3/16

REVIEW OF DEPARTMENT OF ENERGY YUCCA MOUNTAIN SITE CHARACTERIZATION OFFICE THERMOHYDROLOGIC TESTING AND MODELING PROGRAM

Prepared for

Nuclear Regulatory Commission
Contract NRC-02-93-005

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September 1996

4/16

ABSTRACT

A technical review has been conducted of the Department of Energy (DOE) Yucca Mountain Site Characterization Office (YMSCO) Thermohydrologic Testing and Modeling Program. For the purpose of this review, it is assumed that information regarding the YMSCO thermohydrologic testing and modeling program contained in previous DOE reports has been superseded by information contained in three recent documents and information provided during a Nuclear Regulatory Commission (NRC)/DOE Appendix 7 meeting held in Las Vegas on July 24, 1996 and the NRC/DOE Exploratory Studies Facility (ESF) video conference meeting on September 12, 1996. The three documents are: (i) the Peer Review Team (PRT) Record Memorandum Report and Recommendations submitted to DOE by the PRT in January 1996, (ii) the DOE response to the PRT recommendations, prepared and released in July 1996, and (iii) the PRT comments on the DOE response to the PRT recommendations in a letter report dated July 30, 1996. No additional documents regarding this review process have been released by DOE as of September 1996. Major concerns identified in this review include:

- The DOE did not convey an appreciation for the need to evaluate the validity of the equivalent continuum model (ECM)

- The DOE has not demonstrated that bounding assumptions and analyses of the thermo-hydrological-chemical coupled processes are conservative

- A field-scale heater test that is not designed for the thermal regime that will be experienced at the high-level waste repository runs the risk of not testing for all heat and mass transfer mechanisms that may influence the performance of the repository

- The discontinuance of surface based testing may result in unacceptably high uncertainty in infiltration estimates

5/16

CONTENTS

Section Page

ACKNOWLEDGMENTS . . . vii

1 INTRODUCTION . . . 1-1
1.1 SUMMARY OF THE PEER REVIEW TEAM RECORD MEMORANDUM REPORT AND RECOMMENDATIONS . . . 1-1
1.2 SUMMARY OF THE DEPARTMENT OF ENERGY RESPONSE TO THE PEER REVIEW TEAM RECORD MEMORANDUM REPORT AND RECOMMENDATIONS . . . 1-3
1.3 SUMMARY OF THE PEER REVIEW TEAM COMMENTS ON THE DEPARTMENT OF ENERGY RESPONSE TO PEER REVIEW TEAM RECOMMENDATIONS . . . 1-3

2 SPECIFIC CONCERNS . . . 2-1
2.1 OBJECTION . . . 2-1
2.2 COMMENTS . . . 2-1
2.3 QUESTION . . . 2-5

3 REFERENCES . . . 3-1

6/16

ACKNOWLEDGMENTS

This report was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the Nuclear Regulatory Commission (NRC) under Contract No. NRC-02-93-005. The activities reported here were performed on behalf of the NRC Office of Nuclear Material Safety and Safeguards (NMSS), Division of Waste Management (DWM). The report is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the NRC.

The authors thank Dr. A. Chowdhury for his insightful comments, Dr. B. Sagar for his technical review, and Dr. W. Patrick for the programmatic review of the report. The authors are thankful to Y. Lozano for skillful typing of the report and to B. Mabrito, who provided a full range of expert editorial services in the preparation of the final document.

1 INTRODUCTION

The purpose of this letter report is to provide an independent Center for Nuclear Waste Regulatory Analyses (CNWRA) evaluation of the Department of Energy (DOE) Yucca Mountain Site Characterization Office (YMSCO) Thermohydrologic Testing and Modeling Program. For the purpose of this review, it is assumed that information regarding the YMSCO thermohydrologic testing and modeling program contained in previous DOE reports has been superseded by information contained in three recent documents and information provided during a Nuclear Regulatory Commission (NRC)/DOE Appendix 7 meeting held in Las Vegas on July 24, 1996 and the NRC/DOE Exploratory Studies Facility (ESF) video conference meeting on September 12, 1996. The three documents are: (i) the Peer Review Team (PRT) Record Memorandum Report and Recommendations submitted to DOE by the PRT in January 1996; (ii) the DOE response to the PRT recommendations, prepared and released in July 1996; and (iii) the PRT comments on the DOE response to the PRT recommendations in a letter report dated July 30, 1996. No additional documents regarding this review process have been released as of September 1996. Additional insight into the YMSCO Thermohydrologic Testing and Modeling Program was gained during a NRC/DOE Appendix 7 meeting on the proposed DOE heater tests and a NRC/DOE ESF video conference meeting. The Appendix 7 meeting on thermal testing was held at Yucca Mountain (YM) and included a visit to the ESF and thermal alcove experiments. This Appendix 7 meeting was followed by an update of the DOE ESF heater tests during the NRC/DOE video conference meeting on ESF. This review is predicated on the premise that the current YMSCO thermohydrologic testing and modeling program is accurately presented by these information sources. A summary of the three documents is followed by the comments of this review.

1.1 SUMMARY OF THE PEER REVIEW TEAM RECORD MEMORANDUM REPORT AND RECOMMENDATIONS

The first of three documents reviewed herein was prepared by an independent PRT of six experts assembled by DOE to review the YMSCO Thermohydrologic Testing and Modeling Program. The review was initiated in June 1995 and completed in December 1995 with the Peer Review Record Memorandum Report and Recommendations submitted to DOE in January 1996. The PRT report provides a discussion of introductory background material of YM and the past, present, and planned activities by DOE regarding thermohydrologic testing and modeling. Using the background information, the PRT identified critical issues, the resolution of which they consider necessary. The issues are classified by the PRT as: (i) technical issues, which deal with site characterization, physical processes, their modeling, and parameter estimation; (ii) thermal loading strategy, with emphasis on the concept of the "extended dry repository;" (iii) validation and calibration of the models developed; and (iv) reduction of uncertainty. Specific technical subissues which address certain key boundary conditions, parameters, and processes are: (1a) infiltration, (1b) the impact of heterogeneities, (1c) the fracture-matrix interaction, (1d) thermochemical and thermomechanical effects on fracture permeability, and (1e) process scale-up.

The PRT emphasized the need for a reliable mathematical and numerical model to assess the thermal loading strategy. For example, the PRT noted that there are contrary scoping calculations for the extended-dry repository concept. The PRT contends that this suggests "...that fracture flows are not properly considered in the theoretical calculations, and that deleterious consequences could arise from high thermal loadings." The PRT adds that the theoretical premise for the conceptual model of equivalent continuum model (ECM) "...has not been tested experimentally at any scale (laboratory or field)."

8/16

The PRT recognized the large level and the diverse types of uncertainties associated with the thermohydrologic processes and parameters at YM. The types of uncertainties have been classified into five groups: (i) process uncertainty; (ii) geologic uncertainty; (iii) parameter uncertainty; (iv) uncertainties in model idealization; and (v) uncertainty in the performance of engineered components. It is the opinion of the PRT that reduction of process uncertainties should take the highest priority, with geologic uncertainty second and parameter uncertainty third. Reductions in process uncertainty will be achieved largely through laboratory and field experimentation and associated model validation and calibration.

The PRT focused the assessment of the sufficiency of models on: (i) the fundamental physics represented in the model; (ii) use of the ECM to upscale basic properties; (iii) the implementation of the concepts in a variety of thermal-hydrologic-mechanical-chemical codes; and (iv) dimensionality and boundary conditions. The PRT recognized that a difficult step in the modeling effort is to represent the heterogeneous nature of the hydrogeologic system on the scale of the computational grid. The ECM is the current methodology used in this effort. However, work to date has not examined the efficacy of the ECM approach. Additionally, the PRT noted that the ECM is not general and is likely to be inadequate for many types of fractured-rock geometries, as well as conditions where non-equilibrium fracture-matrix interactions develop.

The PRT made a total of 23 recommendations with respect to the laboratory and field testing program and with respect to modeling activities. These recommendations are divided into several categories: (i) site characterization, (ii) laboratory tests, (iii) field tests, and (iv) modeling. The PRT recommended that as part of the site characterization exercises, existing programs directed at infiltration, age dating of water, air injection and pneumatic testing, and mapping and borehole programs be continued. The PRT recommended that additional tracer tests and natural analogue studies of geothermal sites be included in the site characterization activities. The emphasis of site characterization should entail a hypothesis testing approach designed to produce a better understanding of fracture-matrix interactions, fast paths, and infiltration under the impact of thermal loads.

The PRT recommended that laboratory testing contain two facets: (i) testing of rock properties, and (ii) testing of processes, in particular coupled processes. Specific laboratory tests recommended by the PRT include: (i) hydraulic characterization of rocks, (ii) thermally driven fracture flow test, (iii) evaluation of the formation of heat pipes in fractured rock, (iv) verification of the critical infiltration rates, and (v) fracture healing experiments.

The PRT had only two recommendations with regard to field testing: (i) reinstating the Fran Ridge large block heater test (LBT); and (ii) conducting the large-scale, long-duration (LSLD) field test in the ESF. The LBT was recommended because of the need for a preliminary test prior to conducting the LSLD test and the LBT is essentially already prepared. A large-scale field test is required because information regarding the thermally driven flow of moisture through fractured rock is not available through any other means. The heater test has to be of sufficient thermal strength and duration (e.g., 4 yr) that an adequate volume of rock (e.g., 30 m in diameter) is tested for large-scale processes with temperatures as high as 200° C.

The PRT made ten recommendations with regard to the thermohydrologic modeling program. The PRT felt that existing codes are adequate but require certain enhancements, including the ability to better represent several aspects of the fundamental physics, infiltration at the upper boundary, and the appropriateness of the water table as the lower boundary. They recommended that thermohydrologic modeling continue at both the mountain and drift scales and that models should be validated in connection with laboratory and field testing rather than retroactive calibration and fitting. Uncertainty analysis using traditional geostatistical analyses should be replaced with hypothesis testing in a decision framework. The PRT made general statements that thermochemical and thermomechanical modeling should move forward but with a lower priority than thermohydrologic modeling.

The PRT states that the "most important of the recommendations is the one associated with the ECM." The PRT noted that the conditions under which the ECM is valid need to be clearly identified. Likewise, alternative conceptualization will be required for those conditions when the ECM is not valid. The PRT recognized this issue needs to be resolved before moving forward on various fronts such as repository design, predictions of performance, test designs, etc.

1.2 SUMMARY OF THE DEPARTMENT OF ENERGY RESPONSE TO THE PEER REVIEW TEAM RECORD MEMORANDUM REPORT AND RECOMMENDATIONS

The DOE prepared a focused response to the 23 recommendations contained in the PRT report. No additional commentary addressing the main body of the PRT report was included by DOE in their response letter report. The DOE stated acceptance of 22 of the 23 recommendations. The notable exception was PRT Recommendation 12, which stated "The (PRT) is unanimous in its primary recommendation, which gives the highest priority, in terms of all TH activities, to the following *in situ* field test: Carry out the large-scale, long-duration (LSLD) *in situ* field test in the ESF." Although the DOE indicated acceptance of 22 of the recommendations, there were actually two others which were not accepted in their entirety (i.e., Recommendations 1 and 6). Recommendation 1 calls for the continuation of the "measurement and interpretation of infiltration rates at ground surface and in the shallow subsurface over YM." DOE stated that "the Long Range Plan does not support measurements of infiltration at the ground surface." DOE added that all interpretations related to infiltration will be derived using only data that has already been collected.

Recommendation 6 calls for the continuation of "natural analogue studies of geothermal sites such as the Geysers, or those under study in New Zealand." DOE states they recognize the value of natural analogues, however, they further state they hope to "revitalize natural analogue studies but at a reduced workscope compared to prior years." Based on the DOE response, it appears that there are no significant analogue studies either ongoing or planned by DOE at this time.

1.3 SUMMARY OF THE PEER REVIEW TEAM COMMENTS ON THE DEPARTMENT OF ENERGY RESPONSE TO PEER REVIEW TEAM RECOMMENDATIONS

The final action of the PRT was a letter report commenting on the DOE response of the original PRT report. In this letter report, the PRT reiterated its position regarding several of its recommendations, one of which was not accepted by DOE (the LSLD Test). The PRT stated that several recommendations which address the assessment of infiltration and the evaluation of fracture-matrix interactions and its representation (Nos. 7-11, 15, and 16) were accepted by DOE, however, not with the same intensity as recommended by the PRT.

On several occasions in the PRT response letter, the PRT stated reservations that DOE provided insufficient emphasis to observations in the original PRT report. The PRT noted that "...there appears to

10/16

be a difference in strengths of opinions...." This observation may be attributed to the DOE responses that were restricted to the summary of recommendations included at the end of the PRT report. Specific comments included the following.

DOE cited the prioritization of activities within the Long Range Plan in defense of their discontinuance of surface-based infiltration studies. The Long Range Plan identifies modeling and data synthesis as the highest priority, *in situ* testing (and associated laboratory testing) as next important, and surface-based testing as the lowest priority. When the PRT recognized the need for prioritization, however, it also noted the extremely large range of recharge estimates at the time of their review and the relative importance of establishing acceptable bounds on the range of infiltration at YM. The PRT stated that it is unclear whether the geochemical dating program can provide the needed reduction in uncertainty without supporting confirmatory surface measurements.

The PRT identified assessing the validity of the ECM conceptual model as the most important recommendation in their review. The PRT was not convinced by the DOE response that the DOE is "sufficiently cautious with regard to the suitability of the current levels of understanding, or sufficiently motivated with respect to the need for experimental and *in situ* validation of the ECM approach." The PRT observed that there appeared to be an over-reliance on modeling activities that are fundamentally tied to the ECM formulation in the absence of adequate laboratory and field validation.

Several aspects of the thermal testing program were addressed in the PRT response to DOE. The PRT views the single-heater test as less revealing and possibly redundant to previous experiments conducted in G-Tunnel. The rejection of the LSLD test was cited as a matter of concern by the PRT. The PRT views the drift heater test as intermediate in scale and incapable of adequately testing the ECM formulation, the principal upon which the drift-scale test was designed. The PRT summarized their concerns by stating "...it is not clear whether the results from an intermediate-scale test, such as the drift-scale test, will be sufficiently convincing to provide a basis for moving forward with the planned license application before a LSLD test is conducted."

2 SPECIFIC CONCERNS

The YMSCO Thermohydrologic Testing and Modeling Program is continuously undergoing modification as a consequence of budget revisions, programmatic considerations, and technical developments. The DOE-sponsored peer review of the YMSCO Thermohydrologic Testing and Modeling Program and the subsequent documents discussed above have provided NRC an opportunity to review the program status at a critical time during which key experiments are being initiated and others are in the final stages of planning. The findings of the CNWRA reviews have been documented in the form of specific concerns. These are presented in a standard format consistent with previous NRC submittal of concerns to the DOE (e.g., Nuclear Regulatory Commission, 1989). The standard format includes objections, comments, and questions.

2.1 OBJECTION

There is no objection based on the CNWRA review of the DOE YMSCO Thermohydrogeologic Testing and Modeling Program.

2.2 COMMENTS

Comment 1

The DOE did not identify a program that will effectively evaluate the validity of the ECM.

Basis:

The DOE program will not address several key technical areas, especially those related to understanding fundamental physics (Recommendations 7–11), adequate representation of the system (Recommendation 5), and critical assessment of the ECM (Recommendation 16). In doing so, the DOE did not convey an appreciation for some of the substantive issues raised by the PRT and discussed in the text of the PRT report. This concern was also raised in the PRT comments on the DOE response. In particular, the PRT stated "We are not convinced from the DOE responses to the above recommendations that the YMSCP is sufficiently cautious with regard to the suitability of the current levels of understanding, or sufficiently motivated with respect to the need for experimental and *in situ* validation of the ECM approach. There appears to be a potential for overreliance on modeling activities using models that are fundamentally tied to the ECM formulation. It is our view that these modeling activities cannot be afforded full weight unless and until laboratory and field validation of the ECM concepts are achieved."

Recommendation:

The DOE should bound the validity of the ECM which is used as the basis in the DOE performance assessments.

Comment 2

The DOE has not demonstrated that bounding assumptions and analyses of the thermo-hydrological-chemical (THC) coupled processes are conservative.

Basis:

Neither the PRT nor the DOE stressed the importance that THC coupled effects could have on the hydraulic properties of media near the heat-generating waste package or on the flow and transport regimes that could form, particularly below the repository horizon. The PRT recommended that THC modeling "...should move forward, but at a lower priority, and at a different scale than the current mountain-scale studies." They went on to say: "The PRT would prefer to see simple scoping calculations first, followed by numerical simulations at a scale that can be validated and calibrated by proposed laboratory and field tests. Another possible approach would be to try to apply thermochemical models, such as EQ3/6, to conditions anticipated to occur at the boiling front, rather than trying to fully couple TH flow models and HC transport models."

The PRT stated that because of the relatively limited work related to THC processes, "...they could not assess how important these processes are to the overall performance of the repository system." The PRT noted, however, that "... simply lacking knowledge about the THC processes is not justification for assuming them to be unimportant." Finally they stated: "The PRT believes that there remain possibilities for significant 'surprises' associated with THC processes."

The DOE response was basically that they agreed with the PRT recommendations and: "The coupled THC calculations remain only a small part of the program designed to understand rock-water reactions." The DOE concluded: "... THC studies will continue to be centered around the use of EQ3/6 to examine possible rock-water reactions in detail, as recommended by the PRT."

At high thermal loads, significant concentrations in dissolved species such as chloride and elevation in the pH can be expected to occur near the boiling front surrounding the repository. Prediction of such effects can only be achieved with models that adequately couple THC processes. Synergistic effects could result from an increase in the fluid density, for example, promoting dripping. In addition an inverted density gradient will occur below the repository leading to unstable conditions. Alteration of host minerals could be expected to change sorption properties and porosity and permeability of the host rock. Precipitation in fractures could limit the effect of retardation by matrix diffusion.

The current codes mentioned by the PRT and DOE (TOUGH, TOUGH2, VTOUGH, FEHM, and NUFT) do not include chemistry suitable for describing rock-water interactions and the effects on solution chemistry due to evaporation and condensation processes. An additional code mentioned in the DOE response, GIMRT/OS3D, is a fully saturated code that does not include two-phase fluid flow. The code EQ3/6, and geochemical reaction path model, does not appear adequate for the job either, although use of this code was recommended by the PRT. The problem to be solved is fundamentally a moving boundary problem. The reaction fronts will not remain stationary with time. Therefore it is difficult to see the utility of using EQ3/6 which does not incorporate fluid transport to model such processes.

Both the PRT and the DOE response mention the work of Robinson (1995) as the only work taking THC processes into account. Robinson carried out a two-dimension calculation using a repository-scale model with a single component, SiO_2, taking into account reaction with quartz. Robinson concludes that the dryout zone could be extended due to precipitation and dissolution of quartz resulting in changes in permeability. However, the permeability-porosity relation used by Robinson seems highly questionable. He associates a 6 order of magnitude change in permeability with a variation in porosity from 0.09 to 0.13. No attempt was made by Robinson to estimate changes in pH and salinity due to evaporation and condensation processes. At the evaporation front where a high pH ($\geq$ 10) is expected from the degassing of CO_2, it is well known that quartz solubility will be effected. Therefore, it is difficult to see how Robinson's calculations can be valid even for the extremely simple system he considered for pure quartz representing the host rock.

Recommendation:

DOE should demonstrate that THC bounding assumptions and analyses are conservative. If the THC bounding assumptions and analyses cannot be shown to be conservative, then THC coupled effects need to be evaluated using coupled THC models.

Comment 3

Deploying a field-scale heater test that is not designed for the thermal regime that will be experienced at the high-level waste (HLW) repository runs the risk of not testing for all heat and mass transfer mechanisms that may influence the performance of the repository.

Basis:

The DOE field-scale heater test at the ESF will probably provide the best source of data for assessing conceptual models. Therefore, it is imperative that the ESF heater test be designed: (i) to be able to discriminate among the candidate conceptual models, and (ii) for conditions representative of the proposed repository. Heterogeneities preclude assigning single representative property values to the repository block, therefore, it will be difficult to design a single field test to represent conditions expected for the entire block. For example, a throttled, advective flow regime may be experienced in one portion of the repository, while an unthrottled, buoyant flow regime may be found elsewhere.

If the ESF heater test is not appropriately designed, the results will not provide a valid assessment of the ECM conceptual model currently used in performance prediction. The PRT stated concerns regarding the drift-scale heater test proposed by DOE, mostly addressing the limited size of the single drift test versus a multiple drift test. In addition to the reservations of the PRT, a second issue was raised during the Appendix 7 meeting: the temperature at which the proposed heater test will be conducted. During this meeting, DOE stated the heater temperatures would be high, as high as 400° C in wing heaters, to expedite the heating of a large mass of rock (i.e., 15,000 to 30,000 m^3) to temperatures above boiling within a 2–4 yr time period. This would result in drift wall temperatures in excess of 200° to 250° C during the heating portion of the test.

Operating the heater test at temperatures this high could jeopardize the objectives of the heater test. Preliminary scoping calculations indicate that drift wall temperatures in the repository will probably be 120°-130° C, with a maximum of 150° C possible. Heat and mass transport mechanisms, such as episodic gravity driven refluxing and dripping, that could occur with drift wall temperatures less than 150 C, would be much less likely to occur if the drift wall temperatures exceed 200° C and highly unlikely for temperatures as high as 250° C. Therefore, the dripping of liquid water onto above-boiling heaters, that was observed during heater tests at Climax and G-Tunnel in the 1980s, would be avoided in a heater test conducted at the higher temperatures. The results of a heater test in which the drift walls attained temperatures excessively higher than those expected at the HLW repository could erroneously be interpreted to support the ECM conceptual model since the ECM lacks the capability to represent refluxing and dripping from individual fractures.

Statements were made during the Appendix 7 meeting and the follow-up NRC/DOE ESF video conference that gravity driven refluxing and/or dripping can be observed during tests conducted at the higher temperatures either: (i) at some distance within the rock mass during the heating period of the test using the high level of instrumentation planned, or (ii) during that window of time during which the boiling isotherm has only penetrated a short distance past the drift wall and drift wall temperatures would have not reached temperatures greater than 150° C. In response to (i), the dripping phenomenon occurs when a quantity of liquid water episodically flows down fractures whose surface temperatures are cooled below the boiling temperatures experienced further within the adjacent rock mass (Phillips, 1994) and conceivably drips into the drift upon reaching the drift wall (or ceiling). It is doubtful that the instrumentation is capable of detecting this phenomenon within the rock mass. Additionally, the dripping phenomenon will only occur when episodic fracture flow occurs at the drift wall (or ceiling) and not within the rock mass. In response to (ii), the accelerated temperature ramp-up of the heater test provides only a short duration when the drift-wall temperatures are similar to those predicted for the HLW repository. It is not clear whether this limited period of time will allow for the formation of a zone of condensed water above the central drift area to initiate and maintain the refluxing/dripping phenomenon. This second argument is further eroded by the single-drift design of drift-scale experiment and the plan to uniformly heat the entire length of drift floor and wing heaters to high temperatures. Condensed water that is more easily shed away from above a single uniformly heated drift may not be as easily shed from the multitude of drifts in the HLW repository that experience a range of temperatures. Similarly, the excessively high temperatures may drive the zone of condensed water sufficiently far from the drift wall so that water refluxing back to the single drift may not be experienced during the cool-down period of the heater test.

Recommendation:

The ESF large- or drift-scale heater test should be designed to discriminate among various conceptual models and be representative of the heat and mass transfer mechanisms expected at the HLW repository. Because a single heater test conducted at a single location may not provide the full range of physical conditions (i.e., permeability) found within the repository block, the heater test could be designed to evaluate a wider range of flow regimes if the test is conducted for a range of temperatures, rather than conducting the entire test at a single, uniform thermal load. The variable thermal load test, if properly designed, would subject different parts of the test drift to the different flow regimes that could be expected to occur at the proposed repository.

Comment 4

The discontinuance of surface-based testing may result in unacceptably high uncertainty in infiltration estimates.

Basis:

As stated by the PRT in their comments on the DOE response, current estimates for recharge cover an extremely large range, with the result that this uncertainty will hinder future attempts to model infiltration. Although chemical dating and subsurface measurements will provide some reduction in uncertainty, "...it is unclear whether such reduction will be sufficient without supporting confirmatory surface measurements."

The CNWRA/NRC staff consider that the spatial extent of the recently discontinued surface-based measurement program was adequate but do not consider the duration of previously collected information as sufficient to adequately reduce the large uncertainty in infiltration rate predictions.

Recommendation:

The DOE should reinstate the recently discontinued program of surface-based measurement of infiltration rates.

2.3 QUESTION

There is no question based on the CNWRA review of the DOE YMSCO Thermohydrologic Testing and Modeling Program.

16/16

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