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TEMPERATURE AND MOISTURE CONTROL USING PRE-CLOSURE VENTILATION

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INTRODUCTION

Pre-closure ventilation has the potential to enhance repository performance in four ways. It can (1) reduce peak and average near-field temperatures due to sensible and latent heat removal, (2) reduce temperature variations between hot and cold spots along emplacement drifts, (3) reduce relative humidity around the waste packages (WPs) due to air dilution and rock dryout, and (4) delay the return of water to the near-field due to reduced rock moisture content.

This paper analyzes the results of ventilation studies conducted by the University of Nevada for the CRWMS M&O Contractor^{1,2} and the Nuclear Waste Technical Review Board³. Numerical simulation results^{1,2} were used as input to a larger CRWMS M&O Report⁴.

PRE-CLOSURE VENTILATION CALCULATIONS

The model repository contains 83 metric tons of uranium (MTU) per acre, with identical waste packages (WPs) containing 26-year-old spent nuclear fuel. The 1150 m long emplacement drifts were 5 m in diameter, with 22.5 m spacing. Center-to-center spacing of the 5.3-m long WPs along each drift was 16 m, leaving a gap of 10.7 m between the ends of the WPs. At each drift entrance, 26°C air with 30% relative humidity was assumed. The results presented here are based on 600-m drift length because, in the current reference design, the ventilation air enters the two drift ends and exits at the drift mid-length, through a shaft to an exhaust drift below the repository horizon.

The Mackay School of Mines ventilation simulation model, MULTIFLUX, was coupled to the NUFT (Nonisothermal Unsaturated-Saturated Flow and Transport) code which was developed by Lawrence Livermore National Laboratory to model hydrothermal processes in the rock mass. NUFT and MULTIFLUX are fully coupled in two dimensions and partially coupled in the third (axial) dimension. 2-D NUFT runs are used to solve the heat and mass transfer in the rock, using the equivalent continuum method, for each axial location in one section of the drift. MULTIFLUX is then run to solve the heat transfer and ventilation flow within that section of the drift, and the process is repeated until the drift wall heat flux and temperatures match at selected axial nodes. Then, the exit air temperature and humidity from this section of the drift provide the inlet conditions for the next section of the drift. The process is repeated for successive drift sections until temperature, saturation, and humidity values have been calculated for the entire rock mass and the complete drift. Finally, the time is incremented and the procedure is repeated, beginning with the first drift section.

Hydrologic and thermal properties for the rock units included in the model were obtained from the YMP 1996 reference database. The coupled NUFT/MULTIFLUX code was used to calculate temperature and humidity distribution in the air and the rock wall around the hottest emplacement drifts, several drifts from the repository edges. Approximately 500 nodes were used for spatial discretization. Three drift ventilation air quantities were used: 10, 1, and 0.1 m³/s (termed high, medium and low elsewhere in this paper). A pre-closure time period of 100 years was assumed.

RESULTS

Drift wall temperature envelopes are shown in Figure 1 for 10 m³/s and 1 m³/s, at the times of maximum temperatures and at 100 yrs. The oscillation in each envelope shows the variation along the drift, with locally higher temperatures near the WP mid-lengths and lower temperatures near the middle of the gaps between WPs.

For high ventilation, the maximum rock temperature of 50°C is reached in ten years at the mid-drift-length (approximately 600 m from either end); the nearby gap temperature is about 7°C lower. For medium ventilation, the maximum temperature of 135°C is reached in 20 years, and the temperature in the nearby gap is about 30°C lower. For low ventilation (not shown in Figure 1), the maximum temperature of 177°C is reached in 100 years, and the nearby gap temperature is about 15°C lower.

The moisture flux removed by the ventilation air is shown in Figure 2 for the three ventilation rates. Percolation is also shown, assuming that either an average percolation flux of 10 mm/yr from mid-pillar to mid-pillar is focused to the drift (curve a) or that the same flux is uniformly distributed over the repository surface area without focusing (curve e).

CONCLUSIONS AND DISCUSSION

The conclusions presented below should be regarded as examples of how modeling can be used to help decide whether or not to ventilate emplacement drifts during the operating phase of the potential Yucca Mountain Repository. *They are not recommendations, because the model has not been calibrated to field data.* Future work to analyze ambient ventilation data obtained after completion of the main loop of the ESF, along with analyses of thermohydrological response of heater tests, may lead to different results.

Wang et al. presented⁵ a preliminary analysis of data collected in the ESF during the construction phase, including ventilation rates, temperatures, and relative humidity measurements at different locations. These data indicate that the evaporation flux ranged from 100 to 300 mm/yr. over a six-month period, based upon the total drift wall and invert area of 23.7 m² per m of tunnel length. There was no clear tendency for the flux to decrease over time. The ventilation rate was highly variable, but averaged around 45 m³/sec. This study does not necessarily contradict the model results presented here, because the ESF was at ambient rather than elevated temperature, and the use of large amounts of water in construction may have produced apparent evaporation fluxes much larger than can be sustained by the rock under stable

conditions. Measurements have continued since the completion of the main ESF loop, and analyses of these more recent data, along with the large block, single heater, and drift scale tests, would provide a much-needed check on the parameter values needed to use these models for making design and operating decisions.

The model results described below predict much lower evaporation fluxes at ventilation rates ranging from 0.1 to 10 m³/sec. Danko³ reported calculations with the same model, using a ventilation rate of 30 m³/sec in the ESF under ambient conditions, which gave an evaporation flux of 10 mm/yr. This value is about an order of magnitude lower than the evaporation rate measured in the ESF during the construction phase.

Over the first 10 years, the highest evaporation flux predicted by the model averages about 25 mm/yr., based on a drift diameter of 5 m, at a ventilation rate of 1 m³/sec. In other words, observed data at a nominal rock temperature of 25 °C are consistent with an evaporation flux about an order of magnitude higher than the highest of the results discussed below. A model sensitivity study presented⁵ by Wang et al. shows that the evaporation flux is very sensitive to capillary properties of the fractured rock mass surrounding the drifts and to parameters controlling vapor phase transport toward the drift. This is reasonable, because these parameters will control the rate of transport of water to the evaporation front, as well as the location of the front relative to the drift wall. Until rock properties are calibrated against field data, model predictions should be regarded as reasonable speculations.

Subject to the caveats implied in the preceding paragraphs, this model study supports the following conclusions:

1. A high pre-closure ventilation rate of 10 m³/s maintains the drifts below 50°C, which is within the operational capabilities of modern mining equipment. With mobile radiation shielding, personnel could conduct locally controlled operations such as contact maintenance, WP inspection, and (if appropriate) WP retrieval.
2. For a medium ventilation rate (1 m³/s), the maximum air temperature remains below 120°C. The pillar area is dominantly sub-boiling, allowing for efficient shedding of mobilized water through the pillars. This ventilation rate could potentially be supplied through the natural buoyancy pressure difference, using the waste decay heat to power air movement^{6,7}. Such a design would be intrinsically reliable as long as the underground structure is stable.
3. The current reference design uses a low ventilation rate of 0.1 m³/s, chosen to force flow away from occupied areas toward sensors and HEPA filters, in case of juvenile WP failures. Drift temperatures are substantially above boiling, narrowing or possibly eliminating (depending on the local percolation flux) the portion of the pillars that are available for efficient shedding of mobilized water. A low ventilation flow does not remove much heat because the air heat capacity is not capable of removing sensible heat beyond 400 m of drift at early times and 100 m of drift at later times. Beyond these locations, ventilation is limited to smoothing the longitudinal temperature variation, without affecting the average heat balance of the

drift. Substantial dryout of the near-field can occur, but its extent and duration depend on the thermal-hydrologic properties of the nearby stratigraphic sub-units.

4. For each ventilation case, the moisture balances calculated with the coupled NUFT_MULTIFLUX code, shown as curves B, C, and D in Figure 2, include ambient and mobilized moisture removed by ventilation, but do not include additional contributions due to focusing of ambient and mobilized percolation.
5. For a high ventilation rate, moisture removal by ventilation (curve b) is limited because below-boiling temperatures do not result in the mobilization of much pore water. For 90 years, a $10 \text{ m}^3/\text{s}$ ventilation rate is capable of removing unfocused ambient percolation (curve e) from the drift vicinity. In contrast, focused percolation (curve a) may deliver a considerably higher water flux than the calculated ventilation moisture removal. The calculation removed water from the drift wall assuming a uniform equivalent continuum permeability in the rock. In the calculation (without focused flow), the drift surface remained dry, and the relative humidity in the drift was below 30%. Focused flow would make more water available for removal by ventilation; hence, Curve b in Figure 2 would increase in a dual-continuum or discrete fracture calculation of the thermal-hydrology in the rock. Additional calculations are required to determine if the ventilation system can vaporize focused percolation (ambient or mobilized) quickly enough to prevent pre-closure seeps. Preliminary calculations show that the moisture transfer capacity of air from the drift walls is a few orders of magnitude higher than the average moisture transport through the rock. Also, since the pillars will be sub-boiling, shedding will be facilitated, minimizing focusing.
6. For a medium ventilation rate, moisture removal (curve c) is greater than for the previous case, because more water is mobilized and available for removal at higher temperatures. Ventilation moisture removal is always higher than unfocused ambient percolation (curve e) and exceeds focused percolation (curve a) for 40 years. Beyond this period, additional calculations are required to determine if ventilation can prevent seeps. Because much of the pillar is sub-boiling, shedding through the pillars will likely limit focusing. In the present calculation without focused percolation, the relative humidity remained below 6%.
7. For a low ventilation rate, high temperatures and near-field dryout result in moisture removal (curve d) lower than for a medium ventilation rate, but much greater than for a high ventilation rate. Low ventilation can easily cope with unfocused ambient percolation (curve e). For focused percolation flux, beyond 30 yrs, additional calculations are required to determine if ventilation can prevent seeps. Because much of the pillar reaches boiling temperatures, refluxing and focusing of percolation is a more likely possibility than for the other ventilation rates.
8. Future studies with the coupled NUFT-MULTIFLUX code of heater test results and ESF moisture movement data could provide additional opportunities for model and parameter validation, and may change the predicted optimum ventilation rate.

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Figure 1. Drift wall temperatures along the drift length, for 10 and 1 m³/s. Peak temperatures and 100 year temperatures are shown. The envelopes span the rock temperatures near WPs and near gaps.

Figure 2. Moisture balance. The drift-length-averaged moisture removed by 10, 1, and 0.1 m³/s ventilation rates (curves b, c, and d) was calculated using equivalent continuum models and thus does not include focused flow contributions. The moisture added by a 10 mm/yr ambient percolation flux, with and without pillar-to-pillar flow focused to the drift, is shown by curves a and e. The moisture mobilized by heat is not shown.

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