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Evolution of Repository, Container, and Waste Form Characterization and Design at Proposed US Disposal System in Volcanic Tuff

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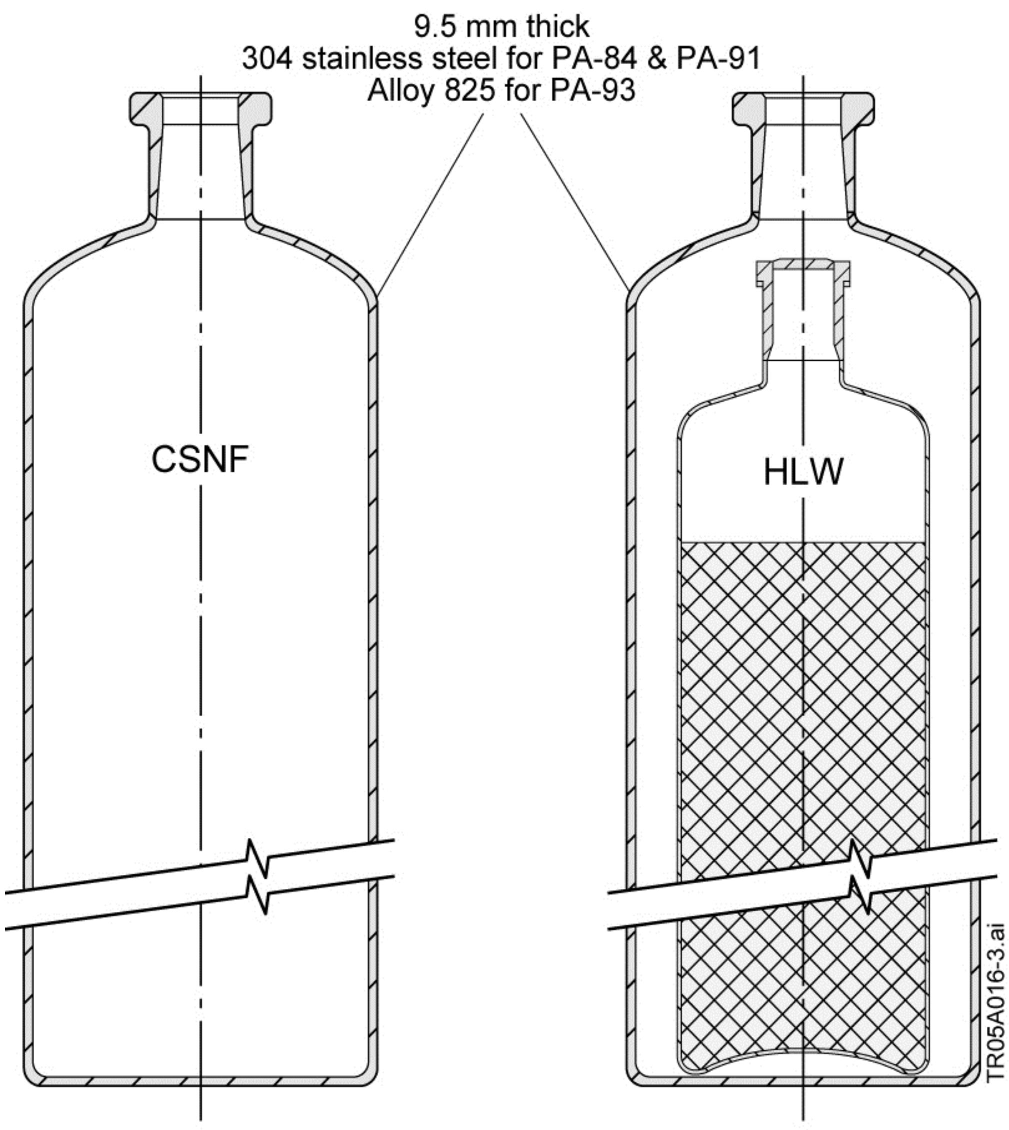
NNSA National Nuclear Security Administration

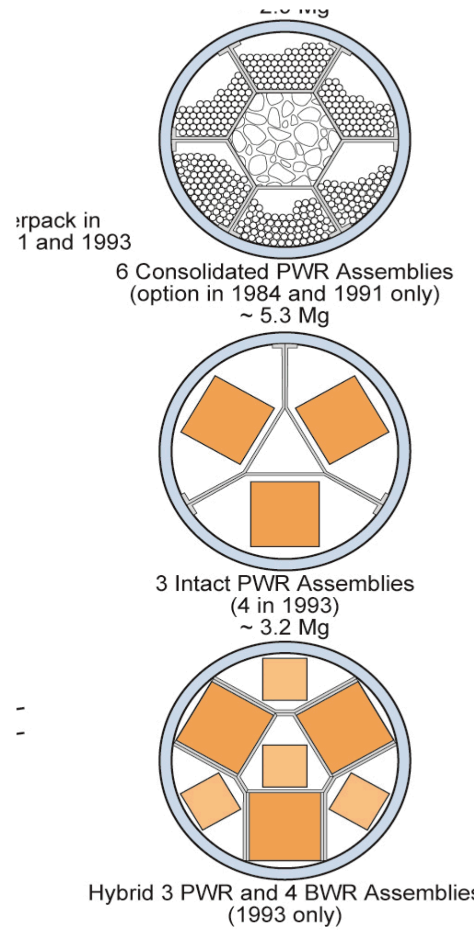
Talk explores past engineered barrier designs used in US for geologic disposal

- What engineered barrier system (EBS) designs have been used for volcanic tuff at Yucca Mountain?
  - Look at 7 EBS designs between 1984 and 2008
  - Floor, pillar, and in-drift designs have been proposed
  - Thin- and thick-shelled, short- and long-term corrosion-resistant containers have been proposed
- What has motivated these changes?
  - Flexibility
  - Operations
  - Disposal performance and regulations

Flexible container design important when many sites considered in 1980s

Small, thin-shelled canister can be used in various geologic media





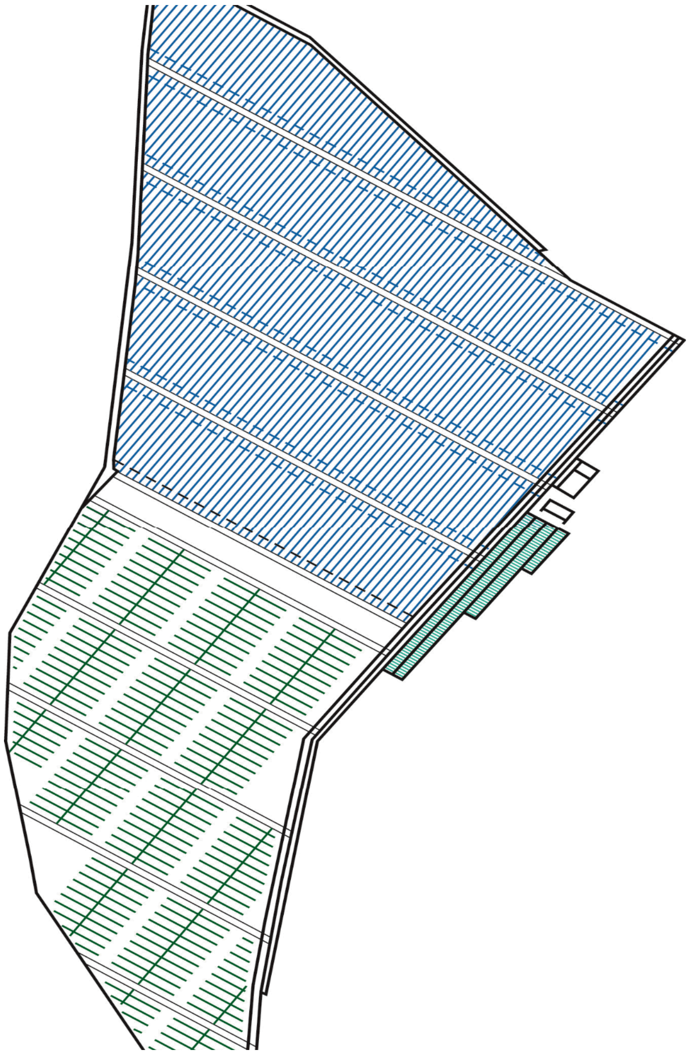
Small, thin-shelled canister can be used in various geologic media

- Some geologic media cannot handle high thermal heat loads (e.g., clay/shale and bentonite filler in crystalline rock)
- Small, thin-walled (9.5 mm) container designs allow flexibility
- Initial design in 1984 considered stainless steel
- Later designs for small containers considered high-nickel alloys but not multiple layers of different materials

Early analysis placed small canisters in floor or pillar of repository

Floor placement in long drifts common design concept for various geologic media

Blast and drill excavation technique usually anticipated



In 1987, Congress chose volcanic tuff at Yucca Mountain to characterize

Several advantages for Nevada Nuclear Security Site (formally Nevada Test Site or NTS)

Several additional advantages for using the thick, unsaturated zone of the volcanic tuff at Yucca Mountain

In 1987, Congress chose volcanic tuff at Yucca Mountain to characterize

Several advantages for Nevada Nuclear Security Site

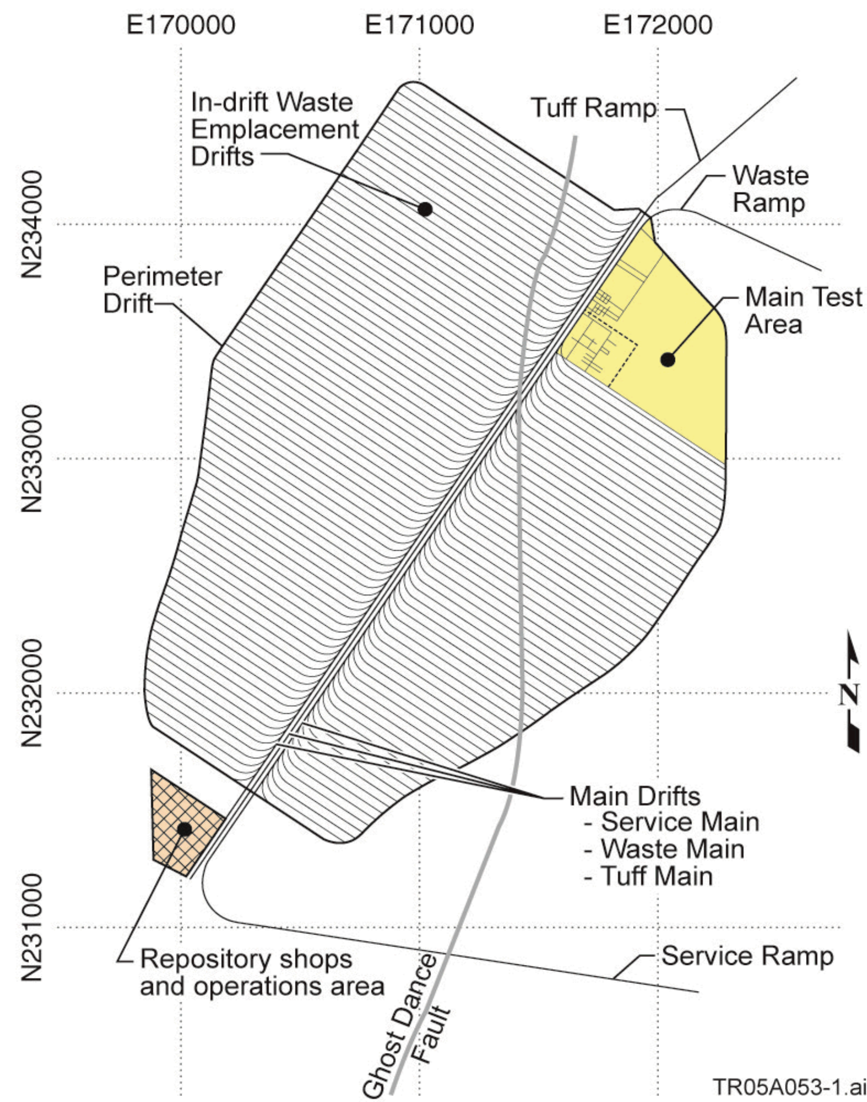
- Remoteness
- Past nuclear testing
- Closed groundwater basin
- Many suitable rocks not associated with resources
- Desert

Several additional advantages for using the thick, unsaturated zone of volcanic tuff at Yucca Mountain

- Mineable and requires little supplemental support
- Fractured tuff host layer to rapidly pass percolation
- Long period with easy retrieval because repository does not flood
- Long period with passive ventilation because backfilling drifts unnecessary
- Ability to use large waste packages

Repository design gradually adapted to Yucca Mountain after its selection

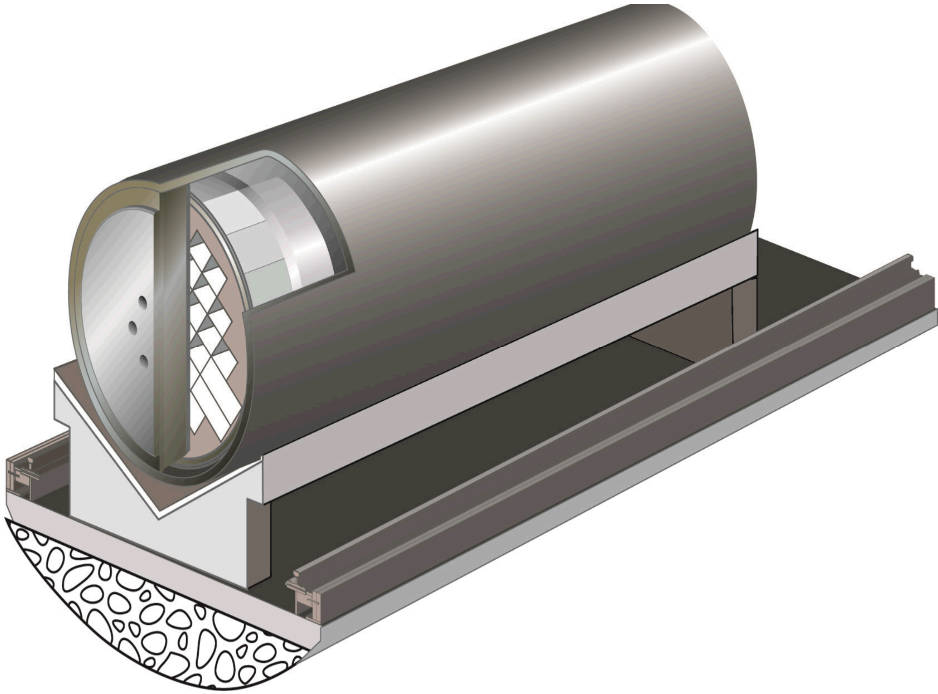
- Repository design developed for site characterization plan in 1987 and used for 1991 analysis
- Layout slightly revised in 1993 analysis to accommodate tunnel boring machine



Drift container design suggested in 1993 and adopted for 1995 analysis

Regulation motivation

- **Design for 100-year retrieval**
- **Container lifetime >>1000 yr**
- **Multi-barrier container**
  - **Corrosion resistant layer**
  - **Sacrificial allowance layer**

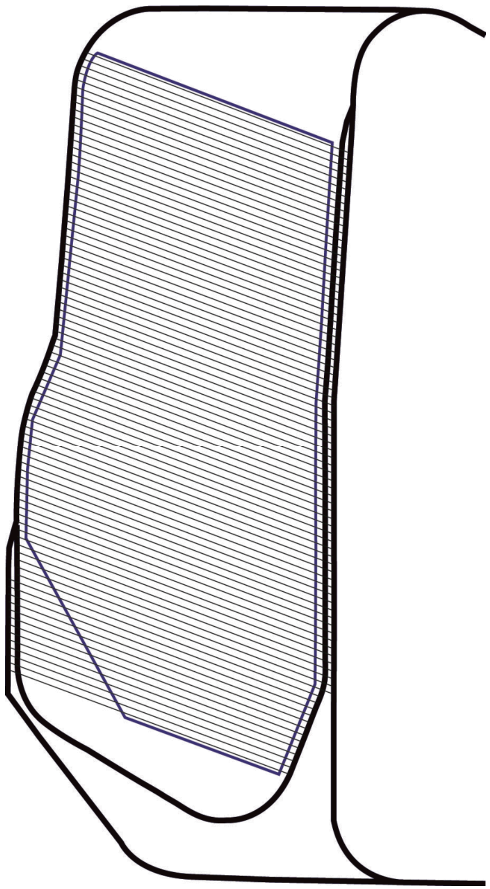


In-drift container emplacement helped with operations

Operation motivation

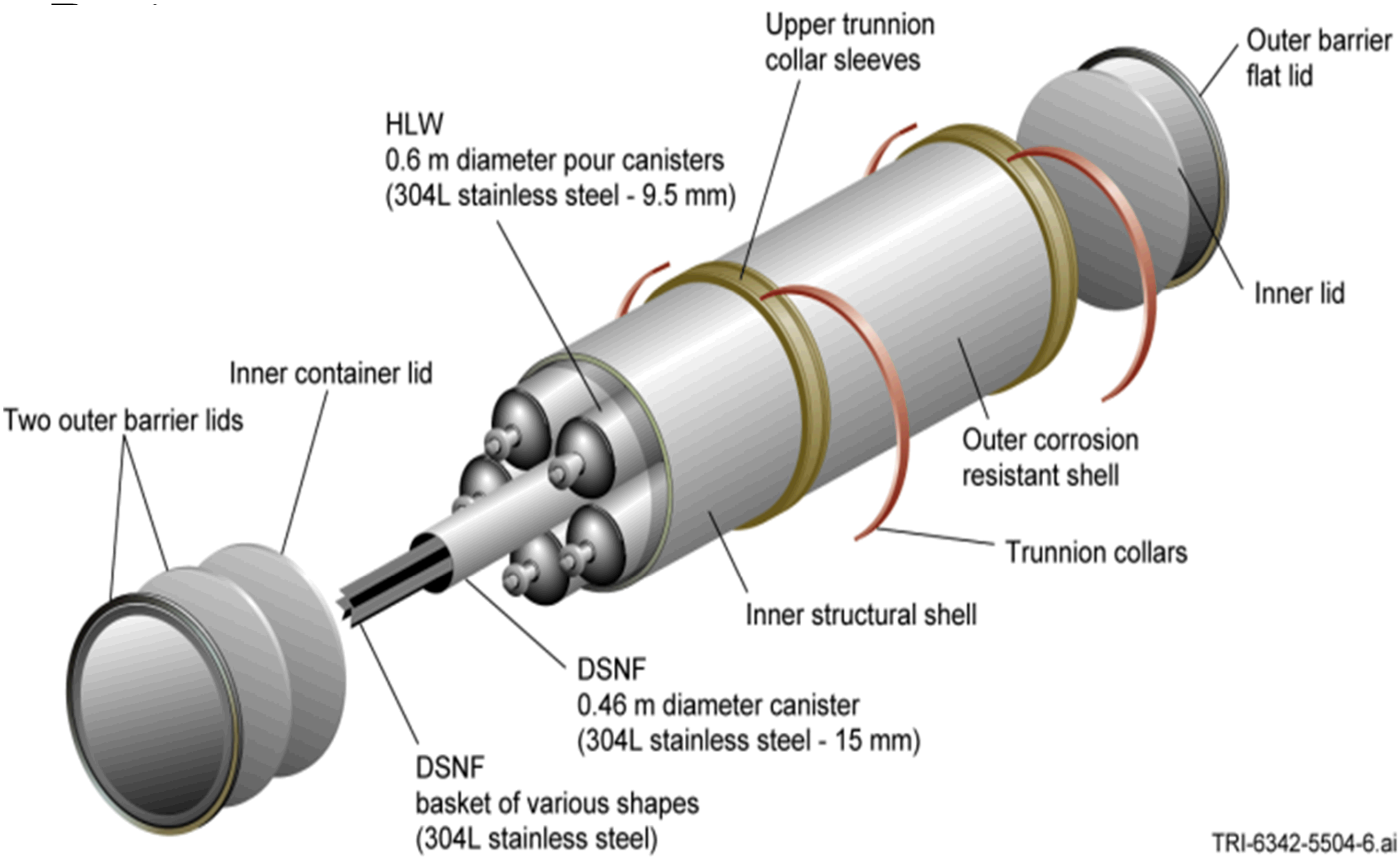
- Hotter design with drift disposal for 1995 analysis allowed repository to reside entirely to the west of the Ghost Dance fault

- Easier to meet goal of 3000 tonnes U/yr with bigger packages placed in drift
  - Transport by rail



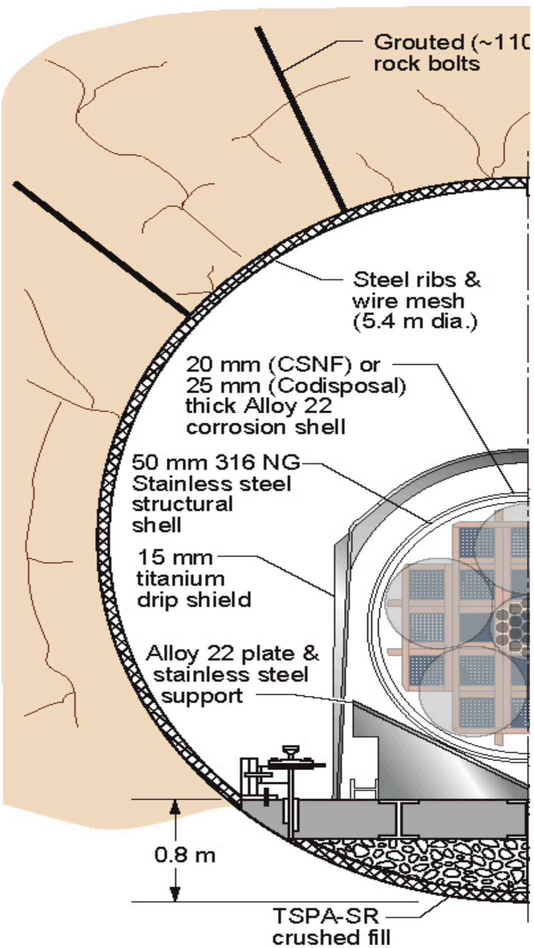
Co-disposing defense SNF with HLW limited fissile content yet efficient use of container

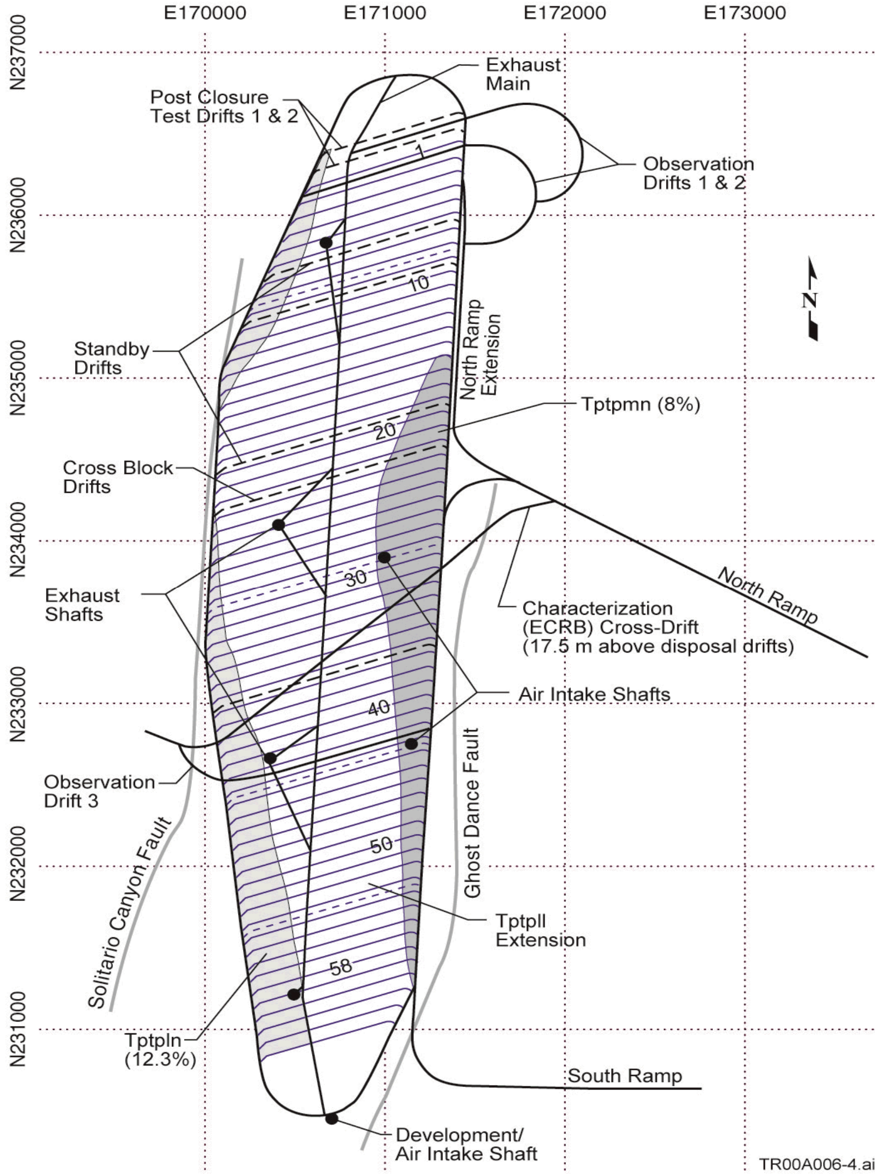
Adopted for 1998 VA



Repository design gradually adapted to Yucca Mountain after its selection

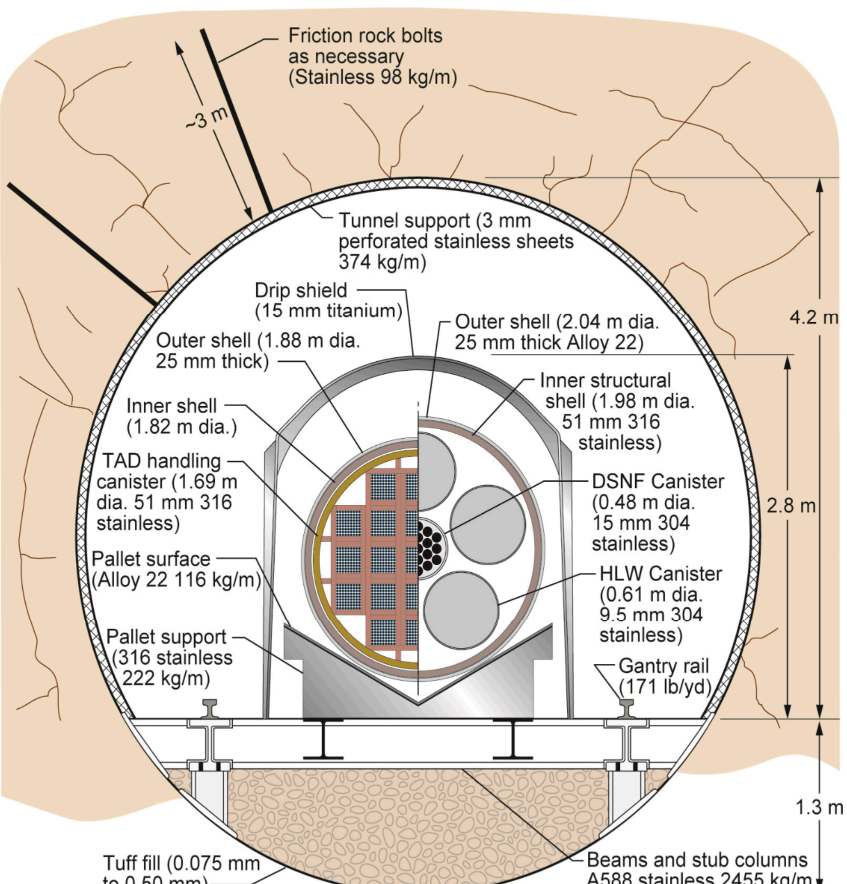
2000 Design for Site Recommendation (SR) added drip shield

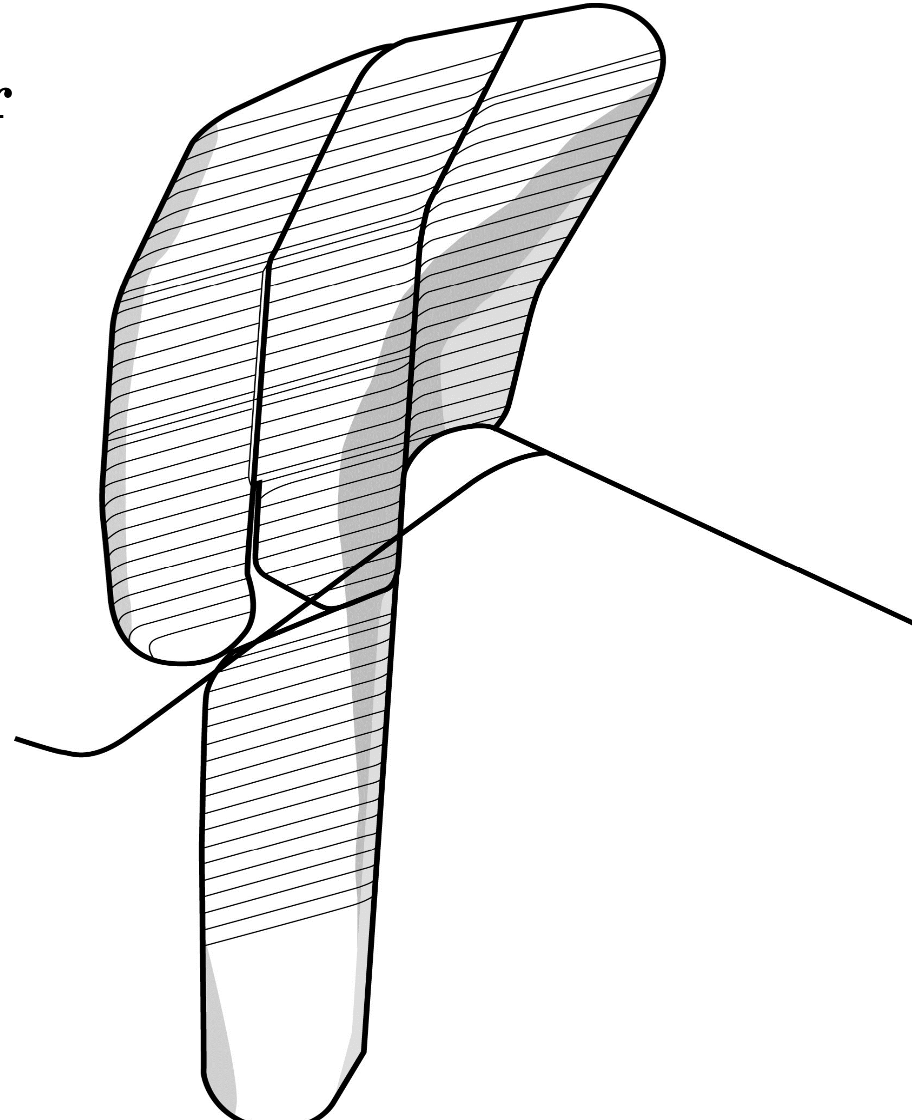




Repository design gradually adapted to Yucca Mountain after its selection

License application (LA) adopted modular design for constructing underground





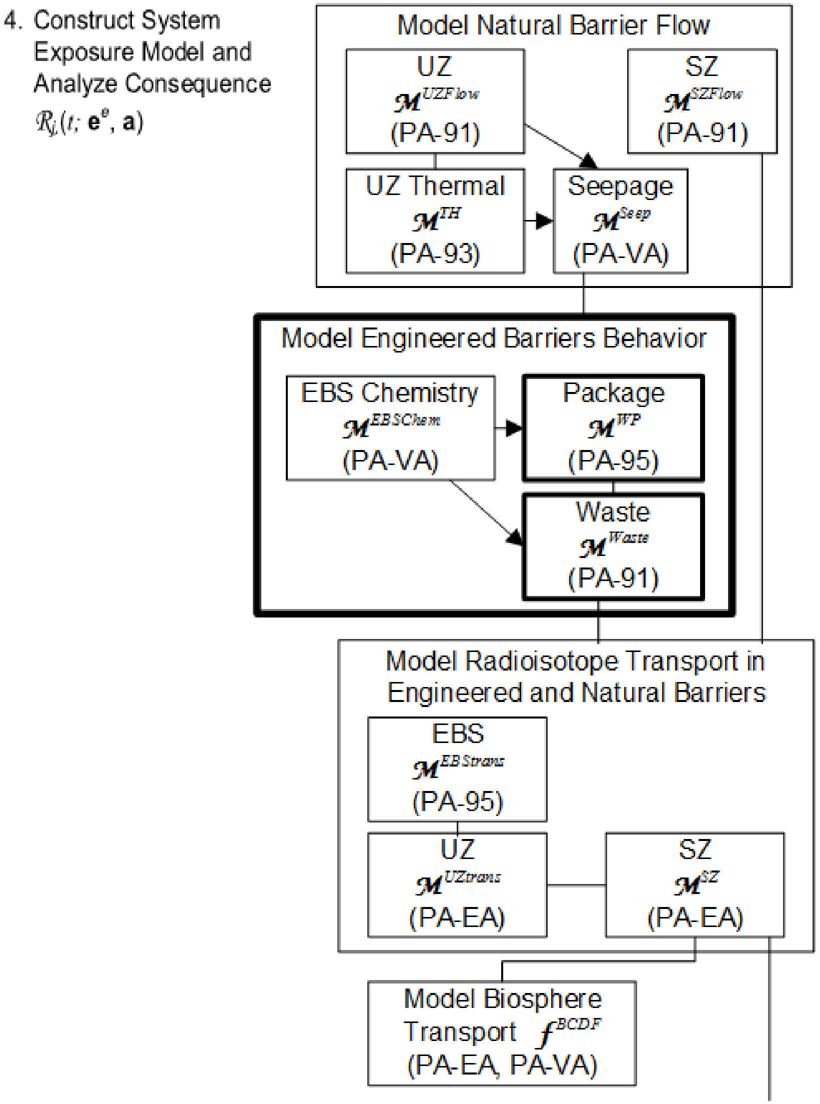
2 types of models developed for engineered barrier system

1. **Detailed mechanistic model to develop understanding of EBS behavior**

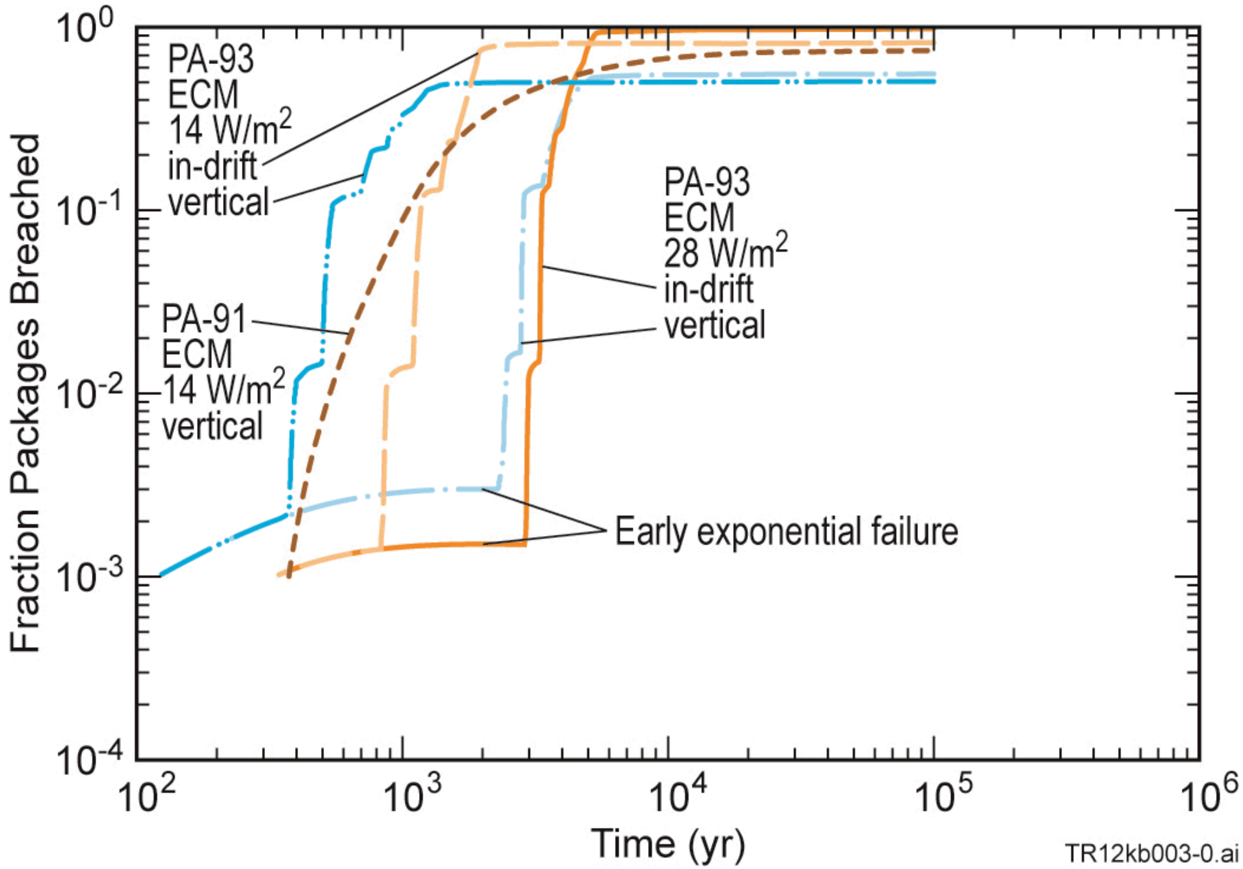
2. **EBS model as component in disposal system model to understand role in overall performance**

Whether the same model is used for both roles depends upon the computational capabilities and influence of component to overall performance

For Yucca Mountain Project, model of EBS in system model greatly simplified

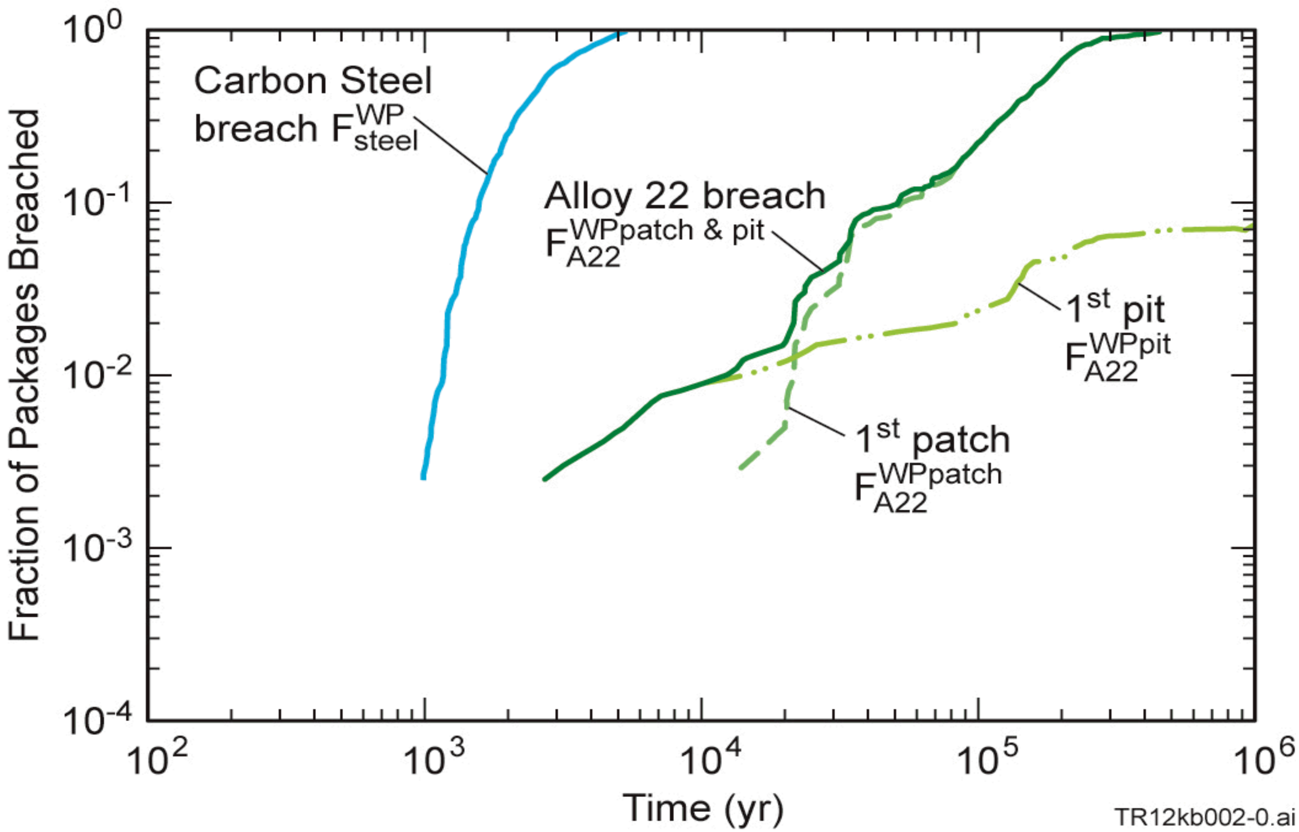


Container breach times between ~300 and 3000 years in 1991 and 1993 analysis



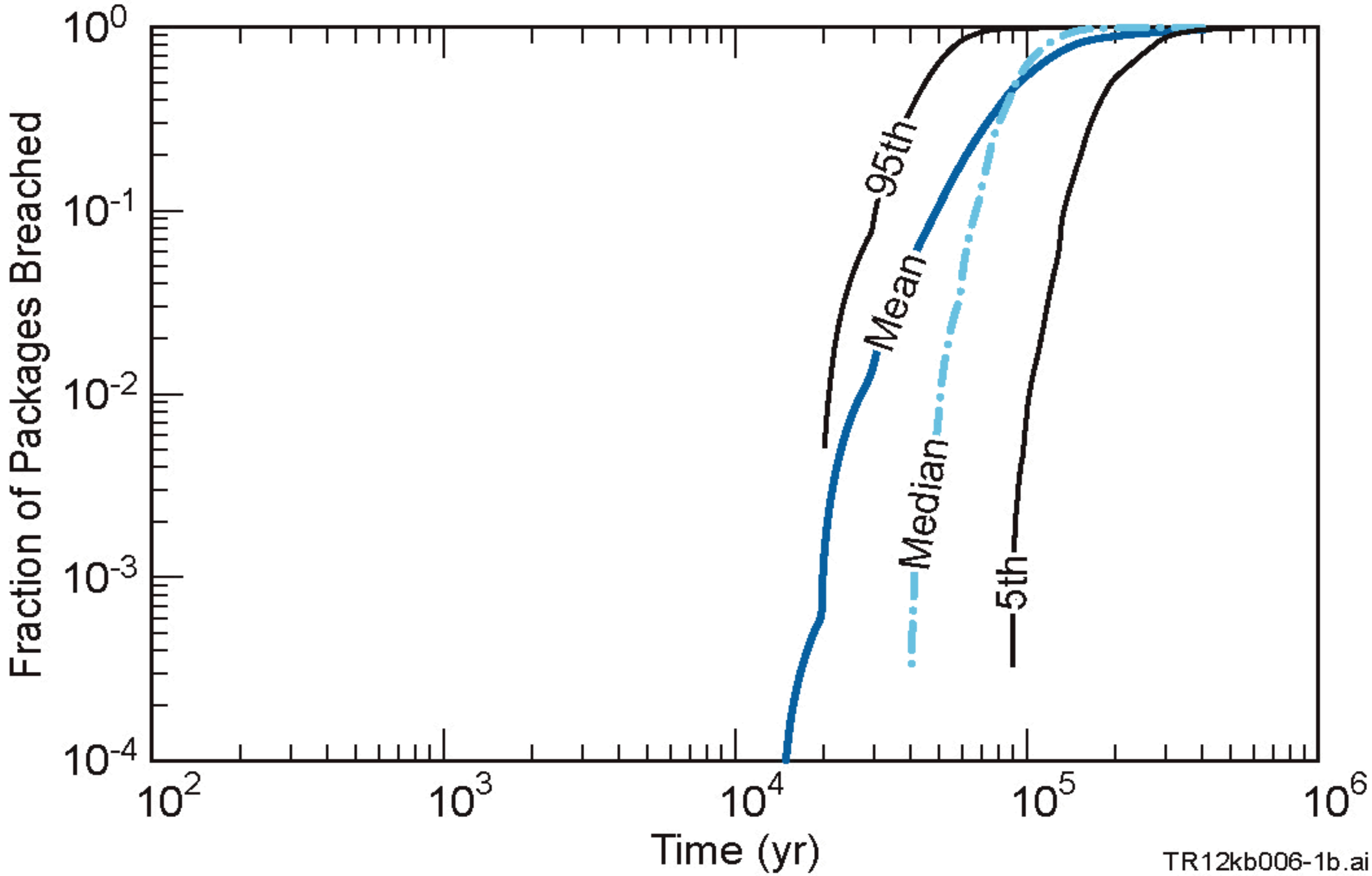
- Vertical package with single layer of (a) stainless steel in 1991 and (b) high nickel Alloy 825 in 1993 analysis
- In-drift package two layers in PA-93: outer layer of carbon steel (parabolic equation) and inner layer of Alloy 825 (PDF)

Breach times of Alloy 22 varied between 2×10^3 and 5×10^5 yr in 1998 VA



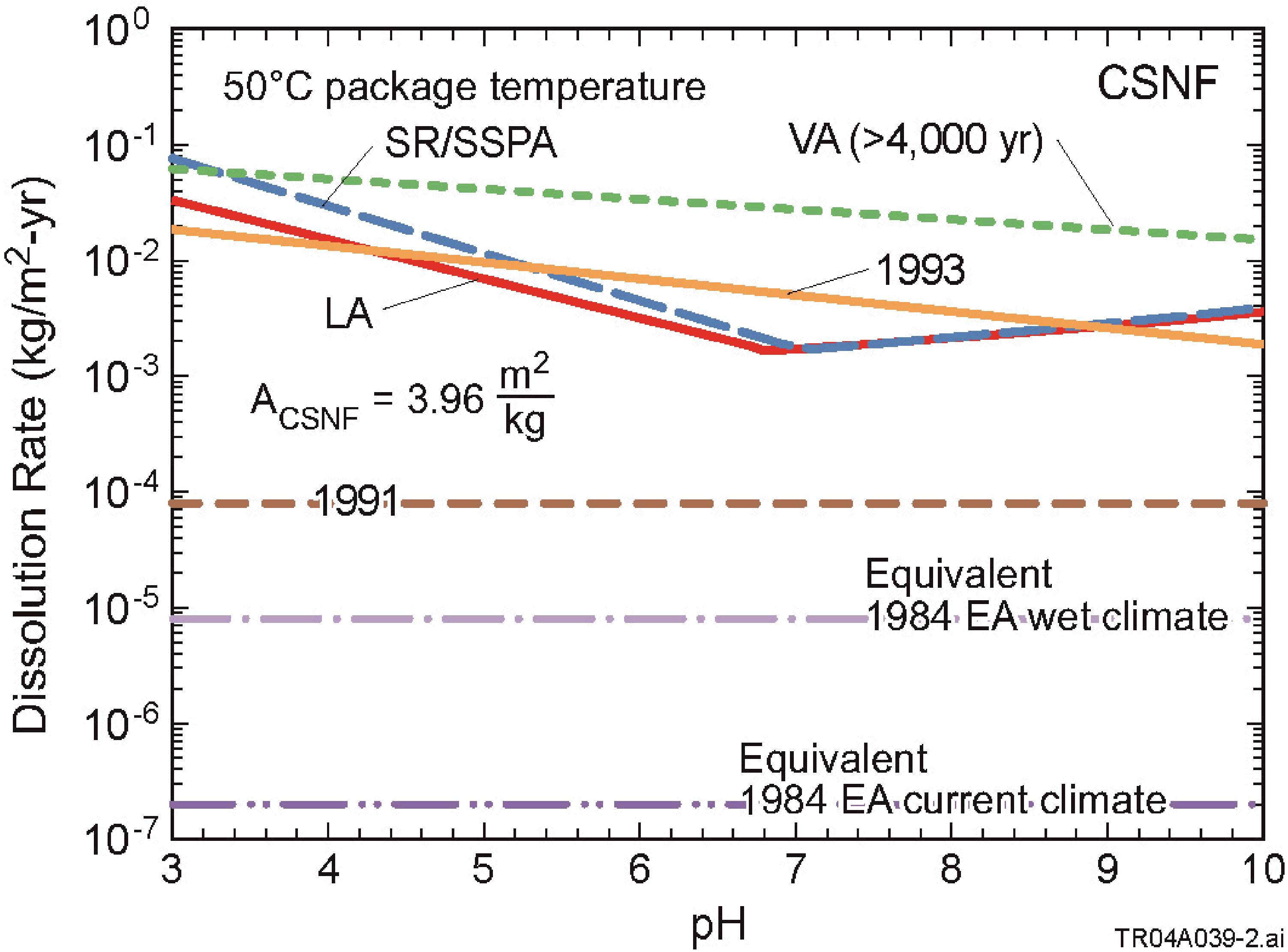
- **General corrosion of outer carbon steel layer modeled with exponential function of time and temperature**
- **General corrosion of layer of new high nickel Alloy 22 modeled with probability distributions at 3 temperatures**
- **Pitting of Alloy 22 limited to dripping conditions and high temperature**

Mean breach times varied between 10^4 and 10^5 yr for 2000 site recommendation

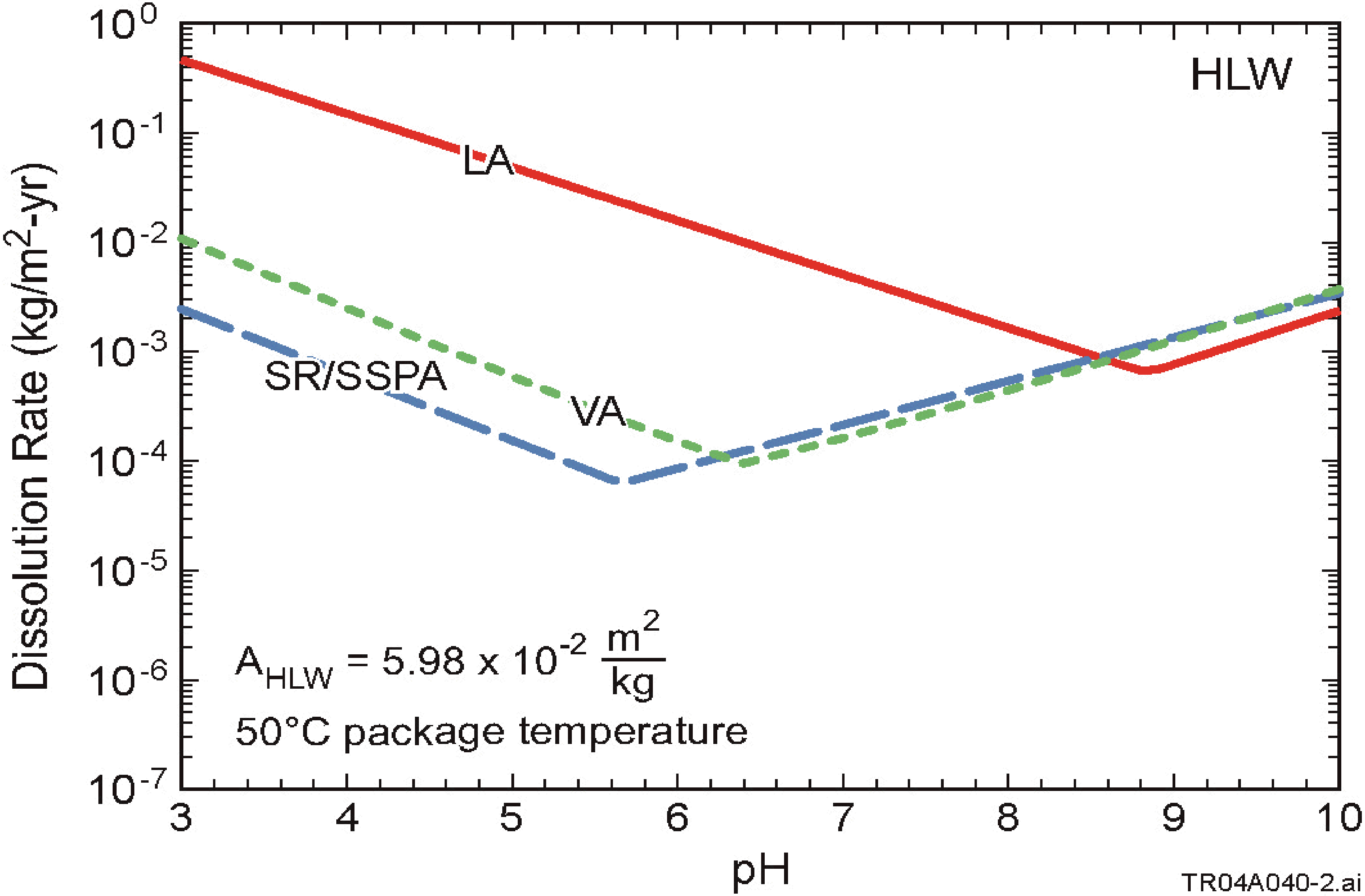


- Alloy 22 placed on outer layer (only generalized corrosion)
- Drip shields added to avoid pitting of Alloy 22
- Stainless steel inner layer for strength; not corrosion

Rapid commercial SNF matrix degradation used for 1993 and thereafter



Rapid HLW glass dissolution similar to CSNF but specific surface area reduced



Saturation dissolution rate equation for glass matrix of HLW in 1995 and 1998 VA

$$\dot{r}_{HLW}(t) = \kappa^0(pH(t), T(t))\left(1 - \frac{C_{SiO_2}}{K_{SiO_2}}\right) + k_{long}$$

κ^0 **Intrinsic glass dissolution rate (function of pH & Temperature via regression analysis**

$1 - \frac{C_{SiO_2}}{K_{SiO_2}}$ **Affinity term that accounts for reduced glass dissolution as concentration of SiO_2 increases**

$\frac{C_{SiO_2}}{K_{SiO_2}} = h(T)$ **Yet, affinity term function of temperature thus become first-order rate equation**

k_{long} **Long-term degradation rate added for VA**

HLW degradation used Arrhenius rate equation for 2000 SR and 2008 LA

$$\dot{r}_{HLW}(t) = \kappa^{0}_{pHseg} \cdot 10^{\eta_{pHseg}\, pH(t)} \cdot e^{-\frac{E^{a}_{pHseg}}{\Re T(t)}}$$

κ^{0}_{pHseg} **= Glass dissolution rate constant in either the low or high pH segment**

Power term represented catalyzing influence of H^+ or OH^-

η_{pHseg} **= Coefficient dependent upon either low or high pH segment**

$pH(t)$ **= Time varying pH (requires estimating package chemistry**

Exponential term represented increase in SiO_2 hydrolysis as temperature increased

E^{a}_{pHseg} **= Activation energy in either low or high pH segment**

$T(t)$ **= Temperature (requires estimating thermal history of package)**

Engineered barrier designed but objective not always performance after disposal

- Repository Design
  - Underground emplacement operations had strong influence
  - In-drift disposal scheme helped throughput and reduced size of repository (and thereby cost)
  - Shape defined by geologic conditions for disposal but operations also influential (e.g., modular design)
  - Tunnel boring machine decreased disturbance

Engineered barrier designed but objective not always performance after disposal

- Package
  - Initial containment important for all repositories;
  - Long-term performance important for crystalline and volcanic tuff media
  - Material corresponds to containment goals: short- and long-term containment
  - Flirted with multi-barrier containment (2 layers)
  - Size of packaged influenced by
    - desired for flexibility when geologic media unknown;
    - throughput and operations when optimizing to specific geologic media

Waste form design objective often operations rather than long-term disposal performance

- HLW design often based on desire for high waste loading
- Fuel design based on efficient reactor designs

Influence of waste behavior diminished in geologic disposal because of other barriers

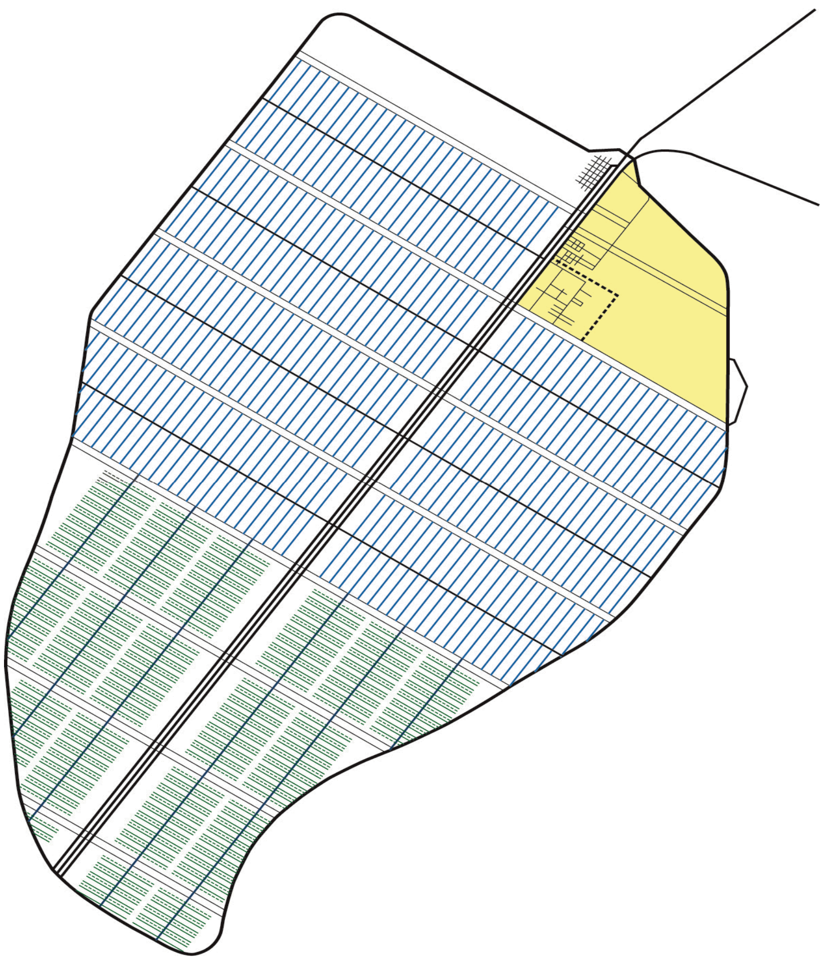
- Combination of the natural and engineered barriers mitigates the unknowns of waste form

- Geologic disposal provides sufficient flexibility to accommodate a large variety of radioactive wastes from existing commercial reactors, experimental reactors, and reprocessed fuel from future fuel cycles

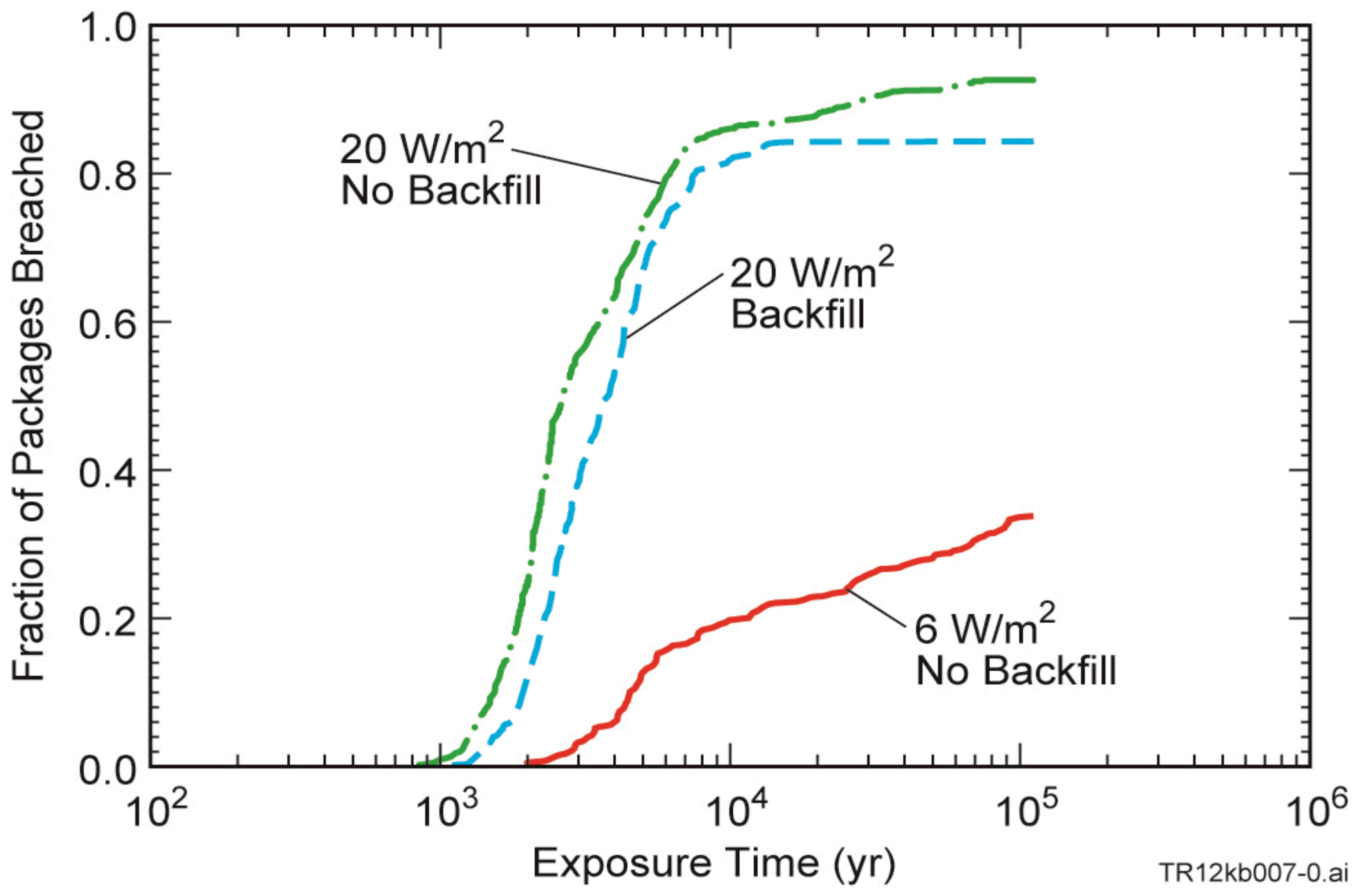
Backup slides

Repository design gradually adapted to Yucca Mountain after its selection

A new repository design developed for site characterization plan in 1987 and used for 1991 performance assessment (PA) analysis



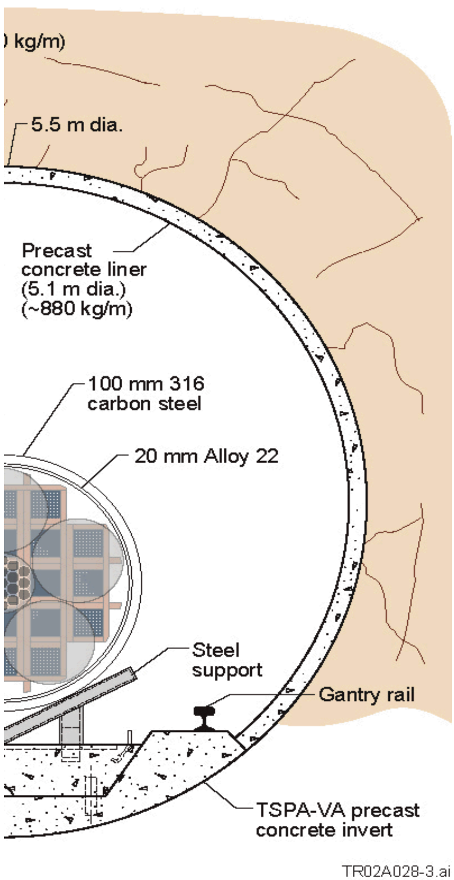
Breach times of Alloy 825 varied between 10^3 and 10^4 yr for high heat in 1995 analysis

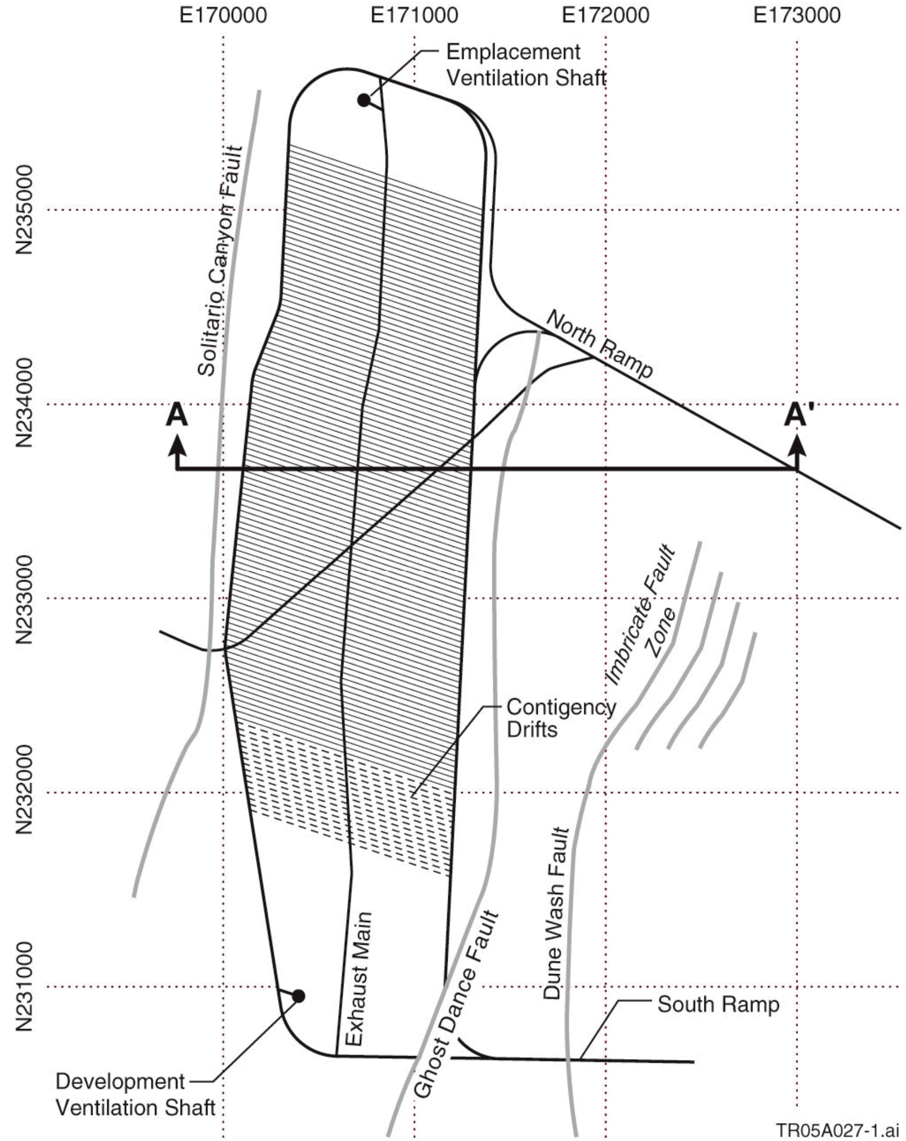


- **Humid and wet corrosion of outer layer of carbon steel modeled with exponential function of time and temperature**
- **Pitting of inner layer of Alloy 825 modeled with exponential function of temperature**

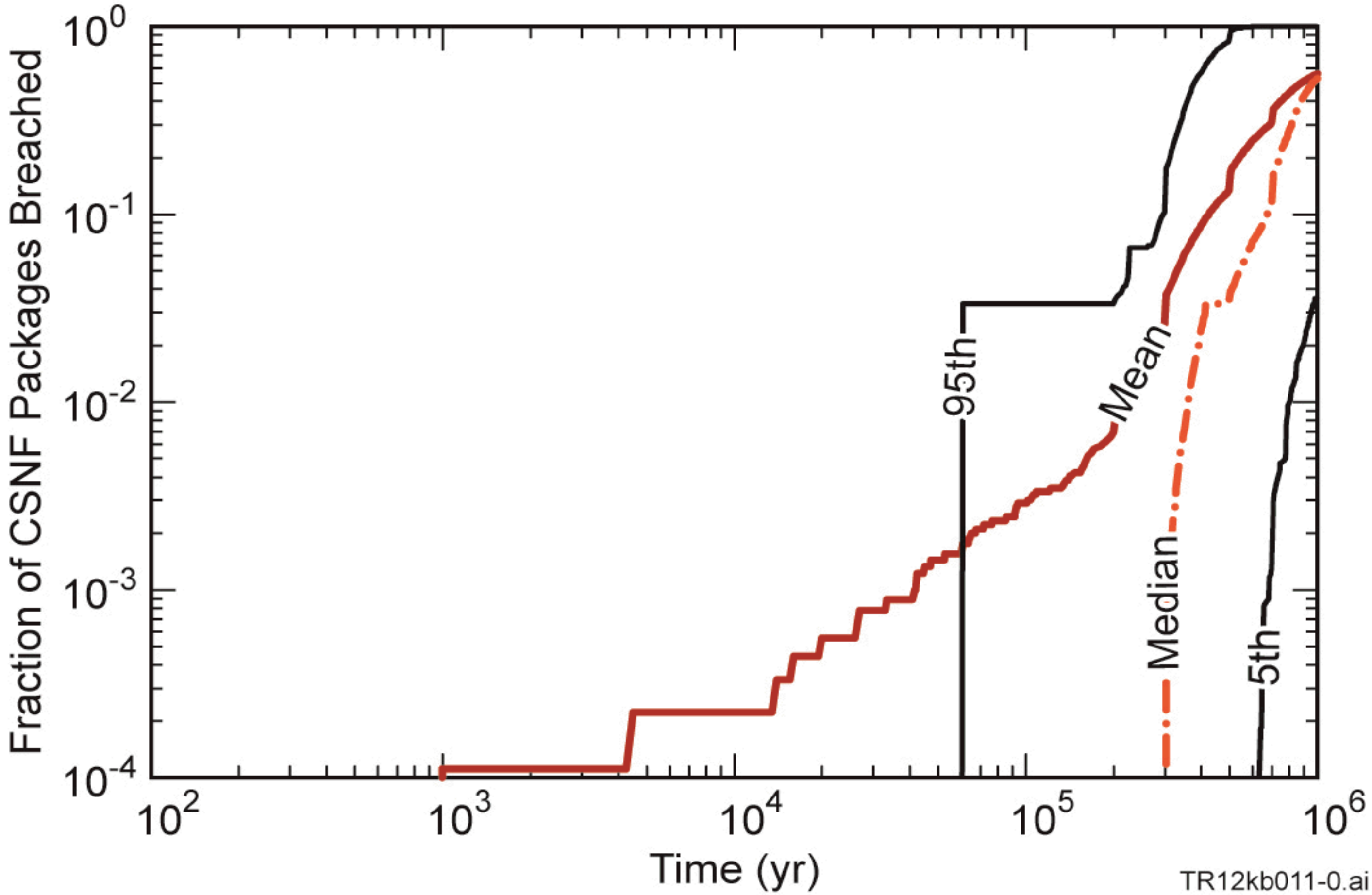
Repository design gradually adapted to Yucca Mountain after its selection

1998 Viability Assessment (VA) Design





Mean breach times varied widely between 10^3 and 10^6 yr in 2008 LA from seismic affects



- Seismic damage to container contributed to failure
- Temperature dependence of generalized corrosion included