Evaluation of Thermal Capacity for Spent-Fuel Disposal at Yucca Mountain

W. Zhou, M.J. Apted
Monitor Scientific, LLC
3900 S. Wadsworth Blvd., Suite 555, Denver, CO 80235
USA

J.H. Kessler
Electric Power Research Institute
1300 West W.T. Harris Boulevard, Charlotte, NC 28262
USA

ABSTRACT

This paper describes the model and results for evaluating the spent-fuel disposal capacity for a repository at Yucca Mountain from the thermal and hydrological point of view. Two proposed alternative repository designs are analyzed, both of which would fit into the currently well-characterized site and, therefore, not necessitating any additional site characterization at Yucca Mountain. The two-dimensional TOUGH2 model for coupled thermo-hydrological analysis extends from the surface to the water table, covering all the major and subgroup rock layers of the planned repository, as well as formations above and below the repository horizon. A dual-porosity and dual-permeability approach is used to model coupled heat and mass transfer through fracture formations. The waste package heating and ventilation are all assumed to follow those of the current design. For each alternative design, two bounding cases are simulated using TOUGH2: (1) all waste packages are emplaced at the same time and (2) waste packages are emplaced in stages. The results show that the repository is able to accommodate three times the amount of spent fuel compared to the current design, without extra spatial expansion or exceeding current thermal and hydrological design specifications. Cases with extended ventilation have also been studied.

INTRODUCTION

The current statuary limit for commercial spent nuclear fuel (CSNF) at Yucca Mountain is 63,000 MTHM. To explore actual capacity of the site, EPRI conducted an analysis [1] to evaluate thermal and hydrological response of the disposal system (including waste package, drift, and surrounding host rock) to the enhanced loading of CSNF. The analysis considered two alternative repository concepts as shown in Fig.1, and explained below.

In the multi-level repository design, a level of repository is added above and below the current repository emplacement horizon, respectively. The levels of repository are 30 m apart, basically maintaining the 300-m depth below the ground surface and 300-m above the water table. Drifts in all levels are aligned, with the drift spacing at all levels the same as the current design of 81 m. In this way, the added emplaced waste packages do not increase the plane area of the current repository. All levels of repository are within tsw35 – a unit in Topopah Spring welded tuff hosting the current-design repository.

In the grouped-drift repository design, two additional drifts are added on both sides of the current-design drift. These drifts are 20-m apart. Therefore, there is no change in the drift spacing nor the total repository area.

An earlier scoping analysis [1] used a simplistic approach to evaluate potential thermal and hydrological impact arising from the two repository designs. The two-dimensional model included major formations from the surface to the water table, equivalent continuum approach for fractured media, and a constant infiltration rate of 16 mm/yr. After calibration against published results, the model was used to simulate the system response to the two designs with various combinations of thermal loading and ventilation strategies. The results indicated that the current repository plane can at least accommodate two-times the statuary limit of spent fuel waste [1].

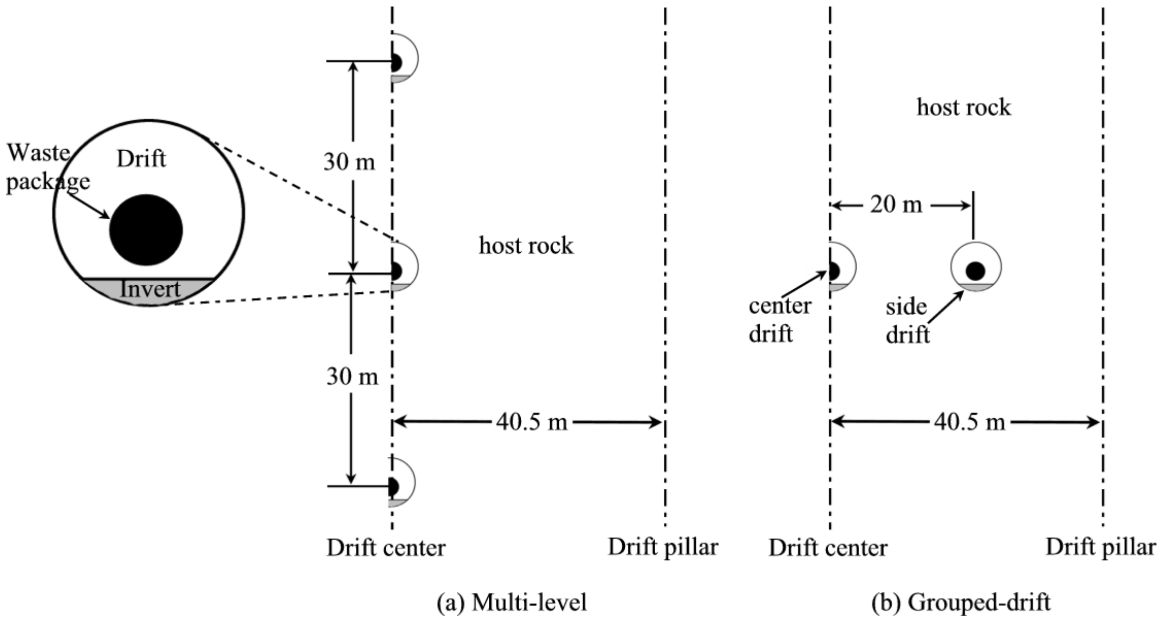


Fig. 1. Illustration of alternative repository designs for studying spent-fuel disposal capacity in Yucca Mountain: (a) multi-level repository design and (b) grouped-drift repository design.

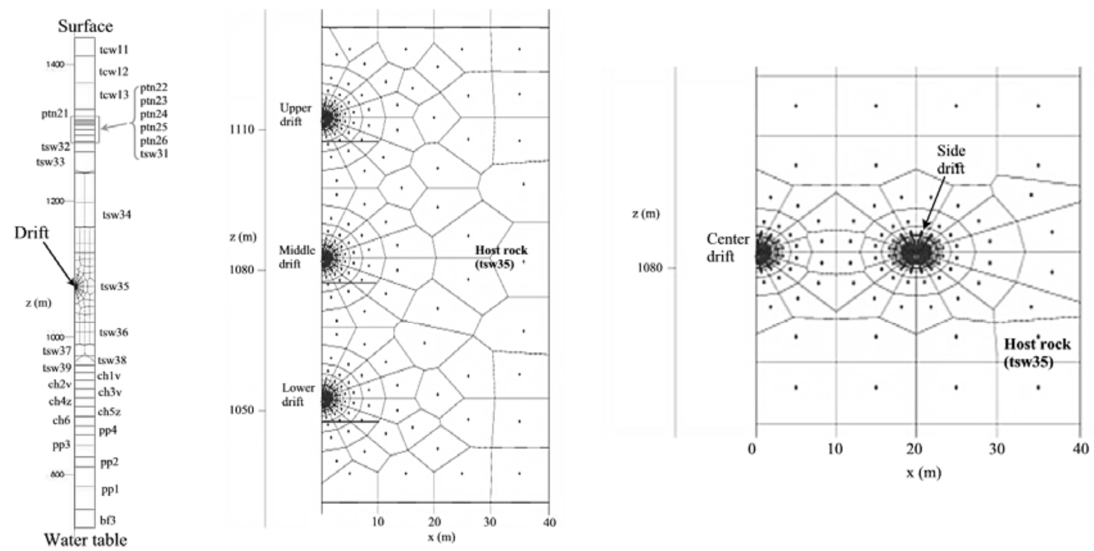
Due to simplified assumptions in that analysis, one uncertainty was identified: when the capacity is increased to three times the current design, the drift pillar (see Fig. 1) was calculated to be temporarily (for a few hundred years) closed to liquid flow due to vaporization. This might, under unlikely circumstances, redirect water liquid through the above-boiling region around drifts and on to waste packages. It was speculated [1] that such an occurrence might be an artifact of the simplified model used; to clarify this issue, an enhanced model incorporating all the unsaturated-zone model layers [2] and using a dual porosity/ dual-permeability capability has been conducted. The model and results will be described below.

MODEL

The new two-dimensional model extends from ground surface to water table, encompassing typical rock formations in the potential site at Yucca Mountain and the repository horizon. The horizontal extent is 40.5 m, half of the drift spacing, covering from the drift center to the centerline between the two drifts (see Fig. 1). The top boundary is assumed to be at constant temperature (16 °C) and pressure (85 kPa) and is open to gas flow. The bottom boundary is assumed to be at 33 °C and 92 kPa. The major changes are:

(1) all the major layers and units, as shown in Fig. 2(a), identified in the previously published work [2], have been included;
(2) dual porosity and dual permeability approach is used to model fractured media;
(3) heat conduction at the bottom boundary is assumed; and
(4) constant infiltration rate of 32 mm/yr, from the latest proposed revision to 10 CFR 63 [3], is assumed.

Parameters include hydrogeological and thermal parameters for all the formations. The values of these parameters and the boundary conditions are taken from [2,4,5,6,7]. Before simulating the alternative repository designs, the same model with the current design was simulated using TOUGH2 [8] for the purpose of parameter calibration and model benchmarking. The simulation used the Baseline heating and ventilation, i.e., the initial heat output is 1.45 kW/m combined with the 50-yr ventilation that removes 86.3% of the total heat [2]. Note that the heat output corresponds to the current high-temperature operation model (HTOM). The ventilation efficiency is modeled by effectively reduced heating rate from waste package [2]. The calibration model adopted the infiltration rate used in [2]. The results were compared with the previous work [2] that used the similar modeling scale, parameters values, and the Baseline heating and ventilation waste package. The comparison showed that a good agreement is achieved between the two models without significant parameter calibration effort.



(a) Total cross section of the model (b) The multi-level model. (c) The grouped-drift model.

Fig. 2. Description of the model for simulating thermal and hydrological response to the alternative repository designs.

The calibrated model was then used to study the alternative designs. The models for each design are illustrated in Fig. 2(b) and (c). Before simulating the model with heating from waste package, the model is simulated without the heating until steady state is reached. The steady-state results (i.e., pressure, temperature, and water saturation distribution) are used as the initial conditions for the simulation with waste heating. We first studied the cases in which all the drifts are loaded with the Baseline waste packages at the same time. Then, we simulated the staged loading in which the drifts are loaded at different times. The results are described in the next section.

Note that the two-dimensional modeling reported here is conservative in terms of meeting thermal and hydrological requirements because it neglects heat and moisture transfer by both conduction and convection in axial direction of the drift. Because the repository edge is cooler, the axial heat transfer and fluid flow may take more heat away from the repository center, as well as allowing condensation and free drainage of water at these cooler edge regions. Therefore, the analysis deems to overestimate the temperature and vaporization.

RESULTS AND DISCUSSIONS

Four cases studied include different loading times to investigate the impact arising from the delayed loading in the added drifts. All the waste package heating and ventilation are of the Baseline, as described above. The total capacity increase in all the cases is three times the current design.

Multi-level Design Results

The two cases studied for the multi-level repository design include:

Case 1: This case assumes that the Baseline waste packages are loaded into all three drifts at the same time.

Case 2: This case assumes that the lower drift is loaded with the waste package at the beginning of repository operation. Fifty years later, the middle drift is loaded. Then, fifty years after loading the middle drift, the upper drift is loaded. Therefore, it is assumed to take 100 years for the three-level repository to be complete loading. The total increase in capacity after 100 years is three-times that of the current design.

The results include temperature and water saturation distributions in the waste package, drift walls, and drift pillars. The key results are summarized in Table I. The waste package temperature distributions are shown in Fig. 3.

Table I. Summary of Multi-level Repository Baseline-loading Results

Results	Level	Case 1 (same-time loading)	Case 2 (staged loading)
Waste package peak temperature	Upper	163 °C at 80 yrs	184 °C at 170 yrs
	Middle	183 °C at 100 yrs	176 °C at 120 yrs
	Lower	183 °C at 120 yrs	158 °C at 220 yrs
Drift wall peak temperature	Upper	146 °C at 90 yrs	164 °C at 170 yrs
	Middle	167 °C at 125 yrs	158 °C at 190 yrs
	Lower	170 °C at 120 yrs	150 °C at 270 yrs
Drift wall fracture dry-out period	Upper	51 – 3,100 yrs	103 – 3,200 yrs
	Middle	51 – 6,100 yrs	101 – 6,100 yrs
	Lower	51 – 7,200 yrs	51 – 7,200 yrs
Drift wall matrix dry-out period	Upper	52 – 1,900 yrs	150 – 2,000 yrs
	Middle	52 – 3,600 yrs	101 – 3,700 yrs
	Lower	52 – 4,700 yrs	52 – 4,800 yrs
Pillar peak temperature	Upper	99 °C at 430 yrs	99 °C at 480 yrs
	Middle	99 °C at 430 yrs	99 °C at 480 yrs
	Lower	99 °C at 430 yrs	99 °C at 480 yrs
Pillar fracture minimum liquid saturation[1]	Upper	0.09	0.09
	Middle	0.09	0.09
	Lower	0.09	0.09
Pillar matrix minimum liquid saturation[2]	Upper	0.94	0.94
	Middle	0.89	0.89
	Lower	0.64	0.72

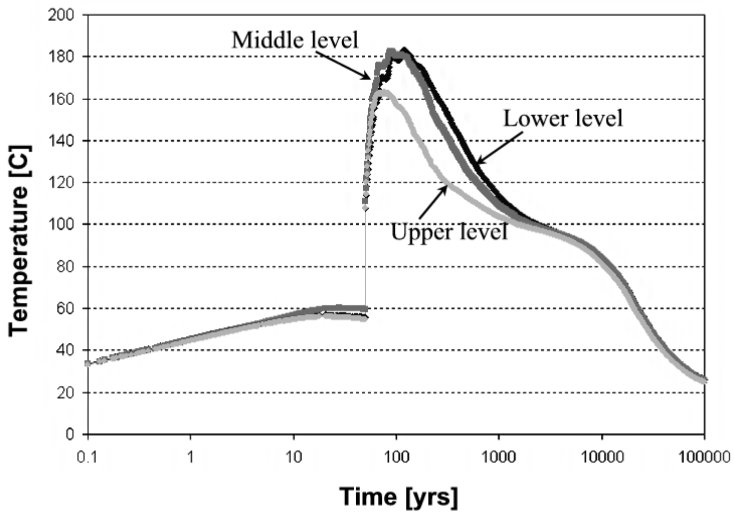
[1]: The initial fracture saturations at pillars are 0.12 at the top, 0.12 at the middle, and 0.11 at the lower levels, respectively. The irreducible water saturation is 0.01.
[2]: The initial matrix saturations at pillars are 0.97 at the top, 0.98 at the middle, and 0.99 at the lower levels, respectively. The irreducible water saturation is 0.12.

It can be seen from Fig.3(a) that there is a sudden increase in waste package temperature at 50 years after emplacement as a result of stop of ventilation. In Fig.3(b), waste packages are loaded at different times and each waste package is vented for 50 years after loading, which results in several peaks at different times. For example, for the waste package loaded into the lowest drift at time zero, termination of ventilation 50 years later gives rise to the first temperature increase. At 100 years when the middle drift is loaded, the heating from the middle drift causes the lower waste package temperature to increase again.

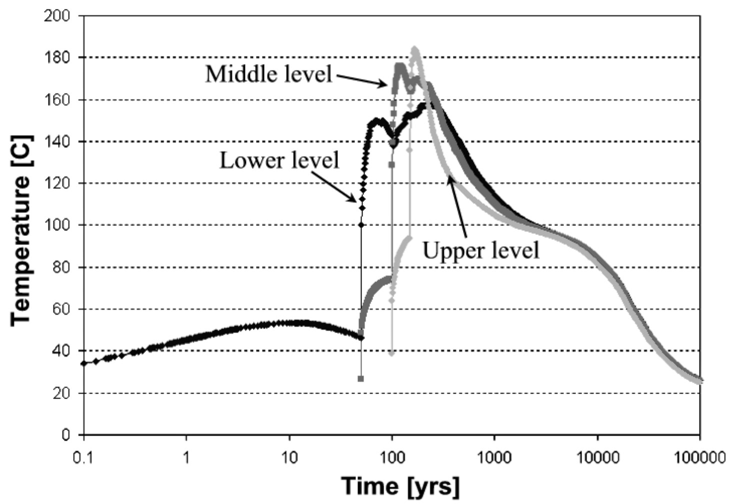
Referring to Fig. 3(a) and Table I, the results show that in Case 1, the waste package temperature in the upper level is similar to that of the single-level repository. The waste packages in the lower levels have higher temperatures due to shielding effect in which liquid flow above the lower drifts are partially blocked by the top drift where complete dry-out occurs. The highest waste package temperature is 183 °C, occurring in the two lower levels. The drift wall temperatures have the similar behavior, with a peak temperature of 170 °C. All these temperatures satisfy the design and performance requirements. Corresponding to the elevated temperatures in the drift walls, there is a dry-out period in all drifts, i.e., all the liquid water in both the fracture and matrix are completely vaporized. The dry-out period is the longest in the lower level due to the shielding effect.

Referring to Table I, in the pillar locations, although the temperature reaches up to 99 °C for short period of time and water saturations decrease in all levels, there is no total dry-out of both fracture and matrix. The maximum drop in water saturation is 25% in the fracture and 35% in the matrix, occurring in the lower level. Several competing mechanisms act in the pillar locations, notably heat conduction and convection, water infiltration, and elevated pore pressure induced by heating that virtually increases local boiling point. The combined dynamic effect results in a small decrease (or sometimes increase) in fracture water saturation. Because the irreducible water saturation of the fracture is assumed to be 0.01, theoretically, saturations greater than this value will keep fracture open to liquid flow. In fact, small change in fracture liquid saturation indicates that the fracture flow ability is not fundamentally altered.

The Case 2 results, shown in Fig. 3(b) and Table I, indicate lowered peak temperatures in the lower level drifts compared to Case 1. The peak temperature in the top level is increased due to the heating effect from earlier-loaded waste packages. At the time of the middle level drift is loaded, the host rock temperatures are lower than 30 °C. For the top level, the host rock temperature is about 40 °C, which is still a feasible temperature for emplacement operation [9]. There are no significant differences in the drift wall temperatures and dry-out periods, compared with Case 1. Furthermore, in the pillar locations, although the peak temperatures go to 99 °C, the matrix and fracture water saturation decrease is less than Case 1. Again, no total dry-out in all pillars is observed and the pillars remain open to liquid flow.



(a) Waste package temperature vs. time for Case 1.



(b) Waste package temperature vs. time for Case 2.

Fig. 3. Results of multi-level design model simulation.

Grouped-drift Design Results

The two cases studied for the grouped-drift design are:

Case 3: This case assumes that the Baseline waste packages are loaded into all three drifts at the same time. This is equivalent to a three-fold increase in total capacity of the current design.

Case 4: In this case, the center drift is loaded with the Baseline waste package at beginning of the repository operation. Fifty years later, the side drifts are built and loaded. At this time, the total capacity in this design alternative is three times the current repository design.

The key results are summarized in Table II. The waste package temperature distributions for the two cases are shown in Fig. 4.

Table II. Summary of Grouped-drift Repository Baseline-loading Results

Results	Drift	Case 3 (same-time loading)	Case 4 (staged loading)
Waste package peak temperature	Center	191 °C at 80 yrs	171 °C at 180 yrs
	Side	179 °C at 80 yrs	191 °C at 120 yrs
Drift wall peak temperature	Center	174 °C at 80 yrs	161 °C at 180 yrs
	Side	162 °C at 90 yrs	171 °C at 125 yrs
Drift wall fracture dry-out period	Center	51 – 2,200 yrs	51 – 2,200 yrs
	Side	51 – 2,300 yrs	100 – 3,000 yrs
Drift wall matrix dry-out period	Center	52 – 1,400 yrs	53 – 1,400 yrs
	Side	52 – 1,600 yrs	100 – 1,700 yrs
Pillar peak temperature		100 °C (400 – 420 yrs)	100 °C (440 – 460 yrs)
Pillar fracture minimum liquid saturation[1]		0.09	0.05
Pillar matrix minimum liquid saturation[2]		0.60	0.55

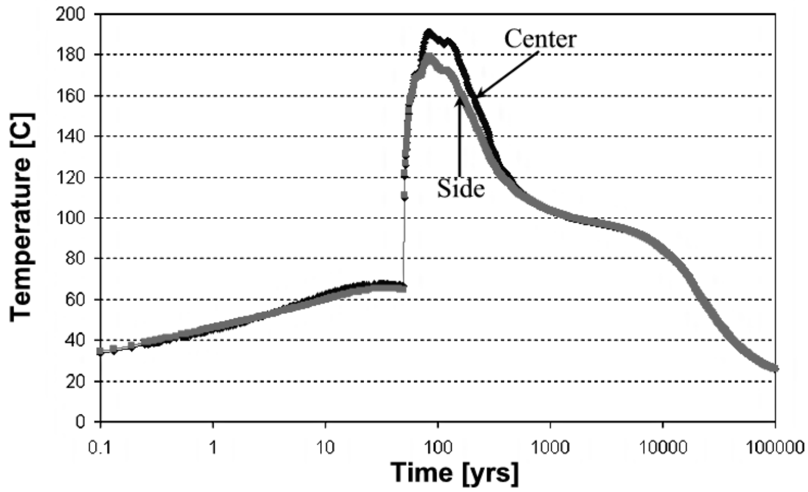
[1]: The initial pillar fracture saturation is 0.12. The irreducible water saturation is 0.01.
[2]: The initial pillar matrix saturation is 0.98. The irreducible water saturation is 0.12.

In Case 3, as shown in both Fig. 4(a) and Table II, the waste package in the center drift has a higher temperature compared to the single-drift (current) design due to the block of heat transfer as well as heating by the presence of the waste package in the side drift. The maximum temperatures are 191 °C at the waste package and 174 °C on the drift wall. In Case 4, it can be seen from Fig. 4(b) and Table II that with a staged loading plan, the waste package in the side drift has a higher temperature because by the time the side drift is loaded, the host rock is slightly heated up (~30 °C) by the center waste packages. All these temperatures, however, do not violate thermal requirements.

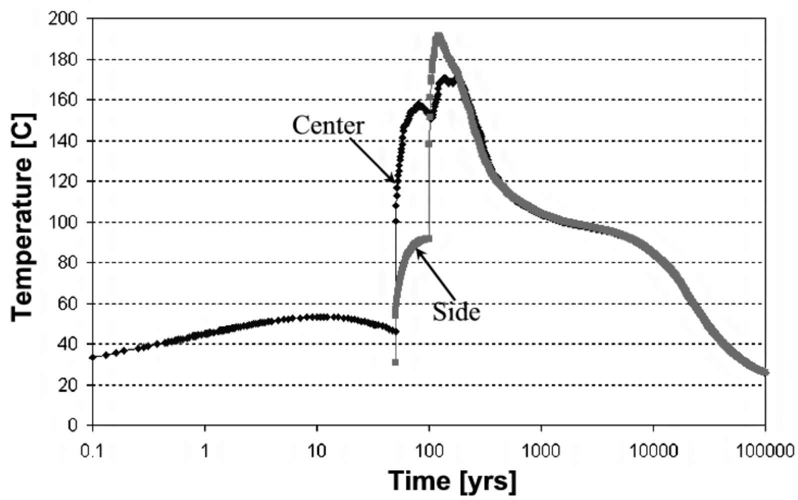
Similar to what has been observed in the multi-level design results, although the pillar temperature rises to almost 100 °C for several decades, there is no complete loss of water liquid in both matrix and fracture at the pillar location. This means that the pillars remain open to water flow. Comparing Cases 1 and 2, there is a greater loss in water saturation in Cases 3 and 4 due to enhanced vaporization because the heat source is closer to the pillar. The loss, nevertheless, is not great enough (i.e., the minimum fracture water saturation is greater than the irreducible saturation) to completely shut down pillar to liquid flow. To ensure enough "safety margin", however, the grouped-drift design should consider longer ventilation strategies, which is the focus of next-step investigation.

These results show that in both cases, the alternative designs comply with thermal and hydrological requirements.

The discrepancy between the current and previous modeling results can be attributed to more realistic approach to modeling fractured media and more comprehensive hydrogeological profile across the mountain. For example, the equivalent continuum permeability of the repository used in the previous scoping analysis was derived by averaging all the units in one geological layer, which is higher by two orders of magnitude than the tsw35 fracture permeability used by the current and many other previous studies (e.g., [2]). In addition, a higher infiltration rate value adopted in the current study compared to the previous scoping analysis.



(a) Waste package temperature vs. time for Case 3.



(b) Waste package temperature vs. time for Case 4.

Fig. 4. Results of grouped-drift design model simulation.

CONCLUSIONS

A two-dimensional, dual-porosity and dual-permeability model is used to study the thermal and hydrological impact in two alternative repository designs. Both designs add two additional systems of drifts within the current repository footprint, basically tripling the amount of spent fuel emplaced within the currently well-characterized Yucca Mountain area, which is equivalent to 189,000 MTHM. This analysis assumed that all drifts are loaded with waste packages that have the same drift spacing, heat generation rate and ventilation duration/efficiency as the current design. The analysis looked at the effect of different loading times in the different drifts. Overall, the maximum temperature on waste package is 191 °C. The maximum host rock temperature is 174 °C. No complete dry-out in the drift pillars is predicted for all the sensitivity cases studied. These results confirm earlier, more simplified calculations [1] that show that both design alternatives satisfy current thermal and hydrological requirements. Because the two-dimensional aspect of the model neglects axial heat transfer, these results are conservative with respect to peak temperature and vaporization, and thus provide high confidence that these design alternatives can readily accommodate significantly more commercial spent nuclear fuel for disposal at Yucca Mountain.

REFERENCES

1. EPRI, "Room at the Mountain: Analysis of Maximum Disposal Capacity for Commercial Spent Nuclear Fuel in a Yucca Mountain Repository," TR-1013523, Electric Power Research Institute, Palo Alto, California, USA.
2. BSC 2005, Drift-Scale THC Seepage Model, MDL-NBS-HS-000001 REV4, Bechtel SAIC Company, LLC, Las Vegas, Nevada, USA.
3. NRC, Proposed Rule; 10 CFR Part 63: "Implementation of a Dose Standard after 10,000 years", Nuclear Regulatory Commission, Washington, D.C., SECY-05-0144, 2005.
4. BSC 2004, Calibrated Properties Model, MDL-NBS-HS-000003, REV02, Bechtel SAIC Company, LLC, Las Vegas, Nevada, USA.
5. BSC 2003a, Drift-Scale Coupled Processes (DST and THC Seepage) Models, MDL-NBS-HS-000001, REV02, Bechtel SAIC Company, LLC, Las Vegas, Nevada, USA.
6. BSC 2003b, Analysis of Hydrologic Properties Data, MDL-NBS-HS-000014 REV00, Bechtel SAIC Company, LLC, Las Vegas, Nevada, USA.
7. BSC 2000, Calibrated Properties Model, MDL-NBS-HS-000003, REV00, Bechtel SAIC Company, LLC, Las Vegas, Nevada, USA.
8. Pruess, K., C. Oldenburg, and G. Moridis, TOUGH2 User's Guide, Version 2.0, LBNL-43134, Earth Science Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA.
9. C. Fairhurst, 2006, personnal communication.