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Thermal Management and Analysis for a Potential Yucca Mountain Repository

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1. Introduction

In the current Yucca Mountain repository design concept, heat from the emplaced waste (mostly from spent nuclear fuel) would keep the temperature of the rock around the waste packages higher than the boiling point of water for hundreds to thousands of years after the repository is closed. The design concept allows below-boiling portions of the pillars between drifts to serve as pathways for the drainage of thermally mobilized water and percolating groundwater by limiting the distance that boiling temperatures extend into the surrounding rock. This design concept takes advantage of host rock dry out, which would create a dry environment within the emplacement drifts and reduce the amount of water that might otherwise be available to enter the drifts and contact the waste packages during this thermal pulse. Table 1 provides an overview of design constraints related to thermal management after repository closure.

Table 1. **Design Constraints Related to Postclosure Thermal Management for the Higher Temperature Operating Mode**

REPOSITORY FEATURE	CONSTRAINT	PURPOSE
Zircaloy clad fuel assemblies	Cladding temperature not to exceed 350C	Protect cladding integrity
Emplacement drifts	Achieve average thermal line loading of 1.45 kW/m of drift length	Allow full utilization of repository within thermal constraints
Waste packages	Thermal load per package should not exceed 11.8 kW at emplacement	Allow full utilization of repository within thermal constraints
Emplacement drift wall	Temperature not to exceed 200C postclosure	Prevent potentially undesirable mineral changes in host rock

The Yucca Mountain repository design concept also provides flexibility to allow for operation over a range of lower thermal operating conditions. The thermal conditions within the emplacement drifts can be varied, along with the relative humidity, by modifying operational parameters such as the thermal output of the waste packages, the spacing of the waste packages in the emplacement drifts, and the duration and rate of active and passive ventilation. A lower range has been examined to quantify lower-temperature thermal conditions (temperatures and associated humidity conditions) in the emplacement drifts and to quantify impacts to the required emplacement area and excavated drift length. This information has been used to evaluate the potential long-term performance of a lower-temperature repository and to estimate the increase in costs associated with operating a lower-temperature repository.

This presentation provides an overview of the thermal management evaluations that have been conducted to investigate a range of repository thermal conditions and includes a summary of the technical basis that supports these evaluations. The majority of the material presented here is summarized from the Yucca Mountain Science and Engineering Report [1]. A companion paper in this publication entitled "Characterizing the Evolution of the In-Drift Environment in a Proposed Yucca Mountain Repository" schematically illustrates the processes being controlled through the management of thermal loading in its Figure 3.

2 Thermal Management

The statutory capacity of the Yucca Mountain repository is 70,000 metric tons of heavy metal (MTHM). This is to be allocated between 63,000 MTHM commercial spent nuclear fuel (CSNF) and 7,000 MTHM defense spent nuclear fuel (DSNF) and high-level waste (HLW). An areal mass loading of approximately 60 MTU/acre, combined with pre-closure ventilation that is to continue for at least 50 years beyond the time emplacement is completed, will prevent the boiling zones from coalescing in the pillars between emplacement drifts. Waste packages are placed in the emplacement drifts in a line load configuration with a waste package to waste package spacing of approximately 10 cm. The diameter of a waste emplacement drift is 5.5 m. Emplacement drifts are arranged with a uniform spacing of 81 m between their centerlines. The total emplacement drift length is calculated from adding the waste package inventory and the package-to-package gaps. The emplacement area encompasses just over 60 kilometers of emplacement drift length.

This paper focuses on commercial spent nuclear fuel waste forms since they are the dominant waste form to be disposed. Other waste forms have relatively low heat-generation rates and a correspondingly lesser effect on the thermal performance of the repository. Each spent nuclear fuel assembly has a specific set of characteristics including enrichment, burnup, and age. These characteristics determine how much thermal power each assembly produces and the rate of decline of that power. Waste package heat output at emplacement is required not to exceed 11.8 kW in order to be compatible with the current design's thermal goals.

Thermal conditions in the postclosure repository can be managed by altering several operational design features. These features include (1) varying the thermal load to the repository by managing the thermal output of the waste packages; (2) managing the period and rate of drift ventilation prior to repository closure; and (3) varying the distance between waste packages in emplacement drifts. Other parameters such as post-emplacement natural ventilation could also be used to reduce long-term repository temperatures. These factors are described in the following paragraphs.

2.1 Thermal Output of Waste Packages

The thermal load of a repository is directly related to the amount of thermal energy contained in the waste packages. The fuel inventory can be managed by manipulating one or more features: (1) fuel blending (i.e., placing low heat output fuel with high heat output fuel); (2) de-rating (i.e., limiting the number of spent fuel assemblies to less than the waste package design capacity); (3) placing high heat output fuel in smaller waste packages; or (4) aging in a surface storage facility.

2.2 Duration and Rate of Forced Ventilation

During active repository operations, some of the heat generated by the waste and the moisture in the surrounding rock could be removed from the repository by forced ventilation of the loaded emplacement drifts. The amount of energy transferred from the waste to the host rock can be managed by varying duration and the rate of emplacement-drift ventilation.

2.3 Distance between Waste Packages

As waste packages are spaced further apart, the average linear thermal density in the drift (measured in kilowatts of heat output per meter of drift length) decreases, delivering less heat per unit volume of the host rock when the drift-to-drift spacing remains fixed. Note that the distance between emplacement drifts has some effect on the thermal response of the repository as temperature profiles from adjacent drifts interact with one another. However, the use of drift spacing in controlling repository thermal response is not considered further in this discussion, and is fixed at the current design value of 81 meters.

2.4 Natural Ventilation

Heat from the waste will induce natural convective airflow currents through the emplacement drifts, resulting in passive removal of heat. To facilitate natural ventilation, the ventilation system could be enhanced through a combination of air balancing techniques, such as size of ventilation shaft diameters, location and number of intake/exhaust openings, and flow controls.

Figure 1 illustrates the engineered system variables associated with spent nuclear fuel assemblies, waste packages, and in-drift emplacement that affect repository performance. Changing these variables through design modification or preclosure operation would directly impact the postclosure thermal response of the repository and in turn influence the postclosure in-drift environment of the repository, which is described in the companion paper in this volume entitled "Characterizing the Evolution of the In-Drift Environment in a Proposed Yucca Mountain Repository." These impacts may affect performance of the repository's engineered barriers.

Examples of some operational objectives considered in thermal management evaluations are:

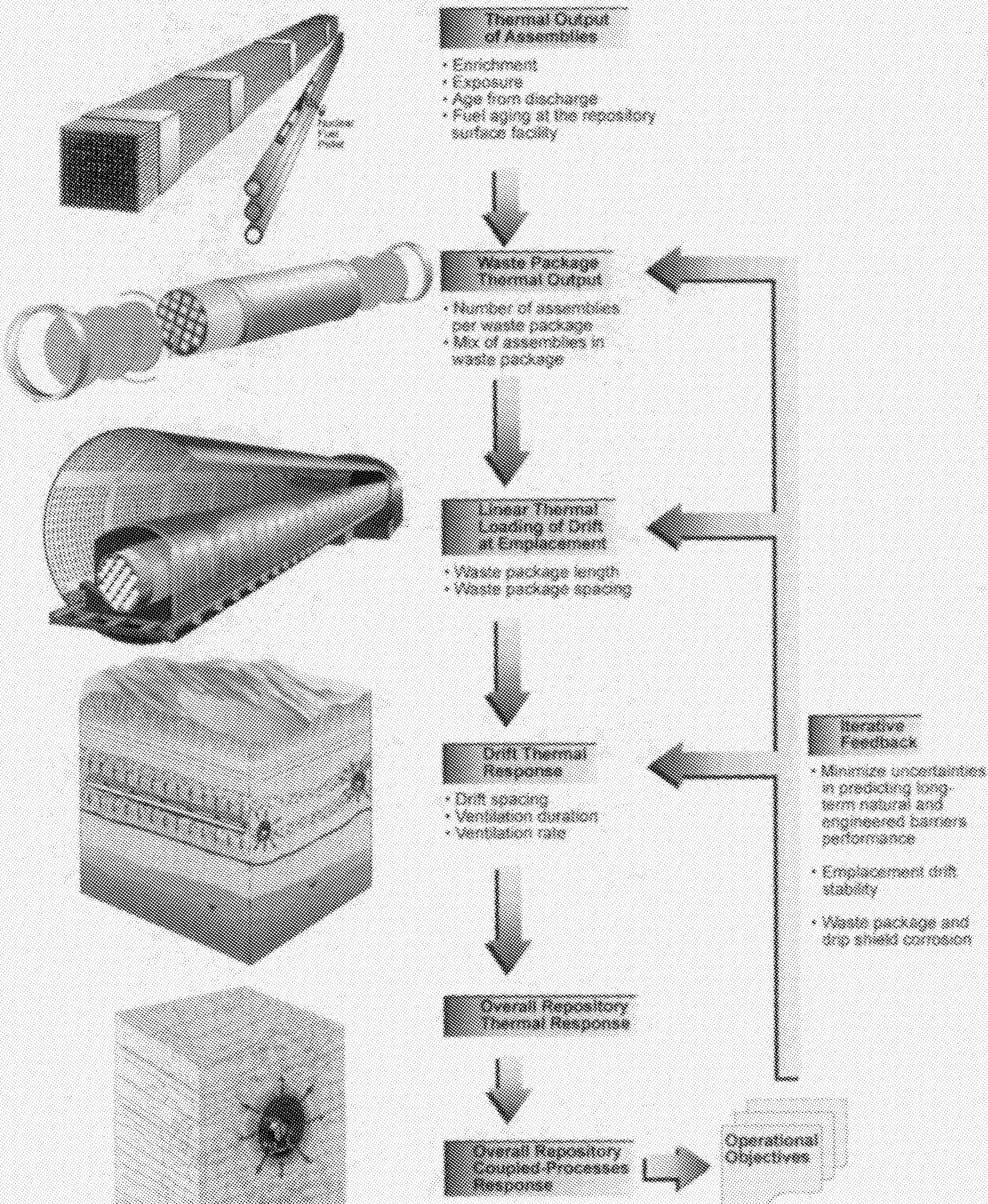
- **Waste Package Performance:** Operating the repository such that the combination of in-drift temperature, relative humidity, and chemical conditions on the waste package outer surface do not lead to enhanced corrosion. A possible lower temperature operating mode objective may be to minimize chemistry changes in water in the rock.

- **Drift wall and Pillar temperatures:** In the current design, the rock temperatures in the first several meters of the emplacement drift exceed the boiling point of water. The primary temperature objective is to ensure that boiling fronts do not coalesce at pillar centers to ensure that water can drain freely between pillars. A possible lower-temperature objective would be to keep the rock in the repository below the boiling point of water, minimizing the movement of water and associated chemical changes.

- **Capacity for waste inventory:** ensure that the repository has the capacity to contain the specified inventory of 70,000 MTHM.

- **Duration of Ventilation Period:** the repository has been designed to support ventilation throughout a preclosure operational period of 100 years. However the thermal analyses have been performed to demonstrate that the thermal goals can be achieved with 50 years of post-emplacement ventilation. This removes approximately 85% of the decay heat during the preclosure period, with a ventilation rate at or above $15 m^3/s$ per drift.

Figure 1. **Variables affecting thermal performance of the Yucca Mountain Repository**



3. Comparison of Thermal Operating Modes

This section compares five examples of lower-temperature operating modes. These examples provide a preliminary basis for understanding the technical and cost issues associated with developing a particular operating mode. The examples illustrate the effects that varying operational parameters can have in achieving an objective of lower temperatures. The primary reason to select a lower temperature operating mode for the repository is to reduce uncertainties associated with the processes coupled with moving boiling fronts, which include hydrological, geochemical and mineralogical effects. The primary reason to select a hotter operating mode is to increase repository efficiency by reducing the excavated area. An evaluation of relative uncertainties and system performance for cooler and hotter operating modes showed differences to be insignificant, however, justifying the decision to select the hotter mode for development. The discussion of the lower and higher thermal modes is given below to illustrate the design input to the larger selection process.

Table 2 compares operational parameters used to achieve the different lower-temperature operating modes. The first four lower-temperature operating modes have the objective of maintaining waste package surface temperature below 85 °C, the last scenario has the objective of maintaining the waste package surface temperature below 96 °C (the boiling temperature at the elevation of the repository horizon). As noted in the table, parameters are separated into variable, or independent, parameters and dependent parameters. The variable parameters considered include waste package spacing, linear thermal loading, the duration of forced ventilation, and the duration of natural ventilation after forced ventilation.

Results summarized in the table indicate that reducing peak waste package temperatures so that peak temperatures remain below 85C would require a significant reduction in the linear thermal load in each drift. In addition, scenarios 1 – 4 would require a larger repository area. However, if ventilation can be extended well beyond 100 years, meeting the goal of temperatures at or below 85C would not require as much expansion of the disposal area, but would add significant cost.

Field and laboratory thermal testing during site characterization has aided the development and validation of thermal models used to calculate ventilation and thermal-hydrologic processes at Yucca Mountain. 1/4-scale ventilation tests have also been conducted to provide heat transfer data to support validation of the preclosure ventilation model. The field test program has included in chronological order the Large Block Test (conducted at the surface near Yucca Mountain), the Single Heater Test, and the Drift Scale Test (DST). These tests have supported significant advances in thermal-hydrology understanding and modeling.

4. Conclusions

A program of testing, analysis and modeling has allowed the prediction of long-term thermal effects in the potential Yucca Mountain repository to be evaluated. This capability, in turn, allowed the setting of a number of thermal goals and constraints to describe a preferred, higher temperature alternative and several lower thermal loading scenarios. The thermal loading of the potential repository can be managed to meet thermal goals. This involves the designing of the physical layout and specifying the thermal loading of the repository, in combination with specifying the duration and intensity of active and passive heat removal through forced ventilation. Taking advantage of natural ventilation can also be optimized through design. Allowing heat to build up in the repository removes moisture from the emplacement drifts during the time when the waste package is somewhat more susceptible to corrosion than it is after the thermal pulse. Controlling the extent of the boiling zone to be but a fraction of the pillar thickness allows for drainage of condensing and percolating waters between drifts during the period of higher temperatures. Thermal management allows control of the range of environments likely to be seen by waste packages during the thermal period.

5. Acknowledgements

The material presented here is summarized from the Yucca Mountain Science and Engineering Report [http://www.ocrwm.doe.gov/documents/ser_b/index.htm] and from a series of Yucca Mountain Project presentations recently made and in turn based on documents currently in preparation. The help of personnel from the Operating and Management contractor for the Yucca Mountain Project, Bechtel-SAIC LLC, and its affiliated national laboratories, is appreciated and acknowledged. Particular thanks go to Robert MacKinnon of Sandia National Laboratories for compiling much of the information reported in this paper.

Table 2. **Comparison of Operational Parameters for a Higher Temperature Operating Mode and Five Examples of Lower Thermal Operating Modes**

		Example Lower Thermal Operating Modes				
		1	2	3	4	5
Parameters	Higher-Temperature Operating Mode	Increased WP Spacing and Extended Ventilation	De-Rated or Smaller WPs	Increased Spacing and Duration of Forced Ventilation	Extended Surface Aging with Forced Ventilation	Extended Natural Ventilation
Variable Parameters						
WP Spacing (m)	0.1	2	0.1	6	2	0.1
Maximum WP thermal loading (kW)	11.8	11.8	<11.8	11.8	<11.8	11.8
Linear thermal loading (kW/m) at emplacement	1.45	1	1	0.7	0.5	1.45
Years of Forced Ventilation after emplacement	50	75	75	125	125	75
Years of natural ventilation after forced ventilation	0	250	250	0	0	>300
Dependent Parameters						
Size of PWR WPs	21	21	<21	21	21	21
Total excavated drift length (km)	~60	~80	~90	~130	~80	~60
Required emplacement area (acres)	~1,150	~1,600	~1,800	~2,500	~1,600	~1,150
Average WP maximum temperature (°C)	>96	<85	<85	<85	<85	<96