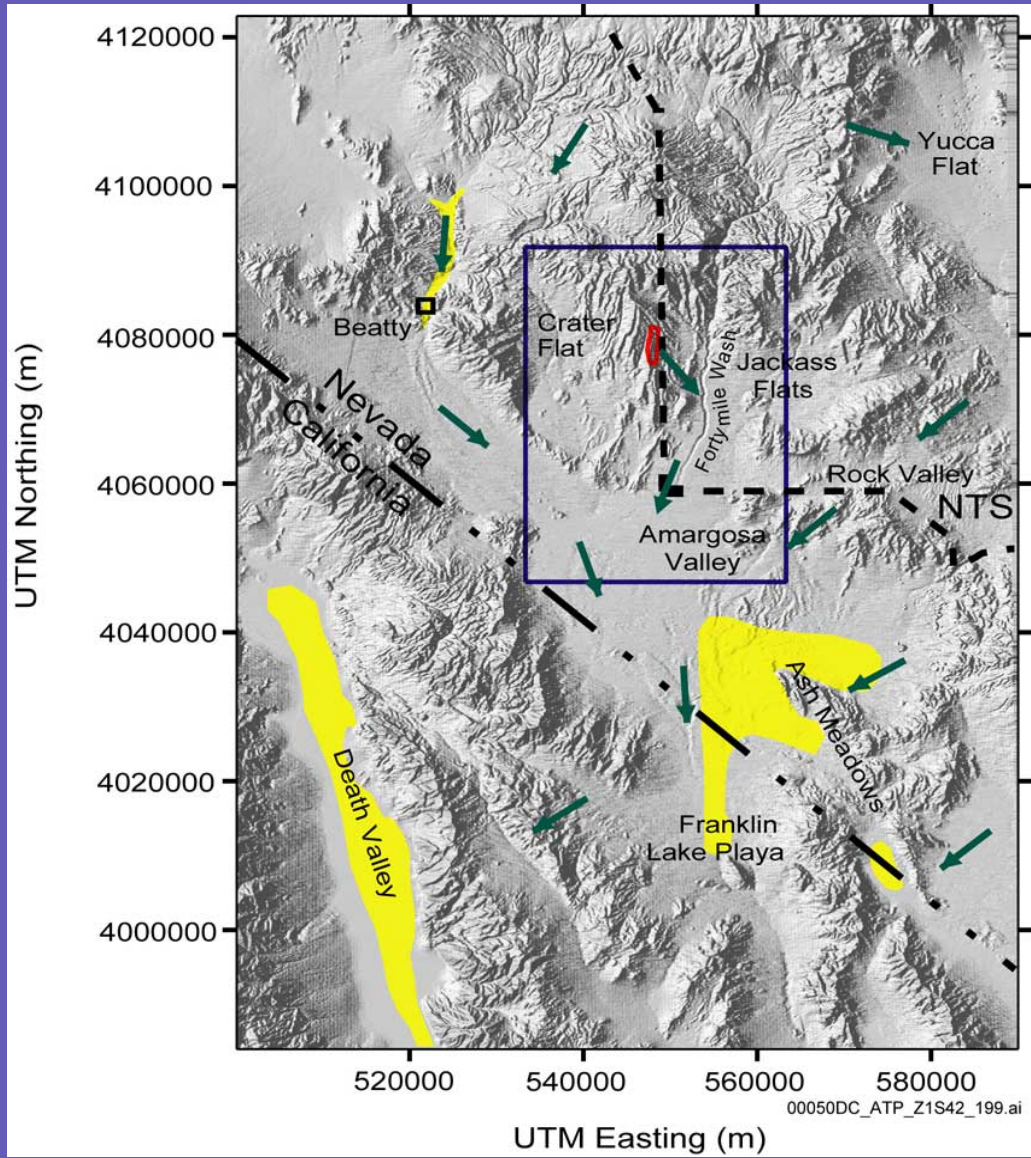
Transport in the Unsaturated Zone

- Initial conceptual model assumed water moved slowly: estimates of infiltration rates changed from <0.5 mm/yr to 4 mm/yr in 1980s
- Current model: mix of fast and slow pathways:
 - 5-10 mm/yr with some locations receiving up to 80 mm/yr
- Change in model largely a result of Cl-36 issue:
 - Normal levels of Cl-36/Cl at Yucca Mtn: 450×10^{-15} - 1200×10^{-15}
 - Around some fractures/faults - much higher levels detected
 - Bomb-pulse Cl-36 - evidence for fast water transport pathways
- Remaining unresolved technical issues:
 - Don't know how much water is transported along fast pathways or which pathways transport water



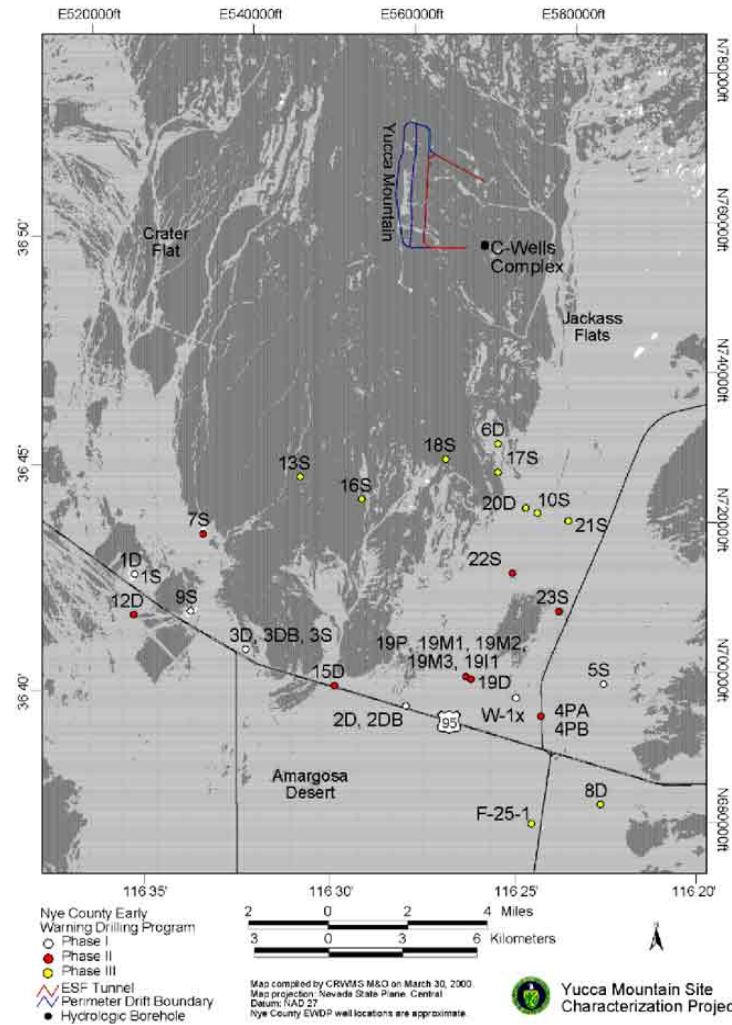
Engineered Barriers: Spent Fuel

- UO_2 not stable under oxidizing conditions + in presence of water
 - Forms UO_2^{6+} - complexes with CO_3^{6+} , HCO_3^{3-} , SO_3^{6-} , PO_4^{3-}
 - These phases are highly soluble
 - Alteration reactions will occur within 100-1000 years once spent fuel exposed to environment
 - **Uncertainty: how alteration products will behave**



Saturated zone

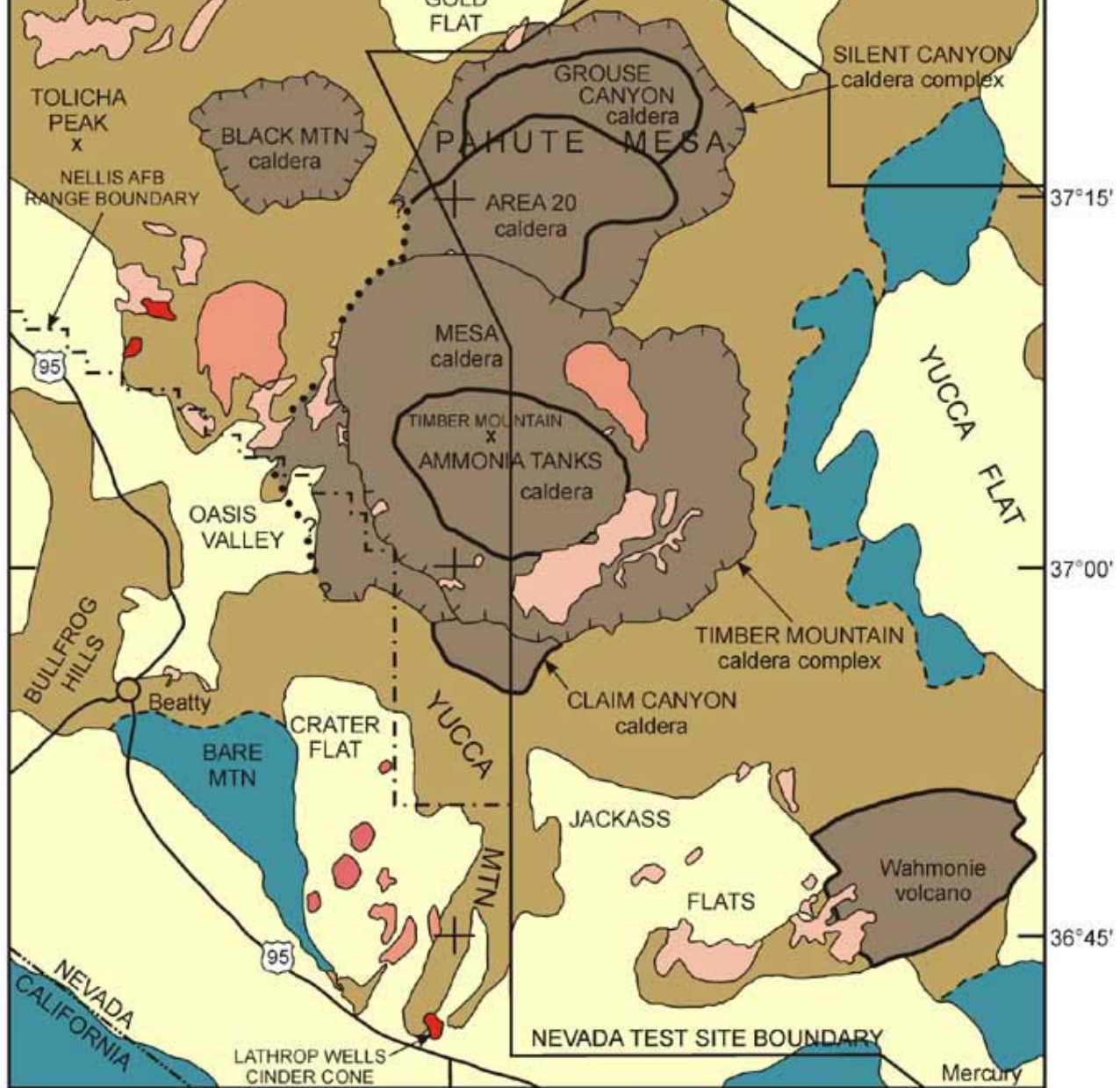
- Flow to the southeast/south
- Uppermost aquifer in volcanics extends 10-15 km S of Yucca Mtn, discharge in alluvial sediments in Amargosa Valley
- High permeability due to fractures, but not well quantified
- Significant lack of data:
 - Subsurface geology
 - Water table configuration
 - Hydraulic parameters
 - Division of flow between matrix and fractures
 - Magnitude of K_d values
- Lack of boreholes
 - many concentrated in alluvial aquifer
 - only one multi-well test site



Source: Nye County Nuclear Waste Repository Project Office (2000)




Figure 2-3. Nye County Early Warning Drilling Program Boreholes and the C-Wells Complex





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EXPLANATION

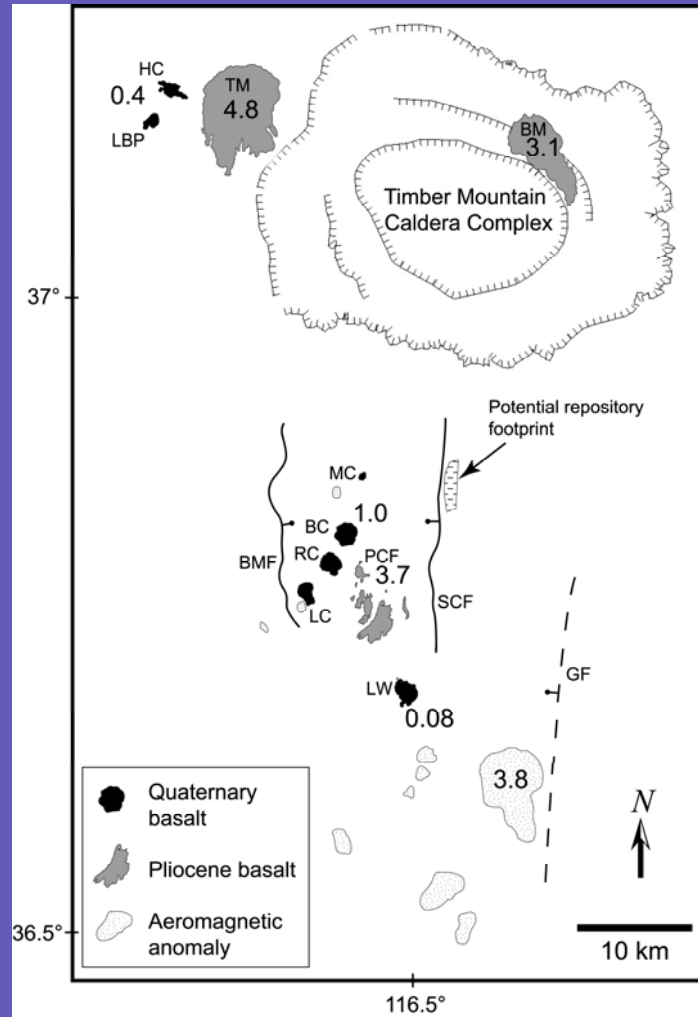
-  Caldera topographic walls
-  Caldera structural margins
-  Inferred caldera margins

Typ Late Tertiary (Pliocene) basaltic volcanic rocks, ranging from about 5.0 to 1.6 million years in age

Tvb Tertiary (Miocene) basaltic volcanic rocks, greater

Volcanism

- 5 Quaternary basaltic volcanoes within 20 km of Yucca Mtn
 - Youngest volcanism Lathrop Wells: 80,000 years
- Could a new volcanic center form under YM? 2 possibilities
 - Explosive eruption
 - Magma doesn't vent but fills drifts - corrosive gases, thermal effects
- Current probability estimates (controversy between NRC and DOE)
 - DOE: 5.4×10^{-9} to 4.9×10^{-8} events/yr
 - NRC: 10^{-7} to 10^{-8} events/yr
- Remaining Uncertainties
 - “buried” basalts (from magnetic anomaly data) suggest the number of young events in the area could be larger than initially thought
 - DOE has convened a new Volcanic Hazards Assessment expert elicitation
 - DOE wants to eliminate from consideration rocks that are older than 1.8 million years (allows them to hide volcanism btwn 1.8-5.3 my)
 - Predicting out to 1 million years introduces more uncertainties



How to Decide Whether Yucca Mt is Suitable?

- DOE/NRC using “Total System Performance Assessment”
- “Probabilistic analysis identifies all the features, events, and processes that affect repository performance”

Performance Assessment

- Ewing analysis
- Vaucanson's duck - how much can we learn about real ducks by studying a mechanical one?
 - Analogy for performance assessment
- Problems with PPA
 - Models in PPA are simplified
 - Do not include low probability events
 - Models that omit low-probability events produce overly optimistic results

Performance Assessment (con't)

- Models in PPA may not be scaled in time and space
 - Space: models are based on lab- and small field-scale
 - Time: models extrapolated from short times
- Boundary conditions change over time
 - May get changes in climate, volcanism, seismicity
- Conceptual models may be wrong
 - “unknown unknowns”

Models and Predictions

- Uncertainty may be a result of a lack of coherence among scientific subdisciplines
 - IAEA scholars found that among 6 performance assessment models of the same phenomenon, there were large differences
 - Resulted from differences in “problem formation, model implementation, and parameter selection”
 - Implications for YM: if a different group created the model, would the results be different?

But, Earth System Models Cannot Be Validated or Verified

- These models simulate open systems
 - in an open system, there's no way to know all input parameters, processes, or assess the boundary conditions that might affect the system over geologic times
- Models of open systems require modeler to know all input parameters for all processes that will occur over period modeled
 - For geologic systems, can't do this because our current datasets are incomplete
 - Field geology based on observations of natural world - investigate the past; learn that equilibrium is rarely reached, so it's almost impossible to decipher the detailed history of a rock, let alone predict its future

How should siting decisions be made then?

- Use Technical Judgment
 - Includes use of multibarriers, multiple techniques to analyze site, with weighting as judged reasonable by experience
- Compare site to others (1982 NWPA)
 - Right now, with one site being evaluated against itself, it's difficult to grasp the important issues that will affect safety
 - Compare site to other sites about which there's a substantial set of data:
 - Swedish sites, Olkilouto, French clay site, WIPP

If Yucca Mt Is Not Suitable, Then What?

- Even if Yucca okay, capacity there is limited by the geology
- If the US experiences an expansion in nuclear power, there will likely be a need for additional repositories

Other Sites for a Repository

- Many decent sites in US, including East
 - Fit the IAEA criteria
 - BUT - Nuclear Waste Policy Act Amendments of 1987 forbid study of crystalline rock - which underlies much of the eastern half of the US
- Process for selecting future repository sites must be perceived to be fair

Conclusions

- Solution to high-level waste not an easy problem technically or politically
- Geologic repositories are needed no matter what path is followed
- Should be working on them now
- Siting must be perceived as fair

IAEA Siting Criteria

- Long-term (millions of years) geologic stability - no seismicity or volcanism
- Low groundwater content and flow at repository depths - stable for tens of thousands of years
- Stable geochemical or hydrochemical conditions at depth, mainly described by a reducing environment
- Good engineering properties that readily allow construction of a repository
- Yucca Mt violates 2, maybe 3 of above criteria