SAND2012-3943C

# Used Fuel Disposition Campaign

## Open Emplacement Mode Disposal Concepts

***What are they and why do we need them?***

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**Used Fuel Disposition R&D Campaign Working Group**
**Las Vegas, Nevada**
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# Outline

- **Geologic Disposal Concepts**
  - Reference concepts and thermal analyses
  - Mined disposal: open vs. enclosed emplacement
  - Proposed reference open-mode concepts
  - Direct disposal of multi-purpose canisters
  - Engineering and performance modeling challenges
- **Connection to BRC Recommendations**

Prompt efforts → Multi-purpose canisters

Multi-purpose canisters → Direct disposal

Direct disposal → Open emplacement modes

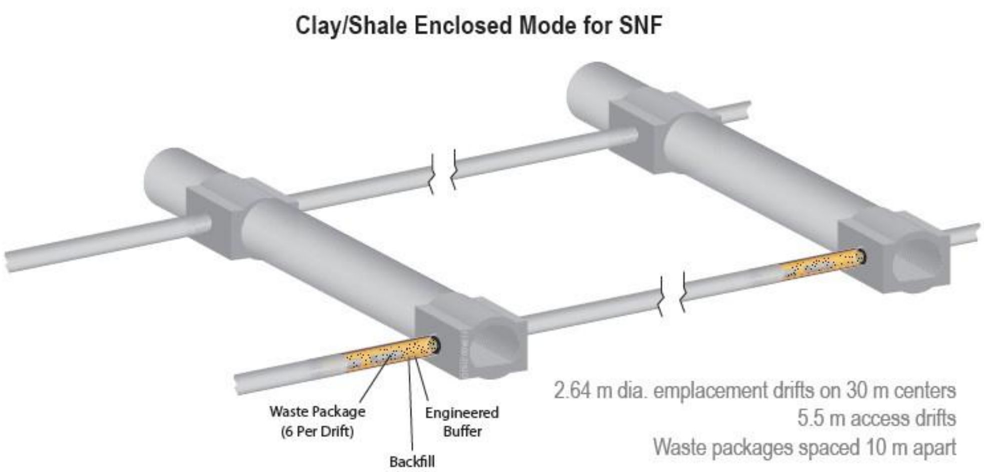
# Reference Disposal Concepts and Thermal Analysis

# Disposal Concept Definition Three Main Elements:

1. **Waste inventory**
   - Waste types from a sample of possible future commercial fuel cycles
   - *Inventory is the link to fuel cycle options and upstream technologies*
2. **Geologic setting**
   - Reference settings: clay/shale, crystalline rock, bedded (or domal) salt, and deep crystalline basement
3. **Engineering concept of operation**
   - Initial reference concepts (≤ FY11):
     - ***Clay/shale repository (Andra, Dossier 2005)***
     - ***KBS-3 (vertical) disposal (SKB, SR-Can 2006)***
     - ***Generic salt repository (Carter et al. 2011)***
     - ***Deep borehole concept (Arnold et al. 2011)***

# Reference Disposal Concepts (FY11) Example: Mined Clay/Shale, Horizontal Emplacement

- Ref: Based on Andra 2005
- Depth: ~500 m
- Hydrologic setting: Saturated
- Near-field temp. limit: 100ºC



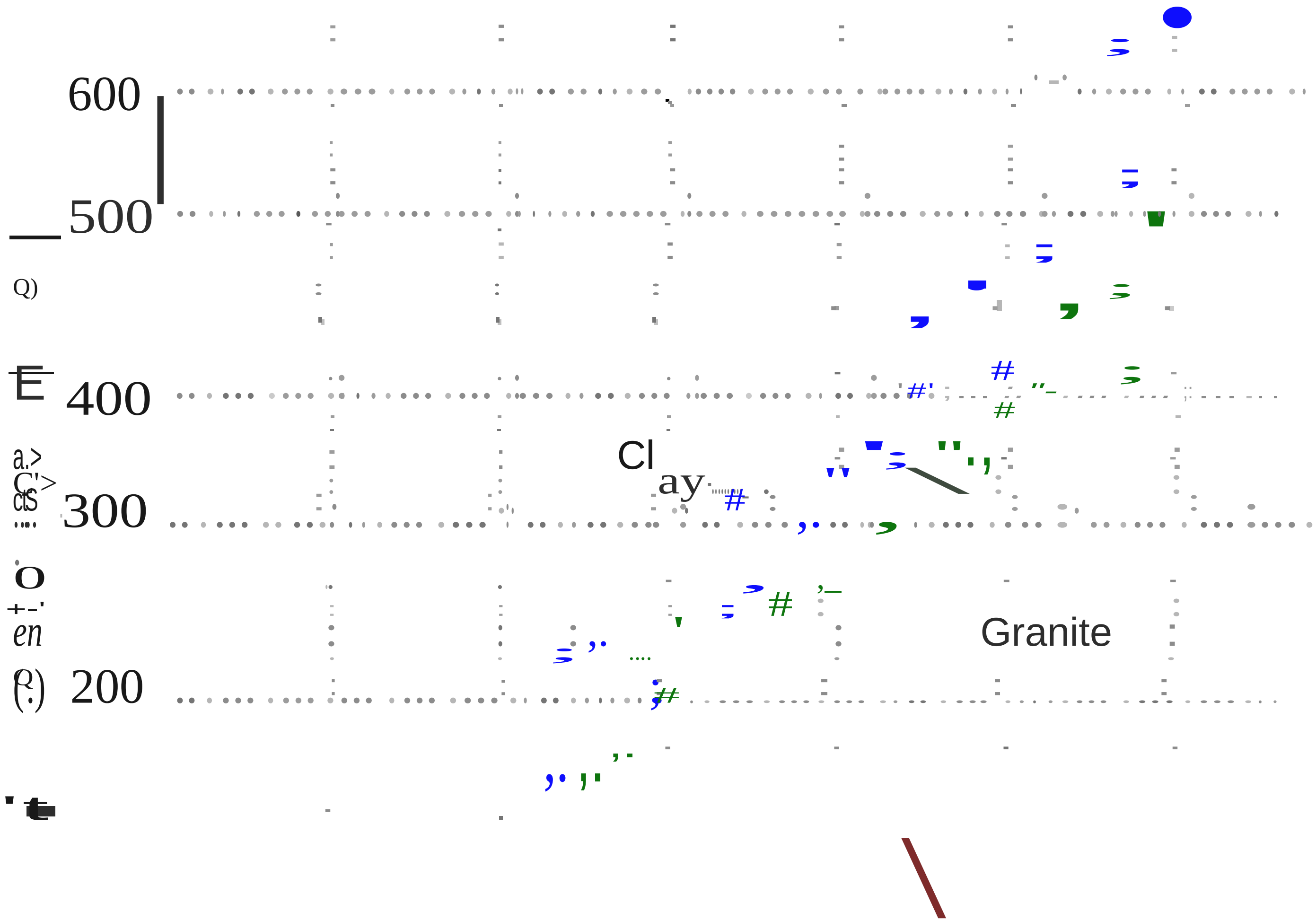

| Disposal Characteristic | SNF | HLW |
|---|---|---|
| Emplacement mode | Horizontal, in drift | Horizontal, boreholes |
| Overpack material | Steel | Steel |
| Package spacing, m | 10 | 6 |
| Drift (borehole) spacing, m | 30 | 30 |
| Borehole liner material | Steel | Steel |
| Buffer material | Bentonite clay | - |
| Backfill material | Crushed clay/shale | Crushed clay/shale |

Andra 2005. *Dossier 2005 argile – architecture and management of a geological disposal system*. December 2005. http://www.Andra.fr/international/download/ Andra-international-en/document/editions/268va.pdf.

# Reference Mined Disposal Concepts: Temperature Limits

- **Temperature limits selected for this analysis are based on material degradation properties**
  - 100ºC for clay/shale media and buffer material (e.g., SKB and Andra programs)
  - 200ºC for salt (e.g., Salt Repository Project 1986, current German work)
  - No limit identified for deep crystalline basement rock
- **Differences between concepts >> uncertainty in temperature limits**
- **Final temperature constraints will be site- and design-specific**

# Thermal Analysis Results (FY11)
## Surface Storage Limits Package Size, for Crystalline and Clay/Shale Concepts



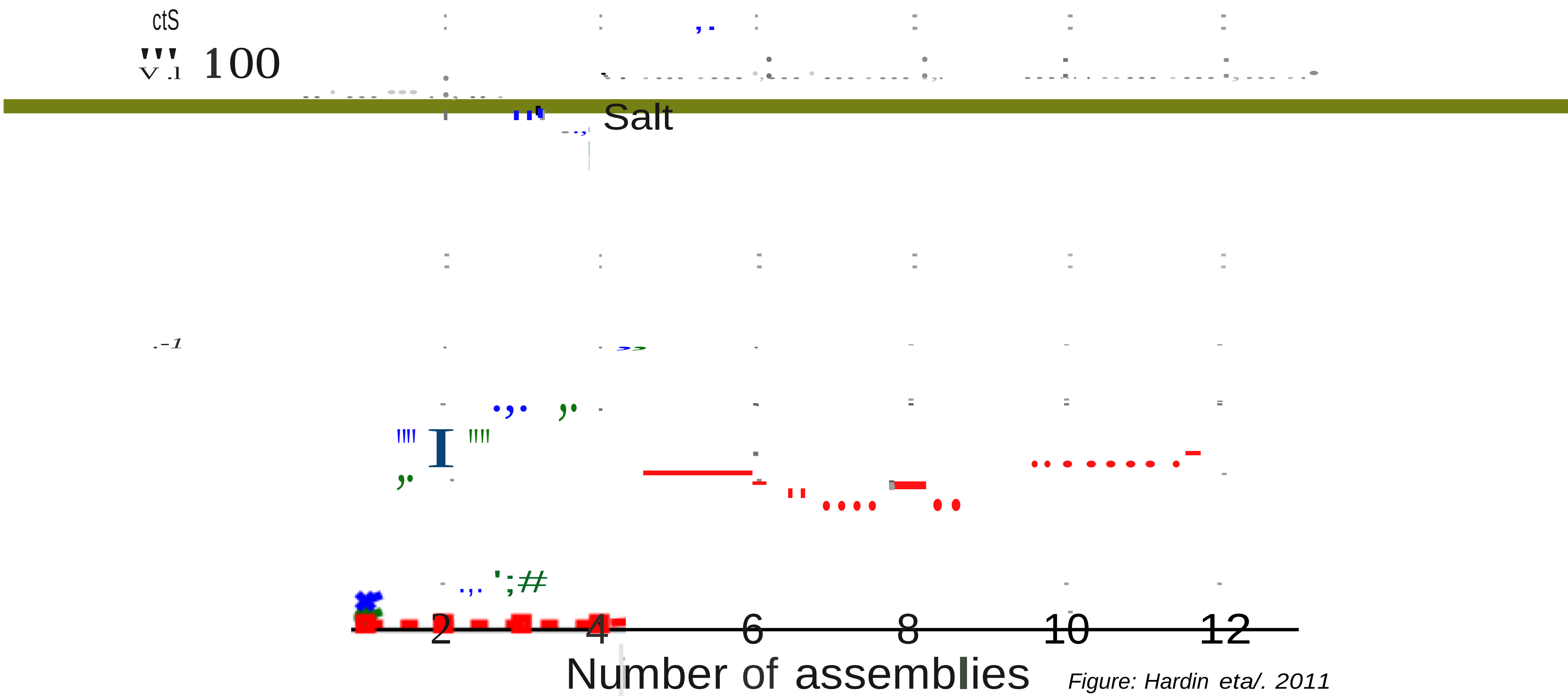



*Figure: Hardin eta/. 2011*

# Thermal Analysis Results
# Effect of Varying the 100°C/200°C Temperature Limits

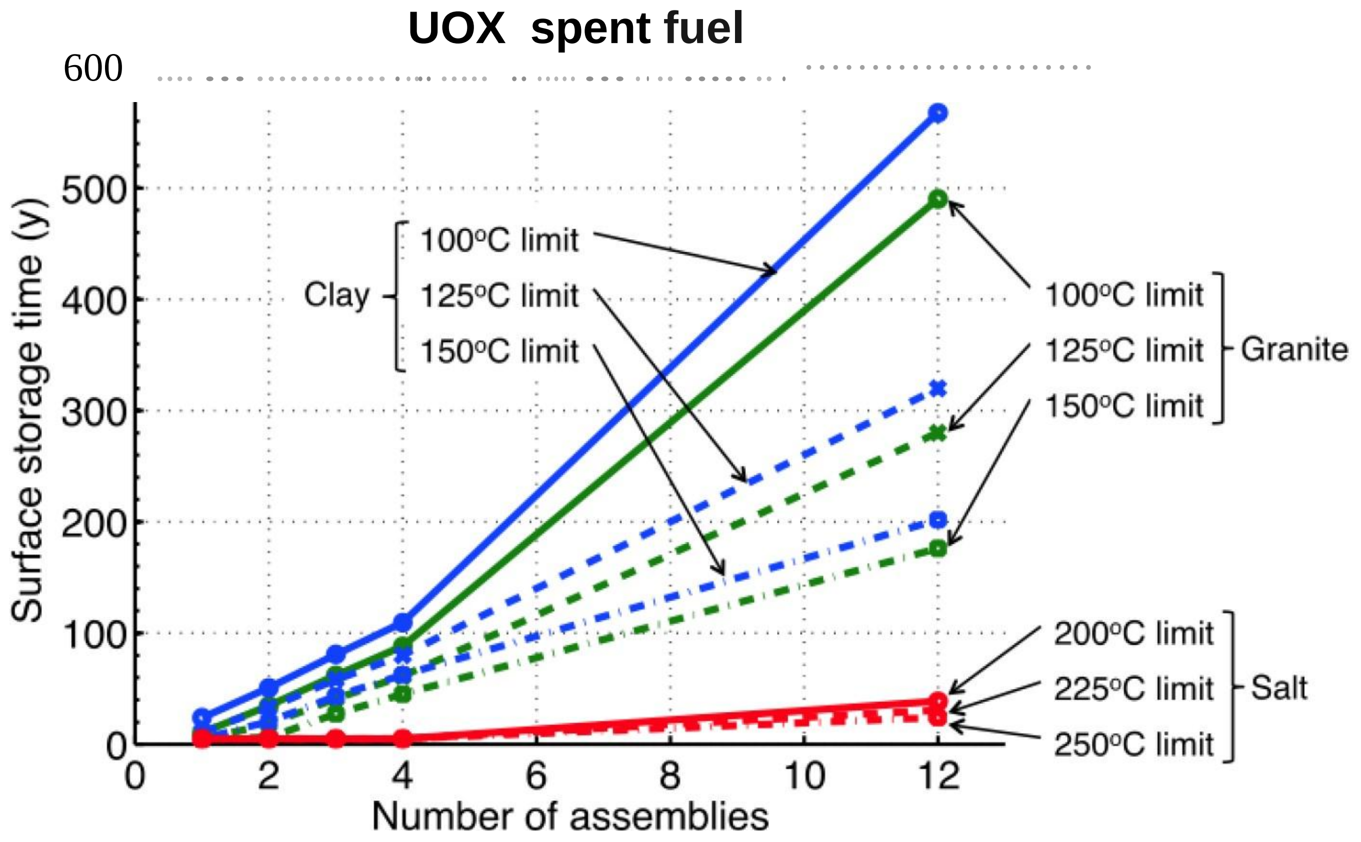



*Figure: Sutton eta/. 2012 (in review)*

*What's missing here?*

# Mined Disposal Concepts: Open vs. Enclosed Emplacement Modes

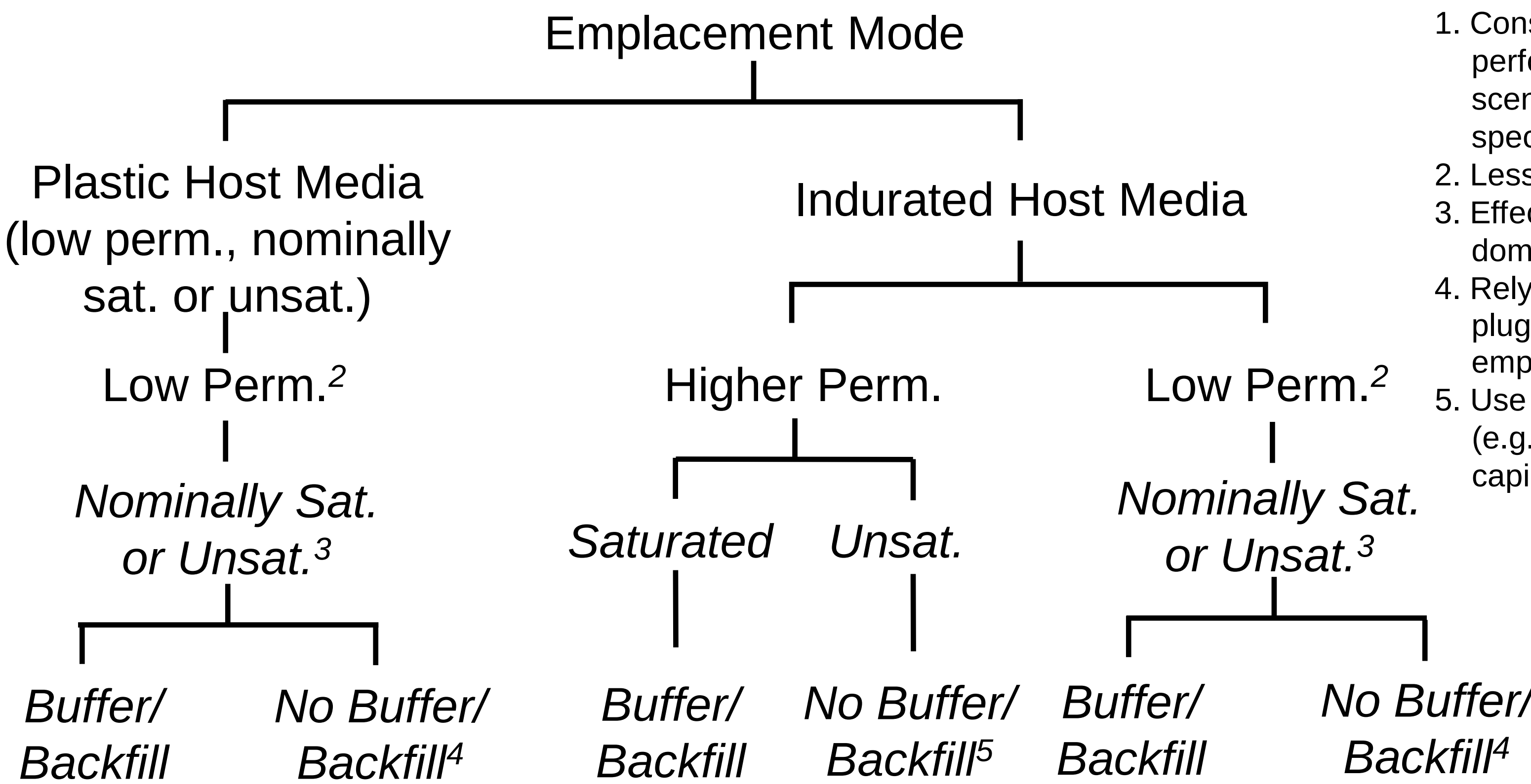
# Mined Disposal Concepts: Open vs. Enclosed Emplacement Modes

- **The emplacement mode directly affects repository thermal management**
  - **Open**: excavated emplacement openings persist
    - ***Heat spread by thermal radiation across gaps***
    - ***Pre-closure ventilation (e.g., Yucca Mountain LA)***
  - **Enclosed**: emplacement openings enclose waste packages (salt, clay/shale) and/or clay buffer surrounds the waste package (crystalline rock)
    - ***Greater near-field thermal resistance → higher temperature at the waste package (e.g., KBS-3, Dossier 2005, other international concepts)***

# Open Emplacement Mode Rationale

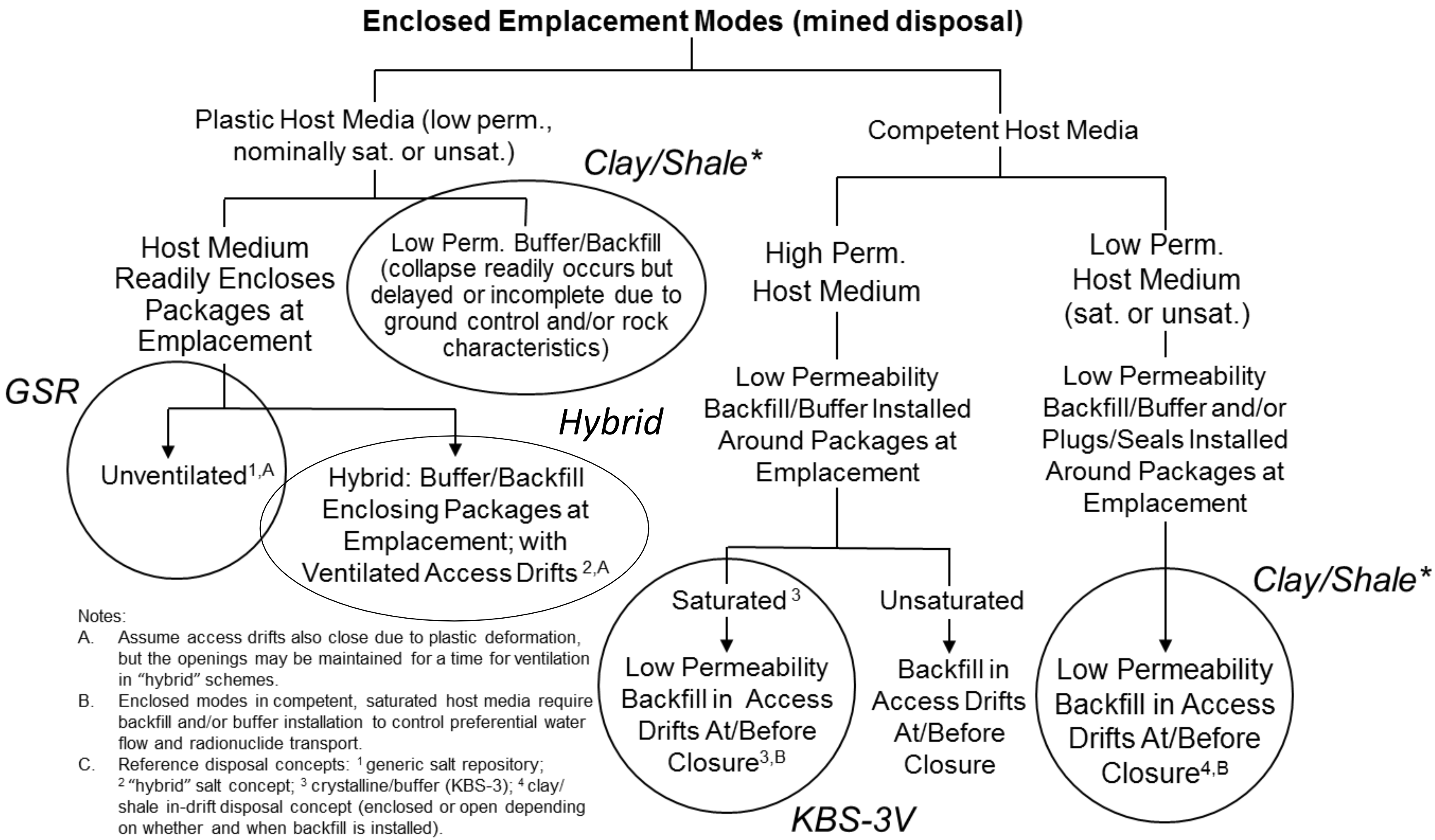
- **Potential advantages/disadvantages for open modes**
  - System Operation
    - ***Fewer transport operations and less transport distance for SNF***
    - ***Minimize repackaging***
    - ***Eliminate interim storage***
    - ***Earlier investment in disposal facilities (minimal overpack?)***
    - ***Completely reversible/reusable***
    - ***Preclosure ventilation and other care-taker costs***
  - System Economics
    - ***Defer disposal by 50 to 100 yrs, vs.***
    - ***Earlier disposal emplacement, preclosure ventilation, long-term monitoring, eventual closure***
    - ***Inter-generational equity***
  - Similar to YM concept

# Generic Taxonomy[1]




1. Consider postclosure performance, nominal scenario (disruption site-specific).
2. Less than ~$10^{-16}$ $m^2$
3. Effectively diffusion dominated transport.
4. Rely instead on remote plugging/sealing of emplacement openings.
5. Use diversion barriers (e.g., drip shields, or capillary barriers).

# Enclosed Emplacement Mode Taxonomy



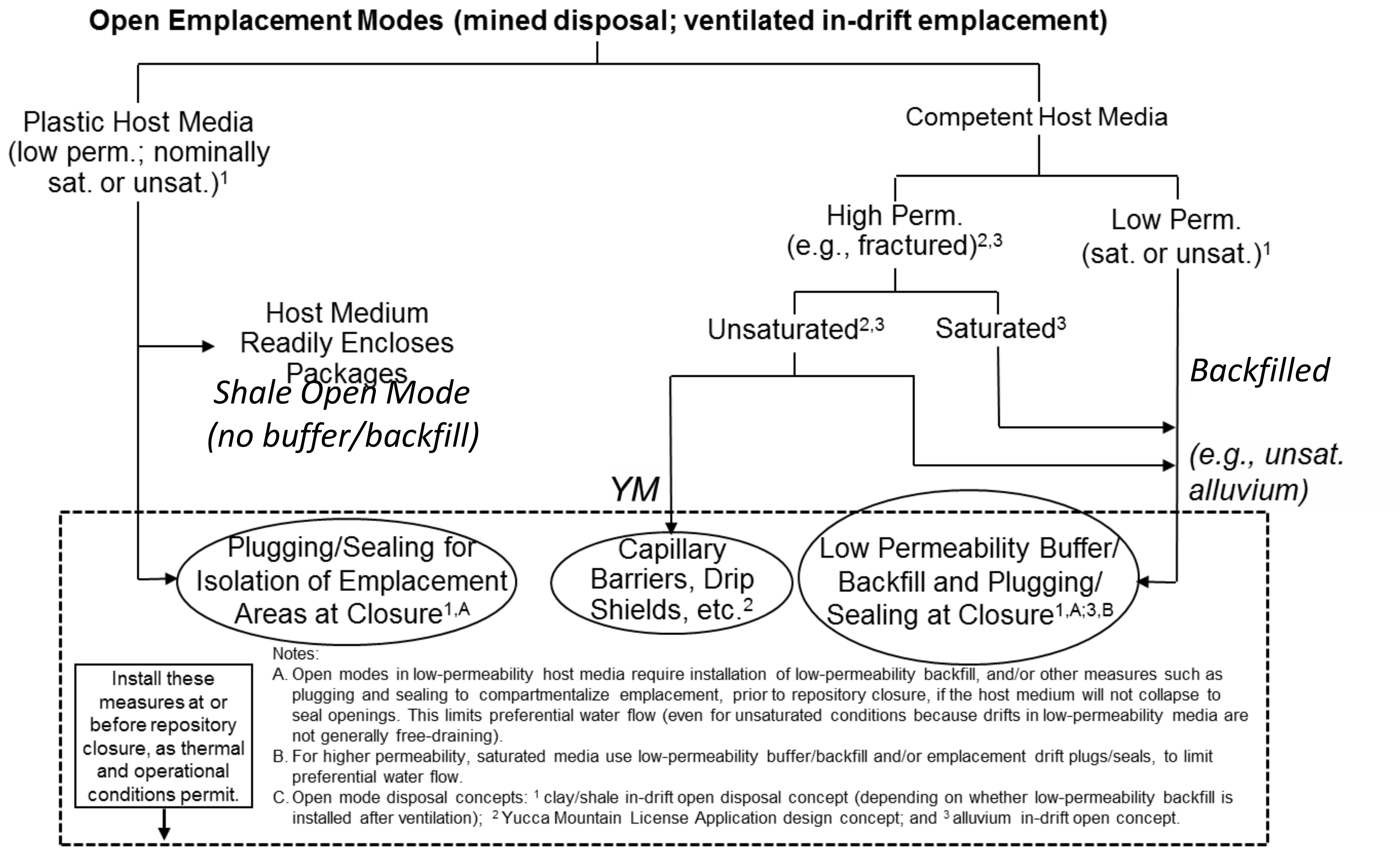

Notes:

A. Assume access drifts also close due to plastic deformation, but the openings may be maintained for a time for ventilation in "hybrid" schemes.

B. Enclosed modes in competent, saturated host media require backfill and/or buffer installation to control preferential water flow and radionuclide transport.

C. Reference disposal concepts: [1] generic salt repository; [2] "hybrid" salt concept; [3] crystalline/buffer (KBS-3); [4] clay/shale in-drift disposal concept (enclosed or open depending on whether and when backfill is installed).

# Open Emplacement Mode Taxonomy



# Proposed Reference Open Emplacement Concepts

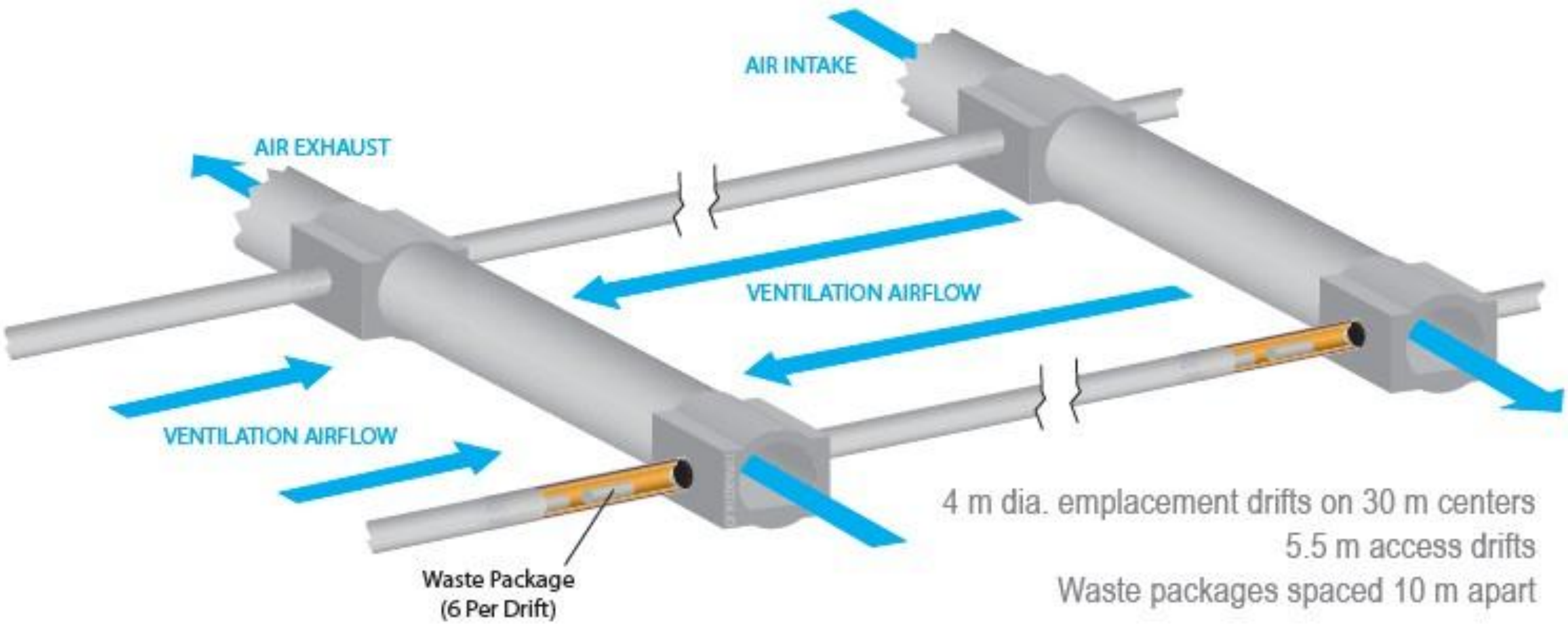
1. Yucca Mountain LA Disposal Concept
2. Shale Open Emplacement Concept
3. Backfilled Open Emplacement Concept (e.g., unsat. alluvi)um)
4. “Hybrid” Concept (salt)

# 1. Yucca Mountain LA Disposal Concept

- **Comprehensive LA Design Selection Study (OCRWM 1999).**
- **Addressed requirements of the Nuclear Waste Policy Act (NWPA) including a timetable (302(a)(5)(B))**
- **Long-term surface decay storage was not included because of restrictions in the NWPA**
- **Heat output for commercial SNF would be managed with pre-closure ventilation for at least 50 years (all design alternatives considered in the LA design study included this feature)**
- **Ventilation >50 years provides an option for a cooler repository**
- **No need for complete backfilling at closure**

***(A similar concept for saturated crystalline rock would require complete backfilling at closure to limit groundwater movement through the repository.)***

# 2. Shale Open Mode Concept for SNF (low permeability, sat. or unsat.)

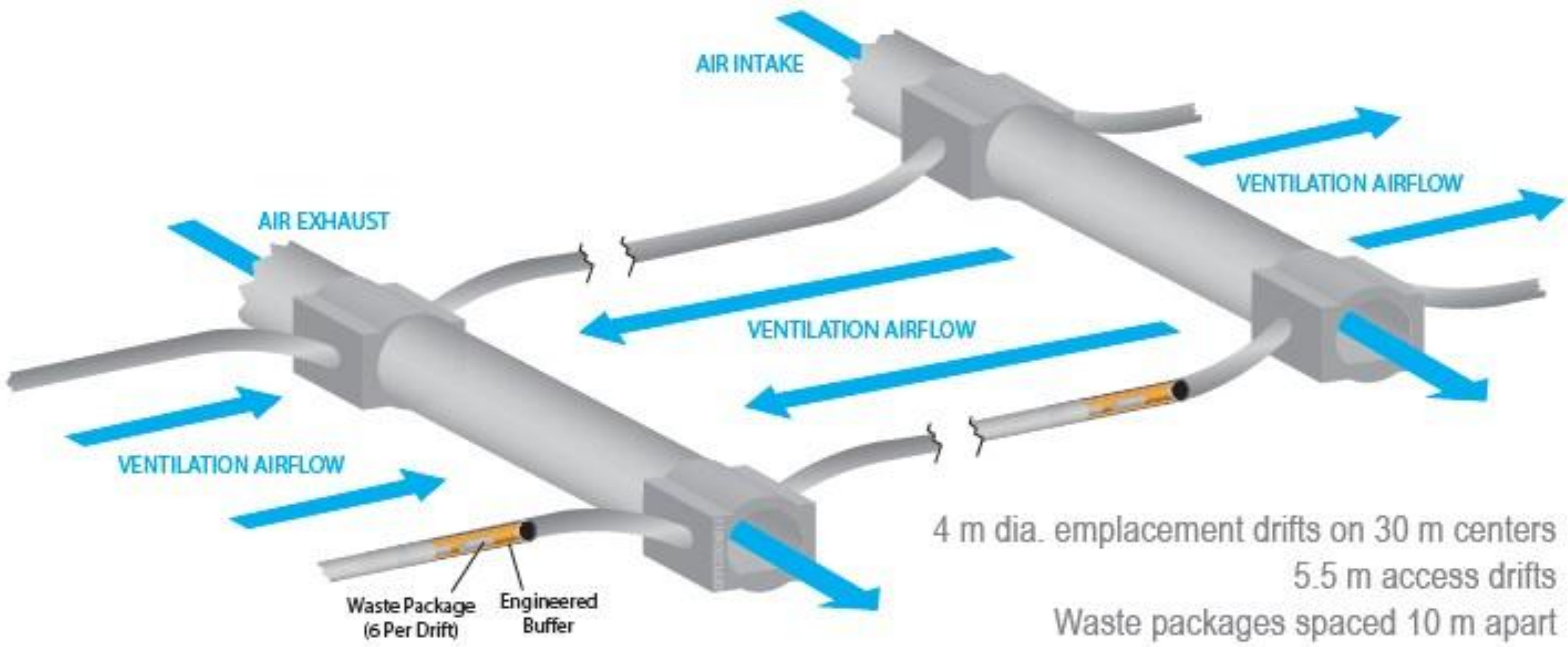



***Drift segments containing small numbers of waste packages are isolated by plugging/sealing (backfill is retained as an option at repository closure).***

**DRAFT**

***Not to Scale***

# 3. Backfilled Open Mode for SNF (e.g., unsaturated alluvium)




***Drift segments containing small numbers of waste packages are <u>backfilled with low permeability (e.g., clay-rich) material at closure</u>***

**DRAFT**

*Not to Scale*

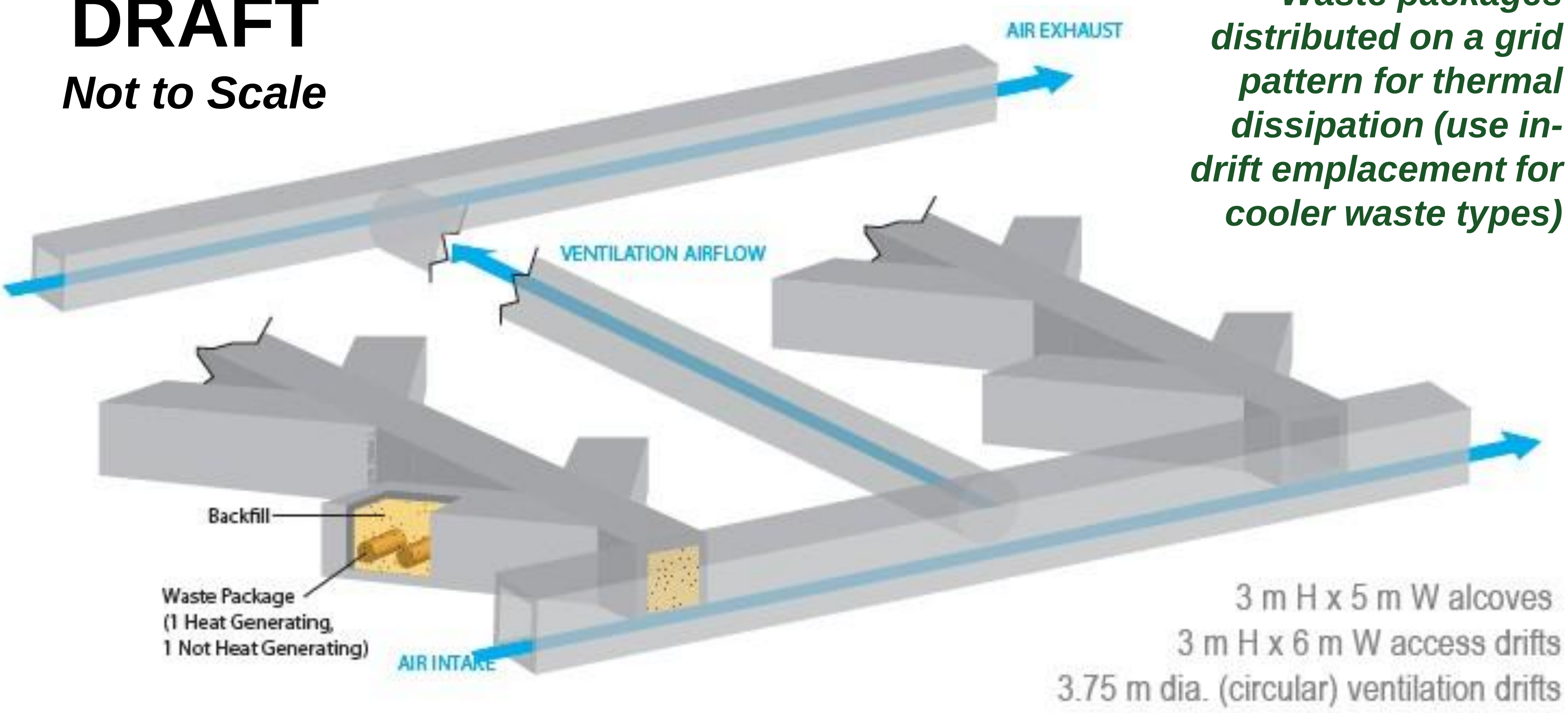
# 4. Salt "Hybrid" Concept for Hotter Waste

## Salt has roughly 2X the thermal diffusivity of other potential host media.

**DRAFT**

***Not to Scale***

***Waste packages distributed on a grid pattern for thermal dissipation (use in-drift emplacement for cooler waste types)***



# Direct Disposal of Multi-Purpose Canisters (Storage, Transport and Disposal)

# Direct Disposal of Dual Purpose (i.e., Multi-Purpose) Canisters

- Magnastor DPC system
- Capacity 37-PWR (equiv.)
- Thermal limits: 35.5 kW storage/24 kW transport
- Fuel cool time ≥4 yr OoR

Pictures and data from NAC International website 31Mar2012

# Direct Disposal of Multi-Purpose Canisters

- **MPCs will be large (DPCs have typ. 32-PWR capacity)**
  - Stainless steel; approx. 2 m dia. × 5 m long; loaded mass~ 50 MT; transportation overpack adds 90+ MT
  - Hypothetical disposal overpack (e.g., 2-in. steel, adds 28 MT)
- **Yucca Mountain TAD canisters**
  - Heaviest = Naval SNF, canister weight 44.5 MT; disposal overpack adds 29 MT
- **Avoid repackaging**
  - Cost $10k to $100k per MTHM
  - Worker dose associated with canister loading, drying, welding, handling, etc.

# Direct Disposal of Large, Multi-Purpose Canisters

- **Disposal Engineering Challenges**
  - Conveyance (shaft or ramp) and emplacement (in-drift mode)
  - Thermal management in all operations
  - Underground structural support (e.g., ramp, invert)
  - Large openings (excavation, ground support, maintenance)
  - Plugging and/or backfilling at closure
- **Postclosure Performance Challenges**
  - Package containment longevity (design, cost, waste isolation)
  - Effects on groundwater flow and radionuclide transport
    - *Waste package size vs. number of packages*
    - *Plug and/or backfill performance*
  - Interaction of cementitious materials (shotcrete and concrete)
  - Plumes (e.g., alkaline, radionuclide transport)
  - Criticality analysis (absorber fate, moderator exclusion)

# Conclusions

# How do open emplacement concepts help implement BRC recommendations?

- **Objectives: Help implement BRC recommendations**
  5. Prompt efforts to develop geologic disposal facility(s)
  6. Prompt efforts to develop consolidated storage facility(s)
  7. Prepare for large-scale transport of SNF and HLW
- **Prompt efforts → Multi-purpose canisters**
  - Integrate storage, transport and disposal in system design
- **Multi-purpose canisters → Direct disposal**
  - Engineering challenges
  - Postclosure performance challenges
- **Direct disposal → Open emplacement modes**
  - Incorporate open-mode reference concepts in UFD R&D program

# Open Modes Summary (1 of 2)

- **Add 3 Open-Mode Reference Cases (+ YM)**
- **Shale Open Mode Concept**
  - Low permeability host rock, limited water inflow even for saturated settings
  - Backfill or plug/seal at closure (e.g., swelling clay-based material if needed)
  - Technical issues: ground stability and support (shotcrete, concrete), desiccation, choice of plugging/sealing or backfilling strategies
- **Backfilled Open Mode Concept**
  - Wide variety of potentially suitable host media (e.g., unsaturated alluvium)
  - Backfill at closure (low permeability, e.g., crushed host rock, swelling clay)
  - Technical issues: ground stability and support (shotcrete, concrete), backfilling operations, waste package longevity strategy
- **"Hybrid" Concept (Salt)**
  - Waste isolation performance and heat dissipation advantages of salt
  - Lower peak salt temperature ~50 C° (similar to 20+ yr aging)
  - Technical issues: heat-removal efficiency and salt creep

# Open Modes Summary (2 of 2)

## Open Emplacement Modes:

- Facilitate direct disposal of existing, large dual-purpose canisters (DPCs)
- Permit a greater range of options (e.g., size, heat output) for future multi-purpose, standardized canisters (e.g., TAD canister system design)
- Enable lower cost direct-disposal concepts
- Allow earlier disposal (including "equity" policy options)
- Readily demonstrate retrievability and reversibility

## Engineering and Performance Modeling Challenges

- Cementitious materials in the repository
- Backfilling at closure
- Repository handling and transport for larger, heavier waste packages
- Waste package longevity strategy
- Postclosure criticality for existing DPCs (or MPCs)
- Related to pre-closure ventilation (feasibility, deliquescence, etc.)

# Backup Slides

# Ongoing Work

- **Develop reference enclosed and open emplacement mode concepts**
  - Develop safety strategies for reference concepts
  - Describe facilities (pre-conceptual), including larger waste packages, conveyances, and emplacement subsystems
  - Cost estimates for comparison
- **Additional waste streams (e.g., existing LWR SNF inventory at ~40 GW-d/MTHM)**
  - Thermal analysis
- **Higher temperature limits (e.g., 250°C in salt)**
  - FEP-based approach
- **Plan new R&D for direct disposal of large MPCs**

# Blue Ribbon Commission (2012)

- **Eight Recommendations**

  1. *New, consent-based approach to siting*
  2. *New organization*
  3. *Access to nuclear waste management funds*
  4. *Prompt efforts to develop geologic disposal facility(s)*
  5. *Prompt efforts to develop consolidated storage facility(s)*
  6. *Prepare for large-scale transport of SNF and HLW*
  7. *Support for U.S. innovation in NE technology and workforce development.*
  8. *Active U.S. leadership in international efforts (safety, waste management, non-proliferation, security)*

# Blue Ribbon Commission (2012)

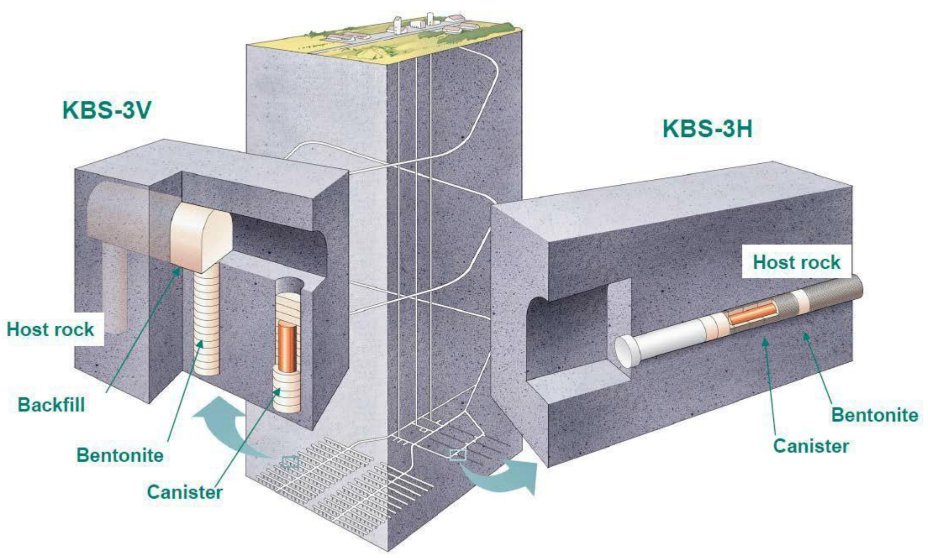
## Section 2.3.1 Ethical Responsibility

*"…the generations who created these wastes and benefited from the activities that produced them have an obligation to ensure that the entire burden of providing for their disposal does not fall to future generations. That means mustering, without further delay, the financial, programmatic, institutional, and political wherewithal to implement a functional system to manage these materials that provides for their safe transportation, consolidated storage, and disposal….the capability to provide for disposal must exist and the process of emplacing long-lived radioactive wastes, including particularly those materials with no realistic possibility of being re-used, must be underway within a reasonable timeframe."*

*"….this generation's responsibility to future generations includes taking care not to foreclose options that future generations may see as being in their best interest…future generations may want to use spent fuel as an energy resource. A well-constructed waste management program….can…provide a solution and leave choices."*

# Reference Disposal Concepts (FY11) Mined Crystalline Rock with Vertical Borehole Emplacement

- Ref: Based on KBS-3 (SKB 2006)
- Depth: ~500 m
- Hydrologic setting: Saturated
- Buffer temperature limit: 100°C

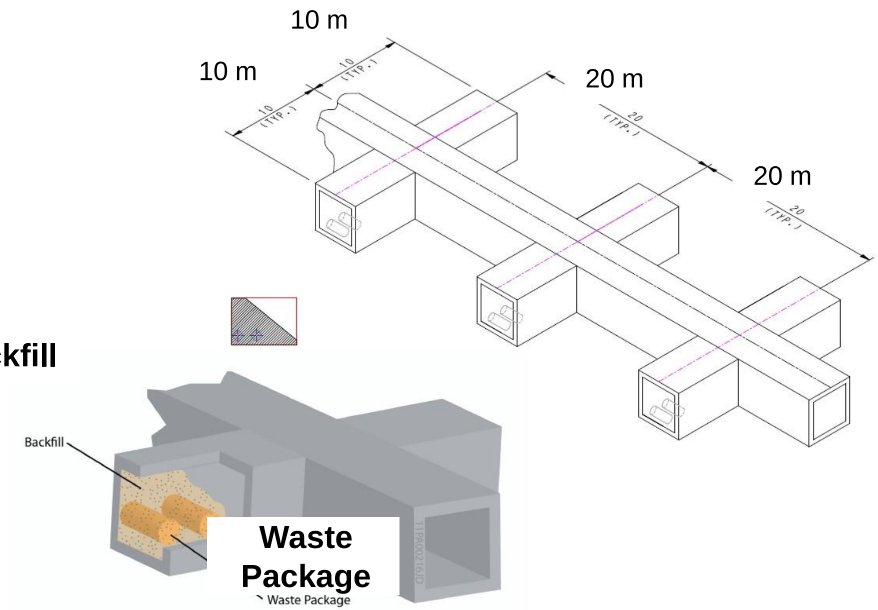



| Disposal Characteristic | SNF | HLW |
|---|---|---|
| Emplacement mode | Vertical boreholes | Vertical boreholes |
| Overpack material | Copper or steel | Steel |
| Borehole spacing, m | 10 | 10 |
| Drift spacing, m | 20 | 20 |
| Borehole liner material | - | - |
| Buffer material | Bentonite clay | Bentonite clay |
| Backfill material | Clay/sand mixture | Clay/sand mixture |

SKB (Swedish Nuclear Fuel and Waste Management Co.) 2006. *Long-term safety for KBS-3 repositories at Forsmark and Laxemar — A first evaluation.* Technical Report TR-06-09.

# Reference Disposal Concepts (FY11) Generic Salt Repository with Alcove Emplacement

- Ref: Generic Salt Repository (Carter et al. 2011)
- Depth: ~500 m
- Hydrologic setting: Saturated
- Salt temperature limit: 200$^{o}$C

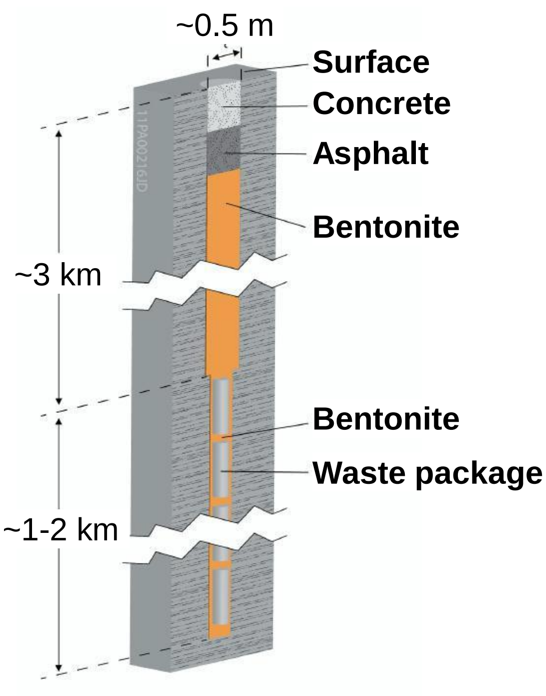



| Repository characteristic | SNF | HLW |
|---|---|---|
| Emplacement mode | Horizontal, in alcoves | Horizontal, in alcoves |
| Overpack material | Steel | Steel |
| Alcove spacing, m | 20 | 20 |
| Access drift spacing, m | 40 | 40 |
| Borehole liner material | - | - |
| Buffer material | - | - |
| Backfill material | Crushed/ compact salt | Crushed/ compact salt |

Carter, J.T., F. Hansen, R. Kehrman, and T. Hayes 2011a. *A generic salt repository for disposal of waste from a spent nuclear fuel recycle facility*. SRNL-RP-2011-00149 Rev. 0. Savannah River National Laboratory.

# Reference Disposal Concepts (FY11) Deep Borehole

- Ref: SNL and MIT studies
- Depth: 3 to 5 km
- Hydrologic setting: Saturated
- Temperature constraint: None




| Disposal Characteristic | SNF | HLW |
|---|---|---|
| Emplacement mode | Vertical, stacked | Vertical, stacked |
| Overpack material | Steel | Steel |
| Package spacing, m | 6 | 6 |
| Borehole spacing, m | 200 | 200 |
| Borehole liner material | Steel | Steel |
| Buffer material | Water/mud | Water/mud |
| Backfill material | - | - |

Brady, P.V., B.W. Arnold, G.A. Freeze, P.N. Swift, S.J. Bauer, J.L. Kanney, R.P. Rechard, and J.S. Stein 2009. *Deep borehole disposal of high-level radioactive waste*. SAND2009-4401. Sandia National Laboratories.

# Reference Enclosed Mode Concept Specifics

| Geologic Media/Concept | Mined Granite | Mined Clay/shale | Mined Salt | Deep Borehole |
|---|---|---|---|---|
| **Repository depth** | 500 m | 500 m | 500 m | >3000 m |
| **Hydrologic setting** | Saturated | Saturated | Saturated | Saturated |
| **Emplacement mode (UNF)** | Horizontal emplacement, boreholes in wall | Horizontal emplacement, boreholes in wall | Horizontal emplacement, boreholes in wall | Vertical emplacement, stacked |
| **Emplacement mode (HLW)** | Same | Same | Horizontal emplacement in alcoves | Same |
| **Normalized areal loading (GWe-yr/acre) *** | 1 to 10 | 1 to 10 | 1 to 10 | <1 |
| **Drift/borehole spacing** | 20 m | 20 m | 20 m | >100 m |
| **Drift/borehole diameter** | ~1 m | ~1 m | ~1 m boreholes; 4 m for alcoves | >30 cm |
| **Waste package arrangement** | Point | Line | Point for SNF boreholes; point for HLW in alcoves | Line |
| **Liner material** | Steel | Steel | Not used | Steel |
| **Overpack material** | Copper or steel | Steel | Steel | Steel |
| **Maximum SNF waste package capacity (size)** | 4-PWR | 4-PWR | 12-PWR | 1 PWR assembly |
| **Buffer material** | Bentonite clay | Not used | Not used | Bentonite clay |
| **Radiation shield plug** | Required | Required | Required | Not used |
| **Backfill material** | Clay/sand mixture | Clay/shale | Crushed salt | Not used |
| **Invert material** | Reinforced concrete | Reinforced concrete | Reinforced concrete | Not used |
| **Ground support material** | Rockbolts, wire cloth & shotcrete | Steel sets & shotcrete | Rockbolts | Not used |
| **Seals and plugs** | Shaft and tunnel | Shaft and tunnel | Shaft and tunnel | Not used |

* Magnitude of allowable thermal loading for these concepts depends on waste heat output at emplacement.

# Six Heat-Generating Waste Types

| **Strategy Sampled** | **Description** | **Waste Types** (Carter et al. 2011a) | **Example Source** |
|---|---|---|---|
| **Once-Through** | Direct disposal of high-burnup (60 GW-d/MTHM) LWR UOX SNF | • UOX SNF | • Generation III+ LWRs |
| **Modified-Open** | Reprocessing of LWR UOX used fuel (51 GW-d/MTHM) to produce MOX fuel that is used once (50 GW-d/MTHM) then directly disposed | • MOX SNF<br>• Co-Extraction HLW borosilicate glass | • "Transitional" variation of the French strategy with direct disposal of MOX SNF<br>• Irradiated MOX fuel from Pu-disposition program (~500 MTHM) |
| **Closed** | Reprocessing of LWR UOX used fuel (51 GW-d/MTHM) to produce U-TRU metal fuel for SFRs (0.75 conversion ratio), and repeated recycle of the SFR used fuel (99.6 GW-d/MTHM) | • "New-Extraction" HLW borosilicate glass<br>• Electrochemical ceramic HLW<br>• Electrochemical fission- product metal HLW | • "Transitional" fast-spectrum burner strategy with TRU recycling |

# Semi-Analytical Thermal Model

## Conduction-only heat transfer

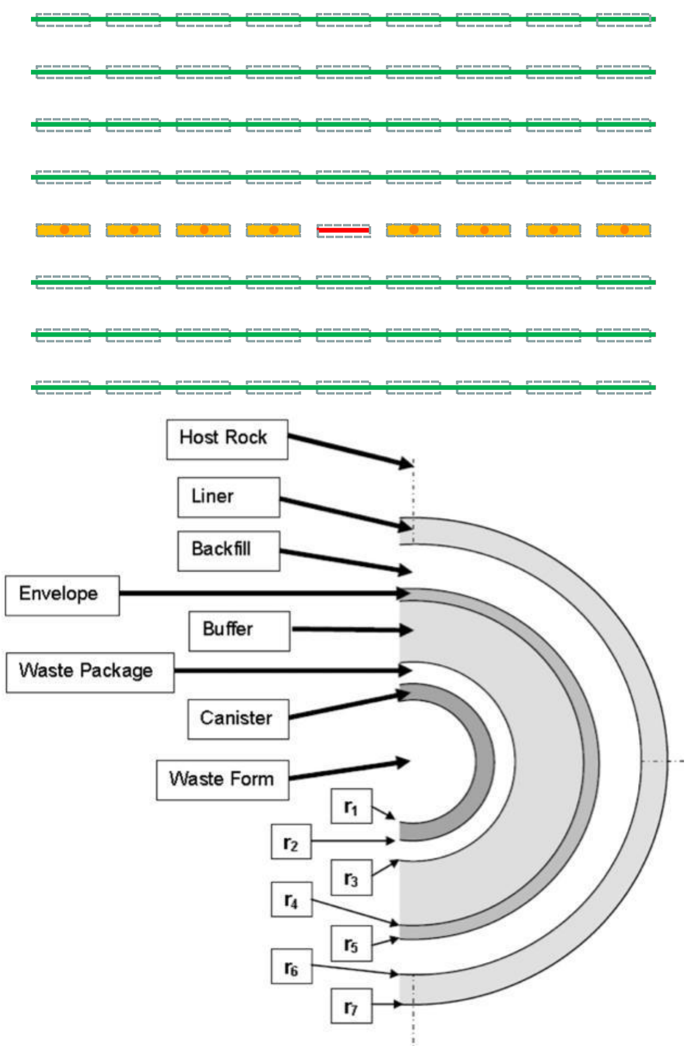
- Convection negligible in low-permeability rock and EBS materials
- Timing of peak temperature (1 to 30 years after emplacement) limits formation of convection cells
- No significant voids (i.e., no radiative transfer)
- Demonstrated suitable for first-order prediction

## Waste package surface peak temperature

- Maximum EBS temperature outside the waste package
- Waste packages and waste forms withstand greater temperatures
- Package internal thermal performance indexed to external surface temperature
- Other measures (e.g., time-temperature) depend on design

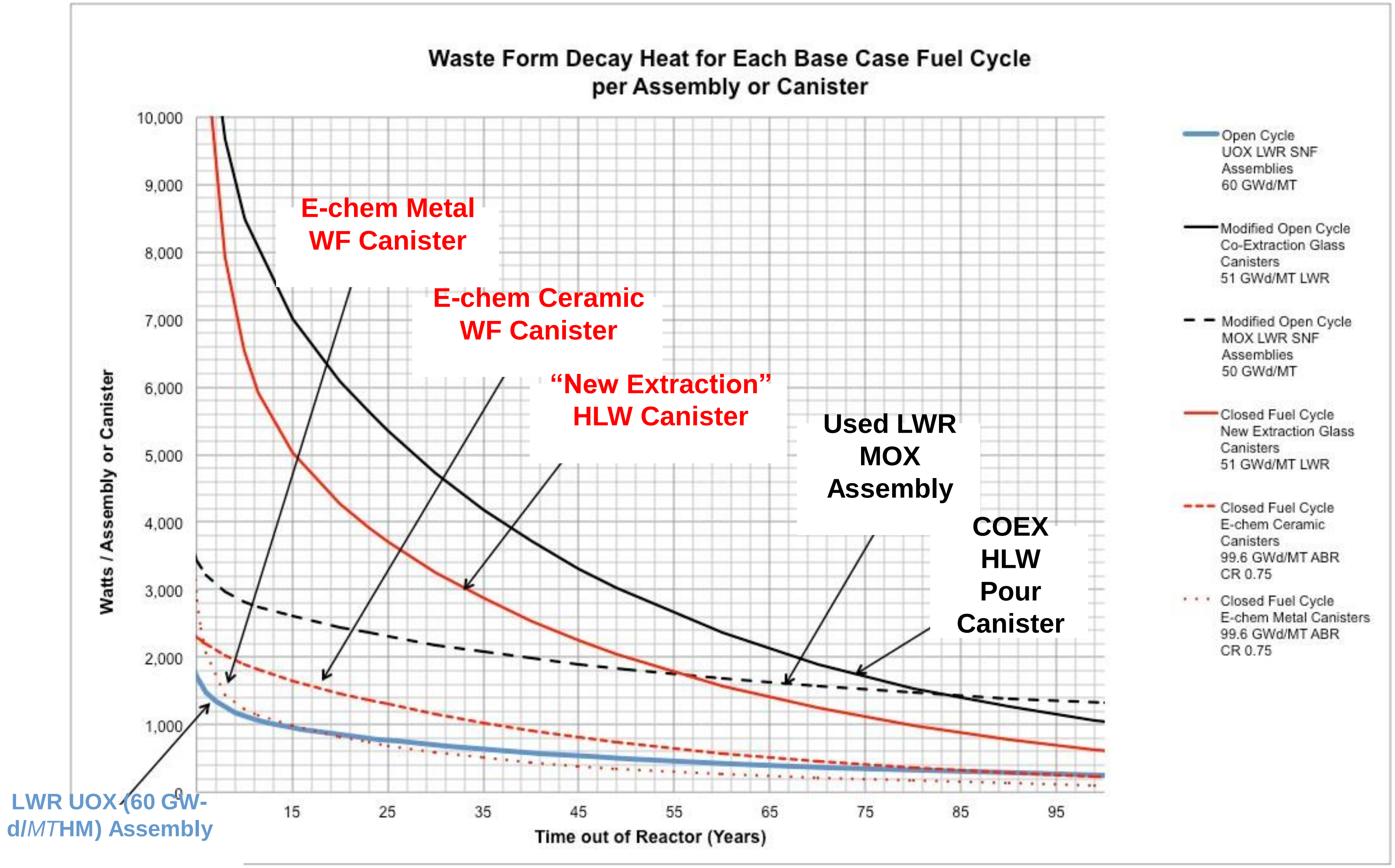
# Disposal Concept Thermal Analysis Approach (FY11)

Superposition: Waste Package/Drift Array




- **Semi-analytical**
  - Evaluate temperature histories on waste package outer surface
  - Multiple combinations of waste types, age, and disposal concepts
- **Compare peak temperatures with assumed limits for engineered or natural materials**
- **Estimate decay storage duration needed for each disposal concept and waste type**
  - For SNF plot decay storage duration vs. # of assemblies per waste package

# HLW Glass Heat Outputs are Highest in the Near Term, MOX SNF in the Long Term

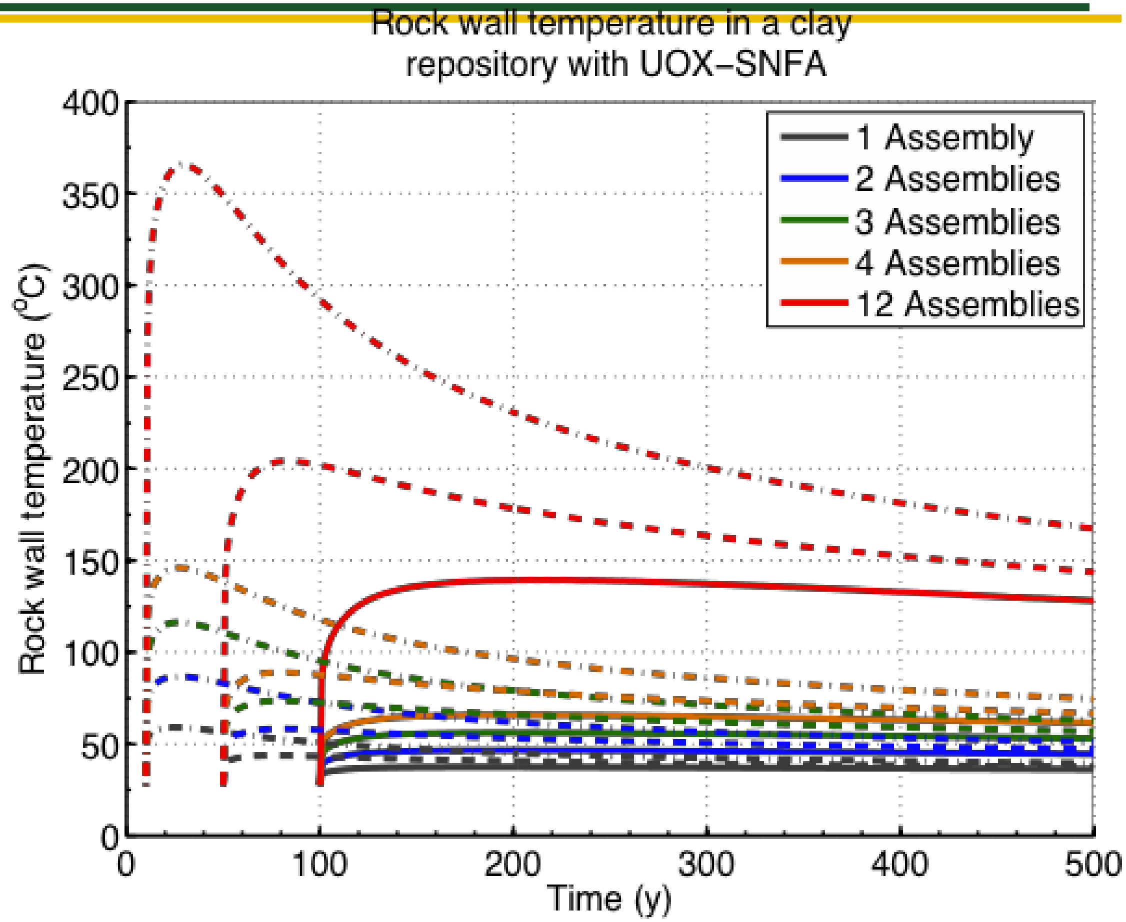





*Hardin, E.L., Open Mode Emplacement Concepts*

# Thermal Analysis (FY11) Temperature Histories for 4 Disposal Concepts and 6 Waste Types

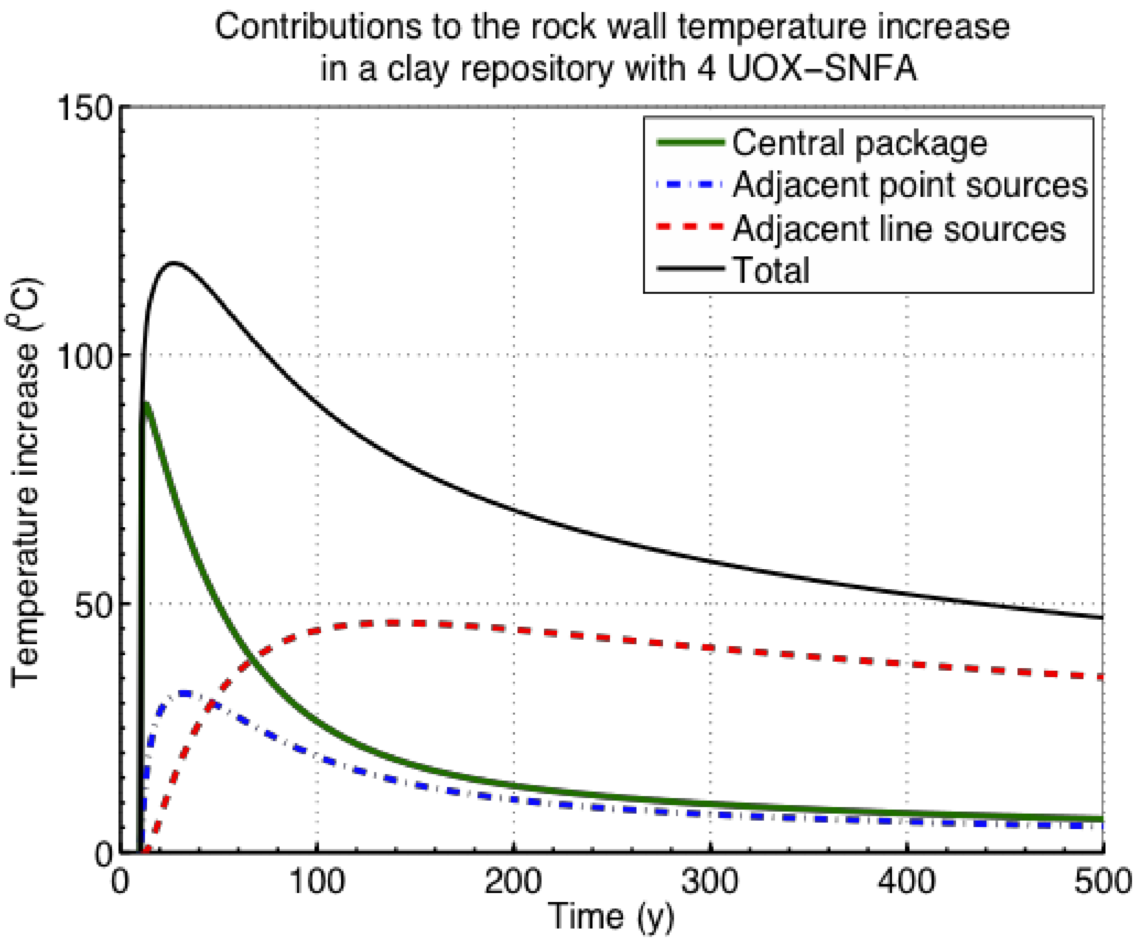
- Example
- Clay/shale repository
  - Results for host rock temperature (at EBS boundary)
  - LWR UOX SNF (60 GW-d/MTHM)
  - Calculate for different package size/capacity




 Hardin, E.L., *Open Mode Emplacement Concepts*

# Thermal Analysis (FY11) Relative Contributions to Transient Temperature Histories

- **Example**
- **Relative contributions to calculated host rock temperature (at EBS boundary)**
  - LWR UOX SNF (60 GW-d/*MT*HM)
  - 10-yr age out-of-reactor
  - 4-PWR package

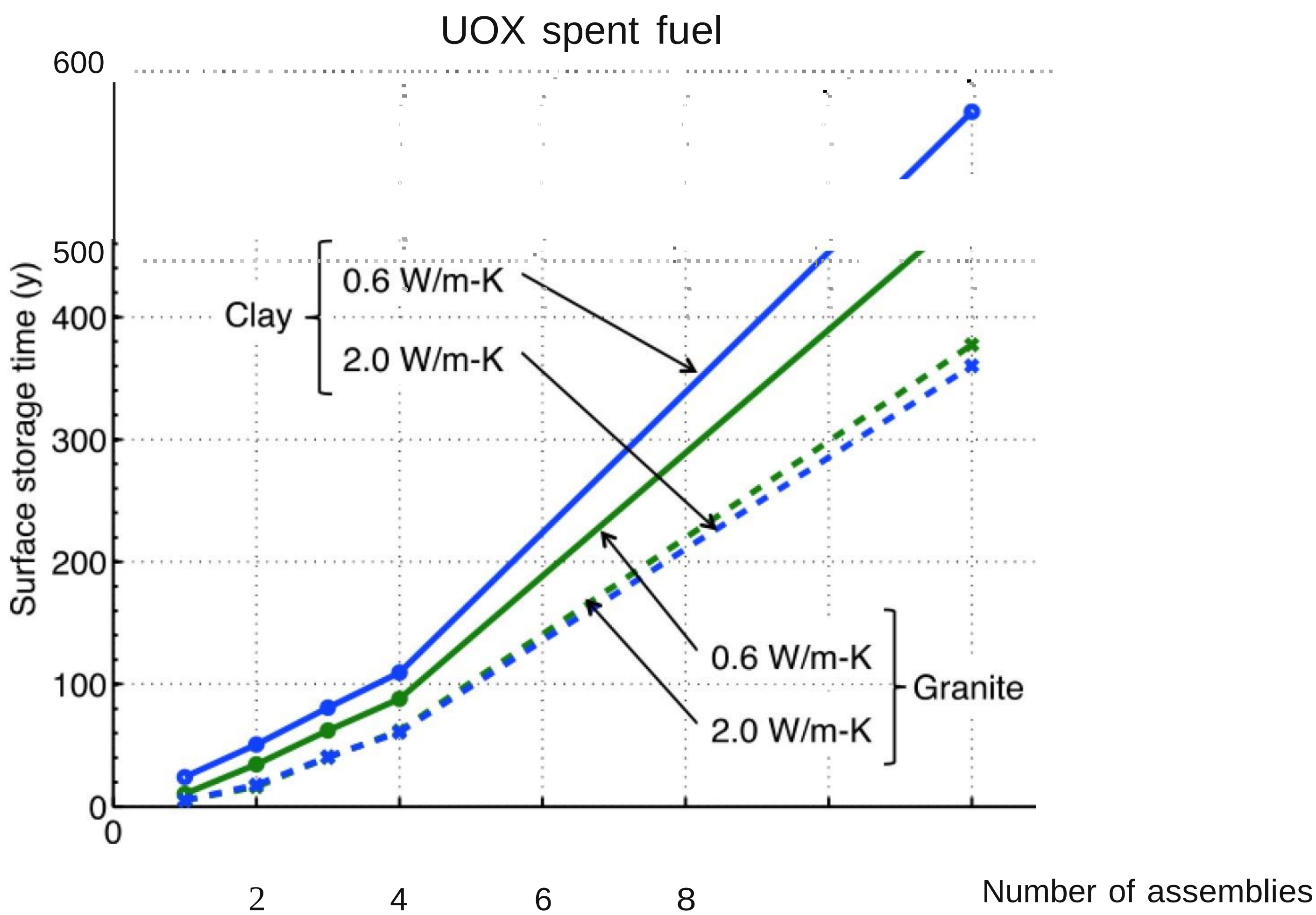


# Peak Temperature at the Waste Package Surface - UOX and MOX SNF, All Disposal Concepts (FY11)

| Disposal Scenario | | | Peak Temperature at the Waste Package Surface, °C | | | |
|---|---|---|---|---|---|---|
| Geology | Waste Type | Assemblies/ Package | Decay Storage Duration | | | |
| | | | 10 yr | 50 yr | 100 yr | 200 yr |
| Crystalline (100°C) | UOX SNF | 4 | 256.9 | 141.2 | 92.8 | 68.9 |
| | MOX SNF | 1 | 229.8 | 172.9 | 144.0 | 116.2 |
| Clay/Shale (100°C) | UOX SNF | 4 | 341.9 | 174.0 | 106.4 | 72.9 |
| | MOX SNF | 1 | 288.6 | 203.4 | 161.8 | 126.8 |
| Salt (200°C) | UOX SNF | 4 | 139.9 | 81.8 | 57.9 | 45.7 |
| | MOX SNF | 1 | 120.8 | 93.1 | 79.0 | 65.9 |
| Deep borehole | UOX SNF | 1 | 186.4 | 161.9 | 151.7 | 146.3 |
| | MOX SNF | 1 | 264.5 | 224.1 | 202.9 | 184.7 |

Used Fuel Disposition

# Thermal Analysis Results
# Effect of Buffer Thermal Conductivity






*Hardin, E.L., Open Mode Emplacement Concepts*

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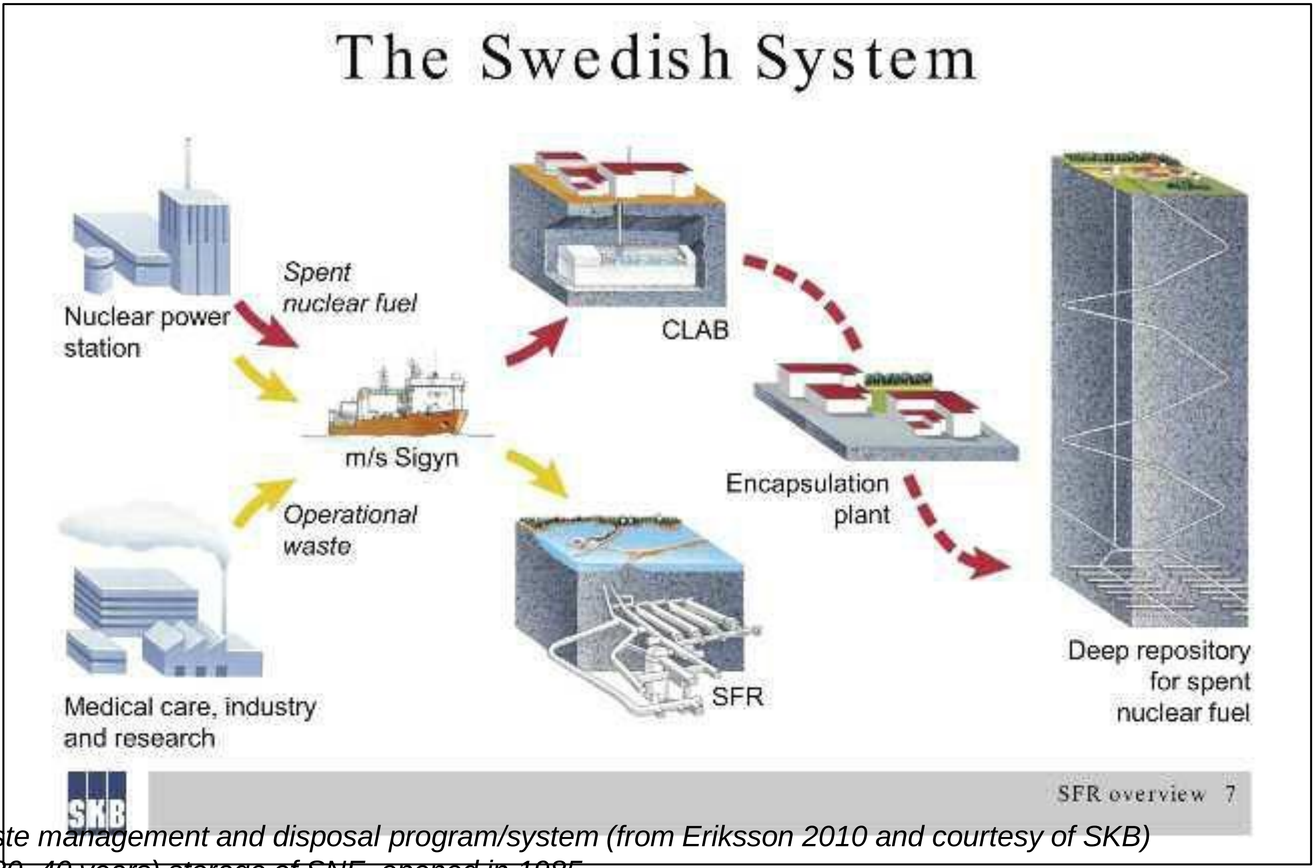
# Reality Check #1: Swedish System-Concept

- Nominally 40 yr of decay storage (CLAB)
- FY11 reference calculation: ~100 yr for 60 GWd/MT burnup

→ Agreement will be reasonable (with correction for burnup)

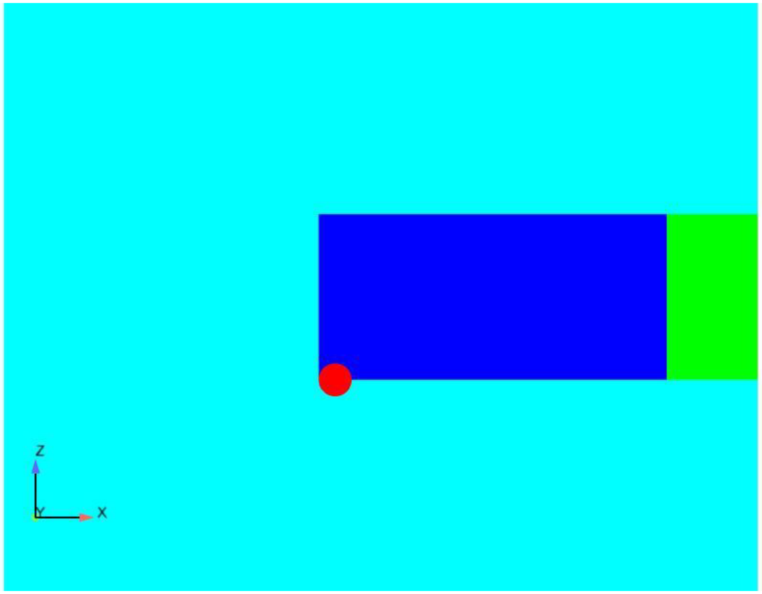



*Schematic of the Swedish nuclear waste management and disposal program/system (from Eriksson 2010 and courtesy of SKB)*
*CLAB = Central facility for long-term (30–40 years) storage of SNF, opened in 1985*
*SFR = Repository for long-lived LLW and ILW, opened in 1988*
*Dark arrows depict SNF, light arrows depict LLW and ILW. Dashed arrows lead to planned facilities (regular operation ~ 2025)*

# Reality Check #2: FEM Simulation for a Generic Salt Repository

- **Based on geometry used in earlier generic salt repository thermal calculations**
  - Sierra Mechanics (see Clayton & Gable 2009)
- **SNF**
  - 4, 12, 21 & 32-PWR packages
  - 40 & 60 GW-d/MTHM
  - Aged 10, 20 and 50 yr OoR
- **HLW**
  - 15 ft. and 9 ft. long packages
  - Aged ~37 years
- **Coupling**
  - Thermal-mechanical (intact salt, crushed salt backfill)
  - Backfill thermal conductivity ← consolidation

2-D Vertical Cross-Section
Along Alcove Centerline



# Coupled Calculation in Salt

- **Used Arpeggio code (Sierra Mechanics) to externally couple**
  - Aria (Galerkin finite element based program for solving coupled-physics problems described by systems of partial differential equations, e.g., energy and mass flow)
  - Adagio (Lagrangian mechanical modeling program with special provisions for modeling salt deformation)
  - Same or different grids, one input file
- **Includes updated salt and crushed salt constitutive models**

## Used Fuel Disposition

# FEM Results Summary

- *Oldest SNF (~50 yr OoR) can be emplaced now in 21-PWR WPs*
- *Large canisters (e.g., 32-PWR) can be emplaced <100 yr OoR*

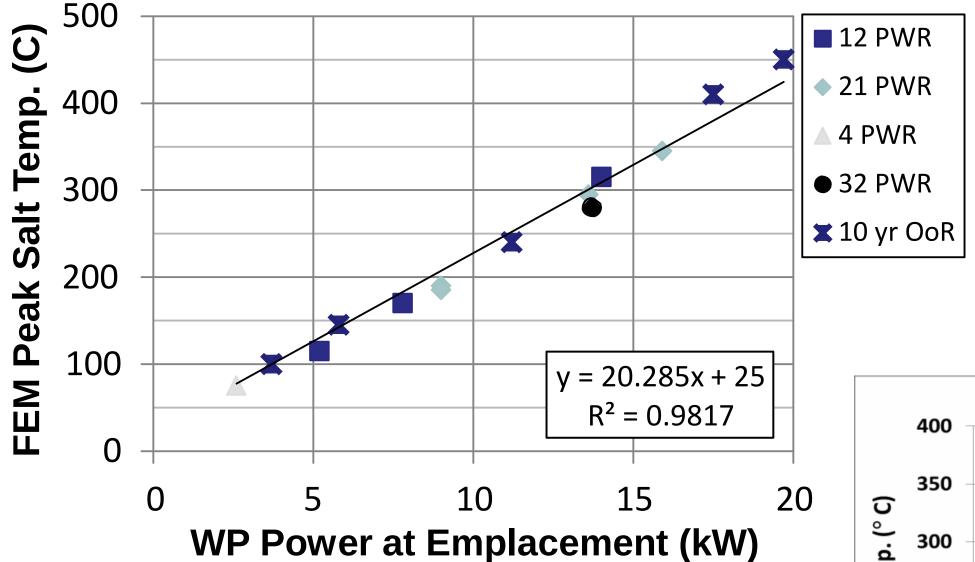
| WF | Package type | WP Dimensions | Fuel burnup | MTIHM | Age OoR, yr | Heat output | Model run | Ventilation | ~ Peak Salt T, C |
|---|---|---|---|---|---|---|---|---|---|
| **WASTE PACKAGE SIZE : 40 and 60 GW-d/MT BURNUP (10 yr AGE OoR)** | | | | | | | | | |
| UNF | 4-PWR | 0.82 m D x 5.00 m L | 40 GWd/t | 1.88 | 10 | 3.7 kW | T, 200 yr | No | 100 |
| UNF | 4-PWR | 0.82 m D x 5.00 m L | 40 GWd/t | 1.88 | 10 | 3.7 kW | TM, 200 yr | No | 100 |
| UNF | 4-PWR | 0.82 m D x 5.00 m L | 60 GWd/t | 1.88 | 10 | 5.8 kW | T, 200 yr | No | 145 |
| UNF | 12-PWR | 1.29 m D x 5.13 m L | 40 GWd/t | 5.64 | 10 | 11.2 kW | T, 200 yr | No | 240 |
| UNF | 12-PWR | 1.29 m D x 5.13 m L | 60 GWd/t | 5.64 | 10 | 17.5 kW | T, 200 yr | No | 410 |
| UNF | 21-PWR | 1.60 m D x 5.13 m L | 40 GWd/t | 9.87 | 10 | 19.7 kW | T, 200 yr | No | 450 |
| | | | | | | | | | |
| **AGING STUDY: 40 and 60 GW-d/MT BURNUP (50 yr AGE OoR)** | | | | | | | | | |
| UNF | 4-PWR | 1.29 m D x 5.13 m L | 60 GWd/t | 1.88 | 50 | 2.6 kW | T, 200 yr | No | 75 |
| UNF | 12-PWR | 1.29 m D x 5.13 m L | 40 GWd/t | 5.64 | 50 | 5.2 kW | T, 200 yr | No | 115 |
| UNF | 12-PWR | 1.29 m D x 5.13 m L | 60 GWd/t | 5.64 | 20 | 14.0 kW | T, 200 yr | No | 315 |
| UNF | 12-PWR | 1.29 m D x 5.13 m L | 60 GWd/t | 5.64 | 50 | 7.8 kW | T, 200 yr | No | 170 |
| UNF | 21-PWR | 1.60 m D x 5.13 m L | 40 GWd/t | 9.87 | 20 | 15.9 kW | T, 200 yr | No | 345 |
| UNF | 21-PWR | 1.60 m D x 5.13 m L | 40 GWd/t | 9.87 | 50 | 9.0 kW | T, 200 yr | No | 190 |
| UNF | 21-PWR | 1.60 m D x 5.13 m L | 40 GWd/t | 9.87 | 50 | 9.0 kW | TM, 200 yr | No | 185 |
| UNF | 21-PWR | 1.60 m D x 5.13 m L | 60 GWd/t | 9.87 | 50 | 13.6 kW | T, 200 yr | No | 295 |
| UNF | 32-PWR | 2.00 m D x 5.13 m L | 40 GWd/t | 15.04 | 50 | 13.7 kW | T, 200 yr | No | 280 |
| | | | | | | | | | |
| **VENTILATION STUDY** | | | | | | | | | |
| UNF | 12-PWR | 1.29 m D x 5.13 m L | 40 GWd/t | 5.64 | 10 | 11.2 kW | T, 200 yr | 1.58 W/m2/K | 205 |
| UNF | 12-PWR | 1.29 m D x 5.13 m L | 60 GWd/t | 5.64 | 10 | 17.5 kW | T, 200 yr | 1.58 W/m2/K | 350 |
| UNF | 12-PWR | 1.29 m D x 5.13 m L | 60 GWd/t | 5.64 | 20 | 14.0 kW | T, 200 yr | 1.58 W/m2/K | 265 |
| UNF | 12-PWR | 1.29 m D x 5.13 m L | 60 GWd/t | 5.64 | 50 | 7.8 kW | T, 200 yr | 1.58 W/m2/K | 145 |
| UNF | 21-PWR | 1.60 m D x 5.13 m L | 40 GWd/t | 9.87 | 10 | 19.7 kW | T, 200 yr | 9.95 W/m2/K | 345 |
| UNF | 21-PWR | 1.60 m D x 5.13 m L | 40 GWd/t | 9.87 | 10 | 19.7 kW | T, 200 yr | 1.58 W/m2/K | 360 |
| UNF | 21-PWR | 1.60 m D x 5.13 m L | 40 GWd/t | 9.87 | 20 | 15.9 kW | T, 200 yr | 1.58 W/m2/K | 280 |
| UNF | 21-PWR | 1.60 m D x 5.13 m L | 40 GWd/t | 9.87 | 50 | 9.0 kW | T, 200 yr | 1.58 W/m2/K | 150 |
| UNF | 21-PWR | 1.60 m D x 5.13 m L | 60 GWd/t | 9.87 | 50 | 13.6 kW | T, 200 yr | 1.58 W/m2/K | 235 |
| | | | | | | | | | |
| **HLW GLASS STUDY** | | | | | | | | | |
| HLW | Pour | 0.61 m D x 2.70 m L | 51 GWd/t | 3.16 | 0 | 2 kW | T, 200 yr | No | 100 |
| HLW | Pour | 0.61 m D x 2.70 m L | 51 GWd/t | 3.16 | 37 | 2 kW | T, 200 yr | No | 115 |
| HLW | Pour | 0.61 m D x 4.50 m L | 51 GWd/t | 5.26 | 10 | 7 kW | T, 200 yr | No | 355 |
| HLW | Pour | 0.61 m D x 4.50 m L | 51 GWd/t | 5.26 | 37 | 3.3 kW | T, 200 yr | No | 162 |

# Reality Check #2: Comparison of FEM Results w/ Semi-Analytical Thermal Analysis (FY11)

| WF | Package typ.e | WP Dimensions | Fuel burnup | MTIHM | Age OoR, yr | Heat output | -Peak Salt T, C | Peak from Hardin etal. 2011 |
|---|---|---|---|---|---|---|---|---|
| WASTE PACKAGE SIZE and AGING STUDY: 40 and 60 GW-d/MT BURNUP (10 yr AGE OoR) | | | | | | | | |
| UNF | 4-PWR. | 0.82 m O x 5.00 m l | 60 GWd/t | L&8 | 10 | 5.8 kW | 145 | 139.9 |
| UNF | 12-PWR. | 1.29 m O x 5.13 m l | 60 GWd/t | 5.64 | 10 | 17.5 kW | 410 | -320 |
| WASTE PACKAGE SIZE and AGING STUDY: 40 and 60 GW-d/MT BURNUP (50 yr AGE OoR) | | | | | | | | |
| UNF | 4-PWR. | 1.29 m O x 5.13 m l | 60 GWd/t | L&8 | 50 | 2.6 kW | 75 | 81.8 |
| HLW GLASS STUDY | | | | | | | | |
| HLW | Pour | 0.61 m O x 4.50 m l | 51 GWd/t | 5.26 | 10 | 7 kW | 355 | 281.5 |
| HLW | Pour | 0.61 m O x 4.50 m l | 51 GWd/t | 5.26 | '''37 | 3.3 kW | 162 | 281.5 at 10 yr<br>119.1 at 50 yr |

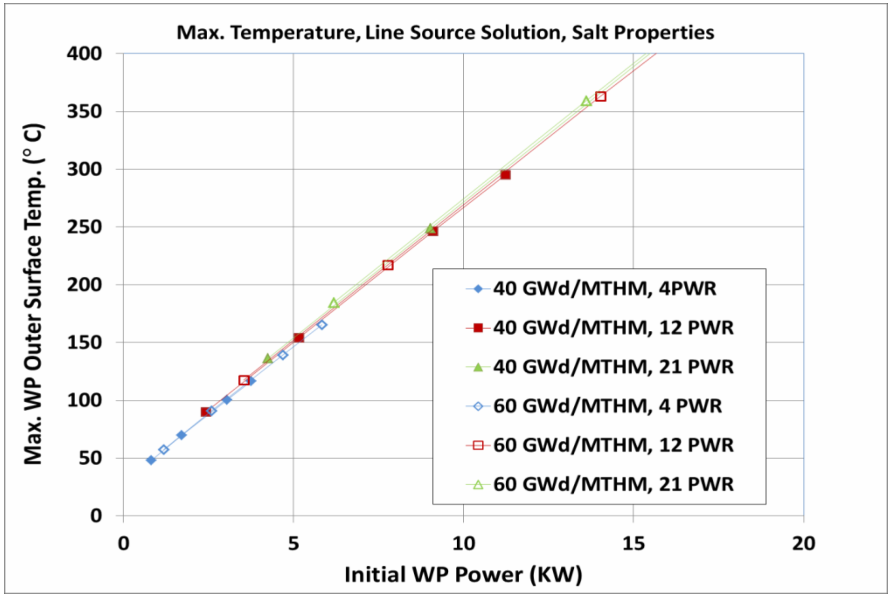
# FEM Results for Generic Salt Repository

## Correlation of Maximum Salt Temperature vs. Initial Heat Output (all package sizes, ages, burnup)




<< FEM Results Summary (GSR without ventilation)

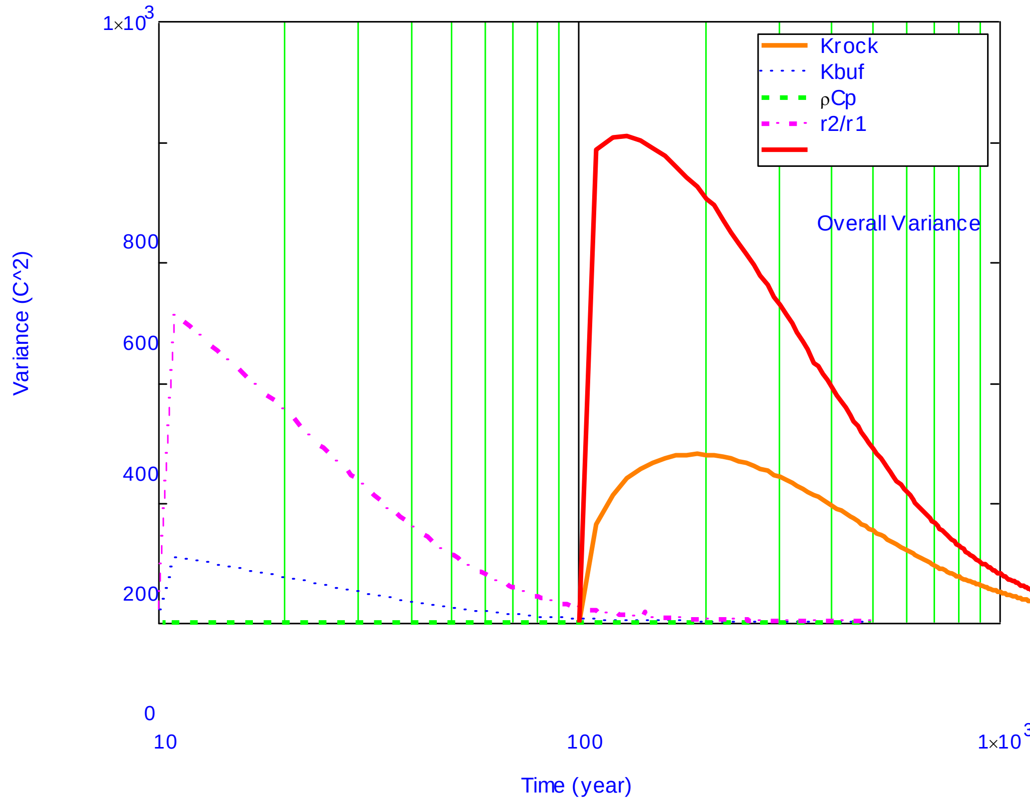
Semi-Analytical Approximation >>
(GSR without ventilation)



Used Fuel Disposition

# Thermal Analysis Parameter Uncertainty

## Combine functional dependence for temperature, with *a priori* variance estimates for constituent parameters




### *Model*

$$T(t) = T_{amb} + \frac{Q(t)}{2\pi K_{buf}} \ln\left(\frac{r_2}{r_1}\right) + \int_0^t \frac{Q(\tau)}{4\pi K_{rock}(t-\tau)} e^{\frac{-r_2^2 \rho C_p}{4K_{rock}(t-\tau)}} d\tau$$

### *Composite Variance*

$$Var\{T(t)\} = \sum_{i=1}^{n} \left(\frac{\partial T}{\partial z_i}\right)^2 Var\{z_i\}$$

### *Analytical Partial*

$$\frac{d}{dKrock} T(t) = \int_0^t \frac{e^{\frac{\rho Cp \cdot (r_2)^2}{4 \cdot Krock \cdot (\tau - t)}} \cdot Q(\tau)}{4 \cdot \pi \cdot Krock^2 \cdot (\tau - t)} + \frac{\rho Cp \cdot (r_2)^2 \cdot e^{\frac{\rho Cp \cdot (r_2)^2}{4 \cdot Krock \cdot (\tau - t)}} \cdot Q(\tau)}{16 \cdot \pi \cdot Krock^3 \cdot (\tau - t)^2} \, d\tau$$

*Contributions to Overall Variance of Temperature at the Waste Package Surface, from Parameters ($K_{rock}$, $K_{buf}$, $\rho C_p$, and $r_2/r_1$) for the Crystalline Rock SNF Disposal Reference Case*

For the case of crystalline host rock, 4-PWR waste packages (0.66 m diameter), 0.35 m buffer thickness, and SNF with 40 GW-d/MT burnup (10 yr out-of-reactor). For buffer thermal conductivity the average of dry and hydrated values was used.

## Used

# Refafence Open Mode Concept Specifics

## Dis nnsitinn

| Media/Concept>>> | [illegible] | [illegible] (alluvium) | [illegible] |
|---|---|---|---|
| Repository depth | -500m | 200 to 300m | 300 to 500 m |
| Hydrologic setting | Saturated | Unsaturated | Saturated |
| Ground support material | Rockbolts, wire cloth & shotcrete | Rockbolts, wire cloth & shotcrete | Rockbolts |
| Seals and plugs | Emplacement drift plugs and seals Shaft & ramp plugs and seals | Shaft & ramp plugs and seals | Shaft & ramp plugs and seals |
| Normalized Areal Loading (GWe-yr/acre) | 1 to 10 | 1 to 10 | 1 to 10 |
| **SNF Emplacement Mode** | Horizontal in-drift emplacement | Horizontal in-drift emplacement | Horizontal emplacement in alcoves |
| WP configuration | Up to 32 PWR | Up to 32 PWR | Up to 32 PWR |
| Overpack material | Steel [8] | Corrosion resistant (e.g., outer layer of nickel based alloy) | Steel [8] |
| Package dimensions | S2 m D x 5 m L | S2 m D x 5 m L (typ.) | S2 m D x 5 m L |
| Drift/borehole dia. | 4 m (drifts) | 4 m (drifts) | 5 m W x 3m H (nominal; alcoves) 3.75 m dia. (nominal; ventilation) |
| Drift/borehole spacing | 20 m (drifts) 10 m (packages) | 20 m (drifts) 10 m (packages) | 40 m (drifts); 20 m (alcoves) Result: packages on 20-meter grid; ventilation drifts centered between access drifts |
| Borehole liner material | NA | NA | NA |
| Buffer material | NA | NA | NA |
| Backfill material | No backfill | Crushed clay/shale with swelling clay added | Crushed salt |
| Line or point loadinQ | Point | Point | Point |

# History of Alluvium in Repository Science

- **First proposed in the 1957 NAS Report**
- **Championed by Winograd and others**
- **Used for Nuclear weapons testing for over 50 years**
- **Currently being used for disposal of transuranic waste at the Nevada Test Site (NTS) in the Greater Confinement Disposal Boreholes (GCDB)**
  - Performance assessment completed for the GCDB
  - Extensive research on the hydrology and climate of NTS alluvium
  - Robust research on paleo-hydrology and paleo-climate of desert alluvium using environmental tracers in soil profiles

# Alluvium – U1a Tunnel Complex

- Cheap construction
- Long lifetime
- 300 m Depth; Dry

# Alluvium Characteristics (NNSS data as representative)

## Composition

- 20% gravel, 70% sand, 8.5% silt/clay, 2.5% cobbles
- Weathered source rock (e.g., silicic volcanic and carbonate)

## Thermal Conductivity

- Lab measurement on re-compacted sediment 0.5 to 0.8 W/m-K
- From existing geothermal gradient – 1 to 1.2 W/m-K

## Porosity

- 38 to 50%

## Sat. Hydraulic Conductivity

- $5.5 \times 10^{-5}$ to 0.5 m/s

## In situ Saturation

- 9 to 16%

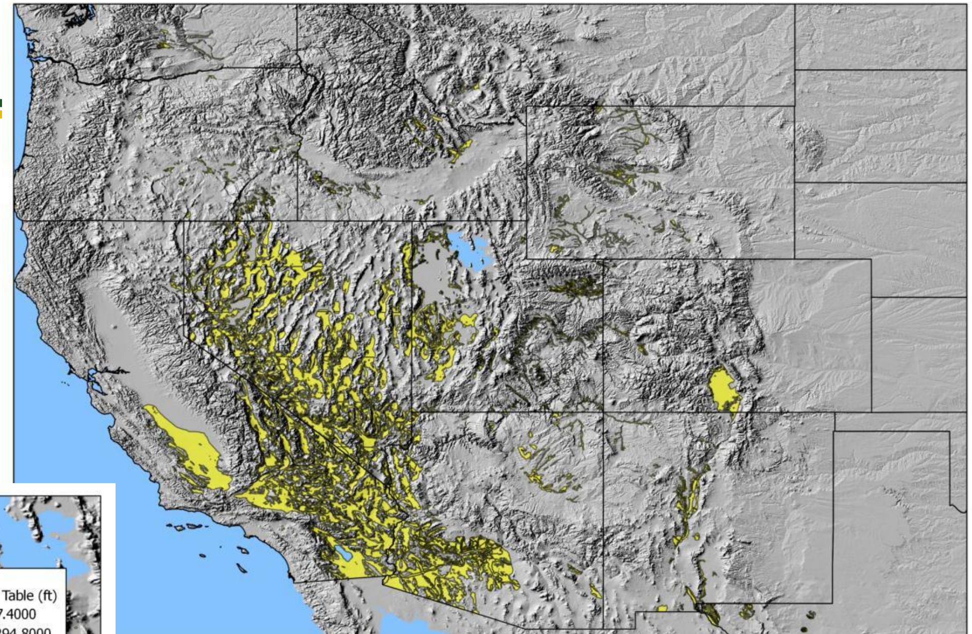
# Alluvium – Hydrologic Summary

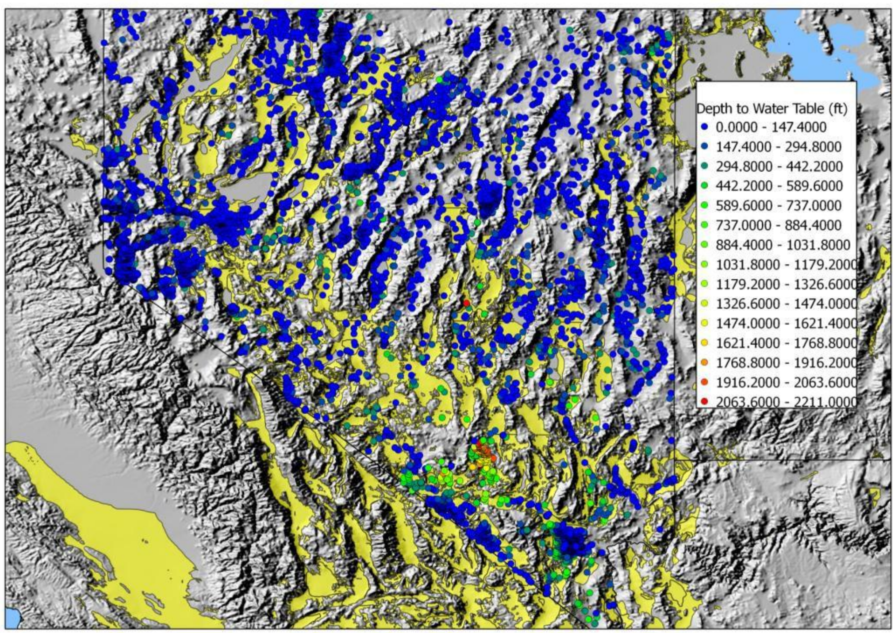
- **Alluvium → very low moisture content and recharge**
  - In some locations and strata, zero recharge for the past 100 ka
  - Low fluid velocities → long residence times (e.g., ~100 ka to water table)
  - Even during sustained pluvial events, recharge rates are limited
  - Nearly ideal porous medium
  - Dilution at the water table
- **$^{36}Cl$ and Cl mass balance from a wide variety of arid sites in Texas, New Mexico and Nevada indicate no modern recharge (Phillips 1994)**
  - Long time scale and uniform hydrologic responses → confidence in paleohydrology/paleoclimate
  - Engineered barriers in a Vadose zone transport time + aquifer transport time
- **Retardation will only slow things down**
  - Large sorption capacity of alluvium (e.g., $R_{Np}$ = 108, after Painter et al 2001)

# Alluvium Beyond the NNSS

- **$^{36}$Cl and Cl mass balance from a wide variety of arid sites in Texas, New Mexico and Nevada all indicate no modern recharge (Phillips 1994)**
  - Natural and bomb-pulse $^{36}$Cl is in the upper 1 meter
  - $Cl^-$ mass balance indicates ~13 ka of chloride accumulation in the upper meter
- **Deep vadose zones are still responding to climatic variations over the last 10 to 100 ka**
  - Very long equilibrium times for vadose zones over 50 m means they might never achieve equilibrium with climatic conditions at the top (Walvoord 2002)
- **Recharge depends on the vegetation type**
  - Pinion-juniper woodlands allow a small amount of recharge
  - Grasslands allow little or no recharge
  - Desert scrub allows zero recharge

# Distribution of Arid Alluvium






# Depth to Water

## (Southern Great Basin)

# 4. Salt "Hybrid" Concept, cont.
# FEM Results Summary: Effect from Forced Ventilation

| Package Type | Fuel Burnup | MTIHM /WP | Age OoR (yr) | Heat Output | Ventilation | – Peak Salt Temperature (°C) |
|---|---|---|---|---|---|---|
| **WASTE PACKAGE SIZE** | | | | | | |
| 4-PWR | 40 GWD MT | 1.88 | 10 | 3.7 kW | No | 100 |
| 4-PWR | 60 GWD MT | 1.88 | 10 | 5.8kW | No | 145 |
| 12-PWR | 40 GWD MT | 5.64 | 10 | 11.2 kW | No | 240 |
| 12-PWR | 60GW D MT | 5.64 | 10 | 17.5 kW | No | 410 |
| 21-PWR | 40GWD MT | 9.87 | 10 | 19.7 kW | No | 450 |
| **AGING STUDY** | | | | | | |
| 4-PWR | 60 GWD MT | 1.88 | 50 | 2.6kW | No | 75 |
| 12-PWR | 40 GWD/MT | 5.64 | 50 | 5.2 kW | No | 115 |
| 12-PWR | 60 GWD MT | 5.64 | 20 | 14.0 kW | No | 315 |
| 12-PWR | 60GW D MT | 5.64 | 50 | 7.8kW | No | 170 |
| 21-PWR | 40 GWD/MT | 9.87 | 20 | 15.9 kW | No | 345 |
| 21-PWR | 40GWD MT | 9.87 | 50 | 9.0kW | No | 190 |
| 21-PWR | 60 GWD/MT | 9.87 | 50 | 13.6 kW | No | 295 |
| 32-PWR | 40 GWD/MT | 15.04 | 50 | 13.7 kW | No | 280 |
| **VENTILATION STUDY (Access Drift Ventilation)** | | | | | | |
| 12-PWR | 40GWD MT | 5.64 | 10 | 11.2 kW | 5 kg/s | 205 |
| 12-PWR | 60 GWD/MT | 5.64 | 10 | 17.5 kW | 5 kg/s | 350 |
| 12-PWR | 60GWD/MT | 5.64 | 20 | 14.0 kW | 5 kg/s | 265 |
| 12-PWR | 60GW D MT | 5.64 | 50 | 7.8kW | 5 kg/s | 145 |
| 21-PWR | 40GWD/MT | 9.87 | 10 | 19.7 kW | 50 kg/s | 345 |
| 21-PWR | 40 GWD/MT | 9.87 | 10 | 19.7 kW | 5 kg/s | 360 |
| 21-PWR | 40 GWD MT | 9.87 | 20 | 15.9 kW | 5 kg/s | 280 |
| 21-PWR | 40GWD/MT | 9.87 | 50 | 9.0kW | 5 kg/s | 150 |
| 21-PWR | 60 GWD MT | 9.87 | 50 | 13.6 kW | 5 kg/s | 235 |

# 4. Salt “Hybrid” Disposal Concept, cont.
## Opening Stability with Pre-Closure Ventilation

- Numercial study with a circular (2-D) opening
- Multimechanism deformation creep model
- Uniformly heated salt
- Access drift closure rates as a function of wall temperature