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EDA II DESIGN FOR THE ENGINEERED BARRIER SYSTEM FOR THE POTENTIAL YUCCA MOUNTAIN REPOSITORY: THE IMPACT ON COUPLED PROCESSES AND REPOSITORY PERFORMANCE

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ABSTRACT

If the U. S. Department of Energy (DOE) submits a license application for a high-level waste repository at Yucca Mountain, the U. S. Nuclear Regulatory Commission (NRC) will need to evaluate DOE's assessment of the impact of coupled thermal-hydrologic-chemical (THC) processes on the projected post-closure performance of the repository. THC processes are largely controlled by the thermal design of the repository and the engineered materials used in the emplacement drifts. During its pre-licensing interactions with DOE, the NRC staff received preliminary information on a possible DOE design that involves a 30 percent lower thermal-load design than was assumed in the recently completed Viability Assessment. This design also includes new engineered features (e.g., a drip shield and backfill) and materials (Ti in the drip shield and undetermined backfill material). NRC's evaluation of this preliminary information addressed DOE's assessment of THC processes, and their effect on the projected post-closure performance, and included a review of DOE's performance assessment scenario analysis, independent process model calculations, total-system performance calculations, and bounding calculations. The NRC evaluation used acceptance criteria and review methods that would be generally consistent with a risk-informed performance-based review of a potential repository license application. We determined that DOE has, in general, developed a comprehensive delineation of the features, events and processes affecting repository performance. However, our preliminary evaluation developed questions concerning the importance of some coupled processes on repository performance we believe will need to be addressed by DOE.

INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) staff is developing the technical skills, tools, and regulatory framework for reviewing a potential license application for a high-level radioactive waste (HLW) repository at Yucca Mountain, Nevada. The potential license applicant is the U.S. Department of Energy (DOE). A risk-informed performance-based regulatory philosophy has been adopted by the NRC (1). Development of NRC HLW regulatory capabilities and conduct of its activities are guided by this philosophy. NRC's strategic plan calls for the early identification and resolution of issues at the staff level (1). The issue resolution approach attempts to reduce the number of, and to better define issues that may be in dispute during the NRC licensing review (2). The NRC HLW program has focused its pre-licensing technical work and its issue resolution activities on those topics most critical to the post-closure performance of the potential geologic repository (3). These topics are called Key Technical Issues (KTIs) and progress reports on the status of issue resolution, known as Issue Resolution Status Reports (IRSRs), are updated for each of the KTIs.

One of the KTIs that the NRC is evaluating during the pre-license application period is the Evolution of the Near Field Geochemical Environment (ENFE). The ENFE team is investigating coupled thermal-hydrologic-chemical (THC) processes that could occur in the potential repository as a result of the introduction of the heat-generating nuclear waste, and engineered materials, into the emplacement drifts (2). Coupled THC processes could affect four areas of repository performance. First, coupled THC processes will influence the movement of water and air through the mountain. Degradation of both the engineered materials and the radioactive waste, and the release and transport of radionuclides are dependent upon the amount of water entering the emplacement drifts. Second, coupled THC processes determine the chemistry of water contacting engineered barriers of the repository. The rate of degradation of the engineered barriers is a function of the chemistry of the water contacting them. Third, coupled THC processes control the chemistry of water contacting the radioactive waste forms. The chemistry of the water contacting the waste forms determines the rates of degradation of the waste forms and the release of radionuclides. Finally, transport of radionuclides to the biosphere will be affected by coupled THC processes. The coupled THC processes could transform potentially sorptive minerals to minerals that will be less effective at retarding the transport of radionulicdes. The coupled processes that will occur and their spatial and temporal extent will depend on the materials used in the engineered barrier system and repository design.

The ENFE team's evaluation to date has addressed the likely impacts of the Enhanced Design Alternative II (EDA II) design (4) on coupled processes in the near-field environment[a]. We have partially reviewed information concerning the DOE's performance assessment scenario analysis, including a preliminary version of their features, events, and processes (FEP) database (5). Our evaluation also includes conducting bounding calculations, modeling coupled processes using the coupled reactive transport code MULTIFLO (6,7,8), and running sensitivity studies using the TPA performance assessment code (9,10) to assess coupled THC processes associated with the EDA II design. This paper discusses how the EDA II design may affect the coupled processes that could occur at a potential Yucca Mountain repository, and the potential impacts on the post-closure repository performance. Our evaluation used acceptance criteria contained in the Total System Performance Assessment & Integration (TSPAI) IRSR (11), and is also presented.

Regulatory Tools

The ENFE team is assessing which coupled processes may occur and their potential importance to repository performance using several tools and approaches (2). Coupled processes are quantitatively assessed by the NRC through use of numerical codes for both process-level models and a total-system performance assessment model (9,12,13). In the first approach, coupled processes are evaluated using a stand-alone heat and mass transfer code. The NRC has sponsored the development of the MULTIFLO numerical code (6,7,8) to evaluate the details of coupled processes that may occur. MULTIFLO allows analyses to be conducted at various scales (e.g., drift-scale or mountain-scale). The code can be used to assess both coupled thermal-hydrologic (TH) and THC processes (13,14). These types of calculations provide insights on which coupled THC processes may occur, and the possible spatial and temporal extent of the process (13). However, detailed coupled process models do not provide direct insights into the likely impact of coupled processes on repository performance.

NRC has developed the TPA code (9,10) as a tool to evaluate quantitatively the safety case that could be made by the DOE if it were to submit a potential license application for the proposed repository at Yucca Mountain, Nevada. The TPA code is designed to estimate total-system performance measures of annual individual dose or risk and is developed through iterative performance assessment activities. The code is designed to simulate the behavior of the potential geologic repository, taking into account the essential characteristics of the natural and engineered barrier systems. Coupled processes are represented in the TPA code as abstracted results of process-level MULTIFLO calculations (9). Thus the impacts of coupled processes on repository performance can be assessed through the use of the TPA code (2,12,15). Both the MULTIFLO and TPA codes are used by the NRC to further issue resolution on the ENFE issue (2) in pre-licensing interactions with DOE, and to assist in the development of a risk-informed performance-based regulatory framework for the potential Yucca Mountain repository. For the potential license application, the DOE will use its own performance assessment code to support its safety case.

Regulatory Framework

Federal regulations applicable to the geologic disposal of HLW at Yucca Mountain, Nevada, have been proposed by the U.S. Environmental Protection Agency (EPA) and the NRC (16,17). Both EPA's proposed environmental radiation protection standard at 40 CFR Part 197 and NRC's proposed implementing regulation at 10 CFR Part 63 would require that DOE conduct a performance assessment to determine compliance with the standard for a 10,000 year post-closure period (16,17). NRC's proposed regulations specify, at Section 63.114, certain criteria that such a performance assessment must satisfy.

The NRC staff is also developing a review plan to evaluate a potential DOE license application for the potential Yucca Mountain repository (18). Both the Yucca Mountain Review

Plan (YMRP) and 10 CFR Part 63 incorporate NRC's risk-informed and performance-based regulatory approach. The YMRP will contain acceptance criteria and review methods (18). The YMRP acceptance criteria for the performance assessment for the post-closure period will be risk-informed and performance-based and generally are expected to be similar to the acceptance criteria contained in the NRC's TSPA&I IRSR (11). The post-closure portion of the YMRP will also likely contain acceptance criteria on the system description and demonstration of multiple barriers; scenario analysis; model abstraction; and demonstration of compliance with the overall performance objective (18). Review methods for some of these topics may be derived from the acceptance criteria contained in the other KTI IRSRs (18).

NRC's evaluation of DOE's total-system performance assessment for the Viability Assessment (TSPA-VA) was based upon the acceptance criteria and review methods contained in the NRC's Issue Resolution Status Reports (11,19). The next major DOE milestone is the Site Recommendation (20). DOE will conduct a total-system performance assessment as part of the Site Recommendation (this is known as the TSPA-SR) (20). To the extent appropriate, the YMRP may be used by the NRC staff to assist or inform its evaluation of any site suitability report submitted by DOE as part of its the Site Recommendation (18).

ENHANCED DESIGN ALTERNATIVE II

The EDA II design is substantially different from the design used by DOE in their recently completed Viability Assessment (21). The EDA II design includes: introduction of titanium drip shields; the absence of concrete emplacement drift liners; introduction of backfill; lowering of the thermal load; introduction of active ventilation during the pre-closure period; and changing from a point loading strategy for waste packages to a line loading strategy (Table I). These aspects of EDA II could have important effects on the evolution of the near-field environment and must be addressed.

Preliminary analysis suggests that some near-field coupled THC technical problems are probably lessened by the EDA II design. Non-coalescing boiling isotherms, a result of the lower thermal load and wider emplacement drift spacing, will likely simplify thermal-driven reflux and seepage issues (4). The absence of concrete drift liners simplifies near-field chemistry and lessens potential chemical-driven hydrologic changes in the drift vicinity. The lower temperatures may simplify and lessen the spatial and temporal extent of changes to water and mineral chemistry. However, the EDA II design could introduce technical uncertainty because some of the near-field coupled technical issues are relatively unstudied. For instance, the effects of the titanium drip shield on the near-field chemical and flow environment needs to be evaluated. Steep thermal gradients due to backfill and the effects of backfill on seepage are relatively unstudied in the potential repository environment. Interactions between and due to new or undefined materials, such as backfill, have also increased uncertainty in potential repository performance.

DOE is conducting current laboratory tests, at a one-quarter scale drift size, as part of the engineered barrier system (EBS) development (22). One of the basic issues evaluated by EBS testing is verification of performance of the EBS. The testing will evaluate the effect of components of the EDA II design (i.e., drip shield and backfill) on overall EBS performance (22). The primary emphasis of the testing program is on heat and mass transfer processes in the drift environment. The in-drift geochemical environment model assumes that the coupled THC processes can be decoupled, calculated separately, and linked (20). In addition, the model assumes that a set of mixing cells can be used to represent the spatial domain of the drift (20). The ENFE team identified questions concerning whether the current test plan will result in validation of the model assumptions. For instance, seven different potential backfill materials are being characterized (23). However, only one potential backfill material is used in the one-quarter scale thermal tests (24). In addition, the ENFE team identified possible questions on the treatment of chemical processes in a preliminary (Revision 00) in-drift analysis model report for coupled thermal, hydrologic, and chemical processes (25). Currently the model excludes any chemical interactions between engineered materials and water and does not consider any effects on hydrologic properties resulting from coupled THC processes.

PERFORMANCE ASSESSMENT SCENARIO ANALYSIS

An important element of a license application for a geologic repository for HLW is an analysis of repository safety considering potential future conditions to which a repository may be subjected during the period of regulatory concern (11). Scenario analysis addresses those features, events, or processes (FEPs) necessary to describe what can reasonably happen to the repository system and includes assumptions about the repository system and the processes and events that can affect that system. Because there are many possible ways in which the geologic repository environment can evolve, the goal of scenario analysis in a license application generally should be to evaluate repository performance for a sufficient number of these possible evolutions to support a defensible representation of performance. Thus, to support a licensing determination a satisfactory scenario analysis should ensure a comprehensive consideration of the possible future states of the repository system.

Table I. Comparison of Enhanced Design Alternative II and Viability Assessment Design

Design Characteristics	EDA II	Viability Assessment
Areal mass loading (kgHM/m^2) [MTHM/acre]	14.8 [60]	21 [85]
Drift spacing (m) [ft]	81 [265.8]	28 [91.9]
Drift diameter (m) [ft]	5.5 [18]	5.5 [18]
Length of emplacement drifts (km) [mile]	54 [33.6]	107 [66.6]
Repository area (km^2) [acre]	4.3 [1060]	3 [740]
Ground support	Steel sets	Concrete lining
Invert	Steel with sand or gravel ballast	Concrete
Number of Waste Packages	10,039	10,500
Waste package materials and thickness (cm) [inch]	2 cm [0.8] Alloy-22 over 5 cm [2.0] Stainless Steel (316L)	10 cm [3.9] carbon steel over 2 cm [0.8] Alloy-22
Waste package spacing (cm) [inch]	10 cm [3.9] (line loading)	Spacing varies; several meters (point loading)
Maximum waste package capacity (Power Water Reactor (PWR) spent fuel assemblies)	21	21
Peak to average heat output for PWR package	120%	195%
Drip shield (emplaced at closure)	2 cm [0.8 inch] Ti-7	None
Backfill (emplaced at closure)	Yes	None
Pre-closure period (years)	50	50
Pre-closure ventilation rate (m^3/sec) [ft^3/sec]	2 - 10 [70.6 - 353.1]	0.1 [3.53]

The proposed rule 10 CFR Part 63 addresses the use of scenario analysis in the licensing requirements for a performance assessment (17). Section 63.114 would require that DOE:

- "Consider alternative conceptual models of features and processes that are consistent with available data and current scientific understanding, and evaluate the effects that alternative conceptual models have on the performance of the geologic repository."

- "Consider only events that have at least one chance in 10,000 of occurring over 10,000 years."

- "Provide the technical basis for either inclusion or exclusion of specific features, events, and processes of the geologic setting in the performance assessment. Specific features, events, and processes of the geologic setting must be evaluated in detail if the magnitude and time of the resulting expected annual dose would be significantly changed by their omission."

- "Provide the technical basis for either inclusion or exclusion of degradation, deterioration, or alteration processes of engineered barriers in the performance assessment, including those processes that would adversely affect the performance of natural barriers. Degradation, deterioration, or alteration processes of engineered barriers must be evaluated in detail if the magnitude and time of the resulting expected annual dose would be significantly changed by their omission."

Review Of DOE Features, Events, And Processes Database

DOE is developing a database of FEPs that may affect repository performance (5,26)[b]. If ultimately submitted to NRC as part of a license application the database would be expected to include the entire set of FEPs considered for inclusion in a potential TSPA. Such a database could include descriptions, technical justifications for inclusion or exclusion into the TSPA, and disposition of FEPs in the TSPA (5). The database would also aid in DOE's effort to attain transparency and traceability in its post-closure safety case and the technical arguments underlining the safety case (26) in the license application. In order to obtain early feedback on their scenario development process, DOE provided the database in a preliminary form as Revision 00b to the NRC (5). NRC had previously promised to review the DOE FEPs screening analysis to evaluate its completeness and the technical basis for those FEPs associated with coupled THC processes that would be screened out of a DOE license application (2).

The NRC reviewed the preliminary draft database (27) with respect to the scope of ENFE KTI and NRC acceptance criteria regarding scenario development (2,11). Relevant database entries were identified and categorized into the four areas of repository performance that could be impacted by coupled THC processes. The database consists of primary entries and secondary entries. Entries were derived from international lists and many are duplicated due to overlap among the multiple sources. Similar or identical entries for a particular feature, event, or process are entered as secondary entries. These multiple entries describing the same feature, event, or process are grouped together and listed as single feature, event, or process known as a primary entry. ENFE-related entries composed 35 percent of the 1,786 database entries and 50 percent of the 310 primary entries.

The NRC review procedure for scenario analysis contains sequential steps for review in five areas: identification of an initial set of processes and events; classification of processes and events; screening of processes and events; formation of scenarios; and screening of scenario classes (11). The preliminary draft database (Revision 00b) addresses the first three steps in the review process (5). Pickett and Leslie (27) applied the first acceptance criterion, which is that "DOE has identified a comprehensive list of processes and events that: (i) are present or might occur in the Yucca Mountain region, and (ii) includes those processes and events that have the potential to influence repository performance" (11).

Pickett and Leslie (27) found that, in general, the Revision 00b database was a comprehensive delineation of FEPs. However, they found several potentially important FEPs were not included in the preliminary draft database. Two of the FEPs not included in the preliminary draft address the natural setting. First, dehydration and decomposition of zeolites below the repository could lead to large-scale volume changes affecting flow and/or drift stability. This process was previously identified by the DOE Yucca Mountain project (28) and is addressed further in the discussion of MULTIFLO and bounding calculations. The second natural system FEP is that mineralogic dehydration reactions releasing water could affect hydrologic conditions. This FEP was also discussed by Bish et al. (28), but is not addressed further in this paper. The other two FEPs not included in the preliminary draft database relate to the EDA II design. The first FEP is that condensation of water on the underside of the drip shield may affect the waste package hydrologic and chemical environment. The second FEP describes potential interaction with and degradation of the drip shield affecting the chemistry of the water contacting the waste package. Current laboratory tests being conducted by DOE at a one quarter-scale-drift size as part of the EBS program will address TH aspects of the drip shield (22). However, presently, these tests do not appear to reflect the chemical environment or the potential chemical interactions with the drip shield (20,24).

Pickett and Leslie (27) then applied the next acceptance criteria in the scenario analysis procedure ["DOE has provided adequate documentation identifying how its initial list of processes and events has been grouped into categories. Categorization of processes and events is compatible with the use of categories during the screening of processes and events." (11)] to the preliminary draft database. They identified questions regarding documentation on the categorization of secondary entries into individual primary FEP entries (27). In addition, they identified questions concerning the degree of correspondence between primary and secondary entries. DOE intends to screen FEPs at the primary level, requiring that the primary entries stand independent of the secondary entries (20). The questions concerning correspondence between primary and secondary entries thus indicate that the current categorization scheme may need additional documentation to ensure that categorization of processes and events is compatible with the use of categories during the screening of processes and events. In this regard, DOE has indicated that additional documentation on the screening would be provided in other reports describing the disposition of FEPs and with the FEP database (20).

Finally, Pickett and Leslie (27) applied the next acceptance criteria in the scenario analysis procedure (11) to DOE's FEP database. The acceptance criteria are:

> "Categories of processes and events that are not credible for the Yucca Mountain repository because of waste characteristics, repository design, or site characteristics are identified and sufficient justification is provided for DOE' s conclusions. The probability assigned to each category of processes and events is consistent with site information, well documented, and appropriately considers uncertainty. Processes and events may be screened from the performance assessment on the basis of their probability of occurrence, provided DOE has demonstrated that they have a probability of less than one chance in 10,000 of occurring over 10,000 yr. Categories of processes and events may be omitted from the performance assessment on the basis that their omission would not significantly change the calculated expected annual dose, provided DOE has demonstrated that excluded categories of processes and events would not significantly change the calculated expected annual dose."

DOE provided preliminary placeholder screening arguments in the preliminary draft database (5). A total of 58 entries were found to be unresolved using the analysis technique outlined in Pickett and Leslie (27). Due to the preliminary nature of the database, it is expected that screening arguments will have a stronger technical basis in the final version of the database (27) before a license application.

Previously NRC noted that coupled THC processes discussed in the ENFE IRSR might not be specifically included within the DOE FEP database (2). The review of the preliminary draft database indicates that several FEPs potentially important to performance are not contained in the database. In addition, current engineered barrier testing may not reflect potential coupled THC interactions with the drip shield. A further assessment to determine whether dehydration and decomposition of zeolites could occur (and, thus, should be included as a FEP) is presented next.

MULTIFLO MODELING

MULTIFLO can be used to investigate the potential for temperatures to rise sufficiently to dehydrate and decompose zeolites contained in the zeolite-rich zones beneath the repository. Green et al. (13) presented MULTIFLO calculations showing temperature contours in a vertically oriented, two-dimensional, drift-scale numerical model from a thermal load of 14.8 $kgHM/m^2$ (60 MTHM/acre). This thermal load is consistent with waste emplacement under EDA-II (13). The stratigraphic column used in the MULTIFLO calculations (Fig. 1) shows the position of the relevant zeolite-containing zones in the Calico Hills Formation (CH1vc, CH2vc, CH3zc, and CH4zc). Temperature contours at different times from two different simulations are shown in the vertical cross sections in Fig. 2 and Fig. 3. The only difference between the models is an allowance for 20 percent heat loss from 50 years of ventilation in the second model simulation (Fig. 3). The cross sections represent half the distance between drifts, with a drift heat source at zero meters. The plots show that, after 1000 years, the temperature at the top of the Calico Hills Formation exceeds 70°C and stays elevated beyond 2500 years. Comparison of Fig. 2 and Fig. 3 suggests that ventilation has little effect on the temperature contours at this depth in the mountain. Similar calculations by Hardin (29) using the TSPA-VA thermal load of 21 $kgHM/m^2$ (85 MTHM/acre) showed temperatures at this horizon after 1000 years 10 to 15 degrees higher. However, a temperature of 70°C is sufficient to initiate reversible dehydration of zeolite minerals and could be sufficient to cause decomposition of clinoptilolite to analcime (28). Thus, the EDA-II thermal load is sufficient for dehydration and potential decomposition of zeolites. Therefore, these processes appear to be credible enough to be accounted for in the DOE scenario analysis if DOE were to submit a license application.

BOUNDING CALCULATION

Bish et al. (28) assessed the potential effects from dehydration of clinoptilolite and decomposition of clinoptilolite to analcime. They determined that these processes could release a large quantity of water and cause a substantial increase in void space due to the smaller molar volume of analcime (28). Their bounding calculations indicated an increase of porosity by 8 to 19 percent, due to decomposition of clinoptilolite to analcime. Bish et al. (28) conclude that, "in either case, very significant changes in the mechanical and hydrologic properties of the Calico Hills Formation may occur as a consequence." Bish et al. (28) also suggest that the amount of water liberated could be significant and is a function of the temperature that the zeolites obtain. A third effect of zeolite dehydration would be on the sorptive properties of the Calico Hills Formation (28). These observations support the potential importance of dehydration and decomposition of clinoptilolite to repository performance.

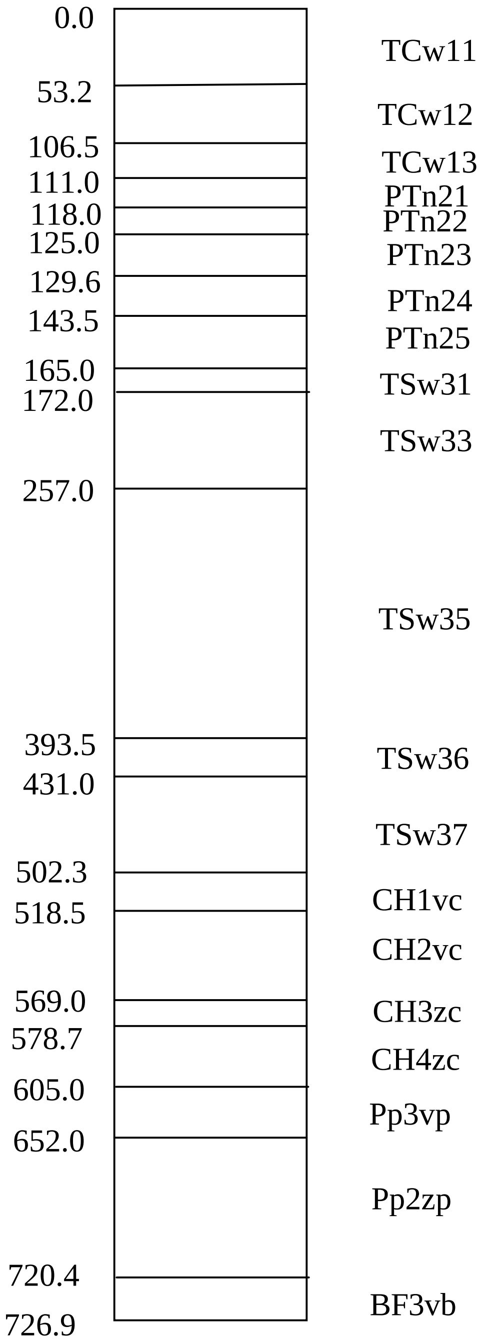

Fig. 1. Stratigraphic units and vertical grid used in MULTIFLO process level analyses [based on Hardin (29)]. Depth below ground surface is in meters.

CONCLUSIONS

Although the EDA-II design was driven, in part, by the desire to limit thermal effects on the proposed YM repository, coupled THC processes remain relevant to assessment of repository performance. NRC has conducted a preliminary evaluation of information provided by DOE concerning the analysis of THC processes. The key regulatory and pre-licensing tools used included the MUTLIFLO and TPA codes, proposed 10 CFR 63, and acceptance criteria and review methods in the TSPAI and ENFE IRSRs. We determined that the preliminary draft FEP database was comprehensive. The NRC preliminary evaluation also identified questions for DOE about the approach to coupled THC processes in the preliminary draft FEPs database and current near-field process models.

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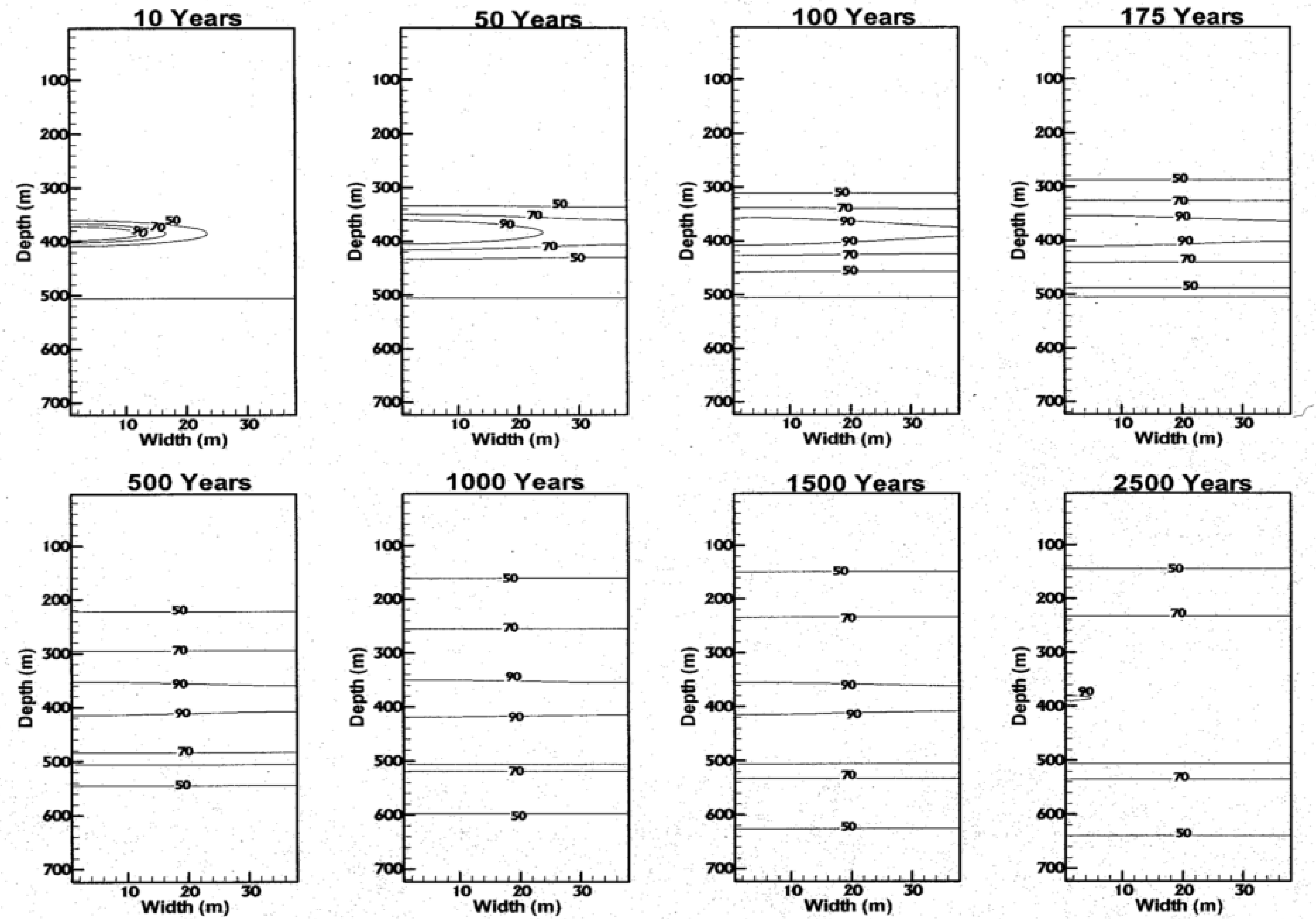

Fig. 2. Temperature contours (ºC) at 10, 50, 100, 175, 500, 1,000, 1,500, and 2,500 yr after final waste emplacement predicted using MULTIFLO for a thermal load of 14.8 kgHM/m^2 [60 MTU/acre], an infiltration rate of 10 mm/yr, and no heat loss due to ventilation [after (13)]. The top of the CH1vc unit at a depth of 502.3 meters below ground surface is indicated by the unlabeled solid line.

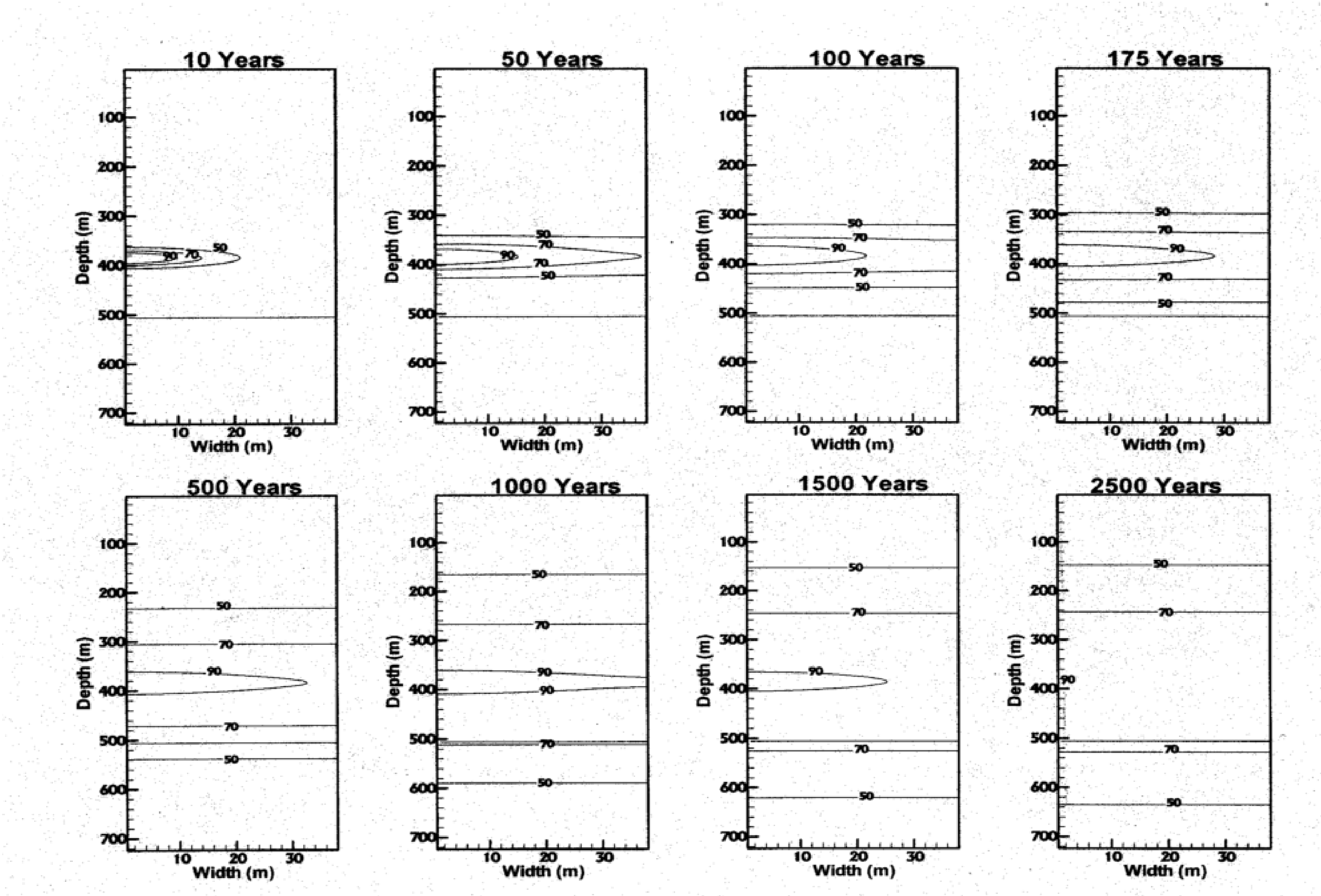

Fig. 3. Temperature contours (ºC) at 10, 50, 100, 175, 500, 1,000, 1,500, and 2,500 yr after final waste emplacement predicted using MULTIFLO for a thermal load of 14.8 kgHM/m^2 [60 MTU/acre], an infiltration rate of 10 mm/yr, and 20 percent heat loss for 50 yr after waste emplacement due to ventilation [after (13)]. The top of the CH1vc unit at a depth of 502.3 meters below ground surface is indicated by the unlabeled solid line.

FOOTNOTES

a) The EDA II design was recently proposed to the DOE by their management and operating contractor as the initial repository design concept for the Site Recommendation and a potential license application (4). DOE has selected this design as the reference design for development of the Site Recommendation (20). Recent information indicates a potential change to the EDA II design (personal communication with Paul Harrington, DOE, February 7, 2000). This potential change could include no longer using backfill as part of the basic design of EDA II.

b) The development of the database is part of DOE's scenario analysis process for the TSPA-SR (20).

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