Temperature Moderation and Water Removal by Ventilation in a Laboratory-Scale Model of a High Level Waste Repository

S.C. Leppala
Center for Nuclear Waste Regulatory Analyses
6220 Culebra Road
San Antonio, TX 78238-5166 U.S.A.
(210) 522-5077

R.T. Green
Center for Nuclear Waste Regulatory Analyses
6220 Culebra Road
San Antonio, TX 78238-5166 U.S.A.
(210) 522-5305

R.D. Manteufel
The University of Texas at San Antonio
Division of Engineering
6900 North Loop 1604 West
San Antonio, TX 78249-0665
(210) 458-5522

Abstract

Groundwater removal and temperature moderation by ventilation at a proposed high-level nuclear waste (HLW) repository were investigated using a series of laboratory experiments and scaling analysis. The laboratory model was designed to be representative of the thermohydrologic environment at the proposed HLW repository at Yucca Mountain, Nevada. The study was conducted to evaluate the effects of ventilation on heat and mass transport around and within a laboratory-scale drift containing an electric heat source. Moisture removal was observed to be linearly related to and dominated by ventilation flow rate and relatively insensitive to drift air temperature. Furthermore, increasing the ventilation flow rate enhanced the relative importance of liquid advection and reduced the significance of vapor diffusion.

Nomenclature

A_c cross-sectional area of drift; $A_c = \pi D_d^2/4$ [m^2]

A_{wall} drift wall surface area; $A_{wall} = \pi D_d L_d$ [m^2]

$c_{p,a}$ specific heat of air [J/(kg-K)]

D_d drift diameter [m]

D_o reference binary diffusion coefficient [= 26×10^{-6} m^2/s]

D_v binary diffusion coefficient [m^2/s]

h_{fg} latent heat of vaporization [J/kg]

j_v'' average flux of water vapor from the medium through the drift wall [kg/m^{2}s]

L_d total length of drift [m]

$\dot{m}_a$ mass flow rate of air [kg/s]

M_a molecular weight of air [= 28.97 kg/kmol]

$\dot{m}_{advect}$ mass flow rate of liquid water from the drift wall by advection [kg/s]

$\dot{m}_{diff}$ mass flow rate of water vapor through the drift wall by diffusion [kg/s]

$\dot{m}_{in}$ mass flow rate of water vapor in air that flows into the drift from the inlet [kg/s]

$\dot{m}_{out}$ mass flow rate of water vapor in air removed from the drift via the outlet [kg/s]

M_v molecular weight of water vapor [= 18.02 kg/kmol]

$\dot{m}_w$ mass removal rate of water vapor [kg/s]

P_a dry air pressure [N/m^2]

P_t total gas pressure [N/m^2]

P_v	vapor pressure [N/m^2]
Q_a	volumetric flow rate of air [m^3/s].
q'_{cond}	average linear heat transfer rate by conduction into the drift wall [W/m]
q'_{heater}	average linear heat transfer rate generated from the heat source [W/m]
q'_l	average linear heat transfer rate by latent heat of vaporization [W/m]
q'_s	average linear heat transfer rate by sensible heating [W/m]
q'_{vent}	average linear heat transfer rate removed by ventilation from the drift via latent and sensible heating [W/m]
r	radial distance into porous medium from the drift wall [m]
R	universal gas constant [= 8,314 J/(kmol-K)]
r_{dry}	depth of penetration of dryout [m]
r_f	radial distance to the dryout front from the center of the drift [m]
r_i	radius of the drift tunnel [m]
t	elapsed time [s]
T_{in}	inlet temperature of drift [K]
T_o	reference temperature [= 298 K]
T_{out}	outlet temperature of drift [K]
U	overall vapor transfer coefficient [kg/m^2s]
V_a	velocity of air [m/s]
$x_v(r=r_f)$	vapor mass fractions at the drying front [-]
$x_v(r=r_i)$	vapor mass fractions at the drift wall [-]

GREEK SYMBOLS

α_{lab}	thermal diffusivity for alumina powder medium used in the experiments [m^2/s]
α_{repos}	thermal diffusivity for the Topopah Spring tuff at YM [m^2/s]
δ_{lab}	thermal penetration depth for the repository laboratory [m]
δ_{repos}	thermal penetration depth for the repository [m]
Δm	water removed from the drift [g]
η	advective enhancement factor [-]
ω_{in} , ω_{out}	humidity ratio defined as the ratio of the mass of water vapor in air to mass of dry air at the inlet and outlet of the drift, respectively [g/kg].
ϕ	porosity of the medium [-]
ϱ_a	partial density of air [kg/m^3]
ϱ_{avg}	average density of humid air [kg/m^3]
$\varrho_{v,sat}$	partial density of saturated water vapor in air [kg/m^3]
ϱ_w	density of liquid water [kg/m^3]
τ	tortuosity [-]
θ	initial moisture content defined as the ratio of volume of water to the total volume of the medium [-]

SUBSCRIPTS

a	air	l	latent heating
advect	advection in the liquid phase	lab	laboratory
c	cross-sectional	out	outlet of drift
cond	conduction	repos	repository

d	drift	s	sensible heating
diff	diffusion in the vapor phase	t	total
dry	dryout of the medium	v	vapor
f	at the dryout front	vent	ventilation
heater	electric resistance heater	v,sat	saturated water vapor
i	at the drift wall	w	water in liquid phase
in	inlet of drift	wall	drift wall

INTRODUCTION

Yucca Mountain (YM), Nevada, is the proposed site for geologic disposal of high-level nuclear waste (HLW) in the United States. The US Department of Energy (DOE) is responsible for characterizing the geologic site and designing the repository. Critical to meeting these responsibilities is the need to understand the thermal and hydrologic processes at the YM site resulting from the effect of heat-generating waste packages (WPs) on the repository environment. WP performance, in terms of canister degradation, will be affected by the thermohydrologic processes that exist at the repository. The DOE is currently analyzing the effects of repository engineering designs on thermohydrologic processes for the YM site [1–3]. Quantitative predictions of temperature and groundwater flow are used to assess the ability of the site and engineered system to isolate HLW for long periods of time such that regulatory objectives established by the Nuclear Regulatory Commission (NRC) and the US Environmental Protection Agency (EPA) are met [4].

The repository is to be located approximately 300 m below the ground surface in the Topopah Spring formation, a fractured welded tuff with low matrix permeability. The thermal load of the repository remains a design variable and will be a function of the WP spacing, drift spacing, and age of the spent fuel and defense waste. The current repository design provides for an extended operational period (i.e., 100 yr) to monitor emplaced HLW before permanent enclosure. Ventilation may be used during this period to remove water from the open emplacement drifts and to lower temperatures. Lower temperatures could provide workable conditions for maintenance activities during the emplacement and monitoring periods [5]. More importantly, maintaining a dry environment by ventilation throughout the repository could increase the time before the WPs encounter water, delay corrosion processes, and thereby increase the lifetime of the WPs to contain waste.

The processes that control mass and energy transport at below boiling temperatures are water removal by advection and diffusion, as well as temperature reduction by removal of latent and sensible heat. Mass and energy transport processes for above-boiling temperatures associated with the emplacement of heat-generating waste are boiling and condensation, capillary adsorption and vapor pressure lowering, and thermal buoyancy-driven vapor flow [6]. A laboratory-scale ventilation experiment and related scaling analyses were evaluated in this investigation to assess the processes that will control groundwater removal and temperature reduction by ventilation at the proposed repository.

BACKGROUND

Previous studies that investigated the effects of ventilation on water removal and temperature moderation on repository performance were mostly based on conceptual models using numerical methods [5, 7–13]. Hopkins et al. [7] assumed that water removal is isothermal, and advection dominant, and they neglected the effects of vapor diffusion. The assumption by Hopkins et al. [7] of isothermal water removal tends to oversimplify repository conditions, thus introducing uncertainties about generating the significance of water transport mechanisms. Manteufel et al. [12] assumed groundwater removal to be vapor diffusion controlled. However, by neglecting gas advection, a large fraction of the water vapor that may flow to regions above the repository and eventually condense therein is ignored. This upward flow of water vapor could be important because temporary "perched" zones of groundwater may form, thereby leading to the increased potential of downward groundwater seepage toward the repository horizon through preferential flow paths [14].

Danko and Mousset-Jones [8, 9] related water removal to a wall wetness ratio, which they defined as the fraction of repository drift wall that is wet. Recent mining and ventilation codes such as CLIMSIM [13], MFIRE [15], and MTECS [10] use the wall wetness ratio or a wetness factor for water-removal predictions. However, this approach is predicated on the assumption that water from the host rock is readily available for removal at the drift wall, a condition that may not represent realistic repository drift wall characteristics. Sandia National Laboratories use the code SAGUARO, which assumes a fixed drift-wall temperature of 25 °C, to simulate ventilation by inducing pressure-driven gas advection from the heated host rock to the cooled drift wall [16]. However, a constant, low drift wall temperature is an inappropiate assumption for the nonisothermal conditions expected at the repository, thus causing water removal calculations to be excessive due to (i) a constant source of water available for vaporization at the drift wall as a result of low drift wall temperature and (ii) a high simulated ventilation flow rate capable of maintaining the assumed drift wall temperature of 25 °C. This experimental study is predicated on the assumption that ventilation will cause drift wall and airway temperatures to be sub-boiling such that water removal from the drift will be controlled by liquid advection and vapor diffusion from the medium to the drift wall and into the drift air.

DEVELOPMENT OF THEORY

Governing equations and constitutive relations were formulated to evaluate the effects of ventilation on heat and mass transfer processes occurring near a heat source emplaced in a drift and surrounded by a nearly saturated porous medium. The development of the governing and constitutive equations was based on the assumption that ventilation will keep drift temperatures below boiling. The affected area around the drift was assumed to have constant and uniform thermal, hydrologic, and physical property values evaluated for sub-boiling temperatures. Newton's law of cooling for heat transfer from the drift wall into the drift air and Fourier's law of heat diffusion for heat transfer occurring from the drift wall into the medium were used as the constitutive equations to evaluate heat transfer. Fick's law of vapor diffusion was used as the constitutive equation to evaluate mass transfer of water vapor from the medium into the drift air.

Heat Transfer

An energy balance for the drift was used to equate the amount of energy generated by the drift heat source to the sum of the heat withdrawn from the drift by ventilation and the amount of heat transferred into the porous medium by conduction.

$$q'_{heater} = q'_{vent} + q'_{cond} \tag{1}$$

The lengths of the drift and heat source are assumed to be sufficiently long such that the effects of heat losses at the ends of the drift are neglected and only the linear rates of heat transfer are included in the energy balance. A schematic of the control volume containing the drift and the primary heat transfer processes incorporated in this analysis is shown in Fig. 1. The schematic consists of a drift tunnel inserted into 80 percent saturated medium and containing an electric resistance rope heater.

The amount of heat removed from the drift wall to the drift air and out of the drift by latent heat of vaporization, q'_l, and sensible heating, q'_s, is approximated (based on thermal properties of air evaluated at an average drift air-temperature) by equations (2)–(3):

$$q'_l \doteq \frac{\dot{m}_w}{L_d} h_{fg} \tag{2}$$

and

$$q'_s \doteq \dot{m}_a c_{p,a} \left[\frac{T_{out} - T_{in}}{L_d}\right] \tag{3}$$

Equation (1) is expressed in terms of heat conduction into the porous medium as follows:

$$q'_{cond} \doteq q'_{heater} - \frac{\dot{m}_a c_{p,a}(T_{out} - T_{in}) + \dot{m}_w h_{fg}}{L_d} \tag{4}$$

Mass Transfer

Governing equations for mass transfer in a nearly saturated (i.e., 80 percent saturated) nonisothermal porous medium are formulated to evaluate the movement of water through the medium to the drift wall by advection and diffusion and out of the drift by ventilation. Ventilation through the drift is assumed to maintain drift wall and airway temperatures below boiling, which determines the relative importance of water transport processes for removing water from a drift. Water transport out of the medium and into the drift is assumed to be dominated by liquid advection driven by the liquid water gradient and vapor diffusion driven by the vapor density gradient generated by the heating and venting processes. Liquid diffusion is considered negligible because liquid water is the only species present in the medium, and vapor advection is considered negligible because sub-boiling temperature results in small vapor pressure gradients. Water removal is predicated on the assumption that rates of water vapor diffusion and liquid advection through the drift wall into the drift and water vapor advection through the drift air and out of the drift are uniform for the entire drift. A schematic of the control volume (i.e., the drift and that portion of the porous medium affected by the heating and venting) containing the drift and the primary water transfer processes considered in this analysis is shown as Fig. 2.

The amount of water removed from the drift via the outlet by heating and venting is equated to the sum of the liquid water advected into the drift through the drift wall, the water vapor diffused into the drift through the drift wall, and the water vapor transported into the inlet of the drift by ventilation.

$$\dot{m}_{out} = \dot{m}_{advect} + \dot{m}_{diff} + \dot{m}_{in} \tag{5}$$

The above terms can be expanded and expressed as follows:

$$\dot{m}_{out} = \dot{m}_a \omega_{out} \tag{6}$$

$$\dot{m}_{in} = \dot{m}_a \omega_{in} \tag{7}$$

$$\dot{m}_{diff} = A_{wall}\, j_v'' \tag{8}$$

By combining equations (6)–(8) and rearranging equation (5), the mass flow rate of liquid water advected from the medium into the drift can be expressed as

$$\dot{m}_{advect} = \dot{m}_a(\omega_{out} - \omega_{in}) - A_{wall}\, j_v'' \tag{9}$$

Mass Transfer from the Medium to the Drift Air

The mass transfer of water from the medium into the drift air is dependent on the temperature of the drift air and wall. The amount of water available at the drift wall is limited by the rate of transport of water from the medium into the drift. The temperatures of the drift air and the drift wall determine whether the water transport through the medium is by vapor diffusion or liquid advection. Fick's law is used to calculate the flux of water vapor removal through the drift wall by water vapor diffusion:

$$j_v'' = U[x_v(r=r_f) - x_v(r=r_i)] \tag{10}$$

The drying front is defined as the theoretical interface between the completely dried medium and the partially saturated medium with the assumption that liquid water does not replenish the dried medium. However, scoping tests provided evidence that water does replenish the dried medium allowing for water to be available at the drift wall for removal by ventilation. Nevertheless, this assumption should be valid for the first 100 yr (preclosure period) when the repository is vented. The depth of penetration of dryout into the medium from the drift wall is calculated by determining the total volume of dried medium that equates to a specified amount of water, Δm, removed from the medium by heating and venting.

$$r_{dry} = \left[\frac{\Delta m}{\varrho_w \theta \pi L_d} + \left(\frac{D_d}{2}\right)^2\right]^{0.5} - \frac{D_d}{2} \tag{11}$$

where:

$$\Delta m \doteq \int_0^t \dot{m}_a \left(\omega_{out} - \omega_{in}\right) dt \tag{12}$$

The dryout penetration depth is used to calculate the vapor transfer coefficient and determine the distance of the dryout front from the drift wall into the porous medium. The overall vapor transfer coefficient, used to calculate vapor diffusion from the medium into the drift, is defined as [5]

$$U = \frac{\eta \varrho_{avg} \tau \varphi D_v}{\frac{D_d}{2} \ln\left[\frac{2r_{dry} + D_d}{D_d}\right]} \tag{13}$$

The tortuosity of the medium is defined as the ratio of the actual length of a flow channel for a fluid particle to the length of the porous medium sample. The porosity of the medium is defined as the ratio of void volume to total volume [17].

The advective enhancement factor accounts for gas advection induced by water vapor diffusion and is a function of total gas pressure relative to vapor pressure.

$$\eta = \frac{P_t}{P_t - P_v} \tag{14}$$

The binary diffusion coefficient for water vapor diffusing into air is evaluated relative to a reference temperature [18].

$$D_v = D_o \left(\frac{T}{T_o} \right)^{1.5} \tag{15}$$

The air and water vapor densities are calculated using the ideal gas law and the assumption that low drift-air temperatures due to ventilation will cause the partial pressure of air to be significantly higher than the partial pressure of water vapor. This assumption permits the evaluation of water vapor density as an ideal gas. The average density of humid air is defined as the sum of the partial density of air, ϱ_a, and the partial density of saturated water vapor in air, $\varrho_{v,sat}$. The average density is expressed as

$$\varrho_{avg} = \varrho_a + \varrho_{v,sat} \tag{16}$$

or in terms of the ideal gas law

$$\varrho_{avg} = \frac{P_aM_a}{RT} + \frac{P_vM_v}{RT} \tag{17}$$

The mass fraction of water vapor at the drying front for sub-boiling temperatures is the ratio of water vapor density to the average mass density of air-vapor mixture.

$$x_v(r=r_{dry}) = \frac{\varrho_v}{\varrho_a + \varrho_v} \tag{18}$$

With ventilation, the drift saturated water vapor density remains low so that $\varrho_v << \varrho_a$ and the average mass fraction of water vapor in the drift air at the drift wall equals the average between the inlet and outlet humidity ratios.

$$x_v(r=0) \doteq \frac{\omega_{in} + \omega_{out}}{2} \tag{19}$$

Equations (13), (18), and (19) can be combined in Fick's Law [equation (10)] to obtain the flux of water vapor diffusion through the medium to the drift wall.

$$\dot{j}_v^{//} = \frac{\eta\rho_{avg}\tau\varphi D_v}{\frac{D_d}{2}\ln\left[\frac{2r_{dry}+D_d}{D_d}\right]}\left[\frac{\rho_v}{\rho_a+\rho_{v,sat}} - \frac{\omega_{out}+\omega_{in}}{2}\right] \tag{20}$$

Scaling Analysis

A geometric scaling factor relating a laboratory-scale experiment is used to design an experiment representative of the proposed repository at YM. The thermal penetration depth into the drift wall, obtained from the Fourier number, is used to formulate a geometric scaling factor for the design of the laboratory-scale repository model. The thermal penetration depth is an estimate of the distance that heat will propagate through a medium during a specified time. The thermal penetration depth is based on an evolving temperature distribution in a medium subjected to an abrupt temperature change at the boundary [18]. The thermal penetration depths shown as equations (21)–(22) are the repository and laboratory heat penetration radii at 100 yr and 8 hr, respectively, assuming that $\alpha_{repos} = 1 \times 10^{-6}$ m^2/s for the Topopah Spring tuff from the repository horizon at YM [6] and $\alpha_{lab} = 2.2 \times 10^{6}$ m^2/s for an alumina powder medium used in the experiments conducted in this investigation [19–20]. (Note that an 8 hr timeframe was chosen to be the duration of the experiment for convenience.)

$$\frac{\delta_{repos}}{2} = (\alpha_{repos} t)^{0.5} \qquad (\delta_{repos} \sim 120 \text{ m for } t = 100 \text{ yr}) \tag{21}$$

$$\frac{\delta_{lab}}{2} = (\alpha_{lab} t)^{0.5} \qquad (\delta_{lab} \sim 0.5 \text{ m for } t = 8 \text{ hr}) \tag{22}$$

Using the thermal penetration depth for the Topopah Spring tuff and the alumina powder, the geometric scaling factor is calculated as 240 to 1.

EXPERIMENTAL PROCEDURE

A series of laboratory-scale experiments representing the proposed HLW repository at YM was designed using the 240 to 1 geometric scaling factor. Scaling was used to minimize the physical size of the laboratory experiment, while allowing meaningful observation of key physical processes at the laboratory scale. Experiment design dimensions such as drift diameter, drift spacing, drift length, and WP diameter are chosen to be consistent with the 240 to 1 geometric scaling factor. The dimensions of the repository design parameters and the laboratory-scale parameters are summarized in Table 1. Although the rope heater diameter was scaled using the 240 to 1 scaling factor, the heat load used in the laboratory-scale experiment was not. The experiment heat load was selected to provide a heater temperature of 145 °C, representing an average 83 Metric Ton Uranium (MTU) per Acre WP surface temperature.

The conceptual design of the experiments consisted of measuring water and heat removal due to heating and venting in a drift emplaced in a porous medium. An evaluation of the experiments was achieved by measuring temperature, airflow rate, relative humidity (RH), and water removal at a drift emplaced in a laboratory-scale test cell filled with a nearly saturated porous medium. The series of tests consisted of five experiments: one scoping experiment, two preliminary experiments to refine the final test design, and two final quantitative experiments. The scoping experiment and the two preliminary experiments were conducted to refine the experimental design and provide insight for the design of the subsequent final laboratory-scale experiments. Only results from the two final experiments were analyzed to evaluate water removal and temperature conditions from the drift wall and airway at two different ventilation flow rates.

The medium used in the experiments was a mixture of 95 percent alumina powder and 5 percent bentonite by volume. This mixture was selected to provide a medium that exhibited a low permeability and the ability to maintain structural integrity after wetting and heating. A saturation of 80 percent was attained assuming the porosity of the mixture was the same as the measured value of 0.31 for 100 percent alumina powder [19].

Instrumentation

The instrumentation for the experimental test cell was selected to permit monitoring drift wall and air temperatures, suction pressure of the porous medium, RH of the drift air, quantity of water removal from the test cell, and ventilation flow rate. Temperature measurements were recorded using 20 type-T and 10 type-J thermocouples. Nine tensiometers were installed into the test cell to measure the suction pressure of the partially saturated medium to evaluate local saturation changes along the length of the drift. A humidity sensor was installed at the outlet of the drift into a male run-T fitting to capture outlet flow without interference from the ambient air outside of the test cell. The humidity sensor was capable of measuring RH and temperature, from which dewpoint, humidity ratio, and absolute humidity were calculated. The inlet humidity ratio was calculated using RH measurements of the laboratory air measured with an temperature/RH recorder and temperature measured using a thermocouple at the inlet of the drift. Water removal from the test cell was measured using two independent methods: (i) a cantilever with mass loss measured as a function of cantilever displacement and (ii) the combined measurement of the inlet flow rate and the outlet humidity ratio.

Cantilever Mass Measurement

A 30-kg balance scale was placed underneath one end of a 5.4-m long cantilever I-beam equipped with weights at one end of the cantilever to counter the mass of the test cell at the opposite end (Fig. 3). The cantilever was used to measure small quantities of mass change in the much larger test cell. The mass of the test cell was counter balanced such that the scale would carry an initial load between 1 and 3 kg. As water was removed from the test cell, the load on the scale under the opposite end of the beam increased. The mass of water removed from the test cell was calculated to be the difference between final and initial mass readings. The cantilever balance was calibrated in the laboratory and found to be accurate within ± 3 g.

Flow Rate Mass Measurement

The ventilation flow rate was measured using a direct flow meter placed at the inlet of the drift in the test cell. With constant cross-sectional drift area and continuous flow, the volumetric flow rate was assumed to be constant from inlet to outlet. The maximum amount of water that can be carried from the drift by ventilation is equated to the amount of water in a stream of saturated air [21]:

$$\dot{m}_w \doteq V_a\, A_c\, \rho_a \left(\omega_{out} - \omega_{in}\right) \tag{23}$$

Equation (23) can be reduced to

$$\dot{m}_w \doteq Q_a \rho_a (\omega_{out} - \omega_{in}) \tag{24}$$

and

$$\Delta m = Q_a\, \rho_a \sum_{j=1}^{n} \left(\omega_{out} - \omega_{in}\right)_j \Delta t \tag{25}$$

where j = 1 to n is the number of the measurement for the difference in the outlet and inlet humidity ratios for a time interval of Δt for a total of n measurements. Implicit in equation (25) is that both volumetric flow rate and density of air were constant and not dependent with time.

Experimental Design

The experiments were conducted in a $1.2 \times 0.6 \times 0.5$-m test cell filled with the alumina powder/bentonite mixture at a saturation of 80 percent. A 120-volt electric resistance rope heater was inserted into the 5-m long drift to heat the surrounding medium. The drift tunnel consisted of five adjacent 1-m segments connected by C-shaped copper fittings to maintain continuity for ventilation airflow rate. The alumina powder/bentonite mixture was packed into the test cell with care to minimize the formation of preferential flow paths. Each experiment was conducted for 8 hr using constant ventilation volumetric flow rates of 40.0×10^{-5} and 67.0×10^{-5} m^3/s and a rope heater output of 421 W (84.2 W/m).

RESULTS

The two final experiments are referred to as the low-flow rate and high-flow rate experiments. Measured results for suction pressure using the tensiometers were inconclusive for both experiments and were not used in the analysis.

Low Airflow Rate Experiment Results

A total of 346 g of water was removed during the 8-hr period for the low flow rate experiment (Fig. 4). An anomalously large amount of water was removed at the onset of the experiment. After the first 0.5 hr into the experiment, the water removal was observed to be essentially linear.

The outlet air temperature reached 46.0 °C and the RH reached 68.8 percent at the end of the 8-hr experiment (Fig. 5). Within the first 1.5 hr of the experiment the outlet temperature increased from 18.0 to 38.0 °C, while the outlet RH of air rapidly decreased from 100.0 to 59.0 percent. This relationship between decreasing RH and increasing temperature is consistent with a psychometric chart [22]. However, the RH returned to 68.8 percent by the end of the experiment, while outlet air temperature continued to increase from 38.0 to 46.0 °C. The humidity ratio increased from 14.0 g/kg at the start of the experiment to 45.0 g/kg at the end and was observed to be essentially linear after the first 0.5 hr of the experiment (Fig. 6).

After 8 hr, measured drift-wall temperatures varied from 33.8 °C midway along the segment of the drift connected to the inlet of the test cell to 39.6 °C midway along the middle segment of the drift and down to 37.7 °C midway along the segment of the drift connected to the outlet of the test cell (Fig. 7). Similar to the outlet drift-air temperature, drift-wall temperatures measured at the top and center of the drift segments increased precipitously during the first 0.5 hr of the experiment.

After this time, the temperatures increased essentially linearly for the duration of the experiment.

High Airflow Rate Experiment Results

A total of 745 g of water [nearly twice as much as for the low flow rate experiment] was removed during the 8 hr long high flow rate experiment (Fig. 4). Similar to the low flow rate experiment, the removal of water was essentially linear the first 0.5 hr. The outlet air temperature reached 48.0 °C and the RH reached 63.3 percent at 8 hr (Fig. 5). The outlet air temperature and RH observed during the high flow rate experiment closely resembled that observed for the low flow rate experiment. The humidity ratio increased from 10.0 to 46.0 g/kg and was essentially linear after the first 0.5 hr of the experiment (Fig. 6). Drift-wall temperatures varied from 33.3 °C midway along the segment of the drift connected to the inlet of the test cell to 38.7 °C midway along the middle segment of the test cell and down to 35.9 °C midway along the segment of the drift connected to the outlet of the test cell (Fig. 7).

ANALYSIS

The analysis of mass and energy removal was conducted using documented values for the hydrogeologic and physical properties for the alumina/bentonite mixture [19, 23], the thermal properties for air inside the drift evaluated at an average temperature of 40 °C [18, 22], and the laboratory-scale geometric parameters of the drift. These values are summarized in Table 2.

Low Airflow Rate Experiment

The average water removal rate from the test cell for the low flow rate experiment was calculated to be 43.3 g/hr from mass measurements obtained from the cantilever assembly. This removal of water was compared to the water removal rate of 44.3 g/hr approximated using the flow rate mass measurement [using equation (12) for an 8 hr period]. The comparison of water removal from the test cell calculated using the cantilever assembly is compared with the flow rate mass measurement at selected times for the low flow rate experiment in Fig. 8. As illustrated, the mass of water removal calculated using the flow rate mass measurement is consistent with the measurement obtained from the cantilever assembly.

A dryout zone extending 2.6 mm into the medium was calculated [equation (11)] using the 346×10^{-6} m^3 volume of water removed from the medium measured using the cantilever assembly, a 5-m long drift with a 2.1-cm diameter, and an average medium porosity of 0.31. It is assumed that the dryout front is abrupt with no dryout beyond the front and complete dryout behind the front. A dryout zone extending 2.7 mm into the medium was estimated using the approximated 354×10^{-6} m^3 volume of removed water obtained from the flow rate mass measurement.

Calculations of heat conducted into the medium and removed by ventilation were based on conservation of energy [equation (4)] for the drift, with an average drift air humidity ratio of 31.0 g/kg and a temperature increase of 28.0 °C from the inlet of the drift to the outlet of the drift. These calculations demonstrated that approximately 88 percent of the total heat produced by the heater was transferred into the medium by conduction, while ventilation removed 12 percent of the heat from the drift. The contribution to energy removal from the drift by latent heating was 8 percent and by sensible heating was 4 percent.

Fick's law [equation (10)] and laws of conservation of water [equation (9)] for water entering and leaving the drift were used to calculate the amount of water removed from the drift by liquid advection and vapor diffusion. The overall vapor diffusion coefficient was calculated to be 2.97×10^{-3} kg/m^2-s [equation 13] based on an average mass density of the drift air/vapor mixture of 1.10 kg/m^3, a binary diffusion coefficient for water vapor diffusing into air of 2.8×10^{-5} m^2/s, an advective enhancement factor accounting for gas advection induced by vapor diffusion of 1.08 and a dryout length of 2.6 mm. The flux of water vapor diffusion from the drift was then calculated [equation (20)] to be 2.38×10^5 kg/m^2-s for a mass fraction of water vapor at the dryout front of 0.046 and a mass fraction of water vapor in the drift of 0.038. The flux of water vapor by diffusion through the drift wall into the air space and the surface area of the drift wall were used to calculate that the amount of water removed from the medium by vapor diffusion was 224 g. This value was subtracted from the measured mass of water (346 g using the cantilever assembly) removed from the drift by ventilation to obtain the amount of water removed from the medium and through the drift wall by liquid advection to be 122 g. The previous observation indicated that low drift wall and air temperatures, attributed to low flow ventilation, resulted in moisture transport out of the medium to be 65 percent by vapor diffusion and approximately 35 percent by liquid advection.

High Airflow Rate Experiment

Analyses for the high flow rate experiment are the same as those described for the low flow rate experiment. The average water removal rate from the test cell for the 8 hr long high flow rate experiment averaged 93.1 g/hr based on mass measurements obtained from the cantilever assembly. This water removal rate is approximately two times the rate of water removal measured for the low flow rate experiment. The water removal rate of 81.8 g/hr calculated using the flow rate mass measurement is approximately 12 percent less than the measurement obtained from the cantilever assembly. Water removal from the test cell using the cantilever mass measurement is compared to the flow rate mass measurement in Fig. 8. Dryout zones extending 5.5 and 4.9 mm into the medium were calculated using the 745×10^{-6} m^3 of water measured using the cantilever assembly and the 654×10^{-6} m^3 of water calculated from the flow rate mass measurement. The higher ventilation flow rate resulted in approximately twice the dryout depth (i.e., 5.5 mm) as compared to the low flow rate experiment (i.e., 2.6 mm).

Calculations of heat conducted into the medium and removed from the drift by ventilation indicated that approximately 80 percent of the total heat produced by the heater was transferred into the medium by conduction while 20 percent was removed from the drift by ventilation. This difference represents a 67 percent increase (i.e., from 12 to 20 percent) in energy removal for the high flow rate experiment compared to the low flow rate experiment. The contribution to energy removed from the drift by latent heating was 14 percent and by sensible heating was 6 percent in the high flow rate experiment.

Similar average drift-air temperatures observed during both experiments caused the average mass density of the drift air/vapor mixture, the binary diffusion coefficient for water vapor diffusing into air, and the advective enhancement factor accounting for gas advection induced by vapor diffusion to be relatively the same. The overall vapor diffusion coefficient for the high flow rate experiment was calculated to be 1.56×10^{-3} kg/m^2-s. From this value, the flux of water vapor diffusion from the drift was calculated as 1.87×10^{-5} kg/m^2-s for a mass fraction of water vapor at the dryout front of 0.046 and a mass fraction of water vapor at the drift wall of 0.034. The mass fraction of water vapor in the drift was slightly lower due to the higher flow rate of air removing more vapor. The amount of water removed from the drift by vapor diffusion was 178 g. This value was subtracted from the measured mass of water (745 g using the cantilever assembly) removed from the drift to determine that the amount of water removed from the drift by liquid advection was 567 g. This value indicated that the higher ventilation flow rate removed 8 percent more energy from the drift than the low flow rate experiment, causing temperatures to be slightly lower. Moisture transport out of the medium was 76 percent liquid advection dominant, while approximately 24 percent was transported by vapor diffusion.

Repository Predictions

Predictions for water removal from the drift and the dryout depth into the drift wall at the repository for low and high flow rate strategies were based on a 1,200-m long drift with a total drift wall surface area of 18,850 m^2 and a drift diameter of 5 m. The medium at the repository was assumed to be 80 percent saturated, with an effective porosity of 0.12. The mass of water removed from the 1,200-m drift for the low and high flow rate strategies using the values scaled to the cantilever assembly mass measurement was 2.0×10^4 kg and 4.3×10^4 kg, respectively. The water removed from the drift for the low and high flow rate strategies using values scaled to the flow rate mass measurement was 2.0×10^4 kg and 3.7×10^4 kg, respectively. The dryout depth for the low and high flow rate strategies were approximated to range from 1.4 and 3.9 m, respectively.

CONCLUSIONS

The effects of ventilation on moisture removal from a drift wall and temperature reduction in a drift emplaced with heat-generating HLW were evaluated using laboratory-scale experiments conducted at two ventilation flow rates. The use of ventilation has proven to have a significant impact on water and heat removal from the drift.

Ventilation was observed to be the driving force for removing water from the drift. In contrast, the authors in references 8–11 found that heat was the real driver at eliminating moisture from the drift wall.

The extent of dryout occurring in the laboratory-scale ventilation experiment was 5.5 mm (745 g) for the high flow rate strategy and 2.6 mm (346 g) for the low flow rate strategy.

Moisture removal, based on the surface area of the drift wall at the repository with a drift length of 1,200 m and a time frame of 100 yr, is expected to range between 2.0×10^4 kg and 4.3×10^4 kg (20 and 43 metric tons) of water, depending on the ventilation flow rate. The corresponding extent of dryout for the repository would range between 1.4 to 3.9 m, respectively.

The lower drift air temperature of 48.0 °C and the drift wall temperature of 39.0 °C, were achieved using ventilation, causing moisture removal to be increasingly advection dominant in the liquid phase as temperatures decrease. Results for drift-air temperature from prior ventilation studies, using NUFT code for hydrothermal calculations in the near field [11] and the MTECS model for the heat and mass transport calculations in air [8–10], are similar with maximum drift-air and wall temperatures of 45.0 and 40.0 °C, respectively, for a 83 MTU/acre WP heat load and a 10 m^3/s ventilation flow rate [24]. Saterlie et al. [24] states that without ventilation, peak wall temperatures can reach 170 °C.

Approximately 20 percent of the heat produced by the heater was removed from the laboratory-scale drift by ventilation using the high ventilation flow rate strategy of 67.0×10^{-5} m^3/s. The low ventilation flow rate strategy of 40.0×10^{-5} m^3/s removed 12 percent of the heat produced by the heater, demonstrating that the flow rate is directly proportional to the removal of heat.

ACKNOWLEDGMENTS

This technical project was sponsored by the Nuclear Regulatory Commission (NRC) under contract No. NRC-02-97-009 to the Center for Nuclear Waste Regulatory Analysis (CNWRA). The activities performed were on behalf of the NRC Office of Nuclear Material Safety and Safeguards, Division of Waste Management. This paper is an independent product of the CNWRA and does not necessarily reflect the views or the regulatory position of the NRC. The authors are thankful to

J. Wike for skillful preparation of this paper. Editorial reviews by J. Pryor and B. Long, technical review by F. Dodge, and programmatic review by B. Sagar helped improve the quality of this paper.

REFERENCES

1. Birkholzer, J. T., Tsang, C. F., Tsang, Y. W., and Wang, J. S. Y., *Drift Scale Modeling*, Yucca Mountain Milestone T6540, Chapter 4, Lawrence Berkeley National Laboratory, Berkeley, 1996.

2. Buschek, T. A., *Near-Field and Altered-Zone Environment Report*, UCRL-LR-124998, Vol. II, Chapter 1, Lawrence Livermore National Laboratory, Livermore, 1996.

3. Ho, C.L., and Webb, S.W.,A review of porous media enhanced vapor-phases diffusion mechanisms, models and data-does enhanced vapor-phase diffusion exist?, Technical Report, SAND96-1198, Albuquerque, NM: Sandia National Laboratory.

4. Andrews, R. W., Sevougian, S. D., Lee, J. H., Mishra, S. and McNeish, J. A., *Executive Summary*, B00000000-01717-2200-00136, Rev. 01, CRWMS M&O, Las Vegas, 1995.

5. Manteufel, R. D., Effects on ventilation and backfill on a mined waste disposal facility. *Nuclear Engineering and Design*, 1997, **172**, pp. 205–219.

6. Lingineni, S., Mishra, S., Kennedy, L. R., Reeves, M., Tsai, F., and Sassani, D. C., *Total System Performance Assessment. An Evaluation of the Potential Yucca Mountain Repository, Near-Field Environment.* B00000000-01717-2200-00136, Rev. 01, CRWMS M&O, Las Vegas, 1995.

7. Hopkins, P. L., Eaton, R. R., and Sinnock, S., *Effect of drift ventilation on repository hydrology and resulting solute transport implications-flow and transport through unsaturated fractured rock*, Geophysical Monograph **42**, D. D. Evans and T. J. Nicholson, eds., American Geophysical Union, Washington, DC, 1987, pp. 177–183.

8. Danko, G. and Mousset-Jones, P., Coupled heat and moisture transport model for underground climate prediction. *Proceedings of the International High-Level Radioactive Waste Management Conference*, American Nuclear Society, La Grange Park, 1992, pp. 790–798.

9. Danko, G. and Mousset-Jones, P., Modeling of the ventilation for emplacement drift re-entry and rock drying. *Proceedings of the International High-Level Radioactive Waste Management Conference*, American Nuclear Society, La Grange Park, 1993, pp. 590–599.

10. Danko, G., Buscheck, T. A., Nitao, J. J., and Saterlie, S., Thermal management with ventilation. *Proceedings of the International High Level Radioactive Waste Management Conference*, Las Vegas, 1996, pp. 420–424.

11. Nitao, J. J., Reference Manual for the NUFT Flow and Transport Code. Version 1.0., UCRL-ID-113520, Lawrence Livermore National Laboratory, Livermore, 1995.

12. Manteufel, R. D., Castellaw, H. M., and Stothoff, S. A., Microslab model for diffusion-controlled drying of a fractured porous medium. HTD-309, *Melanly I. Hunt* ed. American Society of Mechanical Engineers, New York, 1995, pp. 31–40.

13. McPherson, M. J., The analysis and simulation of heat flow into underground airways. *International Journal of Mining and Geological Engineering*, 1986, **4**, pp. 165–196.

14. Manteufel, R. D., *Large-scale buoyant flows at an unsaturated HLW repository*, 94-WA/HT-39. American Society of Mechanical Engineers, New York, 1994, pp. 1–10.

15. Laage, L., Yang, H., Greur, R., and Pomroy, W., Recent Improvements in the MFIRE Ventilation and Fire Simulator. *Mining Engineering*, 1994, pp. 145–148.

16. Hickox, C. E., *Comparison of Waste Emplacement Configurations for a Nuclear Waste Repository in Tuff. II.* Ventilation Analysis, SAND83-0678, Sandia National Laboratories, Albuquerque, 1983.

17. Domenico, P. A. and Schwartz, F. W., *Physical and Chemical Hydrogeology*. John Wiley & Sons, New York, 1990.

18. Lienhard, J. H., *A Heat Transfer Textbook*, Prentice Hall, Englewood, 1987.

19. Green, R. T., Dodge, F. T., Svedeman, S. J., Manteufel, R. D., Rice, G., Meyer, K. A., and Baca, R. G., *Thermally Driven Moisture Redistribution in Partially Saturated Porous Media*. NUREG/CR-6348, Nuclear Regulatory Commission, Washington, DC, 1995.

20. Mills, A. F., *Basic Heat and Mass Transfer*, Richard D. Irwin, Inc., Chicago, 1995.

21. Mondy L. A., Wilson, R.K., and Bixler, N.E., *Comparison of Waste Emplacement Configurations for a Nuclear Waste Repository in Tuff.* Vol. IV, Thermo-hydrological Analysis. SAND83-0757, Sandia National Laboratories, Albuquerque, 1983.

22. Moran, M. J. and Shapiro, H. N., *Fundamentals of Engineering Thermodynamics,* John Wiley & Sons, Inc., New York, 1992, p. 788.

23. Marshall, T. J. and Holmes, J. W., *Soil Physics*, 2nd edn. Cambridge University Press, New York, 1988.

24. Saterlie, S. F., Memory, R. D., Wagner, R. C., *Thermal Management with Ventilation.* Thermal Loading Study for FY 1996 Volume I of II, B00000000-01717-5705-00044, Rev. 01, CRWMS M&O, Las Vegas, 1996.

Table 1. Repository and laboratory-scale dimensions based on a 240 to 1 geometric scaling factor.

Parameter	Repository	Laboratory
Drift Spacing	25 m	0.104 m
Drift Diameter	5 m	0.021 m
Drift Length	1200 m	5 m
WP Diameter	1.8 m	0.008 m
Time	100 yr	8 hr
Thermal Penetration Radius	120 m	0.5 m

Table 2. Values associated with the laboratory experiment

Parameter	Value
latent heat of vaporization, h_{fg}	2,406.7 kJ/kg
specific heat of air, $c_{p,a}$	1,004 J/(kg-K)
kinematic viscosity of air, ν	1.695×10^{-5} m²/s
thermal diffusivity of air, α	2.389×10^{-5} m²/s
thermal expansion coefficient, β	3.2×10^{-3} K^{-1}
thermal conductivity of alumina, k_m	4 W/(m-K)
tortuosity, τ	0.67
porosity of alumina, ϕ	0.31
heater diameter, D_h	0.006 m
crossectional area of drift, A_c	3.46×10^{-4} m^2
surface area of drift wall, A_{wall}	0.3299 m^2