Powered, and Natural, Passive Ventilation at Yucca Mountain

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Abstract

Temperature and relative humidity variations are analyzed in a conceptual, ventilated nuclear waste repository at Yucca Mountain (YM). The drifts are assumed to be mechanically ventilated for 25 years with a forced, constant air flow rate of 15m^3/s for 25 years, then ventilated from year 25 until year 300 under natural buoyancy pressure driving force through an open system and, finally, naturally ventilated by air infiltration through backfilled intake and exhaust shafts and tunnels from year 300 until year 5,000. The hydrothermal-ventilation software MULTIFLUX provided balanced results for air, heat, and moisture flows. A balanced solution between the pressure loss and pressure gain due to buoyancy was achieved in 15 total system iterations. The natural ventilation was found to adequately keep temperatures below boiling for the 25 to 300 years time period. The air flow rate decreases only moderately when the fans are removed in year 25. The backfill of the access shafts and tunnels at year 300 decreases, but does not eliminate natural ventilation that is beneficial to controlling temperatures and relative humidities. The trend of the post-closure natural air flow rate variation with time indicates that natural ventilation may continue for much longer time periods. The relative humidity levels were found consistently lower than those expected in some of the current corrosion and performance assessment studies at YM.

I. INTRODUCTION

The current site recommendation design of the proposed repository at Yucca Mountain (YM) includes continuous emplacement drift ventilation for an extended period of time up to 300 years. Ventilation fans are assumed to be used for maintaining the air flow in the emplacement drifts at a rate of 15 m^3/s for the low thermal operating mode, in which the drift wall temperatures are kept below 95 ^{o}C, the approximate boiling-point temperature at YM.

In order to use the repository emplacement area efficiently, there is an advantage using the highest-possible areal waste mass load density for a given maximum target operating temperature. Continuous ventilation reduces temperatures, therefore, it is beneficial to increase the allowable mass load density for a given temperature.

A frequent question asked is whether a hot or a cold repository should be designed. Current results[1] in performance assessments (PA) indicate that there is no significant difference in long-term safety performance between the hot and the cold design options. However, the PA analyses did not provide evaluation for the hot and the cold options each with and without ventilation. In general, since little is known about the repository ventilation, partially due to lack of availability of a qualified hydrothermal-ventilation code, the assumptions in the PA models are over-simplified. For example, the relative humidity history given in a corrosion analysis[2] is about 300% higher for the ventilation period than in the AMR Rev01 study report[3] prepared for ventilation for the YM Project.

A hot repository with a high air flow may be significantly different in performance from the one with the same maximum temperatures but with no ventilation, since, for example, the waste package density and the associated dilutions, as well as the hydrology and dryout conditions will be different. It may be necessary to include these variations in the future PA studies in order to achieve more specific evaluations comparing not only the hot and cold, but also the hot and ventilated-hot, or cold and ventilated-cold options. It is especially important to address these scenarios in order to gain a better understanding of how a flexible design option with various rates of ventilation may affect the safety of the repository.

Long-term ventilation of several hundred years is quite feasible using fans, however, the use of fans for the entire time period may not be necessary. A better understanding is needed of the role that natural, buoyancy-driven ventilation may have in the design to achieve optimum drift and waste package layout for (1) maximizing safety, (2) maximizing the use of the available emplacement area, and (3) minimizing the cost of construction and operation. In addition, natural ventilation of several hundred years may assist in achieving a high mass-load density, but below-boiling temperature operation that has several advantages including (1) increased drift roof stability, (2) better predictability of performance with close-to-linear rock properties, and (3) decreased variation in the hydrologic conditions with no water accumulation over the repository horizon. Continuous ventilation may help provide the advantages of lower temperatures while achieving a high mass and associated high thermal load.

After permanent closure at year 300, natural air infiltration will take place through the backfill and the natural fracture and faults system at YM. Moist air flow will be driven through the mountain by a buoyancy pressure generated by the density difference between the cold and dry incoming and hot and humid exiting air. The effects of such hydrothermal-driven air infiltration have not yet been studied and included in the process models used by DOE. The air infiltration may be engineered for maximum efficiency in order to achieve a favorable, benign psychrometric waste container environment for several thousands of years.

The purpose of the present study is to analyze the temperature and relative humidity variations along a 600 m emplacement drift for 5,000 years under the following ventilation conditions:

(1) The drift is ventilated with a forced, constant air flow rate of 15 m3/s for 25 years, using fan(s),
(2) With the fan(s) turned off, the drift is ventilated without interruption from year 25 until year 300 under natural buoyancy pressure driving force,
(3) With the access shafts and tunnels backfilled, the drift is naturally ventilated until the end of the study time period.

II. DESCRIPTION OF THE NUMERICAL MODEL

II.A. The Conceptual Repository Arrangement

The arrangement follows the conceptual design developed by DOE, assuming 178 emplacement drifts and a total of 14 shafts and tunnels for air access for ventilation. The geometry of the drift used in the study is shown in Figure 1. Two peripheral drifts, an intake and an exhaust, are assumed as manifolds to distribute and collect air flows for 26 emplacement drifts, of which only 3 are shown in Figure 1. Finally, two vertical shafts, an intake and an exhaust, are used to connect the peripheral drifts to the atmosphere, also shown in Figure 1. The airflow resistances of the peripheral drifts and the shafts are included in the numerical analysis.

II.B. The Model of the Rock Domain

The rock domain is divided into 17 cells bounded with adiabatic surfaces on the vertical planes. One cell is depicted in Figure 1. The numerical model assumes a porous, wet, but unsaturated rock formation in which both heat and moisture transport are present and affect the thermal and psychrometric waste container environment. The simulations are carried out using MULTIFLUX[4] (MF3.0), a hydrothermal-ventilation code developed at the University of Nevada, Reno, Mackay School of Mines (UNR). MF 3.0 is configured to model the cells using NUFT[5] (Non-equilibrium, Unsaturated-saturated, Flow and Transport model) as a module for simulating heat and moisture flows in the rock domain. A modeling method called NTCF (Numerical Transport Code Functionalization) is used in all versions of MULIFLUX, to compress and process the time-dependent heat and moisture responses from the hydrothermal process model into matrix equations. An experimental, preliminary, nonlinear NTCF processor is applied, using matrix polynomial equations for modeling heat and moisture fluxes on the boundaries in a wide range of temperature and partial vapor pressure variations with constant-coefficient matrices. The NTCF numerical model of the time-dependent heat and moisture transport on the rock-air interface of a model cell, shown in Figure 1, is a set of matrix equations with identified constant coefficients determined based on NUFT runs.

The numerical discretization points on the drift wall are bundled into 21 averaged, independent surface nodes with respect to temperature and partial vapor pressure variations in the model. The NTCF rock model defines heat and moisture flux vectors as a function of the 21 time-dependent input vectors of surface temperature and partial vapor pressure boundary conditions. The 21 nodes represent the interface boundary at the representative points between a rock cell and the airway that include the waste packages. Conductive heat flow between neighboring rock cells is calculated using an experimental, mountain-scale model element.

II.C. The Model of the Airway with the Waste containers

A lumped-parameter CFD (Computational Fluid Dynamics) model is used in MF3.0 to describe the air flow, and heat, and moisture transport in the airway. Heat and moisture transport by laminar or turbulent convection are modeled on the drift and the waste container wall. Although no fan is used after 25 years to ventilate the storage system and the air flow is maintained only by natural buoyancy pressure difference, the air in each drift is forced to move by the system pressures known as the chimney effect. Natural, secondary flow may be due to the local temperature differences and related local, superimposed natural convection. The heat and moisture transport coefficients in the annulus between the waste containers and the drift wall are calculated in MF3.0 using transport coefficients in the lumped-parameter CFD. A differential-parameter CFD model[6] can also be used in MF3.0 if refinement of the transport coefficients is needed, however, this option is not applied in the present study. A direct thermal radiation between the waste containers and drift wall is also included in the model configuration.

The flow resistances in the airflow model include laminar or turbulent friction, and shock loss in the drift, the peripherial tunnels, as well as the access shafts, all 6.5 m in diameter. The air flow resistances of the intake and the exhaust shafts are changed at year 300 to model the effect of a coarse backfill. The backfill resistance assumes 40 % available area of the original shafts, 0.02 m hydraulic diameter of the flow channels, and 50 % length increase in the rubble fill. In addition, 40 shock loss coefficients, 0.3 (unitless) value each, are assumed in series per unit length.

II.D. Total System Model

The NTCF and CFD modules are coupled on the rock-air interface by MF3.0 until the heat and moisture flows are balanced at the common surface temperature and partial vapor pressure at each surface node and time instant. In the time period of natural ventilation between years 25 and 5,000, the air flow rate is also balanced, iteratively equating the pressure loss through the system with the buoyancy driving pressure difference caused by differences between the intake and exhaust air temperatures. Three simplification assumptions are used as follows to reduce the complexity of the task due to hydrothermal rock modeling :

1) The air mass flow rate is uniform in the 26 drifts,
2) The intake and exhaust shafts are thermally insulated from the rockmass. In order to compensate for the possible loss in chimney efficiency due to heat exchange, a reduced height of 250 m is used in the simulation,
3) The emplacement panel is infinite in lateral direction, eliminating mountain-scale heat and moisture flows between the repeating parallel drifts across the pillars. However, mountain-scale heat flow along the length of the drifts in the rockmass is iteratively modeled by MF3.0.

The NTCF modeling technique with nonlinear processing is an efficient way to reduce the necessary number of NUFT runs during the iterative numerical calculations, incorporating the five nested iteration loops as follows:

- -NTCF model re-functionalization with NUFT
- -buoyancy pressure and air flow iteration for 26 drifts
- -mountain-scale heat flow correction iteration between cells along the driifts
- -heat balance iteration in each cell between NTCF and airway CFD models
- -moisture balance iteration in each cell between NTCF and airway CFD models

Being the outside loop, one set of NUFT runs and NTCF model preparation serves four internal, nested iteration cycles, minimizing the number of time-intensive NUFT runs.

II.E Input Data

The input data used in the calculation essentially agree with those used in the AMR Rev01 study. The main input parameters are as follows:

Rock input data:	NUFT3.0 input deck specified in the AMR Rev01 study. The spatial rock domain is represented by 17 NUFT cells, shown in Figure 1.
Drift dimensions:	600 m long, 5.5 m in diameter.
Ventilating air:	25^{o}C intake temperature with 30% relative humidity.
Air flow rate:	15 m3/s at intake properties until year 25; variable, balanced value afterward.
Waste packages:	Eight Waste Packages (WP) in a repeating drift segment of 35.5 m according to the rock domain.
Waste mass load:	85 MTU/acre.

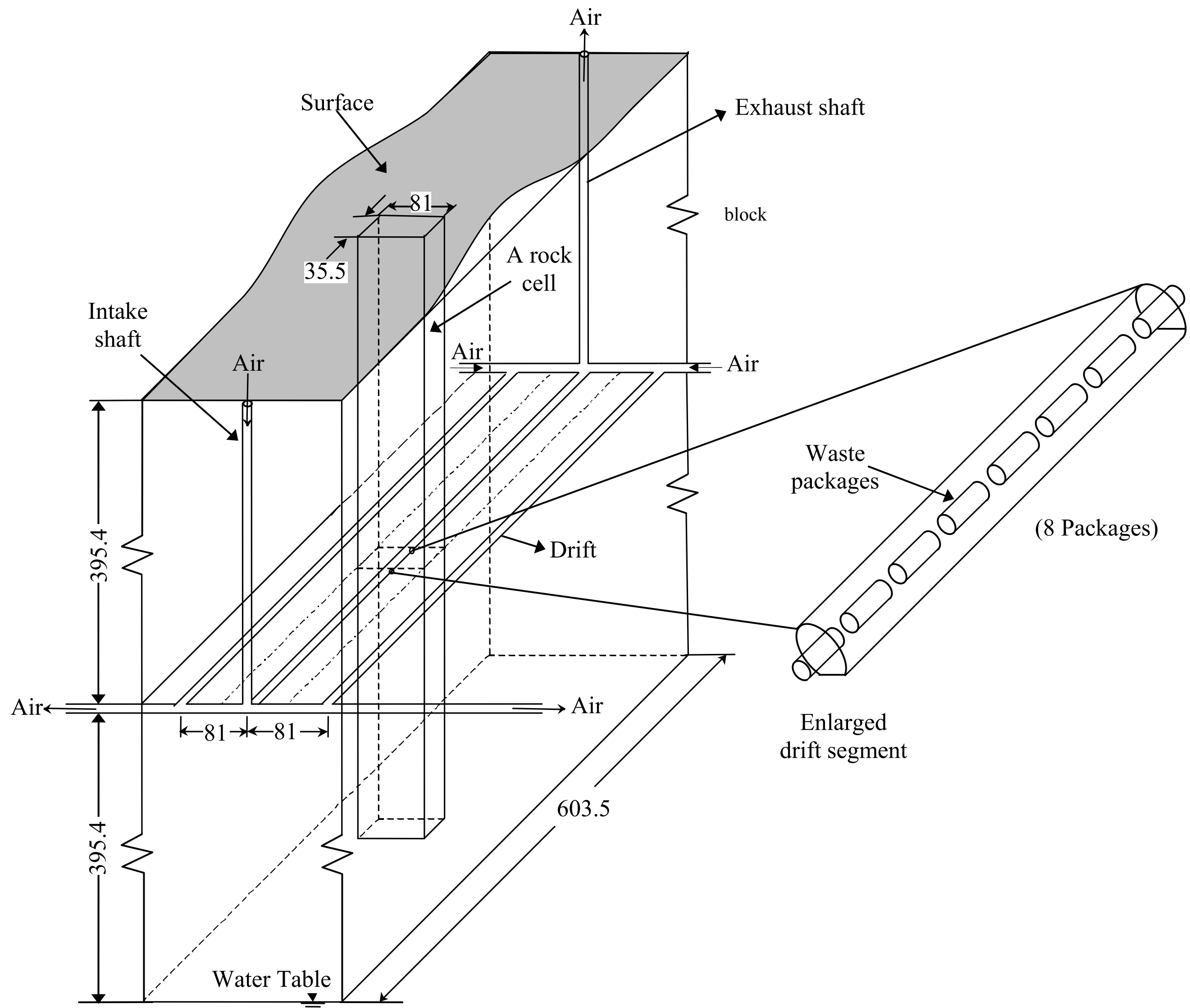

Figure 1. A three-drift section of an emplacement panel of 26 drifts with the peripherial tunnels, the intake and exhaust shafts, and the surrounding rockmass. The waste packages in a repeating rock cell of 17 are also shown.

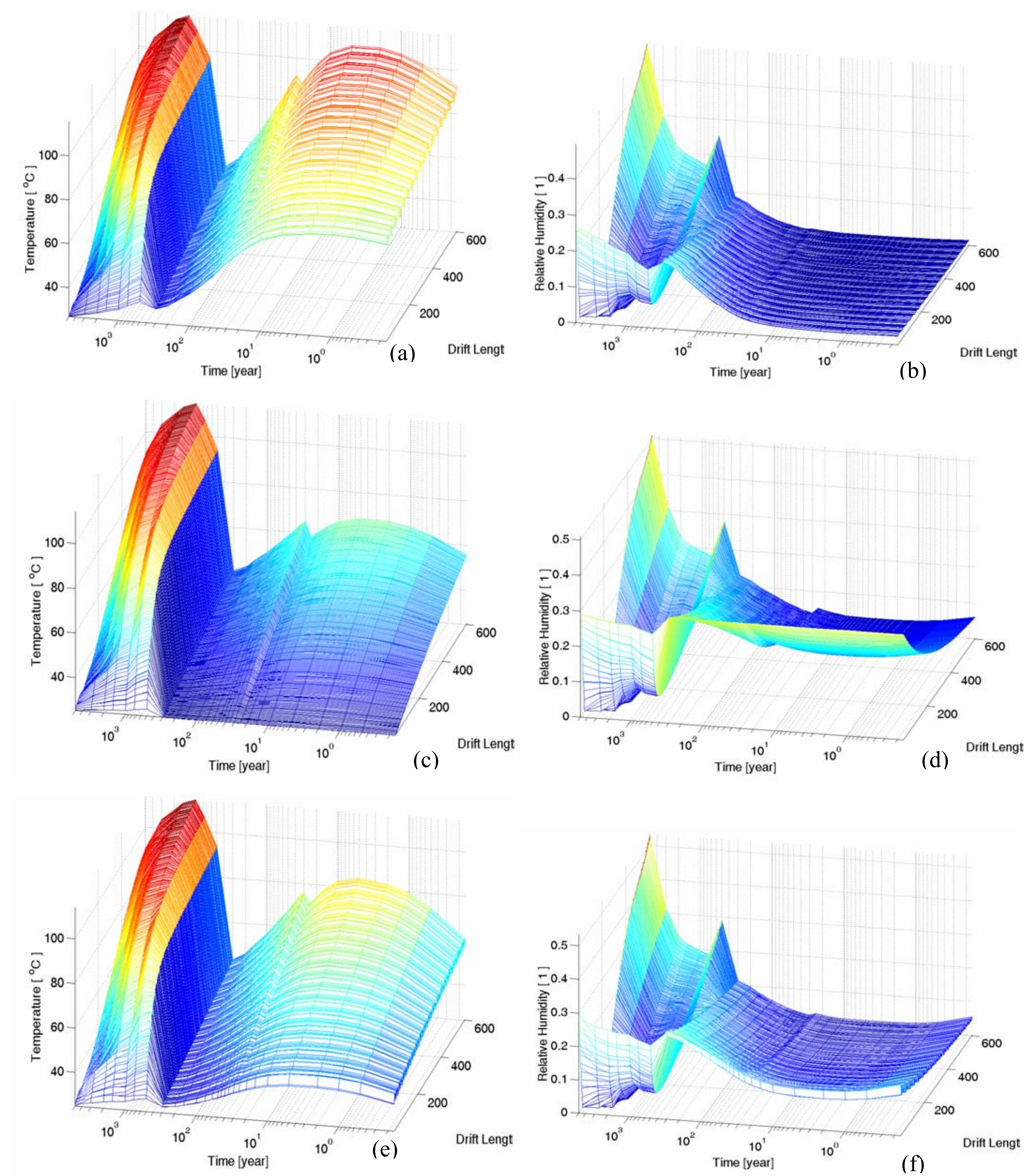

Figure 2. (a) Waste package temperature; (b) waste package relative humidity; (c) Air temperature; (d) Air relative humidity; (e) wall temperature; (f) wall Relative Humidity distributions in time and space

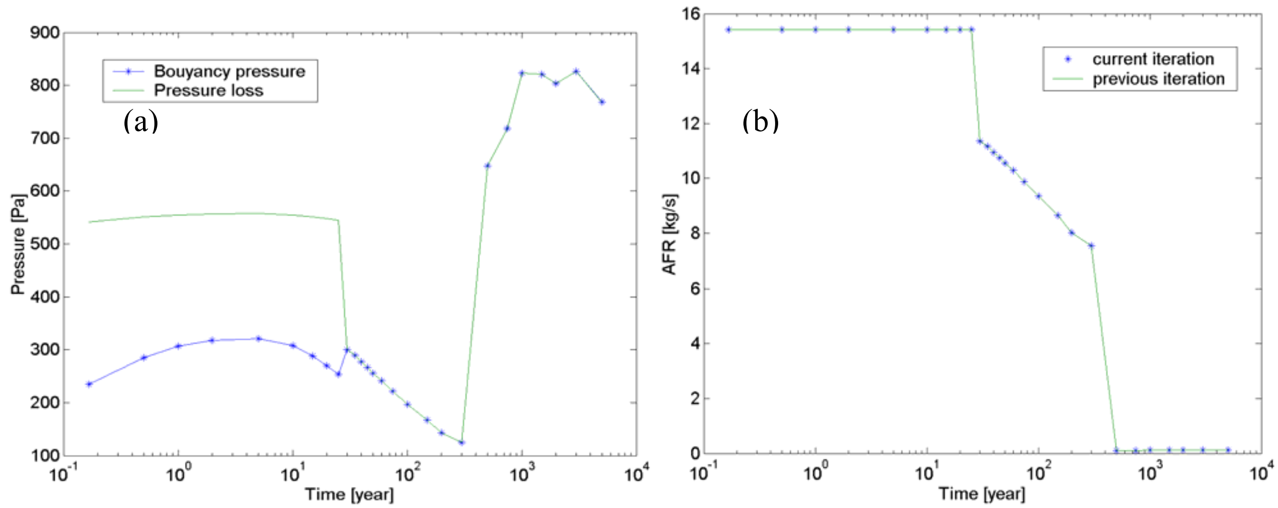

Figure 3. . (a) Balanced total pressure loss and buoyancy pressure difference as a function of time; (b) Balanced air flow rate in the emplacement drift as a function of time.

III. RESULTS

The fully-balanced calculation results for temperatures and relative humidities in the central, representative drift are shown in Figure 2 as a function of time and drift length. Results are given for the wall, waste package surface, and the ventilating air. The pressure loss and the buoyancy driving pressure difference across the total system that includes the intake shaft, peripherial intake manifold drift, peripherial exhaust manifold, and exhaust shaft, are given in Figure 3 a. The ventilating air flow rate variation with time in the emplacement drift is given in Figure 3 b.

Fifteen total iteration steps were needed to achieve balancing within a 10 Pa pressure error. During the course of the balancing calculations with the five nested iteration loops previously described, MF3.0 used each NTCF model approximately 3 times for moisture and 50 times for heat balance iterations in each rock cell, repeated 17 times along the drift length. The total number is 2550 runs with each NTCF model, which is further multiplied by the 12 mountain-scale heat flow correction iterations and the 15 buoyancy pressure balancing iterations, giving a number of 459,000 hydrothermal model runs, each with different boundary condition variation for the entire time interval of 5,000 years.

The NTCF modeling technique reduced the number of necessary NUFT runs, making it feasible to complete the complex calculations in two months in spite of the total number of close to half a million iterations with the hydrothermal model. For comparison, a single NUFT run with one set of boundary condition variations for 5,000 years for the rock cell took 2.5 hours. Comparing runtimes between MF3.0 with the NTCF method and a hypothetical case without the NTCF method indicates that without using the NTCF method, but replacing it with direct NUFT runs and assuming the same number of balancing iterations, the modeling task would take a minimum of 131 years of non-stop computation to complete.

IV. DISCUSSION

The numerical results prove the concept of controlling temperature and relative humidity around the waste containers for a long period of time using natural ventilation. The waste container surface temperatures and relative humidities are within 108 ^{o}C and 30 % for the storage period of 300 years with open ventilation, given in Figures 2 a and b. The temperatures and relative humidities in the air are within 70 ^{o}C and 30 %, respectively, given in Figures 2 c and d for the same time period. The maximum temperature and relative humidity on the drift wall were kept below the maximum of 90 ^{o}C and 30 %, respectively, shown in Figures 2 e and f. The variation of the air mass flow rate during the open ventilation operating mode shows a moderate decrease from the constant, forced value of 15.4 kg/s for 25 years to approximately 8 kg/s by the end of year 300.

Subsequent to repository closure using rubble backfill of the access shafts and tunnels, the air mass flow rate according to Figure 3 b rapidly decreases to about 0.1 kg/s and remains approximately constant during the post-closure ventilation period of 4,700 years. The air mass flow rate of 0.1 kg/s coincides in value with the lowest ventilation flow rate used in previous YM ventilation studies[7] restricted only for the pre-closure time period, assuming open ventilation for 100 years.

Due to decreased cooling, the temperature goes through a second and higher surge than the first increase during the pre-closure time period. Both the waste container surface and the air temperatures and relative humidities are within 120 ^{o}C and 50 %, respectively, for the post-closure ventilation period of 4,700 years, given in Figures 2 a, b, c, and d. The maximum temperature and relative humidity on the drift wall were kept below the maximum of 125 ^{o}C and 55 %, respectively, shown in Figures 2 e and f.

The total buoyancy pressure difference and air flow friction resistance curves are different during the mechanized, forced ventilation period of 25 years, shown in Figure 3 a. The pressure difference between the curves has to be provided by the fans. The total buoyancy pressure difference and air flow friction resistance curves are perfectly balanced during the natural ventilation period from year 25 to year 5,000 according to the overlapping curves shown in Figure 3 a. The buoyancy pressure difference increases with time due to increasing temperature and resulting density difference between the intake and exhaust air. In addition, the density difference is further increased by the increasing water vapor content with time. The trend of the buoyancy pressure difference driving force indicates that the natural, post-closure ventilation will most likely be maintained much longer than the time period used in this study.

V. CONCLUSIONS AND RECOMMENDATIONS

- The combined forced-flow ventilation for 25 years followed by natural, buoyancy-driven ventilation until year 300 was simulated using MF3.0 a new hydrothermal-ventilation software. A balanced solution between the pressure loss and pressure gain due to buoyancy was achieved in 15 total-system iterations.
- The natural ventilation was found to be efficient to keep temperatures below boiling between year 25 and year 300 in spite of the high mass load density of 85 MTU/acre. The air mass flow rate decreased only moderately when the fans were removed in year 25 to about 11 kg/s, and was still at around 8 kg/s at year 300.
- Subsequent to closure with loose backfill in the access shafts and tunnels, the air flow rate rapidly decreased, but stabilized at a low level over the 4,700 years time period. The trend indicates that natural ventilation may continue for much longer time periods.
- The temperature reached a peak value around year 1,000, exceeding slightly the boiling temperature at the wall of the second half of the emplacement drift. A lower areal mass load density, or a longer pre-closure ventilation time period may alleviate this condition, if necessary.
- The relative humidity was consistently lower than the intake humidity, and continuously decreasing during the 300 years time period. This result provides more favorable conditions than those expected in some of the current corrosion and PA studies.
- The relative humidity continued to be lower than 50 % until year 5,000. This result also provides more favorable conditions than those expected in some of the current corrosion and PA studies.
- The natural ventilation buoyancy driving pressure difference may be strong enough to drive air flow through the natural fractures, faults, and the lithophysal rock layers in the natural geologic system at YM. This phenomenon, not included in the present study, is beneficial to further reducing relative humidity around the waste packages for the entire, thermally active time span of the repository. This spontaneous, natural process is part of the repository system, therefore, further studies are recommended.
- A fully-coupled, hydrothermal-ventilation model and software, MF3.0 is proven efficient in solving the multiphase, non-equilibrium transport problem of heat, moisture, and ventilating air flows involving a large and geometrically complex geologic regime.

VI. ACKNOWLEDGMENTS

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VII. REFERENCES

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