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OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT **ANALYSIS/MODEL COVER SHEET** *Complete Only Applicable Items*	1. QA: QA Page: 1 of: 45

2.		3.	
☐ Analysis	☐ Engineering ☐ Performance Assessment ☐ Scientific	☒ Model	☒ Conceptual Model Documentation ☐ Model Documentation ☐ Model Validation Documentation

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Ventilation Model

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12. Remarks:

This Analysis and Model Report (AMR) was prepared by the Engineered Barrier System Operations (EBSO) as an internal input to the activities related to the Process Model Report (PMR) within the EBSO. No external organization that may be affected by this document was identified. Therefore, a technical review under procedure AP-2.14Q is not required.

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Yiming Sun of Repository Subsurface Design Department made significant contribution to this document in preparation of computer input files, computer program running, and preparation of output data for the thermal analysis cases established in this document.

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OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
ANALYSIS/MODEL REVISION RECORD
Complete Only Applicable Items

2. Analysis or Model Title:

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3. Document Identifier (including Rev. No. and Change No., if applicable):

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1. PURPOSE

The purpose of this analysis and model report (AMR) for the Ventilation Model is to analyze the effects of pre-closure continuous ventilation in the Engineered Barrier System (EBS) emplacement drifts and provide heat removal data to support EBS design. It will also provide input data (initial conditions, and time varying boundary conditions) for the EBS post-closure performance assessment and the EBS Water Distribution and Removal Process Model.

The objective of the analysis is to develop, describe, and apply calculation methods and models that can be used to predict thermal conditions within emplacement drifts under forced ventilation during the pre-closure period.

The scope of this analysis includes:

- Provide a general description of effects and heat transfer process of emplacement drift ventilation.
- Develop a modeling approach to simulate the impacts of pre-closure ventilation on the thermal conditions in emplacement drifts.
- Identify and document inputs to be used for modeling emplacement ventilation.
- Perform calculations of temperatures and heat removal in the emplacement drift.
- Address general considerations of the effect of water/moisture removal by ventilation on the repository thermal conditions.

The numerical modeling in this document will be limited to heat-only modeling and calculations. Only a preliminary assessment of the heat/moisture ventilation effects and modeling method will be performed in this revision. Modeling of moisture effects on heat removal and emplacement drift temperature may be performed in the future.

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2. QUALITY ASSURANCE

The analyses in this AMR have been determined to be Quality Affecting in accordance with CRWMS M&O procedure QAP-2-0, *Conduct of Activities*, because the information will be used to support Performance Assessment and other quality-affecting activities. Therefore, this AMR is subject to the requirements of the *Quality Assurance Requirements and Description* (QARD) document (DOE 1998). This AMR is covered by the Activity Evaluation for *EBS Performance Modeling* (CRWMS M&O 1999g).

Personnel performing work on this analysis were trained and qualified according to Office of Civilian Radioactive Waste Management (OCRWM) procedures AP-2.1Q, *Indoctrination and Training of Personnel*, and AP-2.2Q, *Establishment and Verification of Required Education and Experience of Personnel*. The repository subsurface ventilation system has been classified as Conventional Quality (CRWMS M&O 1999h, p. 9, Section 7.1) in accordance with CRWMS M&O procedure QAP-2-3, *Classification of Permanent Items*. The governing procedure for preparation of this AMR is OCRWM procedure AP-3.10Q, *Analyses and Models*, as an implementing document of Work Package 12012383MX. Development Plan TDP-EBS-MD-000015 (CRWMS M&O 1999i) and Technical Change Request (TCR) (T1999-0122) were processed in accordance with AP-2.13Q, and AP-3.4Q respectively.

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3. COMPUTER SOFTWARE AND MODEL USAGE

A commercially available computer program, ANSYS Version 5.2, is used to support the calculation. ANSYS Version 5.2 is a general purpose finite element analysis (FEA) code, and is used in many disciplines of engineering that deal with topics including structural, geotechnical, mechanical, thermal, and fluids. ANSYS is installed on the Silicon Graphics (SGI) and Sun Microsystems workstations with the Unix operating system. ANSYS Version 5.2 has been verified and validated (CSCI#: 30013 V5.2SGI, CRWMS M&O 1997a) according to applicable M&O procedure. ANSYS was used in thermal calculations for predicting the effect of continuous ventilation. The computer files for the ANSYS runs are included in this document in Attachment V.

The ANSYS Version 5.2 software was obtained from the Configuration Management (CM) in accordance with the applicable M&O procedure. The software was appropriate for the applications used in this calculation. The software was used within the range of validation as specified in the software qualification report (CRWMS M&O 1997a).

The ventilation model used for the analysis of emplacement drift ventilation considers only sensible heat transfer. Moisture removal by ventilation and potential water movement in the rock mass are not included in the model. This type of heat-only model is based on routine application of established scientific laws (e.g. Newton's cooling law, Fourier's law, and Stefan-Boltzmann law) and standard engineering practice for calculating heat transfer in and around an underground opening. Detailed description of the model is provided in Sections 6.1 through 6.3. The ventilation model is an application of existing industry standard and related software; therefore, traditional validation approach to validate the model was used. The validation is documented in Sections 6.1 through 6.3. The model validation includes provision of scientific literature, parameter input, assumptions, simplifications, initial and boundary conditions; explanation of how the software are used; expected source of uncertainty (TBV tracking); and computer data files to allow independent repetition of the model simulation. It is determined that the model is validated for its intended use.

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4. INPUTS

This section presents data, parameters, and criteria used to develop this analysis. The majority of the input data presented in this section is considered preliminary and unqualified and will be designated as TBV and tracked in accordance with AP-3.15Q. The outputs from this analysis cannot be used for procurement, fabrication, or construction prior to qualification of the input data.

4.1 DATA AND PARAMETERS

4.1.1 Stefan-Boltzmann Constant

For thermal calculations the Stefan-Boltzmann constant value of 5.669×10^{-8} $W/m^2{\cdot}K^4$ (0.1714×10^{-8} $Btu/h{\cdot}ft^2{\cdot}R^4$) is used (ASHRAE 1989, p. 3.7).

4.1.2 Average Ground Surface Temperature and Thermal Gradient

The average ground surface rock temperature is 18.7°C (CRWMS M&O 1998a, Volume I, p. 16) (TBV-334). The rock thermal gradients used in this analysis are listed in Table 1.

Table 1 Rock Thermal Gradient

Depth (m)	Value (°C /m)
0 - 150	0.020
150 - 400	0.018
400 - 541	0.030
541 - 700	0.030[a]

Note: [a] Assumed value because the rock thermal gradient below 541 m is not available.

The undisturbed rock temperature at the repository level is calculated from the ground surface temperature, the thermal gradient (Table 1), and the elevation at the repository level (4.1.3).

$$18.7° + 0.02(150-0) + 0.018(348.98-150) = 25.3°C.$$

A value of 25°C is used in Section 5.5.

Using the same method, the undisturbed rock temperature at 606.57m (Section 4.1.3) below the ground surface is determined as follows.

$$18.7° + 0.02(150-0) + 0.018(400-150) + 0.030(541-400) + 0.030(606.57-541) = 32.40°C.$$

4.1.3 Lithostratigraphy

The thicknesses of the lithostratigraphic units are listed in Table 2 (CRWMS M&O 1999a, pp. 1 of 2, TBV-3529). These are the average values at the point, (N233, 760m, E170, 750m), of the repository emplacement area based on CRWMS M&O 1999a. The average elevations of the surface and the repository levels are 1421.28 m (CRWMS M&O 1999a, p. 2) and 1072.3 m (CRWMS M&O 1998b, Figure 4-1), respectively (TBV-3528). Therefore, the depth of the repository level (the invert) is at 348.98 m (1421.28 - 1072.3 = 348.98 m) from the surface. The depth of the centerline of the emplacement drift is at 346.23 m (348.98 – 5.5 m (drift diameter, Sec. 4.1.9)/2 = 346.23 m).

From the ground surface elevation of 1421.28 m and the Tpcpv2 elevation of 1306.98 m (CRWMS M&O 1999a, p. 2), the thickness of the overburden above the Tpcpv2 is 114.3 m (1421.28 – 1306.98 = 114.3m).

The thickness of the units from Tpcpv2 (including Tpcpv2) to Tacbt is calculated based on data in Table 2 as follows:

$$5.49 + 4.69 + 0.53 + 7.05 + 4.58 + 14.09 + 9.69 + 4.58 + 0.53 + 1.06 + 46.85 + 8.98$$

$$+ 77.68 + 29.94 + 106.21 + 47.73 + 20.61 + 2.99 + 11.27 + 3.35 + 84.37 = 492.27 \text{ m}$$

Therefore, the total thickness for all units shown in Table 2 is 606.57 m (114.3 + 492.27 = 606.57 m). The thickness from the emplacement drift centerline to the bottom of the Tacbt unit is 260.34 m (606.57 – 346.23 = 260.34).

Table 2 Thermal Modeling Parameters by Stratigraphic Unit

T/M Unit	USGS Unit	ISM 3.0	Thickness (m)	Grain Density (kg/m^3)	Thermal Conductivity T≤100°C (W/m·K)	Thermal Conductivity T>100°C (W/m·K)	Specific Heat T≤95°C (J/kg·K)	Specific Heat 95°C<T≤114°C (J/kg·K)	Specific Heat T>114°C (J/kg·K)
TCw	Tpcrv	No Data	No Data	2550	2.00	1.60	823	3879	823
	Tpcrn	No Data	No Data	2550	2.00	1.60	823	3879	823
	Tpcrl	No Data	No Data	No Data	No Data	No Data	No Data	No Data	No Data
	Tpcpul	No Data	No Data	2520	1.67	1.23	882	4352	882
	Tpcpmn	No Data	No Data	2510	1.94	1.53	837	4010	837
	Tpcpll	No Data	No Data	2510	1.76	1.02	847	4019	847
	Tpcpln	No Data	No Data	2510	1.88	1.28	837	4010	837
	Tpcplnc	No Data	No Data	No Data	No Data	No Data	No Data	No Data	No Data
	Tpcpv 3	Tcpv3	0.0	2470	0.98	0.54	857	4570	857
PTn	Tpcpv 2	Tcpv2	5.49						
	Tpcpv1	Tcpv1	4.69	2380	1.07	0.50	1037	6048	1037
	Tpbt4	Tcbt4	0.53	2340	0.5	0.35	1077	21976	1077
	Tpy	Yucca	7.05	2400	0.97	0.44	849	16172	849
	Tpbt3	Tcbt3_dc	4.58	2370	1.02	0.46	1016	20669	1016
	Tpp	Pah	14.09	2260	0.82	0.35	1330	25560	1330
	Tpbt2	Tpbt2	9.69	2370	0.67	0.23	1224	23878	1224
	Tptrv3	Tptrv3	4.58	2510	1.00	0.37	834	5137	834
	Tptrv2	Tptrv2	0.53						
TSw1	Tptrv1	Tptrv1	1.06						
	Tptrn	Tptrn	46.85	2550	1.62	1.06	866	5629	866
	Tptrl	Tptrl	8.98	2510	1.58	0.89	882	5693	882
	Tptpul	Tptpul	77.68	2510	1.80	0.71	883	5694	883
TSw2	Tptpmn	Tptpmn	29.94	2530	2.33	1.56	948	4568	948
	Tptpll	Tptpll	106.21	2540	2.02	1.20	900	4663	900
	Tptpln	Tptpln	47.73	2560	1.84	1.42	865	4523	865
TSw3	Tptpv3	Tptpv3	20.61	2360	2.08	1.69	984	1958	984
CHn1	Tptpv2	Tptpv2	2.99						
	Tptpv1	Tptpv1	11.27						
	Tpbt1	Tpbt1	3.35	2310	1.31	0.7	1057	21076	1057
	Tac5 Tac(v)	Calico	84.37	2240	1.17	0.58	1201	23863	1201
	Tac4								
	Tac3								
	Tac2 Tac(z)			2350	1.2	0.61	1154	22086	1154
	Tac1								
CHn2	Tacbt			2440	1.35	0.73	1174	13561	1174

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4.1.4 Rock Mass Thermal Properties

The rock mass grain density, thermal conductivity and specific heat values (TBV-3529) are used in the thermal modeling. These values are listed in Table 2 based on *Input Transmittal for Thermal Modeling Parameters by Stratigraphic Unit* (CRWMS M&O 1999a, pp. 1 to 2). The emissivity of 0.9 for the Tptpll unit where the majority of emplacement drifts will be located was used based on *Fundamentals of Heat and Mass Transfer* (Incropera and Dewitt 1985, p. 780).

4.1.5 Waste Package Parameters and Properties

4.1.5.1 Waste Package Thermal Properties

The thermal properties for waste package used in the analysis are listed in Table 3 (TBV-3684). These values are for Alloy 22 material based on *Thermal Calculation of the Waste Package with Backfill* (CRWMS M&O 1999b, Section 5.1.3).

Table 3 Thermal Properties for Waste Package

Parameter	Value
Density (kg/m^3)	8690
Thermal Conductivity (W/m·K)	12.52[a]
Specific Heat (J/kg·K)	435.25[b]
Emissivity	0.87

Note: [a] Averaged value over the temperature range of 48 to 300°C.
[b] Averaged value over the temperature range of 52 to 300°C.

4.1.5.2 Waste Package Length and Diameter

The length and diameter for waste packages are listed in Table 4 (TBV-3685), based on *Enhanced Design Alternative (EDA) II Repository Estimated Waste Package Types and Quantities* (CRWMS M&O 1999c, Item 1, pp. 25 to 26).

Table 4 Number and Initial Heat Generation Rates for Average CSNF and DHLW Waste Packages

Waste Package Type		Length of Waste Packages (m)	Diameter of Waste Packages (m)	Number of Waste Packages	Initial Heat Generation Rate (kW/package)
21-PWR	Absorber Plates	5.305	1.564	4,279	11.3337
	Control Rodes	5.305	1.564	87	2.3709
12-PWR	Long	5.791	1.250	158	9.5402
44-BWR	Absorber Plates	5.275	1.594	2,889	7.1346
24-BWR	Thick Plates	5.245	1.238	6	0.4910
5-DHLW	Short	3.73	2.030	1,249	4.0580
5-DHLW	Long	5.357	2.030	414	5.8280[a]
Navy	Combined	5.888	1.869	285	7.1350[b]
DOE/Other		5.57	No Data	598	0.7930

Note: [a] Assumed value by assuming that the initial heat generation rates for 5-DHLWs, short and long, are linearly proportional to their lengths (4.058kW×5.357m/3.73m=5.828kW).
[b] Averaged value equal to that of 44-BWR (CRWMS M&O, 1998c, p. 14. TBV-398).

4.1.5.3 Number and Initial Heat Generation Rates of Waste Packages

Table 4 lists the number of CSNF and defense high-level waste (DHLW) packages and their initial heat. The data are from *Enhanced Design Alternative (EDA) II Repository Estimated Waste Package Types and Quantities* (CRWMS M&O 1999c, Item 2, p.7 (TBV 3695), and Item 2, p.15 (TBV 3686)).

4.1.5.4 Average Waste Package Heat Generation Rates

The decay characteristics of the commercial spent nuclear fuel (CSNF) waste packages, as listed in Table 5, are used in this analysis. These values are provided in CRWMS M&O 1999c, Item 2, Table 3, pp. 7 to 9 (TBV 3695). The values of heat flux and volumetric heat generation rate of the waste packages used in thermal models are calculated in Attachment II.

4.1.6 Ventilation Air Properties

The properties of ventilation air are listed in Table 6 (TBV-3683 and TBV-3691). The values of thermal conductivity, dynamic viscosity and Prandtl Number are based on an intake air temperature of 25°C (298.16 K) (Section 5.5) and using linear interpolation from *Heat Transfer*. 8[th] Edition (Holman 1997, p. 646). The density of ventilation air was obtained from *Repository Subsurface Waste Emplacement and Thermal Loading Management Strategy* (CRWMS M&O 1998c, p.II-2). This was done to include air density difference due to the elevation difference between the sea level and average elevation of emplacement area.

Table 5 Time-dependent Heat Generation Rates for Average CSNF Waste Packages

Time (years)	21-PWR Absorber Plates (kW/package)	21-PWR Control Rods (kW/package)	12-PWR Long (kW/package)	44-BWR Absorber Plates (kW/package)	24-BWR Thick Absorber Plates (kW/package)
0.01	11.3337	2.3709	9.5402	7.1346	0.4910
1	10.9954	2.3285	9.2722	6.9146	0.4829
5	9.9653	2.1785	8.4286	6.2682	0.4445
10	8.9956	2.0095	7.5901	5.6536	0.4030
15	8.1887	1.8547	6.8815	5.1467	0.3689
20	7.5138	1.7241	6.3149	4.7102	0.3341
25	6.9115	1.6038	5.8009	4.3098	0.3065
30	6.3792	1.4942	5.3407	3.9701	0.2806
40	5.4984	1.3106	4.5868	3.3915	0.2369
50	4.7912	1.1649	3.9792	2.9326	0.2033
60	4.2229	1.0443	3.5026	2.5621	0.1754
70	3.7685	0.9479	3.1031	2.2625	0.1536
80	3.3915	0.8698	2.7908	2.0227	0.1361
90	3.0866	0.8070	2.5304	1.8264	0.1222
100	2.8314	0.7545	2.3024	1.6685	0.1111
150	2.0790	0.5983	1.6766	1.1977	0.0799
200	1.7291	0.5244	1.3818	0.9878	0.0684
250	1.5128	0.4796	1.2029	0.8725	0.0622
300	1.3654	0.4452	1.0804	0.7889	0.0583

Table 6 Property Values for Ventilation Air

Parameter	Value
Density (kg/m^3)	1.0561
Thermal Conductivity (W/m·K)	0.0261
Dynamic Viscosity (kg/m·s)	1.8371×10^{-5}
Prandtl Number (dimensionless)	0.7079
Specific Heat (Cp) (J/kg·K)	1005.7

4.1.7 Emplacement Drift Spacing

The emplacement drift spacing is 81 meters centerline to centerline (Heath and Wilkins 1999, p.1).

4.1.8 Waste Package Spacing

The waste packages will be spaced 10 cm apart (Heath and Wilkins 1999, p. 2).

4.1.9 Emplacement Drift Diameter

The diameter of the waste emplacement drifts is 5.5 m (Heath and Wilkins 1999, p. 1).

4.2 CRITERIA

Each drift segment in the repository will be ventilated during preclosure, which for base case analyses should be assumed to be 50 years… The ventilation system shall be designed to remove at least 70% of the heat generated by the waste packages during preclosure (Heath and Wilkins 1999, p.3).

4.3 CODES AND STANDARDS

Not used.

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5. ASSUMPTIONS

5.1 WASTE PACKAGE DIAMETER

It is assumed for the purpose of the continuous ventilation calculation that all waste packages have the same diameter. The diameter used is that of the 21 PWR waste packages, 1.564 m (See Table 4). This assumption is based on the waste stream, where the largest number of waste packages are 21 PWR. (TBV-3686)

5.2 WASTE PACKAGE PLACEMENT

For the preclosure ventilation calculation, it is assumed that the waste packages are placed in the center of the emplacement drift (CRWMS M&O 1999f, p. 37). This is a limitation of the ANSYS software. (TBV-3689)

5.3 AVERAGE EMPLACEMENT DRIFT LENGTH

For the preclosure ventilation calculation, the average drift length from the air inlet of emplacement drift to the central exhaust main is assumed 600 m (CRWMS M&O 1999f, p. 7). (TBV-3688)

5.4 PRECLOSURE VENTILATION RATES

The preclosure ventilation calculations were performed for airflow rates of $10 m^3/s$ and $15 m^3/s$. This is based on the *ANSYS Calculations in Support of Enhanced Design Alternatives* (CRWMS M&O 1999f). Page VI-6 of this document shows that for EDA II, a ventilation rate of $10 m^3/s$ removed 67% of the heat after 50 years. The EDA II requirements state that 70% of the heat must be removed (Section 4.2), so $15 m^3/s$ will also be evaluated. (TBV-3687)

5.5 INTAKE AIRFLOW TEMPERATURE AT EMPLACEMENT DRIFT INLET

The preclosure ventilation calculations, the temperature of intake airflow at emplacement drift inlet is assumed to the same as the undisturbed rock temperature at repository level, 25 °C (see Section 4.1.2). (CRWMS M&O 1999f, p. 10, Section 3.1.7) (TBV-3690)

5.6 ROCK PROPERTIES FOR OVERBURDEN ABOVE TPCPV2 UNIT

The rock properties for the overburden above the Tpcpv2 unit are incomplete. This is due to the lack of thickness data for individual units within the overburden (Table 2). For the entire overburden of 114.3 m (Section 4.1.3) on top of Tpcpv2 unit, the rock properties are assumed to the same as those of Tpcpv2 unit, which is the closest unit to the overburden. (TBV-3529)

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6. ANALYSIS/MODEL

6.1 INTRODUCTION TO VENTILATION MODEL

It is required that each segment of the repository will be ventilated during preclosure. The repository system shall be designed to remove at least 70% of the heat generated by waste packages during preclosure (Section 4.2).

Ventilation is the most direct means to remove the heat energy generated by spent fuel in the emplacement drifts. Ventilation of emplacement drifts after waste emplacement, if considered desirable, could be employed as a part of the thermal management process. The net effect of ventilation of emplacement drifts should be to delay the onset of the peak rock temperature and to lower the peak when it does occur (CRWMS M&O 1995, pp. 28 to 36; CRWMS M&O 1996, Section 5.3; and CRWMS M&O 1997b, pp. 75 to 78).

As discussed later in this section, analysis of the heat transfer processes in the vicinity of a ventilated emplacement drift is a complex problem which cannot be solved by direct analysis. The heat removal by ventilation (thermal energy transferred into the airflow) must be determined by analyzing the thermal conduction, thermal convection and thermal radiation occurring simultaneously in the drift and the surrounding rock mass. This section will provide an explanation of the thermal energy exchange mechanism in ventilated emplacement drifts. The numerical analysis method developed to quantify the heat flow rates and drift temperatures will also be discussed.

6.2 HEAT TRANSFER DURING VENTILATION

When an air flow initially at ambient temperature is applied to an emplacement drift to manage the drift temperature, thermal energy released from a waste package (WP) will be transferred to the surroundings through the following processes, as shown in Figure 1.

1) Convective heat transfers from the surface of the WP directly to the air flow, due to the temperature difference between the surface and the moving air. The heat flow rate can be calculated using Newton's cooling law, if the mean temperature of airflow and the temperature of the WP surface are known.

2) Thermal radiation heat exchange occurs between the surface of the WP and the drift wall. The net rate at which the radiative heat is transferred to the drift wall can be described by the Stefan-Boltzmann Law. Determination of the net thermal radiation will require known WP surface temperature and drift wall temperature.

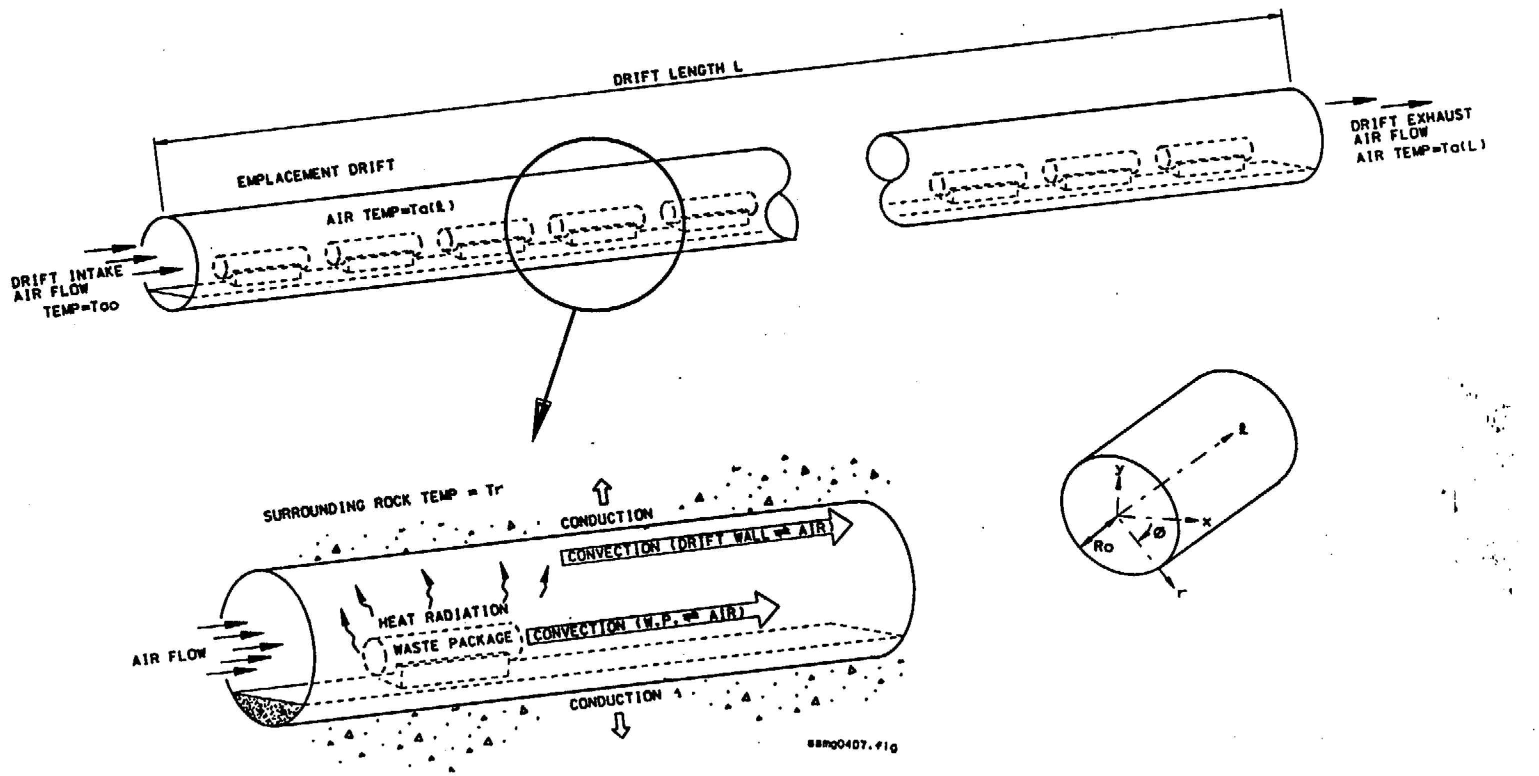

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Figure 1. General Heat Transfer Modes in a Ventilation Drift

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3) Convective heat transfers between the drift wall surface and the air flow, due to the temperature difference between the wall surface and the moving air. The heat flow rate can be calculated using Newton's cooling law, if the mean temperature of airflow and the temperature of drift wall are given.

4) Conduction heat transfer occurs in the rock mass due to increased drift wall temperature caused by thermal radiation to the wall surface. The heat flow rate into the rock can be determined using Fourier's conduction law, after the temperature gradient in the rock mass is specified.

The heat transfer rates and the temperatures resulting from these heat transfer modes are all time-dependent and coupled throughout the entire thermal process.

6.3 VENTILATION MODEL DESCRIPTION

6.3.1 Software

The heat transfer rates for the processes described in the previous section can be related by considering the overall thermal energy conservation (i.e. the sum of convective heat transfer into the airflow and the conductive heat transfer into the rock is equal to the total heat released from the waste emplaced in the drift). However, the problem cannot be directly solved from this relation since both convective and conductive heat transfers are unknown and their solutions will be dependent on each other. Determining the convective heat transfer into the airflow (or, alternatively, the conductive heat transfer into the rock) requires knowledge of both air and drift wall temperatures which are constantly changing with time since emplacement, and the distance from the drift entrance. In other words, the number of energy equations is less than the number of variables involved. Analytical solutions of the coupled air and drift wall temperatures are not possible even with the help of the energy conservation equation. Therefore, it is necessary to develop a calculation method and appropriate assumptions to find approximate solutions.

In pursuing numerical solutions to the problem of quantifying the thermal processes during continuous ventilation, an initial attempt was made to investigate the currently available computer software that may be used to directly solve this problem. It was found that although almost all thermal or thermal-fluid analysis programs perform simulations of thermal conduction, thermal convection and thermal radiation, they require some known parameters (which are variables to be solved in this problem) as input. For example, modeling conductive heat transfer in a solid imposed with both thermal convective and thermal radiative boundaries can only be accomplished under the conditions of known temperatures for the fluid and the radiating surfaces.

To overcome this difficulty, an approach to be used in conjunction with general thermal analysis programs (e.g. ANSYS) was developed for reaching an approximate solution to this problem. In this method, a ventilated emplacement drift is treated as a series of finite drift segments. Thermal analysis with computer models is performed for each drift-section sequentially from the beginning (air-inlet) to the end (air-exhaust) of the drift. Then the heat transfer processes for the entire drift can be evaluated through assembly and comparison of the results from individual segments. Figure 2 is a simple flow chart illustrating the main steps of this process.

As shown in Figure 2, this process starts with defining a number of time-steps (Δt_i) to represent the entire ventilation time period of interest (t_{vent}). The total number of time intervals (n), and the length of each time-step (Δt_i) can be selected according to the degree of calculation accuracy demanded and considerations of the expected computational time. The values of Δt_i may be set differently to accommodate the variations of the thermal decay rate of the waste during different time periods. Generally, during the initial stages when the waste decays rapidly, short time steps can be arranged to justify the use of a constant heat output, which is obtained by averaging the heat output from the waste over a time interval. In the later stages of heat transfer, the thermal decay curves become relatively flat, thus longer time-steps would be desirable in order to reduce computational efforts.

In this approach, the entire drift (total length of L) is considered as a series of connected drift segments with Δl_j in length. The total number of drift segments (m) is related to segment length (Δl_j) It is desirable to choose a short Δl_j for individual drift segments, to the extent practicable, so that the temperature of air traveling within the segment can be reasonably represented by a constant, irrespective of the distance traveled. The values of Δl_j may be set differently to accommodate the variations of air temperature increases as the air flows through the drift.

Calculations are performed sequentially for each time-step, as indicated in Figure 2, from $\Delta t_{i=1}$ to $\Delta t_{i=n}$. Within each time span (Δt_i) thermal analysis with computer models is performed for each drift segment sequentially from the beginning (air-intake) to the end (air-exit) of the drift. The calculating process within each finite drift segment (Δl_j) starts with identification of the initial and boundary conditions within segment (Δl_j) and during time span (Δt_i), which are required by the computer thermal analysis model as input data. Typically, these include the heat output rate (q_{waste}) from the decay of waste, mean temperature of the intake air entering the segment, initial drift wall surface temperature, air flow quantity (Q), and convective heat transfer coefficient (h) for the drift wall surface. Then the thermal modeling using general heat transfer computer software ANSYS is performed to predict the rock temperature distributions in the vicinity of the drift segment. From the outputs of the simulation, an average drift wall temperature of that segment can be found.

Applying the determined average wall temperature together with the mean airflow temperature, convective heat transfer rate in the segment can be calculated using Newton's cooling law. The obtained heat removal rate, and the known airflow rate will enable the determination of the increase in internal thermal energy of the air, and the mean temperature of the air flow exiting the segment, which will be used as the mean temperature of air entering the next segment. The above described process will be repetitively performed until the calculation reaches the end of the drift.

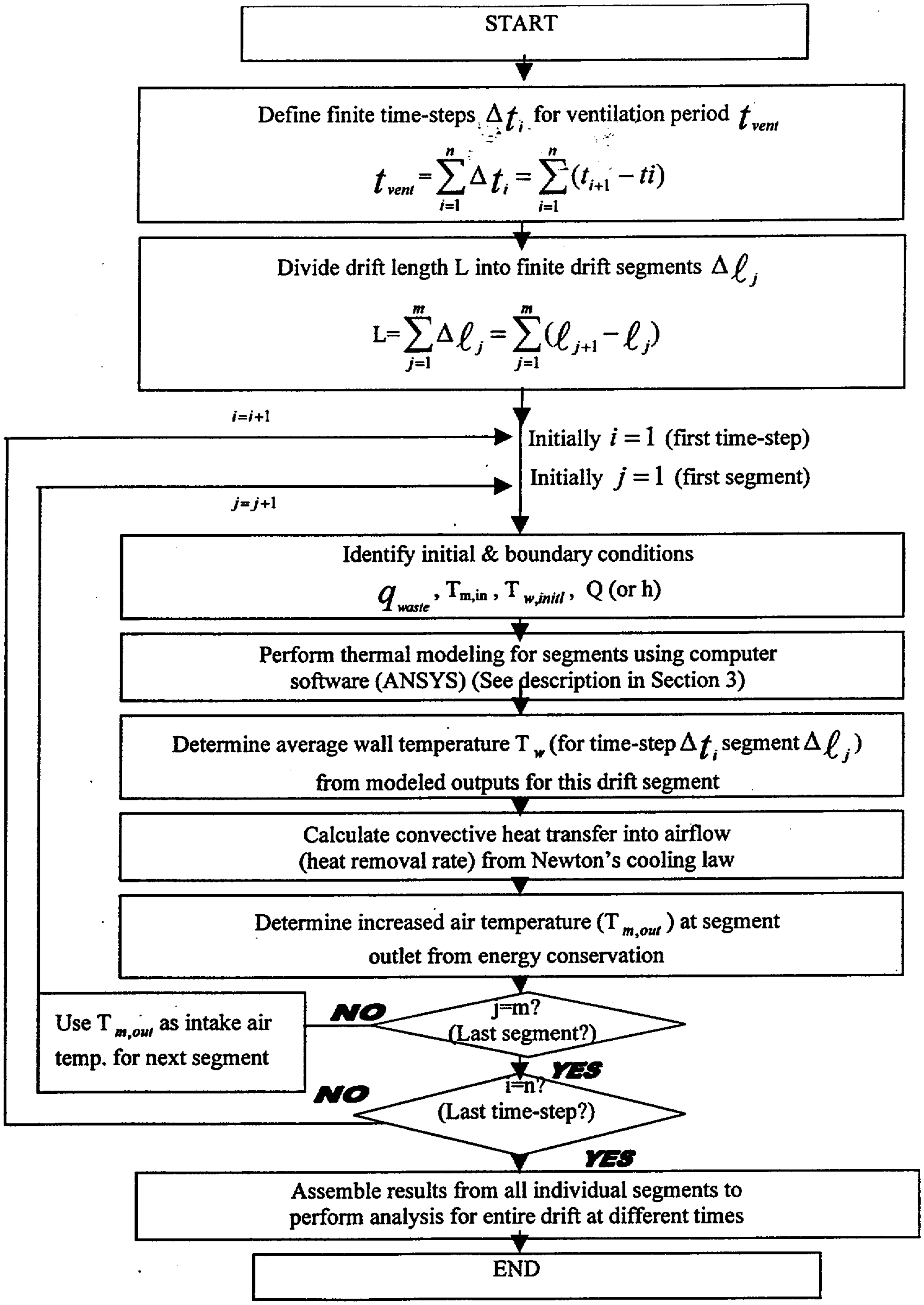

Figure 2 Methodology to Estimate Heat Flows in Ventilation Drift

When calculations of all drift segments are completed for a time-step, the results will be used as inputs to the next time step.

Upon the completion of the required computational efforts for all time-steps, results for all individual segments and time intervals are assembled. The outcome forms a comprehensive description of the heat transfer process for the entire drift at different times after emplacement. With this information, alternative concepts and some subjects regarding emplacement drift temperature management by ventilation may be further evaluated.

6.3.2 Model Setup

The calculation uses the Enhanced Design Alternative (EDA) II as the basis for simulation of the heat transfer process during ventilation. EDA II has the following characteristics (CRWMS M&O 1999e, second para. of Section 5.1., Sections 5.1.1 and 5.1.2):

- Temperature above the boiling point of water in the emplacement drifts.
- Temperatures below the boiling point of water in the center areas of the pillars (areas of rock between emplacement drifts) with the expectation that moisture mobilized at the emplacement drift walls will drain through this pillar region and be transported below the repository.
- Continuous ventilation for fifty years to remove moisture and heat generated prior to closure.
- Backfill and a 2-cm thick titanium alloy drip shield will be placed over the waste packages at closure.
- Close spacing (10 cm between WPs) within a drift (line loading) and 81-m center to center spacing between emplacement drifts.
- Blending of WP composition to achieve an average heat output of 9.8 kW and a maximum heat output of 11.8 kW per package.
- WPs are constructed with 2-cm thick Alloy 22 outer layer and 5-cm thick 316NG stainless steel interlayer.
- Spent Nuclear fuel cladding temperature below 350 °C.
- Closure 50 years after start of emplacement.

The ANSYS program was used to simulate the conditions in the rock mass of the repository based on the EDA II characteristics with ventilation flows of 10, and 15 cubic meters per second (cms). The simulation was performed as follows:

- An emplacement drift was divided into six 100m segments, each represented as a 2-dimensional case.

- ANSYS calculated the drift wall and waste package temperatures for the first segment by assuming the air temperature is constant.

- Given the WP, drift wall, and air intake temperatures, the exhaust air temperature for the first segment is calculated (external to ANSYS).

- This process is repeated for the remaining drift segments.

- The thermal conditions of the rock mass and exhaust air temperature for a given time step were used as inputs for the next time step. The intake air temperature for a time step is the exhaust air temperature from the previous drift segment in the previous time step. Also, the WP heat output varies with time and additional time periods are affected by the thermal decay curve.

- Calculations for the convective heat transfer coefficients used in the modeling are documented in Attachment III.

- Pre-closure ventilation duration of up to 300 years was modeled, but results of temperature and heat removal were plotted and discussed just for up to 200 years in Sections 6.4 and 6.5 of this document.

The block representation used in the calculation are shown in Figure 3. The height of the block is 606.57 m (346.23 m + 262.13 m = 606.57 m) (see Section 4.1.3). The diameter of emplacement drift is 5.5 m (see Section 4.1.9). The boundary temperatures (18.7 °C at the top and 32.40 °C at the bottom) are described in Section 4.1.2.

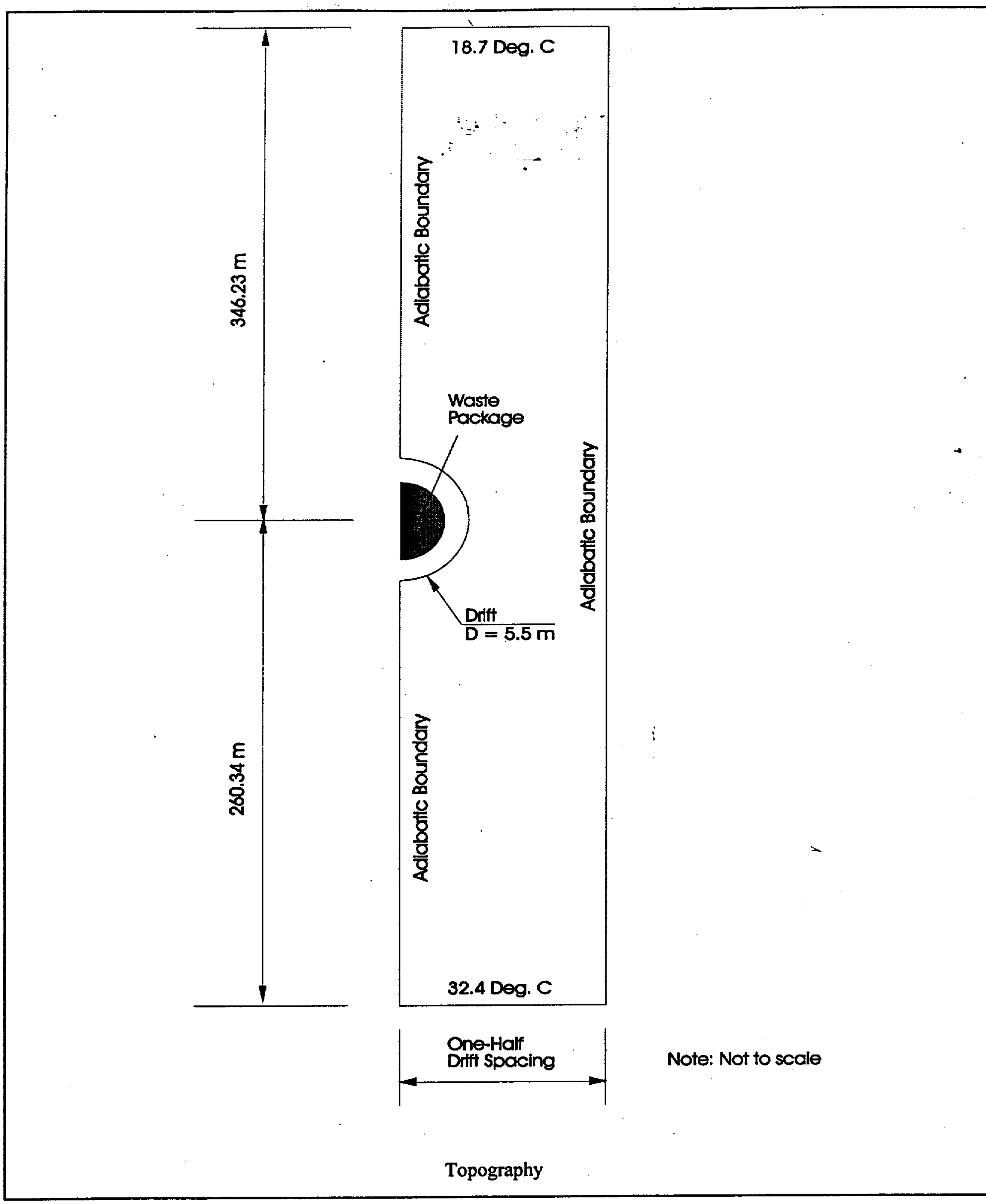

Figure 3 Block Representation of a Typical Drift (Cross Sectional View)

6.4 TEMPERATURE RESULTS

For the two ventilation flow scenarios and ventilation through 300 years after placement, drift wall rock and the exit air temperatures were calculated at various time increments. The calculated results for the drift wall temperatures are shown in Figures 4 and 7. The resultant air temperatures are shown in Figures 7 and 9. Drift wall temperatures presented are averages of the crown, springline and invert temperatures calculated by ANSYS. Air temperatures presented are the calculated values at the end of the segment. Individual wall temperatures and air temperature calculations are presented in Appendix IV.

Wall temperature peaks within the first few years at the air inlet end of the drift and within five to fifteen years at the air discharge end of the drift. Air temperature peaks slightly later at the inlet end of the drift but in the same time frame as the walls at the outlet end. For ventilation of 10 cms, the maximum temperatures calculated occurred at year 10 and are 94° C average wall temperature, with a corresponding maximum air temperature of 79° C. For ventilation at 15 cms, calculated maximums occurred at the same time but were lower, 76° C for the wall and 64° C for air.

Under this continuous ventilation flow scenario all temperatures remain below the boiling point of water.

6.5 HEAT REMOVAL RESULTS

The rate of heat generated and removed with time for the 10 cms and 15 cms ventilation scenarios are presented in Figures 4 through 6, and Figures 7 through 9, respectively. Details of the temperature and heat removal values shown in Figures 4 through 9 are documented in Attachment IV. Heat removal by convective transfer from both the WP surface and from the wall surfaces is accounted for. Heat removal is by dry air, the additional heat removal that will occur if moisture is accounted for is not addressed in these calculations. Heat generated is the same for both scenarios and is the heat produced by average WPs that are placed to produce a linear heat load of 1.55 kW per meter in the drift.

Heat removed by ventilation at the rate of 10 cms has been calculated to be 68% of the heat generated after 50 years, 73% after 100 years, and 77% after 200 years. Heat removed by ventilation at the rate of 15 cms has been calculated to be 74% of the heat generated after 50 years, 78% after 100 years, and 82% after 200 years. Peak removal rates occur within the 5 to 15 year time frame.

From the results of heat removal indicated that for thermal loading cases evaluated in this document, the airflow rate to remove 70% of heat generated during 50-year preclosure (see Section 4.2) will be between 10 to 15 cms per drift.

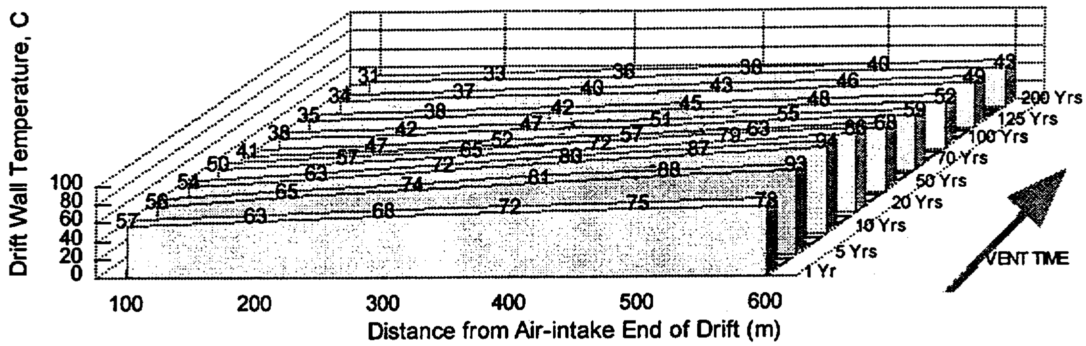

Figure 4 Wall Temperature During Continuous Ventilation at 10 cms.

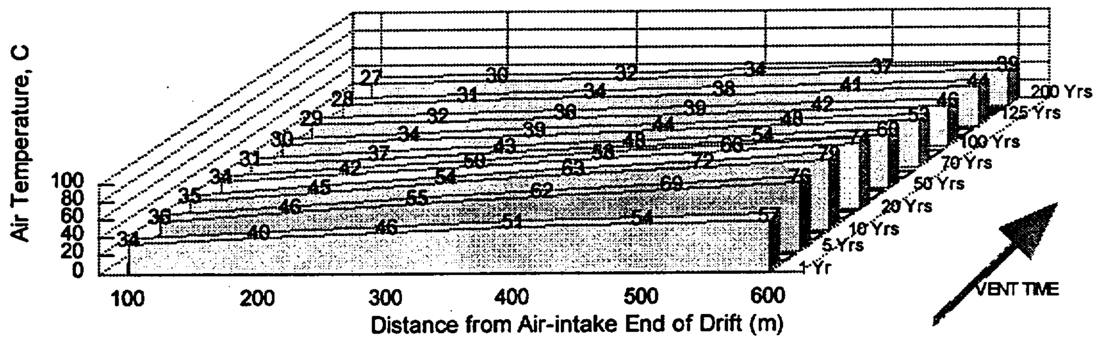

Figure 5 Air Temperature During Continuous Ventilation at 10 cms

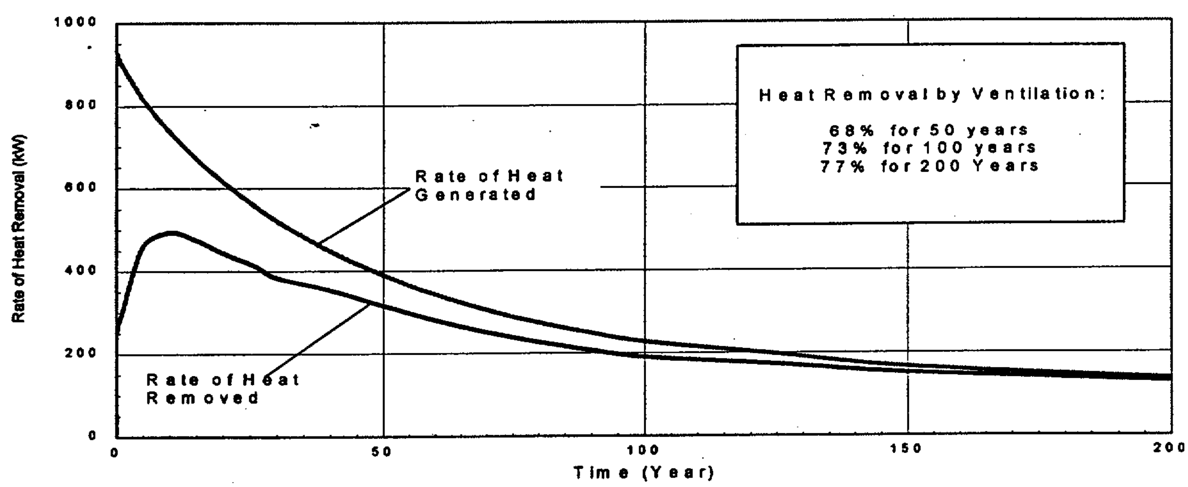

Figure 6 Heat Removed During Continuous Ventilation at 10 cms

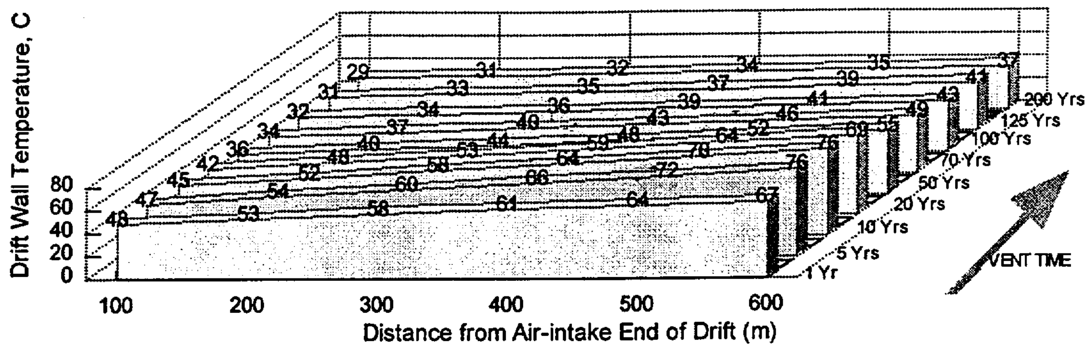

Figure 7 Wall Temperature During Continuous Ventilation at 15 cms

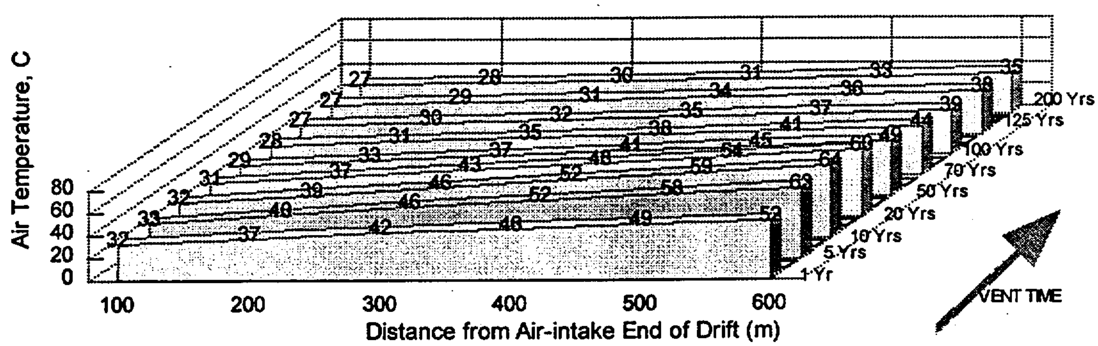

Figure 8 Air Temperature During Continuous Ventilation at 15 cms

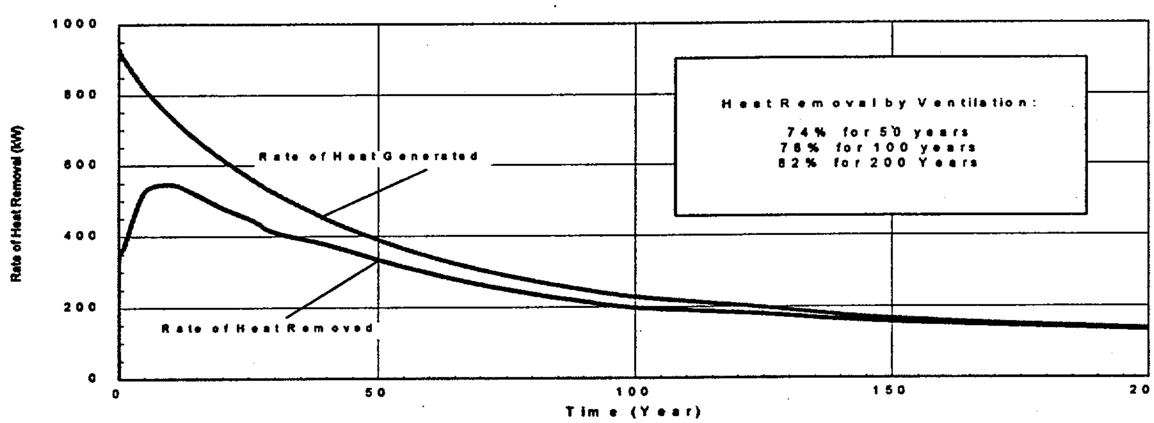

Figure 9 Heat Removed During Continuous Ventilation at 15 cms

6.6 CONSIDERATION OF MOISTURE EFFECTS

The results of temperature and heat removal discussed in Sections 6.4 and 6.5 were based on a consideration that the heat transfer associated water vaporization was negligible. In other words, only "sensible heat" was included in the calculations. "Sensible heat" is the energy associated with increasing the temperature of air at a constant water content, whereas the "latent heat" is the energy associated with vaporizing water and adding it to the air stream. The sensible heat model tends to over-predict the emplacement drift temperature, which is conservative for repository thermal loading and ventilation temperature calculations.

However, the moisture contained in the rock mass, if transported into the ventilation air, will have certain degree of influences on the temperatures and total heat removal. The Spent Fuel Test - Climax conducted in an underground testing facility for a period of about 3 years showed that about 76.7% of the heat removal by ventilation was associated with "sensible heat", and 23.3% was associated with "latent heat" (CRWMS M&O 1997, p. 86).

Determination of the potential latent heat in a ventilated emplacement drift requires description of water movement within the rock during ventilation. The rate at which the water is transported to the drift surface contacted with the airflow, and the time duration of the water movement in the surrounding rock mass must be evaluated. A coupled simulation program, known as MULTIFLUX, was developed for the Yucca Mountain Project to model the psychrometric environment in and around the emplacement drift (Danko et al.1998, p. 762). This program is currently being validated in accordance with the quality administrative procedure for software management, and may be available for modeling the repository ventilation with consideration of moisture effects. To demonstrate the overall approach developed to simulate the coupled heat and mass transfer problem during ventilation, the major processes of the program is discussed below.

The MULTIFLUX program is developed by University of Nevada, Reno (UNR) under the contract with the CRWMS M&O. The MULTIFLUX is coupled to the NUFT (Non-isothermal Unsaturated-Saturated Flow and Transport), a thermal hydrologic model, developed by Lawrence Livermore National Laboratory. The NUFT software is capable of analyzing flow (moisture mass transport or infiltration) and coupled mass and energy transport in geological media by conduction, convection, and diffusion with multiple gas and liquid phases including phase change.

The MULTIFLUX program uses a predetermined number of NUFT runs to solve the heat and moisture mass transfer in the rock. These runs will establish relationships among the rock temperature, partial vapor pressure, heat flux, and moisture flux at the drift wall surfaces. Then, the MULTIFLUX performs the airway model that solves the heat and mass transfer within predefined drift segments. This airway model is based on computational fluid dynamic (CFD) and is designed to model the heat and mass transfer in and around the subsurface opening. The calculation using the airway model is repeated until the drift wall heat flux and temperatures match at selected axial nodes. Then the exit air temperature and humidity from a drift segment will be used as the inlet conditions for the next segment. This process is repeated for successive drift segments until temperature, saturation, and humidity values have been calculated for the entire drift. Then, the above steps are iterated for successive time intervals of ventilation time.

Preliminary calculations performed previously during the development of the program (CRWMS M&O 1996, Section 5.3) will be discussed in this paragraph. Although the thermal loading arrangement considered at that time (83 MTU/acre, 22.5-m drift spacing and 16-m WP spacing) was different from the current concept, it can be used to illustrate the overall effect of moisture removal on the repository thermal conditions. The results indicated that emplacement drift ventilation is capable of removing significant amount of water out of the repository system. The total water removal from a 600-m long drift in 100-years of ventilation was calculated to be 3 to 9×10^6 kg for airflow rates ranging from 0.1 to 10 m^3/s. The previous calculation showed that during the ventilation of 10 m^3/s, the maximum drift wall temperature was 51 °C for heat-only model, and 45 °C for the coupled heat/moisture model. The lower temperatures predicted with the coupled heat/moisture model were due to the additional heat being removed through the latent heat of vaporization.

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7. CONCLUSIONS

The unqualified input data used for the analysis work performed in this document are identified and listed with TBV numbers in the Section 4 and Attachment I of this document. The results of this report are considered unqualified.

This report addressed the preliminary ventilation model to be used to analyze the effects of pre-closure continuous ventilation in the EBS emplacement drifts. Based on the information and discussions presented in the previous sections, the following conclusions are made:

- Heat transfer processes during continuous ventilation of emplacement drifts were evaluated. A method that can be used to model the thermal conditions in and around the emplacement drifts was developed and documented in this report.

- Numerical analyses were performed using the heat-only model for airflow rates of 10 and 15 m^3/s. The results indicate that use of ventilation with appropriate airflow rate is capable of removing heat from emplacement drifts and is capable of controlling emplacement drift temperatures.

- The modeling results for ventilation of 10 m^3/s showed that the maximum drift wall temperatures of 94° C occurred at year 10, with a corresponding maximum air temperature of 79° C. For ventilation airflow rate of 15 m^3/s, calculated maximums occurred at the same time but were much lower, 76° C for the drift wall and 64° C for the airflow.

- Heat removed by ventilation at the rate of 10 m^3/s has been calculated to be 68% of the heat generated after 50 years, 73% after 100 years, and 77% after 200 years. Heat removed by ventilation at the rate of 15 m^3/s has been calculated to be 74% of the heat generated after 50 years, 78% after 100 years, and 82% after 200 years. Peak rates of heat removal occur within the 5 to 15 year time frame. For thermal loading cases evaluated in this document, the airflow rate to remove 70% of heat generated during 50-year preclosure (see Section 4.2) will be between 10 to 15 cms per drift.

- Moisture contained in the rock mass, if transported into the ventilation air, will have certain degree of influences on the temperatures and total heat removal. The principle steps of a coupled simulation program developed to model the psychrometric environment in the emplacement drift were described. Further study of the moisture effects on heat removal and temperature management may be conducted.

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8.2 PROCEDURES

AP-2.1Q, *Indoctrination and Training of Personnel*

AP-2.2Q, *Establishment and Verification of Required Education and Experience of Personnel*

AP-2.13Q, *Technical Product Development Planning*

AP-3.4Q, *Level 3 Change Control*

AP-3.10Q, *Analyses and Models*

AP-3.14Q, *Transmittal of Input*

AP-3.15Q, *Managing Technical Product Inputs*

QAP-2-0, *Conduct of Activities*

QAP-2-3, *Classification of Permanent Items*

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9. ATTACHMENTS