DOE/RW/00134--T15-Vol.1-Rev.1

WBS: 1.2.1.5
QA: N/A

Civilian Radioactive Waste Management System
Management & Operating Contractor

FY 93 THERMAL LOADING SYSTEMS STUDY FINAL REPORT

B00000000-01717-5705-00013

Volume I

Rev. 1

August 29, 1994

MANAGED COPY
No.
THIS IS A GREEN STAMP

Prepared for:

U.S. Department of Energy
Yucca Mountain Site Characterization Project Office
P.O. Box 98608
Las Vegas, Nevada 89193-8608

FIRST SUBMITTAL

Prepared by:

TRW Environmental Safety Systems Inc.
101 Convention Center Drive
Las Vegas, NV 89109

Under Contract Number
DE-AC01-91RW00134

MASTER

Number of pages in this report: Volume I - 186 pages, Volume II - 269 pages.

DOE and DOE contractors can obtain copies of this report from: Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831. (615) 576-8401.

Civilian Radioactive Waste Management System
Management & Operating Contractor

FY 93 THERMAL LOADING SYSTEMS STUDY FINAL REPORT

B00000000-01717-5705-00013

Volume I

Rev. 1

August 29, 1994

Authors:

Steven F. Saterlie
Study Manager and
Document Preparer

Brent H. Thomson
Co-Author

Concurrence:

Richard D. Memory
Department Manager

Thomas C. Geer
Office Manager

APPROVED BY:

R. M. Sandifer
Deputy MGDS Operation, CRWMS M&O

ACKNOWLEDGEMENT

This report was prepared from work done by the Management and Operating (M&O) Contractor under Contract Number DE-AC01-91RW00134 for the U.S. Department of Energy Civilian Radioactive Waste Management System. The work was supported in part by Dr. Thomas Buscheck of Lawrence Livermore National Laboratory and Eric Ryder of Sandia National Laboratory who performed various calculations. Schon Levy and Dave Bish of Los Alamos National Laboratory performed the geochemical analysis. Dr. Mark Abhold's efforts to initiate this project and his reviews which helped improve the work are appreciated. Dennis Royer and J. C. de la Garza of the Yucca Mountain Project Office are acknowledged for their suggestions. Principal Investigator of the study were Dr. Steven Saterlie and Brent Thomson and any questions should be addressed to them.

EXECUTIVE SUMMARY

Background

The ability to meet the overall performance requirements for the proposed Mined Geologic Disposal System (MGDS) at Yucca Mountain, Nevada requires the two major subsystems (natural barriers and engineered barriers) to positively contribute to containment and radionuclide isolation. In addition to the postclosure performance the proposed repository must meet preclosure requirements of safety, retrievability, and operability. Cost and schedule were also considered. The thermal loading strategy chosen may significantly affect both the postclosure and preclosure performance of the proposed repository. Although the current Site Characterization Plan (SCP) reference case is 57 kilowatts (kW)/acre, other thermal loading strategies (different areal mass loadings) have been proposed which possess both advantages and disadvantages.

Depending on the areal mass loading (AML), waste package capacity, age of the fuel, emplacement mode and other factors, the temperatures in regions of the host rock could be significantly above the boiling point of water for a very long period of time. In the near term, high temperatures can have a significant impact on preclosure performance from the standpoint of safety and retrievability of the waste since the ability to emplace and/or retrieve waste can be impaired under conditions of higher temperature. Over a longer period, above boiling temperatures will tend to dry out the rock which may result in reducing the aqueous corrosion rate of the waste canisters for a significant period of time. Conversely, high temperatures and thermal gradients can, under certain conditions, induce fractures in the rock as well as initiate water movement and/or mineral dissolution and precipitation along pre-existing fractures in the form of heat pipes, and in the presence of moisture even exacerbate corrosion. These effects could significantly alter the hydrologic behavior around the repository. Dissolution and precipitation may also occur, altering the hydrologic framework. This behavior could change the structural integrity of the host rock which may in some cases minimize or enhance water mobility. High temperatures can also induce chemical and/or phase changes in some minerals which, under certain conditions, can produce conditions either more or less favorable for adsorption of radionuclides. When Thermal-Mechanical-Hydrological-Chemical (T-M-H-C) coupled behavior is considered, the problem of establishing the performance of the potential repository is further complicated. Lower thermal loadings may minimize the coupling of T-M-H-C. However, the lower temperatures may allow increased aqueous corrosion and may have negative impacts from high relative humidity at the WPs in conjunction with relatively high temperatures.

Objective

The objectives of the FY 1993 MGDS Thermal Loading Study were to 1) place bounds on the thermal loading which would establish the loading regime that is "too hot" and the loading regime that is "too cold," to 2) "grade" or evaluate the performance, as a function of thermal loading, of the repository to contain high level wastes against performance criteria, and to 3) evaluate the performance of the various options with respect to cost, safety, and operability. Additionally, the effort was to 4) identify important uncertainties that need to be resolved by tests and/or analyses in order to complete a performance assessment on the effects of thermal loading. The FY 1993 Thermal Loading Study was conducted from December 1, 1992 to December 30, 1993 and this final report provides the findings of the study.

Approach

The approach taken in the study was to develop a consistent, common basis for all the analysts to use and perform thermal calculations using existing thermal models and data. A key element of the study involved a reevaluation of the thermal goals listed in the SCP. "It is believed that meeting those criteria should result in adequate performance of the potential repository and the natural and engineered barrier systems, and that the criteria could be used to evaluate and rank thermal loading options (M&O, 1993a)." The goals used in this study are preliminary and will be reevaluated in the follow-on study. This approach is based on a top-level strategy of providing for multiple barriers. Therefore, these revised SCP goals were used as criteria to evaluate performance of the various thermal options. The evaluation against these goals was the primary means for making recommendations to narrow the range of thermal loadings.

For consistency, all thermal calculations were performed using the same waste stream. The system scenario used to generate the waste stream assumes Youngest Fuel First (YFF) , greater than or equal to 10 years old (YFF(10)) pick up, the reference schedule (1998 acceptance into an Monitored Retrievable Storage (MRS) and 2010 repository opening), and single-purpose containers. The resulting average fuel characteristics are 22.5 years old and 42.7 GWd/MTU (gigaWatt days per Metric Tonne Uranium) for Pressurized Water Reactor (PWR) assemblies and 24.1 years old and 32.5 GWd/MTU for Boiling Water Reactor (BWR) assemblies.

The Waste Package (WP) Design Group developed WP concepts for the calculations which had capacities of 6 PWR or 12 BWR, 12 PWR or 21 BWR, and 21 PWR or 40 BWR. The Subsurface Design Group provided generic repository concepts for the various thermal loading options (24, 36, 55, 83, and 111 MTU/acre) considered in the study. Based on an average waste stream (using an average characteristic for the YFF(10) waste stream), the 55 MTU/acre corresponds to the 57 kW/acre reference case. This analysis did not consider fuel variability which can be significant.

The performance regimes of interest were basically divided into preclosure (near field) and postclosure (far field). Sandia National Laboratories (SNL) provided thermal calculations of the near-field environment that were used to assist in evaluating preclosure performance. Lawrence Livermore National Laboratory (LLNL) provided hydrothermal calculations which were used to evaluate the postclosure performance due to changes in temperature and water movement on a mountain scale. These calculations were then used to examine operability and thermomechanical response. Los Alamos National Laboratory used the results to examine geochemical alterations. The ability to monitor the repository under heated conditions was also evaluated. The costs of the various options were evaluated to determine if any sensitivities to thermal loading exist.

The results of the above analyses were examined to evaluate performance. The performance at the various thermal loads was determined in part by comparing the thermal predictions against the revised SCP thermal goals. Additionally, some total system performance assessment (TSPA) calculations were done to estimate radionuclide releases with time to the accessible environment. Although remanded for repromulgation, the Environmental Protection Agency (EPA) health and safety standard originally found in 40 CFR 191 [Code of Federal Regulation (CFR)] was used as a point of comparison. Based on these results sufficient technical basis appeared to exist to make recommendations as to what thermal regimes were "too hot (high)" and also "too cold (low)." As a part of the study some recommendations were also made as to what uncertainties, associated with certain parameters, needed to be reduced to adequately evaluate performance of waste isolation.

Limitations

A constraint on the ability of the study to select an option stemmed from the lack of primary hard data, uncertainties in derived data, relying on unsubstantiated models and the inability to consider simultaneously coupled processes. As such the uncertainties are high in most aspects of the study at this time. This ought to be taken into account in considering the results of the study.

Results

Several major conclusions were established in the course of the study. The following synopsis provides highlights of those conclusions and, although difficult to separate into groups, an attempt was made to divide them according to the objectives of the study:

The first set of conclusions was used to help establish reasonable upper bounds that are "too hot" and lower bounds that are "too cold."

- Thermal loads greater than 100 MTU/acre are "too hot" and should be avoided. This limit was determined based on interpolations between the 111 and 83 MTU/acre cases and established that all the goals which were violated at 111 MTU/acre would very likely still be violated at 100 MTU/acre. This conclusion may not be the most conservative depending on the choice of average fuel characteristics and the way those averages were done. However, it should be noted that the study does not exclude any range that would not have been excluded with other choices. This means that the upper limit would likely be lowered if other fuel averaging methods had been chosen or perhaps fuel variability were considered.

- A below boiling repository (bulk average temperature of the repository horizon less than 97 degrees Celsius) will, if acceptable conditions exist, fit into the primary area plus revised expansion areas (e.g., emplacement areas of about 1750 and 2600 acres for 36 and 24 MTU/acre respectively).

The following set of conclusions was found as a result of the evaluations of performance:

- Below boiling (bulk average [the temperature at the potential repository horizon that one would get with a homogeneous heat distribution]) loadings produce negligible hydrologic perturbation for bulk permeabilities around 280 milliDarcy, given conditions appropriate for the use of the equivalent continuum model. However, the observation may not be completely applicable if a significantly heterogeneous medium were to exist or substantially enhanced binary gas-phase diffusions were to occur.

- Moderate thermal loads of above boiling (above 36 MTU/acre) to around 55 MTU/acre produce conditions which do not yield above boiling temperatures for significant portions of the repository since bulk temperature varies significantly across the repository. This may result in degraded postclosure performance over a 10,000 year period. Radionuclide releases to the accessible environment are sensitive to thermal loads for times between 10,000 to 100,000 years. At times greater than 100,000 years the performance is not predicted to be a function of thermal load since the WPs under any scenario have all degraded over these very large time scales.

- Equivalent continuum model predictions for above boiling strategies appear to result in large scale water redistribution resulting in long term increases in saturation levels above the repository. This was demonstrated by comparing water saturation profiles at post closure time periods with ambient conditions.

- Some local boiling will exist for AMLs of 24 and 36 MTU/acre, except for the 6 PWR WP (small amount of boiling on the walls for the 4.3 m diameter drift at 36 MTU/acre). However, appreciable areas (80 to 100 percent) of the pillars between drifts will remain below boiling. This appears to hold with any of the capacity WPs considered (e.g., capacities of 6, 12, or 21 PWR) for the 4.3 m diameter drifts or larger (AMLs $\leq$ 36 MTU/acre). Although the host rock thermal response does depend on layout, WP capacity, and waste characteristics, appreciable areas of the pillar will remian below boiling.

- Vertical borehole or small diameter horizontal borehole emplacement is limited to WP power output of less than about 5 kW (capacities less than 10 to 12 PWR) based on rock temperature thermal limits.

Various options were evaluated to examine operability, safety, and cost with the following results being concluded:

- Cost does not appear to vary significantly (less than 15 percent) between hot (above boiling) and below boiling strategies. Thus it does not appear that cost is a useful discriminator between thermal loading options based on our current understanding. This conclusion applies only to the conditions in this study which considered a single repository with maximum emplacement of 70,000 MTU.

- Electronic components exhibit high failure rates above about 160 degrees Celsius which means that the required monitoring during the operational and performance confirmation phases will be a significant challenge at these temperatures. It is believed that monitoring can be done with existing instruments at temperatures below 160 degrees Celsius. Thus, it appears that some monitoring can be accomplished at AMLs below 100 MTU/acre. The feasibility of monitoring at temperatures above 160 degrees Celsius will be explored in the follow-on study.

- Aging the fuel can be done to reduce WP power at emplacement sufficiently to meet certain preclosure goals, and modify sub-repository scale effects assuming constant AML, but will not appreciably affect mountain-scale performance.

- To facilitate retrievability, ventilation can be used to reduce temperatures in a few drifts from 190 to 50 degrees Celsius within a few weeks. However, using ventilation to reduce temperatures to 50 degrees Celsius over the entire repository appears impractical. Ventilation of the entire repository to reduce temperatures somewhat to permit monitoring might be practical or may be able to reduce wall temperatures to below 200 degrees Celsius.

Two conclusions were identified in the evaluations of key uncertainties important to waste isolation.

- High thermal loads appear to significantly increase the uncertainty of the effects of geochemical alterations in the far field on radionuclide retardation.

- Based on current understanding of uncertainties, lower thermal loads will likely minimize the influence of localized permeability variations on thermally driven fluid flow based on the range of permeabilities of 0.1 to 10 Darcy considered. However, the study based this on calculations done using the equivalent continuum model. If nonequilibrium conditions were to exist as a result of significant heterogeneity or enhanced binary gas-phase diffusion were to occur, the study would need to reexamine this issue.

A follow-on study is planned and many of the issues identified in the FY 1993 Thermal Loading Systems Study will be addressed at that time. The performance of the potential repository at 36 and 83 MTU/acre needs to be evaluated. Also a sensitivity analysis is needed to better establish what the uncertainties are of those parameters important to waste isolation and link this with the test program to ensure necessary data will be obtained.

The following provides a more detailed discussion of some of the above conclusions. Based on the results of the study, recommendations can be made to narrow the range of thermal loading and to perform specific tests and analyses to reduce the uncertainties in making the final thermal loading decision. Specifically, the study found that there is a thermal loading that is "too hot." Above an AML of 100 MTU/acre the thermal environment produced is such that most of the thermal goals are violated. The moderate thermal loading case around 55 MTU/acre was shown to produce conditions which would not keep the majority of the repository dry (less than residual saturation, which was assumed to be about 10 percent).

Results extracted from the Total System Performance Analysis (TSPA) and included in this report indicated that this hot, moist environment may result in larger radionuclide releases to the accessible environment over 10,000 years than either the hot or the below boiling cases. The range of thermal loads where this potentially degraded performance occurs is from just above boiling in the potential repository (above 36 MTU/acre) to an as yet to be defined AML above 55 MTU/acre. At below boiling conditions, the study showed that negligible perturbations of the ambient liquid saturation would occur if the average bulk permeability is on the order of 280 milliDarcys or lower. This conclusion applies for conditions which are appropriate for the use of the equivalent continuum model (e.g., significant heterogemetery or enhanced binary gas-phase diffusion are not present). If acceptable (from the standpoint of waste isolation and available area) ambient conditions are found to exist underground, the below boiling strategy would minimally perturb this condition and would reduce uncertainties.

The cost impacts for the MGDS including site characterization, WP, underground construction, and surface facilities, were examined. Since thermal loading strategies (areal extent) are believed to affect site characterization costs, the dependency of these costs on thermal loading were examined. Higher thermal loads result in a smaller repository area but because of the increased thermal perturbation may require additional testing and site characterizations to quantify mountain scale effects. These issues need to be addressed in follow-on studies and the test program. At this time, it is believed that the primary Site Characterization program cost changes needed to accommodate repository area changes would primarily be based on the change in the systematic drilling program and not in the Exploratory Studies Facility (ESF). This resulted in higher costs for lower thermal loads but at most only higher by 10 to 15 percent of the total project costs. This variation is within the uncertainties of the costs. As a consequence of the small difference (at most 10 to 15 percent of the total system costs) between a hot (above boiling) or below boiling strategy, cost does not appear to be a significant discriminator among thermal loads at this time. Additional study of the sensitivity of cost to thermal load is required to add detail to the cost analysis.

Various uncertainties were identified as important to understand and resolve so that performance could be better established, to support the thermal loading decision. Based on the analyses done to date, it is clear that critical factors contributing to the hydrologic uncertainties need to be better understood. They include bulk permeability, fracture densities, and percolation flux. Additionally, the reader is cautioned that a major portion of the analysis was done with simplified models using large-scale averages. The effects of heterogeneity and the simplifications assumed need to be investigated. More effort needs to be applied to verification of hydrothermal models and ultimately to validation of these models with some underground data. The WP corrosion performance and impact of fuel variability must be understood. Reducing uncertainty associated with thermal goals and establishing how important a particular goal is will be needed. Some uncertainties in cost must be resolved. Finally, the Site Characterization program must address the extent of useable repository area. The useable area will dictate the capacity of the repository once the appropriate thermal load is determined.

In summary, besides identifying the thermal region that was "too hot," the evaluations indicated that the uncertainties in geochemical alteration, mountain scale water movement, thermomechanical, and operational aspects were all found to increase with increasing thermal load. The study also identified a number of the uncertainties important to waste isolation that must be reduced to adequately evaluate performance. At this point it is recommended that, until the uncertainties are reduced by further tests and/or analyses, no final decisions be made between either the above boiling, hot regime, or the below boiling regime. Developing a thermal loading decision will be an iterative process which must be developed as data and models mature. A follow-on study is planned to address many of the issues identified above.

The results of this and follow-on studies will be used to provide information to the Advanced Conceptual Design efforts of the program. Additionally, the work will attempt to provide some integration to a number of the design activities in the thermal loading area.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

LIST OF FIGURES

LIST OF FIGURES (Continued)

Page

LIST OF FIGURES (Continued)

Page

LIST OF TABLES

1. INTRODUCTION

1.1 OBJECTIVE

The objective of the Mined Geologic Disposal System (MGDS) Thermal Loading Systems Study being conducted by the is to identify a thermal strategy that will meet the performance requirements for waste isolation and will be safe and licensable. Specifically, both postclosure and preclosure performance standards must be met by the thermal loading strategy ultimately selected. In addition cost and schedule constraints must be considered. The Systems Engineering approach requires structured, detailed analyses that will ultimately provide the technical basis for the development, integration, and evaluation of the overall system, not just a subelement of that system.

It is also necessary that the systems study construct options from within the range that are allowed within the current legislative and programmatic framework. For example the total amount of fuel that can legally be emplaced is no more than 70,000 metric tons of uranium (MTU) which is composed of 63,000 MTU spent fuel and 7,000 MTU of defense high level waste. It is the intent of this study to begin the structured development of the basis for a thermal loading decision. However, it is recognized that to be able to make a final decision on thermal loading will require underground data on the effects of heating as well as a suite of "validated" models. It will be some time before these data and models are available to the program. Developing a final, thermal loading decision will, therefore, be an iterative process.

In the interim, the objective of the thermal loading systems study has been to utilize the information available to assess the impact of thermal loading. Where technical justification exists, recommendations to narrow the range of thermal loading options can be made. Additionally, recommendations as to the type of testing and accuracy of the testing needed to establish the requisite information will be made.

A constraint on the ability of the study to select an option stems from the lack of primary hard data, uncertainties in derived data, unsubstantiated models, and the inability to fully consider simultaneously coupled processes. As such, the study must rely on idealized models and available data to compare the thermal loading options.

This report presents the findings of the FY 1993 MGDS Thermal Loading Systems Study. The objectives of the study were to: 1) if justified, place bounds on the thermal loading which would establish the loading that is "too hot;" 2) "grade" or evaluate the performance as a function of thermal loading of the potential repository to contain high level spent nuclear fuel against performance criteria; 3) evaluate the performance of the various options with respect to cost, safety, and operability; and 4) recommend the additional types of tests and/or analyses to be conducted to provide the necessary information for a thermal loading selection.

1.2 BACKGROUND

The ability to meet the overall performance requirements for the proposed MGDS at Yucca Mountain, Nevada relies on the two major subsystems (natural barriers and engineered barriers) to positively contribute to containment and radionuclide migration retardation. In addition to the postclosure performance the proposed repository must meet certain preclosure requirements of safety, retrievability, and operability and also must take into consideration cost and schedule. The thermal loading strategy chosen for such a repository may significantly affect both the postclosure and preclosure performance of the proposed repository. Additionally, Nuclear Regulatory Document (NUREG) 1466 (Nuclear Regulatory Commission (NRC), 1992a) specifies that demonstrating the system performance of the proposed repository in compliance with the regulations in CFR 10 CFR 60.133 (CFR, 1993) will require that the coupled thermal, mechanical, hydrological, and chemical (T-M-H-C) aspects of the repository performance be considered. To address the thermal loading issues of the repository, a systems study was recommended by the M&O and funded for FY 1993 by the U.S. Department of Energy (DOE).

Developing an accurate estimate of the effects of thermal loading on the repository will be necessary to ensure that the regulatory standards for nuclear waste disposal are met. Understanding and predicting the behavior of the host rock and Engineered Barrier System (EBS) in the potential repository, when subjected to heat released from the stored waste, are essential to obtaining a license to emplace waste. The effectiveness of these barriers for the various alternative thermal loads must be compared and presented in the licensing argument [10 CFR 60.21 (c) (1) (ii) (D)].

The rate of heat generation by nuclear waste decreases continuously with time. However, heat from the waste will be generated in appreciable quantity for thousands of years after the initial emplacement of the nuclear waste. Temperatures throughout the repository and host rock environment will increase and reach a maximum at different places in the repository at different times. Depending upon the waste package size, age of the fuel, emplacement mode and other factors the temperatures in the host rock could be significantly above the boiling point of water for a very long period of time. In the near term, high temperatures can have a significant impact on preclosure performance from the standpoint of safety and retrievability of the waste. Over a longer period of time, the high temperatures could in some cases improve performance by drying out the rock or, conversely, may contribute to degradation of the waste isolation capabilities. For example, temperatures above boiling will tend to dry out the rock which could result in reducing the aqueous corrosion of the waste canisters for a significant period of time. Conversely, high temperatures and thermal gradients can, under certain conditions, induce fractures in the rock as well as initiate water movement along pre-existing fractures. This behavior could change the structural integrity of the host rock and could enhance fracture permeability to potential water flow. High temperatures can also induce chemical and/or phase changes in some minerals and under some conditions can produce unfavorable or favorable conditions for adsorption of radionuclides. At intermediate temperatures the effects may result in changes to the water chemistry, causing an increase in the corrosion rate of the waste package. When T-M-H-C coupled behavior is considered, the problem is further complicated. From the standpoint of safely emplacing the waste and/or retrieving the waste, high temperatures can degrade our ability to perform these operations.

The above considerations indicate that the ability of the MGDS to meet pre- and postclosure objectives will be affected by the thermal loading. According to NUREG/CR-5428 (NRC, 1992b), "the thermal loading capacity is probably the single most important parameter to determine for a repository."

The study was designed to address the systems issues associated with the potential MGDS. In the first step performance standards were examined. To obtain a license for nuclear waste emplacement, a potential repository must comply with certain performance standards for both postclosure and preclosure and meet the performance objectives established in the regulations. However, early in the design stages it is difficult, if not impossible, to assess the complete performance of the system due to lack of mature ("validated") predictive models and adequate data. Additionally, because performance standards are not established for the Yucca Mountain Site (the U.S. Environmental Protection Agency [EPA] standards have been remanded), it is necessary to define surrogate criteria or goals. "It is believed that meeting those criteria should result in adequate performance of the potential repository and the natural and engineered barrier systems, and that the criteria could be used to evaluate and rank thermal loading options." This approach is based on a top-level strategy of providing for multiple-barriers. The Site Characterization Plan (SCP) (DOE, 1988a) attempted to establish the necessary criteria by developing thermal goals. DOE commissioned an effort to reevaluate these thermal goals, the results of which were presented in the SCP Thermal Goals Reevaluation Report (M&O, 1993a). These reevaluated thermal goals were used in the thermal loading study as measures to evaluate performance. The systems analysis will be an iterative process which will periodically review the goals as site characterization data and validated models become available.

The detailed work of meeting the objectives of the study was done through the steps discussed in the following paragraphs. The first of these processes was for the waste package design group to develop a range of waste package sizes to use in the study. Two basic types of waste packages were considered; a single, thin-walled container similar to that described in the SCP (DOE, 1988a) and a multi-barrier container with an inner wall thickness of 0.95 cm and an outer wall thickness varying between 10 and 45 cm. However, it should be noted, that except for some thermal calculations extracted from pervious work and a cost baseline, the thin walled WP was not considered in detail. The container capacities varied between 2 to 21 Pressurized Water Reactor (PWR) and 4 to 40 Boiling Water Reactor (BWR) assemblies. Weights, costs, and radiation shielding requirements for handling were established for each of the cases. Average fuel stream characteristics were calculated for the fuel that would be most likely to be emplaced in the repository. Using this information, several thermal loadings were chosen for the thermal study. These thermal loadings correspond to Area Mass Loadings (AMLs) of 24, 36, 55, 83 and 111 Metric Tonnes Uranium (MTU)/acre[1]. It should be noted that this report presents results in terms of AML. Area Power Densities (APDs) change with time while AMLs do not. The near-field environment is essentially a function of APD while the mountain-scale behavior is primarily a function of AML. For these reasons it was

[1] Metric units are used throughout the report except for AML and APD. A convention has been established to use MTU/acre or kW/acre for these units.

decided to use AML, but conversions between the two are presented in Chapter 3, 4, and Appendix A.

A number of generic subsurface designs were completed to accommodate the range of waste package sizes and thermal loadings. Designs were established for both a vertical borehole and a horizontal borehole concept at loadings of 24, 36, and 55 MTU/acre. It should be noted that no near-fieled calculations of a vertical borehole were done. Some earlier analyses by Hertel and Ryder (1991) were used for the thermal analysis. The designs mentioned above were used in the costing analysis. Also, designs were completed for two in-drift concepts (two different diameters; one for a tracked vehicle emplacement and another for wheeled vehicle) at the five AMLs. Both near-field and far-field thermal calculations were accomplished for the various subsurface designs and thermal loads.

The results of the efforts described above were analyzed to evaluate the effect of thermal loading on performance. These included evaluating the impact of the various thermal loadings on the geochemical aspects of the potential site. Very limited thermo-mechanical analyses were evaluated to establish the impact of the thermal loads on rock stability and the potential for mechanical and geochemical alteration of the natural barriers. The thermo-mechanical calculations, were very preliminary and only considered a single AML, a different waste stream than YFF (10), nor were the drift spacings necessarily the same as those used in this study. This thermo-mechanical analysis was only used to provide a basis for the Goal 8[1] and to establish some estimates of uncertainty in rock stability at the higher thermal loads. An evaluation was completed on the ability of the various configurations (subsurface designs, waste package options, and thermal loads) to meet the thermal goals and to determine which goal was the most stringent for the system performance. The impact of thermal loading on the performance was evaluated based on the ability of the various options to achieve thermal goals, operability constraints and preclosure safety, and ultimately to meet postclosure release standards. Complementary cumulative distribution functions were calculated for a large number of the different cases to estimate radionuclide cumulative releases.

Finally, cost analysis was also included in the assessment. The parameters of importance to waste isolation were identified and an assessment completed to determine the degree of uncertainty associated with each parameter and the ability to reduce this uncertainty through testing or analysis.

1.3 SCOPE

The scope of this effort encompassed a wide range of activities and involved a number of different organizations within the M&O as well as several national laboratories. The effort extended from December 1, 1992 to December 30, 1993. The range of activities follows:

1. Existing studies and data were evaluated to ensure that valid and up-to-date data were used in the study and, additionally, that the study did not "re-invent the wheel."

2. Performance criteria used in the study were established using the MGDS Requirements Document (DOE, 1992b), the Engineered Barrier Design

Requirements Document (M&O, 1993b), the Repository Design Requirements Document (M&O, 1993c), and the SCP (DOE, 1988a). These documents were used to guide the establishment of waste package input, MGDS design inputs, and temperature criteria. As a critical element in this effort, the thermal goals established in the SCP were reevaluated (M&O, 1993a), and those reevaluated goals were used to develop temperature and other criteria for the study.

3. The effort involved performing parametric thermal calculations over a fairly wide range of thermal loadings,Waste Package (WP) capacities, and subsurface designs. The investigation attempted to establish a better definition of what the thermal loading bounds might be based on such criteria as rock mechanics limits, safety, and waste package limits. However, only a selected set of WP sizes and emplacement modes were considered due to the limited funding and time constraints. For example, the emplacement modes considered (in-drift and vertical borehole) were established by direction of the program office. This study should not be construed as advocating one emplacement mode over another.

4. The repository performance was evaluated for various thermal loads using a range of spent nuclear fuel loadings from 24 to 111 MTU/acre. The performance was evaluated using both postclosure and preclosure (safety, operability, and cost) criteria.

5. Additional thermal needs for licensing of an MGDS in the areas of modeling efforts and test data needed were identified as much as possible in this activity.

The thermal loading study involved the assistance and participation of a large number of different groups within the Office of Civilian Radioactive Waste Management (OCRWM) program. The WP specifications, costs, and package radiation calculations were developed by the M&O WP Design Group. The subsurface layouts, costs, and evaluations of operability were performed by the M&O Subsurface Design Group. The near-field thermal calculations were done by Sandia National Laboratories (SNL) and the far-field hydrothermal calculations were performed by Lawrence Livermore National Laboratory (LLNL). Support in the area of geochemical evaluations was provided by Los Alamos National Laboratory (LANL). M&O Performance Assessment played an integral role in providing Total System Performance Assessment calculations of radiological exposures and rock mechanics calculations. The M&O Systems Analysis Group in Vienna, Virginia provided the waste stream inputs, while the MGDS Systems Analysis group performed analysis and evaluation of the results, and provided overall management for the study.

The thermal loading study built upon the experience and information developed in several other OCRWM studies. The results of the Phase I Thermal Loading Study (M&O, 1992) found "that any of the waste stream scenarios appear to be compatible with the entire range of thermal strategies without any special management of waste" were used as a starting point of this study. This study focused on receipt of waste and transporation issues for the most part. The thermal study was integrated closely with two other systems studies, the Waste Package Performance Allocation Study and the Emplacement Mode Study, and relied on some of the information developed in those studies. The study results were coordinated with the M&O

Vienna Systems Analysis Group to evaluate the impact on activities external to the "Dispose of Waste" functions. As part of this effort, the Systems Architecture program was used to evaluate system wide implications.

1.4 ORGANIZATION OF THE REPORT

It is recognized that thermal loading requirements can impose specifications on the system which reach beyond the MGDS. Restrictions might have to be placed on the waste steam which could impact waste acceptance strategies. If a Multi-Purpose Canister (MPC) is used, thermal loading decisions may impact WP construction/size and transportation. Fuel aging, if required, could impact storage requirements; a monitored retrievable storage (MRS) facility might be needed. Although this study did not look at these issues, a Systems Architecture Study (M&O, 1993k) did examine some of them. The cost evaluations done in the Systems Architecture Study were considered in this study and this is summarized in Section 6.

The MGDS FY 1993 Thermal Loading Systems Study final report is organized in two volumes. Volume I is the main body of the text and summarizes the requirements and assumptions, analysis results, and conclusions. Volume II contains appendices that provide additional details of the analyses presented in the body of the report.

The Executive Summary of the report is contained in Volume I. Section 1 provides the study objective, background and scope of the report. The performance requirements are described in Section 2. Input and assumptions for the report are discussed in Section 3. Sections 4 and 5 provide results of the near-field and far-field analyses. Cost analysis results are provided in Section 6. Section 7 contains additional calculations and analyses that would not conveniently fit in one of the earlier sections. A systems analysis that integrates and consolidates the study results is provided in Section 8. A recommendation of those issues to be addressed in additional thermal analyses is provided in Section 9. Section 10 contains the conclusions and recommendations of the report. A glossary and references are provided in Sections 11 and 12 respectively.

Volume II contains nine appendices. Additional details of the waste characteristics, waste package design, and subsurface design are contained in Appendices A, B, and C. The details of the model inputs are provided in Appendix D. Near-field and far-field calculation details are discussed in Appendices E and F. Appendix G provides detail on the reliability of instrumentation. Details of the cost calculations are contained in Appendix H. Chapter I describes the geochemistry calculation details.

2. PERFORMANCE REQUIREMENTS

2.1 REGULATORY BASIS

Disposal of high-level radioactive wastes in geologic repositories is regulated under 10 CFR 60 and this regulation specifically requires that the impact of heat produced by the spent nuclear fuel on the natural and engineered barriers be considered. This is clarified by the NRC guidance, NUREG 1466 (NRC, 1992a) which specifies that demonstrating the system performance of the proposed repository complies with the regulations in 10 CFR 60.133 (CFR, 1993) and will require that the coupled T-M-H-C aspects of the repository performance be considered. NUREG 1466 further states that "repository-induced thermal loading of the host rock, surrounding strata and groundwater system may be one of the most important Geologic Repository Operations Area (GROA) MGDS design parameters." Other regulations such as 10 CFR 960 and 40 CFR 191 (which was vacated by the U.S. First Circuit Court of Appeals and remanded for repromulgation) were also considered in formulating this study.

Congress passed the Nuclear Waste Policy Act in 1982 and amended it in 1987 to direct the DOE to study and develop a high-level nuclear waste repository. The NRC issued 10 CFR Part 60, its regulation covering the geologic disposal of high-level radioactive wastes, in 1981, and has since revised the regulation several times. The EPA issued 40 CFR Part 191, its standard for geologic disposal of high-level radioactive waste, in 1985. However, in 1987 the U.S. Court of Appeals remanded the standard. The court cited insufficient public notice and unjustified inconsistencies associated with groundwater protection and individual protection (dose limits) as the reasons for the remand. 40 CFR Part 191 was repromulgated in 1993, but the new standard does not apply to Yucca Mountain. In the Energy Policy Act of 1992 Congress directed the National Academy of Sciences to study individual dose-based standards and to make findings and recommendations to the EPA on "... reasonable standards for protection of public health and safety for Yucca Mountain." The NAS report is currently scheduled to be completed in December 1994. No later than one year following the NAS study, the Energy Policy Act directs the EPA to promulgate standards for a repository at the Yucca Mountain site. The standards shall prescribe the maximum annual effective dose equivalent to individual members of the public from releases from a repository, and the standards shall be consistent with the NAS recommendations. Within one year of the promulgation of the new EPA standards, the NRC is required to modify its regulations to be consistent with those standards.

The results of the NAS study, and the subsequent impacts on the EPA and NRC regulations, are unknown. Potential changes include, but are not limited to, modification or elimination of the radionuclide release limits; modification of the 10,000 year time frame for evaluating regulatory compliance; and implementation of risk standard for long time periods. In the interim, this study will evaluate the results based on the existing regulatory framework, i.e., the remanded 1985 version of 40 CFR Part 191 and the current version of 10 CFR Part 60. In order to produce a reasonably robust study, the study will examine a wide range of parameters and conditions as well as effects for time frames well in excess of 10,000 years.

The following provides a brief summary of the regulatory guidelines in 10 CFR 60 (CFR, 1993) that served as a basis for the study:

> 10 CFR 60.111(b) Retrievability of waste. (1) The geologic repository operations area shall be designed to preserve the option of waste retrieval throughout the period during which wastes are being emplaced and, thereafter, until the completion of a performance confirmation program and Commission review of the information obtained from such a program. To satisfy this objective, the geologic repository operations area shall be designed so that any or all of the emplaced waste could be retrieved on a reasonable schedule starting at any time up to 50 years after waste emplacement operations are initiated, unless a different time period is approved or specified by the Commission.
>
> 10 CFR 60.112 Overall system performance objective for the geologic repository after permanent closure. The geologic setting shall be selected and the engineered barrier system and the shafts, boreholes, and their seals shall be designed to assure that releases of radioactive materials to the accessible environment following permanent closure conform to such generally applicable environmental standards for radioactivity as may have been established by the Environmental Protection Agency with respect to both anticipated processes and events and unanticipated processes and events.
>
> 10 CFR 60.113 Performance of particular barriers after permanent closure.

(a) General provisions

- (1) Engineered barrier system.
  - (i) The engineered barrier system shall be designed so that assuming anticipated processes and events:
    - (A) Containment of HLW will be substantially complete during the period when radiation and thermal conditions in the engineered barrier system are dominated by fission product decay; and
    - (B) any release of radionuclides from the engineered barrier system shall be a gradual process which results in small fractional releases to the geologic setting over long times.
  - (ii) In satisfying the preceding requirement, the engineered barrier system shall be designed, assuming anticipated processes and events, so that:
    - (A) Containment of HLW within the waste packages will be substantially complete for a period to be determined by the Commission taking into account the factors specified in CFR 60.113(b) provided, that such period shall be not less than 300 years nor more than 1,000 years after permanent closure of the geologic repository; and
    - (B) The release rate of any radionuclide from the engineered barrier system following the containment period shall not exceed one part in 100,000 per year of the inventory of that radionuclide calculated to be present at 1,000 years following permanent closure, or such

other fraction of the inventory as may be approved or specified by the Commission; provided, that this requirement does not apply to any radionuclide which is released at a rate less than 0.1 percent of the calculated total release rate limit. The calculated total release rate limit shall be taken to be one part in 100,000 per year of the inventory of radioactive waste, originally emplaced in the underground facility, that remains after 1,000 years of radioactive decay.

(2) Geologic setting. The geologic repository shall be located so that pre-waste-emplacement groundwater travel time along the fastest path of likely radionuclide travel from the disturbed zone to the accessible environment shall be at least 1,000 years or such other travel time as may be approved or specified by the Commission.

(b) On a case-by-case basis, the Commission may approve or specify some other radionuclide release rate, designed containment period or pre-waste emplacement groundwater travel time, provided that the overall system performance objective, as it relates to anticipated processes and events, is satisfied. Among the factors that the Commission may take into account are:

(1) Any generally applicable environmental standard for radioactivity established by the EPA;

(2) The age and nature of the waste, and the design of the underground facility, particularly as these factors bear upon the time during which the thermal pulse is dominated by the decay heat from the fission products;

(3) The geochemical characteristics of the host rock, surrounding strata and groundwater; and

(4) Particular sources of uncertainty in predicting the performance of the geologic repository.

(c) Additional requirements may be found to be necessary to satisfy the overall system performance objective as it relates to unanticipated processes and events.

10 CFR 60.131 General design criteria for the geologic repository operations area.

(a) Radiological protection. The geologic repository operations area shall be designed to maintain radiation doses, levels, and concentrations of radioactive material in air in restricted areas within the limits specified in Part 20 of this chapter. Design shall include:

(1) Means to limit concentration of radioactive material in air;

(2) Means to limit the time required to perform work in the vicinity of radioactive materials, including, as appropriate, designing equipment for ease of repair and replacement and providing adequate space for ease of operation;

(3) Suitable shielding;

(4) Means to monitor and control the dispersal of radioactive contamination;

(5) Means to control access to high radiation areas or airborne radioactivity areas; and

(6) A radiation alarm system to warn of significant increases in radiation levels, concentrations of radioactive material in air, and of increased radioactivity released in effluents. The alarm system shall be designed with provisions for calibration and for testing its operability.

This is discussed in more detail in the Emplacement Mode Systems Study report (M&O, 1993e). However, the standards that must be met are now specified in the Radiation Control Manual (DOE, 1992a) which captures the requirements of 10 CFR 20 and has been mandated by the Secretary of Energy that these standards will be used in all DOE facilities and programs. The Radiation Control Manual states that the allowable dose for an individual that is permitted will be as low as reasonably achievable (ALARA) and less than 500 mrem per year.

(b) Structures, systems and components important to safety.

(1) Inspection, testing, and maintenance. The structures, systems, and components important to safety shall be designed to permit inspection, testing, and maintenance, as necessary, to ensure their continued functioning and readiness.

(2) Instrumentation and control systems. The design shall include provisions for instrumentation and control systems to monitor and control the behavior of systems important to safety over anticipated ranges for normal operation and for accident conditions.

10 CFR 60.133 Additional design criteria for the underground facility.

(a) General criteria for the underground facility.

(1) The orientation, geometry, layout, and depth of the underground facility, and the design of any engineered barriers that are part of the underground facility shall contribute to the containment and isolation of radionuclides.

(2) The underground facility shall be designed so that the effects of credible disruptive events during the period of operations, such as flooding, fires, and explosions, will not spread through the facility.

(b) Flexibility of design. The underground facility shall be designed with sufficient flexibility to allow adjustments where necessary to accommodate specific site conditions identified through in situ monitoring, testing or excavation.

(c) Retrieval of waste. The underground facility shall be designed to permit retrieval of waste in accordance with the performance objectives of CFR 60.111.

(d) Control of water and gas. The design of the underground facility shall provide for control or water or gas instrusion.

(e) Underground openings.

(1) Openings in the underground facility shall be designed so that operations can be carried out safely and the retrievability option maintained.

(2) Openings in the underground facility shall be designed to reduce the potential for deleterious rock movement or fracturing of overlying or surrounding rock.

(f) Rock excavation. The design of the underground facility shall incorporate excavation methods that will limit the potential for creating a preferential pathway for groundwater to contact the waste packages or radionuclide migration to the accessible environment.

(g) Underground facility ventilation. The ventilation system shall be designed to:

(1) Control the transport of radioactive particulates and gases within and releases from the underground facility in accordance with the performance objectives of CFR 60.111(a).

(2) Assure continued function during normal operations and under accident conditions; and

(3) Separate the ventilation of excavation and waste emplacement areas.

(h) Engineered barriers. Engineered barriers shall be designed to assist the geologic setting in meeting the performance objectives for the period following permanent closure.

(i) Thermal loads. The underground facility shall be designed so that the performance objectives will be met taking into account the predicted thermal and thermomechanical response of the host rock, and (sic) surrounding strata, [and] groundwater system.

10 CFR 60.135 Criteria for the Waste Package and its components.

(a) High-level-waste-package design in general.

(2) The design shall include but not be limited to consideration of the following factors: solubility, oxidation/reduction reactions, corrosion, hydriding, gas generation, thermal effects, mechanical strength, mechanical stress, radiolysis, radiation damage, radionuclide retardation, leaching, fire and explosion hazards, thermal load and synergistic interactions.

2.2 SYSTEM PERFORMANCE

To obtain a license to emplace nuclear waste, a potential repository must comply with certain performance standards for both postclosure and preclosure, and meet the performance objectives established in the regulations. However, early in the design stages it is difficult, if not impossible, to assess the complete performance of the system due to lack of mature ("validated") predictive models and adequate data. Additionally, because performance standards are not established for the Yucca Mountain Site (the EPA standards have been remanded), it is necessary to define surrogate criteria or goals. "It is believed that meeting those criteria should result in adequate performance of the potential repository and the natural and engineered barrier systems, and that the criteria could be used to evaluate and rank thermal loading options (M&O, 1993a)." This approach is based on a top-level strategy of providing for multiple barriers.

The SCP (DOE, 1988a) attempted to define surrogate criteria that could be used to establish repository performance and meet design objectives. These criteria or SCP thermal goals were developed from knowledge existing at the time and, as a reference case, emphasized performance for waste emplacement in a vertical borehole. Since that time, new knowledge has become available and some additional analyses of thermal loading have been performed. Additionally, other emplacement modes such as in-drift emplacement are being considered to accommodate larger waste packages. New concepts such as "extended hot" (produced by thermal loading well above the SCP case) are also being considered as possible methods to achieve improved waste isolation. Thus it became clear that the thermal goals established in the SCP should be reevaluated. This is consistent with a phased design approach that incorporates maturing design concepts.

The DOE Yucca Mountain Site Characterization Office (YMSCO) authorized a two month effort to reevaluate the SCP thermal goals. The objectives of the effort were to: 1) provide thermal criteria that would support an FY 1993 Thermal Loading Systems Study; 2) help focus planned testing and analysis efforts; and 3) acquire information that potentially could be used to initiate a change to the project technical baseline. To achieve the objectives an expert Working Group was established and tasked to address the following questions:

1. What was the technical rationale for establishing a goal?

2. Is the rationale still applicable and valid for more than just vertical borehole emplacement? If the goal is not completely adequate should it be deleted or changed?

3. Are there any other goals that are needed or would be appropriate to add?

4. If uncertainties exist in the waste isolation performance of the repository under a specific goal, what tests and/or analyses should be recommended to reduce or eliminate the uncertainty?

Fifteen thermal goals identified in various sections of the SCP were evaluated by the Working Group. It was recommended that two goals be deleted: 1) to keep borehole wall temperature <275 degrees Celsius and 2) to keep the mid-drift temperature <100 degrees Celsius. It was recommended to add one goal to establish a thermal loading that would not degrade the Upper Paintbrush Tuff Formation (Lowermost Tiva Canyon; Yucca Mountain; Pah Canyon; and Uppermost Topopah Spring Members) (Vitric nonwelded) (PTn) barrier. Two other thermal goals and a process statement were reworded to afford compatibility with any emplacement mode, not just the vertical borehole. A recommendation was made to increase the conservatism of a goal to limit potential impact on the surface environment by limiting temperature rise to <2 degrees Celsius rather than <6 degrees Celsius. Additionally, and probably more important, is the fact that based on the evaluation, additional tests and analyses were recommended to reduce the uncertainty associated with some of these goals. A summary of these goals is shown in Table 2-1. Some of these goals were used in the thermal loading report to evaluate the various options. Not all of the goals could be used in the evaluations since such things as model limitations and/or boundary conditions prevented predictions of temperature or stress at a specific level (e.g., the surface temperature). Thus, only about eight of the goals shown in Table 2-1 plus a monitoring goal which is discussed later were used in the evaluation. The "starred" goals in Table 2-1 were those used. A more detailed discussion of all the goals and a mapping of these goals to the regulatory requirements is discussed below. The evaluations against the goals along with a summary table are shown in Section 8.

To determine how each of the goals listed in Table 2-1 met the regulatory requirements, some discussion was presented as to the rationale that established each goal. One of the first things done in the SCP Thermal Goals Reevaluation (M&O, 1993a) was to review work completed at the time the goals were established and question some of the original members of the SCP team about what rationale was used for a goal. A short summary of the rationale for establishing each goal was extracted from the M&O report (1993a) and is the following:

> Goals 1 and 2: The principal SCP rationale for setting upper limits on temperature in these units is the concern that mineralogic changes could occur due to dehydration induced by potential repository heating and that these may cause "chemical and physical effects that could be detrimental to waste isolation." (Smyth, 1982) These goals are somewhat redundant because the CHn unit underlies the TSw3 unit but both were retained by the working group doing the goals reevaluation.

Table 2-1. Revised SCP Thermal Goals

Number	Thermal Goal
1*	Limit Temperature of CHn to <115°C
2*	Limit Temperature of TSw 3 to <115°C
3	Relative Motion <1m at the top of TSw1
4	Rise in Surface Temperature <2°C
5	Surface Uplift <0.5 cm/year
6	Design Basis Thermal Loading Less Than Allowable Thermal Loading
7	Deleted
8*	Keep The Rock Mass Temperature at 1~m From Vertical Borehole <200°C
8[1]*	Keep In-Drift Wall Temperatures <200°C
9*	Boreholes That Do Not Load Container Beyond Limits Imposed Under Issue 1.10
10*	Maximize Time the Waste Package Container Stays Above Boiling, Consistent With the Thermal Strategy Developed
11*	Fuel Cladding Temperature <350°C
12	High Level Waste Glass Temperature <500°C
13*	Temperature in Access Drift <50°C for First 50 Years, Any Emplacement Mode
14	Deleted
15	Emplacement Drift Wall Temperature <50°C for First 50 Years for Horizontal Borehole
16	Establish a Thermal Loading Which Would Not Degrade PTn Barrier

*Thermal goals used in this evaluation

Goals 3 and 5: These goals should be treated together as far-field thermomechanical goals. Their purpose was to ensure that far-field thermal effects would not produce preferential pathways for fluid flow.

Goal 4: This goal originated as an environmental requirement to limit surface temperature changes to levels which would not result in significant changes in the near-surface biological environment.

Goal 6: This goal was very generic so that the potential repository would be designed to accommodate borehole and drift spacing which would provide the flexibility necessary to achieve the thermal loading in the potential repository.

Goal 7: This goal was deleted.

Goal 8: This goal was established to minimize adverse stresses in the rock around the borehole that may cause closure of the borehole, local rock failures resulting in damage to the container (pre-and postclosure concern), and/or to prevent retrieval of the container (preclosure concern).

Goal 8^1: This goal was recommended for addition. It deals with in-drift emplacement and based on thermo-mechanical analysis that was done it was determined that it is primarily the temperature gradient rather than the actual temperature that will give rise to stresses in the rock that may result in failure. The study determined that for rock present at Yucca Mountain, steep thermal gradients into the rock can develop if the rock surface temperature starts to exceed about 200 degrees Celsius. These gradients result in large stresses which conceivably could result in rock failure. Keeping the temperatures below 200 degrees Celsius would prevent thermal gradients of a magnitude that could cause large-scale failure to develop. It is possible to have very steep thermal gradients around a drift without the wall temperatures exceeding 200 degrees Celsius. However, the 200 degrees limit was also to keep possible increases in thermal expansion of the silica phase inversions from occurring which would have an adverse impact on the rock strength. This goal needs to be reexamined as more data becomes available.

Goal 9: This goal was established so that waste package integrity would not be compromised due to borehole loading.

Goal 10: This goal was linked to nuclide containment in 10 CFR 60 and the belief that the waste package lifetime could be extended by keeping the drift walls above boiling as long as possible. Since it was realized that it will be the waste package material, temperature, and environment, not strictly borehole or drift temperatures, that will ultimately govern waste package lifetime, a decision was made to revise this goal. The goal was revised to state that the time the waste package stays above boiling should be maximized as long as it is consistent with the thermal strategy selected.

Goal 11: The thermal goal to limit the fuel cladding temperature was originally established based on studies performed at Pacific Northwest Laboratories. In those studies, if the temperature of the fuel rods exceeded about 380 degrees Celsius, the

Zircaloy fuel cladding would likely fail due to creep. To ensure that the cladding would not undergo creep failure a conservative "not to exceed" goal of 350 degrees Celsius was established. However, additional experiments are needed to better characterize this number.

Goal 12: It was believed that temperatures above this value could result in devitrification of the borosilicate glass waste form.

Goal 13: The rationale for this goal is to establish an environment during the emplacement period that could be modified to allow access by thermally unprotected workers and, in closed areas, could be cooled within eight weeks to allow such access. This goal was established for the vertical borehole emplacement mode.

Goal 14: This goal was recommended for deletion.

Goal 15: This goal, found in the SCP on page 8.3.5.2-10 (item 2) in Section 8.3.5.2 (Waste Retrievability), is similar to the goal for the vertical borehole case. What may be confusing is that the words "emplacement drift" are used. However, the horizontal borehole emplacement drift is similar to the vertical borehole access drift. This is clearly shown in Figure 6-64 on page 6-151 of the SCP (DOE, 1988a). Hence, the rationale for this goal is similar to that for Goal 13.

Goal 16: This goal was proposed for addition. It was suggested that a goal be established to keep the Paintbrush nonwelded member (PTn) below boiling to prevent ^{14}C release or conditions that might enhance water percolation. The PTn unit exists between the Tiva Canyon (TCw) and Topopah Spring (TSw) welded units and is recognized as potentially important for controlling the rate and spatial distribution of water entering the deep unsaturated zone as net land-surface infiltration. The presence of thin vitrophyres in the basal TCw and upper TSw, and the relatively high hydraulic conductivity and storage capacity of the nonwelded and bedded tuffs of the intervening PTn unit, combine to divert ground water laterally down-dip and away from the potential repository. Although the effectiveness of this potential barrier remains to be evaluated fully, the PTn may be capable of limiting the amount of infiltrating water that could readily percolate to the potential repository horizon under present day arid as well as possible future wetter climatic conditions. It is speculated that the PTn may also provide a barrier against release of ^{14}C if a waste package is breached. Since the group could not establish a quantitative goal, such as boiling, without any technical basis, it was decided (M&O, 1993a) to provide a more qualitative goal as a placeholder until the adequate technical evaluation is completed.

To show how the above goals are perceived to meet the regulatory requirements in 10 CFR 60 mentioned above, the mapping of these goals to the specific regulation is shown in Table 2-2.

Table 2-2. Mapping of Thermal Goals to Regulatory Bases

Regulation	Goal #
10 CFR 60.113 (a) Substantially complete containment	3, 6, 8, 9 10, 11, 12, 16
10 CFR 60.133 (e) and 10 CFR 60.113 (a)(1)(ii)(B)Avoid adverse structural deformation, geochemical process, or geomechanical	3, 5, 8, 8[1], 9, 16
10 CFR 60.133 (c) and 60.111(b) Permit retrieval	6, 8, 8[1], 9, 13, 15
10 CFR 60.133 (h) EBS assist geologic setting in meeting performance objectives	10, 11, 12
10 CFR 60.133 (i) Thermal effects will allow performance objectives to be met	1, 2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 15, 16
10 CFR 60.113(b) and 10 CFR 60.135 () Interaction of WP with Environment does not compromise performance	1, 2, 3, 5, 9, 10, 11
10 CFR 60.131 (b)(8), 10 CFR 60.143, and 10 CFR 60.141 Provide for monitoring through permanent closure	Criteria developed in Section 7 and Appendix G

Although monitoring the potential repository after emplacement and until permanent closure was not spelled out in the SCP as a thermal goal, it is nevertheless required by regulations. Specifically, 10 CFR 60.143 (CFR, 1993) mandates that a program be established to monitor the waste packages until permanent closure. Additionally, 10 CFR 60.141 states that appropriate in-situ monitoring of the thermo-mechanical response of the underground facility shall be conducted until permanent closure to ensure that the performance of the natural and engineered features is within design limits. Other passages such as 10 CFR 60.141, 140, 133, 131, 101 and 51 all state that monitoring of the underground facility will be done. The ability to monitor the potential repository will be impacted by the thermal loading since instrumentation and components can have significantly reduced lifetimes under high temperatures. The criteria for monitoring were developed in a small study done by the M&O in support of this study and the details reported in Appendix G. The evaluation against the thermal performance is presented in Section 9.

One way to evaluate or "grade" the performance against the thermal goals is to weight each of the goals equally. These are, however, goals and not inviolate criteria and thus ultimately such an application would be unrealistic. Specifically, studies and data may ultimately indicate that improved performance could be achieved by relaxing a particular goal. An example of this may be allowing the waste package to exceed the 350 degrees Celsius centerline temperature to achieve an extended hot condition if it is ultimately shown that this will substantially improve waste isolation performance. One way to determine the weighing that a given goal should have is to rely on expert elicitation. Steps were taken to initiate this process but the effort was not completed and will have to be done on the follow-on study. Thus, the combined performance against each goal was measured and, although somewhat unrealistic, each goal was considered to carry the same weight as any of the other goals.

The revised set of goals was used in the FY 1993 Thermal Loading Systems Study as the criteria against which the performance was "graded." The study also provided some specific recommendations that certain work be done to allow a better evaluation to establish a more definitive basis for the thermal goals. These preliminary goals need to be evaluated further once the recommended studies have been completed. As information becomes available, some goals are likely to be changed, dropped, or added. Ultimately the licensing arguments must be based, for the most part, on performance calculations.

3. INPUT AND ASSUMPTIONS

The purpose of this section is to identify some of the input conditions for the study and some of the assumptions used. The section starts by introducing the reference case against which the various cases are compared. An important aspect of the problem that must be applied consistently across the range of thermal loads is what are the waste stream and the fuel characteristics most likely to exist at the time of disposal. The rationale for the WP capacities ultimately chosen for the parametric studies is discussed in this section. The generic subsurface designs chosen are presented with a discussion of how and why the specific designs were developed. The methodology used to establish what thermal loadings would be considered in the study is described. Finally, some of the important aspects of the data used and the assumptions selected are described.

3.1 REFERENCE CASE

The thermal loading study reference case for the MGDS is based on the current baseline. The MGDS baseline design consists of a site, surface facilities, subsurface facilities, waste packages, and shafts and ramps connecting the surface and subsurface facilities. Many of these features of the MGDS design are dependent on the performance allocated to the EBS which includes the waste package design and the way in which it interacts or works in concert with the natural barriers, hence the thermal loading plays a key role in the performance. The technical baseline for the MGDS is detailed in the following reference documents. These documents, a subset of the Level 2 - Change Control Board (CCB) Baselined Documents, consist of the following:

DOE (1991a): "Yucca Mountain Site Description Baseline (Basis for Site Characterization Plan, Chapter 8)," (YMP/CM-0008), describes the site of the potential first repository.

DOE (1991b): "Conceptual Design of a Repository (Basis for Site Characterization Plan, Chapter 8)," (YMP/CM-0009), provides the baseline repository design description.

DOE (1991c): "Waste Package Design (Basis for Site Characterization Plan, Chapter 8)," (YMP/CM-0010), provides the baseline waste package design.

DOE (1993a): "Exploratory Studies Facility Technical Baseline (Vol. I and II)," (YMP/CM-0016), provides the ESF technical baseline. After completion of the site characterization project and if the site is deemed suitable, portions of the ESF will become part of the repository, the ESF ramps will provide access to the underground levels, the ESF ramps and main drift will provide the conduit for ventilation air to support waste emplacement operations, and the exploratory drifts of the ESF will penetrate waste emplacement areas.

The "Reference Description of the Civilian Radioactive Waste Management System (CRWMS)" (M&O, 1993g) provides a summary description of the CRWMS and the MGDS. The MGDS performs the waste disposal function of the CRWMS, and includes waste isolation. A very brief description of the MGDS functions performed by the reference case design is provided. Waste is received from the CRWMS transportation system in the form of transportation casks. The casks are unloaded in the surface facilities and transferred into waste packages for disposal. The waste packages are transported to the underground facilities for emplacement. The EBS is designed so that the waste packages are retrievable. A period of retrievability of 50 years after initial waste emplacement in the repository has been prescribed in the baseline documents. The performance of the repository is to be monitored to confirm that the system can perform the waste isolation function. At the end of the performance confirmation program, a license application for permanent closure will be submitted, if judged appropriate. If a license for permanent closure is issued, the repository will be closed and decommissioned.

The Thermal Loading Systems Study reference case is a thin-walled WP emplaced in a vertical borehole at a thermal loading of 57 kW/acre. This case provides the cost basis for comparison that was used for all the other cases considered in this study. The waste stream used in the SCP reference case was 10 year old fuel and 33 gigaWatt days (GWd)/MTU burnup (DOE, 1988a). More recent information in the fuel characteristics data base indicates that the average fuel will have a higher burnup and older age at disposal and this is discussed in more detail in Section 3.2. Because of this it was decided to update the waste stream with the most current characteristics. However, as one of the concepts evaluated, the updated fuel was packaged in a 6 PWR package which would produce a heat output at emplacement in the range produced by the SCP WP. The average fuel characteristics selected for the study were a PWR fuel with an average age of 22.5 years, 42.2 GWd/MTU burnup, and 3.92 percent enrichment and a BWR fuel that had an average age of 23.5 years, a 32.2 GWd/MTU burnup, and a 3.10 percent enrichment.

Regarding thermal calculations, the far-field analysis performed calculations at 55 MTU/acre which, for the fuel used, produces the reference loading of 57 kW/acre at emplacement. In the near-field area an evaluation of earlier work by Hertel and Ryder (1991) was done to evaluate performance. The cited work showed how large a WP could be for a vertical borehole and not violate thermal goals and also how large an Area Power Density (APD) could be accommodated without violating goals. The Total System Performance Assessment (TSPA) work, which is referenced and included in the report to evaluate radionuclide release dosages, also considered as one of the various options evaluated, a thin-walled WP emplaced in a vertical borehole. For this study, the 55 MTU/acre case was calculated for the near-field analysis, but unfortunately, no vertical borehole cases were run. Therefore, in the evaluation of near-field or preclosure performance the study did not produce the calculations that would directly tie to the reference case.

There was a need to vary the potential repository size to obtain the different thermal loadings. Comparisons are made with the reference case for various WP capacities and in-drift emplacement. The SCP case at 57 kW/acre required a repository area of about 1420 acres, and a heated area of 1215 acres, out of the potential useable primary area of 1850 acres as discussed on page 6-227 of the SCP (DOE, 1988a). To evaluate the different thermal loads this area had to be varied in the thermal study since the amount of fuel to be emplaced was fixed at 63,000 MTU. The area was allowed to vary over a range of about 570 to 2600 acres as discussed in Section 3.4. The fuel used in the study required about 1200 acres to emplace the fuel at an AML of 55 MTU/acre, which corresponded to the 57 kW/acre reference case. This was a similar area to that used in the SCP. This will be discussed in more detail below.

3.2 WASTE STREAM ANALYSIS

The waste stream arriving at the repository depends on the scenario and assumptions used in the analysis. The waste stream implicitly reflects the system designs and operating concepts. It can be thought of as the "fingerprint" of the system. A given waste stream also yields unique average characteristics and distributions around those averages. These parameters may be expressed in a number of ways depending on the needs of subsequent analyses. For this study, average characteristics at emplacement and equivalent, aggregated thermal source terms for temperature analyses were needed. These average source characteristics were used in the far-field analysis. However, for the near-field analysis only a single element of this average fuel, the hotter PWR fuel characteristics was used to be conservative. These provided some conservatism since the PWR fuel will produce higher near-field temperatures than either BWR or a mix of PWR and BWR. This section presents summary results of the waste stream analysis; Appendix A discusses the methodology and models used to produce the results. Detailed results are documented in the References King, 1993a and King, 1993b.

The key system scenario parameters and assumptions are shown below.

- Youngest Fuel First with minimum age of 10 years [YFF(10)] waste acceptance
- Flowthrough/passthrough at the Monitored Retrievable Storage (MRS) facility
- Full core reserves (FCRs) maintained
- Oldest Fuel First (OFF) selection for dry storage when pools are full
- Dry storage fuel pickup deferred.

Fuel selection for pickup at the waste generators is done according to the rule Youngest Fuel First, greater than or equal to 10 years old (YFF(10)). For a given year's allocation, the appropriate pools' inventories are examined and fuel is selected YFF(10) at each pool until that year's allocation has been filled. Other selection schemes were examined, but YFF(10) was chosen since it represents a conservative middle ground between oldest fuel first (OFF) and YFF. OFF and YFF selection yield bounding waste stream characteristics, and YFF(10) is a convenient point between but towards the conservative bound. It should be noted that, as discussed above, only simple aggregate averages were used in the thermal calculations although the cost analysis considered the entire YFF(10) scenario. As such, the thermal calculations did not include the full variation in heat output that can occur. This variability and its impacts will be examined in a later study.

MRS passthrough/flowthrough refers to the common assumption that during steady state (3000 MTU/yr) MRS operation, inventory turnover is minimized by shipping all fuel arriving at the MRS on to the repository. Flowthrough refers to receiving rail casks and assembling them into unit trains without opening them; passthrough refers to receiving truck casks and repackaging the fuel into from-MRS rail casks.

At the reactor spent fuel pools, assumptions about inventory management can have significant impacts on the waste stream characteristics. These assumptions deal with how pool overflow into dry storage is handled and how fuel in dry storage is withdrawn. Although not explicitly required by the NRC, FCRs are routinely maintained in practice. Maintaining a full core reserve (FCR) means leaving room in the pool to discharge one full core of fuel to allow for emergency discharge of all fuel in the reactor. When a pool has filled to the point of FCR, any additional discharges result in pool "overflow," requiring on-site dry storage (outside the pool) to maintain FCR. Pools serving multiple reactors, called shared pools, maintain only one FCR, not one for each reactor.

A selection rule is needed to computationally track which fuel assemblies are placed into dry storage when the pool is full. This choice is important because under typical assumptions, only 63,000 MTU out of a total of 86,000 MTU (projected total fuel by Energy Institute of America assuming no new reactors) are picked up for emplacement in the first repository. This "subsetting" of the fuel leads to significant differences in average characteristics seen at the repository, depending partially on at-reactor inventory management assumptions. Another closely related analysis assumption is whether or not to defer pickup of fuel placed in dry storage until the pool is empty or contains only fuel less than five years old. The assumptions made for this analysis are those typically made in waste stream analyses: fuel is placed into dry storage OFF and pickup of fuel in dry storage is deferred. These assumptions lead to significant amounts of fuel being placed into dry storage but never picked up since only a subset of the total inventory is ultimately accepted (for the first repository). This effect skews the average characteristics seen at the first repository.

For this study, containerization upstream of the repository is not important, but containerization into WPs at the repository clearly is important for any repository thermal analysis. WP capacity was parametrically varied for the waste stream produced using the system level assumptions discussed above. The detailed results for all WP combinations are not presented here; they can be found in References (King, 1993a and King, 1993b). The methods and models used to simulate loading discrete WPs and converting WP inventories into equivalent thermal source terms are discussed in Appendix A. Relatively few assumptions and scenario parameters are needed for this portion of the waste stream analysis. The primary assumptions and parameters concern WP capacity, lag storage, blending, and source term aggregation.

For a given waste stream, WP capacity drives the number of WPs needed and the average WP characteristics. Of the many combinations of WP capacities analyzed, three were used in subsequent calculations. All are uniform packages, meaning only one assembly type (BWR or PWR) is in a given package. The three packages retained were: 6 PWR/12 BWR, 12 PWR/21 BWR, and 21 PWR/40 BWR. Summary results for these cases are shown in Table 3-1.

Table 3-1. Aggregate Average Waste Package Summary Data

PWR			BWR		
Cap.	No. Pkgs	Avg Heat[1]	Cap.	No. Pkgs	Avg Heat[1]
6	15,863	2,907	12	10,394	1,843
12	7,931	5,814	21	5,939	3,226
21	4,532	10,174	40	3,118	6,145

NOTES: 1) Average Heat Output at Emplacement (watts/package)

The term lag storage, used generically here, refers to the assumed quantity of fuel on hand from which WPs are loaded. Blending refers to the approach used to load the packages with individual assemblies. For computational convenience, each year's total arriving inventory of assemblies was assumed to be available for loading packages. The actual number of assemblies that will be available for loading packages is unknown and could be quite small. The lag storage parameter affects distributions of package characteristics (especially heat) around the averages but has only a second order effect on the averages themselves. System implications of repository above ground storage and lag storage are the subject of a system study planned for FY 1994. That study is intended to provide a basis for repository storage requirements. Currently, the waste packaging model allows parametrically varying lag storage capacity, but for this study, the annual method was used (corresponding to 3000 MTU "lag" storage). For a given quantity of lag storage, blending is done with a simple algorithm that alternately picks the hottest and coldest assemblies from a heat sorted list. This approach minimizes the distribution of waste package heats. Blending was used in all the waste stream analyses done for this report. It is recognized that complete freedom to select assemblies from an inventory of 3000 MTU has significant design and logistical implications and is probably unrealistic. However, since only average quantities are needed for this study, the blending issue is not critical. Ultimately the fuel variability must be considered but it was determined to be beyond the scope of this first study.

Source term aggregation is discussed in Appendix A. Aggregation is required as a practical matter since most thermal models cannot handle discrete waste packages and still maintain reasonable run times. Equivalent thermal source terms were produced from the actual WP inventories generated by the packaging model. The aggregation can be done three different ways: by waste package, by year, or by equivalent mass increment. Aggregation by year was used for this study. The annual method results in equivalent thermal source terms, one for BWRs and one for PWRs, for each emplacement year. BWR and PWR assemblies are aggregated separately since the heat decay curves are distinctly different for the two fuel types. The source terms are reported as the mass weighted average characteristics and the corresponding total mass and number of waste packages for each source term. The lumped characteristics yield a unique thermal decay curve for each source term, and the total mass and number of waste packages are needed for proper spatial distribution of the sources in the thermal models. Since the source terms are aggregated up to the annual level, waste package capacity does not affect the averaged characteristics. Table 3-2 shows typical equivalent source terms.

Finally, a brief discussion is warranted on the assumed receipt rates used in the system level waste stream analysis discussed at the beginning of this section. This discussion is warranted because the receipt rates changed slightly towards the end of the study. Receipt rates are specified in the system level waste stream analysis as the annual amounts to be picked up at waste generator sites and the annual amounts to be emplaced. Initially, receipt rates based on the System Throughput Rate Study (M&O, 1993j) were used and the waste stream resulting from these receipt rates was used in most thermal calculations. However, the Mission Plan Amendment receipt rates are considered to be the baseline and thus the OCRWM Mission Plan and Mission Plan Amendments (DOE, 1988b and DOE, 1991d) rates were used to perform a sensitivity analysis. A brief discussion of the differences between the two is warranted to show that negligible differences, from the standpoint of the study, exist between the two receipt rates. In both cases, the steady-state throughput rate is 3000 MTU/yr; the differences occur in ramp up and ramp down rates in the transition periods of the scenarios. The use of one or the other receipt rate would produce negligible impact on the thermal loading since the resulting change in average characteristics was much less than the inherent uncertainty in thermal properties and theoretical models. The maximum changes in average characteristics resulting from the revised receipt rates were 1-2 percent. The Mission Plan receipt rates are within the range used in the baseline, and these rates will be used consistently in any follow-on analysis to this study. Table 3-3 shows the Mission Plan receipt rates, and Table 3-4 shows how the difference in receipt rates affected the characteristics.

The Spent Nuclear Fuel (SNF) decays at a very predictable rate once it is removed from the reactor. The isotopes that produce the majority of the energy given off by the fuel change as the fuel ages since the shorter lived isotopes decay and are replaced by longer lived ones until ultimately all the isotopes have decayed. To notionally demonstrate this a characteristic decay curve is provided in Figure 3-1. The isotopes responsible for the very rapid decay in the first 5 years are primarily Ru^{106}, Co^{60}, and Cs^{134}. Over the 30 year time frame the decay of Sr^{90} and Cs^{137} are primarily responsible. The decay in energy produced over the first 300 years is roughly two orders of magnitude. At longer times the decay in the long-lived transuranics produces much slower decreases in energy with another order of magnitude taking about 10,000 years. Fuel aging and the effects on thermal strategy will be discussed in Section 7.

Table 3-2. YFF(10) Equivalent Source Term Mission Plan Amendment Receipt Rates (21 PWR and 40 BWR Assemblies)

Time at Emplace	Type (1-BWR), (2-PWR)	MTU	Wgt Avg Age	Wgt Avg Burnup	Wgt Avg Enrich	No. of BWRs or PWR WPs
2010	1	128.13	10.98	35263.94	3.1	18
2010	2	265.5	10.83	41496.88	3.8	29
2011	1	162.64	11.18	36996.95	3.3	23
2011	2	243.76	12.65	40599.81	3.9	27
2012	1	125	10.49	37610.62	3.3	18
2012	2	272.71	12.15	42495.71	4	30
2013	1	410.91	12.7	36277.61	3.3	58
2013	2	481.59	10.48	43431.7	4	53
2014	1	487.49	13.53	36701.89	3.3	68
2014	2	1274.41	11.88	44199.35	4	143
2015	1	978.66	12.77	37045.92	3.3	138
2015	2	2043.21	13.92	43794.82	4	226
2016	1	991.22	14.59	36657.88	3.3	139
2016	2	1980.98	13.16	45368.24	4.1	218
2017	1	837.08	15.05	35783.89	3.2	117
2017	2	2170.88	17.13	43473.44	4	241
2018	1	1098.59	12.5	37277.05	3.3	154
2018	2	1873.97	14.83	45638.01	4.1	209
2019	1	969.91	18.47	35218.21	3.2	136
2019	2	2032.03	17.9	44287.2	4	224
2020	1	1024.43	13.74	34700.3	3.3	143
2020	2	2000.48	16.93	45159.43	4.1	223
2021	1	1063.21	18.66	32794.93	3.2	149
2021	2	1872.45	16.41	46066.61	4.2	208
2022	1	936.22	16.47	31733.81	3.3	131
2022	2	2098.26	19.46	43898.26	4.1	232

Table 3-2. YFF(10) Equivalent Source Term Mission Plan Amendment Receipt Rates (21 PWR and 40 BWR Assemblies) (Continued)

Time at Emplace	Type (1-BWR), (2-PWR)	MTU	Wgt Avg Age	Wgt Avg Burnup	Wgt Avg Enrich	No. of BWRs or PWR WPs
2023	1	1045.2	17.08	34844.2	3.3	147
2023	2	1923.52	19.67	42253.6	4	213
2024	1	893.67	16.18	32231.61	3.3	126
2024	2	2115.78	19.44	42491.98	4.1	233
2025	1	1014.9	16.76	32016.54	3.3	142
2025	2	1962.19	20.04	43879.06	4.1	217
2026	1	999.83	17.97	35146.93	3.3	139
2026	2	2013.73	23.97	41390.75	4	223
2027	1	1137.69	25.3	29937.71	3	156
2027	2	1811.87	23.82	42350.6	3.9	200
2028	1	1275.09	30.75	27956.86	2.9	173
2028	2	1757.44	26.98	40041.13	3.8	194
2029	1	1127.63	39.59	24252.52	2.6	152
2029	2	1855.03	26.25	42168.04	3.9	205
2030	1	1341.27	43.35	25675.29	2.7	200
2030	2	1608.14	41.99	34877.21	3.4	193
2031	1	1207.03	40.05	30779.61	2.9	176
2031	2	1814.8	38.1	38028.32	3.6	207
2032	1	1153.72	36.93	32979.42	3	163
2032	2	1852.72	35.64	41027.68	3.7	209
2033	1	976.04	37.7	32252.19	3.1	137
2033	2	1683.83	34.72	42591.4	3.8	191
2034	1	813.99	38.35	30038.21	3	115
2034	2	1613.51	35.53	42099.95	3.8	184

Table 3-3. Mission Plan Receipt Rates

Year	Pick Up	Emplace
1998	300	0
1999	400	0
2000	550	0
2001	875	0
2002	875	0
2003	875	0
2004	875	0
2005	875	0
2006	875	0
2007	875	0
2008	875	0
2009	875	0
2010	1800	400
2011	1800	400
2012	1800	400
2013	1800	900
2014	1800	1800
2015	3000	3000
2016	3000	3000
2017	3000	3000
2018	3000	3000
2019	3000	3000
2020	3000	3000
2021	3000	3000
2022	3000	3000
2023	3000	3000
2024	3000	3000
2025	3000	3000
2026	3000	3000
2027	3000	3000
2028	3000	3000
2029	2875	3000
2030	0	3000
2031	0	3000
2032	0	3000
2033	0	2700
2034	0	2400

Table 3-4. Effect of Changing Receipt Rates on Average Characteristics

		Burnup	Age
(M&O)	PWR	42211	22.5
	BWR	32236	23.5
(MPA)	PWR	42595	22.7
	BWR	32504	24.0
Deltas:	PWR	0.91 percent	0.89 percent
	BWR	0.83 percent	2.13 percent

3.3 WASTE PACKAGE ANALYSIS

The thermal loading calculations were done over a range of different WP capacities to evaluate the effect that capacity had on performance. To establish the sizes, capacities, and weights for the WP a number of studies were done by the Waste Package Design Group of the M&O. The details of these analyses, including some thermal calculations of WP temperatures needed to determine whether or not the various emplacement methods considered would violate the centerline WP goal of 350 degrees Celsius, are summarized in memos included in Appendix B of this report. A synopsis of the Waste Package Design Group efforts is provided below.

Because of the large number of combinations that would be produced by the thermal loads (five), WP sizes, and emplacement modes (three), it was decided to limit the number of WP sizes to three for the systems study. The waste package capacities chosen for the Thermal Loading Study were packages that could hold 6, 12, and 21 PWR assemblies or alternatively 12, 21, and 40 BWR assemblies. The reasons for choosing a 21 PWR package were based on work done by the Waste Package Design Group who, early in FY 1993, felt that this would be an optimum design for MPC because of space efficiency and criticality considerations (Bahney and Doering, 1993; included in Appendix B of this report). Also, from an efficiency standpoint, a 12 PWR package would provide an optimum configuration that also could be handled by most of the electric power companies. This was a suitable, mid-range size WP and therefore chosen for the study. However, earlier studies (Hertel and Ryder, 1991) have shown that anything over about 5.2 kW would violate the thermal goals for a vertical borehole. Thus, at 5.8 kW, a 12 PWR package would exceed the thermal goals of centerline temperature and 1 m wall temperature if placed in a vertical borehole. Although an 8 or 9 PWR package could likely be placed in a vertical borehole without exceeding the thermal goals, a package was needed which would be comparable in quantity and energy output to that used in the baseline established in the SCP. The baseline was a waste package which had 6 consolidated PWR assemblies (DOE, 1988a Chapter 7 page 7-28), although several other options including a hybrid (3 PWR and 4 BWR)

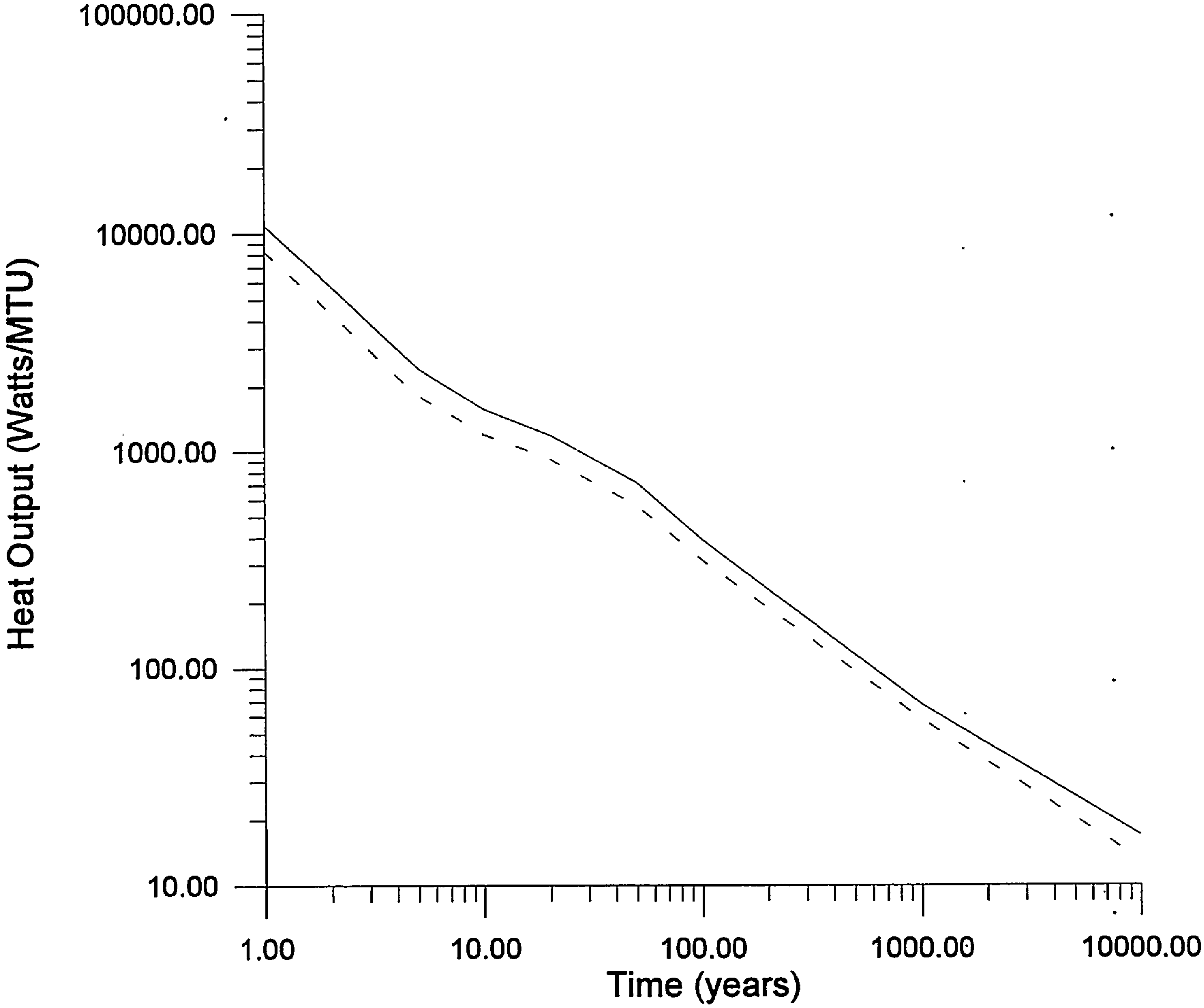


Figure 3-1. Thermal Decay of SNF for Burnup of 42.3 GWd/MTU and 3.85 percent Enrichment (Solid Curve is PWR Fuel and Dashed Curve is BWR Fuel)

package are discussed in the SCP. This was one reason that a 6 PWR size package was considered, although there was no intention to use fuel consolidation. The 6 PWR package will produce an initial (at emplacement) power of about 2.9 kW using the YFF(10) fuel specified in Appendix B. This is essentially identical to the 3 kW power output of the hybrid WP defined in more detail in the SCP-CDR (SNL, 1987). Thus, for the above reasons, the above identified WP package sizes were chosen for the Thermal Loading Study.

WP wall thickness affects the performance from the standpoint of corrosion and also affects the ability to emplace and retrieve the WPs since different thicknesses will result in different weights. However, with the criteria used, the WP wall thickness only affects the calculation of fuel centerline temperatures and therefore only one of the thicknesses shown in Appendix B was selected for the thermal loading study. Thus, System Study Case 2 shown in Appendix B was selected as a representative case to use in the thermal loading study. It should be noted that while the thermal loading did not specifically address WP wall thicknesses, the TSPA study did and these results are factored into this analysis.

The WP concepts identified as System Study Case 2 had an outer barrier thickness which varied from 10 to 45 cm and consequently package lengths from 4.83 to 5.53 m. An example of one of the concepts is the WP with a 10 cm outer barrier and the characteristics (diameter, length, and weight in tonnes) for this case for the three package sizes are summarized in Table 3-5. This case has an inner corrosion-resistant barrier of 0.95 cm thickness, alloy 825 with an outer corrosion allowance barrier of 10 cm carbon steel. The material properties of these metals were taken from the American Society of Mechanical Engineers (ASME) (1986) standards. This WP is about 4.8 m in length. This compares with the reference WP that has a single wall 1 cm thick with an outer diameter of 66 cm, a length between 3.1 and 4.7 m, and a weight of 2.7 to 6.4 tonnes (page 7-25 of DOE, 1988a). It should be noted that the maximum WP length that might possibly be used is 5.64 m; this length was used for considerations of package spacing in the near-field thermal calculation work discussed further in Section 4.

Table 3-5. Waste Package Characteristics

1st barrier = 0.95 cm
2nd barrier = 10 cm
Overall Length = 4.831 m

# of PWRs	# of BWRs	Outer Diameter (m)	Empty Weight (tonnes)	Loaded with PWRs (tonnes)	Loaded with BWRs (tonnes)
6	12	1.19	18.5	23.2	22.3
12	21	1.41	24.7	34.1	31.4
21	40	1.75	34.1	50.5	46.9

3.4 SUBSURFACE DESIGNS

Subsurface designs were required for the various thermal calculations and the operability assessments. The Subsurface Design Group of the M&O provided the necessary input for the study. The designs developed amounted to a determination of the emplacement drift spacing, WP spacing, number and length of emplacement drifts, amount of repository area required for access tunnels, and the total repository area required for a given thermal loading. Detailed repository designs were neither needed nor warranted for this study. Therefore the requirement levied on the Subsurface Design Group was to provide a generic design that could be scaled in a consistent manner among the various thermal loadings being evaluated.

The generic design ultimately chosen for the assessment was one which encompassed a rectangular area that varied with thermal load from about 570 to 2600 acres. The width of the rectangle was established as 1250 m, based on the length of an emplacement drift of 1235 m with an access drift on each end. The average length of an emplacement drift in recent repository layouts using the upper block of the primary area (west of the Ghost Dance Fault) is approximately 1235 m from the centerlines of access drifts located at each end per the "Repository Subsurface Layout Options and ESF Interface" (CRWMS B00000000-01717-5705-00009, Rev. 00, December 1993, pp. 5-51.) This allowed a stand-off distance of about 120 m from the Ghost Dance Fault (CRWMS B00000000-01717-0200-00089, Rev. 01, December 1993, pp. 14). The number of emplacement drifts was then calculated based on the number of WPs per drift and the total number of WPs to emplace. A setback distance from the access drifts to the first WP of 40 m for most of the emplacement modes and 20 m for the vertical emplacement mode was based on information provided in the SCP (DOE, 1988a). The spacing of the drifts was established based on the spacing of the WPs within an emplacement drift and the desired thermal loading AML to be achieved. The spacing of the drifts was also restricted to ensure that the drifts were no closer together than allowed using a 30 percent extraction ratio, per Table 8.3.2.2-3 of the SCP (DOE, 1988a). Generic repository layouts were designed for the following cases:

Vertical Borehole Emplacement; 6 PWR package; 24, 36, and 55 MTU/acre

Horizontal Borehole (long and short); 6 PWR package; 24, 36, and 55 MTU/acre

In-Drift Emplacement (4.3 and 7 m diameter drifts); 6 PWR package; 24, 36, 55, 83, and 111 MTU/acre

In-Drift Emplacement (4.3 and 7 m diameter drifts); 12 and 21 PWR packages; 24, 36, 55, 83, and 111 MTU/acre

Only the 6 PWR package was considered for emplacement in the vertical borehole due to size constraints and the fact that larger packages would exceed thermal goals as discussed above in Section 3.3. However it should be noted that the thermal goals would likely not be exceeded by a 9 PWR WP placed in a vertical borehole.

Additionally, it should be noted that the far-field calculations used a smeared source circular disk model, not the rectangular areas established in these designs. However, the area was consistent with the subsurface designs provided and the AMLs were the five identified above.

Early in the study it was decided to limit the number of cases under consideration. This was done by restricting the WP spacing to values that would assure meeting the thermal goal to maintain the WP centerline temperature below 350 degrees Celsius. Some preliminary calculations (see Appendix B) were performed to determine the spacing where this goal would not be violated. The results depended on WP size and the drift diameter. Thus, in the 4.3 m diameter drift, it was necessary to space the 21 PWR packages 16 m apart (center to center). For the 7 m diameter drift, the 21 PWR packages could be spaced 12 m apart. The lower capacity packages did not experience any difficulties and therefore were spaced at 6.64 m, which was basically one meter space between the package ends if one considers the maximum WP length as 5.64 m.

The above discussion deals with the repository emplacement method chosen by the Subsurface Design Group which would keep the WP spacing a constant and allow variable drift spacing to achieve the desired thermal load. This methodology tends to minimize the excavation distances and hence the excavation costs. However, since it is realized that there are performance issues with the emplacement method chosen, the other technique which fixes the drift spacing and varies WP spacing was examined in the near-field thermal calculations discussed in Section 4.

The details of these calculations and the results for the various cases run (using the method of keeping WP spacing constant and varying drift spacing) are presented in Appendix C. However, a summary of the drift spacing, the WP spacing, and the theoretical repository areas provided in Table 3-6. The local area mass loading (LAML) necessary to achieve the specified average LAML of the repository considering set backs, access, and operations areas is identified in Table 3-6. The AML and LAML are related as a ratio of emplaced area to total area, including access tunnels and operations areas. These WP and drift spacings were used as a guide and were used in the cost analysis. As mentioned above in the case of the far-field analysis only the area of the potential repository at the various AMLs was used since it was necessary to use a disk model. For the near-field calculations the WP and drift spacings differed from these values based on constraints imposed by SNL; this is discussed in Section 4.

Table 3-6. Summary of Repository Designs for Thermal Loading Study

Required Drift Spacing for In-Drift (7 m) and 21 PWR				
AML (MTU/Ac)	LAML (MTU/Ac)	C/C Space (m)	Drift Space (m)	Area (Acres)
111	124	12	22	570
83	94	12	29	755
55	63	12	43	1139
36	40	12	67	1755
24	27	12	99	2598

Required Drift Spacing for In-Drift (4.3 m) and 21 PWR				
AML (MTU/Ac)	LAML (MTU/Ac)	C/C Space (m)	Drift Space (m)	Area (Acres)
111	127	16	16	570
83	93	16	22	755
55	62	16	33	1139
36	41	16	50	1755
24	28	16	74	2598

Required Drift Spacing for In-Drift (7 and 4.3 m) and 12 PWR				
AML (MTU/Ac)	LAML (MTU/Ac)	C/C Space (m)	Drift Space (m)	Area (Acres)
111	123	6.64	22	569
83	93	6.64	29	755
55	62	6.64	44	1139
36	40	6.64	68	1754
24	28	6.64	98	2596

Table 3-6. Summary of Repository Designs for Thermal Loading Study (Continued)

Required Drift Spacing for In-Drift (7 and 4.3 m) and 6 PWR				
AML (MTU/Ac)	LAML (MTU/Ac)	C/C Space (m)	Drift Space (m)	Area (Acres)
55	62	6.64	23	1141
36	41	6.64	35	1757
24	28	6.64	52	2601

Required Drift Spacing for Long Hole Horizontal and 6 PWR				
AML (MTU/Ac)	LAML (MTU/Ac)	C/C Space (m)	Drift Space (m)	Area (Acres)
55	97	8.6	11.4	1141
36	63	8.6	17.6	1757
24	43	8.6	26	2601

Required Drift Spacing for Short Borehole and 6 PWR				
AML (MTU/Ac)	LAML (MTU/Ac)	C/C Space (m)	Drift Space (m)	Area (Acres)
55	60	3.6	88	1141
36	39	3.6	135	1757
24	26	3.6	200	2601

Required Drift Spacing for Vertical Hole Horizontal and 6 PWR				
AML (MTU/Ac)	LAML (MTU/Ac)	C/C Space (m)	Drift Space (m)	Area (Acres)
55	59	3.6	45	1141
36	38	3.6	69	1757
24	26	3.6	103	2601

An analytic method was used to provide an estimate for the maximum areal mass density that can be emplaced while still allowing for sub-boiling pillars between adjacent emplacement drifts at all times (Saterlie and Abhold, 1993). At or below this areal mass density, a sub-boiling path is provided where liquid water condensate could drain through the repository horizon between drifts. Above this areal mass density, different physical processes operate. Liquid water at ambient pressure (neglecting vapor-pressure lowering due to capillary effects) is excluded from the center of the repository for some period of time, and during this period water above the repository can only be removed by one of three methods: 1) vapor-phase transport; 2) liquid transport around the boiling region across large lateral distances, perhaps hundreds to thousands of meters; or 3) superheated or pressurized liquid movement through the repository horizon including penetration of liquid water into depressions in the thermal profile.

Assuming that the heat source can be adequately represented by a function which decreases linearly with time, an exact solution for the temperature history resulting from either a linearly increasing or decreasing heat source at the boundary of a semi-infinite solid (half plane) for heat conduction is found as (Rohsenow and Hartnett, 1973):

$$(T-T_0)\,\frac{\sqrt{\pi\ \rho C\ k/D}}{q''_{max}} = 2\left(1-\frac{2}{3}\frac{t}{D}\right)\sqrt{\frac{t}{D}} \qquad (3\text{-}1)$$

where

T	=	repository horizon temperature (°C) at repository center at time t
T_o	=	initial repository horizon temperature (°C) at repository center; chosen as 27°C (RIB, p. 1.2.7-3)
t	=	time measured after emplacement (years)
D	=	equivalent heating duration (years)
q''_{max}	=	areal power density at time zero into the half plane (watts/m^2)
ρC	=	volumetric specific heat of rock at repository horizon (W-yr/m^3-°C); value chosen for tuff is 0.0697 (equivalent to 2.19 J/cm^3-K at 72–C in RIB, p. 1.2.4-4, Table 2)
k	=	thermal conductivity of rock (W/m-°C); value chosen for tuff is 2.1 (RIB, p.1.2.2-4)

The peak temperature in the rock occurs at a time when:

$$\frac{dT}{dt} = 0. \qquad (3\text{-}2)$$

Differentiating Equation (3-1) and solving for the time at which maximum temperature occurs gives

$$t_{max} = 0.5D \qquad (3\text{-}3)$$

Substituting back in Equation (3-1) and solving for the maximum temperature yields

$$T_{max} = 27° + 0.172 \cdot P_{max} \cdot AML \cdot D^{1/2} \quad (3\text{-}4)$$

where

T_{max}	=	maximum repository horizon temperature (°C) at the repository center
P_{max}	=	specific thermal output of the waste at emplacement (kW/MTU)
AML	=	average areal mass loading of waste in the repository (MTU/acre)

It should be noted that Equation (3-1) for the heat produced is derived for heat into a half-plane while P_{max} above is heat generated in all directions. Thus, to use this value of P_{max}, Equation (3-1) was divided by a factor of 2 to produce Equation (3-4).

Four different fuel characteristics were chosen for this analysis. The equivalent heating duration D and the time t_{max} to maximum repository horizon temperature T_{max} at the repository horizon were derived by fitting a straight line to the thermal output curve such that Equation (3-3) was fulfilled (see cited reference for details). The fuel characteristics, the heating durations, and the calculated AMLs which just produce the boiling temperature are given in Table 3-7.

Table 3-7 lists the AMLs at which boiling occurs on the average everywhere in the repository as derived from Equation (3-4); they range from 36 to 45 MTU/acre. For the purposes of the System Study calculations, the conservative value of 36 MTU/acre (the lowest AML) was chosen as a representative AML below which at least a portion of the unheated pillars between emplacement drifts in the repository will certainly remain below the boiling temperature.

Besides the AML of 36 MTU/acre, believed to be the lowest AML at which the boiling temperature will be reached throughout the unheated pillars, on average, certain other calculation points needed to be selected. The thermal loading calculations needed to be compared with the baseline case of 57 kW/acre. Thus, dividing this thermal loading by the power at emplacement of the average fuel of 1.03 kW/MTU from Table 3-7 yielded a second calculation point of 55 MTU/acre.

Some freedom existed in selecting higher thermal loading values and thus a value of 111 MTU/acre, twice the value above, was chosen. It corresponds to 114 kW/acre which, being twice the baseline SCP loading, is another convenient upper limit that analysts have chosen (Buscheck and Nitao, 1993). An intermediate point of 83 MTU/acre was an appropriate fourth value based on the two values above.

Finally, a lower AML bound of 24 MTU/acre was selected based on economic considerations with the goal of minimizing the average temperature within the bounds of the available emplacement area. This value was obtained by dividing the 63,000 MTU of spent fuel planned for a potential repository (SCP, page 6-224) by a potential repository area of 2,630 acres. This area is comprised of the potentially useable primary repository area of 1850 acres (SCP, page 6-227), plus the more favorable potential expansion areas 2EA, 2EB and SE which contain 1280 acres (SCP, pages 6-227 and 6-228), less an estimate of 500 acres for support facilities or area not usable for geological reasons; this latter value consists of the 300 acres or about 16 percent of the primary repository area (SCP, page 6-227), plus assuming the same percentage, which is 200 acres, for the three expansion areas (See Figure 3-2 which was extracted from the SCP and shows the primary area plus expansion areas).

Table 3-7. Fuel Characteristics and AMLs Where Boiling is Estimated to Occur

Characteristics	Avg. PWR YFF(10)	Avg. PWR+BWR YFF(10)	Peak YFF(10)	Peak OFF(16)
Age[1] (yrs)	22.5	*	10	16
Burnup[1] (GWd/MTU)	42.2	*	42	44
Peak power[1] (kW/MTU)	1.13	1.03	1.56	1.37
Time to peak temp.[2] (yrs)	36.5	37	27	34.5
Equiv. heating duration[2] (yrs)	73	74	54	69
AML[2] (MTU/acre)	42	45	36	36

* This is an average based on both PWR and BWR fuel and therefore a specific age and burnup are inappropriate.
1) From King (1993).
2) Calculated by Saterlie and Abhold (1993).

Overall, five AMLs were selected as appropriate for thermal calculations in the Systems Studies. These values are summarized in Table 3-8.

Table 3-8. Area Mass Loadings to be Used for Thermal Calculations

MTU/Acre	MTU/m^2
111	2.7×10^{-2}
83	2.0×10^{-2}
55	1.4×10^{-2}
36	0.89×10^{-2}
24	0.59×10^{-2}

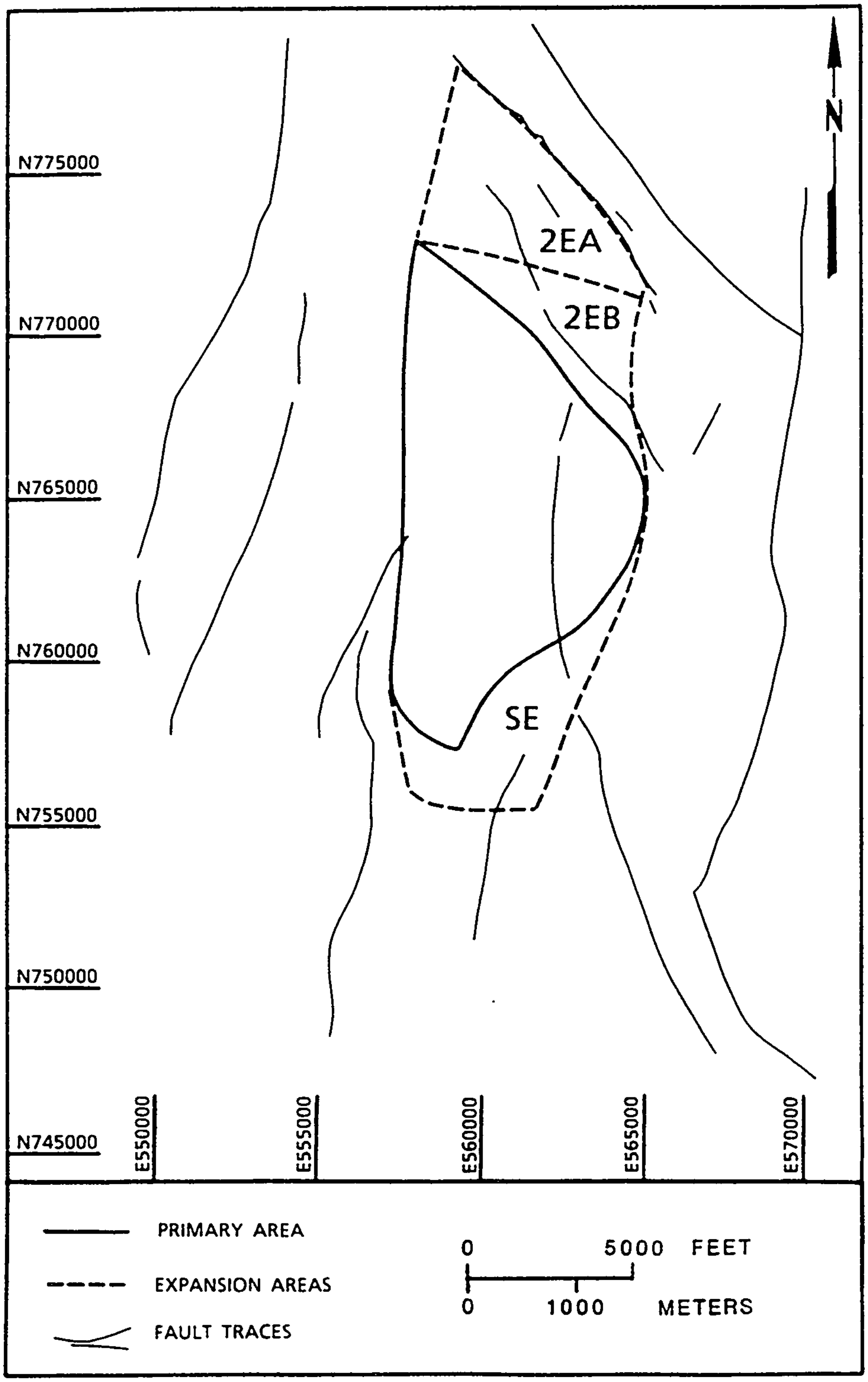


Figure 3-2. Revised Usable Portion of the Primary Area and Expansion Areas (Per Figure 6-88 on page 6-228 of the SCP)

3.6 DATA AND ASSUMPTIONS PERTINENT TO YUCCA MOUNTAIN

The heat conduction and thermal-hydrologic calculations required information about both the near- and far-field environmental conditions in Yucca Mountain. Since there is a paucity of certain types of data, various assumptions were needed. The purpose of this section is to identify some of the basic assumptions and the input data used. Many of the detailed assumptions and inputs required for the specific models used to calculate the waste stream characteristics, the near-field temperatures, the far-field hydrologic and thermal profiles, and the TSPA results are discussed in the section or appendix that discusses those particular calculations.

Certain basic assumptions were made that need to be called out. Specifically, it was assumed that all the generic rectangular repository area out to at least 2600 acres is suitable for waste emplacement. This will probably not be known until actual exploration into the underground areas occurs. It was assumed there was minimal heterogeneity in the rock at the repository horizon and thus a single permeability was used. A permeability of 280 milliDarcy is certain experts', "best guess" from preliminary fracture data at what might exist at the repository horizon. This value is representative of rock with three, 100 micron fractures per meter and has been used in previous work (Buscheck and Nitao, 1993). Sandia has reported (Wilson, et al., 1994) that the range of permeabilities is from about 0.1 to 10 Darcy in the TSw2 layer. This is a significant uncertainty and could affect the results. These calculations assumed that a uniform fuel was used; either an average of the PWR and BWR fuel or an average PWR fuel. Fuel variability, which can certainly be important, will be examined in a follow-on thermal loading study. Both the thermal conduction model and the thermal-hydrologic model assumed that the surface of Yucca Mountain is a constant value of 13 degrees Celsius and a constant temperature of 53 degrees Celsius is maintained at a depth of 1 km below the top of the saturated zone (about 1300 m below the potential repository).

Many of the details of the inputs used in the thermal models were taken from the RIB (DOE, 1992c). However, for many of these parameters the RIB has a range of values and a single value needed to be selected for the model calculations. It should be pointed out that values in the RIB do not in the most part have an adequate basis in primary hard data at this time; in some cases the values are theoretically computed. Considerable uncertainties remain in many of the parameter values in the RIB. Notwithstanding the appearance, if any, reference to the use of RIB values in any calculation does not necessarily mean the calculation has a sound basis in input data of adequate level of confidence.

A good evaluation of the data inputs used by LLNL for the thermal-hydrologic modeling and a comparison with the range of values found in the RIB were done by SNL. With SNL's permission this comparison is attached in Appendix D. The majority of the inputs are described in Appendix D and the remainder are identified in the various sections or appendices dealing with the specific calculations.

4. NEAR-FIELD THERMAL ANALYSIS

4.1 PURPOSE OF ANALYSIS

The purpose of this analysis is to provide the basis for comparison of the performance of thermal loading options against the thermal goals presented in Section 2. Additionally, this analysis provides near-field temperature profiles necessary to evaluate preclosure operability and to perform thermo-mechanical analysis. The thermal behavior of the near field is considered only as a surrogate for both pre- and postclosure performance. This analysis only examined heat conduction in the surrounding rock and was not able to evaluate the coupled hydrothermal system that may be operating at the repository horizon although the formulation of heat capacitance used was developed to try to account for the impacts of the heat of vaporization of water. Therefore, this analysis was only used to evaluate the near-field preclosure effects. It is expected that over these time periods and distance scales the conduction models can provide reasonably accurate results although hydrologic perturbations do occur over even short time scales. It is only over the very long periods of time associated with postclosure performance that coupled hydrothermal effects become most important and must be modeled. The discussion of these effects will be provided in the next section. This section will only provide temperature histories at select points.

In addition to grading the performance against thermal goals, the analysis was able to provide some evaluation of the extent of local boiling. The question of how far boiling extends into the rock is an important issue if the decision is ultimately made to adopt a below boiling thermal loading strategy with below boiling defined in terms of the bulk average or more strictly as no boiling in the rock at all. Although this analysis has predicted the spatial extent of boiling with time, the performance issues of how much local boiling is acceptable need to be addressed.

The near-field calculations provided information on the different performance of two types of emplacement methodologies, which consisted of: 1) keeping waste package spacing at a minimum and varying drift spacing to obtain the different AMLs as described in Section 3; and 2) keeping drift spacing at a minimum, but not exceeding the 30 percent extraction ratio, and varying waste package spacing. Both methodologies have advantages and disadvantages with respect to performance and cost and these will be discussed further below.

This analysis is instrumental in identifying residual uncertainties in performance predictions. It will form a part of the basis for recommendations for future work pointed toward improving confidence in future performance predictions.

4.2 BACKGROUND

Previous studies investigating heat and fluid flow in Yucca Mountain take into account the thermal influence of SNF generated heat. This section only discusses the analyses associated with heat conduction, as these conduction-only models are more amenable to complicated geometries than the coupled heat and fluid flow models. Heat conduction analyses with varying degrees of detail about the specific emplacement configurations and waste stream characteristics have been done by Ryder (1993), Holland (1993), Hertel and Ryder (1991) and Danko and Mousset-Jones (1993). Such analyses have shown the importance of understanding the temperature distribution across the repository.

Significantly different temperatures can exist at the edges of panels and the edge of the repository than exist in the center. Additionally, the temperatures can be influenced by the repository configuration.

In the past, comparisons of the various studies have been limited by the wide range of fuel characteristics, repository configurations, thermal loads, and repository total capacities. So that comparisons could be made between thermal loadings, a consistent set of calculations was needed to examine the various aspects of this very complicated problem. A single set of fuel characteristics and a given repository total capacity needed to be evaluated over a range of potential thermal loadings. Additionally a repository design that can accommodate the different thermal loadings in a straightforward parametric fashion must be used. Both pre- and postclosure issues must be evaluated in a systematic manner to understand the trade-offs needed to establish a thermal loading that will be effective for the system as a whole. Only in this way can one avoid the pitfall of optimizing one aspect of the system with the result that other elements of the system cannot be achieved.

4.3 ANALYSIS METHOD

The near-field thermal analysis to be presented was done by SNL using the COYOTE code (Gartling, 1982). This code has been modified to a three-dimensional code that calculates heat conduction in the rock. The code does not consider fluid flow in either liquid or gas phases or convection of heat in these phases. However, for the near-field analysis, this is felt to be a minor problem since it is expected (Buscheck et al., 1991) that the near-field effects, those occurring within the first few hundred years after emplacement, are modeled very well by heat conduction only.

The COYOTE code has significant advantages in that the source effects can be modeled and evaluated which, of course, is not possible with a smeared source model. Specifically, the effects on thermal loading of different waste package spacings, drift spacings, package sizes, and waste characteristics can be evaluated. To examine the effect of different waste package sizes, three different capacity WPs were used. These were emplaced at five different AMLs, and to achieve these different AMLs, two different emplacement techniques of spacing the packages and the emplacement drifts were employed. The calculations are sensitive to the WP loading, spacing, and the repository configuration. Representative results at distances that are on the order of the drift spacing were examined to give indications of the preclosure performance under these various conditions.

The calculation methodology is discussed in more detail in Appendix E. Briefly, the method assumes that the drift under evaluation is one drift in an infinite series of drifts that were simultaneously emplaced with SNF. As such the model cannot fully incorporate edge effects and may slightly overestimate the temperature (no more than 15 degrees celsius) in the center of the pillar. The vertical boundaries were modeled as isothermal surfaces. The ground surface is modeled to have a constant temperature of 18 degrees Celsius while the rock at

1611 m below the mountain surface (about 1300 m below the potential repository) is assumed to have a constant temperature of 52.5 degrees Celsius.

4.4 PROBLEM DEFINITION

The critical parameter for the case of uniform heat distribution, the AML measured in MTU per acre, is a surrogate designation of repository thermal loading. Unlike APD, which decreases with time after emplacement, AML remains constant through time. As discussed in Section 3, five average AMLs were chosen for further analysis; 24, 36, 55, 83, and 111 MTU/acre. The 55 MTU/acre case corresponds to the reference loading of 57 kW/acre. A total capacity of 63,000 MTU of SNF was assumed. The Defense High-Level Waste (DHLW) heat output was assumed to be low enough that disregarding it would not substantially affect the results. The near-field analyses were formulated with a symmetry-boundary condition such that an infinite array of packages was considered.

The YFF(10) fuel discussed in more detail in Section 3 and Appendix A was used to provide an average fuel characteristic for the calculations. An average PWR fuel characteristic was selected based on an attempt to provide a more conservative calculation of local heating. This PWR fuel had an average age of 22.5 years out of reactor with a 42.2 GWd/MTU burnup. This age and burnup produce a power output at emplacement of about 1.13 kW/MTU. The PWR WP produces somewhat more heat than BWR fuel and it is expected that some areas of the repository might ultimately have waste packages composed only of PWR fuel. Thus, using all nearest neighbor WPs composed of PWR fuel is deemed to be conservative. Three different waste package sizes were used with capacities of 6, 12, and 21 PWR assemblies as described in Section 3. Table 4-1 summarizes the capacities of these packages in MTU and the heat output at emplacement for this fuel. The WP thickness has little influence on the thermal effects although WP size can impact the operations from the standpoint of both weight and size. Thus, no variations in WP container thickness were considered in this effort and the WP sizes selected had diameters of 1.27 m for the 6 PWR package, 1.49 m for the 12 PWR package, and 1.83 m for the 21 PWR package. The maximum length of each WP was about 5.64 m.

Table 4-1. Calculated Initial Canister Power Outputs and Capacities

Number of PWR Assemblies per Package	Initial Power Output (kW/package)	Capacity (MTU/package)
6	2.89	2.57
12	5.78	5.14
21	10.12	8.99

Different emplacement methods can result in different preclosure performance of the potential repository. One can design the subsurface repository layout, as discussed in Section 3, to minimize excavation costs by keeping the WP spacing at a minimum. Different AMLs are achieved with this design by varying the drift spacing. However, the drift spacing is allowed to be no closer than permitted by the 30 percent extraction ratio limitation. The second emplacement technique fixes the drift spacing at the minimum value allowed by the 30 percent extraction ratio (e.g., 23.3 m for a 7 m diameter drift and 14.3 m for a 4.3 m diameter drift). For this case different AMLs are achieved by varying the spacing between WPs. The first technique produces higher near-field temperatures but has lower excavation costs than the second. The second method will ultimately produce the minimum near-field temperatures of the two. The temperature performance the two methods is presented in this section.

The first methodology used to emplace waste for which near-field calculations were done was essentially the case described in the subsurface layout portion of Section 3. Table 4-2 presents the 15 cases that were run for in-drift emplacement with a 7 m diameter drift, the three WP capacities, and the five thermal loads. The case or run number assigned by SNL is noted in the right side of the table. As shown in the table, the canister spacing is set for each capacity WP and kept constant while the drift spacing is varied to achieve the various thermal loadings. As mentioned in Section 3, the difference in WP spacing between the 21 and 12 PWR cases is due to preliminary predictions that showed the spacing between WPs in a 7 m diameter drift would have to be slightly less than 12 m to meet the 350 degrees Celsius WP centerline goal. Similarly, 15 cases were done for in-drift emplacement with a 4.3 m diameter drift, and the cases showing drift and WP spacing are presented in Table 4-3. The drift and WP or canister spacings quoted in the tables are all center-to-center distances.

The second set of runs are shown in Tables 4-4 and 4-5 for in-drift emplacements using 7 m and 4.3 m diameter drifts respectively. For these cases, the drift spacing was kept constant and the thermal loads were achieved by varying the WP spacing. In this method, the excavated emplacement drift length increased as the AML decreased due to the increase in WP spacing. For these cases, some of the thermal loads cannot be achieved with the given spacing. Specifically, if the WP spacing is less than about 5 m (the limit chosen by SNL) the WPs would overlap and this was not allowed. Also, if the WP spacing became much larger than the drift spacing, these cases would be impractical to construct. Therefore, the shaded cases for which no run number is shown were not run.

Note that there are slight differences between the spacings used in these near-field calculations and the subsurface design values quoted in Section 3. The subsurface designs were established based on achieving an average AML, for example 55 MTU/acre, in the repository. To achieve this the service areas and access tunnels needed to be taken into account and therefore local AML had to be higher to accomplish that. However, SNL set the local AML equal to the average AML. Thus the drift spacing values used are slightly different than those shown in Section 3. While using these AMLs for the near-field calculations would not be as conservative as the other method, the differences are not large and the impact on the costs is minimal. Additionally, this allowed a consistent comparison to be made between the cases shown in Tables 4-2 and 4-3 with the cases shown in Tables 4-4 and 4-5.

Table 4-2. Drift and WP Spacings for the Various Cases Run Assuming Variable Drift Spacing and a 7 m Diameter Drift

Table 4-2A. Required Drift Spacings for a 7 m Diameter Drift and a 21 PWR Package Assuming a Constant Canister Spacing of 12 m

Assemblies per Package	Areal Mass Loading (MTU/Acre)	Drift Spacing (m)	Canister Spacing (m)	Run #
21	111	27.30	12.0	18
21	83	36.51	12.0	20
21	55	55.10	12.0	19
21	36	84.18	12.0	28
21	24	126.27	12.0	29

Table 4-2B. Required Drift Spacings for a 7 m Diameter Drift and a 12 PWR Package Assuming a Constant Canister Spacing of 6.64 m

Assemblies per Package	Areal Mass Loading (MTU/Acre)	Drift Spacing (m)	Canister Spacing (m)	Run #
12	111	28.20	6.64	21
12	83	37.71	6.64	22
12	55	56.92	6.64	23
12	36	86.95	6.64	30
12	24	130.43	6.64	31

Table 4-2C. Required Drift Spacings for a 7 m Diameter Drift and a 6 PWR Package Assuming a Constant Canister Spacing of 6.64 m

Assemblies per Package	Areal Mass Loading (MTU/Acre)	Drift Spacing (m)	Canister Spacing (m)	Run #
6	111	14.10	6.64	32
6	83	18.85	6.64	33
6	55	28.46	6.64	34
6	36	46.48	6.64	35
6	24	65.22	6.64	36

Table 4-3. Drift and WP Spacings for the Various Cases Run Assuming Variable Drift Spacing and a 4.3 m Diameter Drift

Table 4-3A. Required Drift Spacings for a 4.3 m Diameter Drift and a 21 PWR Package Assuming a Constant Canister Space of 16 m

Assemblies per Package	Areal Mass Loading (MTU/Acre)	Drift Spacing (m)	Canister Spacing (m)	Run #
21	111	20.48	16.0	24
21	83	27.38	16.0	25
21	55	41.32	16.0	37
21	36	63.14	16.0	38
21	24	94.70	16.0	39

Table 4-3B. Required Drift Spacings for a 4.3 m Diameter Drift and a 12 PWR Package Assuming a Constant Canister Space of 6.64 m

Assemblies per Package	Areal Mass Loading (MTU/Acre)	Drift Spacing (m)	Canister Spacing (m)	Run #
12	111	28.20	6.64	26
12	83	37.71	6.64	27
12	55	56.92	6.64	40
12	36	86.95	6.64	41
12	24	130.43	6.64	42

Table 4-3C. Required Drift Spacings for a 4.3 m Diameter Drift and a 6 m PWR Package Assuming a Constant Canister Spacing of 6.64 m

Assemblies per Package	Areal Mass Loading (MTU/Acre)	Drift Spacing (m)	Canister Spacing (m)	Run #
6	111	14.10	6.64	43
6	83	18.85	6.64	44
6	55	28.46	6.64	45
6	36	46.48	6.64	46
6	24	65.22	6.64	47

Table 4-4. Drift and WP Spacings for the Various Cases Run Assuming Constant Drift Spacing and a 7 m Diameter Drift

Table 4-4A. Required Canister and Drift Spacings for a 7 m Diameter Drift and a PWR 21 Package

Assemblies per Package	Areal Mass Loading (MTU/Acre)	Drift Spacing (m)	Canister Spacing (m)	Run #
21	111	23.3	14.06	1
21	83	23.3	18.80	2
21	55	23.3	28.38	3
21	36	23.3	43.35	–
21	24	23.3	65.03	–

Table 4-4B. Required Canister and Drift Spacings for a 7 m Diameter Drift and a 12 PWR Package

Assemblies per Package	Areal Mass Loading (MTU/Acre)	Drift Spacing (m)	Canister Spacing (m)	Run #
12	111	23.3	8.04	7
12	83	23.3	10.75	6
12	55	23.3	16.22	5
12	36	23.3	24.78	4
12	24	23.3	37.17	–

Table 4-4C. Required Canister and Drift Spacings for a Diameter Drift and a 6 PWR Package

Assemblies per Package	Areal Mass Loading (MTU/Acre)	Drift Spacing (m)	Canister Spacing (m)	Run #
6	111	23.3	4.02	–
6	83	23.3	5.37	8
6	55	23.3	8.11	9
6	36	23.3	12.39	10
6	24	23.3	18.58	11

Table 4-5. Drift and WP Spacings for the Various Cases Run Assuming Constant Drift Spacing and a 4.3 m Diameter Drift

Table 4-5A. Required Canister and Drift Spacing for a 4.3 m Diameter Drift and a 21 PWR Package

Assemblies per Package	Areal Mass Loading (MTU/Acre)	Drift Spacing (m)	Canister Spacing (m)	Run #
21	111	14.3	22.91	--
21	83	14.3	30.64	--
21	55	14.3	46.24	--
21	36	14.3	70.64	--
21	24	14.3	105.96	--

Table 4-5B. Required Canister and Drift Spacing for a 4.3 m Diameter Drift and a 12 PWR Package

Assemblies per Package	Areal Mass Loading (MTU/Acre)	Drift Spacing (m)	Canister Spacing (m)	Run #
12	111	14.3	13.09	13
12	83	14.3	17.51	12
12	55	14.3	26.42	--
12	36	14.3	40.38	--
12	24	14.3	60.56	--

Table 4-5C. Required Canister and Drift Spacing for a 4.3 m Diameter Drift and a 6 PWR Package

Assemblies per Package	Areal Mass Loading (MTU/Acre)	Drift Spacing (m)	Canister Spacing (m)	Run #
6	111	14.3	5.75	14
6	83	14.3	7.70	15
6	55	14.3	11.61	16
6	36	14.3	17.74	17
6	24	14.3	26.61	--

The results of the near-field thermal calculations were also intended to be used as input conditions for some additional thermo-mechanical analyses, which could not be completed for this work. However, previous thermo-mechanical calculations done by SNL were used to complete this task. The results of this analysis are discussed in Section 7.

The temperatures were also used as input to WP analysis codes so that predictions of the WP temperature profiles with time could be obtained. From this, an evaluation was made of the ability to achieve the 350 degree Celsius centerline WP thermal goal.

The calculations were performed at various times to about 1200 years after emplacement. However, the first two hundred years were the primary interest for this effort. It is also over this period of a few hundred years where it is expected that thermal conduction will dominate. Thus, a model such as COYOTE, which calculates only heat conduction, should be reasonably accurate in the absence of ventilation and the results should compare well with hydrothermal models during this time period. However, as noted above, comparisons with the far-field analysis cannot be directly made since the fuel used in the near-field analysis will produce a slightly hotter environment than the average fuel used in the far-field analysis.

4.5 RESULTS

This section summarizes the results obtained from the near-field thermal calculations. Representative temperature plots are provided to illustrate various points; however, the full details of the near-field calculations and additional thermal profiles are provided in Appendix E. Comparisons of near-field temperatures are shown for the two different emplacement methodologies (e.g., variable WP spacing versus variable drift spacing) to evaluate the preclosure performance of the two. The performance is evaluated against the thermal goals to see which of the near-field goals are met and which are not. Finally, an evaluation of what is meant by local boiling is provided in an effort to determine how much of the rock in the repository horizon would stay below boiling under the various thermal loading regimes.

Evaluations of Emplacement Methodologies

The techniques of spacing WPs and drifts can have a significant effect on the preclosure performance measures of emplacing and retrieving waste. Two methodologies were evaluated as discussed above: 1) where the WP spacing was kept at a minimum and the drift spacing varied to achieve the various thermal loads; and 2) the distance between drifts was set at the minimum distance allowed by the 30 percent extraction ratio and the WP spacing was varied. The first method has the advantage that if the decision is made to emplace waste at a low thermal loading, the number of drifts and the total length that waste will be emplaced in do not change, the drifts are just separated farther apart once excavation starts. Thus the total repository excavation costs will be relatively insensitive to thermal loading. On the negative side, this method will result in somewhat higher temperatures in the near field than the second method, and some flexibility may be lost having large spacing between drifts. In the second method the local temperatures will be lower than the first. However, the cost will be a stronger function of the thermal loading since the excavated emplaced drift length will vary with each thermal load to accommodate the larger distance between WPs to achieve a lower thermal load.

To evaluate these issues the temperature profiles, calculated at various points in the near field at the drift wall, drift floor, and various distances into the rock, were plotted and analyzed. This section will provide a synopsis of those plots to illustrate significant performance concerns. More discussion is provided in Appendix E.

An evaluation of the calculations found there was little sensitivity of the temperature profiles to WP size for the 12 and 21 PWR WPs. This is demonstrated by overlaying Figures 4-1 and 4-2 which show the predicted temperature profiles at 111 MTU/acre for a 21 and 12 PWR WP respectively. In each case two curves are plotted; the dashed curve shows temperature profiles for the method where WP spacing is a minimum and drift spacing varies and the solid curve represents the method in which the drift spacing is set at a minimum and WP spacing varied. The above two cases shown in Figures 4-1 and 4-2 were calculated for a 7 m diameter emplacement drift. A similar calculation was performed for a 4.3 m diameter emplacement drift and the results are plotted in Figure 4-3 for the 111 MTU/acre, 12 PWR WP case. A comparison of Figures 4-2 and 4-3 shows little difference in the peak drift wall temperature between a 4.3 and 7 m diameter drift at the highest thermal loading. The different drift diameters do show some temperature differences in the first 100 years but primarily for the minimum WP spacing case (WPs separated by 1 m). Although the method using a WP spacing of 16 m and allowing for variations in drift spacing shows somewhat higher temperatures at times less than about 100 years, the curves are still surprisingly similar to the curves shown in Figures 4-1 and 4-2. In fact, the solid curve representing the method using minimum drift spacing is nearly identical to the curves calculated for the minimum WP spacing. Although not shown here, the 6 PWR WP case shows similar behavior even though the temperatures are slightly lower (at most 5 to 10 degrees Celsius at times less than 100 years) than the 12 and 21 PWR WPs.

Figure 4-4 shows the temperature profiles of the two emplacement methods for a 21 PWR WP at an AML of 83 MTU/acre. The temperature differences between the two emplacement methods are relatively small compared to the significant decrease in temperature from the 111 MTU/acre case. The temperatures produced at this thermal loading are well below the 200 degree Celsius thermal goal. Thus, AML is shown to be the main driver for producing temperature changes and not WP size or drift diameter in the range from 6 to 21 PWR and 4.3 to 7 m diameter drifts for the above boiling options. However, in a below boiling repository, it appears that WP capacity is important in establishing near-field temperatures. At the lower thermal loadings, more significant temperature differences are observed between the two emplacement methods (minimum WP spacing, variable drift spacing or minimum drift spacing, variable WP spacing). As shown in Figure 4-5, for the 36 MTU/acre case with a 12 PWR WP in a 7 m drift, significant temperature differences can be produced, with the minimum WP spacing, the variable drift spacing case yielding as much as over 50 degrees Celsius higher wall temperatures than the minimum drift spacing, variable WP spacing case. The question then is how this might affect performance. At these low thermal loadings the only thermal goals that may be violated would possibly be some operational limits and these are discussed later in the report. If the drift needed to be ventilated at some time after emplacement to reduce the drift temperature to 50 degrees Celsius to retrieve a WP, then a concern is what will this do to ventilation requirements. The hotter drift may require additional time and ventilation capacity to reduce the temperature to a manageable level.

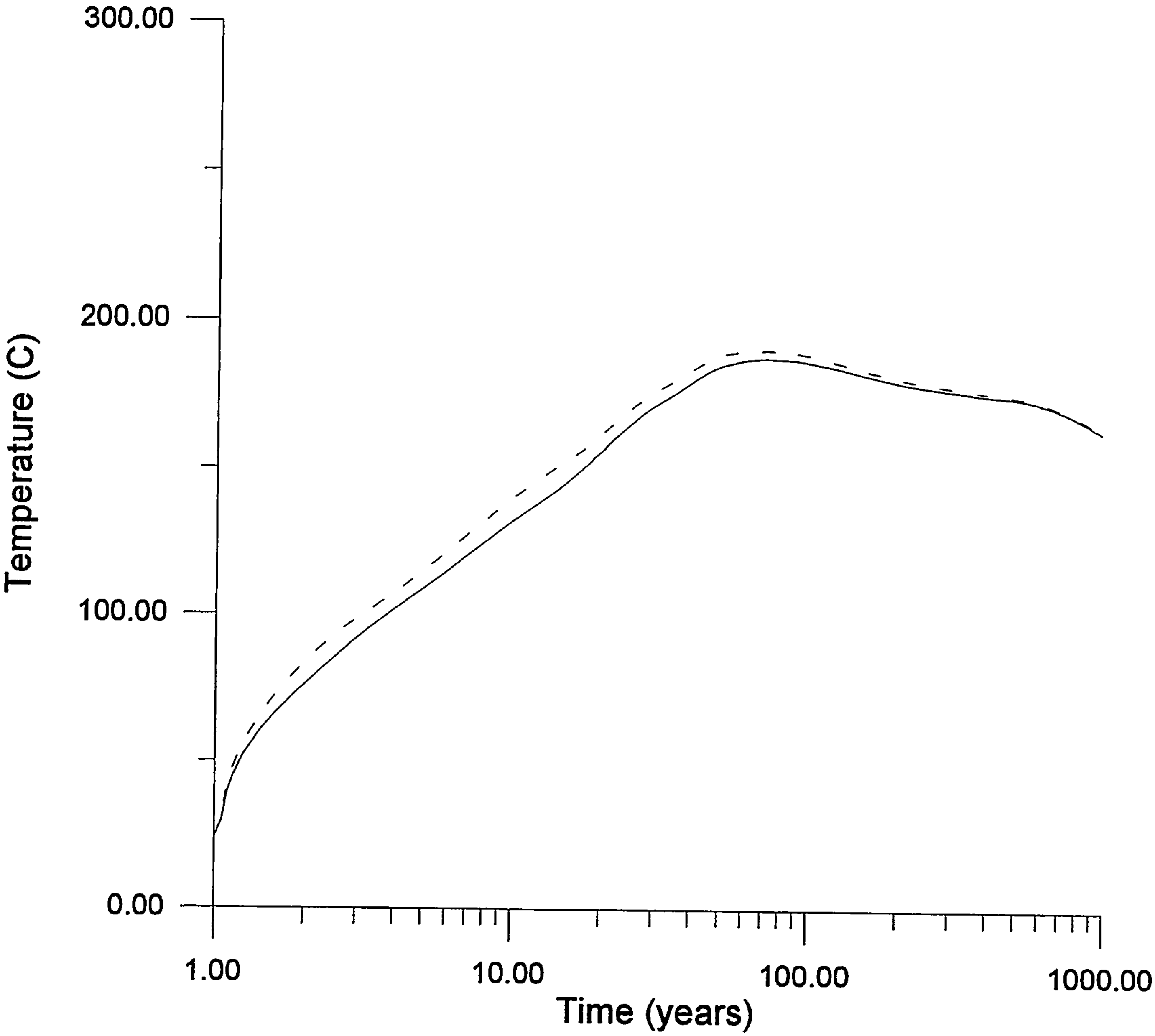


Figure 4-1. Comparison of Drift Wall Temperatures at 111 MTU/Acre for a 21 PWR WP Using a Minimum Drift Spacing or Minimum WP Spacing Emplacement in a 7 m Drift (Solid Curve is Minimum Drift Spacing and Dashed Curve is Minimum WP Spacing)

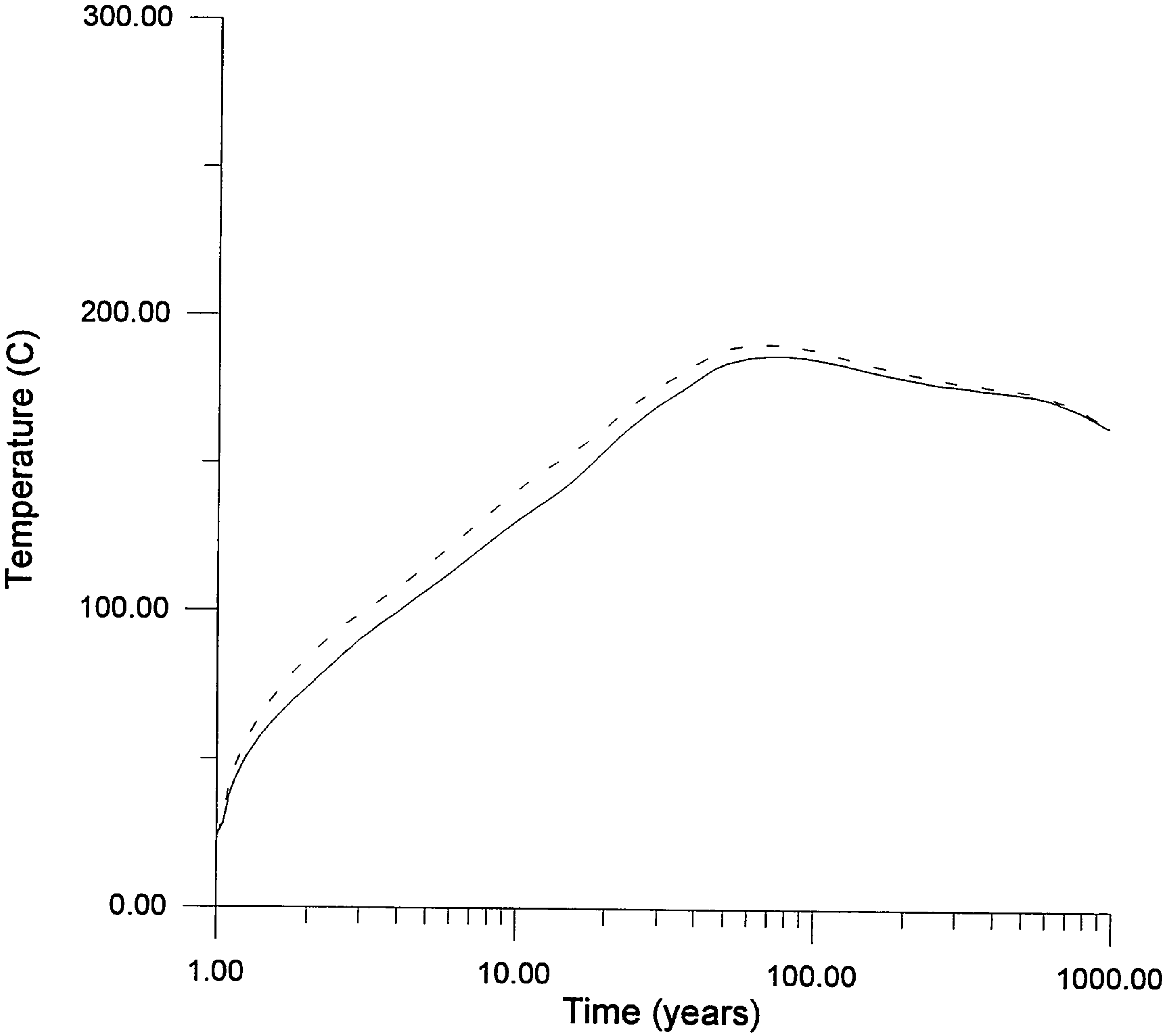


Figure 4.2. Comparison of Drift Wall Temperatures at 111 MTU/Acre for a 12 PWR WP Using a Minimum Drift Spacing or Minimum WP Spacing Emplacement in a 7 m Drift (Solid Curve is Minimum Drift Spacing and Dashed Curve is Minimum WP Spacing)

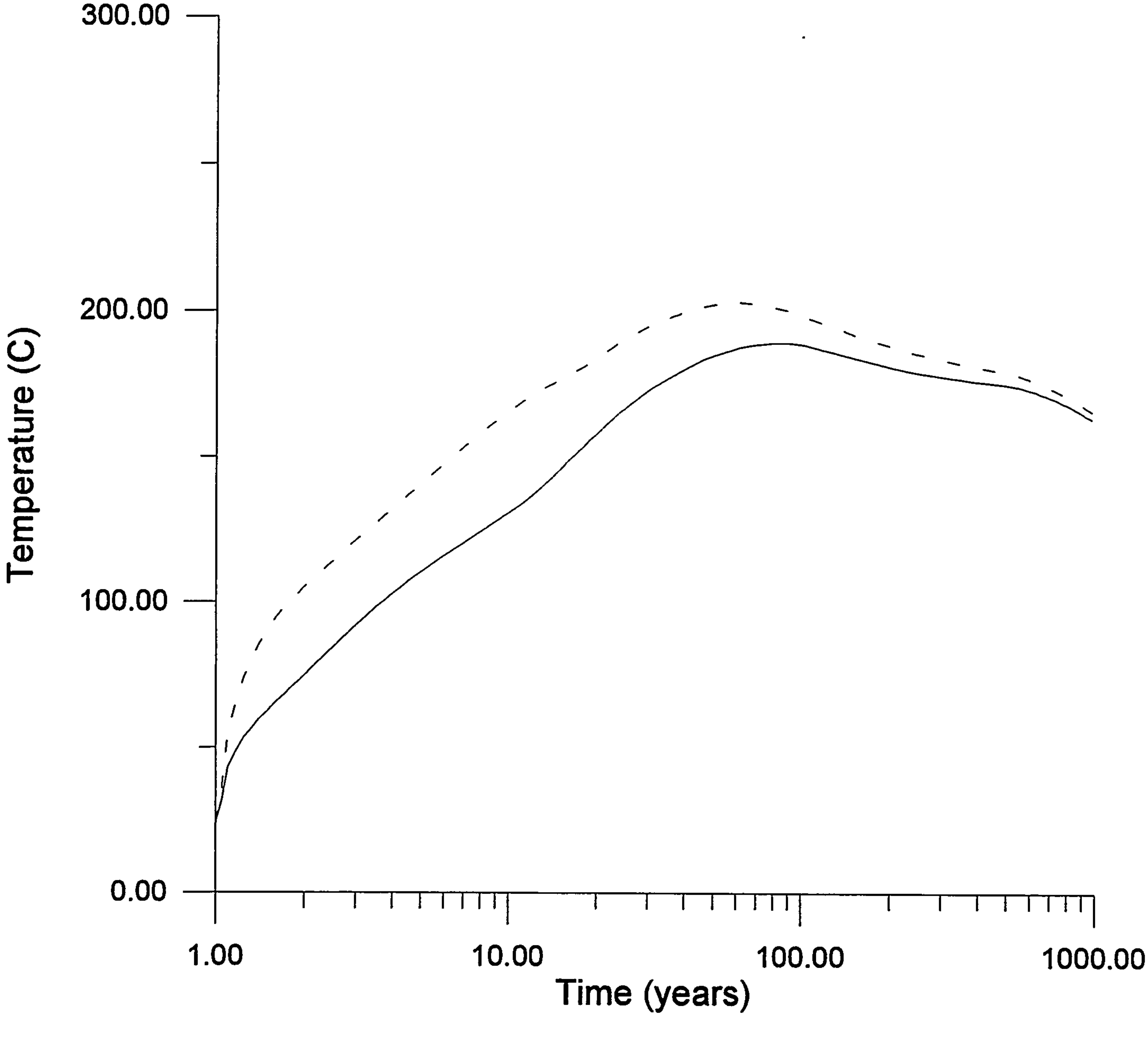


Figure 4-3. Comparison of Drift Wall Temperatures at 111 MTU/Acre for a 12 PWR WP Using a Minimum Drift Spacing or Minimum WP Spacing Emplacement in a 4.3 m Drift (Solid Curve is Minimum Drift Spacing and Dashed Curve is Minimum WP Spacing)

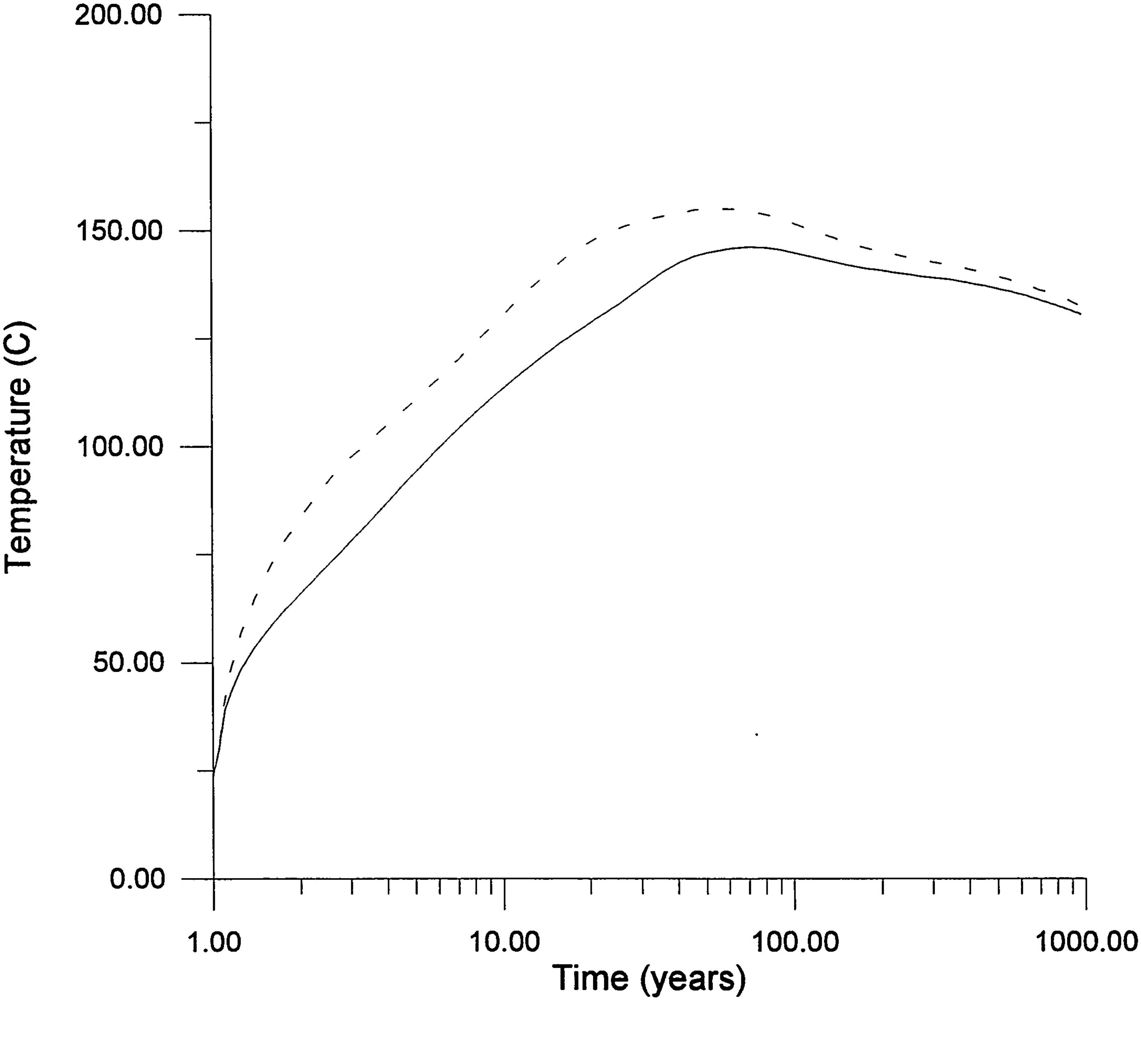


Figure 4-4. Comparison of Drift Wall Temperatures at 83 MTU/Acre for a 21 PWR WP Using a Minimum Drift Spacing or Minimum WP Spacing Emplacement in a 7 m Drift (Solid Curve is Minimum Drift Spacing and Dashed Curve is Minimum WP Spacing)

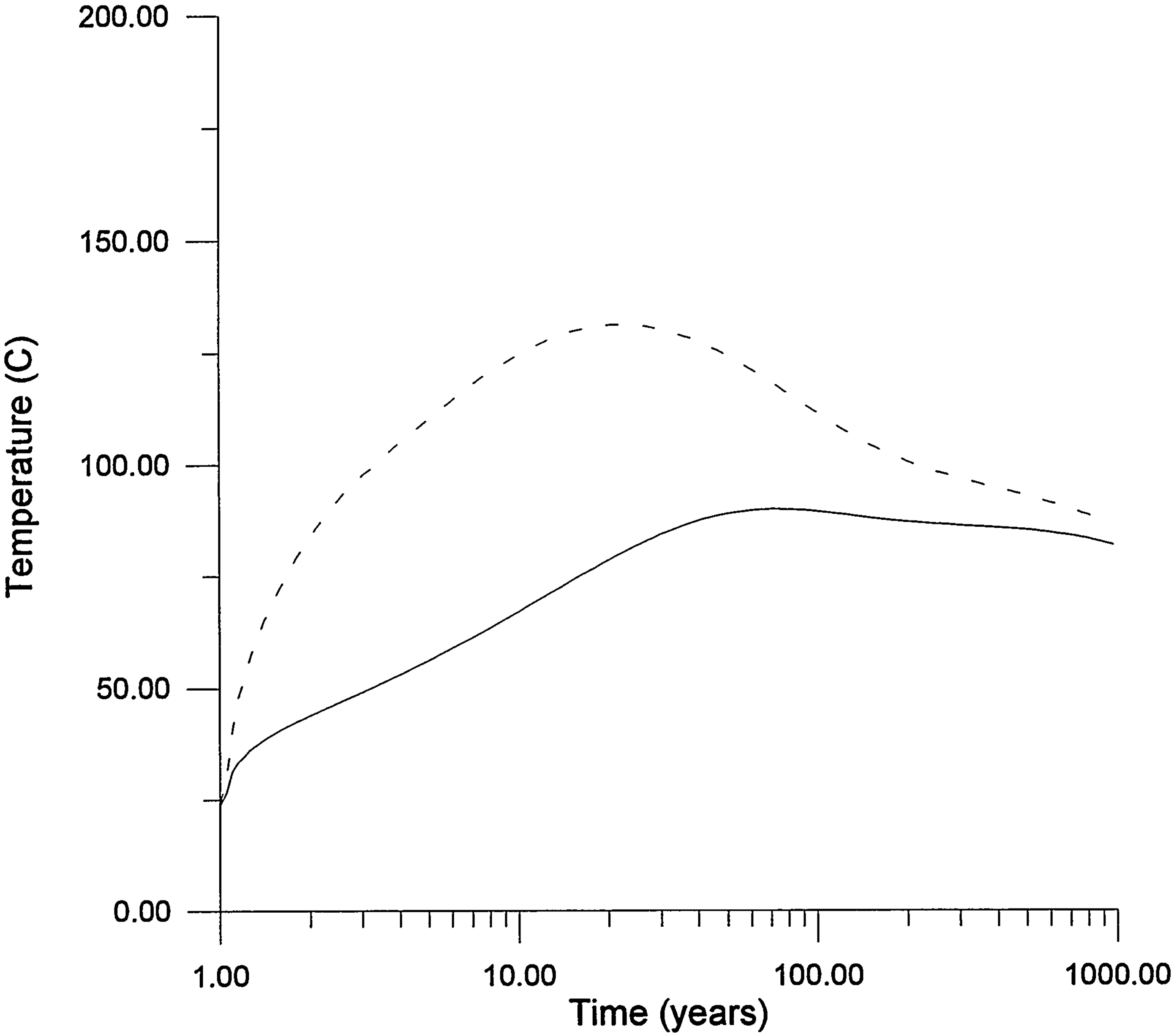


Figure 4-5. Comparison of Drift Wall Temperatures at 36 MTU/Acre for a 12 PWR WP Using a Minimum Drift Spacing or Minimum WP Spacing Emplacement in a 7 m Drift (Solid Curve is Minimum Drift Spacing and Dashed Curve is Minimum WP Spacing)

This issue will be addressed in Section 10. Figure 4-6 shows that with a 6 PWR WP these differences can be moderated to some extent and the differences are not as large. It should also be noted that, except for a short period of time for the minimum WP spacing case, the drift wall temperatures are below boiling.

Note that the above temperature comparisons used drift wall temperatures. As one goes farther into the rock, the temperature variations between emplacement methods will be minimized. For vertical borehole emplacement, however, the spatial temperature gradient will be larger in the near vicinity of the WP, since as the heat is produced it will be exchanged with a much smaller area of rock.

Thermal Goals Evaluation

The goals listed below were considered specifically near-field goals related to preclosure performance. These goals were extracted from Table 2-1 of Section 2. The following discussion relates the relevance of the near-field analysis to these goals.

Number	Goal
6	Design basis thermal loading less than allowable thermal loading
8	Keep rock mass temperature at 1 m from vertical borehole <200 °C
8[1]	Keep in-drift wall temperatures <200 °C
9	Boreholes that do not load container beyond limits imposed under Issue 1.10
11	Fuel cladding temperature <350 °C
12	High level waste glass temperature <500 °C
13	Temperature in access drift <50 °C for first 50 years
15	Emplacement drift wall temperature <50 °C for first 50 years for horizontal borehole

Not all these goals could be evaluated with the near-field temperature predictions done. Goal 6 is a general goal which provides no basis for evaluation and will not be considered here. Goal 9, a general thermo-mechanical goal, is beyond the scope of this study. The study did not evaluate high level defense wastes and thus goal 12 was not evaluated. Both goals 13 and 15 refer to the access drift temperatures in spite of the wording (see discussion on page 18 of the M&O (1993a) reference). However, because of the nature of the COYOTE near-field code the access drift temperatures could not be evaluated. The far-field analyses discussed in the next section will be used to estimate the performance against this goal, so the discussion will be deferred until that section.

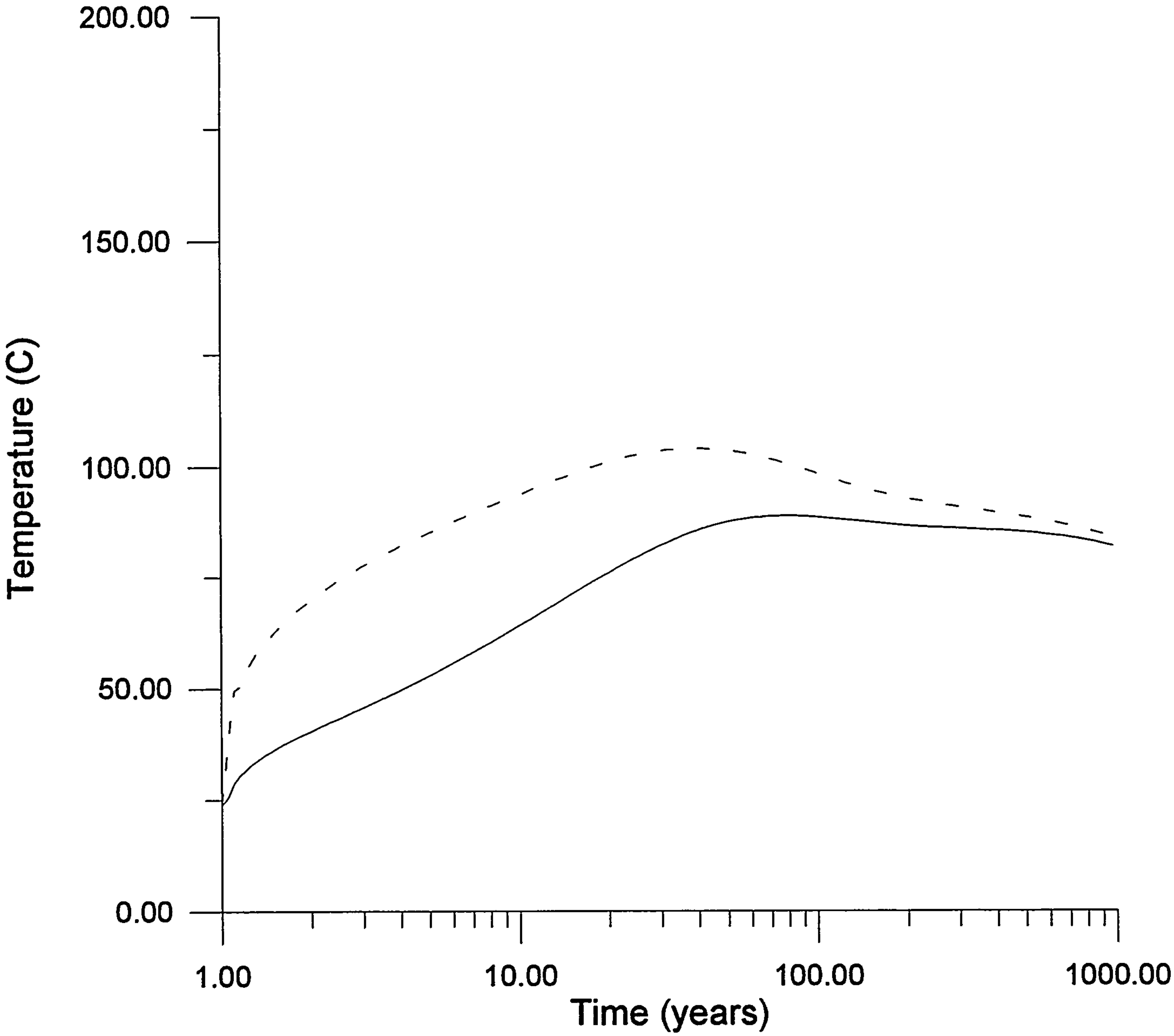


Figure 4-6. Comparison of Drift Wall Temperatures at 36 MTU/Acre for a 6 PWR WP Using a Minimum Drift Spacing or Minimum WP Spacing Emplacement in a 7 m Drift (Solid Curve is Constant Drift Spacing and Dashed Curve is Minimum WP Spacing)

Although no near-field temperatures were calculated for the vertical borehole case in this study, results from an earlier effort by SNL (Hertel and Ryder, 1991) were drawn on to evaluate thermal goal 8 (see above and Table 2-1) to maintain the 1 m rock temperature below 200 degrees Celsius. Hertel and Ryder (1991) varied the WP capacity and spacing of vertical boreholes over a limited range to determine what combinations would meet various thermal goals. For a single WP in a vertical borehole, it was determined that if the WP heat output was 5.2 kW or greater, the 1 m rock temperature goal of 200 degrees Celsius would be exceeded. Thus, when more than a single WP is considered, a credible limit is less than or equal to 5.2 kW. It should be noted that, in practice, the maximum size package that can be placed in a borehole, and still meet thermal constraints, does depend on the size of the borehole. However, it is far less sensitive to borehole diameter than it is to capacity and fuel power output. The borehole emplacement must be able to allow, not just average fuel, but fuel with some variability to be emplaced. To demonstrate this one can take the example of a 6 PWR WP in a borehole. Applying the 5 kW limit above it can be found that this would accommodate fuel that has a power output of almost 2000 W/MTU. Using the characteristics data base this translates to 10 year old fuel (the youngest that is likely to be emplaced) with about 50 GWd/MTU burnup. Instead if a 21 PWR WP which has an 8 kW output is used this would allow 890 W/MTU. In the first case almost all of the fuel can be accommodated (little has more heat output than 10 year, 50 GWd/MTU burnup), but in the second case a significant amount of derating would need to take place because for 10 year old fuel only about a 26 GWd/MTU burnup could be accommodated. Thus, a good share of the fuel could not be emplaced. Of course, if fuel were aged this would modify the amounts and burnups somewhat.

As shown in Table 4-1, neither a 12 nor a 21 PWR would meet the goal and should not be placed in a vertical borehole. The SNL study then calculated the spacings that would just achieve the thermal goals for WP capacities of 2, 3, and 4 kW. The 1 m rock temperature goal of 200 degrees Celsius proved to be the most constraining of the goals analyzed. They calculated the APD that would just meet the goal. The 3 kW case corresponds closely with the 6 PWR package in this study, which has an output of 2.89 kW. SNL found that the largest APD that could be accommodated and still meet the goal was 93 kW/acre. Converting this to AML, for the fuel considered in this study, indicates that the maximum AML that will still meet the goal is 83 MTU/acre. This is the best that can be achieved and still allow contiguous sections containing only PWR fuel. This would require that the fuel all be equal to the average. Thus, for a 6 PWR WP the goal is met for all thermal loads except 111 MTU/acre. Table 4-6 demonstrates this performance against thermal goal 8 by assigning a utility of 1 when the goal is met and 0 when it is exceeded. The results could be varied somewhat by aging the fuel.

Thermal goal 8' (Table 2-1), established to maintain the drift wall temperatures below 200 degrees Celsius, was examined in light of the predictions provided by the near-field thermal analysis. An evaluation of this indicates that in all cases the peak drift wall temperatures produced by 111 MTU/acre exceeded the goal. This is true for both emplacement methods and both size drifts. Lower thermal loadings do not exceed this goal. Table 4-6 summarizes the performance, in terms of utility factors, of each of the thermal options. An example showing the various temperature profiles at the different thermal loads is shown in Figure 4-7. This figure shows the temperature profiles for the 12 PWR WP emplacement using the emplacement method of minimizing the WP spacing and keeping it constant, then varying the drift spacing to obtain the required AMLs. The plot gives the temperature profiles on the floor of the drift beneath the waste package which is the hottest point on the drift wall, although it is at most only 4 to 5 degrees hotter than the other points on the wall at early times.

Thermal goal 11, established to keep the waste package centerline less than 350 degrees Celsius in an attempt to preserve the fuel cladding, was evaluated with the WP design code ANSYS a non-linear finite element code using the near-field drift surface temperature provided by SNL as input. The WP centerline temperatures for only two cases are shown here. Specifically, the 21 PWR WP in a 7 m and in a 4.3 m diameter drift are shown in Figures 4-8 and 4-9 respectively. These were done at the 111 MTU/acre loading which should provide the worst case environment. These results indicate that, as expected, the thermal goal of 350 degrees Celsius as a peak fuel temperature was not exceeded for the WP spacings and drift sizes considered here. The centerline temperature goal of 350 degrees Celsius was met for all other thermal loading cases. It should be noted, however, that these calculations were only done for the average fuel. Some of the fuel received will be hotter and an analysis needs to be done in a follow-on study to evaluate this issue. Further details of the calculations can be found in Appendix B.

Table 4-6. Comparison of Performance with Near-Field Thermal Goals

Utility Factors[a]
Loading (MTU/Acre)

	24	36	55	83	111
Goal 8[b]	1	1	1	1	0
Goal 8'	1	1	1	1	0
Goal 11	1	1	1	1	1

[a]A 1 implies goal is met; a 0 implies goal is violated.
[b]The goal is met only for a WP of less than 5.2 kW. Thus, for the fuel considered here, only the 6 PWR WP would comply and the 12 and 21 PWR WP would not meet the goal at any AML.

Local Boiling Evaluation

If a below boiling strategy (bulk average temperatures <97 degrees Celsius) were to be selected, then the question is whether local boiling might occur and how far into the rock it might extend. Whether large capacity WPs can be used may depend on how much local boiling is allowed. Pillars below boiling may allow small amounts of liquid to drain away from the WPs. The near-field results were used to evaluate this question. From the previous analysis it is clear that for the thermal loadings of 55 MTU/acre or higher, using the hotter

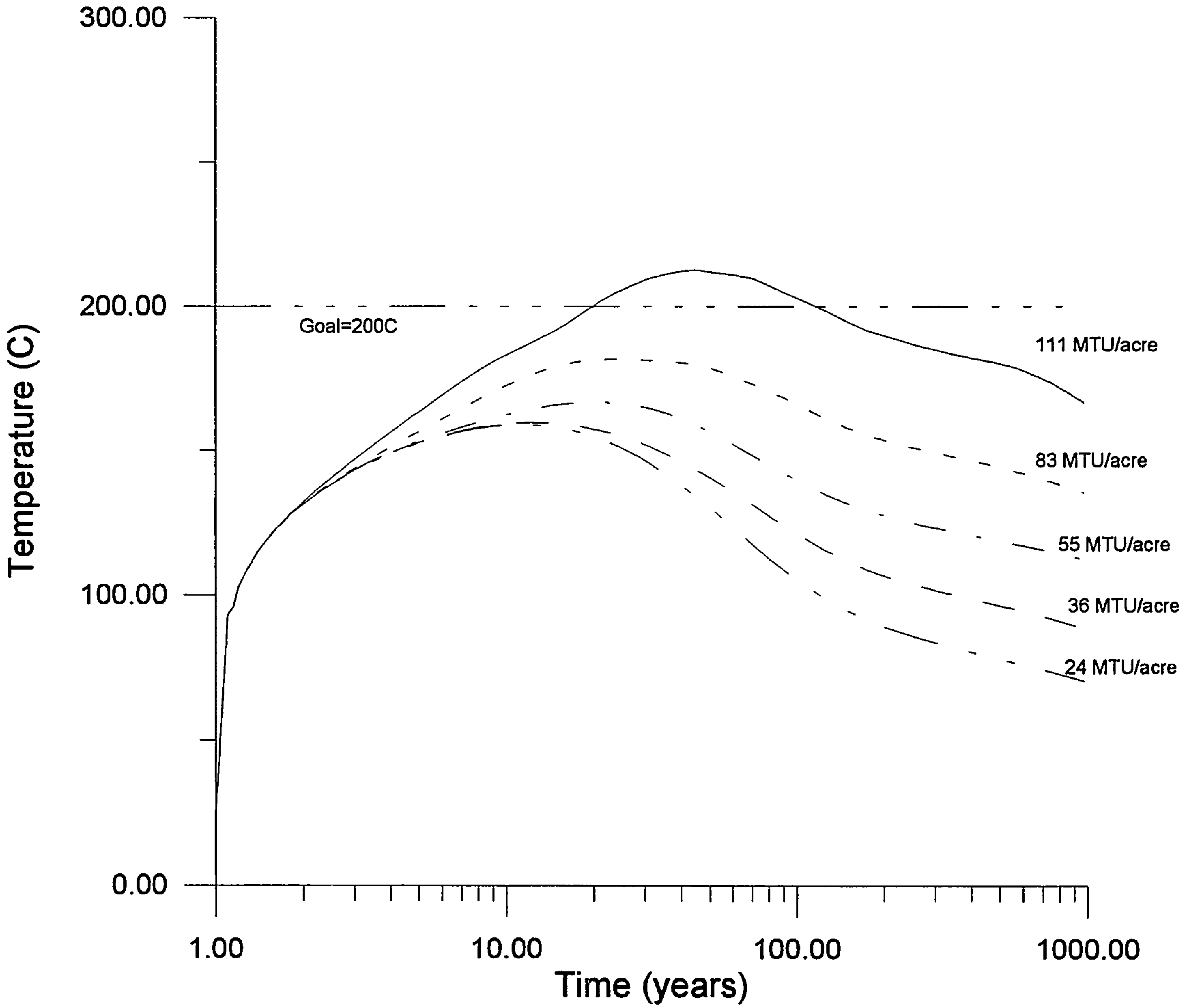


Figure 4-7. Temperature vs Time for the 12 PWR (4.3 m in-drift) at Drift Wall Bottom Using a Minimum WP Spacing of 6.64 m

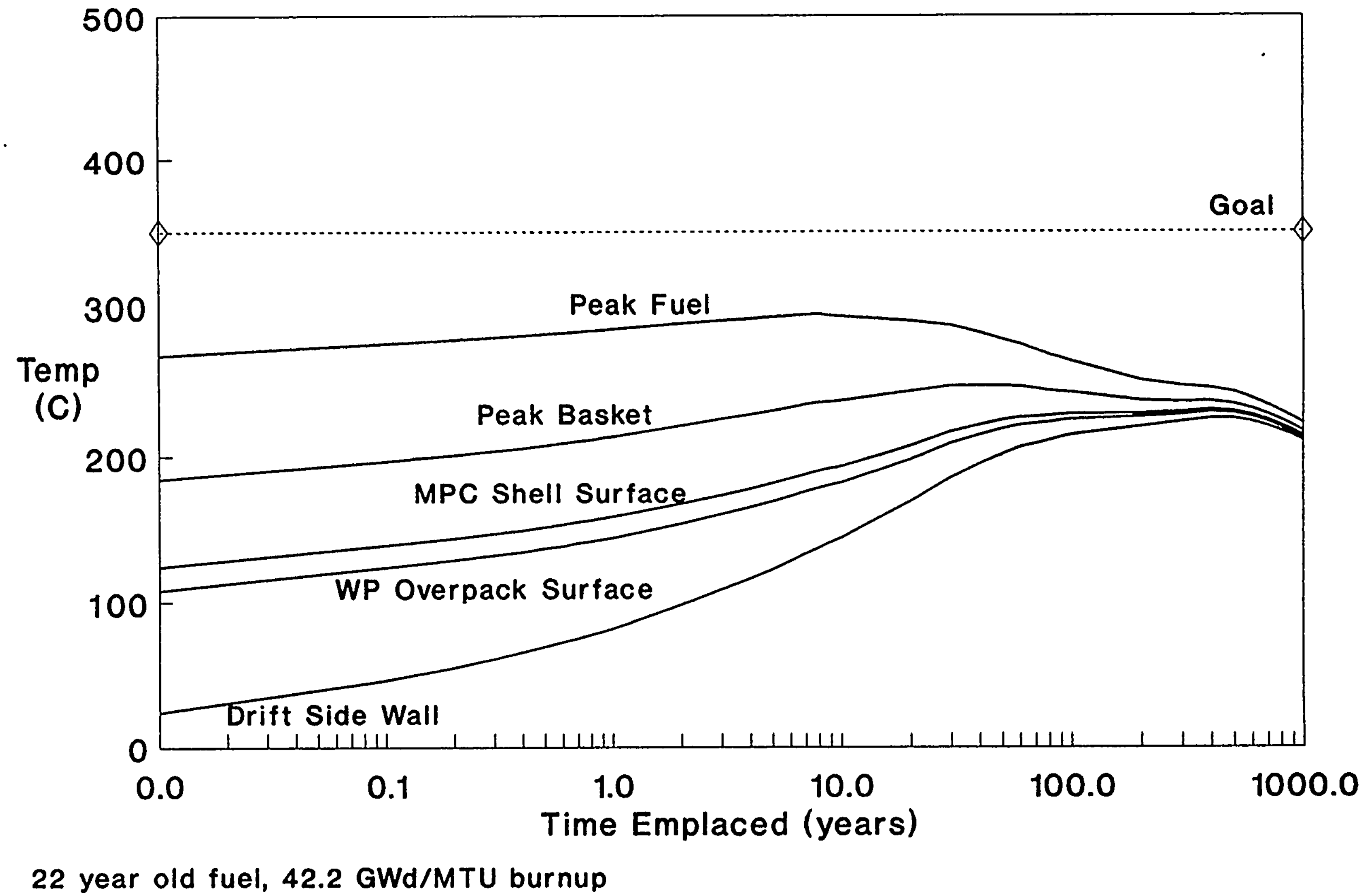


Figure 4-8. Waste Package Temperatures - Case 1
21 PWR MPC, 7.0 m Drift, 111 MTU/Acre

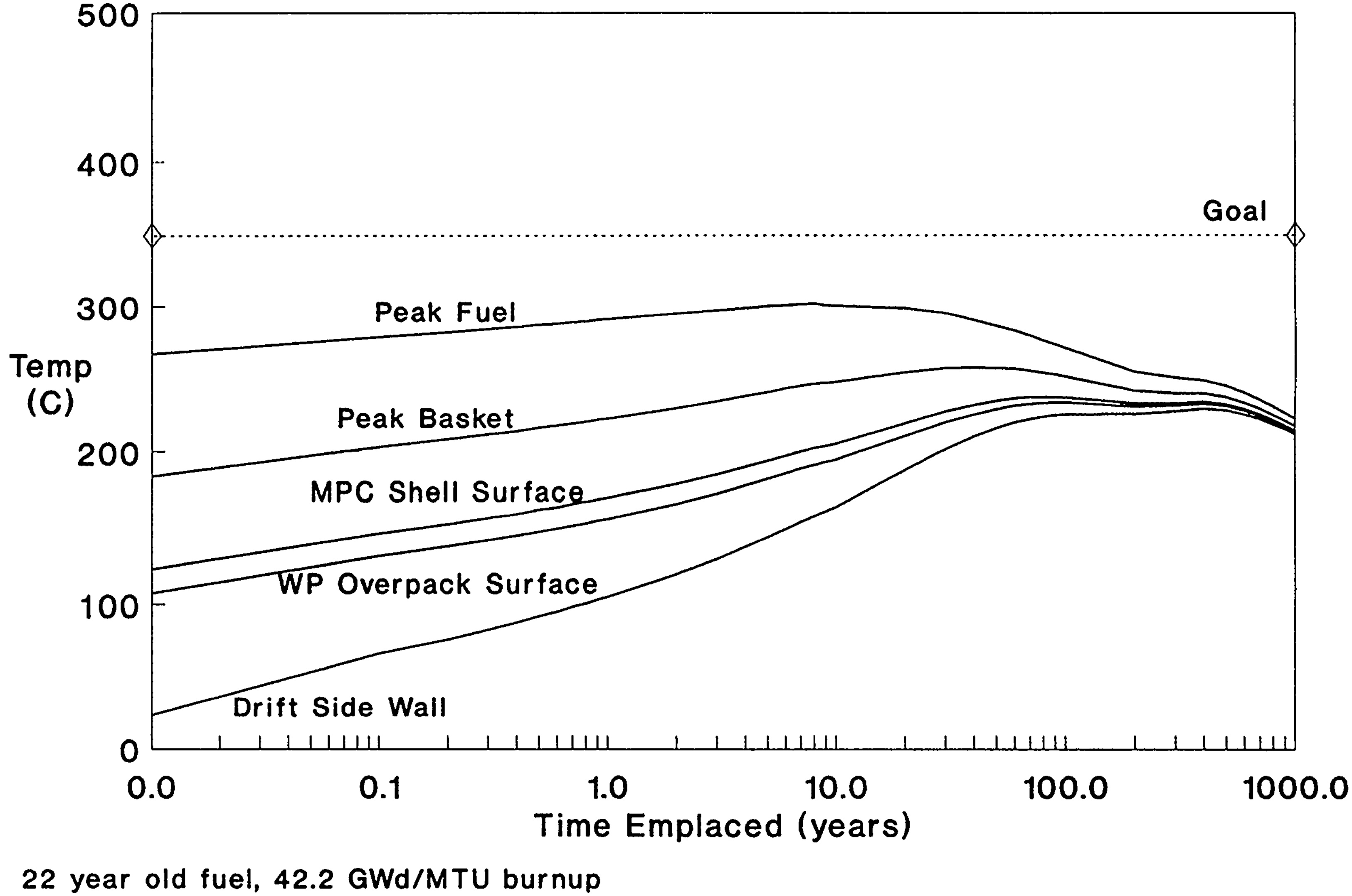


Figure 4-9. Waste Package Temperatures - Case 2
21 PWR MPC, 4.3 m Drift, 111 MTU/Acre

PWR fuel, the majority of the repository is above boiling for a number of years since the boiling isotherms in each pillar coalesce at least at the repository center. However, at the lower thermal loads, a portion of the drift will be below boiling at all times. To evaluate this, the near-field calculations were used to provide temperatures at various distances from the WP center, to a distance approximately midway between drifts at various times. For demonstration purposes, plots of temperature gradients are shown in this report at times of 50, 101, 201, and 451 years. The choice of 451 years for the cases was primarily because this time yielded temperatures mid drift that were near maximum; beyond that time, the temperatures begin to diminish. However, the actual analysis discussed below selected the time at which the boiling front had progressed the farthest into the rock. This time at which the peak occurs is in good agreement with the far-field predictions presented in the next section. For both loadings the boiling front has penetrated as far into the rock as it will around 50 years and at later times begins to retreat.

Figures 4-10, and 4-11 show the temperature profiles perpendicular to the drift as one goes towards an adjacent drift for the 21, 12, and 6 PWR WPs respectively at five time periods selected for the 36 MTU/acre case. Similarly, the temperature profiles into the rock for the two WP capacities and four time periods are shown for 24 MTU/acre in Figures 4-12 and 4-13. These plots again just show the results for the 7 m diameter drift; a similar analysis, although not shown here, was done for the 4.3 m diameter drifts. The boiling point is delineated on each curve and the distances at which these temperature profiles intersect the boiling point was recorded.

The predicted distances that the boiling fronts extended into the rock were determined from the calculations for the two below boiling thermal loadings of 36 and 24 MTU/acre for the two drift diameters (4.3 and 7 m), and for each of the package sizes. The results show that some local boiling will occur in the near vicinity of the drift due to the larger packages. This boiling occurs for times around 30 to 70 years after emplacement corresponding to approximately when the peak drift wall temperature occurs. The boiling front penetrates at most no more than about 10 m into the drift. This occurs for the 4.3 m diameter drift. Little difference was seen between the penetration of the boiling front for the cases which had a 12 or 21 PWR capacity packages. However, in the case of the 6 PWR package there was no local boiling except for a small amount of boiling for the 4.3 m diameter drift at 36 MTU/acre. Thus, for all WP sizes at least 80 to 100 percent of the pillar between drifts stays below boiling.

It should be noted that the calculations in some respects were conservative since the near-field calculations were done using only the hotter PWR fuel. Thus, the boiling fronts will not penetrate as far with the BWR fuel. However, only average PWR characteristics were used and variability needs to be looked at in the follow-on study.

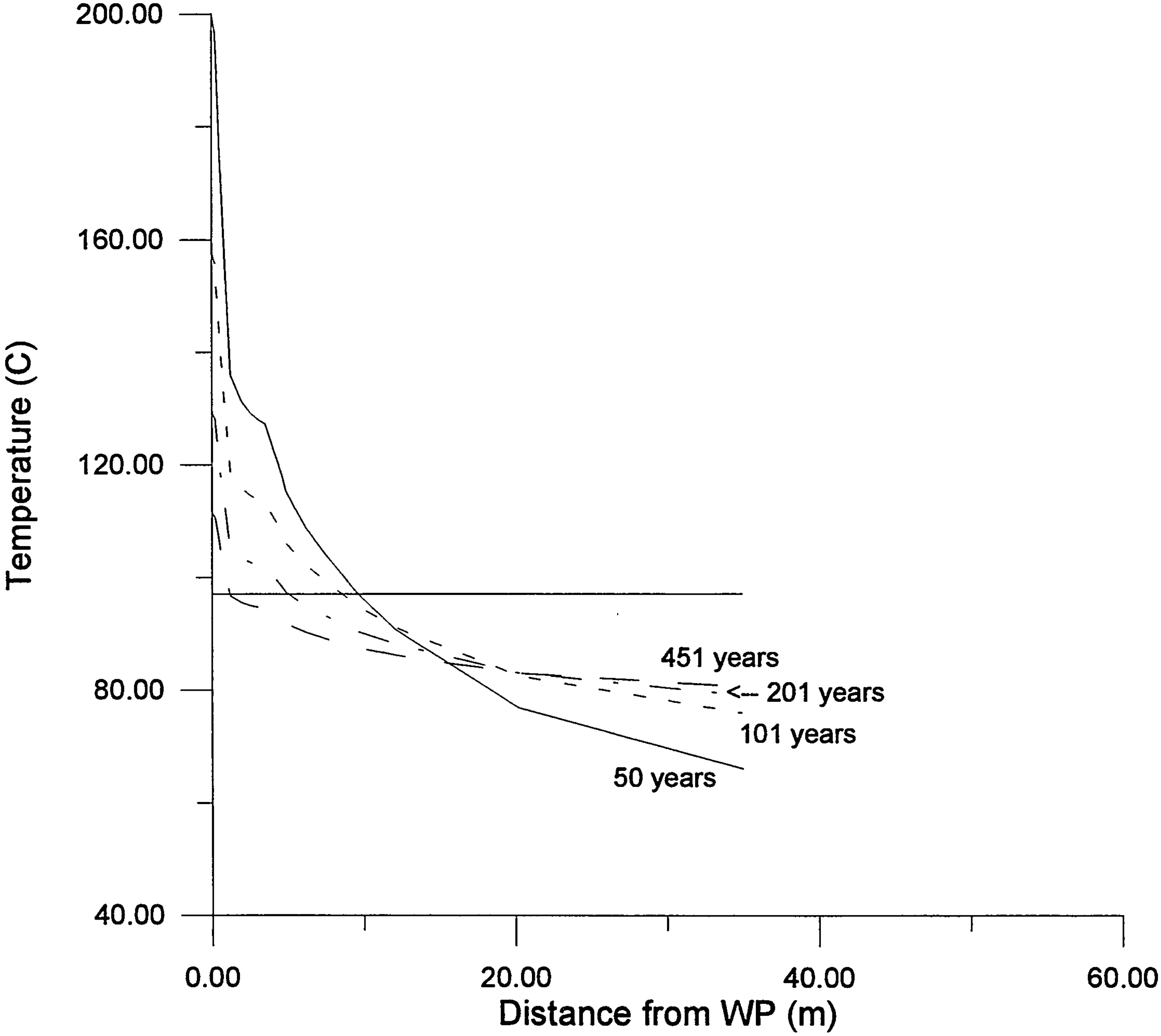


Figure 4-10. Temperature Profile Perpendicular to the Drift for 36 MTU/Acre and a 21 PWR WP Using Minimum WP Spacing at Five Different Times (7 m Diameter Drift)

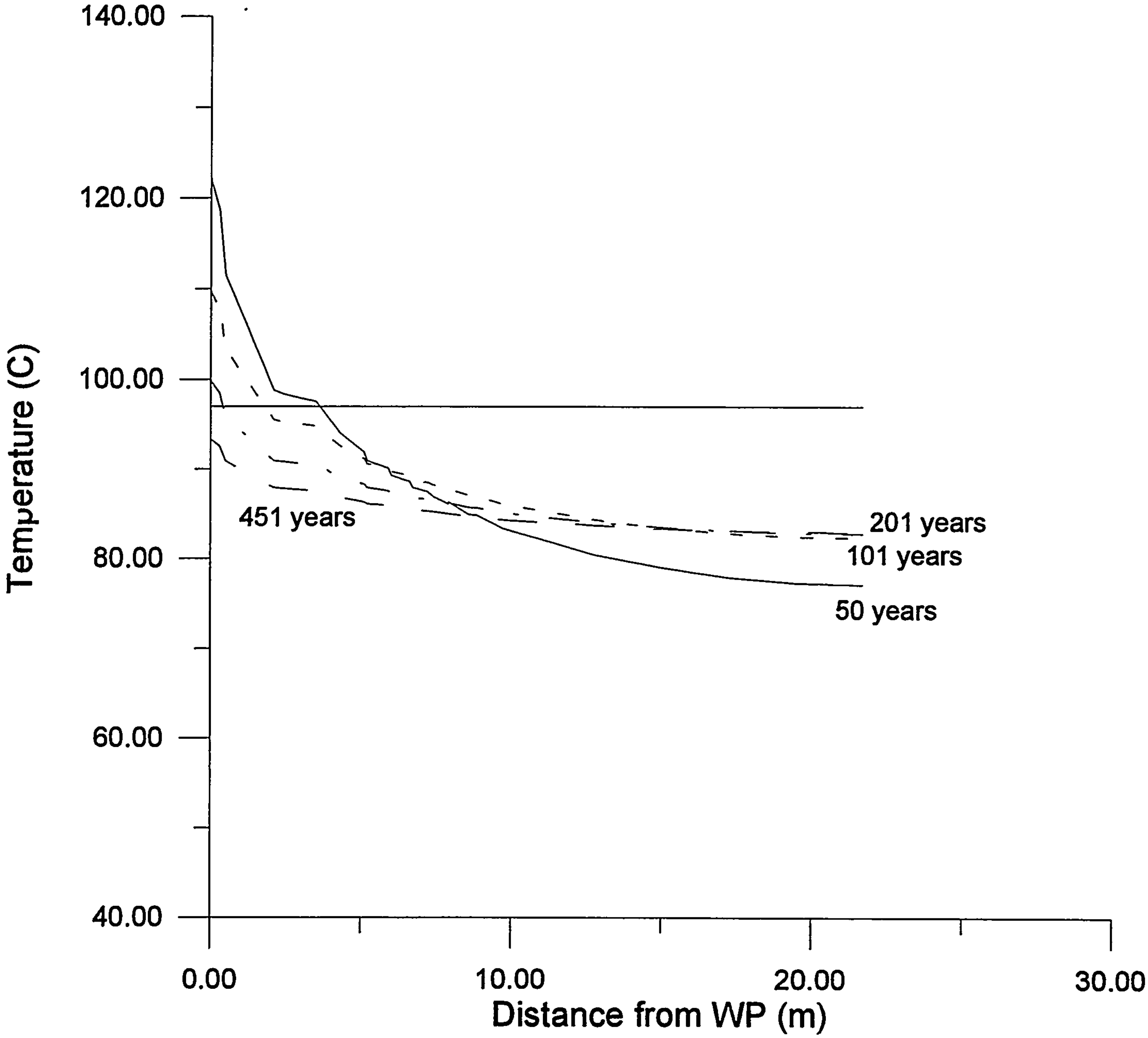


Figure 4-11. Temperature Profile Perpendicular to the Drift for 36 MTU/Acre and a 6 PWR WP Using Minimum WP Spacing at Five Different Times (7 m Diameter Drift)

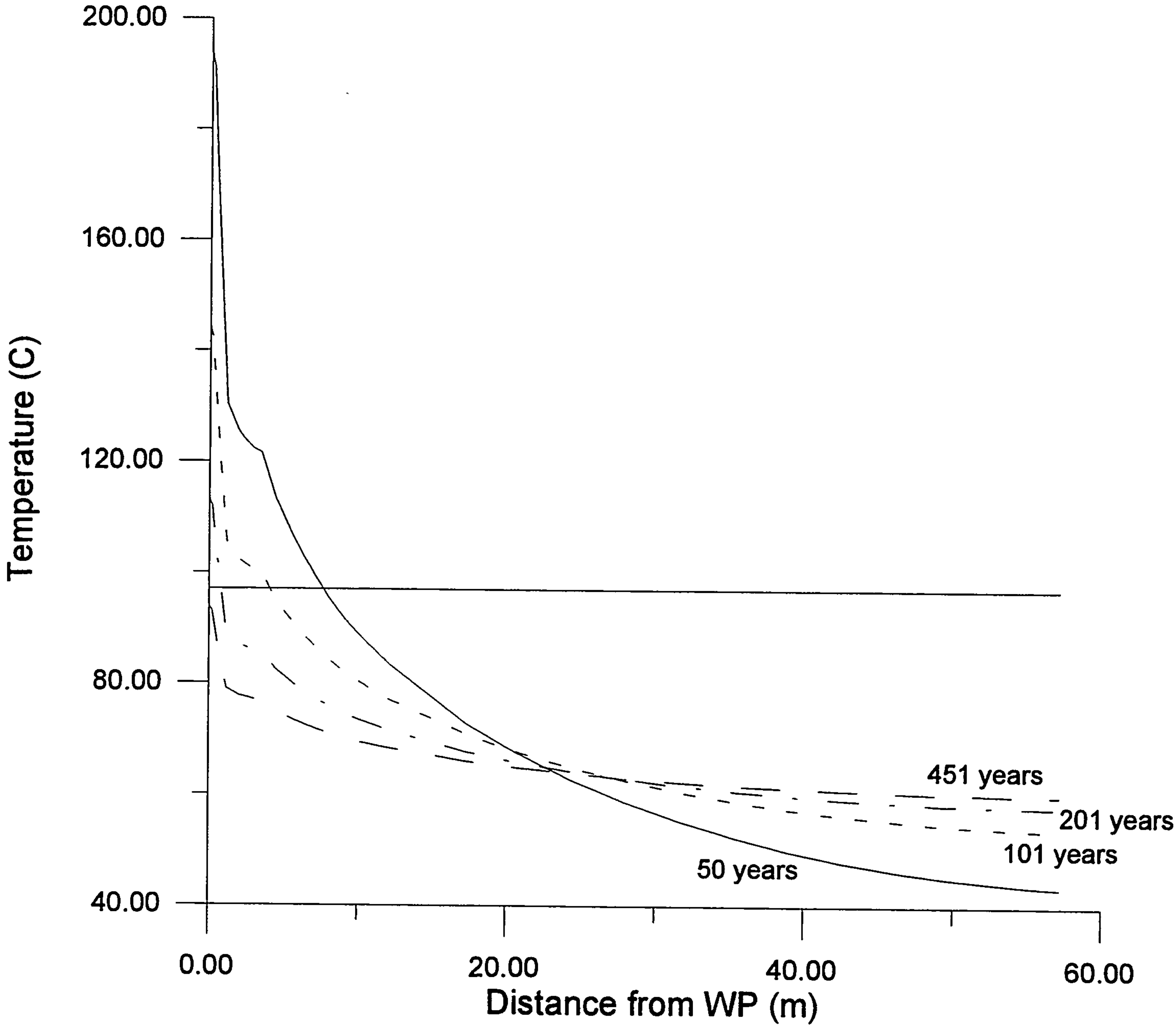


Figure 4-12. Temperature Profile Perpendicular to the Drift for 24 MTU/Acre and a 21 PWR WP Using Minimum WP Spacing at Five Different Times (7 m Diameter Drift)

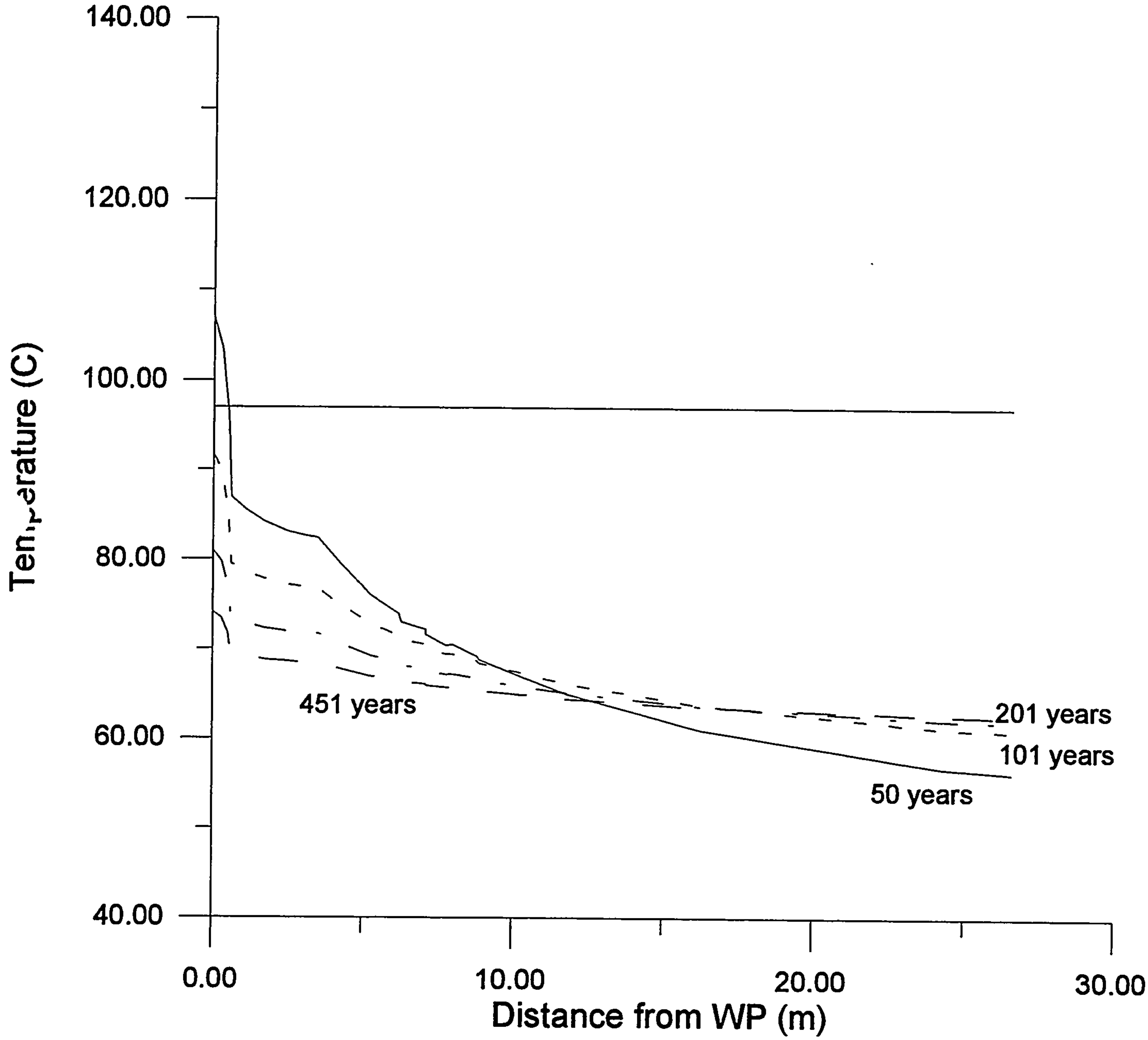


Figure 4-13. Temperature Profile Perpendicular to the Drift for 24 MTU/Acre and a 6 PWR WP Using Minimum WP Spacing at Five Different Times (7 m Diameter Drift)

4.6 SUMMARY

The near-field, preclosure performance was evaluated using calculations done by SNL using a conduction model. Two subsurface design concepts were investigated; one in which the WP spacing was kept at a minimum and the drift spacing varied to obtain the different thermal loads and the second in which the drift spacing was kept at a minimum and the WP spacing varied. Comparisons of the results using the two subsurface design techniques found that, at the lower thermal loads (below boiling strategies), the minimum WP spacing gave somewhat higher temperatures at the WP than the minimum drift spacing concept but that between drifts a larger percentage of the rock was below boiling than for the minimum drift case. At the highest thermal loads the differences between the two methods was negligible. The calculated near-field temperatures were compared with the thermal goals to show that the thermal goal to keep the drift wall temperature less than 200 degrees Celsius was violated for the 111 MTU/acre case but not at 83 MTU/acre or lower. The thermal goal to keep the WP centerline temperature below 350 degrees Celsius was not violated in any of the cases, as expected, since the study attempted to set up the initial conditions that would produce that result. This was done to assist in limiting the number of cases examined in the study. Some additional calculations were referenced in this section which showed that, for vertical or small diameter horizontal borehole emplacement, a WP must be limited to about 5 kW power output (capacities less than 10 to 12 PWR) based on rock temperature thermal limits. For the below boiling (bulk average temperatures less than 97 degrees Celsius at the repository horizon) AMLs of 24 and 36 MTU/acre, the calculations showed that some local boiling would occur. What this implies, though, is that appreciable areas of the pillars between drifts from more than 80 to as much as 100 percent will remain below boiling. This would allow for local hydrologic drainage between drifts if that is deemed desirable. For the 6 PWR capacity WP at 100 percent of the rock between drifts is below boiling (except for the 36 MTU/acre, 4.3 m diameter drift).

5. FAR-FIELD THERMAL ANALYSIS

5.1 PURPOSE OF ANALYSIS

The purpose of this analysis is to provide the basis for comparison of the performance of thermal loading options against the far-field thermal goals presented in Section 2. The thermal and hydrothermal behavior of the far field is considered only as a surrogate for pre- and postclosure performance. This analysis was undertaken to predict the behavior of the coupled hydrothermal system at the repository scale, and as such does not accurately predict near-field temperatures, near-field saturation profiles, drift temperatures, and waste package temperatures. The calculations were performed such that the results would be relatively insensitive to the structure and geometry of the engineered barrier. Nevertheless, it is possible to obtain boundary and limiting conditions for near-field temperatures by observation of the far-field temperature distributions.

In addition to grading performance against thermal goals, this analysis is instrumental in identifying residual uncertainties in performance predictions, and will in part form the basis for recommendations for future work pointed toward improving confidence in future performance predictions.

5.2 BACKGROUND

Several previous studies investigating heat and fluid flow in Yucca Mountain take into account the thermal influence of SNF-generated heat. In general, these analyses fit into two categories; analyses of heat conduction with varying degrees of detail about the specific emplacement configuration [Ryder (1993), Holland (1993), and Hertel and Ryder (1991)], and analyses of coupled heat and fluid flow, usually with a simple axisymmetric uniformly distributed heat source [Pruess and Tsang (1993), Buscheck and Nitao (1993), Buscheck and Nitao (1992) and Danko and Mousset-Jones (1992)]. The coupled conduction-fluid flow models have shown the importance of latent heat and heat pipe effects in calculating far-field temperature distributions. The conduction-only models, which are generally more amenable to complicated geometries, have shown the importance of the temperature distribution across the repository, indicating that the edge can be at a significantly different temperature than the center and that temperatures can be influenced by the repository configuration. In this study, the thermo-hydrologic model was used to make predictions at various locations out to the edge of the repository.

To date, no study has presented temperature and fluid distributions for detailed repository configurations in Yucca Mountain as a function of the thermal load. The coupled models have been limited to simple geometries by computer time, and the conduction-only models are incapable of simulating fluid flow. In addition, comparisons between previous studies have been limited by the wide range of fuel characteristics, repository configurations, and repository total capacities used for various thermal loadings. So that comparisons could be made between thermal loadings, a consistent set of calculations was needed to account for fluid flow effects and variations across the repository.

Conduction-only models cannot capture the simultaneous presence of coupled multi-phase fluid and heat flow processes that can occur in the mountain. These coupled processes can occur on vastly different response times. That is, propagation of gas phase pressure disturbances on the repository scale of about one kilometer occur over a period of about one month while thermal disturbances over such distances can take as long as several thousand years or more. Time scales on the order of 100,000 years are required for the capillary pressure disturbances to propagate in the tight Topopah Spring matrix rock (Pruess and Tsang, 1993). These processes are affected by the homogeneity or lack of homogeneity in the rock properties. The answer to the questions concerning homogeneity of rock properties must await underground data. However, the far-field code applied in this study utilized the best available data to provide estimates of this behavior to the extent possible at this time.

5.3 ANALYSIS METHOD

The far-field thermal analysis to be presented was done by LLNL using the V-TOUGH code (Nitao, 1989 and Pruess, 1987). V-TOUGH is a multi-dimensional code capable of calculating coupled water, vapor, air and heat transfer in porous and fractured media. V-TOUGH accounts for the following:

- Fluid Flow in liquid and gas phases according to Darcy's Law
- Gas phase binary diffusion
- Capillary forces
- Conduction of heat with thermal conductivity as a function of saturation
- Latent heat effects
- Convection of heat in gas and liquid phases

V-TOUGH does not consider transport processes, radionuclide decay, dispersion, chemical reactions, or sorption. Although V-TOUGH has the capability to model non-equilibrium matrix-fracture interaction, the analyses were performed assuming uniform matrix properties within each geologic unit, with the effective continuum approximation.

The continuum model has not been sufficiently tested at this time to be used in a compliance argument. It was selected for use in order to demonstrate and compare behavior with previous calculations. However, the calculations in the study have a higher consistency than other earlier calculations. V-TOUGH does have capability to model dual permeability and porosity conceptualizations. However, at this point site data does not support unambiguous selection of the parameters (i.e., fracture matrix coupling) to use in this model. Also the study should not be construed in any way as an endorsement of the equilibrium continuum model approach.

Although V-TOUGH has very flexible geometry capabilities, it was decided, owing to computer time constraints, that an axisymmetric uniform heat distribution would be modeled, but the temperature and saturation profiles would be produced as a function of the radius from the center of the repository. As such, the calculation would not be sensitive to the waste package loading, spacing, or repository configuration, but could be expected to yield representative results at distances from the repository that are large compared with the drift spacing and could be expected to give an indication of the variation in temperature across the repository.

The boundary conditions selected include a constant-property boundary at the ground surface with temperature and gas phase pressure fixed at 13 degrees Celsius and 0.86 atmospheres respectively. Thus mass flux but not temperature change is allowed at the surface. The lower boundary (about 1568 m below the surface) has a fixed temperature of 53.5 degrees Celsius and a fixed pressure corresponding to the hydrostatic pressure. This boundary condition is slightly different than what was used in the near-field work. Different analysts use somewhat different points where the boundary conditions are applied to insure that the correct temperatures are achieved at the repository horizon.

5.4 PROBLEM DEFINITION

The critical parameter for the case of uniform heat distribution is the AML measured in MTU per acre. As discussed in Section 3, five average AMLs were chosen for further analysis; 24, 36, 55, 83, and 111 MTU/acre. The 55 MTU/acre case corresponds to the reference loading of 57 kW/acre. The emplacement area used for all cases is consistent with a total capacity of 63,000 MTU of SNF and is consistent with the design cases depicted in Table 3-6. The average YFF(10) fuel consisting of the average PWR and BWR properties as described in Section 3 was used in the analysis.

The repository was divided into 12 rings for the purpose of calculation. The inner ring is labeled RP1 and the first six rings each account for 12.5 percent of the area of waste. Ring 7 has 9 percent, ring 8 has 6 percent, ring 9 has 4 percent, with each succeeding ring having 1 percent less area until ring 12, which encompasses the last 1 percent of the area. Temperature profiles were provided as a function of time for each of the rings. Additionally, the vertical profiles of temperature and liquid saturation were calculated at three different locations in the repository; at the center, about 70 percent of the distance to the edge, and at 97.5 percent of the distance to the edge.

All inputs to the model were within the range of values reported in the RIB (DOE, 1992c). The bulk permeability (for the Topopah Spring unit) used in all calculations was 280 milliDarcy, a value which represents tuffaceous rock with about three 100 micron fractures per meter. This value was based on modeling experts' judgment and is discussed in more detail in the notes in Appendix D and in Buscheck and Nitao (1988). Also a more detailed discussion of the assignments of permeabilities to the various stratigraphic units is added to Appendix F, Section II C. Gas permeability measurements taken recently and reported by Wilson, et al. (1994) indicate bulk permeabilities in TSw2 in the range from 0.1 to 10 Darcy. The 280 milliDarcy falls in this range but is on the low side. The potential repository itself is located at a depth of 343 m below the surface. A discussion of the analysis done by LLNL and the approximations used are provided in Appendix F. A discussion of the various inputs and where they fall within the range of values reported in the RIB is provided in Appendix D.

5.5 RESULTS

This section summarizes the results obtained by showing representative temperature and liquid saturation profiles for each thermal loading investigated. The average bulk temperature is plotted for all cases as a function of radius and time. It should be noted that the actual temperature distribution may be higher than this prediction depending on the proximity to a waste package. Observations and conclusions are presented where possible. The complete set of results can be found in Appendix F.

Ambient Conditions

The ambient conditions are shown in Figures 5-1 and 5-2. The ambient temperature profile with depth shows a surface temperature of about 13 degrees Celsius that increases with depth to about 31 degrees Celsius at the top of the saturated zone. The geothermal gradient is important in establishing the initial saturation profile. A compromise was made between matching the temperature data or the thermal conductivity data in the RIB. The choice was made to honor the thermal conductivity and match the temperature boundary values. In this model, the net upward flux of water vapor is a function of the geothermal gradient, the vapor diffusion coefficient, and the gas permeability of the rock mass. The downward movement of water is influenced by gravity and liquid permeability. The initial ambient liquid saturation profile is shown in Figure 5-2 and is based on a calculation using V-TOUGH in a one-dimensional mode. The variations of saturation with depth accounts for differences in the hydrologic character of each geologic unit (i.e., permeability, capillary suction, etc.). This liquid saturation profile corresponds to zero net infiltration flux.

It should be noted that recent data on liquid saturations from boreholes have not been used. Ultimately the borehole data will need to be used to determine if they indicate different infiltration fluxes and what impact this might have on the saturation profiles and heat transport in the mountain.

24 MTU/Acre

Figure 5-3 shows the temperature distribution as a function of radius and time for the 24 MTU/acre case. As predicted by the analytical heat conduction algorithm discussed in Section 3, this case does not produce bulk average temperatures that exceed boiling at any time. The average bulk peak temperature in the repository is predicted to be about 66 degrees Celsius at the center of the repository and, although not shown in this section (refer to Appendix F), 47 degrees Celsius at the edge. The saturation profile as a function of time at the repository horizon, shown in Figure 5-4, does not show any appreciable deviation from ambient conditions.

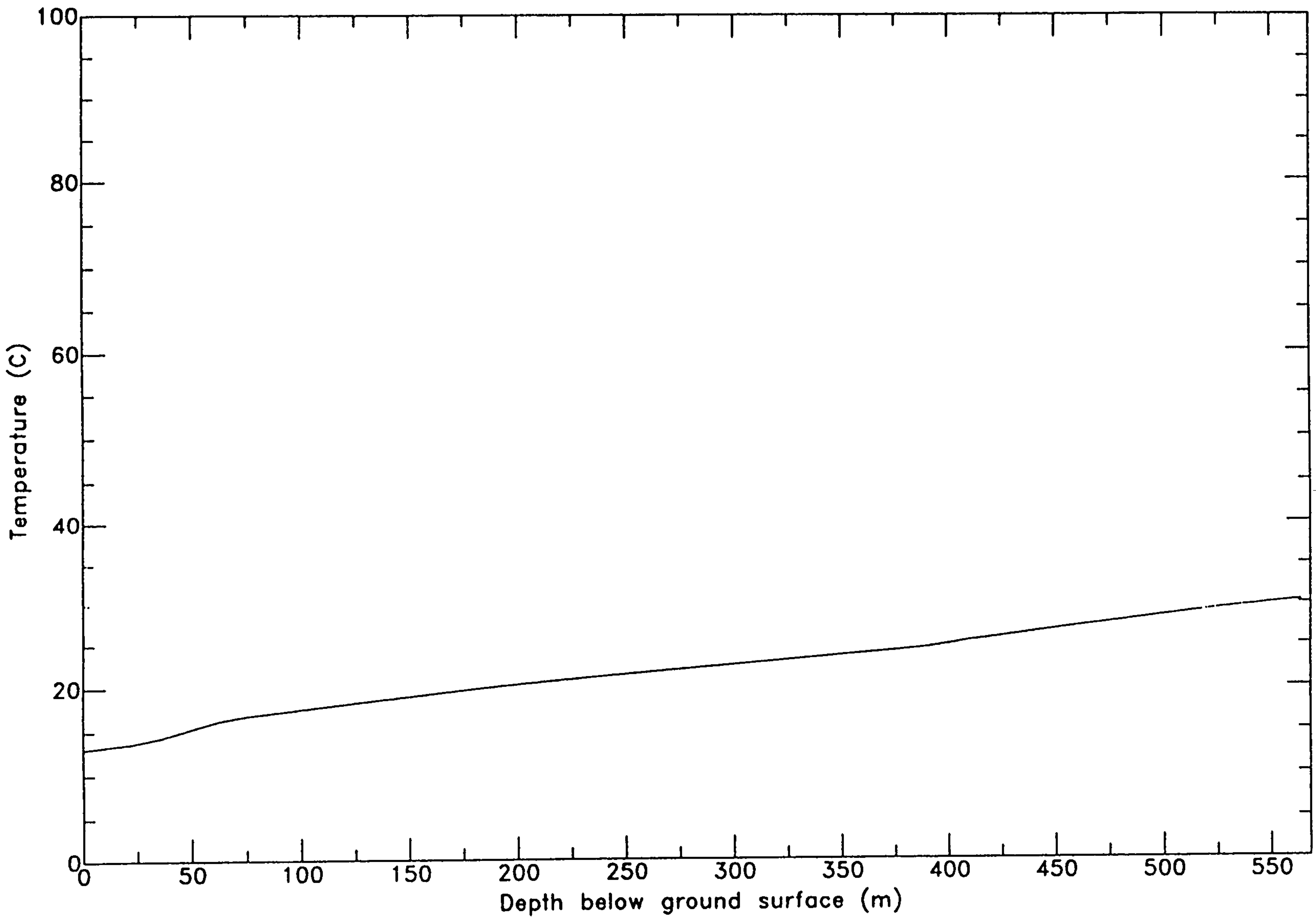


Figure 5-1. Ambient Geothermal Gradient

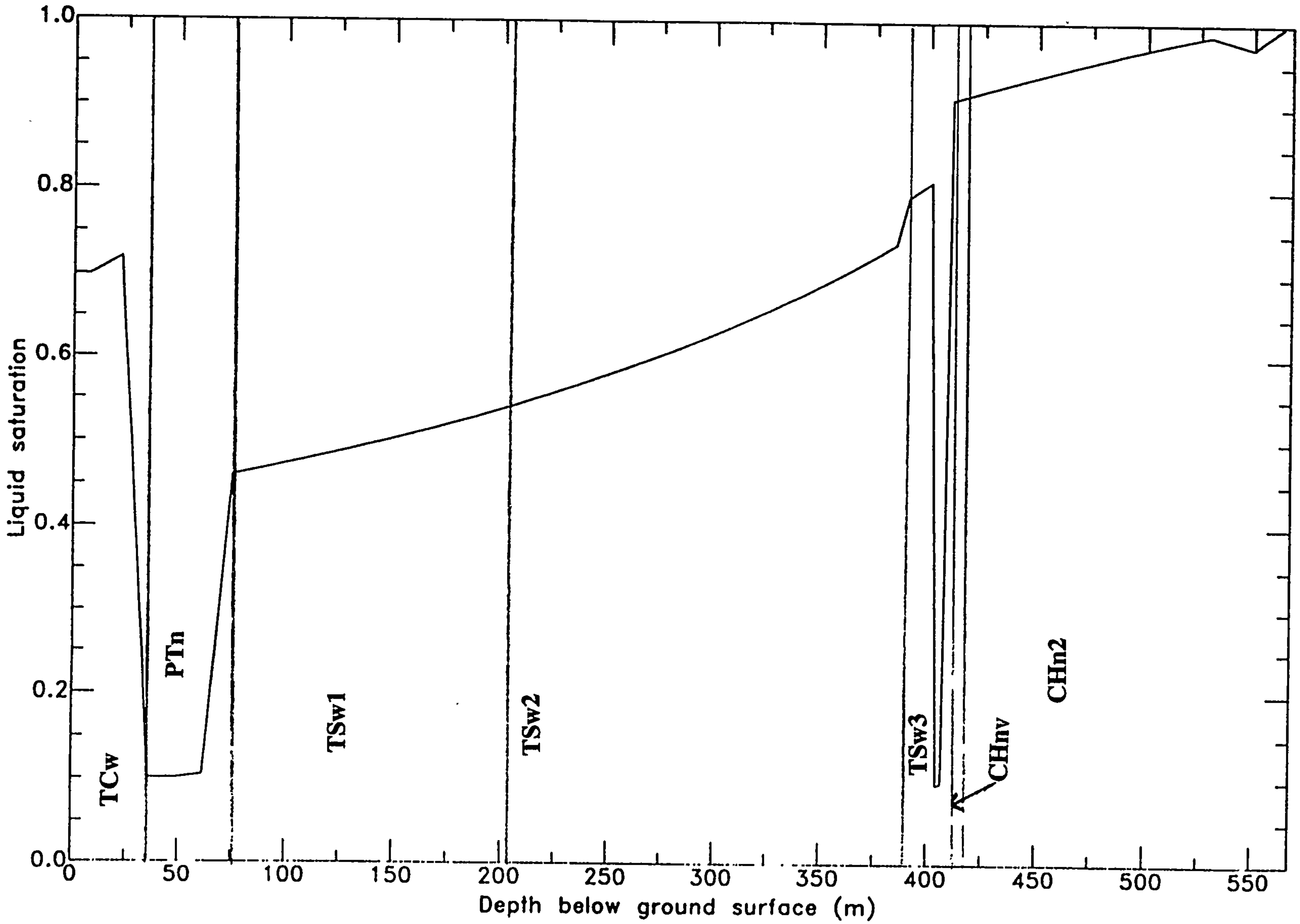


Figure 5-2. Ambient Liquid Saturation

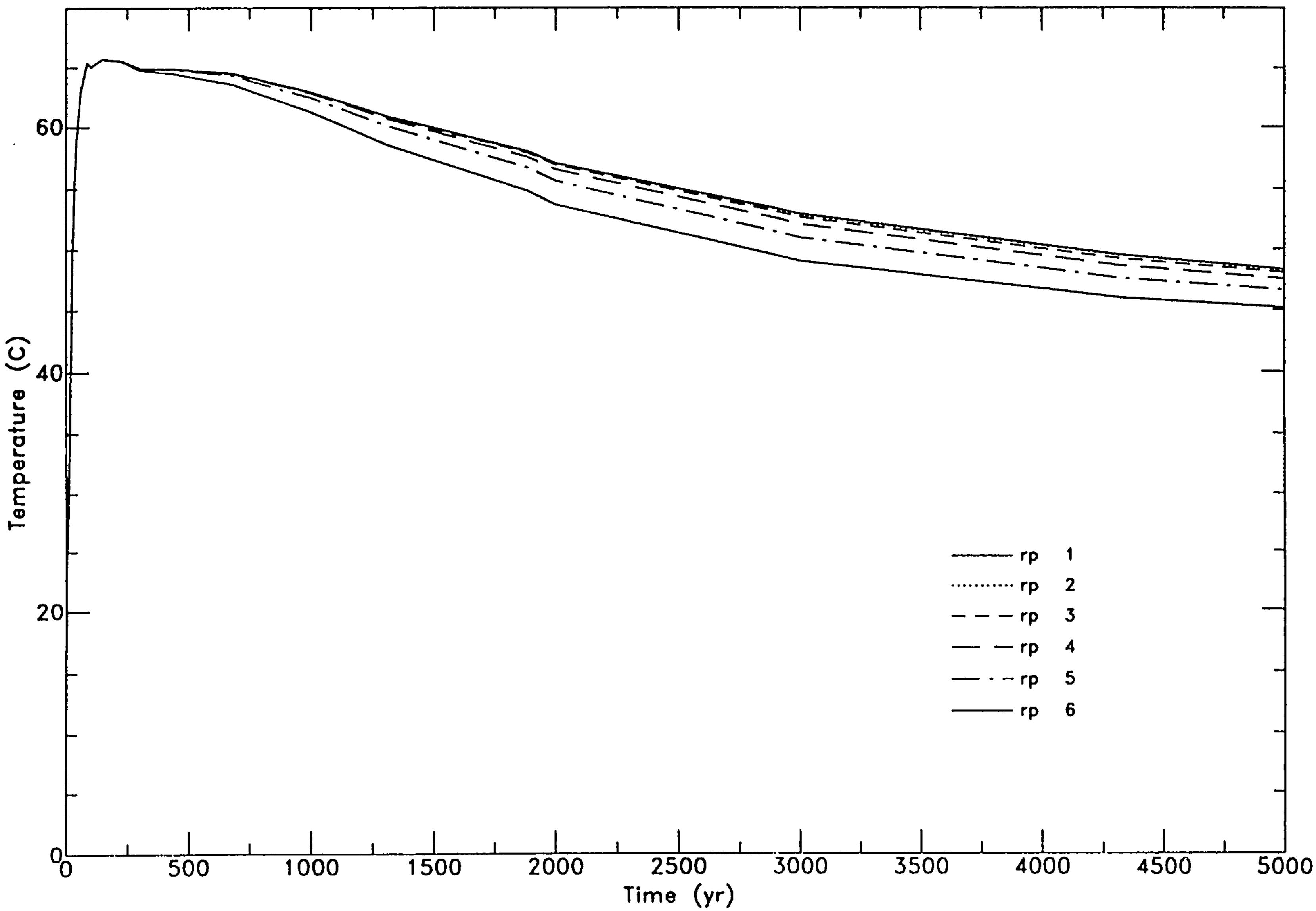


Figure 5-3. Temperature Variation with Time at the Repository for 24 MTU/Acre

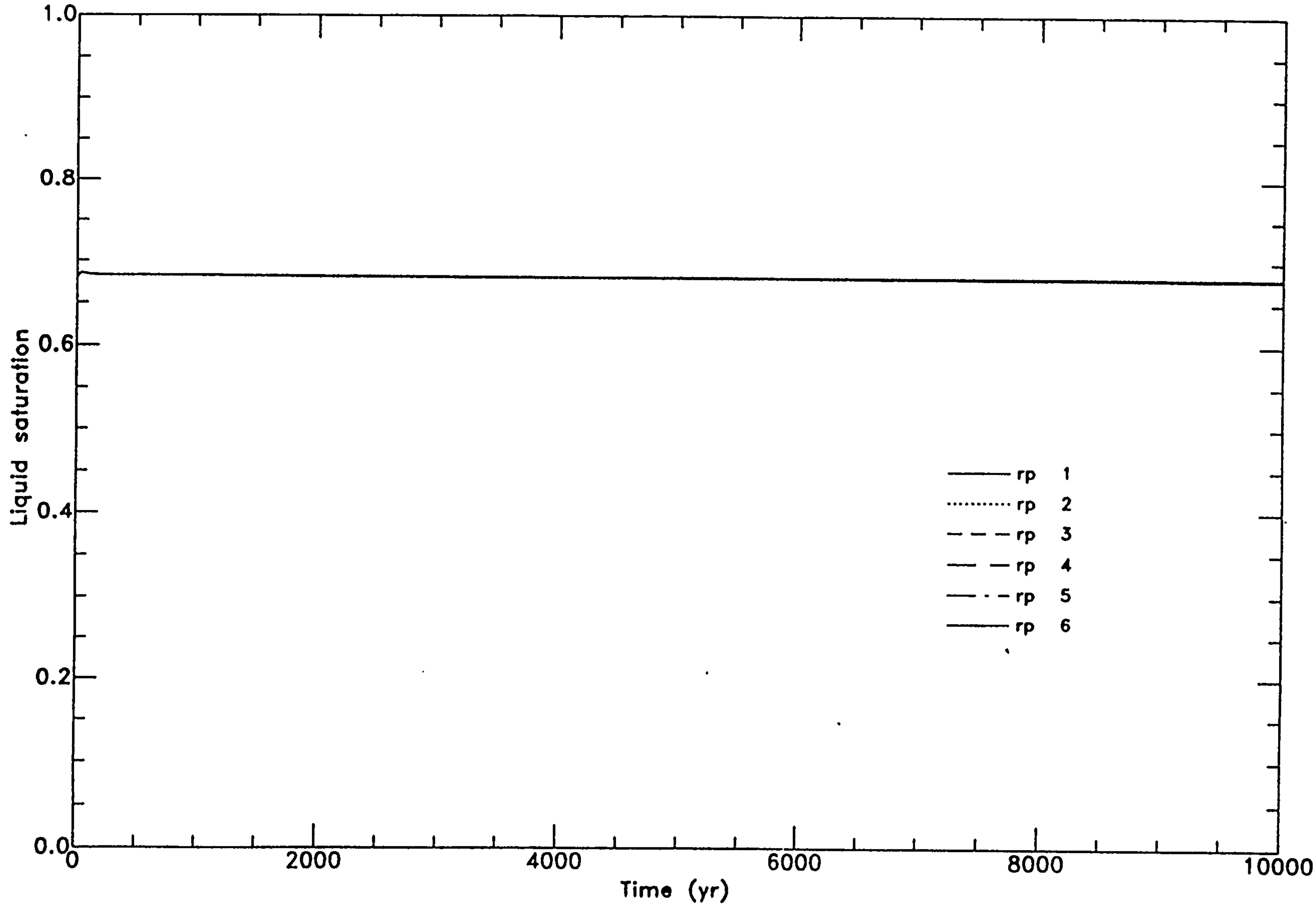


Figure 5-4. Liquid Saturation Profile Variation with Time at the Repository for 24 MTU/Acre

36 MTU/Acre

Figure 5-5 shows the temperature distribution as a function of radius and time for the 36 MTU/acre case. As predicted by the analytical heat conduction algorithm discussed in Section 3, this case also does not produce bulk average temperatures that exceed boiling at any time. The peak temperature is about 86 degrees Celsius at the center and 58 degrees Celsius at the edge. A plot of the vertical temperature profile at three locations in the repository for 5000 years is shown in Figure 5-6. The time of 5000 years was chosen, not because it represents the peak in the repository, but because it shows what the peak temperature at the top of the water table (at 568 m) is predicted to be. The results indicate that the peak at the top of the saturated zone is approximately 55 degrees Celsius at about 5000 years after emplacement, roughly 25 degrees Celsius above ambient but well below boiling.

Figure 5-7 shows the saturation profile with time at the repository horizon and, like the 24 MTU/acre case, it does not show any appreciable deviation from ambient conditions. The saturation profile with depth (not shown here but provided in Appendix F), if compared to the ambient plot, shows minimal hydrothermal perturbation of the system at any elevation.

55 MTU/Acre (Reference Case)

Figures 5-8 and 5-9 show the temperature distribution as a function of radius and time for the 55 MTU/acre case. Unlike the lower thermal loading cases, this case produces bulk average boiling conditions at the center of the repository. The peak temperature is predicted to be about 108 degrees Celsius at the center, and about 75 degrees Celsius at the edge. Bulk average boiling conditions exist at the center for approximately 2000 years, but at no time does the edge (outer 6 percent) exceed the bulk average boiling point. Figure 5-10 shows the temperature distribution with depth at 497 years. Heat pipe regions can be seen flattening the temperature profile away from the repository horizon. Although not shown in this figure this heat pipe effect is relatively short lived, disappearing between 1000 and 2000 years. The peak temperature at the top of the saturated zone (also not shown) is about 65 degrees Celsius.

The heat-pipe effect is a heat transfer mechanism of high efficiency consisting of a cyclic fluid-thermal system. Heat is transported away from a heat source by conversion to latent heat in a gas phase primarily through boiling of a liquid phase. The gas phase is driven away from the heat source by the resulting buildup in gas phase pressure and partial pressure of the vapor. A continual return flux of condensate that is necessary to replenish the liquid phase as it boils is usually provided by a capillary wick. The heat-pipe effect results in heat transfer that can dominate thermal conduction.

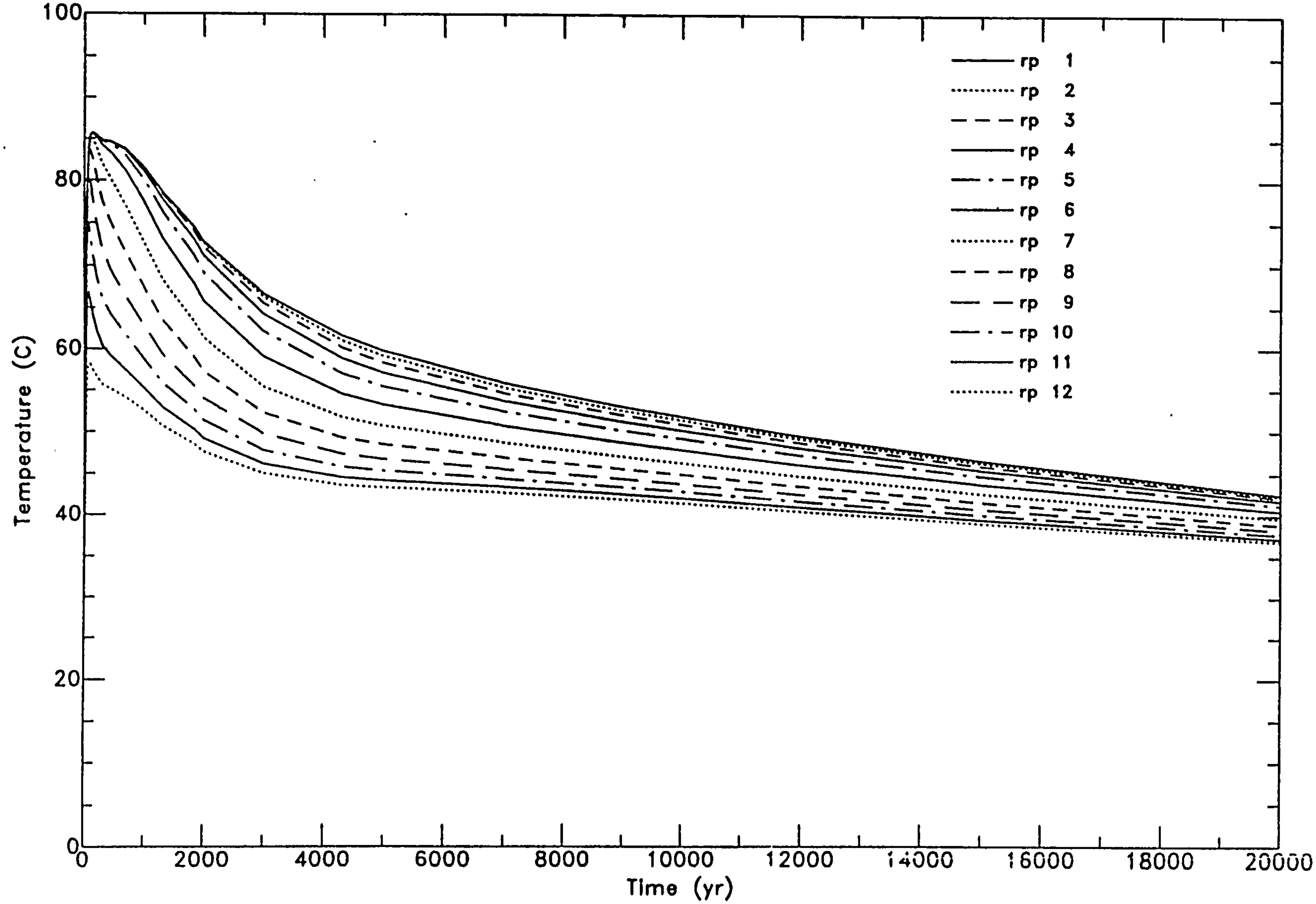


Figure 5-5. Temperature Distribution at the Repository Horizon for 36 MTU/Acre

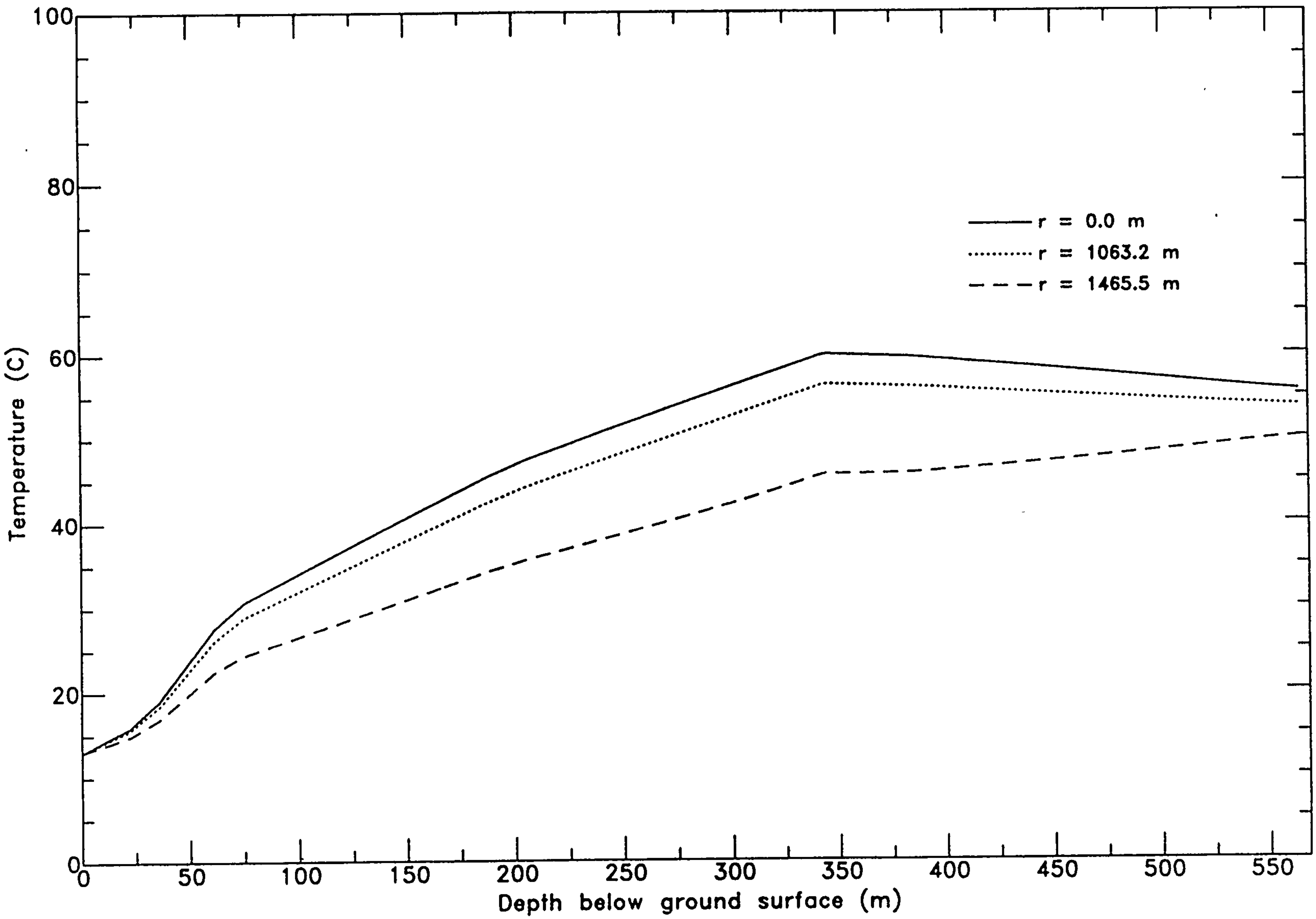


Figure 5-6. Vertical Temperature Profile at 5000 Years for 36 MTU/Acre

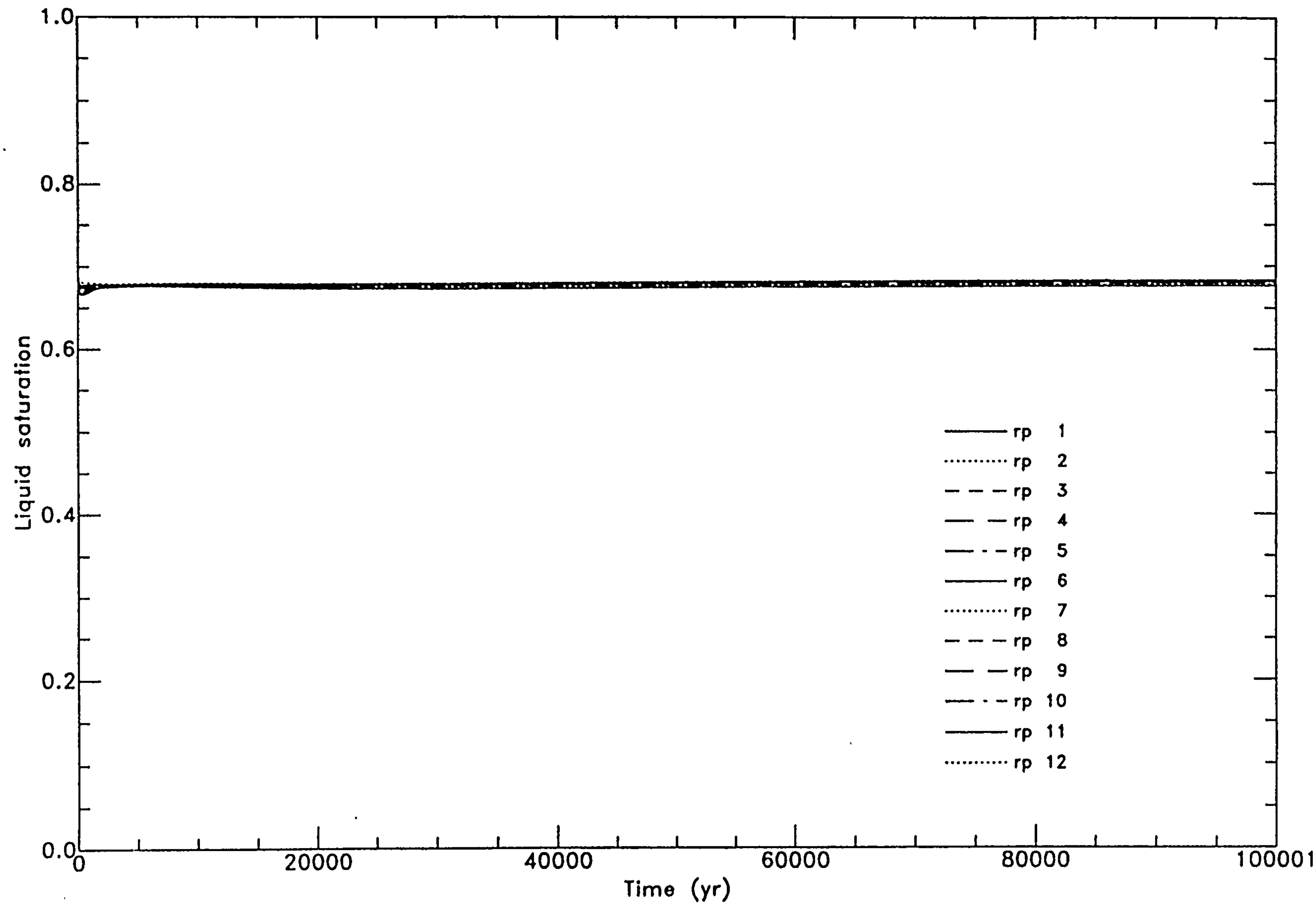


Figure 5-7. Liquid Saturation Profile Variations with Time at the Repository Horizon for 36 MTU/Acre

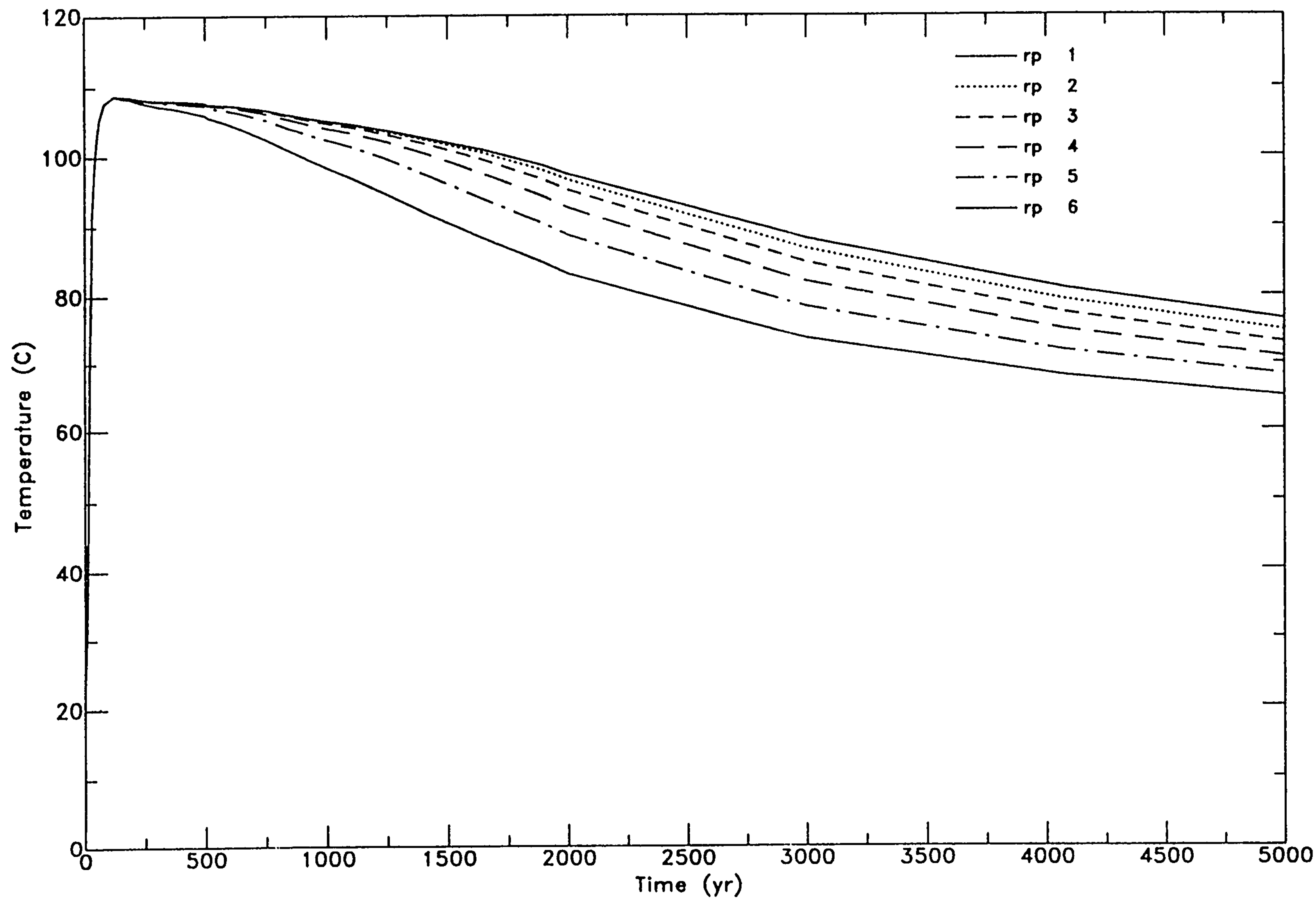


Figure 5-8. Temperature Variations with Time at the Repository Horizon for 55 MTU/Acre (Inner Zones)

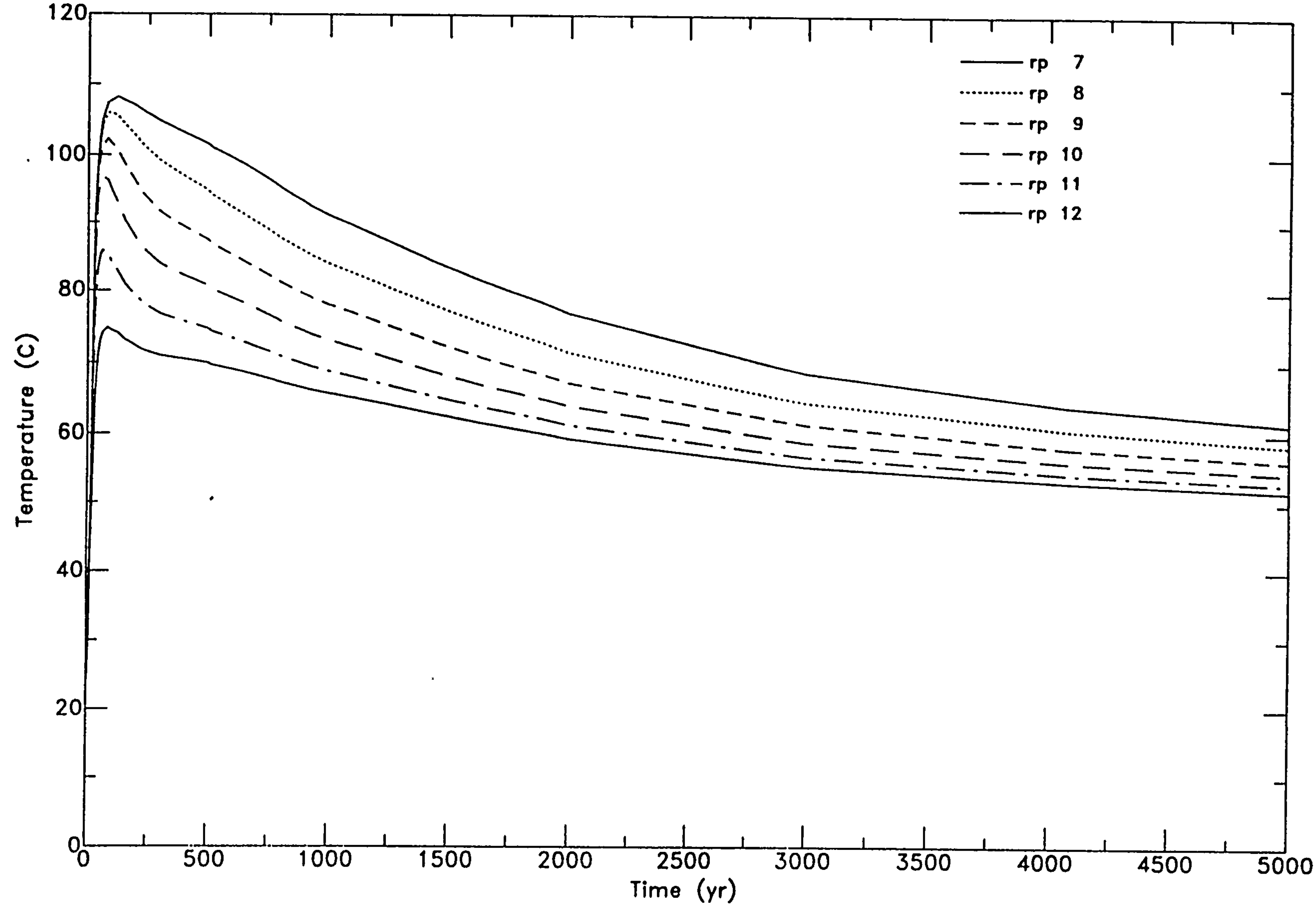


Figure 5-9. Temperature Variations with Time at the Repository Horizon for 55 MTU/Acre (Outer Zones)

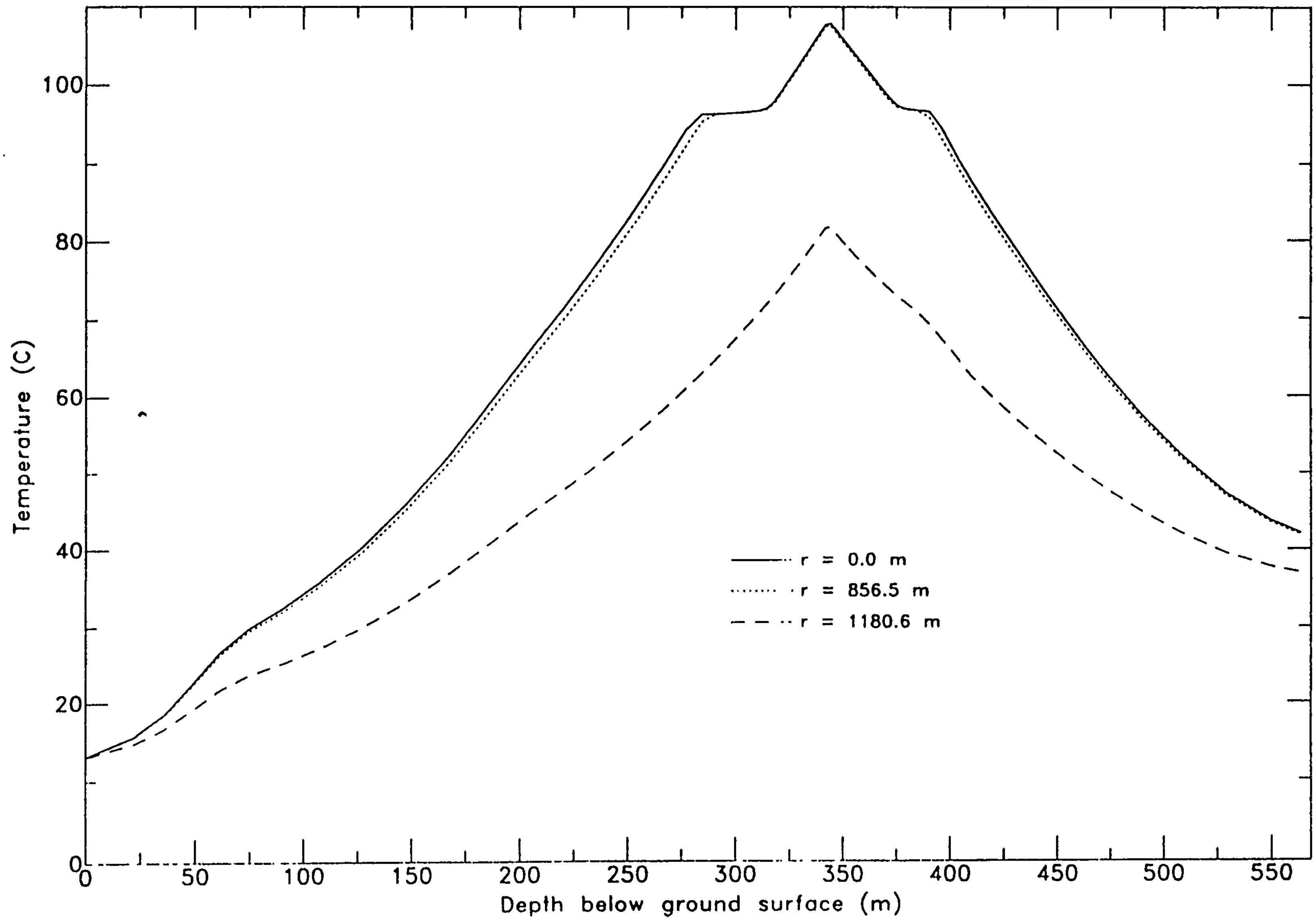


Figure 5-10. Vertical Temperature Profile with Depth at 497 Years for 55 MTU/Acre

In a repository setting, the heat-pipe effect starts when decay heat boils water in the rock matrix, causing a gas phase pressure increase which drives water vapor in the matrix towards the nearest fracture. The gas phase pressure then increases in the fractures causing advective gas phase flow in the fractures away from the heat source. Vapor is also transported away from the heat source by molecular diffusion. Molecular diffusion is driven by water vapor pressure gradients, or more precisely, by gradients in mass fraction of water vapor through Fick's law of diffusion. The movement of water vapor in the fractures continues until a region cooler than the boiling point is reached, whereupon, most of the water vapor condenses. The condensate can return towards the heat source in two separate ways: by gravity drainage in fractures and by suction gradients in the matrix. Gravity refluxing can happen, of course, only when the general direction of return flow is downwards, which occurs in the condensate refluxing zone above the repository. Matrix suction includes both capillary and surface forces. The net result is to draw liquid water from higher matrix saturation to lower matrix saturation regions, for the same matrix material. Therefore, matrix suction pulls water from the condensation region, where there is a relatively high saturation, towards the region closer to the heat source.

Figures 5-11 and 5-12 show the saturation profile with time at the repository horizon. Unlike the lower thermal loading cases, this case shows significant perturbations to the ambient conditions. The center of the repository is shown to dry to about 10 percent saturation very quickly, and begin to re-wet very gradually, returning to near ambient saturation levels after 20,000 years. Unlike the center, the edge remains at the ambient saturation level except for a very short period of insignificant drying. This illustrates the point that, for the intermediate thermal loadings where the temperatures are raised above the bulk local atmospheric boiling point of 97 degrees Celsius, this does not translate to completely dry conditions. This is explained by vapor pressure lowering due to capillary effects in unsaturated porous media. Figure 5-13 shows the saturation profile with depth at 497 years. A region of 100 percent saturation is seen above the center of the repository, some 25 meters thick, and extending radially over approximately 70 percent of the repository. This saturated region persists for roughly 1000 years, dissipating slowly over time.

A brief digression for a discussion of dry-out and rewetting is probably warranted. Rewetting behavior is influenced by the balance between drying and rewetting processes. A major consideration for rewetting is the extent to which water is driven away from the repository. Dry-out behavior is the net result of processes that drive water vapor away from the repository and the processes that cause water to return to the repository.

Processes that drive water away from the repository include:

1. Diffusive gas-phase flow of air and water vapor

2. Advective gas-phase flow driven by

   a. boiling conditions
   b. buoyant gas-phase convection

3. Advective liquid-phase flow of

   a. condensate drainage down the flanks of the dry-out zone
   b. condensate drainage below the dry-out zone.

Processes that return water to the repository include:

1. Diffusive gas-phase flow of air and water vapor

2. Advective liquid-phase flow driven by

   a. natural infiltration
   b. condensate drainage above the dry-out zone
   c. matrix imbibition, generally occurring from high to low liquid saturation.

Buoyant gas-phase convection can enhance the buildup of condensate above the dry-out zone, thereby increasing the return condensate flux above the dry-out zone. Buoyant gas-phase convection can also enhance the rate of vaporization. Gas-phase convection driven by boiling can suppress the impact of buoyant gas-phase convection.

As is evident there are many interrelated processes impacting dry-out and rewetting behavior. Because of the decaying nature of the repository heat source, there is an initial period of time during which the dry-out zone is increasing in spatial extent, followed by a much longer period during which rewetting processes dominate dry-out, causing the dry-out zone to rewet back to ambient conditions. Dry-out and rewetting behavior varies substantially between the center and edge of the repository. The degree of dry-out and the speed of rewetting depends on various assumptions including fracture size, density, and connectivity, matrix imbibition, and other things. A sensitivity study will be conducted in future studies to examine some of these issues.

83 MTU/Acre

The 83 MTU/acre case behaves qualitatively very similar to the reference case. Figure 5-14 shows bulk boiling at the center of the repository which lasts approximately 5000 years with a peak temperature of about 145 degrees Celsius. The edge, however, just reaches the bulk boiling point, falling below boiling at very early times. The temperature profile with depth shown at 451 years in Figure 5-15 shows heat pipe regions extending further from the repository than the reference case and persisting for longer times. The peak temperature at the top of the saturated zone is approximately 75 degrees Celsius.

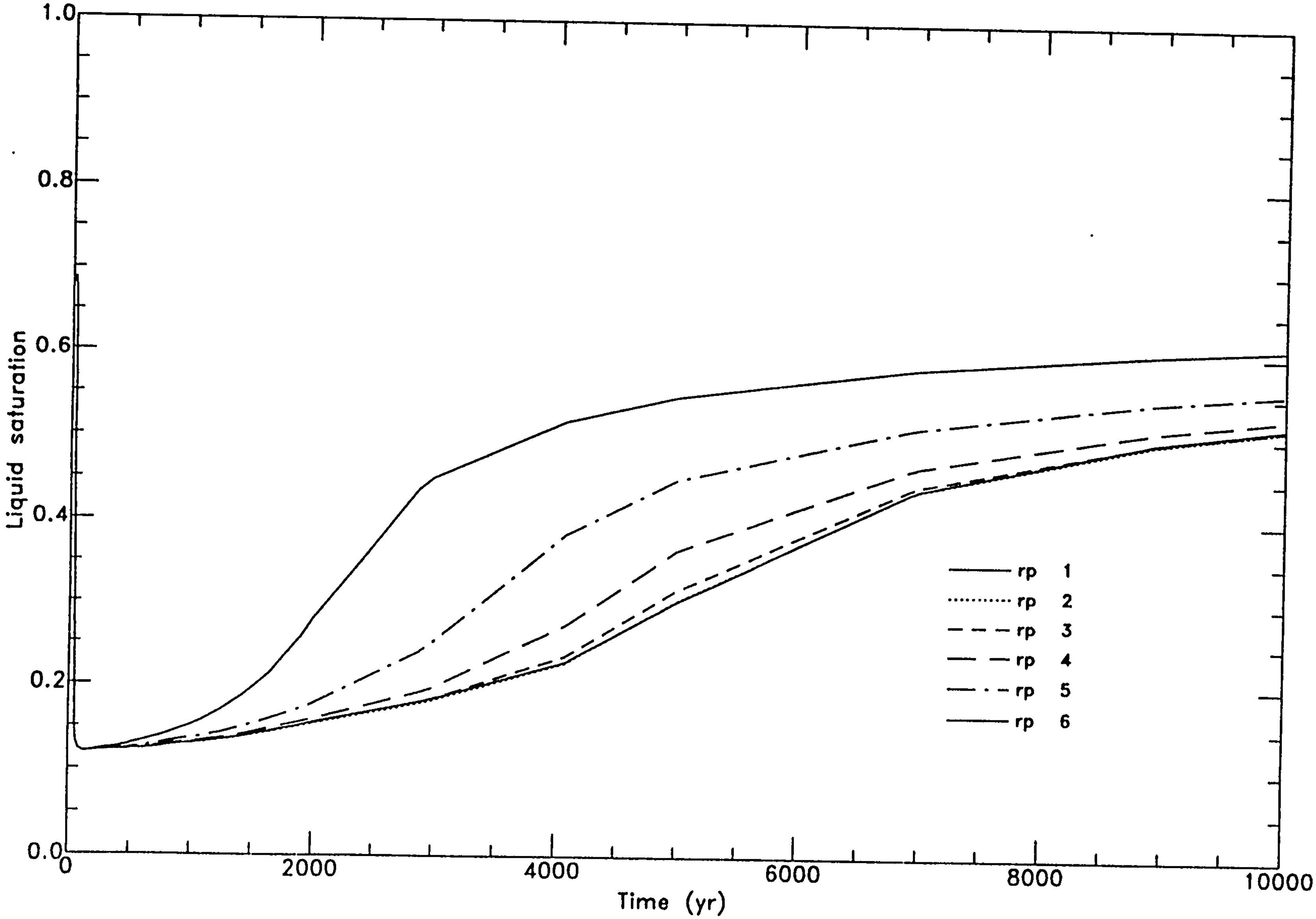


Figure 5-11. Saturation Profile at the Repository Horizon for 55 MTU/Acre (Inner Zones)

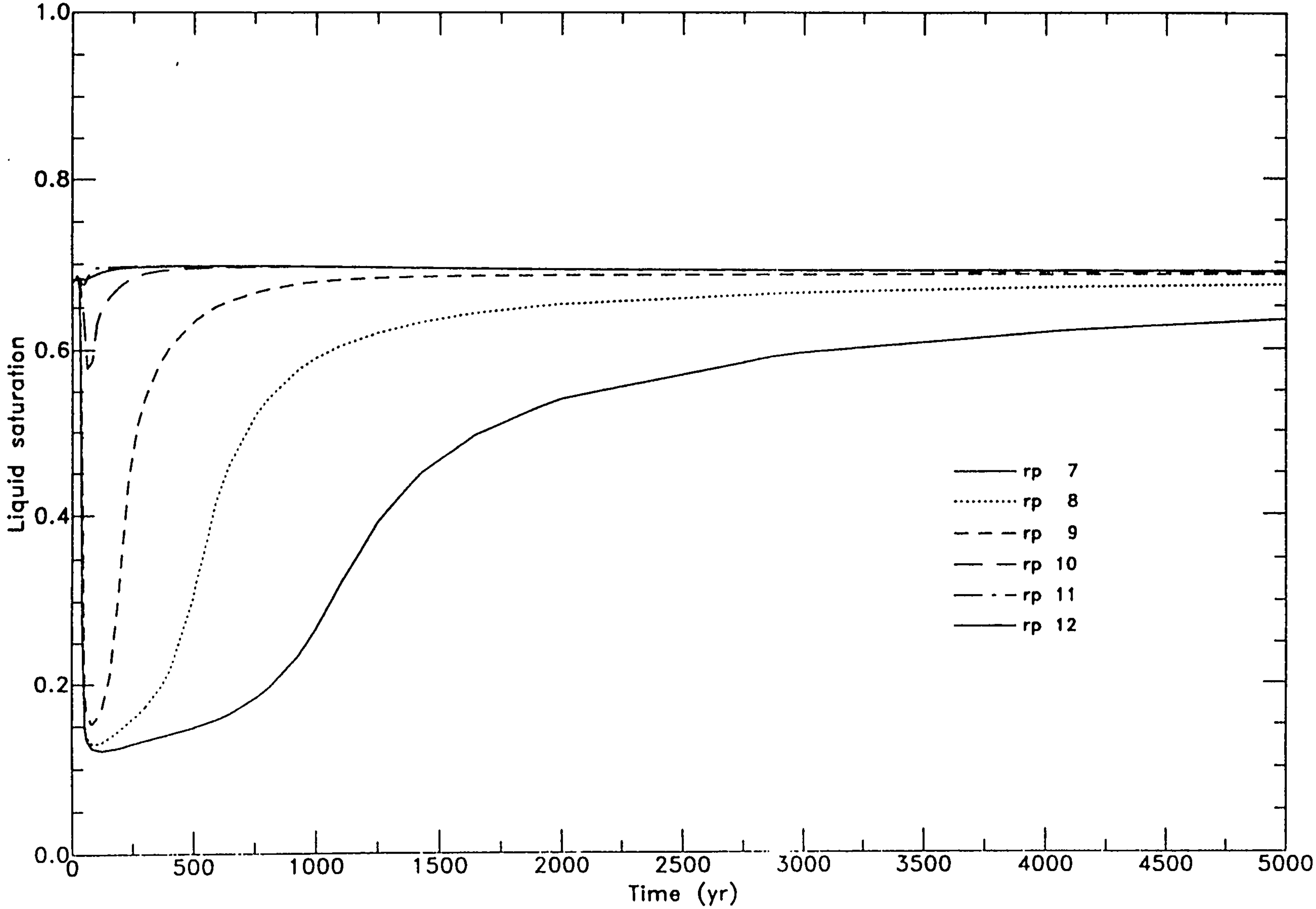


Figure 5-12. Saturation Profile at the Repository Horizon for 55 MTU/Acre (Outer Zones)

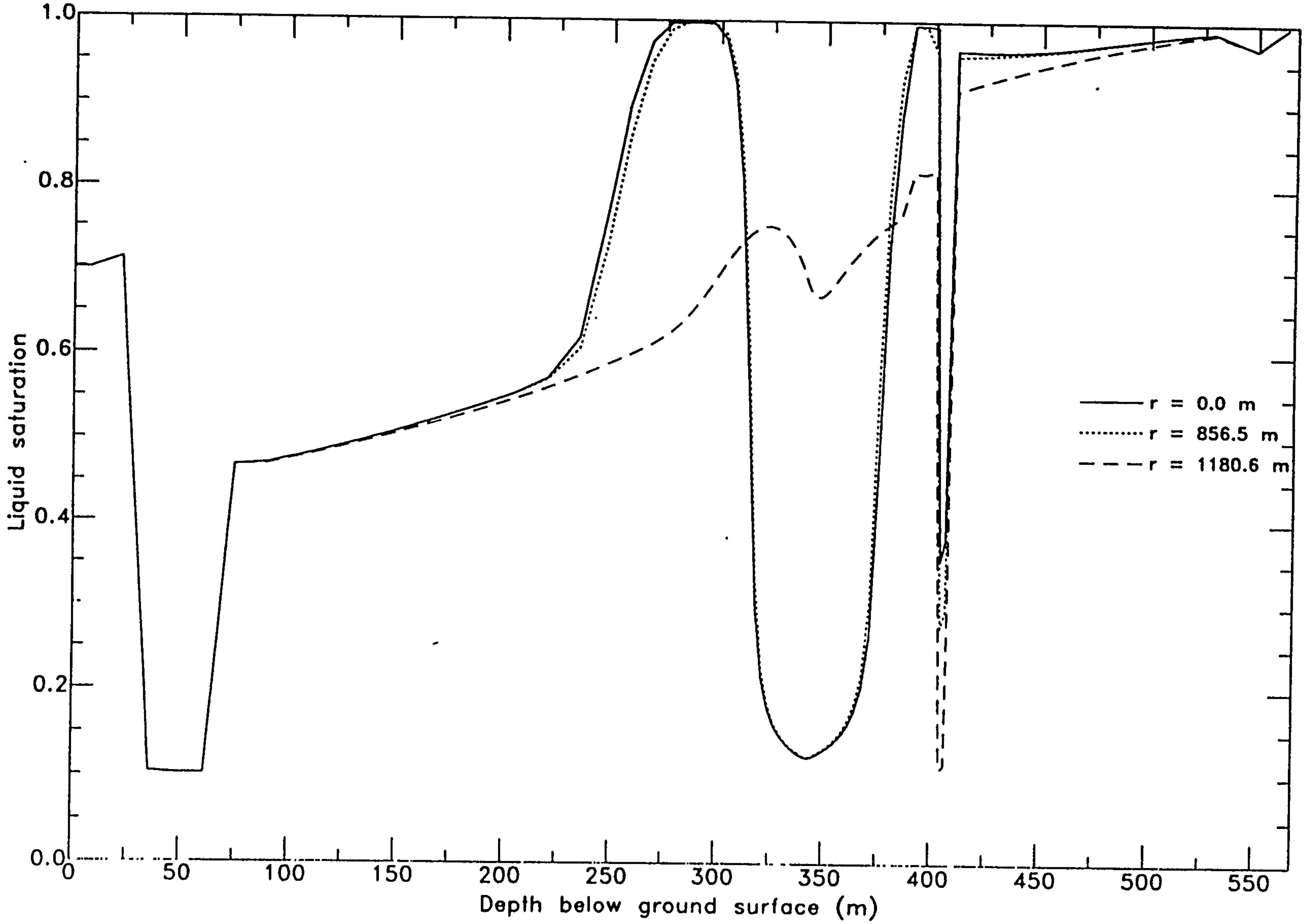


Figure 5-13. Vertical Saturation Profile at 497 Years for 55 MTU/Acre

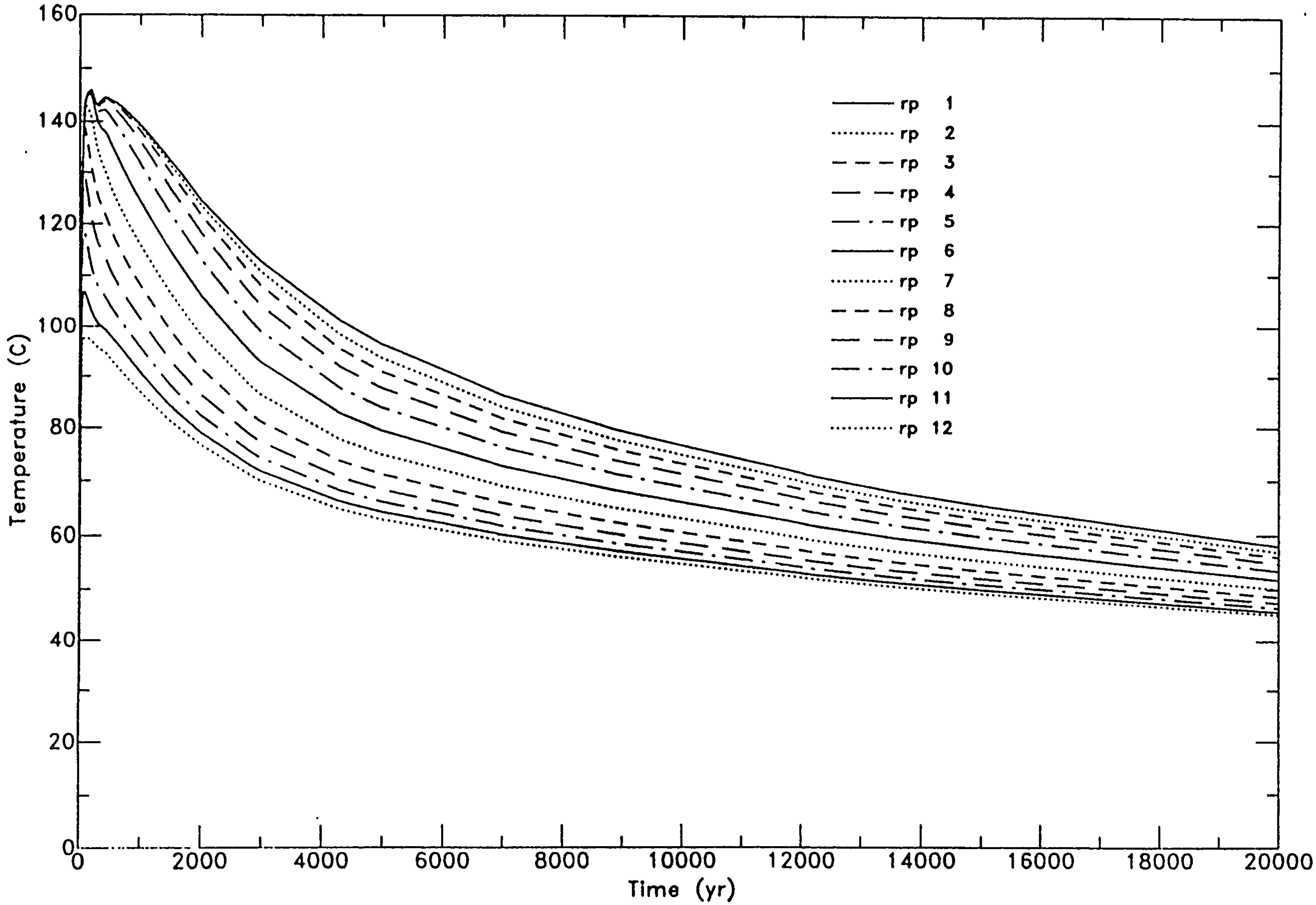


Figure 5-14. Temperature Variations with Time at the Repository Horizon for 83 MTU/Acre

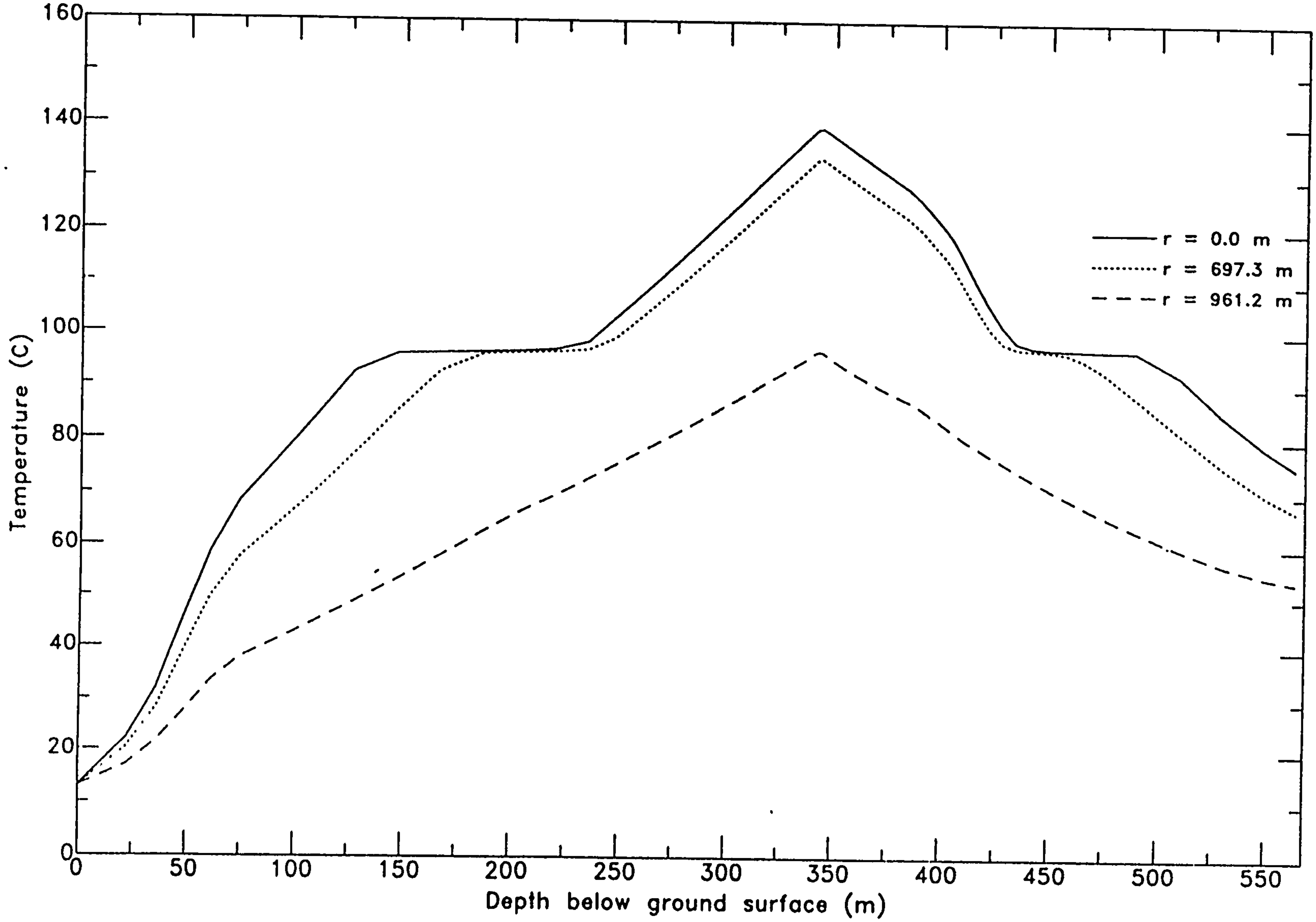


Figure 5-15. Vertical Temperature Profile with Depth at 1000 Years for 83 MTU/Acre

The saturation profile with time at the repository horizon is shown in Figure 5-16. The center of the repository dries rapidly to near zero percent liquid saturation, re-wetting gradually and returning to near ambient conditions after 100,000 years. However, the edge dries for only a short period of time, re-wetting very rapidly to a level that the model indicates may be minimally greater than the ambient saturation. The saturation profile with depth at 1000 years, Figure 5-17, shows behavior similar to the reference case. The region of 100 percent saturation above the repository is somewhat thicker in vertical extent, persists somewhat longer, and extends radially over a larger distance with a pronounced vertical tilt. In addition, perturbations below the repository are now evident, with the region of 100 percent saturation rising nearly 100 m toward the repository at the center.

111 MTU/Acre

The highest thermal loading considered in the study was 111 MTU/acre. The predicted bulk average temperatures at the repository horizon exceed the boiling point for significant periods of time over the entire radial dimension of the repository as shown in Figures 5-18 and 5-19. The peak temperature at the center of the repository of about 185 degrees Celsius is reached very rapidly, and the center remains above boiling for almost 8000 years. However, significant portions of the repository drop below boiling earlier than this. The edge bulk temperature is 30 to 40 degrees Celsius cooler than the center at early times, dropping below boiling in less than 2000 years. The predicted vertical temperature profiles evidenced by Figure 5-20 at 1000 years show the formation of large heat pipes which tend to propagate heat effectively both to higher and lower levels for periods in excess of 1000 years. At 1000 years, above boiling or boiling conditions extend essentially from the water table to about 80 m from the surface. Additionally, as shown on the figure, the thermal goals (see Table 2-1) to keep the temperature at the top of the Calico Hills member (CHn) and the top of the Topopah vitrophyre layer below 115 degrees Celsius are violated. These two thermal goals are not met for periods of time between about 400 to 4000 years. The comparison with thermal goals is discussed in more detail in Section 5.6.

As expected from lower thermal loadings, the liquid saturation profiles are altered significantly. Figures 5-21 and 5-22 show the center of the repository drying rapidly to essentially zero percent liquid saturation and remaining there for almost 3000 years. Significant (less than about 10 percent saturation) dry-out is predicted to persist in excess of 10,000 years, and re-wetting proceeds very gradually with near ambient conditions reached in 100,000 years. The edge dries to about ten percent liquid saturation or less, however re-wetting proceeds more rapidly than at the center. The outer edge returns to near ambient saturation in less than 2000 years, with a slow, steady increase in saturation that places the edge slightly above ambient levels for very long periods of time. The liquid saturation profile with depth at 1000 years is presented in Figure 5-23. This shows a vertical zone above the repository of condensation buildup with a vertical extent of 120 to 150 m where the matrix is nearly fully saturated. In some areas, the top of the condensation zone lies just beneath the Paintbrush tuff (depending somewhat on time and radial distance from the repository center). Beneath the repository, starting about 65 m below (depending somewhat on time and radial distance from the repository center), the model shows an increased zone of condensation buildup in the CHn layer extending to the water table. This case also shows a significant tilt in the

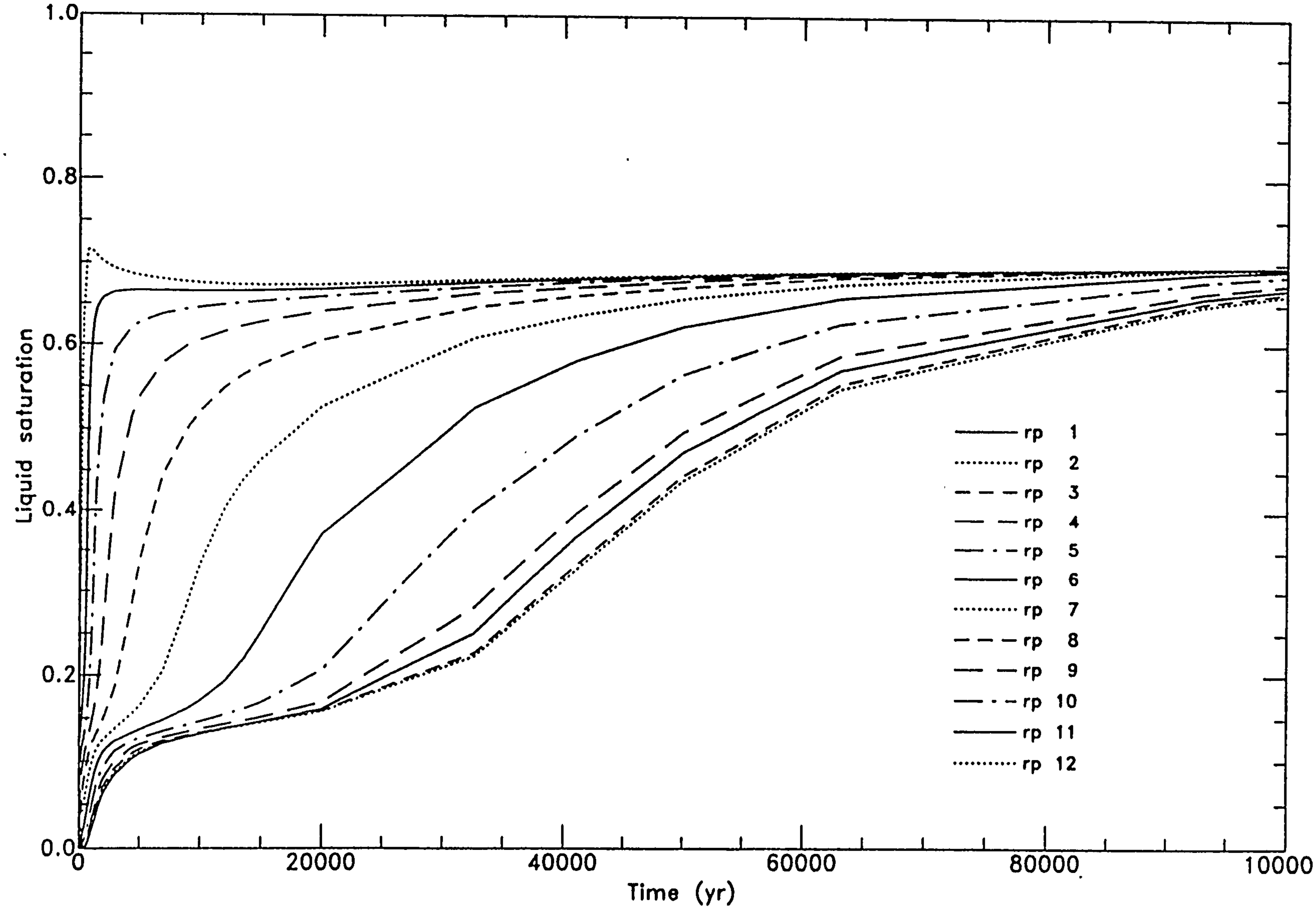


Figure 5-16. Saturation Profile at the Repository Horizon for 83 MTU/Acre

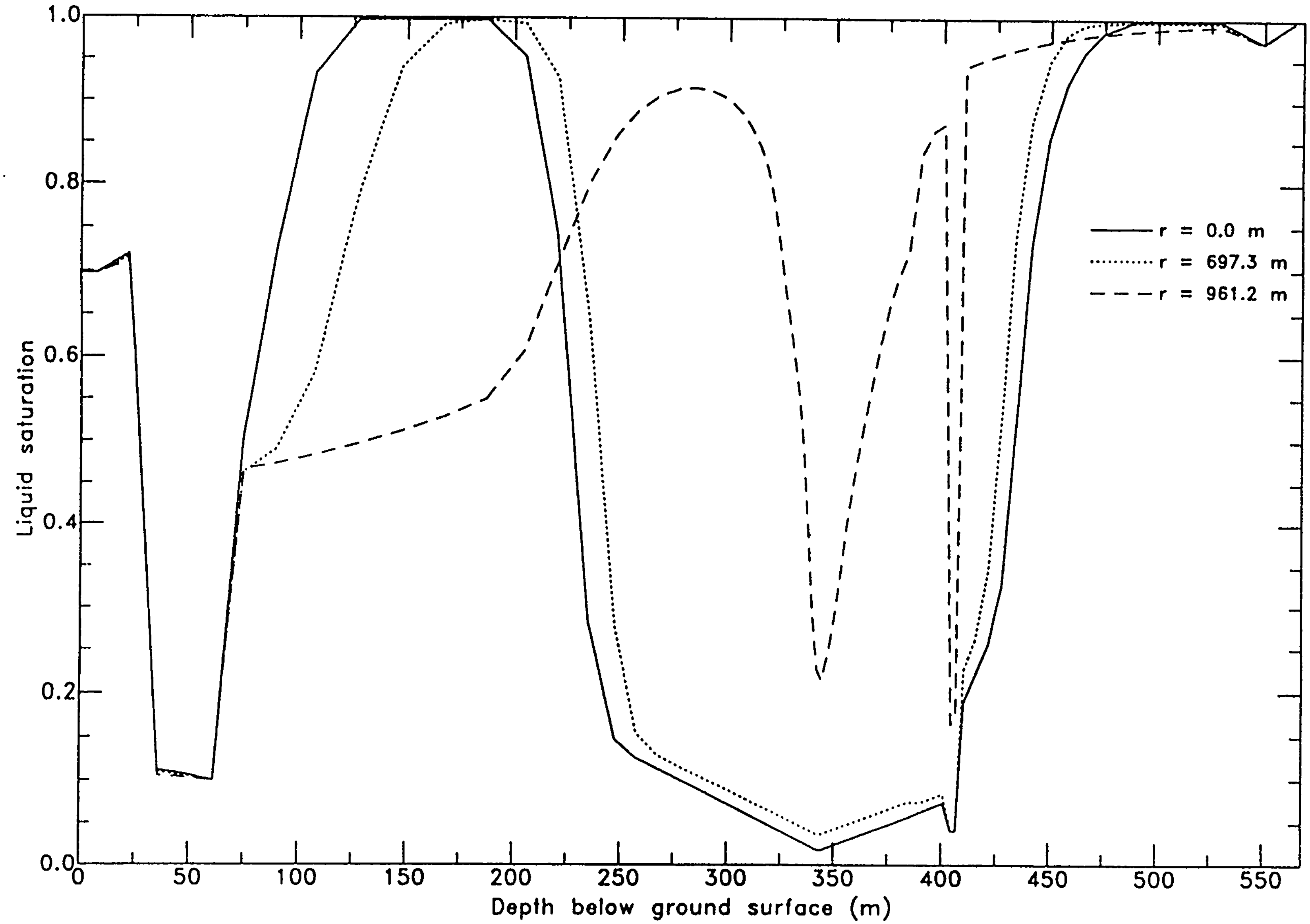


Figure 5-17. Vertical Saturation Profile at 1000 Years for 83 MTU/Acre

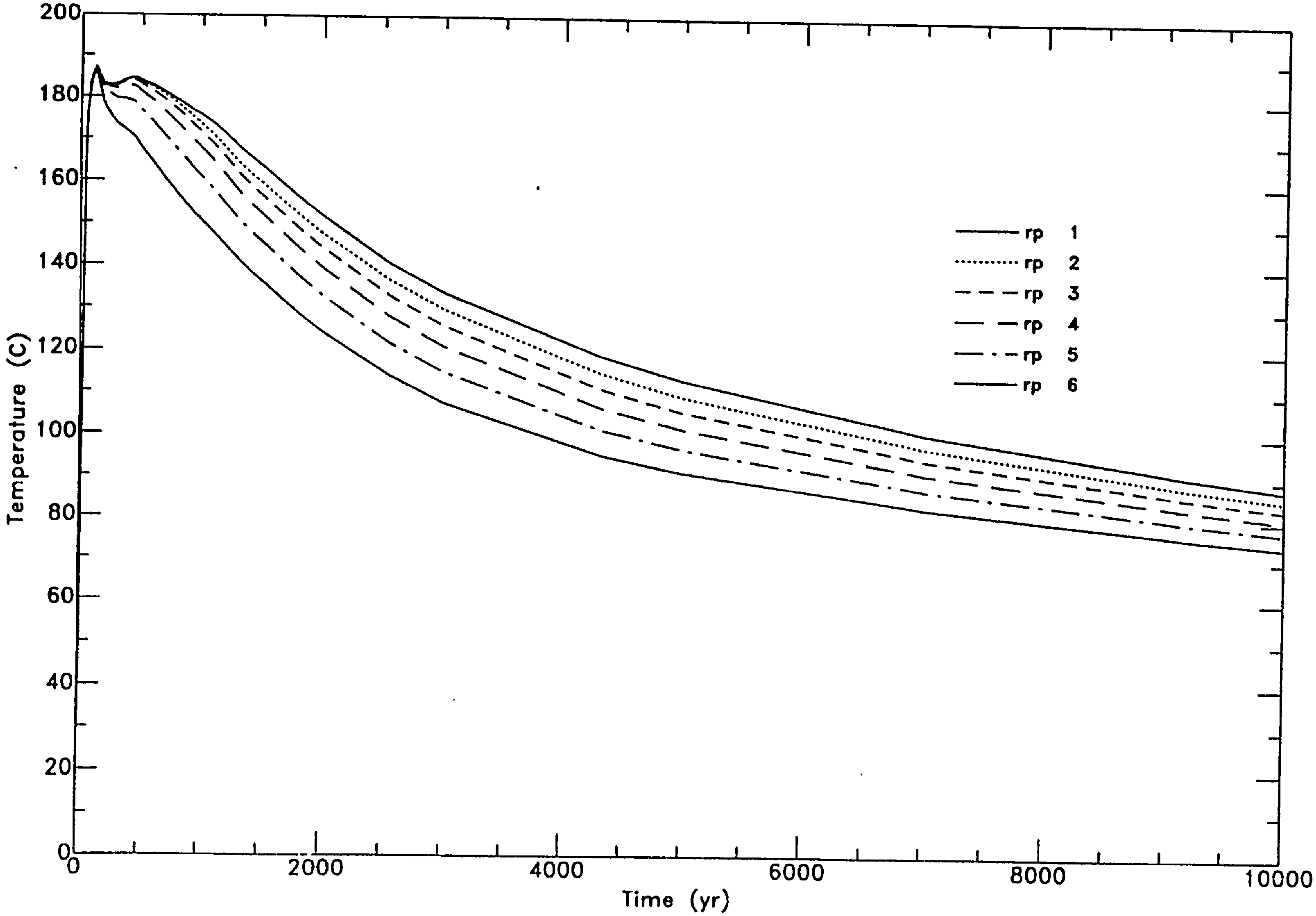


Figure 5-18. Temperature Variations with Time at the Repository Horizon for 111 MTU/Acre (Inner Zones)

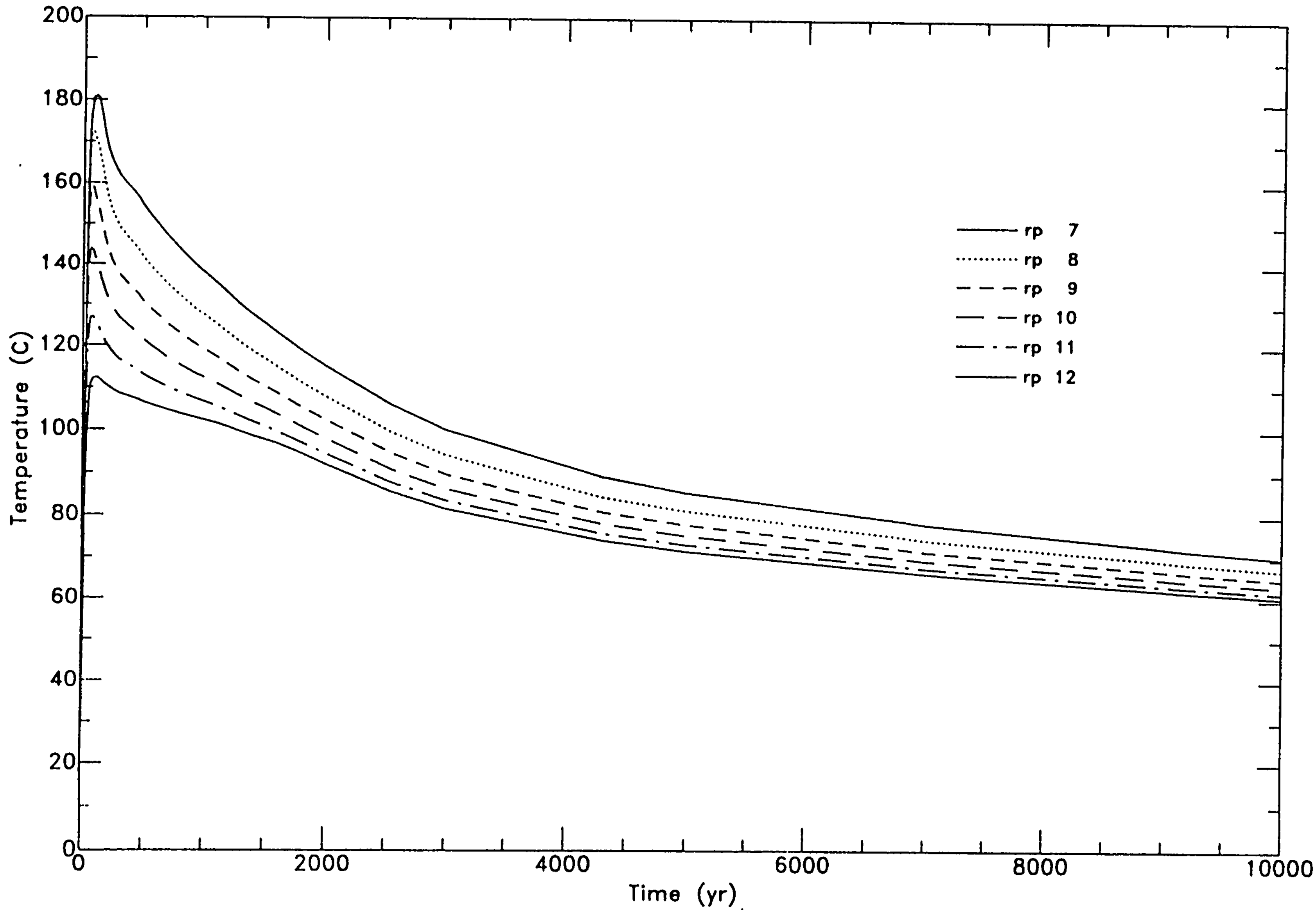


Figure 5-19. Temperature Variations with Time at the Repository Horizon for 111 MTU/Acre (Outer Zones)

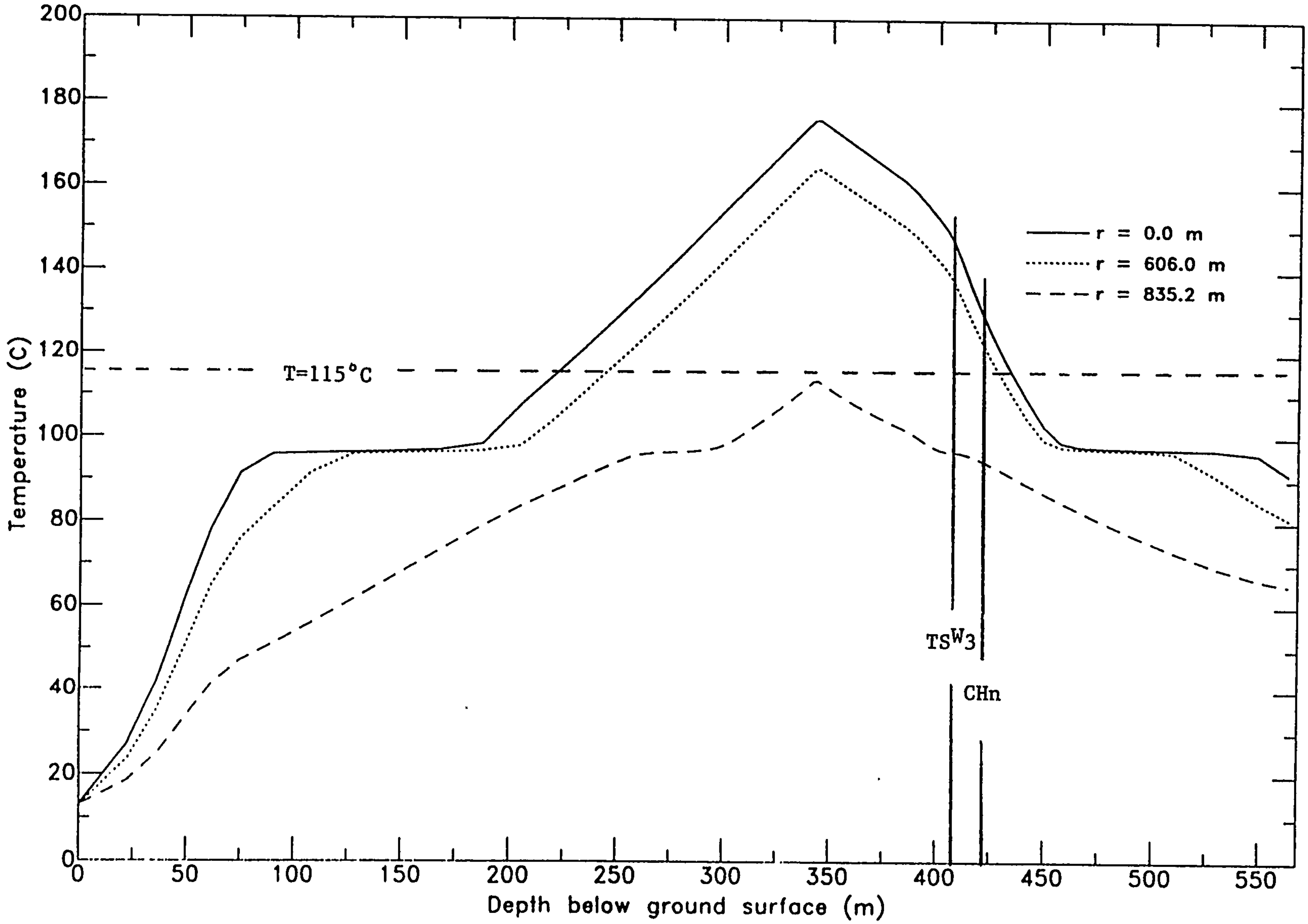


Figure 5-20. Vertical Temperature Profiles with Depth at 1000 Years for 111 MTU/Acre

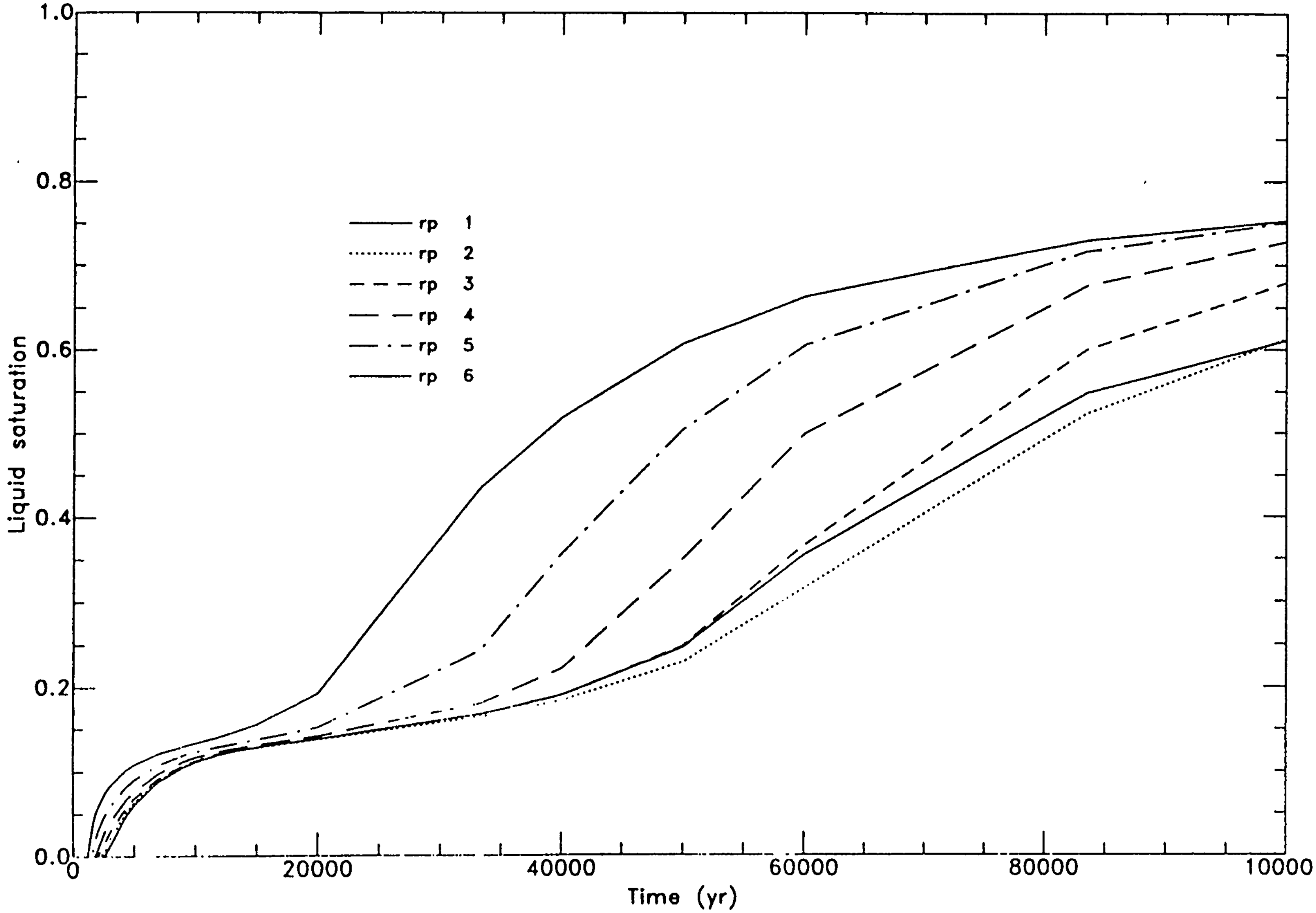


Figure 5-21. Saturation Profile at the Repository Horizon for 111 MTU/Acre (Inner Zones)

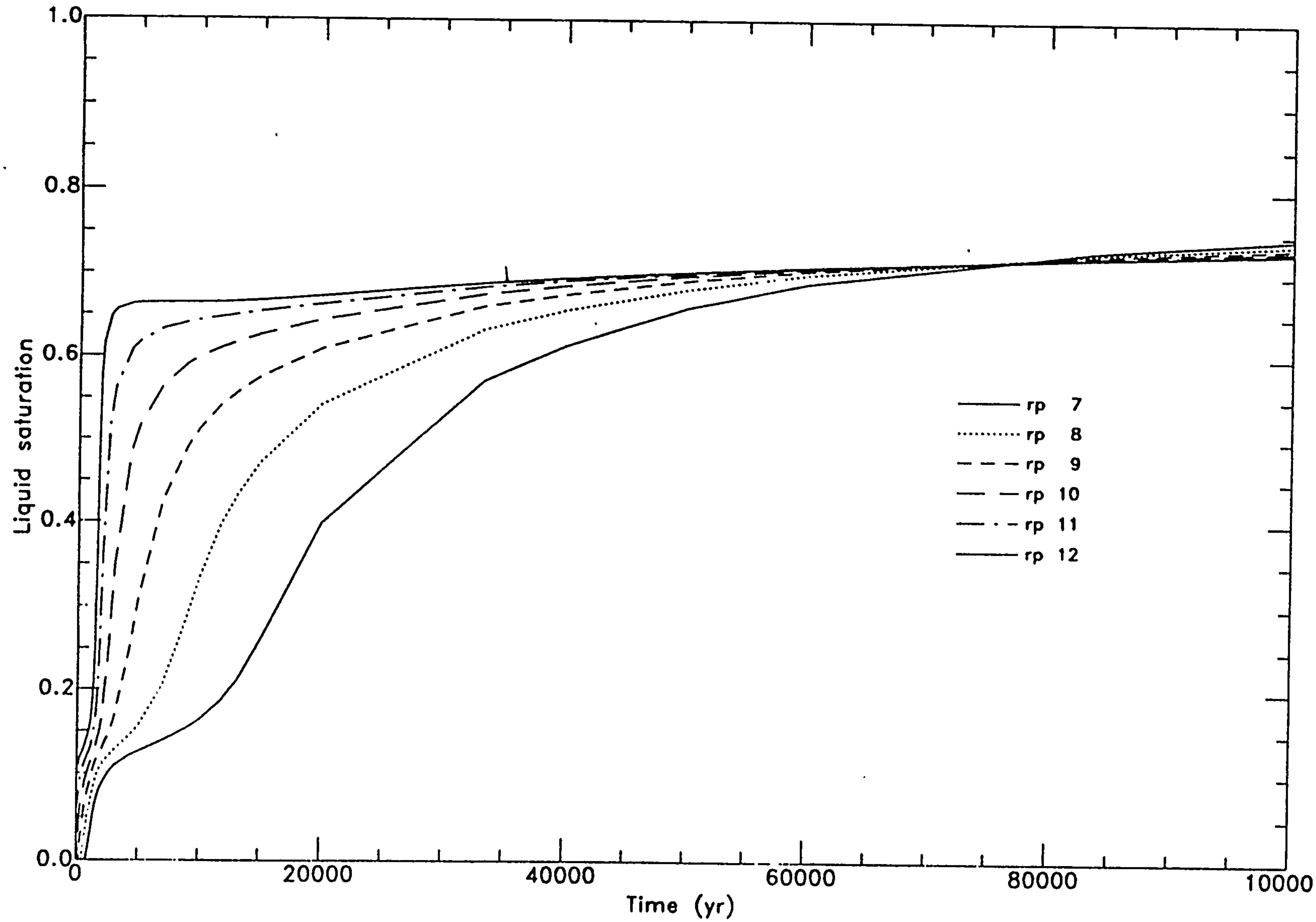


Figure 5-22. Saturation Profile at the Repository Horizon for 111 MTU/Acre (Outer Zones)

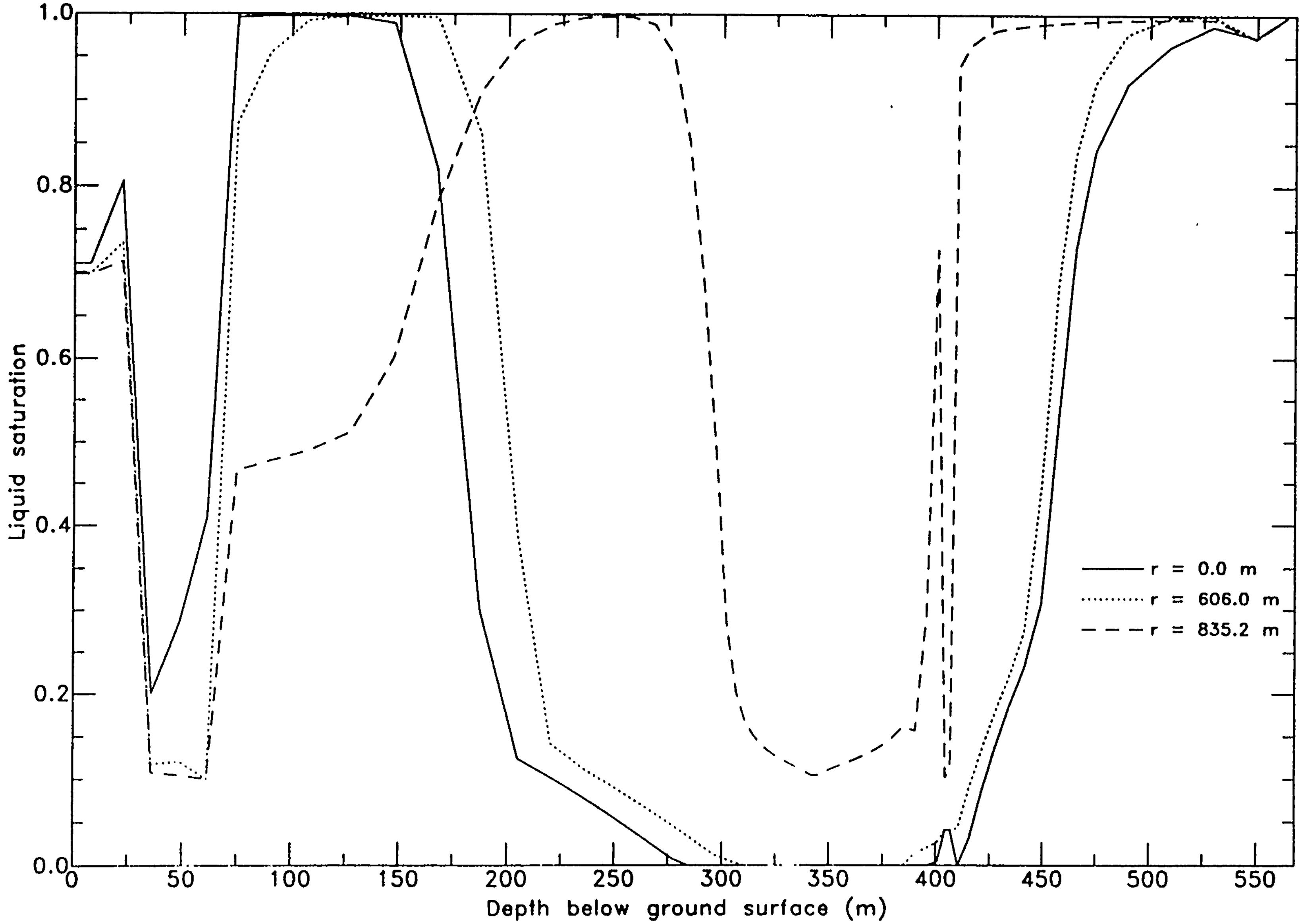


Figure 5-23. Vertical Saturation Profile at 1000 Years for 111 MTU/Acre

saturated layer above the repository with the center as much as 200 meters higher than the edge. The analysis predicts, for this case, that thermally driven vapor fluxes are responsible for a large-scale redistribution of fluid, resulting in a net increase in the amount of liquid water above the repository. This can be confirmed by examining the liquid saturation profiles at 100,000 years as shown in Figure 5-24 and comparing them with the ambient profiles in Figure 5-2. The results indicate, for this case, that the liquid saturation levels above the middle and edge of the repository may increase 5 to 40 percent above the ambient level.

Comparison of Thermal Loadings

Figures 5-3 through 5-24 show a trend of increasing hydrothermal perturbations with increasing thermal loadings. The cases at 24 and 36 MTU/acre show minimal changes from ambient bulk hydrological conditions. Large perturbations are evident at and above the reference case loading with saturated regions forming above the repository. The highest thermal loading of 111 MTU/acre shows significant drying, especially in the near vicinity of the center of the repository.

Water movement and the uncertainty in determining the amount of water movement are important issues in selecting a thermal strategy. The same amount of heat is put into the mountain regardless of thermal load. The heat is just spread over a larger area for the lower thermal load. The amount of water moved by this heat depends on a number of factors including the bulk permeability. The higher the permeability, the easier it is to move the water. A permeability of 280 milliDarcys was used for the majority of the calculations since this is considered at the time of the study by various modeling experts to be a likely value for the bulk average at the repository horizon. However, there is uncertainty in this value; it could be higher or lower on the average and locally some areas of rock could be significantly different. As discussed earlier, air permeability measurements in TSw2 and reported by Wilson, et al. (1994) show bulk permeabilities in the range from 0.1 to 10 Darcy. Thus LLNL, as presented in Appendix F, performed calculations over a much larger range of bulk permeabilities to evaluate some of the sensitivities for hydrothermal response. The calculations were found to have implications on bulk water movement; these are discussed below.

Estimates of liquid flux through the repository are needed to evaluate performance. However, at this time the only estimates provided by LLNL were total volume of liquid moved above the repository. From this an estimate of equivalent column of liquid above the repository was used as a better representation of the flux than would be afforded by the total volume. The LLNL calculations of total volume of water moved above the repository at each AML for each bulk permeability (see Appendix F) were divided by the area over which the heat is distributed (e.g. potential repository area) to determine the equivalent height of the column of water that must be supported by vapor pressure above the potential repository. This volume of water per unit area also gives a measure of the additional amount of water (excluding episodic flow or linkages with perched water) available to contact a waste package upon cooldown. Figure 5-25 shows a plot of the calculated equivalent column height of water as a function of AML for each permeability considered. This plot was done at the time when the

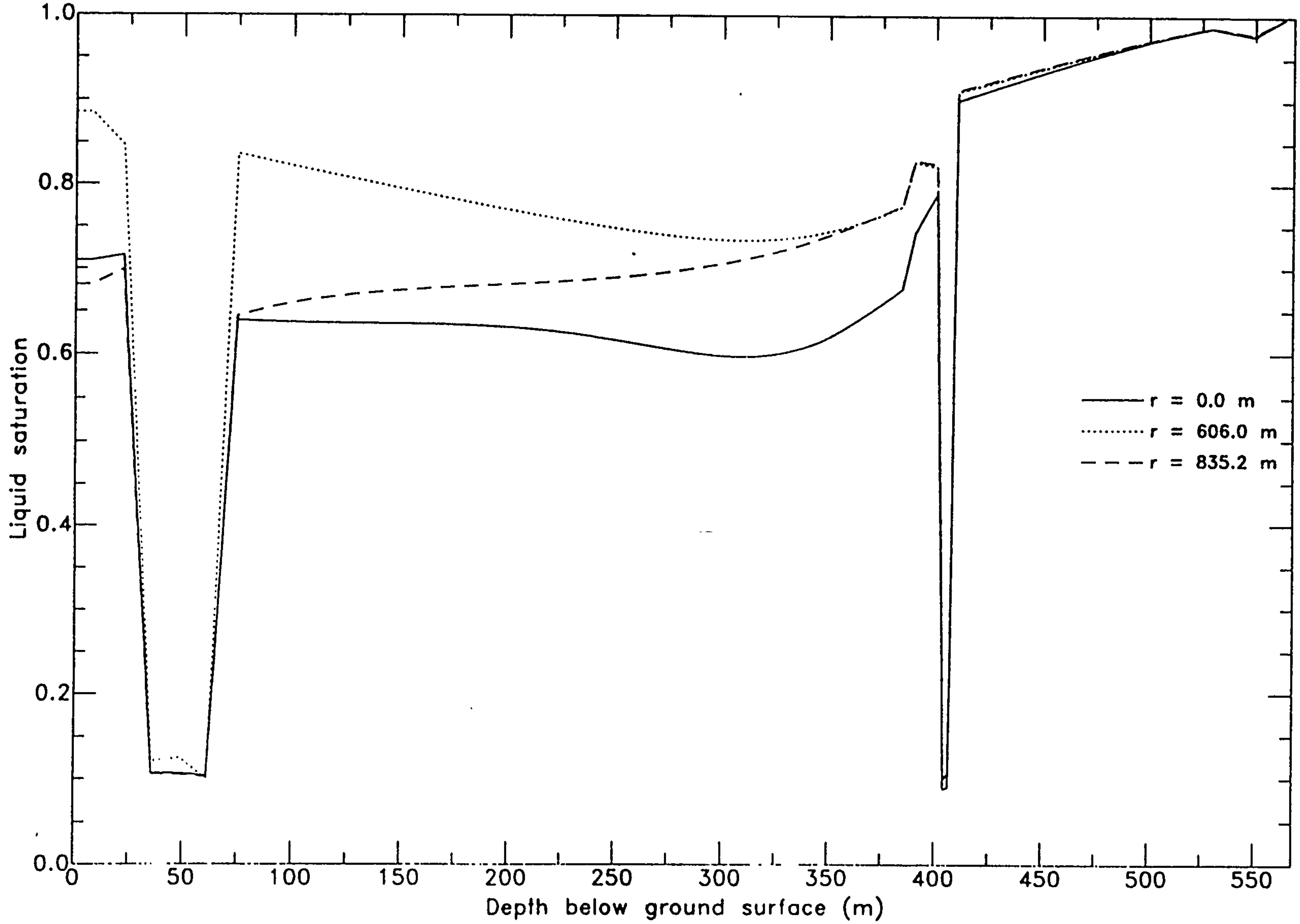


Figure 5-24. Vertical Saturation Profile at 100,000 Years for 111 MTU/Acre

maximum volume of water was perturbed. The 280 milliDarcy curve confirms the negligible water movement shown in earlier figures at low thermal loads (about 0.1 m column affected) and shows that at 111 MTU/acre the column of water affected is about a factor of 10 larger. As the permeability increases, it becomes much easier to move water, as expected. As a result of this, the equivalent column of water becomes larger for all thermal loads. The below boiling thermal loads still produce the smallest equivalent column of liquid. The peak in the equivalent water column tends to move down somewhat as the permeability is increased although the differences between a 55 and 111 MTU/acre loadings are not substantial. It should be noted that a bulk permeability of 40 Darcys would be representative of an extremely porous oil field. While localized areas in Yucca Mountain may have permeabilities of this magnitude, the average bulk permeability is not expected to be in this range.

If the water mobilized is assumed to be available to contact waste packages, Figure 5-25 can be used to draw conclusions with respect to AML and bulk permeability. Figure 5-25 shows that for AMLs less than or equal to 36 MTU/acre the net column height of liquid is less than for any loading above 36 MTU/acre. The potential for enhanced liquid flux reentering the repository is therefore less for the sub-boiling cases than for the above boiling cases. This conclusion is derived from the observation that the predictions of saturation profile (see Figure 5-4) show no regions of 100 percent saturation being produced which, within the assumptions of the equivalent continuum model, preclude fracture flow. At or above 55 MTU/acre, locally saturated regions occur allowing the possibility of liquid flow in fractures which may or may not enter the repository depending on near filed heterogeneity and the extent that liquid may concentrate in fractures. In any case Figure 5-25 indicates that the flux through the repository is minimized by lower thermal loads.

Several factors can alter the conclusions of the preceding paragraph. One or more of the following mechanisms can either remove the water before it contacts WPs or preferentially concentrate water at certain locations. The mechanisms are matrix inbibition, boiling condensate drainage through regions not occupied by WPs, and focussed liquid flow driven by spatial heterogeneity in bulk permeability. The follow-on study will examine these mechanisms.

The calculations predict that the boiling time will decrease, for those cases which produce above boiling conditions, as the bulk permeability of the host rock increases. For bulk average permeabilities up to about 1 Darcy the change in the length of boiling time is small between different permeabilities. However, for permeabilities substantially above 1 Darcy boiling times can decrease by a few hundred to a few thousand years over rock with lower permeabilities. The percent reduction decreases with increasing thermal load but remains appreciable at even the highest thermal loads. This behavior results if the bulk average permeability increases. Further details can be found in Appendix F.

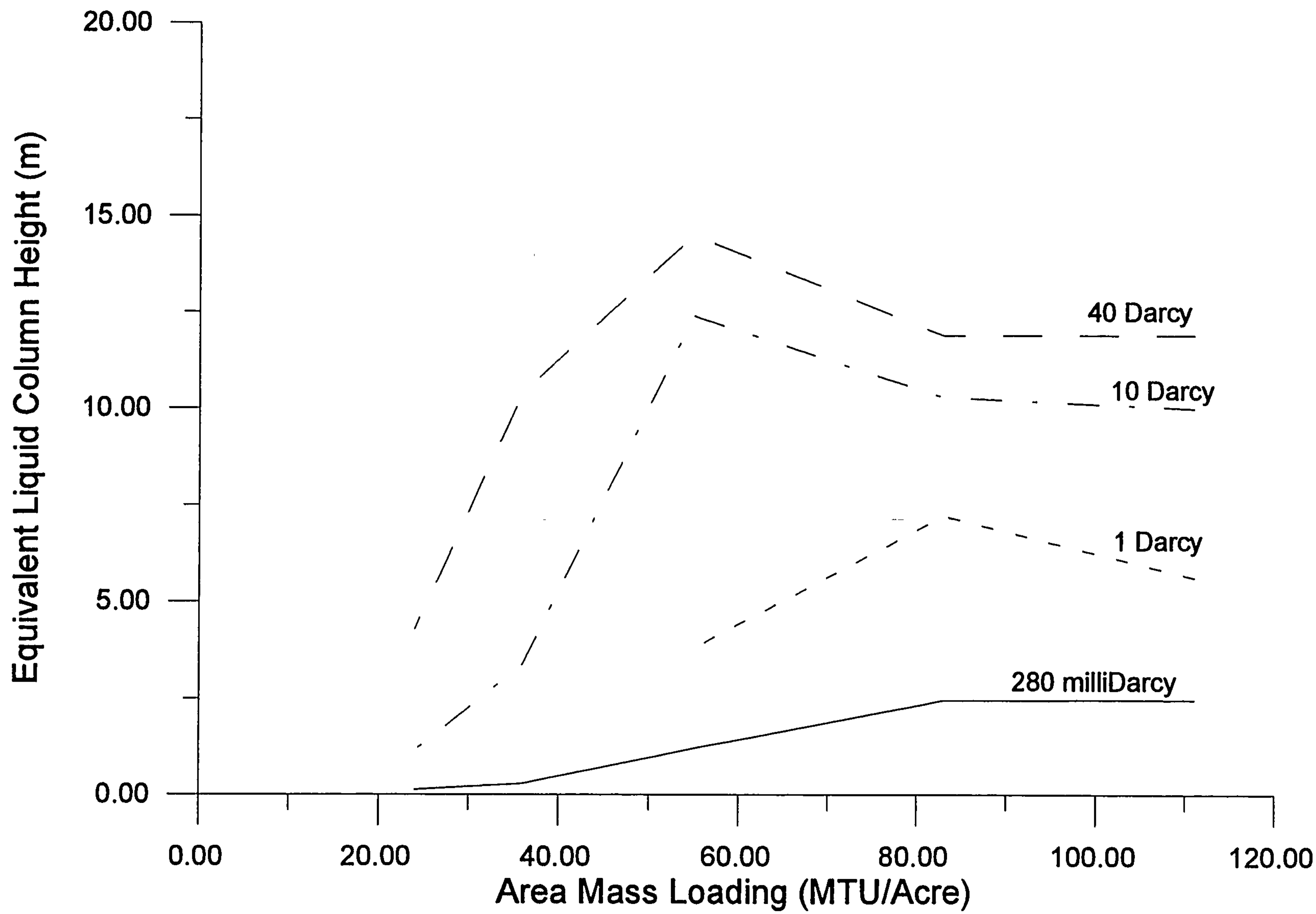


Figure 5-25. Equivalent Liquid Column Height Added Above Repository as a Function of Thermal Load and Permeability

5.6 COMPARISON OF FAR-FIELD RESULTS WITH THERMAL GOALS

The far-field analysis generated results useful in assessing performance against the following thermal goals, which were presented in Section 2 in Table 2-1.

Number	Goal
1	Limit temperature of CHn to <115 °C
2	Limit temperature of TSw3 to <115 °C
3	Relative motion <1m at the top of TSw1
4	Rise in surface temperature <2°C
5	Surface uplift <0.5 cm/year
10	Maximize the time the waste package container stays above boiling consistent with the thermal strategy developed
16	Establish a thermal loading which would not degrade PTn barrier

These goals were considered specifically far-field goals related to postclosure performance. Goals 3 and 5 are thermo-mechanical effects and could not be evaluated with the temperature and saturation pressure data provided in this section. Goal 4 could not be evaluated since the model assumed a constant temperature at the surface. Goal 10 is a qualitative goal primarily dependent on near-field conditions. However, the goal itself addresses postclosure performance and hence will be evaluated. The near-field calculations discussed in the previous section could not be extended to the timescales necessary to evaluate this goal nor did they calculate the hydrothermal characteristics. Therefore, the far-field average bulk temperatures will be used as a measure of how well this goal is met and the time that the bulk temperature is above boiling will be used as a conservative estimate of whether the goal is met. Goal 16 is a qualitative statement which can only be examined in a very general sense. Data on vertical temperature and liquid saturation profiles are given in this section which on examination might lead to some estimates of perturbations of the PTn layer; however, this was not done. Further discussion of this goal is presented in Section 7, where the geochemical aspects of the problem are evaluated. Thus only goals 1, 2, and 10 were examined in this section.

An evaluation was done as to how well each of the thermal loading options met the three thermal goals. In some cases the performance could not be determined unequivocally, so engineering judgement was used to assess the qualitative probability of that goal being exceeded. For goals 1 and 2 a utility of 1 was assigned if the goal was met (e.g., temperatures below 115 degrees Celsius were achieved in the repository) and a utility of zero was assigned if the goal was exceeded. The only exception to this was for the 83 MTU/acre case in which the data showed that a temperature of 115 degrees Celsius was reached at about 451 years and was still that temperature at 1000 years. Since it was possible that the goal was exceeded during that time a utility of 0.5 was assigned to that particular case. Goal 10 assumes that having the waste package above boiling produces conditions in which the waste package and surrounding rock are "dry." At present, no consensus exists as to the definition of dry or dryout of the rock. Thus, this goal is a surrogate for what some believe is dry. In this study, as well as in the total system performance analysis studies that were done in 1993, the definition of dryout is based on having the temperature in the host rock be at or above the boiling point (97 degrees Celsius) in the host rock. The volume of the dry out zone provides an estimate of the perturbation in groundwater that results as a consequence of the repository thermal pulse. Water displaced from the dryout zone and infiltrating water diverted around the dryout zone are considered a result of this perturbation.

The fraction of waste package containers that would be protected from groundwater, hence aqueous flow and transport processes was assumed to be within the repository volume where the temperature was above boiling. Using the hydrothermal predictions which produce bulk average temperature predictions (i.e., an average temperature that would exist some distance into the rock but still remain on the drift scale), estimates of the repository area that would be above the boiling point were calculated. Although this area which the above discussion identifies as the dryout region may not be completely dry, it is assumed that groundwater flow would be interrupted within this volume. The area of this dryout region, as a function of time, was determined form the hydrothermal calculations as those radial rings in the repository that have bulk average temperatures above boiling. This was done for each of the thermal loads. The area of those rings that have temperatures above boiling was normalized by the total repository area and these values are plotted as a function of time in Figure 5-26.

For the 111 MTU/acre case, the area under the curve was the largest of the three strategies that produced above boiling conditions. Thus, the 111 MTU/acre case, which had the largest time above boiling, was assigned a utility of one. The reader is cautioned that above boiling does not necessarily imply complete dry-out. The other cases were assigned utilities based on the fraction of area under the curve in Figure 5-26 that they achieve compared with the 111 MTU/acre case. Of course since the two lowest thermal loadings of 24 and 36 MTU/acre did not have bulk temperatures that exceeded boiling they were assigned utilities of zero with this methodology. It should be noted that, depending on waste package size and emplacement mode, the waste package may have temperatures above boiling. However, this was not considered since there was an attempt to eliminate effects that were simply a function of waste package size and/ or emplacement mode.

Table 5-1 summarizes the performance, in terms of utility factors, of each option with respect to the three goals outlined.

Table 5-1. Comparison of Performance With Thermal Goals

Utility Factors
Loading (MTU/Acre)

	24	36	55	83	111
Goal 1	1	1	1	1	0
Goal 2	1	1	1	0.5	0
Goal 10	0	0	0.2	0.6	1

These comparisons will be used in conjunction with assessments of near-field results, cost, schedule, uncertainty and other considerations to formulate recommendations. These issues will be discussed in succeeding sections, and recommendations that can be made will be presented later in the report.

5.7 SUMMARY

Hydrothermal calculations of temperature and water movement on a mountain scale, using a continuum equilibrium model, were performed by LLNL in support of the study. An evaluation of these calculations was done and the results were used in the evaluations of the various thermal loading cases. Specifically, the calculations showed that the 24 and 36 MTU/acre cases, which produce bulk average conditions below boiling, produce negligible hydrologic perturbation for bulk permeabilities around 280 milliDarcy. On the other hand, the calculations predict that the high thermal loads will move vertically a significant amount of water both above and below the repository horizon. If permeabilities should be different than this in some areas, possibly due to heterogeneities, the calculations show that the below boiling thermal loads will tend to minimize the equivalent column of liquid that is moved above the repository. Additionally, the continuum equilibrium model predicts that the high thermal loads produce a large scale redistribution of fluid resulting in long term increases in saturation levels above the repository. This was determined by observing increased, compared to the ambient, liquid saturation levels above the repository at 100,000 years. The calculations showed that with uniform thermal loading the 55 MTU/acre case has a significant portion of the repository never exceeding the boiling temperature. This would produce a hot, humid environment for the waste packages. The calculated temperatures were evaluated as to whether the far-field thermal goals would be met. The results showed that the thermal goals to keep the temperature below 115 degrees Celsius for the CHn and TSw3 layers were violated at 111 MTU/acre and that at 83 MTU/acre there was a high probability that the goal at the TSw3 layer would also be violated. The goal was to maximize the time the WP is above boiling consistent with the thermal strategy, although a near-field goal was evaluated with the far-field calculations since the bulk average temperatures provide a reasonable estimate of the temperature performance for long times. The calculations, obviously, found the boiling time to be maximized at the 111 MTU/acre case and to not be achieved for the below boiling cases.

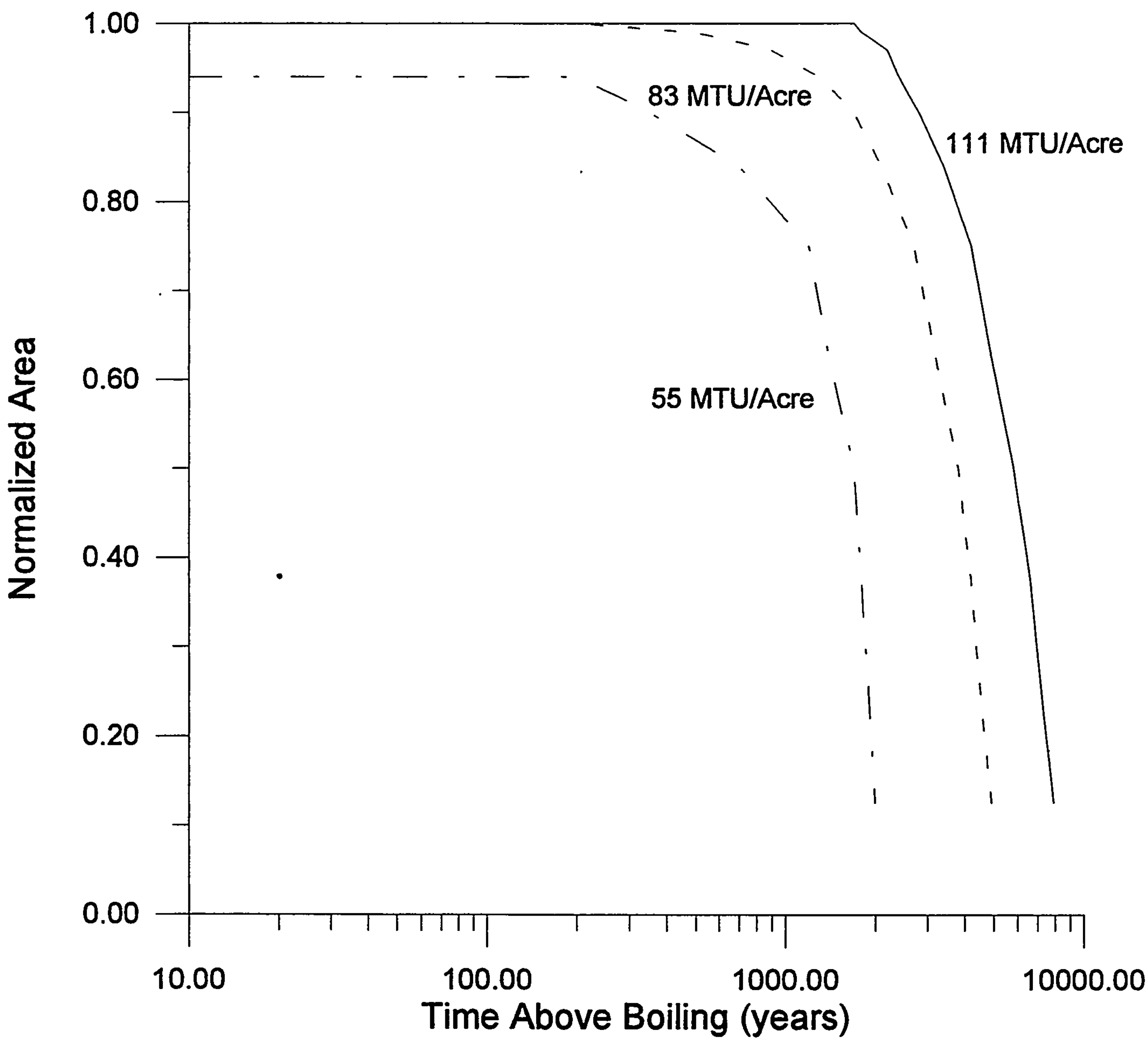


Figure 5-26. Normalized Repository Area Above Boiling vs the Time the Area is Above Boiling

6. COST ANALYSIS

This section describes the results of the cost analyses performed as a part of the evaluation of the thermal loading alternatives. The MGDS Life Cycle Costs (LCC) were estimated as a part of these analyses. The MGDS life cycle is divided into phases based on the completion of major program milestones. The phases are 1) the Yucca Mountain Site Characterization Project (YMP), also considered the Development and Evaluation (D&E) phase of the MGDS life cycle; 2) Engineering and Construction; 3) Emplacement Operations; 4) Caretaker Operations; 5) Decommissioning and Closure. Section 6.1 describes the MGDS D&E costs. The costs for the second through fifth phases are grouped as post-D&E MGDS costs and are reported in Section 6.2. Section 6.3 concerns non-MGDS costs due to the thermal loading. It must be remembered that the cost estimates are based on top level scoping algorithms designed to identify sensitivities to the design variables and to identify the most important design variables. *These costs should not be considered as providing accurate project or life cycle costs but rather as giving an indication of cost trends relative to the design parameters.*

6.1 MGDS D&E COST IMPACTS DUE TO THERMAL LOADING

This section consists of descriptions of the background for the D&E analysis, the approach, key groundrules and assumptions, an analysis summary, and a cost summary. The detailed set of assumptions and detailed analyses are provided in Appendix H.

6.1.1 D&E Background

The thermal loading strategy could impact the work scopes of the YMP by altering the sizes of the emplacement areas. The sizes of the emplacement areas, which are displayed in Table 6-1, are based on the repository area used (see Section 3). The change in the required emplacement area and thus the repository block area required to be investigated is influenced by the thermal loading and is the primary design variable considered in this analysis.

The thermal loading will also affect the coupled T-M-H-C behavior of the site and thus the postclosure performance. The Total Systems Performance Assessment (TSPA) is the primary measure of postclosure performance. The cost of site characterization will increase as the uncertainty in the TSPA increases. However, no attempt to quantify this cost impact was made in this analysis.

Table 6-1. Emplacement Areas for Desired AMLs

AML (MTU/Acre)	Emplacement Area (Acre)
24	2598
36	1755
55	1139
83	755
111	570

6.1.2 D&E Approach

The approach used to determine the cost impacts was to identify the affected Work Breakdown Structure (WBS) elements. The WBS Dictionary (YMP/CC-0001) (DOE, 1993b) provides descriptions of the work scope for each WBS element. A screening of the WBS elements was performed by the M&O MGDS Systems Engineering, Strategic Planning and Technical Integration, Site Characterization, and Budget and Analysis groups. For the affected WBS elements, estimates of the delta costs from the baseline Total Project Cost (TPC) (DOE, 1993c) were developed. The WBS elements 1.2.3 (Site Investigations), 1.2.6 (Exploratory Studies Facility), 1.2.7 (Test Facilities), and 1.2.13 (Environment, Safety, and Health) were identified as possibly having significant cost impacts due to thermal loading.

6.1.3 D&E Key Groundrules and Assumptions

The following key groundrules were used to perform the D&E cost analysis:

1. The TPC baseline is used as the cost basis.

2. Project completion in October 2001 with the submittal of license application.

3. All costs are presented in constant fiscal year 1994 dollars (FY 94 $) based on the guidance described in DOE Order 5700.2D (DOE, 1992d), which states that all construction projects will be estimated in constant-year dollars in the year the estimate is performed.

A key assumption described earlier in sections 3.5 and 3.6 is restated at this point since it is important to the cost analysis. At least 2600 acres of area comprised of the potentially usable primary repository area plus the more favorable potential expansion areas 2EA, 2EB and SE was assumed suitable for waste emplacement (SCP page 6-224 and see Figure 3-2). Emerging subsurface analyses (Rogers, 1993) to investigate the expansion areas for potential waste emplacement are considering that, in order to meet more stringent repository layout criteria than assumed in the SCP, expansion beyond the assumed SCP expansion areas may be necessary to emplace the lower AMLs of 24 and 36 MTU/acre.

The assumptions used to determine the cost impacts on the affected WBS elements are outlined below:

1. The Systematic Drilling (SD) program, which is under WBS 1.2.3, Site Investigations, is modified based on the thermal loading decision. The objective of this program is to obtain, in a systematic process, the analytical data and basic descriptions of the subsurface geology of the potential repository site for determining the detailed, three-dimensional distribution of rock properties underlying Yucca Mountain. The M&O Site Characterization group was consulted concerning the amount of additional surface based testing and characterization that would be required for an increase or decrease in the emplacement area or repository block area based on the thermal load. Their response was that for expansion into the northern areas (2EA, 2EB, and SE) that the regional and site scale characterization was adequate and that only the on-block or SD boreholes were required to be increased. For reduced repository block areas, the regional and site scale characterization could not be reduced and that the SD boreholes could only be reduced to the size of the altered zone which was assumed to be the extent of the boiling front for above boiling thermal loadings. The SD boreholes refer to those boreholes identified in the Study Plan for Study 8.3.1.4.3.1 (DOE, 1993d), "Systematic Acquisition of Site-Specific Subsurface Information."

2. Any ESF, WBS 1.2.6, cost impacts are not included. No consensus was reached concerning the amount of additional or reduced ESF excavation required for the various repository thermal loadings. One idea proposed was that no addition or reduction in the amount of drifting or number of alcoves would be required for the different thermal loadings. Studies of physical, chemical, thermal, and mechanical *processes* will be adequately addressed with currently planned excavations, and *features* will be investigated with surface-based techniques (Johnson, 1993). McKenzie, (1993) suggested it would be difficult to license an expanded repository area without an examination of the extent of the potential repository area. A compromise position offered by the M&O Regulatory and Licensing group (Lugo, 1993) was that the current ESF design resolves the NRC concerns and that the view that no additional or reduced drifting is necessary was reasonable, but that additional drifting in the expansion areas could be done contingent upon receiving unexpected information during the surface-based testing of the expansion area. At this point, it is mentioned that for the higher thermal loads a reduction in the ESF drifting would have to be studied in sufficient detail so that the potential repository would not be adversely affected. The potential repository layouts developed for this study are not of this level of detail. Also, the risk of reducing the ESF drifting for a high thermal loading at this time may be large if a low thermal load must be used for the final repository design. Clearly, there is contention on this issue and a more detailed examination will be needed at a later date. An investigation of sensitivity of the D&E costs to this assumption is planned for the final report of follow-on Thermal Loading System Study which is planned for completion in FY 95. It is realized that if modification of the current ESF design is required due to the thermal loading, the delta cost could be impacted; however, based on current expectations no delta costs were assumed at this time.

3. The cost of roads to access an additional or reduced number of SD boreholes is impacted in the 1.2.7 WBS element (Test Facilities). Late in the study, it was determined that these costs should be accounted for in the 1.2.3 WBS element. Since the cost is relatively small, the costs were not moved to the proper element. They also may be slightly over-estimated since there is a small cost for roads in the 1.2.3 WBS element.

4. The Terrestrial Ecosystems program, which is under WBS 1.2.13 (Environment, Safety, and Health) needs to be expanded for the low thermal loading cases.

6.1.4 D&E Analysis Summary

Based on the above assumptions, the major cost impacts on the YMP are due to the modification of the SD Program and specifically the number of SD boreholes. The number of SD boreholes is based on a uniform areal distribution of boreholes in the repository block. The Study Plan for Study 8.3.1.4.3.1 (DOE, 1993d) "Systematic Acquisition of Site-Specific Subsurface Information" calls for 12 initial SD boreholes in a repository block area of 1600 acres. Table 6-2 provides the repository block areas considered[2] and the total number of SD boreholes required for the desired AMLs.

The delta costs from the baseline for WBS elements 1.2.3, 1.2.7 and 1.2.13 are reported in this section. The WBS 1.2.3 (Site Investigations)-related delta costs by thermal loading are summarized in Table 6-3. These costs included additional drilling equipment, fixed costs per SD borehole, Unsaturated Zone (UZ) monitoring of the boreholes and coordination and planning costs. The WBS 1.2.7 (Test Facilities)-related delta costs by thermal loading are summarized in Table 6-4. The cost of roads to access the SD boreholes is the main cost impact identified in this WBS element. The WBS 1.2.13 (Environment, Safety and Health)-related delta costs due to thermal loading are limited to a $0.3 million increase for the two lowest AML cases. The cost of the Terrestrial Ecosystems program is the main cost impact identified in this WBS element.

6.1.5 D&E Cost Summary

The YMP Cost and Schedule Baseline document (YMP/CM-0015) (DOE, 1993c) reports the TPC as $6,319,337,000 (year of expenditure dollars). The baseline cost is $6,123,058,000 when stated in constant FY 94 dollars (see Appendix H). The cost analysis from the previous section developed delta costs from this baseline in constant FY 94 dollars for various thermal loadings of the potential repository. These cost deltas and the total costs are summarized in Table 6-5.

---

[2] The Area Investigated column of Table 6-2 differs slightly from the Emplacement Area column of Table 6-1 for the 111 AML case due to considering the areal extent of the boiling front. Additional detail concerning the areal extent of the boiling front is explained in Appendix H.

Table 6-2. Repository Block Areas and SD Boreholes for Desired AMLs

AML (MTU/Acre)	Area Investigated (Acres)	Common and Support Area (Acres)	Uncertainty Area (Acres)	Repository Block Area (Acres)	Total Number of SD Boreholes
24	2598	281	180	3059	23
36	1755	281	180	2216	17
55	1139	281	180	1600	12
83	755	281	180	1216	9
111	583	281	180	1043	8

Table 6-3. WBS 1.2.3 Site Investigations Delta Cost for Desired AMLs

AML (MTU/Acre)	Delta Number of SD Boreholes Required	LM-300 Drill Rig Delta Cost (Millions of FY 94 $)	Fixed SD Borehole Delta Cost (Millions of FY 94 $)	UZ Monitoring Delta Cost (Millions of FY 94 $)	Subtotal of Delta Cost (Millions of FY 94 $)	Delta Cost Coordination and Planning (Millions of FY 94 $)	Delta Cost (Millions of FY 94 $)
24	11	6.49	65.56	9.30	81.35	12.20	93.55
36	5	6.49	29.80	6.30	42.59	6.39	48.98
55	0	0	0	0	0	0	0
83	(3)	0	(17.88)	(1.20)	(19.08)	(2.86)	(21.94)
111	(4)	0	(23.84)	(1.80)	(25.64)	(3.84)	(29.48)

Table 6-4. WBS 1.2.7 Test Facilities Delta Cost for Desired AMLs

AML (MTU/Acre)	Delta Number of SD Boreholes Required	Delta Cost (Millions of FY 94 $)
24	11	3.3
36	5	1.5
55	0	0
83	(3)	(0.9)
111	(4)	(1.2)

Table 6-5. Site Characterization Delta and Total D&E Cost for Desired AMLs

AML (MTU/Acre)	Baseline Cost (Millions of FY 94 $)	Delta Costs (Millions of FY 94 $)	Total D&E Costs (Millions of FY 94 $)
24	6123.06	97.15	6220.50
36	6123.06	50.78	6173.84
55	6123.06	0.0	6123.06
83	6123.06	(22.84)	6100.22
111	6123.06	(30.68)	6092.38

In summary, this analysis of the MGDS D&E cost impacts due to thermal loading identified the Systematic Drilling program, associated access roads, and the Terrestrial Ecosystems program as impacted. A differential ESF cost impact due to thermal loading was not resolved and thus not included in the cost analysis. The main cost deltas are in the Systematic Drilling program and are small compared to the total MGDS D&E cost. The MGDS D&E costs will be higher (although not significantly higher) for lower thermal loads primarily because a larger area has to be characterized. Higher thermal loads result in a smaller repository area and slightly lower cost, but may make characterization more complex. Costs will increase as the uncertainty in the total system performance increases although this analysis made no attempt to quantify these costs.

6.2 POST D&E MGDS COST IMPACTS DUE TO THERMAL LOADING

This section consists of descriptions of the background for the post-D&E analysis, the approach, key groundrules and assumptions, an analysis summary, and a cost summary. The detailed set of assumptions and detailed analyses are provided in Appendix H and its references.

6.2.1 Post-D&E Background

Estimates of the post-D&E MGDS life cycle costs were developed in this analysis to determine the cost impacts due to thermal loading. These cost estimates include Engineering and Construction, Emplacement Operations, Caretaker Operations, and Decommissioning and Closure phases of the life cycle. As described in Section 3, a specific set of cases was identified to be costed in the Thermal Loading Study. Table 6-6 provides a list of the cases for which MGDS post-D&E cost estimates were developed. The main design parameters considered as part of the cost exercise are the AML, WP capacity, and emplacement mode. Although the Defense and West Valley High Level Waste (DHLW) contributes little to the thermal considerations of subsurface repository design, it does have a significant impact on WP and repository surface facility cost. Therefore, disposal of DHLW was considered for its impact on cost in these two areas and was included in the analysis. For certain cases of Table 6-6, cost data from the Waste Package Performance Allocation Study (M&O, 1993d) were utilized to obtain subsurface repository costs that account for disposal of DHLW.

6.2.2 Post-D&E Approach

Complete cost estimates of the various cases were not performed. A cost basis was established and only the items determined to be sensitive to the differences between cases were examined in detail. Therefore, the costs reported here may not be accurate and should not be used to quote MGDS cost estimates. However, the cost trends among cases are considered representative of the actual cost impacts on the MGDS.

6.2.3 Post-D&E Key Groundrules and Assumptions

The following key groundrules were used to perform the post-D&E cost analysis:

1. The same cost basis used in the most recently published Total System Life Cycle Cost (TSLCC) analysis (DOE, 1990) is used. The cost basis is Case 4 of the MRS System Study for the Repository (Sinagra, T.A. and Harig, R., 1990).

2. The schedule of MGDS activities and milestones is consistent with the TSLCC analysis.

3. All costs are presented in constant fiscal year 1994 dollars (FY 94 $) based on the guidance described in DOE Order 5700.2D (DOE, 1992d), which states that all construction projects will be estimated in constant-year dollars in the year the estimate is performed.

4. The repository cost account structure from the cost basis is utilized. At the highest level, the cost account structure has the following categories; Management and Integration, Site Preparation, Surface Facilities, Shafts/Ramps - Underground, Subsurface Excavations, Underground Service Systems, and Waste Package Fabrication.

Table 6-6. List of Post-D&E MGDS Cost Cases Examined in Thermal Loading Study

Case #	Waste Package Capacity Combination	Outer Barrier Thickness (cm)	Emplacement Mode	Areal Mass Loading (MTU/acre)
0	Hybrid (3 PWR and 4 BWR), or 4 PWR, or 10 BWR, or 1 DHLW	0.95	Vertical Borehole	55
1	6 PWRs, or 12 BWRs, or 1 DHLW	10	Vertical Borehole	24
2				36
3				55
4			Long Horizontal Borehole	24
5				36
6				55
7			In-Drift (4.3 m Drift Diameter)	24
8				36
9				55
10			In-Drift (7.0 m Drift Diameter)	24
11				36
12				55
13	12 PWRs, or 21 BWRs, or 3 DHLWs		In-Drift (4.3 m Drift Diameter)	24
14				36
15				55
16				83
17				111
18			In-Drift (7.0 m Drift Diameter)	24
19				36
20				55
21				83
22				111

Case #	Waste Package Capacity Combination	Outer Barrier Thickness (cm)	Emplacement Mode	Areal Mass Loading (MTU/acre)
23	21 PWRs, or 40 BWRs, or 4 DHLWs	10	In-Drift (4.3 m Drift Diameter)	24
24				36
25				55
26				83
27				111
28			In-Drift (7.0 m Drift Diameter)	24
29				36
30				55
31				83
32				111

The key assumptions used to develop the post-D&E MGDS cost estimates for the various cases are outlined below and organized by the cost account structure:

1. The Management and Integration (M&I) and Site Preparation costs are fixed. The M&I costs will be impacted by variations in the construction costs; however, this item is a relatively small portion of the overall post-D&E MGDS costs and is not expected to change the trends identified during this study.

2. Only the Waste Handling Building (WHB) costs of the Surface Facilities are impacted.

3. The Shafts/Ramps - Underground costs were not impacted by the design variables considered. The cost basis utilized an MGDS design that contained the Exploratory Shaft Facility. These costs were updated to be consistent with the baseline ESF design (YMP/CM-0016) (DOE, 1993a) and ESF/potential repository interface drawings.

4. Subsurface Excavations costs were impacted. The impacted costs concentrated on determining the length of excavation with a cost per unit length. The cost of Waste Emplacement and Transportation, which is also accumulated in this cost account, considered the number of WPs and the handling mode required by the emplacement mode and waste package shielding.

5. Underground Service Systems costs were not impacted.

6. Waste Package Fabrication costs were impacted. For each PWR capacity WP design, a unit WP cost for SNF and DHLW was estimated.

6.2.4 Post-D&E Analysis Summary

The costs reported in this section are based on cost estimates provided by the M&O Repository Surface Design, Repository Subsurface Design, and Waste Package Design groups. WP average unit costs were provided for each WP capacity. These costs were aggregated into total WP fabrication costs based on the total number of WPs required for each capacity. For each WP capacity, a resource optimization was performed on a WHB concept to establish resource quantities. Using these quantities, a WHB cost estimate was developed. The remainder of the repository surface facilities and site preparation costs were not updated from the cost basis. For each WP capacity, emplacement mode, and AML, a repository subsurface concept was developed and costed to emplace SNF only. These repository subsurface cost estimates were combined with the WP and repository surface costs to provide post-D&E MGDS cost estimates. Details of the cost inputs provided to support this study can be found in the following references: Bali, (1993), Bhttacharyya and Rasmussen, (1993) and Wallin, (1993).

6.2.5 Post-D&E Cost Summary

A subset of the cases from Table 6-6 for which complete post-D&E MGDS costs were developed are displayed in Figure 6-1. The cases shown in Figure 6-1 display cost versus thermal loading for the three WP capacities (6, 12 and 21 PWRs) and for the 6 PWR case for both in-drift and vertical borehole emplacement. As described earlier, all the cases in Table 6-6 did not include the DHLW cost for excavation. The cases shown in Figure 6-1 were also costed in the Waste Package Performance Allocation Study (M&O, 1993d). The reference case, Case 0, is also shown on the figure for comparison. The post-D&E MGDS cost does not appear sensitive to thermal loading. This derives from three facts: (1) the repository layouts were developed to minimize excavation costs for each thermal loading; (2) the thermal environments were not considered in determining underground operational costs since the environments were not available in enough detail to cost the differences among them; and (3) the repository layouts were relatively simple and did not consider specific expansion areas or the excavation required to access these expansion areas. Additional explanation of these three facts is provided in the following paragraphs.

In developing the repository layouts, the WPs were spaced at the estimated minimum allowable distance within the drifts to minimize the number of emplacement drifts required and, in turn, minimize the drift excavation costs. The minimum spacing was determined from considerations of a maximum allowable WP centerline temperature goal as stated in the SCP Thermal Goals Reevaluation WPs (M&O, 1993a), and the minimum space between WPs required to place the

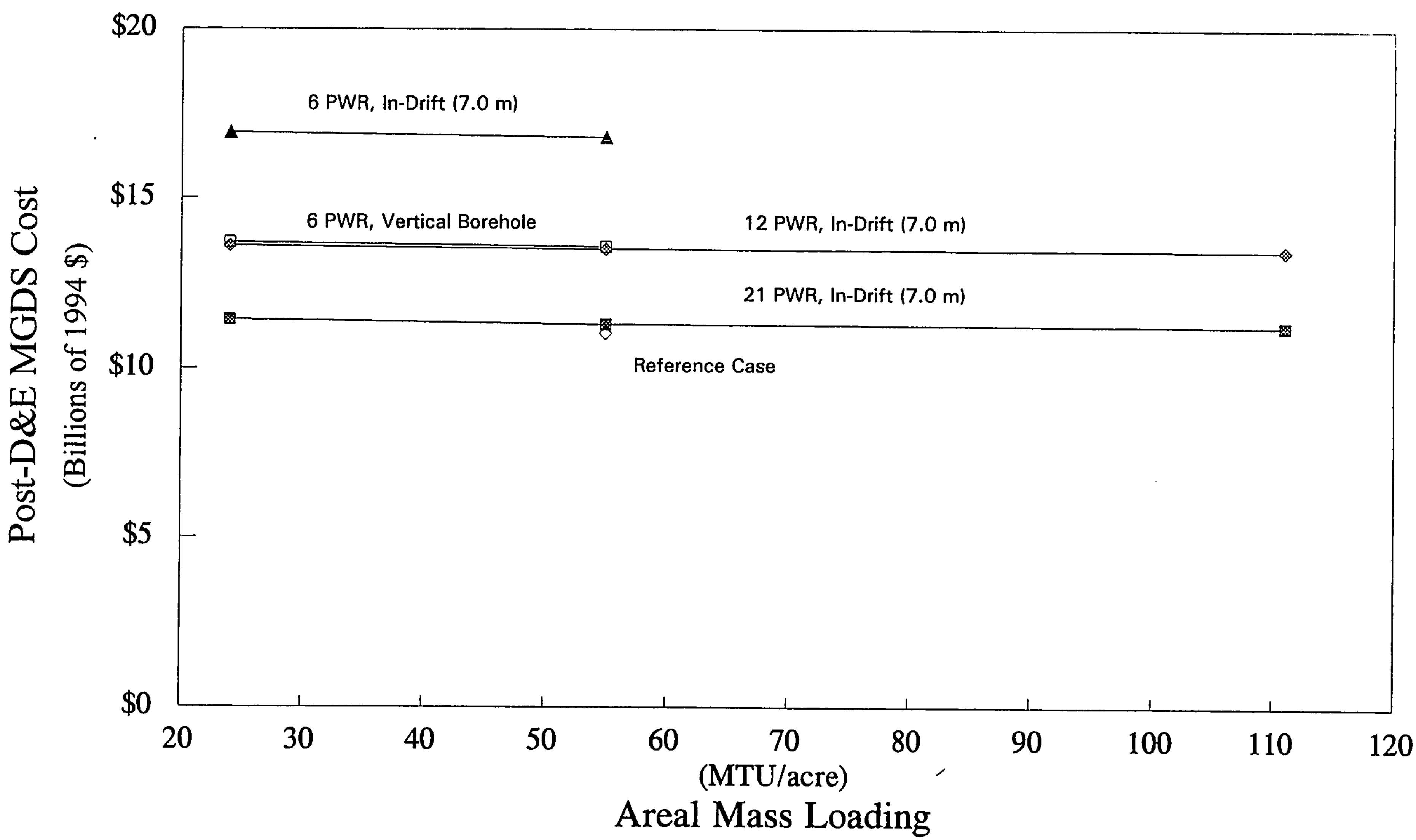


Figure 6-1. Post-D&E MGDS Costs vs. Thermal Loading

WPs in a drift using the WP transporter/emplacement machine. To change the thermal loading of the repository, only the distance between drifts was changed and the total length of emplacement drifts remained the same. Therefore, the only excavation costs that changed with the thermal loading were these associated with the perimeter drifts and access drifts. Since these costs are minor compared to the total excavation costs, little subsurface cost difference is seen among the thermal loading options.

A comparison of emplacement methods (minimum WP spacing, variable drift spacing or square spacing, uniform WP and drift spacing) was also performed. The constant WP spacing case yields minimum excavation costs but, at low thermal loads, produces somewhat more pronounced heating variations in the repository perpendicular to the emplacement drifts than would occur square spacing (uniform WP and drift spacing). However, the square spacing will result in somewhat higher subsurface excavation costs. Table 6-7 provides the WP and drift spacings for these two emplacement methods for the 21 PWR multi-barrier WP emplaced in a 7.0 meter diameter drift. For any emplacement method and 7.0 meter drift diameter, the minimum drift spacing is limited to 23.3 meters due to the extraction ratio. Figure 6-2 provides the cost comparison of the two emplacement methods. For the square spacing, there is an increase in cost as the AML decreases, but for the 24 MTU/acre case the cost increase from the minimum WP spacing case is less than 15 percent.

Table 6-7. Waste Package and Drift Spacings for Emplacement Methods

AML (MTU/Acre)	Emplacement Method for 21 PWR WP, In-Drift (7.0 m)			
	Minimum WP Spacing		Square Spacing	
	WP Spacing (meters)	Drift Spacing (m)	WP Spacing (m)	Drift Spacing (meters)
24	12.0	126.7	38.93	38.93
36	12.0	84.18	31.78	31.78
55	12.0	55.10	25.71	25.71
83	12.0	36.51	18.80	23.30
111	12.0	27.30	14.06	23.30

It should be noted that there are some minimal differences between the cases for which costs were generated and the cases where thermal calculations were run. Thermal calculations were done for all of the minimum WP spacing cases in Table 6-7. For each of the AMLs of 111 and 83 MTU/acre there is a one-to-one correspondence between the cases costed (minimum WP spacing and square spacing) and the cases where thermal calculations were done. The square spacing cases for these two AMLs were not exactly square since the drift spacing could not be reduced below 23.3 m without violating the extraction ratio limitation. For the 55 MTU/acre case the costs were done for a true square spacing (25.71 x 25.71 m), but the

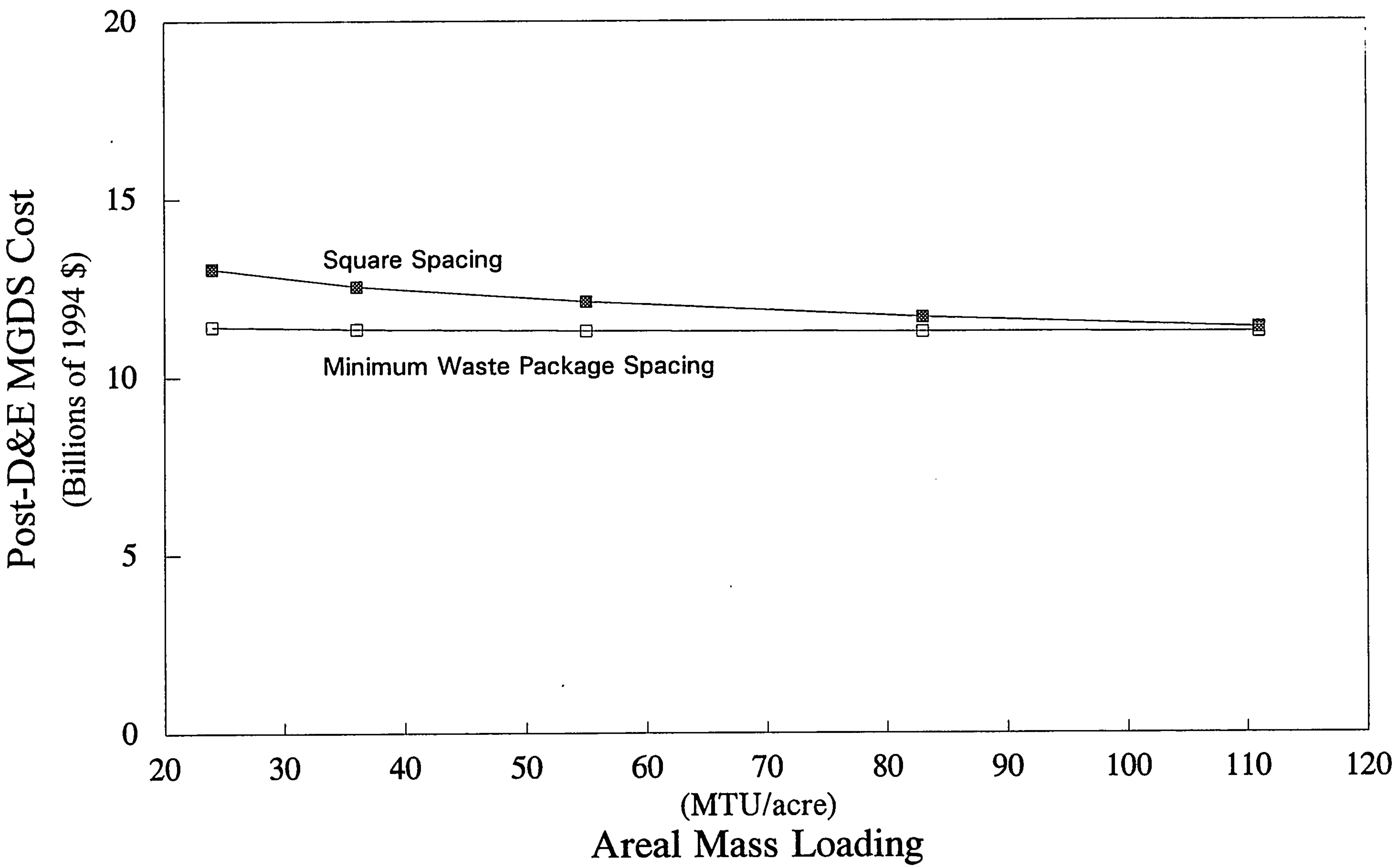


Figure 6-2. Cost Comparison of Emplacement Methods

thermal calculations were done for something slightly different (23.3 x 23.38 m). The cost differences between these two cases are negligible. Thermal calculations were not done for the 24 and 36 MTU/acre cases for either square spacing or minimum drift spacing (see Table 4-4A for the 21 PWR cases.)

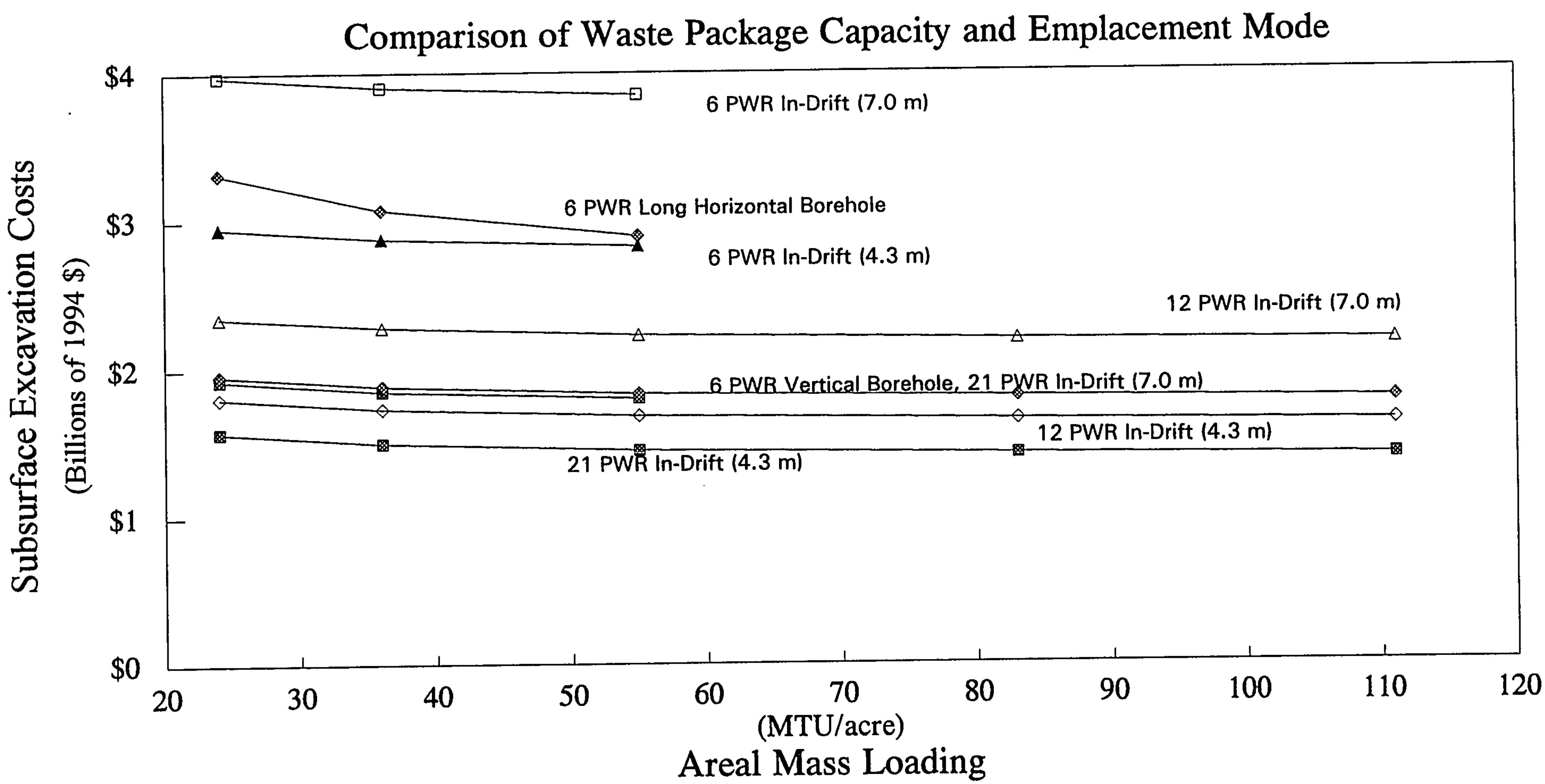
Operations concepts will be affected by thermal loading. For example, there may be limits on the type of vehicles used, the monitoring hardware may need to be thermally shielded and/or of more rugged construction, ventilation costs may be very sensitive to thermal loading, and the need and means for human protection may vary significantly with thermal loading. The SCP Thermal Goals Reevaluation report (M&O, 1993a) specifies a 50 degrees Celsius goal for the upper bound temperature for the first 50 years of operation in the access drifts for any emplacement mode. However, temperatures may be well above this goal in the actual emplacement drifts which may be occupied, at least for a short period of time, by workers and/or machines. The operations concepts and hence the impact that thermal loading will have on the cost of these operations is not yet well known. This uncertainty needs to be resolved to better define the cost impacts.

The simplified repository layouts did not consider the specific expansion areas that would require development for emplacement of waste. Access to the suitable emplacement areas may require additional drifting. The level of detail of conceptual design required to determine this amount of drifting was not available at the time the cost estimates were developed. The expected impact on cost due to thermal loading from this effect is that the cost will be relatively insensitive to thermal loading until an additional expansion area is required, then a jump in the cost of accessing this area might occur.

Surface facility costs were not a function of thermal loading and the WP costs were also independent of thermal loading assuming that the WP being costed was capable of achieving the desired thermal loading. Figure 6-3 shows the subsurface excavation costs for all cases considered. These costs do not include the cost of emplacement of DHLW, but show the limited sensitivity to thermal loading for the set of cases considered.

In the previous figures, it can be seen that the major trend is a decrease in post-D&E MGDS costs as the WP capacity increases. However, a potential cost impact not considered in these cost estimates is the sensitivity of subsurface operations to WP weight. There is, in fact, a substantial weight difference between the WP options. The weight varies as a function of capacity from 23 tonnes to 51 tonnes for the 10 cm outer-barrier WP (Bahney and Doering, 1993). Initial indications are, however, that the impact of weight on the subsurface operations cost will not alter the overall trend of economy in reducing the quantity of waste packages. Considering that the largest waste package capacities lower WP and repository surface costs, the next largest cost impact is to reduce the size of the drift diameter for the in-drift emplacement cases. It should be noted that for the capacity 6 PWR WP the vertical borehole emplacement cost was competitive with the 12 PWR in-drift (7.0 m) emplacement case (see Figure 6-1).

Finally, for the 21 PWR multi-barrier WP and in-drift (7.0 m) emplacement, the total MGDS LCC is displayed in Figure 6-4. The total MGDS LCC is the sum of the D&E (YMP) cost from section 6.1 and the post-D&E costs from Section 6.2. This case was the lowest cost



No DHLW emplaced, only SNF. Minimum waste package spacing used.

Figure 6-3. Subsurface Excavation Costs

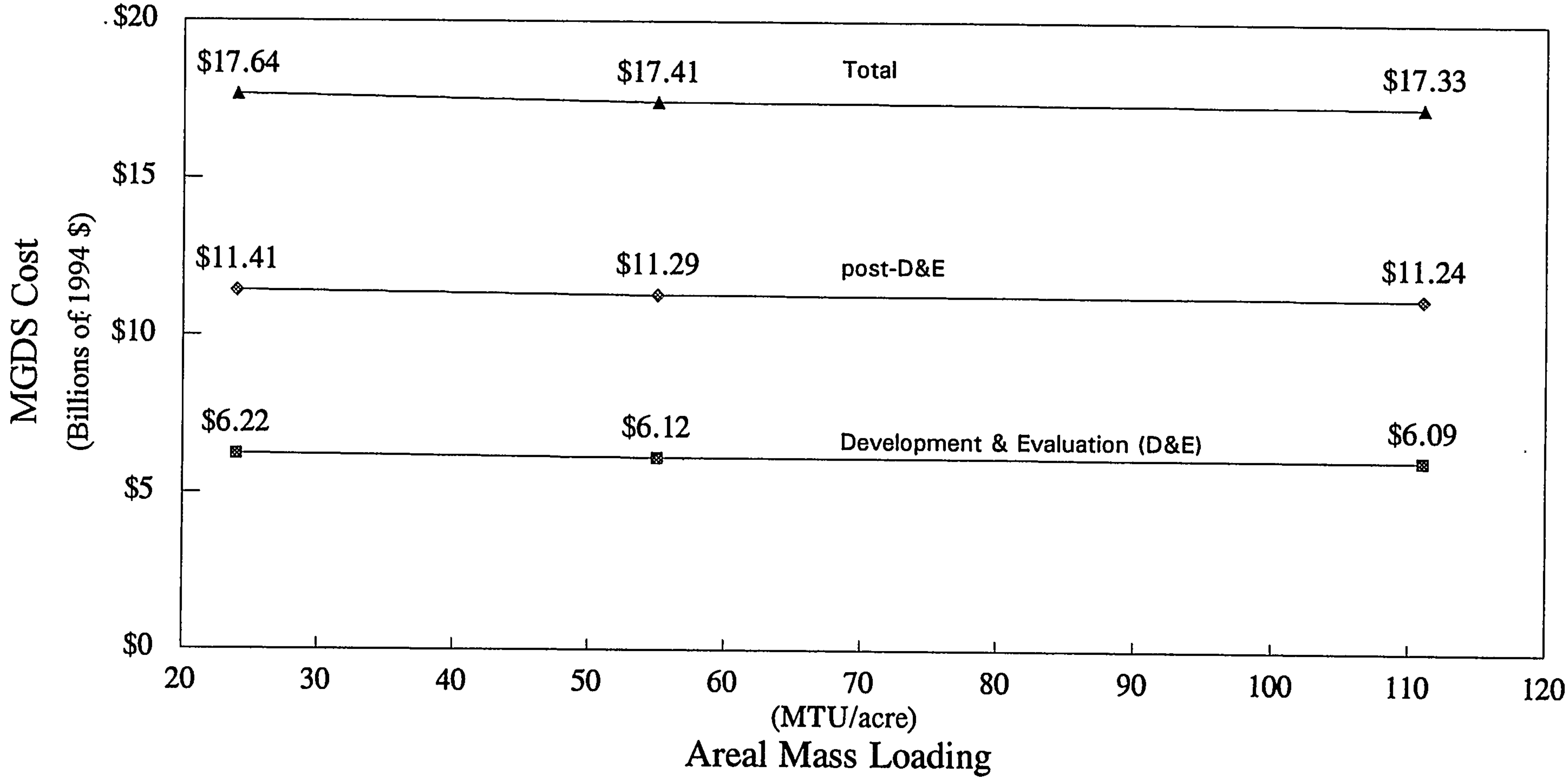


Figure 6-4. MGDS Cost vs. Thermal Loading

alternative of the cases for which a complete post-D&E MGDS cost was computed. The 21 PWR in-drift (4.3 m) emplacement case would be expected to generate lower costs but was not costed in this study to include the emplacement of DHLW. The subsurface excavation cost difference between 7.0 meter and 4.3 meter in-drift emplacement of the 21 PWR WP was on the order of $400 million (FY 94 $) for the non-DHLW cases shown in Figure 6-3.

In summary, the repository subsurface layouts used the minimum WP spacing emplacement method which minimized subsurface excavation costs. The minimum WP spacing results in post-D&E MGDS cost estimates insensitive to thermal loading. Other emplacement methods (e.g., square spacing) involve costs more sensitive to thermal loading, but the cost difference is less than 15 percent. The cost of operating in high thermal environments and monitoring costs were not included, but may make the high thermal loadings more costly. The trend of increasing the WP capacity produces the largest cost reductions. The trend of decreasing the drift diameter for the in-drift emplacement cases also results in a significant cost reduction.

6.3 NON-MGDS COST IMPACTS DUE TO THERMAL LOADING

No options were evaluated in which the non-MGDS segments of the Civilian Radioactive Waste Management System were impacted. The System Implications of Repository Thermal Loading Phase II Study (M&O, 1993i) considers some specific system issues. A summary of the cost evaluations from the cited report is provided in this section for comparison, since a similar conclusion on cost was also reached. This study had a much broader scope than the analysis provided in the previous sections. The cost model used in the referenced study also supported the System Architecture Study (M&O, 1993k). That study states "The System Architecture Study (SAS) model is not detailed and is not appropriate for making precise projections of the absolute costs of the system. However, the model is suitable for estimating relative costs and for identifying and evaluating trends in those costs. The life-cycle costs computed by the SAS model include the construction and operating costs for the repository, the transportation system, and a MRS facility. D&E costs are assumed to be essentially the same for all strategies and are not calculated. The costs include only those associated with the management and disposal of spent fuel. Additional costs associated with high-level waste management and disposal are not included." The system life cycle cost analysis considered a scenario for waste acceptance, storage and transportation that is consistent with the previous analyses' assumptions. For this scenario, the conclusion was reached that there is a broad range in which the costs are not strongly sensitive to the areal mass loading.

6.4 SUMMARY

The analysis of the MGDS D&E cost impacts due to thermal loading identified as impacted the Systematic Drilling program, associated access roads, and the Terrestrial Ecosystem program. A differential ESF cost impact due to thermal loading was not resolved and thus not included in the cost analysis. The main cost deltas are in the Systematic Drilling program and are small compared to the total MGDS D&E cost. The MGDS D&E costs will be higher (although not significantly higher) for lower thermal loads primarily because a larger area has to be characterized. Higher thermal loads result in a smaller repository area and slightly lower cost, but may make characterization more complex. Costs will increase as the uncertainty in the total system performance increases although this analysis made no attempt to quantify these costs.

The analysis of the post-D&E MGDS cost considered repository subsurface layouts that used the minimum WP spacing emplacement method which minimized subsurface excavation costs. The minimum WP spacing results in post-D&E MGDS cost estimates insensitive to thermal loading. With other emplacement methods (e.g., square spacing) the costs are more sensitive to thermal loading, but the cost difference is less than 15 percent. The trend of increasing the WP capacity produces the largest cost reductions. The trend of decreasing the drift diameter for the in-drift emplacement cases also results in a significant cost reduction.

The total MGDS cost does not appear to vary significantly (less than 15 percent) between hot (above boiling) and below boiling strategies. Thus it can be concluded that cost does not appear to be a useful factor in discriminating among options based on our current understanding. The total system life cycle cost analysis, conducted in support of the System Architecture Study, considered a scenario for the waste acceptance, storage and transportation that is consistent with the MGDS analyses assumptions. Somewhat different assumptions were used for the MGDS cost analyses. For this scenario, the conclusion was reached that there is a broad range in which the costs are not strongly sensitive to the areal mass loading. This conclusion applies only to the conditions in this study which considered a single repository with maximum emplacement of 70,000 MTU.

7. OTHER CONSIDERATIONS

7.1 INTRODUCTION

Several evaluations and analyses that would not conveniently fit in one of the previous sections are presented here. This section covers operability issues which can be affected by thermal loading. Thermal effects on operations might be mitigated by such things as ventilation or fuel aging, but might be aggravated by aspects associated with thermo-mechanical effects; these are discussed. The thermo-mechanical issues are briefly covered in this section. The impact of thermal loading on geochemistry in the host rock is presented here. The requirement and ability to monitor the potential repository until final closure are also discussed.

7.2 OPERATIONAL CONCERNS

Ventilation

Emplacing hot waste provides a significant operational challenge. However, an even larger operational challenge results when it becomes necessary, for whatever reason, to retrieve a WP from a very hot drift. In that case ventilation concepts must be considered to reduce the air temperature of an emplacement drift to a more manageable level, such as 50 degrees Celsius. Work done by the M&O Subsurface Group (M&O, 1993f) was used to evaluate the ability to blast cool a drift to a temperature that would allow for operations. The near-field results provided the input temperature profiles used in the evaluation.

Certain things were not considered in this particular analysis. Specifically, off-normal events were not evaluated. Such an event might be a rock fall limiting the amount of ventilation that could be sent through the drift. The removal of moisture through ventilation may provide an advantage that should be considered. Another issue not considered was the thermo-mechanical response of the host rock to the effects of blast cooling. It is possible that such blast cooling may establish a large enough thermal gradient that deleterious rock stresses might occur. These issues were beyond the scope of the current study and will be considered in formulating recommendations for future work.

Ventilation is likely the most effective means of providing an acceptable operating environment for support of retrieval operations. Basically, cooling with air is a process of removing heat from a surface through convective heat transfer generated by the airflow motion and the temperature differences between the bounding surface and the flowing air. The amount of heat energy removed during this process is related to the temperature difference, surface geometry, nature of fluid motion, and a number of the fluid thermodynamic and transport properties. The M&O ventilation study (M&O, 1993f) determined that it would be impractical and very expensive to provide continuous ventilation for all the emplacement drifts due to the extremely large air quantity required and the considerable number of ventilation shafts required to carry the large quantity of air. Consequently, this analysis focused on ventilating one previously sealed drift to allow for limited retrieval operations.

The ventilation study (M&O, 1993f), which uses a fairly simple approach to the problem, used the following relationship relating airflow Q with an ambient temperature of T_i entering the tunnel and exiting with a temperature T_e, to the heat removal rate by this airflow, q_{vent}:

$$q_{vent} = \rho \; Q \; c_p \; (T_e - T_i) \qquad (7\text{-}1)$$

where q_{vent} = heat energy removed from the repository by ventilation (W)
ρ = density of ventilating air (kg/m^3)
Q = volume flow rate of air (m^3/s)
c_p = specific heat of air at constant pressure (J/kg °C)
T_i = the air temperature of inlet air, 26 °C in this analysis
T_e = the air temperature of exit air

Air density, ρ, and specific heat, c_p, vary insignificantly over the temperature ranges of interest. Thus constant values of $\rho = 1.21$ kg/m^3 and $c_p = 1.005$ J/g °C were selected. The M&O report (1993f) derived the temperature change in a cylindrical drift as a function of time using Equation (7-1) as the starting point. The report found that for this configuration to produce a given air temperature at exit, call it T_a, which is set at 50 degrees Celsius, the following relationship holds:

$$T_a = T_{ir} - (T_{ir} - T_i) \exp\{-(k \, C_a \, O \, L)/(\rho \, Q \, c_p \, R_o)\} \qquad (7\text{-}2)$$

where O = perimeter of the airway (m)
L = length of airway (m)
T_{ir} = initial rock mantle temperature (°C)
R_o = hydraulic radius of the airway
C_a = a dimensionless parameter frequently called the coefficient of age. It shows how the wall temperature decreases with time. Mining tables could be used to evaluate this constant or it can be calculated iteratively (see M&O, 1993f report, page 46).
k = the thermal conductivity of rock (W/m °C) set to 2.1 (DOE, 1992c)

The time functionality enters into the problem through the term C_a. This term is expressed as (M&O, 1993f):

$$C_a = B_i - [B_i^2/(0.375+B_i)] \{1-\exp(z^2)[1-(2/\pi^{0.5}) \int_0^z \exp(-z^2) \, dz]\} \qquad (7\text{-}3)$$

where B_i = Biot number (hR_0/k), dimensionless
F_0 = Fourier number ($\alpha\tau/R_0^2$), dimensionless
z = $(0.375 + B_i)F_0^{0.5}$, dimensionless
$\propto$ = Thermal diffusivity of rock (m^2/s)
τ = Time (s)
h = Convective heat transfer coefficient (W/m^2 °K)

Equation (7-3) can be expanded in a series form and solved. To solve for the temperature vs time an iterative solution of Equation (7-2) was done using the time dependency implicit in Equation (7-3).

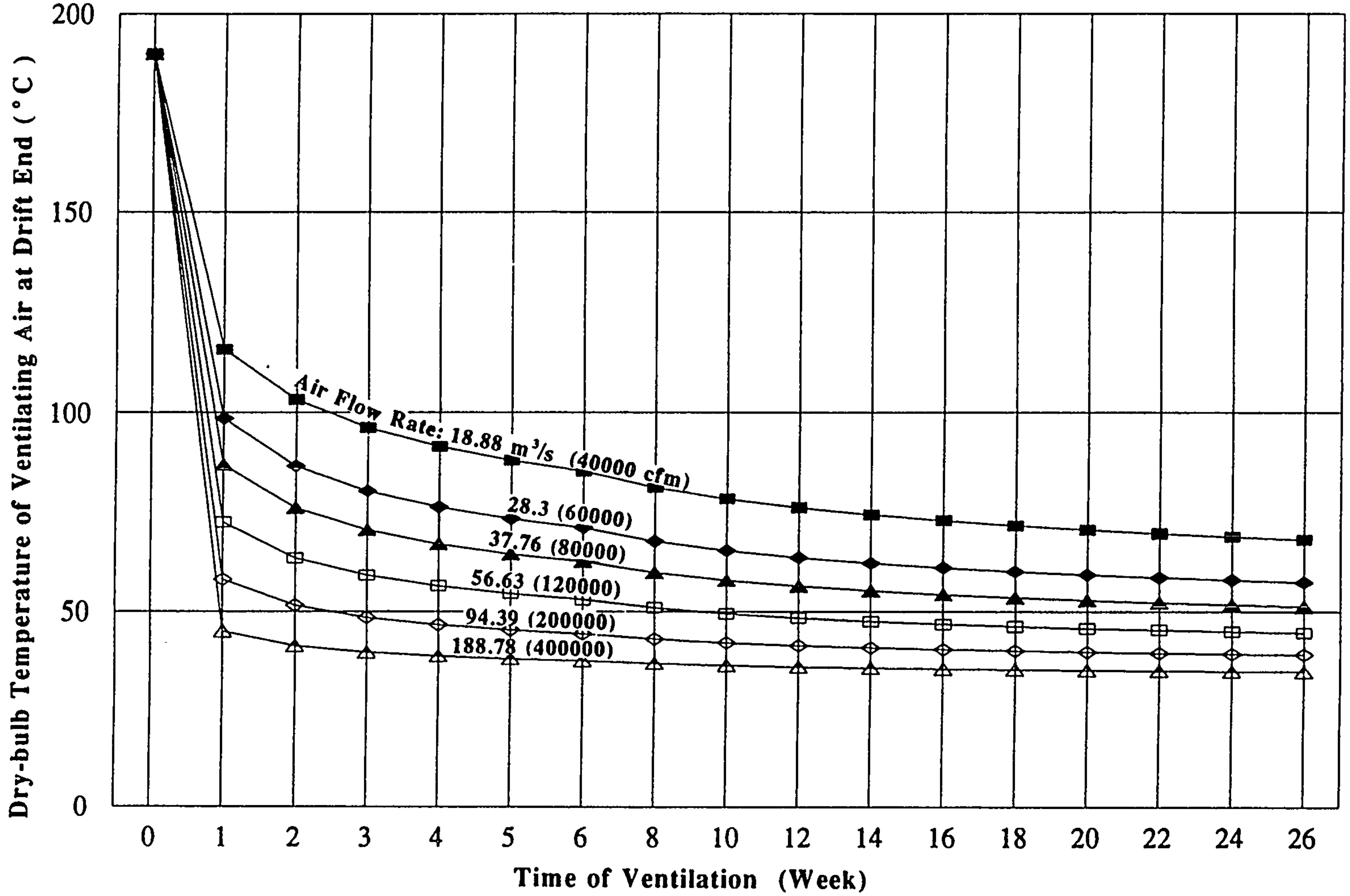
Equation (7-2) was used to evaluate the time it would take to ventilate an emplacement drift from 186 degrees Celsius to 50 degrees Celsius. Figures 7-1 and 7-2 show the results of this analysis for various airflow rates for two different drift diameters of 7 and 4.3 m respectively. The drift length considered was 625 m since it was assumed that there would be a main access tunnel down the center of the potential repository. An examination of these figures shows that the air temperature can be reduced to 50 degrees Celsius over a time frame of about 1 to 8 weeks depending on drift size by using an airflow from 188.8 m^3/s (400,000 cfm) to 56.6 m^3/s (120,000 cfm) respectively. These airflows would require a velocity of about 1.5 to 4.9 m/s in a 7 m drift or about 3.9 to 13 m/s in a 4.3 m drift. This demonstrates that it should be possible to ventilate a few drifts simultaneously since these airflows are achievable with present technology. These results compare well with cooling times calculated with more detailed models (Danko, 1992 and Danko and Mousset-Jones, 1993).

The above analysis used dry-bulb temperatures. Greater ventilation flow rates might be necessary to achieve acceptable temperatures when wet-bulb or globe temperatures are considered. This is due to the fact that humidity, radiant heat load, and air velocity all can have a substantial impact on comfort, safety, and working efficiency of personnel. Thermal conditions are therefore incompletely described by the dry-bulb temperature. Other measures, such as wet-bulb temperature, globe temperature, or specific cooling power, are typically used to more completely describe the thermal environment. As this study used dry-bulb temperatures, the ventilation rates shown here should not be seen as conservative values, but simply indications of the magnitude of the rates that will be required. The expected high humidity and high radiant heat load conditions would require greater ventilation rates than the values presented here to allow manned access.

Access Drift Temperature

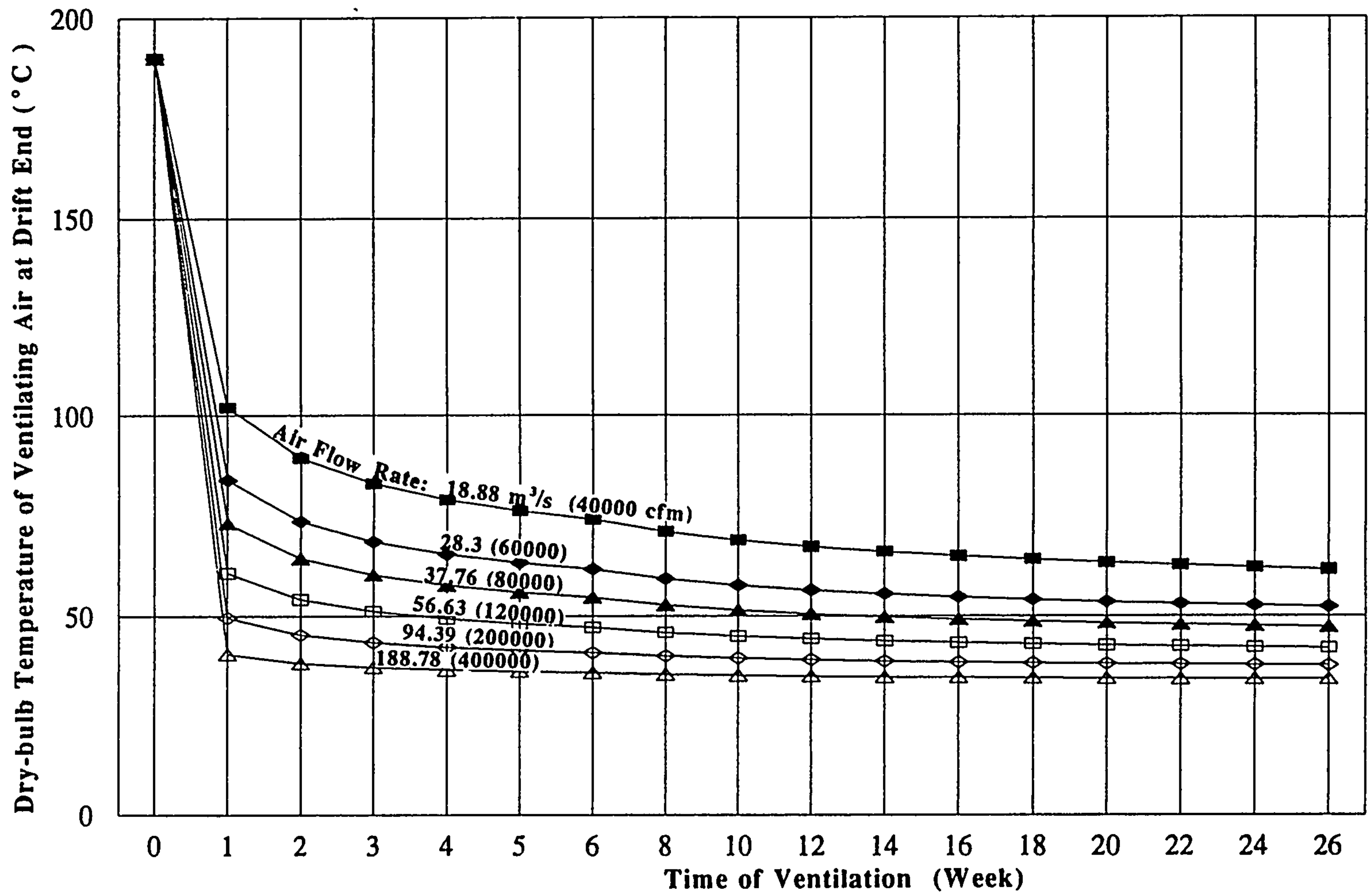
Two of the thermal goals (13 and 15 in Table 2-1) were established to provide for conditions that would allow retrieval of the SNF should such an eventuality be necessary. The goals were to maintain air temperatures in the access drifts at or below 50 degrees Celsius during the first 50 years after emplacement. This was to be done in the original SCP (DOE, 1988) using a combination of setback distances and thermal load. The setback distance is the distance of the first WP from the access drift. The generic designs used in this study, which were discussed in Section 3, allowed for a setback distance between 40 and 44 m.

V-TOUGH just calculates bulk average temperatures; however, the program could also be used to calculate temperatures at a distance from the radial disk source in the same plane as the radial disk source. Calculations were done with V-TOUGH at thermal loadings of 111 and 55 MTU/acre. The temporal variations in temperature at 44 m from the edge of the heated disk are plotted in Figure 7-3.



* *Under conditions of: 1) Drift diameter 7.0 m, 2) Drift length 625 m, 3) Initial rock temperature of 190 °C at beginning of ventilation, , 4) Waste package diameter 2.4 m, 5) Intake air temperature 30.3 °C.*

Figure 7-1. Air Temperature Variation During the Cooling Period After Sealing*
(In-Drift Emplacement, 7 Meter Diameter Drift)



* *Under conditions of: 1) Drift diameter 4.3 m, 2) Drift length 625 m, 3) Initial rock temperature of 190 ° C at beginning of ventilation, , 4) Waste package diameter 2.4 m, 5) Intake air temperature 30.3 ° C.*

Figure 7-2. Air Temperature Variation During the Cooling Period After Sealing*
(In-Drift Emplacement, 4.3 Meter Diameter Drift)

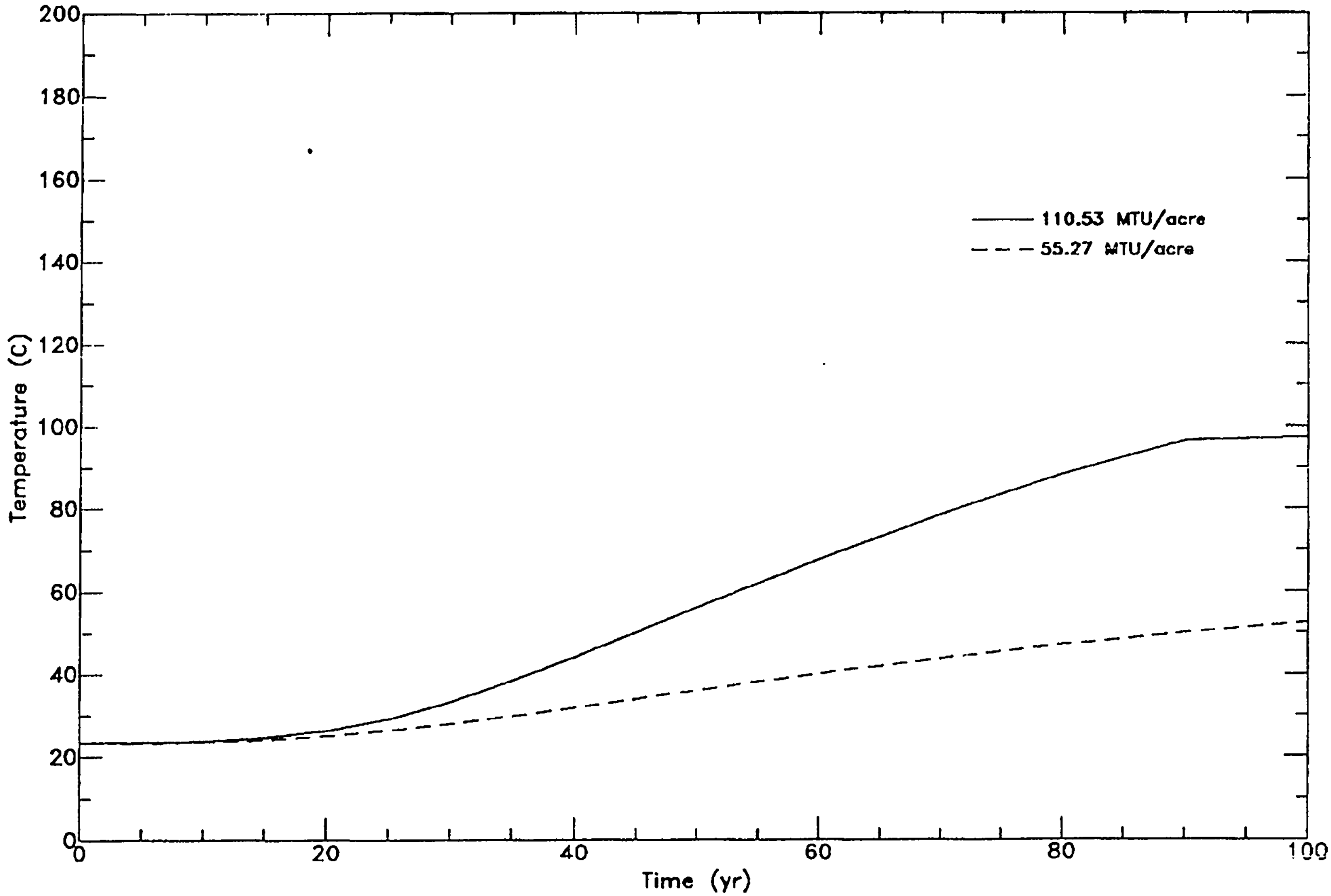


Figure 7-3. Temperature Along the Centerline of the Main Access Drift
(Centerline of the Main Drift is 44 m Away from the Nearest Waste Package)

An examination of the figure shows that only the 111 MTU/acre case exceeds the 50 degree Celsius temperature during the 50 year time span. Although the 83 MTU/acre case was not done, interpolation between the 55 and 111 MTU/acre curves indicates that access drift temperatures would be slightly less than 50 degrees Celsius at 50 years. Thus, loadings of 83 MTU/acre and below would meet the goal and were assigned a utility factor of 1. The 111 MTU/acre case was given a utility factor of 0 since the goal was violated; however, ventilation would likely lower the air temperature to an acceptable level. The utility factors for this thermal goal are tabulated in Table 8-1 in the next section.

Certain caveats need to be discussed before closing this topic. The above analysis was not conservative. If temperatures other than bulk average temperatures were used and if an access drift in the center of the repository were considered, it is almost certain that the goal would be violated at both 111 and 83 MTU/acre. Additionally, if the period of retrieval is extended to say 100 years, even 55 MTU/acre would violate the goal. However, if ventilation were to be used based on the discussion above, the temperatures could be kept below 50 degrees Celsius in the access drifts at times well beyond 50 years. Ventilation and/or other cooling enhancement techniques will be a requirement to allow any access and merit further study and evaluation.

Fuel Variability and Aging

Average waste stream characteristics were used in the study, but there are other considerations associated with the SNF that may affect performance in a potential repository. A wide range of variability in fuel characteristics (age, burnup, and enrichment) can be expected. This can produce hotter or cooler WPs than average. As a result of this, hotter or cooler spots than the average could be produced in the potential repository. Depending on the thermal strategy ultimately selected, fuel variability could cause some areas of the potential repository to exceed thermal goals and other areas might allow condensate flow to concentrate in locations where a cooler WP or WPs are placed. Further discussion of this important aspect of the problem will be deferred until the FY 1994 study.

Fuel emplaced at a specific AML produces near-field temperatures that are a function of factors such as fuel age, burnup, enrichment, and emplacement (WP spacing, drift spacing, and drift size). The temperature profile in the very near field of the WP can be reasonably peaked in the near term after emplacement. This peaked behavior in the near field can be moderated to some extent by aging the fuel either at the reactor or in a Monitored Retrievable Storage (MRS) location. An example of the effect of aging on peak temperature is shown in Figure 7-4. Calculated peak rock temperatures are shown for fuels that have been aged 20, 35, and 50 years and are then all emplaced at an AML of 80 MTU/acre. The example used was taken from earlier work done in the Phase I Thermal Loading Study (M&O, 1992) and the fuel characteristics are slightly different than those used in this study but the trend is expected to be the same.

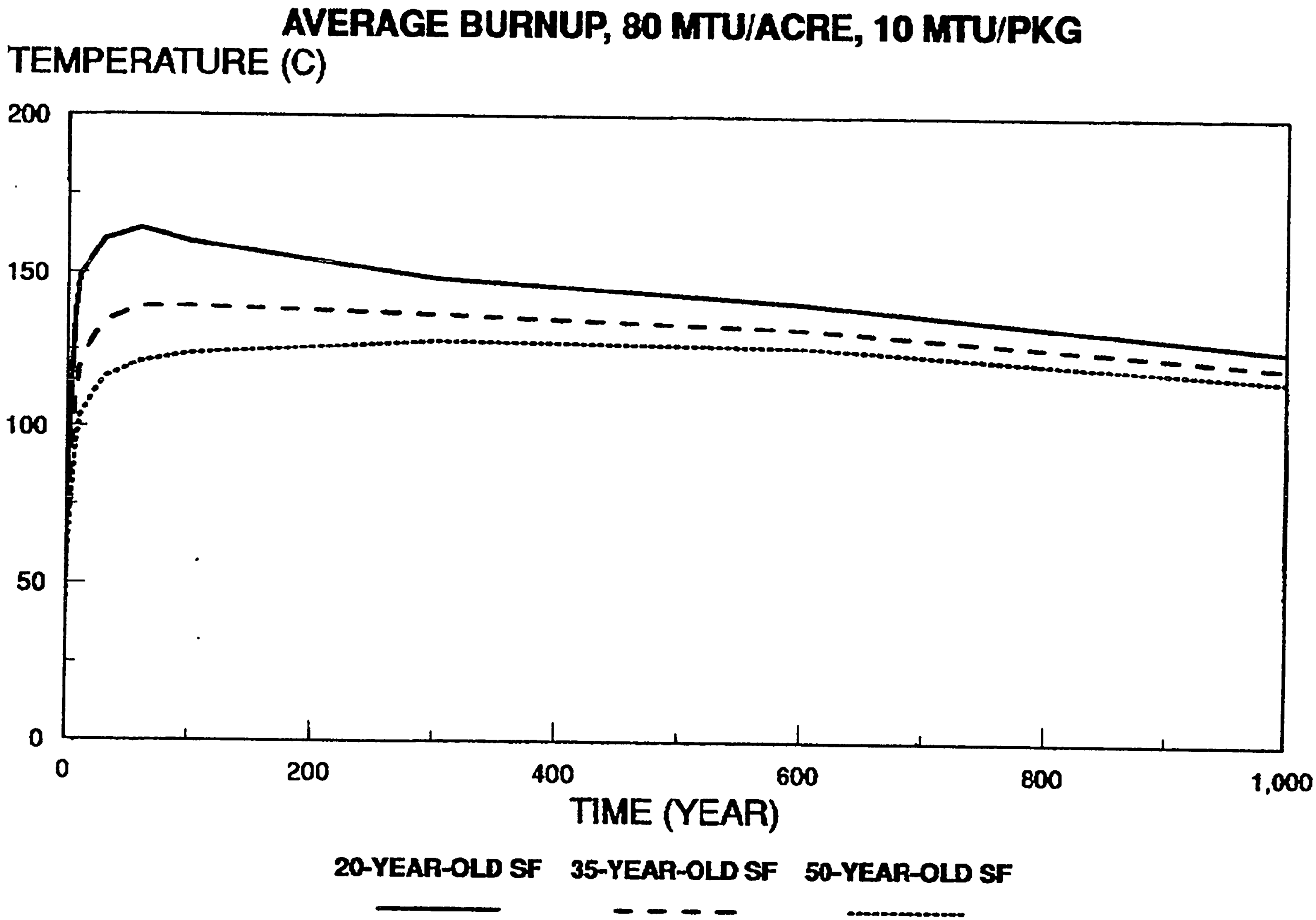


Figure 7-4. Maximum Rock Temperature

An examination of the figure shows that aging the fuel about 30 years over what would normally be received for disposal can result in a decrease in peak temperatures by about 30 to 35 degrees Celsius. This could mean the difference between meeting or exceeding a thermal goal. Beyond about 400 to 500 years, however, the heat profiles differ little among the different age fuels. The thermal effects beyond this time do not depend on the relative local effects, but on the integrated heat deposited up to that time. Thus, for example, it is unlikely that fuel aging for 20 to 50 years could be used to allow the 111 MTU/acre loading to improve much at meeting postclosure goals since calculations in Section 5 show the goals are exceeded at times beyond 400 years.

Fuel aging, however, has a price. A typical MRS is anticipated to cost about $4M; the cost for at-reactor storage varies but is likely to be in the range of $1M per year (M&O, 1993j). Such costs have been looked at in the cited reference and the trade-offs studied as to which storage method is cheaper as a function of storage time required. The advantages and disadvantages of aging the fuel should be examined in more detail but will have to be deferred to a later study.

Thermo-mechanical

Thermo-mechanical calculations were planned using the results of the near-field thermal predictions. Unfortunately they proved to be more difficult than anticipated and could not be completed in the time available. They will be completed in the next phase of the study. However, some preliminary calculations done by SNL earlier in the year and reported in the SCP Thermal Goals Reevaluation report (M&O, 1993a) were used to provide some guidance. This subsection outlines the findings in that area.

Recent thermal expansion analysis (see discussion on page 12 and Appendix A of the M&O, 1993a reference) was done by SNL which indicates that changes of as much as a factor of five in the coefficient of thermal expansion of the host rock may occur around temperatures of 180 to 250 degrees Celsius. A series of simple thermal and structural calculations were performed to determine the ramifications of this change in expansion coefficient. The results (see cited reference) indicate that it is primarily the temperature gradient that causes structural instabilities. In this simple model, which neglects the effects of time at temperature on rock strength, if the wall temperature is kept below about 200 degrees Celsius, the temperature gradients will be kept low enough so that it is unlikely that large-scale failure will occur. However, SNL cautioned that blast cooling could cause large temperature gradients that may have implications for stability which ultimately could impact retrievability.

An analysis of the near-field temperature data shows that for the 111 MTU/acre case the 200 degrees Celsius wall temperature is exceeded. Based on the SNL calculations this would indicate that there is a potential for large-scale failures in rock stability. This could not only severely impact retrievability operations, should it occur, but may result in opening fracture pathways that might impact waste isolation.

7.3 GEOCHEMICAL

A preliminary evaluation was done by LANL of the geochemical effects of the various thermal loads on the far-field repository rock units and what potential impact these geochemical effects might have on radionuclide retardation. The results of the far-field analysis, both temperature profiles and saturation profiles, were provided to LANL and used in their evaluation. The results of their evaluation are attached in Appendix I and the results summarized in this section.

The preliminary assessment concentrated on three general geochemical processes: 1) mineral dehydration of zeolites, clays, and volcanic glass; 2) crystallization of volcanic glass to a secondary mineral assemblage ("zeolitization"); and 3) recrystallization of clinoptilolite-opal cristobalite tridymile mineral assemblages to analcime-quartz assemblages. In the first process, dehydration of minerals, the concern is that the loss of water from zeolites may be partly irreversible and may cause irreversible structural changes. Contraction of the crystal lattices of the minerals may also cause irreversible changes in bulk hydraulic properties. In the second process, crystallization of volcanic glass may cause a reduction in hydraulic conductivity in nonwelded tuffs. In welded tuffs the process may cause a reduction in porosity, but the effects on hydraulic conductivity are unknown at this time because fracture flow is an important component of overall conductivity. The third process of recrystallization may have an impact since analcime, the final product, has less sorptive capacity for some radionuclides than does clinoptilolite.

The geochemical concerns are different in the various stratigraphic units. LANL performed an evaluation by stratigraphic unit as shown in the following summary:

PTn:	glass dehydration (reversible), zeolitization (irreversible)
Repository horizon:	little or no mineralogic effects
TSw3:	glass dehydration (reversible), zeolitization (irreversible)
CHnv:	glass dehydration (reversible), zeolitization (irreversible)
CHnz:	zeolite dehydration (partly reversible), zeolite recrystallization (irreversible)

Since there are only trace quantities of zeolites or other hydrous minerals in the repository horizon, the effects of heat or changes in liquid saturation on mineral dehydration are expected to produce minimal mineralogic effects at the repository horizon. The nearest zone in which significant dehydration may occur is in the devitrified-vitric transition zone (TSw2-TSw3 boundary). Significant water is contained in the zeolites and glass which, upon dehydration, could mediate the temperature increase. Unfortunately nothing quantitative can be concluded at this stage about the impacts on performance. Similar dehydration at the higher thermal loads can be expected for the glass and zeolite-bearing moderately welded and nonwelded tuffs farther down (CHnv and CHnz). Mineral dehydration is likely a negligible concern for the 24 MTU/acre case because the calculations show little or no change in liquid saturation.

Tables describing some of the concerns and possible effects on retardation at the various thermal loads are presented in Appendix I. At 111 MTU/acre there are probably some irreversible changes which can affect hydrologic properties in the CHnv layer and could cause increased channeling of recharge water in the PTn layer. At 83 MTU/acre the changes in the CHnv layer are thought to be reversible, and it is not expected to observe long-term effects either there or in the PTn layer. At lower thermal loads the mineralogic changes are thought to be either minor or not expected at all.

Although the above results are based on the best available data, there currently exists a paucity of information on some geochemical aspects of the host rock at Yucca Mountain. Specific information is required in certain areas. The following information, for example, would assist in the evaluation process:

- Data on energetics of zeolite dehydration and transformation (recrystallization)
- Effects of existing lateral stratigraphic variation, in particular the differences between sections where CHnv is thick (west) and thin or absent (east)
- Effects of mineralogic alteration on rock properties in terms of how or to what degree heterogeneities might be introduced.

With the above unknowns that remain it is not possible to come to a quantitative conclusion at this time. It would appear that for the 111 MTU/acre case the goal (16) to not degrade the PTn layer might be compromised, but the results are not conclusive. This goal will have to wait for further studies to be evaluated. However, one conclusion that can be made is that the higher temperatures and changes in liquid saturation produced by the higher thermal loads, particularly the 111 MTU/acre case, will significantly increase the uncertainty of the effects of geochemical alterations in the far field on radionuclide retardation.

7.4 MONITORING PERFORMANCE

Although monitoring the potential repository after emplacement and until permanent closure was not spelled out in the SCP as a thermal goal, it is required by regulations. Specifically, 10 CFR 60.143 (CFR, 1993) mandates that a program be established to monitor the WPs until permanent closure. Additionally, 10 CFR 60.141 states that appropriate in-situ monitoring of the thermo-mechanical response of the underground facility shall be conducted until permanent closure to ensure that the performance of the natural and engineered features are within design limits. Other passages, such as 10 CFR 60.141, 140, 133, 131, 101 and 51, all state that monitoring of the underground facility will be done. The ability to monitor the potential repository will be impacted by the thermal loading since instrumentation and components can have significantly reduced lifetimes under high temperatures. This section discusses this aspect of performance and provides some recommendations.

A small study was done in support of this work on the reliability of electronic equipment as a function of temperature. The detailed results of this study are reported in Appendix G. The study found that the thermal environment during the emplacement and retrieval period will have an influence on the type and kind of equipment that can be used in the near field. Electronic equipment, such as radiation monitors, alarm systems, communications systems, and electrical motors all are sensitive to elevated temperatures. The study concluded that most electronic equipment will not perform reliably above 160 degrees Celsius. This is certainly a bounding temperature since in most cases equipment failure rates became appreciable between 80 and 160 degrees Celsius. Some examples of normalized failure rates for linear devices such as transistors are shown in Figure 7-5 and failure rates of discrete components are shown in Figure 7-6. Additional component failure rates are provided in Appendix G. An examination of these figures
and those in Appendix G shows that the failure rates for electronic components increase from several times to often two orders of magnitude at elevated temperatures. A summary of the study's conclusions follows:

1. Particular attention should be paid to electronic system maintenance for systems forced to operate above 80 degrees Celsius.

2. Options which require electronic systems to perform above 160 degrees Celsius should not be considered unless active cooling (air conditioning, freon-type cooling loop, or other) of those systems is employed.

3. A review of the total electronic monitoring system as opposed to the piecemeal approach taken here should be undertaken to define the exact capability. It is likely, owing to the complexity of electronic systems, that the absolute upper temperature bound of 160 degrees Celsius will prove to be too high.

Based on the above analysis, an evaluation was done as to the ability to monitor the potential repository from emplacement to closure under the various thermal loads. Both the far-field and near-field temperature profiles calculated for the study were used in the assessment. Both far-field and near-field results indicate that the 160 degree Celsius temperatures are definitely exceeded in the case of a thermal loading of 111 MTU/acre. Thus, as discussed earlier in the evaluation of the thermal goals, a utility factor of 0 can be assigned to this thermal load since it cannot meet the criteria. Recall that a utility factor of 0 implies that the goal is violated and a utility factor of 1 implies that the goal is met. In the case of the 83 MTU/acre thermal load the bulk average temperature is below 160 degrees Celsius but the near-field results show wall temperatures of about 175 degrees Celsius. Instruments to monitor the WP and the wall thermo-mechanical response would have to be placed in the wall and would be subject to these temperatures. However, while it is not practical to ventilate all the emplacement drifts to the extent discussed above, it may be possible to ventilate all the drifts to reduce the temperature about 15 degrees. An issue may be that the rock temperatures could still be high due to radiation heating; this would need further evaluation considering the total electronic monitoring system. Thus, it was felt that this option may or may not be possible and should be assigned a utility of 0.5. All other thermal loads produce temperatures significantly below 160 degrees Celsius and so were assigned utilities of 1. The tabulation of these utility factors for monitoring is found in Table 8-1 in the following section.

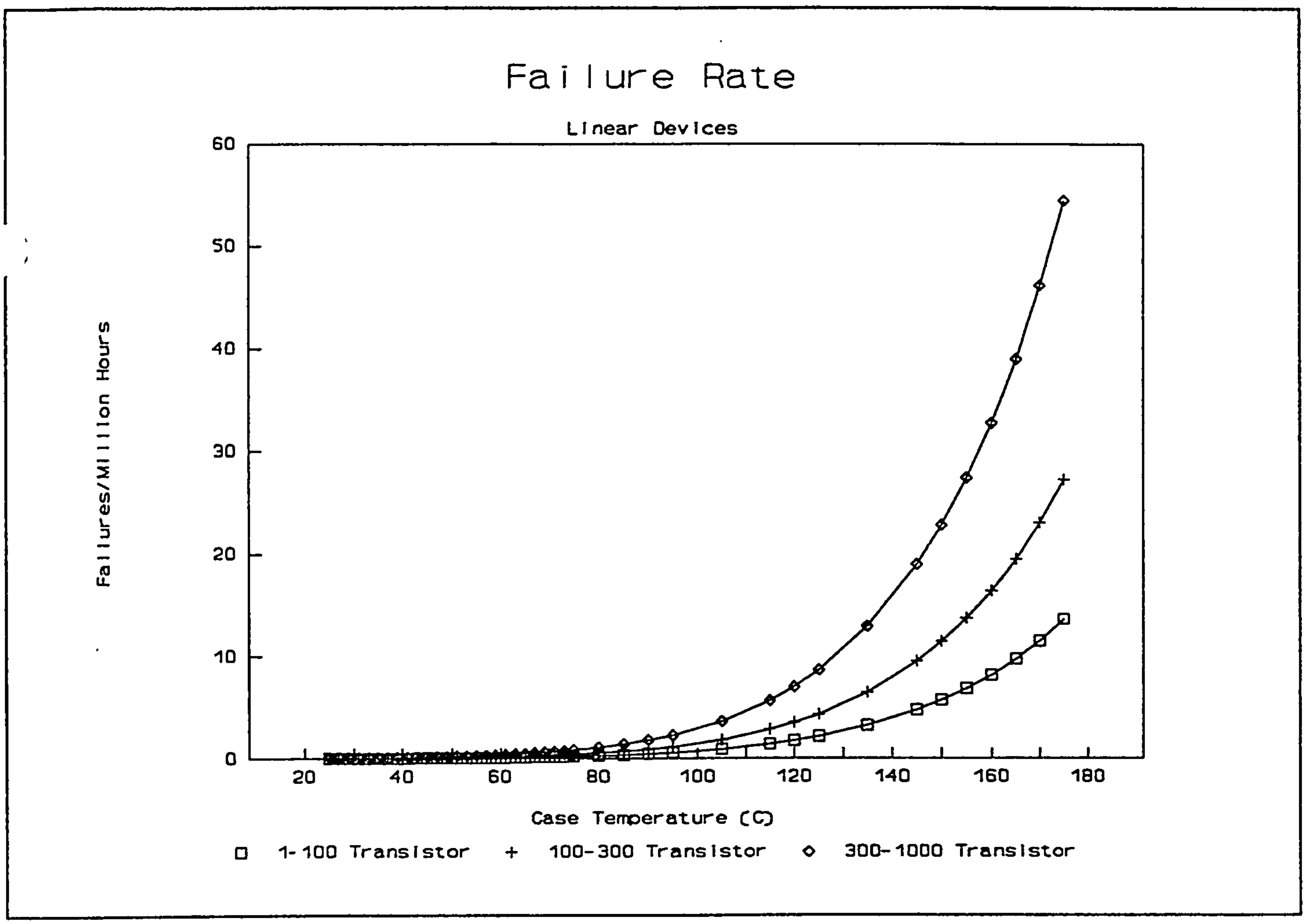


Figure 7-5. Normalized Failure Rates of Linear Devices

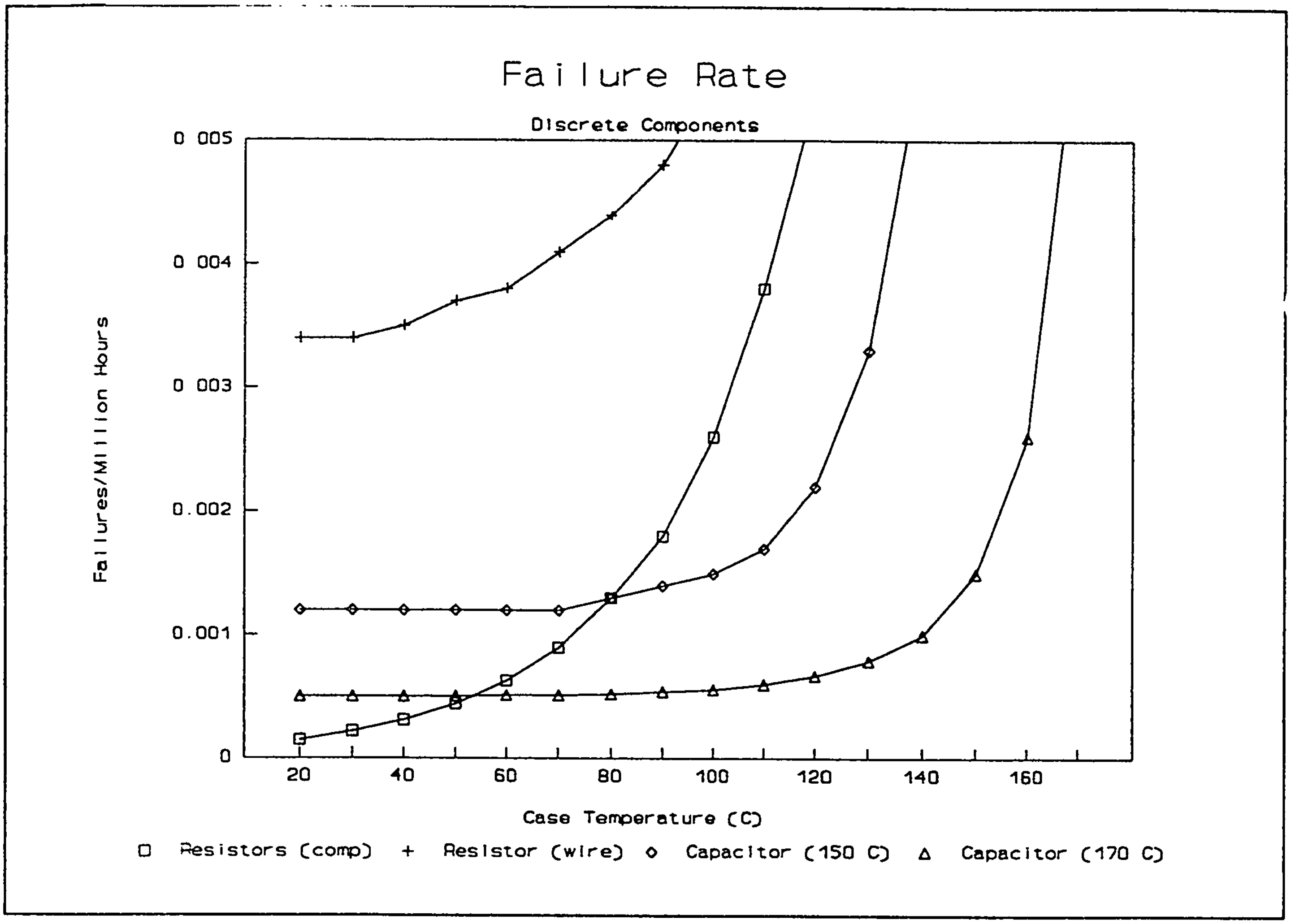


Figure 7-6. Normalized Failure Rates of Discrete Electronic Components

7.5 SUMMARY

A number of other concerns including operational aspects were evaluated in this section. Ventilation was addressed and from the results it was concluded that the temperature in a single drift could be reduced from about 190 to 50 degrees Celsius in a period of one to eight weeks. While it is practical to ventilate a few drifts, it was determined that ventilating the entire repository to reduce the temperature to 50 degrees Celsius would be impractical although some reduction in temperature could be achieved. Some additional predictions were done with the V-TOUGH code to examine the temperature rise at a given distance from the drift (e.g. in the access tunnel). The results showed that the thermal goal to keep the access drifts at 50 degrees Celsius during the retrieval period would be violated in the 111 MTU/acre case. Fuel variability and aging were looked at briefly and it was determined that fuel variability is one of the uncertainties that must be addressed in the next study. Fuel aging can be used to provide some improvement in near-field performance but long term performance is a function primarily of AML and will not be influenced significantly by aging. The thermo-mechanical performance was examined using some calculations done by SNL in another effort. The results showed that the 111 MTU/acre case may have potential for large-scale rock stability problems. LANL used the far-field calculations to draw some conclusions about geochemical alterations. The conclusion from this effort was that the uncertainty of the geochemical alterations and their effect on waste isolation increases with increasing thermal load. Finally, monitoring was addressed and it was determined that at temperatures above 160 degrees Celsius, monitoring is unfeasible and that the 111 MTU/acre case produces temperatures well above this level.

8. SYSTEM ANALYSIS

8.1 INTRODUCTION

The ability to meet the overall performance requirements for the proposed MGDS at Yucca Mountain, Nevada requires the two major subsystems (natural barriers and engineered barriers) to positively contribute to containment and radionuclide migration retardation. In addition to the postclosure performance the proposed repository must meet certain preclosure requirements of safety, retrievability, operability, and also must consider cost and schedule. The thermal loading strategy chosen for such a proposed repository may significantly affect both postclosure and preclosure performance.

Depending on the WP size, age of the fuel, emplacement mode, and other factors, the temperatures in the host rock could be significantly above the boiling point of water for a very long period of time. In the near term, high temperatures can have a significant impact on preclosure performance from the standpoint of worker safety and retrievability of the waste. Over a longer period of time the high temperatures could, in some cases, improve performance by drying out the rock or conversely may even contribute to a degradation in the waste isolation capabilities. For example, temperatures above boiling will tend to dry out the rock which could result in reducing the aqueous corrosion of the waste canisters for a significant period of time. Conversely, high temperatures and thermal gradients can, under certain conditions, induce fractures in the rock as well as initiate water movement and/or mineral dissolution and precipitation along pre-existing fractures in the form of heat pipes. This behavior could change the structural integrity of the host rock and modify fracture permeability in case of potential water flow. Silica dissolution and precipitation can also occur and affect the hydrologic framework. These effects could significantly alter the hydrologic behavior around the repository. High temperatures can also induce chemical and/or phase changes in some minerals which, under some conditions, can produce conditions less favorable or maybe even more favorable for adsorption of radionuclides. At intermediate temperatures the effects may tend to result in changes to the water chemistry which could result in an increase in the corrosion rate of the WP. When T-M-H-C coupled behavior is considered, the problem is further complicated. From the standpoint of safely emplacing the waste and/or retrieving the waste, high temperatures can degrade our ability to perform these operations.

It would not be appropriate or licensable to select a thermal loading that optimizes one aspect of the problem such as postclosure performance but would not allow the SNF to be safely emplaced. All aspects of the problem must be examined and an attempt made to select a strategy that will provide a global optimum system rather than a local optimum. In the previous sections, this FY 1993 Thermal Loading Study has looked at various aspects of the problem such as near-field performance, far-field performance, geochemical, and thermo-mechanical conditions that would allow monitoring, and cost. This section will discuss these issues and their impact on waste isolation, preclosure operations, and cost.

8.2 PERFORMANCE EVALUATION

In the preceding sections an evaluation was made of the performance against the thermal goals. A mapping of the various goals to the applicable regulations is shown in Section 2 in Table 2-2. In the near-field analysis, the near-field temperature profiles were used to determine how well each of the thermal loading ranges did at achieving some of the thermal goals identified as applicable to near field and preclosure. In Section 5 the far-field, postclosure performance was evaluated in terms of the thermal goals applicable to those processes. The results of work discussed in Section 7 on the ability to achieve 50 degrees Celsius access temperatures and on the effect that elevated temperatures might have on the ability to monitor the preclosure performance of a potential repository were also considered. The results of these evaluations are summarized in Table 8-1.

The table uses utility factors to establish performance. As discussed in preceding sections the performance against a particular goal was established in terms of utility factors. The utility factors used were either 1 or 0 based on whether the particular thermal goal was met or violated. Fractional utility factors were allowed in some cases where the goal was exceeded in all probability but it could not be substantiated whether some fraction of the potential repository area met the goal but some fraction did not(e.g. when the temperature equals the limit at 451 and 1000 years but no intermediate data were available).

One way to evaluate or "grade" the performance against the thermal goals is to weight each of the goals equally. These are, however, goals and not inviolate criteria and thus such an application would be unrealistic. Specifically, studies and data may ultimately indicate that improved performance could be achieved by relaxing a particular goal. An example of this may be allowing the waste package to exceed the 350 degrees Celsius centerline temperature to achieve an extended hot condition if it is shown that this will substantially improve waste isolation performance. One way to determine the weighing that a given goal should have is to rely on expert elicitation. Steps were taken to initiate this process but the effort was not completed and will be resumed during the follow-on study. Thus, the combined performance against each goal was measured and, although somewhat unrealistic, each goal is presented with the same weight as all the other goals. *However, the reader is cautioned that at this juncture it would be a mistake to sum the columns of utility factors in Table 8-1 to arrive at a total score for each thermal load.*

An examination of the results in Table 8-1 indicates that the 111 MTU/acre thermal load produces conditions that violate all but two of the thermal goals. In the case of the 350 degrees Celsius fuel cladding goal, efforts were made early in the study to establish subsurface designs and WP spacings that would not violate this goal. The goal to maximize the time that the WP is above boiling is a somewhat different goal than the others and some caution needs to be exercised in applying it since there is considerable uncertainty in the corrosion initiation mechanism and environment (M&O, 1993h). The results of the geochemical analyses indicate that more work needs to be done to evaluate whether increased temperatures degrade the ability of the natural barriers to inhibit radionuclide transport. Thermal goals of 115 degrees Celsius at the Calico Hills unit and the interface between the TSw2 and TSw3 units still apply and they would be violated for the 111 MTU/acre case.

Table 8-1. Evaluation of Thermal Criteria Using Systems Study Results
(Utility of 1 implies goal met; Utility of 0 implies goal violated)

	24 MTU/Acre	36 MTU/Acre	55 MTU/Acre	83 MTU/Acre	111 MTU/Acre
1 m rock temp. in borehole <200°C[1]	1	1	1	1	0
In-drift wall temp. <200°C	1	1	1	1	0
Fuel cladding temp. <350°C	1	1	1	1	1
Access drift temp. <50°C for 50 yr after emplacement	1	1	1	1	0
Do not load WP beyond limits (i.e. borehole collapse)	1	1	1	1	0
Limit temp. of CHn to <115°C	1	1	1	1	0
Limit temp. of TSw3 to <115°C	1	1	1	0.5	0
Maximize time WP above boiling	0	0	0.2	0.6	1
160°C Monitoring Goal	1	1	1	0.5	0

[1] Goal met for 6 PWR package. Any WP with >5.2 kW (e.g. the 12 and 21 PWR) will exceed thermal goal.

These goals were originally established in the belief that compliance would minimize alterations that might impact waste isolation.

The study found and reported in Section 7 that the performance could very likely not be monitored under thermal load at 111 MTU/acre. Although the thermal goal to keep the access drifts at 50 degrees Celsius for 50 years was violated for 111 MTU/acre, the ventilation results showed that this might be mitigated. Although not presented in Table 8-1, the thermo-mechanical calculations presented in Section 7 showed that rock stability in the drifts would likely be compromised under the temperature gradients produced at 111 MTU/acre and, although some significant engineering might be considered to mitigate this condition, it should probably be avoided.

Although the far-field hydrothermal calculations indicate that the majority of the repository will be significantly drier for an extended period of time (several thousand years), the above discussion demonstrates that the thermal environment produced at 111 MTU/acre or above is "too hot" and a recommendation is made to stay below this thermal loading in the potential repository.

In the case of the other thermal loads (24 to 83 MTU/acre), the results show that for the most part the environments produced under these conditions will meet the thermal goals. The results do indicate that at 83 MTU/acre the temperatures in a few cases are close to violating some of the thermal goals but this is probably still an acceptable thermal load. Thus, for these thermal loads the goals discussed above can probably not be used further as discriminators.

Although no cases were run between 83 and 111 MTU/acre, it was concluded that an interpolation could be accurately made between the two to establish at what AML all the thermal goals that were violated at 111 MTU/acre are still violated. The near- and far-field data were examined and interpolations made between the two thermal loads for which predictions were made. The interpolations indicate that the 200 degree Celsius wall temperature goals and borehole goals would be violated for AMLs above about 100 MTU/acre. The 50 degrees Celsius temperature for 50 years goal is violated for AMLs above 89 MTU/acre. The temperature limit of 115 degrees Celsius at the TSw3 unit is violated above about 83 MTU/acre while interpolations indicate that the similar goal for the CHn unit is violated for AMLs above 99 MTU/acre. The thermo-mechanical estimates show that above about 100 MTU/acre there is potential for large scale rock failure and thus the goal to ensure that the WP is not loaded beyond established limits would be exceeded. The results of the instrumentation failure study showed that above about 83 MTU/acre the ability to monitor the potential repository is compromised. Based on these considerations it is apparent that for 100 MTU/acre or higher (based on 100 MTU/acre being the highest limit above) all the thermal goals that were violated at the higher loading of 111 MTU/acre will be violated. Thus, a more stringent recommendation, but still conservative, is that AMLs of 100 MTU/acre or higher are "too hot."

8.3 TOTAL SYSTEM PERFORMANCE ASSESSMENT

Information on the total system performance, estimating radionuclide releases to the accessible environment, was based on the analyses done in TSPA-II (M&O, 1993h). The TSPA-II conducted sensitivity analyses of several different design options to include three thermal loads and three WP sizes in several emplacement modes. The TSPA-II analysis used a robust, two-barrier WP which is one of the options being evaluated by the Waste Package Design Group and should not at this time be considered to constitute a design decision. The fuel characteristics were similar in nature to those used in the thermal loading study. The three thermal loads investigated were 114, 57, and 28.5 kW/acre. The 114 kW/acre case would be identical to the 111 MTU/acre case in this study, while 57 kW/acre represents the reference case corresponding to this study's 55 MTU/acre. The 28.5 kW/acre is close to the 24 MTU/acre (about 25 kW/acre) case chosen in this study. Thus, the cases are very similar and the TSPA results can be directly applied to the thermal loading study.

The calculations of both cumulative radionuclide releases and the peak individual dose were done for TSPA-II for the three thermal loads using the RIP code (Golder, 1993). For each load, the study conducted hydrothermal analyses to determine the water saturations and temperatures in the vicinity of the WPs (out to 5 meters in the rock). These calculations were performed with the V-TOUGH code described elsewhere (Nitao, 1989 and Pruess, 1987). The calculated parameters (water saturation and temperature) were used to define the initiation of aqueous corrosion and a range of thermally-dependent properties affecting the WP/EBS release. The actual WP temperatures, which were calculated separately, were used to evaluate corrosion performance.

The basic assumptions used by TSPA were that no corrosion occurred if the rock moisture content was less than eight percent. Above this, the corrosion of the outer barrier proceeded as a function of time and temperature. Pitting corrosion is the primary mechanism of failure for the inner barrier. Dry oxidation was assumed to be negligible. For more details, refer to the TSPA-II study (M&O, 1993h).

Any conclusions reached regarding the relative advantages or disadvantages of a particular concept must be predicated on the level of understanding that currently exists about the fundamental processes and parameters affecting performance. Significant uncertainties remain in our understanding of the very near-field environment and its effect on the WP lifetime and EBS release. Some of the sensitivities, such as the significance of alternate criteria for corrosion initiation, were investigated but this effort should be expanded. The uncertainties are discussed further in Section 9.

Figure 8-1 shows the predicted Complementary Cumulative Distribution Function (CCDF) for the integrated releases from the WP over 10,000 years for the three thermal loads. These releases are compared to the remanded EPA standard for 10,000 years which is exceeded if the predicted curves enter the shaded area on the right side of the plot. The gaseous releases, primarily ^{14}C, dominate the cumulative 10,000 year release when normalized to the Table 1 limits of 40 CFR 191. The gaseous releases to the accessible environment are controlled by the waste package lifetime, because the travel times from the repository to the accessible environment are short in comparison to the 10,000 year period. The aqueous releases to the

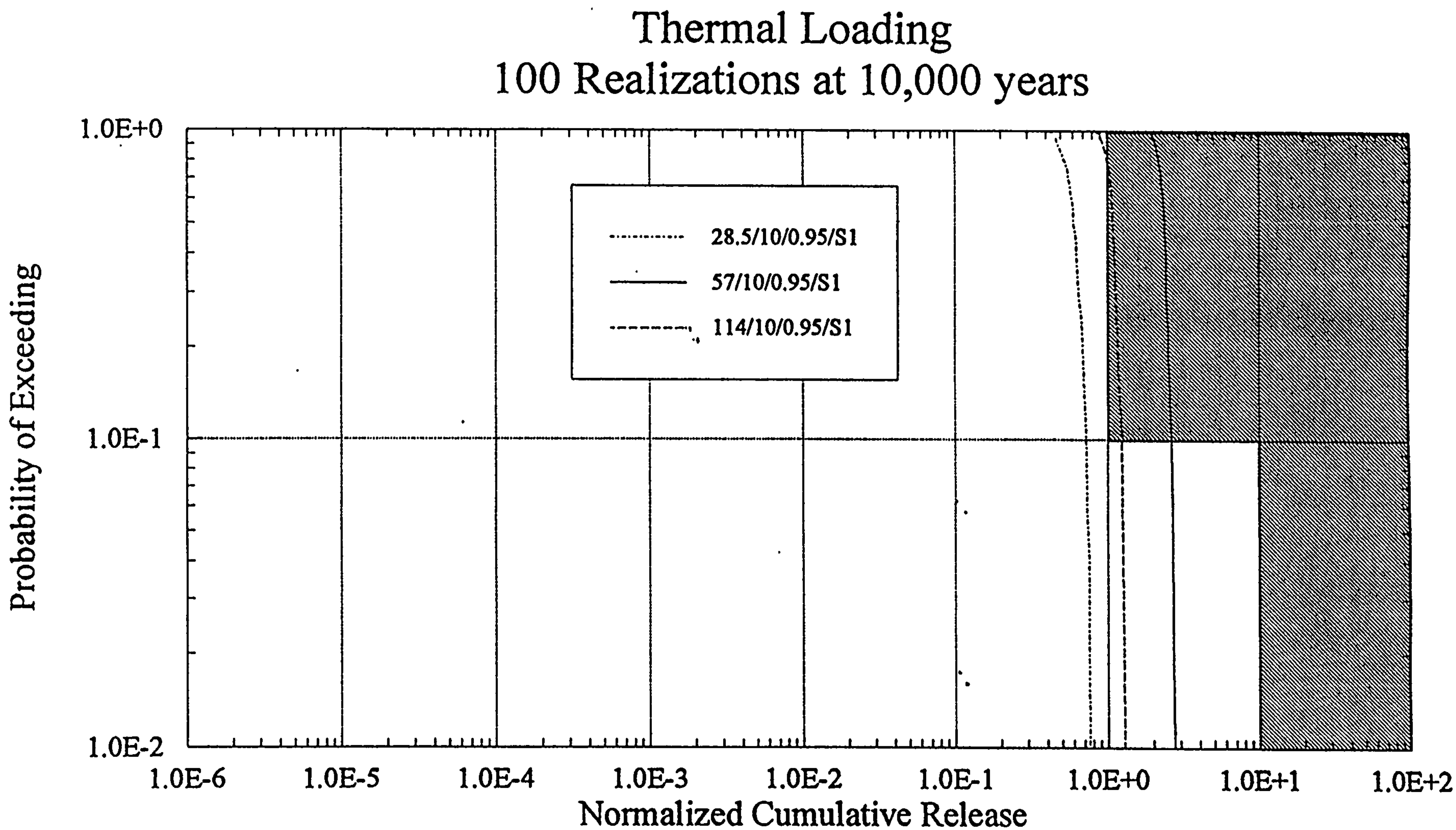


Figure 8-1. CCDF of Gaseous Releases to the AE at 10,000 Years for 28.5 and 114 kW/acre (This calculation used 10 cm mild steel outer barrier, 0.95 cm Alloy 825 inner barrier and the corrosion model with saturation based corrosion initiation)

accessible environment over 10,000 years are extremely small. Because the attached plots do not differentiate as to which radionuclides are contributing the most to the release rates, release standards on individual radionuclides should be considered in more detail by design studies.

The TSPA study concluded that for the 10,000 year integrated released to the accessible environment, the 114 kW/acre case generated lower releases than 57 kW/acre case by about a factor of three. This reduction is primarily a result of the delay in the initiation of aqueous corrosion due to the higher thermal load. The 28.5 kW/acre thermal load case produces releases that are also lower than the 57 kW/acre case. The 28.5 kW/acre case also produces lower releases than the 114 kW/acre case by about a factor of two. The integrated releases over 10,000 years are predominately gaseous releases and the aqueous release contribution is generally less than about 10^{-6} of the EPA values.

In an effort to evaluate releases at much longer times (the time frame of the EPA standard which is being repromulgated is uncertain at this time), the calculations were carried out to 100,000 years and longer. Figure 8-2 shows the integrated releases to the accessible environment for 100,000 years for the three thermal loads. For comparison purposes the EPA 10,000 year standard is drawn on the figure although no 100,000 year standard has yet been established. Using the EPA 10,000 year standard for comparison may be somewhat misleading since, although there are no standards for 100,000 years, the release limits would likely be increased over the 10,000 years. Thus, the fact that the curves exceed the 10,000 year standard is not meant to imply that they would exceed a 100,000 year standard. Unlike the 10,000 year case, where the gaseous releases completely dominate over the aqueous releases, the aqueous releases now are similar in magnitude to the gaseous releases. The releases plotted in Figure 8-2 are only aqueous releases since the gaseous releases were not included in the totals.

When integrating the releases to the accessible environment over 100,000 years, the study again concluded that the higher and lower thermal loads produce lower releases than the moderate 57 kW/acre. However, the cumulative releases for the various thermal loads are closer (within 50 percent of each other) than was the case at 10,000 years. At 100,000 years the aqueous releases are a significant component of the total.

In summary, for time periods on the order of 10,000 years, the high and low thermal loads provide better overall postclosure performance than the medium 57 kW/acre load. The low thermal load generally provides lower releases from the WP/EBS due to the lower corrosion rates at lower temperatures. The high thermal load provides lower releases due to the delay in the initiation of aqueous corrosion although once corrosion starts the higher temperatures result in faster corrosion. For the moderate temperature case, the host rock does not dry out appreciably in a significant portion of the potential repository and the higher temperatures produce higher corrosion rates. At times longer than 100,000 years, the effect of the thermal loading on the peak individual dose appears to be nearly indistinguishable among the three cases (M&O, 1993h). However, there is currently no dose specification for this length of time and the uncertainties associated with predictions to this time scale are substantial. In

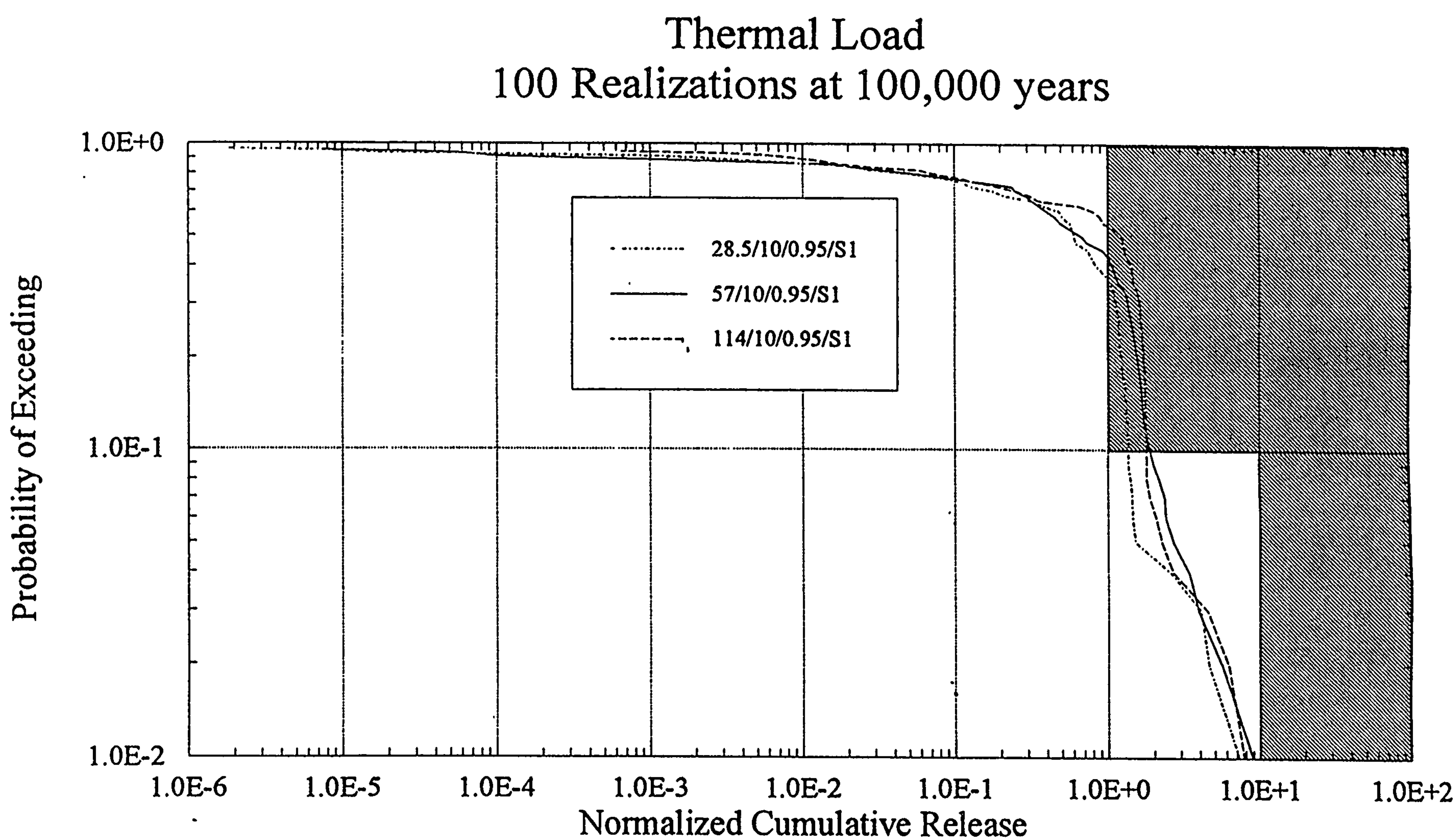


Figure 8-2. CCDF of Releases to the AE at 100,000 Years for 28.5 and 114 kW/acre. (This calculation used 10 cm mild steel outer barrier, 0.95 cm Alloy 825 inner barrier and the Stahl corrosion model with saturation based corrosion initiation)

fact, there are substantial uncertainties associated with all the predictions and an assessment of these uncertainties is left to Section 9.

8.4 COST

An evaluation of the costs associated with waste storage in an MGDS was done in Section 6. The evaluation included costs associated with different WP sizes, underground excavation costs, surface facility costs, development, and site characterization costs. For the MGDS, the cost basis changes with WP size. The most expensive for in-drift emplacement is the 6 PWR compared to the 21 PWR, with the 12 PWR case intermediate between the two. However, the 6 PWR vertical emplacement has costs similar to the 12 PWR case since the additional costs of shielding and operations in a radiation environment were not needed for this case. Each of the three in-drift WP sizes differs in cost by about $2 to $3 B. However, the most significant finding is that, for a given WP size, the variation in costs is relatively insensitive to thermal loading. As one goes from a thermal loading of 111 to 24 MTU/ acre the cost variation is only a few percent. This small variation in costs is achieved by varying the drift spacing to achieve the desired thermal loading. If varying the WP spacing were required the cost differences could increase to as much as 5 to 10 percent between the hottest and coolest strategy.

The above deals only with MGDS costs. As discussed in Section 6, an assessment was made of the total system costs which include transportation, waste acceptance, and storage costs. The basis for this assessment was the work done for the Systems Architecture Study (M&O, 1993k). The study examined costs for a below boiling and above boiling repository. The results indicated that total costs differed at most about 10 percent between the two options.

The conclusions from both the MGDS work and the total system analysis is that cost differences between a hot and a below boiling option are not large (at most 10 percent). Certain specifics of these cost analyses, as discussed in the Section 9, need to be refined somewhat further before a final conclusion can be drawn.

8.5 SUMMARY

The results of the previous sections were compiled and evaluated in this section. The results of the various thermal calculations evaluated against the goals, including the monitoring criteria, were tabulated. The results indicated that the 111 MTU/acre case violated all but two of the thermal goals. Using interpolation between the temperatures predicted at 111 and 83 MTU/acre it was determined that all the goals violated at 111 MTU/acre would also be violated at 100 MTU/acre. This established that thermal loads above 100 MTU/acre are "too hot."

The TSPA calculations done by the M&O to determine the release of radionuclides to the accessible environment were evaluated in this section. The results of the TSPA work indicate that for the double walled WP with 10 cm outer layer, aqueous releases are not significant at 10,000 years. However, at 10,000 years the gaseous releases of C14 are appreciable with the

57 kW/acre case having the highest release, followed by the 114 kW/acre case (a factor of three lower), and the 28.5 kW/acre case having the lowest release (a factor of 2 lower than the 114 kW/acre case). At 100,000 years TSPA concluded that aqueous releases are starting to become appreciable and, although there was not too much difference between the cases, the 28.5 kW/acre case tended to have slightly lower cumulative releases.

9. ADDITIONAL THERMAL ANALYSES

9.1 IDENTIFIED UNCERTAINTIES

A key undertaking of the Thermal Loading Study was to identify areas or parameters where levels of uncertainty are high. If these uncertainties were to be reduced, our understanding of waste isolation/waste emplacement would be improved. The optimum procedure to do this is to use the detailed process models and run a variety of cases that allow variations over the range these parameters are presently known to cover. When sensitivities to waste isolation are shown to exist as a given parameter is varied, further study of this parameter is warranted. The next question, which is beyond the scope of this effort, is are there tests that can be done which will measure the parameter to sufficient accuracy that the uncertainty can be reduced to the level necessary? Unfortunately the optimum procedure could not be done due to restrictions of time and budget. Therefore, for the purposes of the study, it was necessary to rely on the judgement of experts (LLNL, SNL, LANL, and M&O PA) who had made a variety of calculations over the years and have some experience as to which parameters were the most sensitive. Thus, this section provides a synopsis of the parameters or issues those people most familiar with the problem feel should be emphasized. The issues are divided into five areas; waste stream, WP, geochemistry, hydrothermal, and cost.

Waste Stream

In the area of uncertainties about waste and waste characteristics, the issue that must be addressed is the affect that fuel variability has on the thermal loading. The variability could produce local hot or cold spots which could influence pre- and postclosure performance. This issue will be evaluated in the FY 1994 Thermal Loading Study.

Waste Package

Certain issues must be considered in establishing the performance of the WPs. Specifically, the corrosion of the WP materials under the conditions in the potential repository over long time periods is not well known and estimates differing by an order of magnitude are currently used. Thus, it will be necessary to establish when corrosion initiates and the corrosion rates as a function of temperature.

There is considerable uncertainty as to what performance allocation can or should be given for the fuel cladding. It is possible that no postclosure performance can be obtained from the cladding. In either case it will be necessary to ensure that the cladding has sufficient mechanical integrity for retrieval operations. This is particularly important if larger WPs such as MPCs are to be employed. The temperature dependence of fuel cladding performance needs to be investigated.

Geochemistry

The effect of geochemical changes, due to thermal and liquid saturation changes, on radionuclide retardation and bulk hydraulic conductivity is not well understood. To obtain a better understanding of these processes, it was suggested that certain additional information was needed. Specifically data on energetics of zeolite dehydration and transformation (recrystallization) are of interest. There is significant variation in the stratigraphy with respect to concentrations of the zeolite-bearing moderately welded and nonwelded tuffs, clays, and volcanic glasses. Thus, information is required on the effects of existing lateral stratigraphic variations, in particular the differences between sections where CHnv is thick (west) and thin (east). Finally, mineralogic alteration of rock properties in terms of how or to what degree heterogeneities might be introduced needs to be understood.

A significant uncertainty in the geochemistry area is the changing water chemistry occurring as a result of the thermal environment; also, the impact of changes in water chemistry on the EBS (particularly WP corrosion), fuel alteration, and radionuclide dissolution. Silica dissolution and precipitation and its effect on hydrologic flow need to be understood. This information is needed for understanding the implications of above boiling conditions.

Another significant uncertainty at this time is how much actual useable area exists at the repository horizon. Determination of this issue will have to wait until additional drilling is completed and the ESF is actually excavated. Even this may provide only a partial answer on a relatively small area, but the results should be possible to correlate with borehole information.

Hydrothermal

At this point in time hydrologic uncertainties go beyond the uncertainties in the parameters used in the models to support the study. Conceptual uncertainty exists regarding the extent and nature of spatial averaging which would capture the processes and conditions that are important to radionuclide transport. At this point in time the equivalent continuum model has not been validated by site data. The numerical exercises conducted for this study have, however, pointed to some parameter uncertainties that exist within the model and these are discussed below.

Better information is required on the host rock matrix properties and fracture densities in the potential repository. Bulk permeability, both gas and liquid, is uncertain and variations in this parameter can significantly influence the transport of both heat and fluid. The uncertainty must be reduced in this parameter as well as in the degree of heterogeneity that exists in the potential repository. As a part of this, the fracture-matrix interaction in the unsaturated zone must be better known. This information will not only affect the postclosure performance but will impact the WP and drift-scale hydrothermal regimes.

Numerical simulations have predicted formation of dry-out for sufficiently high heat loads. However, these predictions are an average over a fairly extensive area and assume local thermodynamic equilibrium between rock and fracture matrices (Pruess and Wang, 1987 and Pruess and Tsang, 1993). It has not been established whether thermodynamic equilibrium in fact holds on a drift or WP scale. The potential repository host rock is known to be heterogeneous to some degree. As such, one may expect differential drying and condensation effects that could minimize fluid flow near some packages while enhancing it near others. This needs to be investigated further.

An important example of these uncertainties is the bulk permeability. Prediction of water movement has been shown, in Section 5 and Appendix F, to be sensitive to bulk permeabilities. A value of 280 milliDarcys is representative of rock that has three 100 micron fractures per meter. However, recent analysis (Lin et al., 1993) has shown that the linear fracture frequency needs to be corrected by the angle the fracture makes with the borehole. When this is done, the fracture density in the Topopah Spring Unit is estimated at about 15 fractures per meter. Although this is significantly higher than the figures used in the study, no fracture size information was available in the report to estimate bulk permeability. Gas permeability measurements reported by Wilson, et al. (1994) indicate bulk permeabilities in TSw2 in the range from 0.1 to 10 Darcy. The report documented limited checking of the procedure with the conclusion that it appeared valid, but admitted that the correction factor may overestimate the number of vertical fractures. Clearly this uncertainty as to actual bulk permeability must be resolved to be able to accurately predict fluid movement in the mountain.

Another significant uncertainty is the percolation flux that exists in the mountain. The TSPA study (M&O, 1993h) showed that under some conditions, an increased percolation flux will produce a significant increase in release to the accessible environment (AE). An example of this is shown in Figure 9-1 in which the normalized total release of Tc99 to the AE is plotted as a function of liquid flux in terms of a parameter QFLUX for a 10 cm thick WP emplaced at 57 kW/acre.

Thermo-mechanical calculations are needed to determine the response of the host rock under the various thermal loading conditions. These analyses are planned for the follow-on study.

The thermal performance of the host rock and the thermal effect on water movement are not well established either. Underground heated block tests are planned to assist in acquiring this information. These tests are particularly critical in establishing how much water is moved, whether heat pipes occur, and whether convective processes are important.

All the above data are needed to reduce the uncertainties and develop an improved hydrologic data base. The improved data base is needed to provide sufficient information to validate the equilibrium continuum models being considered for the predictions of hydrothermal behavior.

Cost

A number of uncertainties exist in the cost basis at the present time and only some of the major uncertainties are cited here. Specifically, it needs to be determined whether the size of the ESF is a function of thermal loading and any cost impact ascertained. If a low thermal load strategy is chosen, there needs to be an evaluation of which expansion areas are useable and whether there are significant costs incurred to access these expansion areas. Critical information needed for high thermal loads is the cost of the emplacement vehicles, particularly if fully automated vehicles are required, and the cost of shielding. Finally, the costs of monitoring have not been investigated; these may vary with thermal load.

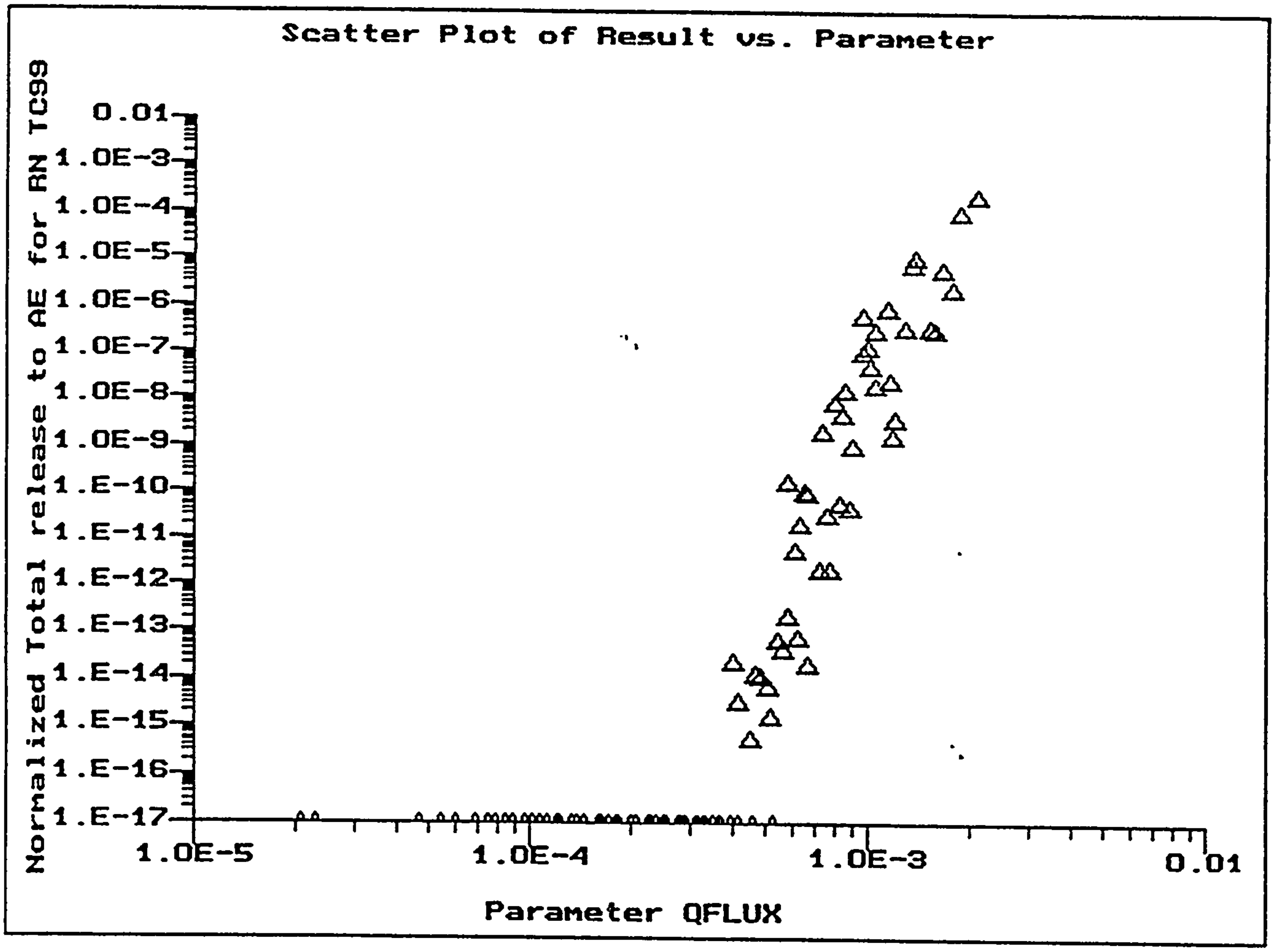


Figure 9-1. Normalized Total Release of Tc99 as a Function of Percolation Flux

9.2 SUMMARY

Key uncertainties important to waste isolation were identified in discussions with the various analysts. Significant uncertainties exist in the area of the hydrothermal response of the host rock. The host rock matrix and fracture properties must be better understood to establish the flow and transport of water in the mountain. As a part of this, the bulk permeability is a significant unknown as well as the extent of any heterogeneities in the mountain. The percolation flux also must be better known. Once these are known, it needs to be determined whether the mountain is in thermodynamic equilibrium.

The thermo-mechanical response of the rock, particularly around drift openings, needs to be better understood. Hot spots or, conversely, cold spots resulting from fuel variability could create areas of stress. Thus fuel variability needs to be investigated. Additionally, fuel aging needs to be looked at to determine if such a solution might be used to moderate near-field temperatures and the impact of aging on the system.

A number of geochemical uncertainties were identified in the study. Some of the important concerns are what lateral stratigraphic variations exist in the zeolite bearing rocks. Also, better information is needed on geochemical alterations as a function of temperature and time.

WP corrosion processes as a function of temperature and water content need to be better known. Are there materials or engineered diffusion shields that might be used to mitigate some of these uncertainties?

The mitigation of some of the near-field high temperatures and possibly moisture removal may be possible using ventilation and cooling enhancement techniques. This effect should be examined further.

The mitigation of some of the near-field high temperatures and possible moisture removal may be possible using ventilation. This effect should be examined further.

Cost impacts of the various aspects of the system need further refinement. Emerging considerations in potential repository layout and operational concepts must be factored into the cost analysis.

The key uncertainty of the amount of useable area will likely remain uncertain until additional borehole and underground data are available. The number and extent of the fault zones need to be understood.

10. CONCLUSIONS AND RECOMMENDATIONS

The FY 1993 Thermal Loading Systems Study was conducted from December 1, 1992 to December 30, 1993. It was originally planned to be completed by September 30, 1993, but DOE granted an extension when delays were experienced in receiving critical input from the laboratories due to their participation in the TSPA-II study. This section describes the conclusions and/or recommendations developed during the study.

The objective of the MGDS Thermal Loading Systems Study being conducted by the M&O is to identify a thermal strategy that will meet the performance requirements for waste isolation that will be safe and licensable. Specifically, the thermal loading strategy selected must meet both postclosure and preclosure performance standards. In addition, cost and schedule constraints must be considered. The Systems Engineering approach provides structured, detailed analyses that ultimately will establish the technical basis for the development, integration, and evaluation of the overall system, not just a subelement of that system. It was the intent of this study to begin the structured development of the basis for a thermal loading decision. However, it is recognized that the ability to make a final decision on thermal loading will require underground data on the effects of heating as well as a suite of "validated" models. It will be some time before these data and models are available to the program.

To accomplish the objectives of the study, a reevaluation of the SCP thermal goals was first done. The report (M&O, 1993a) of this work has been published. The goals were linked to the various requirements as discussed in Section 2. The design groups (WP and Subsurface) supported the program by providing generic designs which became the bases for the calculations done for the study. The national laboratories supported the program by providing thermal, hydro-thermal, and geochemical evaluations of the various thermal loading options (24, 36, 55, 83, and 111 MTU/ acre) considered in the study. For the most part, the latest available data (e.g., those values believed at this time to be most likely to exist in the potential repository) were used in the analyses. An analysis of all this work was done and performance, both pre- and postclosure, operations aspects, uncertainties, and cost were examined to develop the technical basis for making recommendations to narrow the range of thermal loading.

Based on the results of the study certain conclusions could be reached. The study demonstrated that the environment produced by the 111 MTU/acre case or higher violates most of the thermal goals. Currently it is still the experts' consensus (M&O, 1993a) that meeting the thermal goals is necessary to achieve acceptable waste isolation and preclosure performance. Although no weighing of the goals could be done at this time to show which goals were more important, the message that 111 MTU/acre is too hot would almost certainly remain unchanged by weighing the goals since all but two goals are violated by this load. Also, the preliminary thermo-mechanical indications are that under these conditions, there is a potential for large-scale rock failure around the drifts. The geochemical evaluations concluded that the temperature and liquid saturation changes for this thermal load would produce a higher uncertainty in the geochemical processes with potential consequences on waste isolation. Operations aspects are very challenging and would require remote emplacement. The calculations of the vertical extent of perturbed water demonstrate that the high thermal loads will produce conditions that are much more difficult to maintain, particularly in the presence of local heterogeneities. Additionally the study showed that it would be highly unlikely that monitoring could be achieved for this case. Although it was shown that ventilation could be used to reduce the temperature to 50 degrees Celsius in one or two drifts for retrieval, the results showed that ventilation to reduce the entire repository to 50 degrees Celsius would not be practical. Furthermore, since the goals at 111 MTU/acre were exceeded by a wide margin, interpolations of the data were used to determine at what lower AML all those goals would just be exceeded. The evaluation reported in Section 8 showed, conservatively, that all the goals violated at 111 MTU/acre are also violated at 100 MTU/acre. Thus, based on these concerns it is recommended that AMLs of 100 MTU/acre or higher be avoided. Additionally for this case the continuum equilibrium model predicted large scale redistribution of fluid in the mountain for long periods of time.

The 83 MTU/acre case did not violate the thermal goals although in some cases it was close to exceeding them. This high thermal load was predicted to result in some dry-out for extended periods; however, TSPA calculations are needed to show whether enhanced performance would be achieved. The study showed that monitoring would be a significant challenge but could not be ruled unachievable. The geochemical evaluations show that higher temperatures will produce higher uncertainties. Additionally, there will be a need to demonstrate an understanding of both above boiling and below boiling performance. The follow-on systems study should conduct some TSPA analyses to try to determine over what band acceptable performance could be achieved without violating important thermal goals, and confirm this by testing.

The moderate thermal loading case of 55 MTU/acre, the reference case, was shown to produce conditions in which a significant portion of the potential repository never exceeds boiling. This environment, in combination with the higher thermal loads, tends to exacerbate corrosion of WPs. The TSPA-II study (see Section 8 and M&O, 1993h) confirms this and concludes that over a 10,000 or even 100,000 year period the 55 MTU/acre case results in larger releases to the accessible environment than either the high or low thermal load cases. The range of AMLs over which this degraded performance occurs is uncertain, but it certainly begins where the repository becomes above boiling, somewhere just above 36 MTU/acre, to an AML above 55 MTU/acre. TSPA calculations are needed to better define this range. Thus, for this moderate AML range it appears that the environment would have hot enough temperatures to produce operational challenges but would have degraded performance at least over 10,000 years.

For the below boiling cases (24 and 36 MTU/acre), the results of the study show that negligible perturbation of the ambient liquid saturation values occurs. Although some local boiling can occur, the study showed that anywhere from 80 to 100 percent of the pillars between drifts could be kept below boiling. Thus, if ambient conditions are found to be acceptable for waste isolation, these AMLs should not perturb this state. A concern that must be addressed with lower thermal loads is whether sufficient useable area exists since more area will be needed than for the higher thermal loads to emplace the same amount of waste.

It should be noted that the above conclusions are based on a particular set of waste characteristics. Analyses using waste that is hotter or colder than that considered in this evaluation may results in a slightly different conclusion as to those thermal loads at which a particular goal might be exceeded. The dependence of the thermal loading effects on waste characteristics (and variability in these characteristics) is an important subject that will be investigated at the next stage.

The study attempted to determine which uncertainties exist that are important to establishing performance. Although sensitivity studies could not be run, some of the experts supporting the study were polled. A number of areas were found where it would be important to reduce uncertainties, as discussed in Section 9. Summarizing these results it is clear that some of the critical hydrologic uncertainties such as bulk permeability, fracture densities, and percolation flux need to be better known. The WP corrosion performance and the impact of fuel variability must also be understood. Reducing uncertainty associated with thermal goals and establishing their relative importance should be accomplished. Some uncertainties in cost must be resolved. Finally, one of the most significant uncertainties that must be resolved is how much useable area is present in Yucca Mountain. Uncertainties identified in the study plus some identified by the reviewers of this document have been summarized in Appendix J. The relative importance of the various parameters was not determined. To do this a sensitivity analysis is required and this is planned for a follow-on study. Additionally, the reader is cautioned that this list should by no means be considered a complete list.

The evaluation of MGDS costs showed that there was little variation (a few percent) between a hot or below boiling thermal load although there is still a measure of uncertainty associated with these estimates. This was confirmed when the total system costs were examined. For these costs, which include transportation, waste acceptance, and temporary storage, it appears there is at most about a 10 percent difference among the various thermal loads. Thus, barring an unforeseen significant change in cost of some element, costs do not appear to be a significant factor in choosing either a hot or below boiling option. This conclusion applies only to the conditions in this study which considered a single repository with maximum emplacement of 70,000 MTU.

11. GLOSSARY OF TERMS

AE - Accessible Environment

ALARA - As Low As Reasonably Achievable

AML - Areal Mass Loading of spent nuclear waste (MTU/acre)

APD - Areal Power Density of spent nuclear waste emplaced in the repository (kW/acre). This quantity varies with fuel type, amount of fuel, age and burning of fuel, and emplacement density.

ASME - American Society of Mechanical Engineers

B_i - Biot number (hR_o/k), dimensionless

BWR - Boiling Water Reactor

C_a - A dimensionless temperature frequently called the coefficient of age. It shows how the wall temperature decreases with time; mining tables are provided to evaluate this constant (see M&O 1993f report, page 46).

C/C - Center-to-Center spacing

CCB - Change Control Board

CCDF - Complementary Cumulative Distribution Functions

CDB - Characteristics Data Base

CDR - Critical Design Review (see QAP 3.2, Design Reviews); Conceptual Design for Repository; Conceptual Design Report

CFR - Code of Federal Regulations

CH - Calico Hills member (rock unit)

CHnv - Nonwelded vitric tuff

CHnz - Nonwelded, zeolitized tuff

cm - Centimeters

C_p - Specific heat of air at constant pressure (J/kg °C)

CRWMS - Civilian Radioactive Waste Management System

D - Equivalent heating duration (years)

D&E - Development and Evaluation

DHLW - Defense High-Level Waste

DOE - U.S. Department of Energy

EBS - Engineered Barrier System

EIA - Energy Information Administration

EPA - Environmental Protection Agency

ESF - Exploratory Studies Facility

FCR - Full Core Reserve

F_o - Fourier number ($\propto \tau/R_o^2$), dimensionless

ft - Feet

FY - Fiscal Year

GROA - Geologic Repository Operations Area

GWd - gigaWatt Days, a measure of spent fuel burnup

h - Convective heat transfer coefficient ($W/m^2\,^oK$)

HLW - High-Level Waste

hr - Hours

IOC - InterOffice Correspondence

K - Degrees Kelvin

k - Thermal conductivity of rock ($W/m\text{-}^0C$)

kg - Kilogram

km - Kilometer

kW - Kilowatt

L - Length of airway (m)

LAML - Local Areal Mass Loading. This is the areal mass loading in the emplacement area and does not include any areas needed for access to work areas.

LANL - Los Alamos National Laboratory

lb - Pound (1 lb = 16 oz = 0.454 kg)

LCC - Life Cycle Cost

LLNL - Lawrence Livermore National Laboratory

m - Meter

MGDS - Mined Geologic Disposal System

M-K - Morrison-Knudsen Company, Inc.

M&O - Management and Operating Contractor

MRS - Monitored Retrievable Storage

MTU - Metric Tons of Initial Uranium Equivalent

MWD - MegaWatt Days, this is a measure of spent fuel burnup

MPC - MultiPurpose Canister

NQA - Nuclear Quality Assurance

NRC - U.S. Nuclear Regulatory Commission

NUREG - Nuclear Regulatory Document

NWPA - Nuclear Waste Policy Act of 1982, as amended

NWPAA - Nuclear Waste Policy Act of 1982, Amendment of 1987

NWTRB - Nuclear Waste Technical Review Board

O - Perimeter of the airway (m)

OCRWM - Office of Civilian Radioactive Waste Management (DOE)

OFF - Oldest Fuel First

PA - Performance Assessment

Pmax - Specific thermal output of the waste at emplacement (kW/MTU)

PTn - Paintbrush Tuff, non-welded vitric tuff

PWR - Pressurized Water Reactor

Q - Volume flow rate of air (m^3/s)

QA - Quality Assurance, Quality Affecting

q_{vent} - Heat energy removed from the repository by ventilation (W)

q''_{max} - Areal power density at time zero into half plane (watts/m^2)

RIB - Reference Information Base

R_o - Hydraulic radius of the airway

SAS - System Architecture Study

SCP - Site Characterization Plan

SCPB - Site Characterization Program Baseline

SCP/CDR - SCP/Conceptual Design Report

SD - Systematic Drilling

SNF - Spent Nuclear Fuel

SNL - Sandia National Laboratories

t - Time; unless stated otherwise refers to time after emplacement

T - Temperature, also repository horizon temperature at repository center at time t

T_e - Temperature of exit air

T_i - Temperature of inlet air, 26°C in this analysis

T_{ir} - Initial rock mantle temperature, °C

T_o- Initial repository horizon temperature at repository center; chosen as 27°C

T_{max} - Maximum repository horizon temperature at repository center

TBM - Tunnel Boring Machine

TE - Thermal Expansion

TESS - TRW Environmental Safety Systems, Inc.

T-M-H-C - Coupled Thermal, Mechanical, Hydrological, and Chemical processes

TPC - Total Project Cost

TSPA - Total System Performance Assessment

TSLCC - Total System Life Cycle Costs

TSw - Topopah Spring member

TSw2 - Topopah Spring member; densely welded devitrified lithophysal-poor tuff

TSw3 - Topopah Spring member; vitrophyse tuff

U - Uranium

USGS - U.S. Geological Survey

UZ - Unsaturated Zone (above the water table)

W - Watt

Wb - Wet bulb

WBS - Work Breakdown Structure

WHB - Waste Handling Building

WP - Waste Package

WPA3 - Waste Package and Areal Power Density Approximate

WSM - Waste Stream Model

YFF - Youngest Fuel First

YFF(10) - Youngest Fuel First at least 10 years out of reactor

YM - Yucca Mountain

YMP - Yucca Mountain Site Characterization Project

YMSCO - Yucca Mountain Site Characterization Office

Yr - Year

∝ - Thermal diffusivity of rock

ρ - Density (g/cm^3) of rock or air depending on context

ρC - Volumetric specific heat of rock at repository horizon (W-yr/m^3 -°C)

τ - Time used in ventilation analysis

μm - Micro meter

z - $(0.375 + B_i)F_o^{0.5}$, dimensionless

12. REFERENCES

ASME, 1986: ASME Boiler and Pressure Vessel Code, Section III, Appendix I, pp 97-107.

Bahney, R.H. and T.W. Doering, 1993: "Waste Package Sizes Efficiencies and Weights," *TRW Environmental Safety Systems, Inc., Interoffice Correspondence, LV.WP.RHB.05/93-086*, prepared by Civilian Radioactive Waste Management System Management and Operating Contractor under Contract Number DE-AC01-91RW00134, Las Vegas, Nevada, May 11, 1993.

Bali, M. 1993: "Estimates for MPC Implementation Studies," *TRW Environmental Safety Systems, Inc., Interoffice Correspondence, LV.SD.MB.8/93-537*, prepared by the Civilian Radioactive Waste Management System Management and Operating Contractor under Contract Number DE-AC01-91RW00134, Las Vegas, Nevada, August 26, 1993.

Bhattacharyya, K.K. and D.G. Rasmussen, 1993: "Cost Estimates to Support Waste Package Allocation Study and Other Systems Studies," *TRW Environmental Safety Systems, Inc., Interoffice Correspondence, LV.SB.KKB.12/93-625*, prepared by the Civilian Radioactive Waste Management System Management and Operating Contractor under Contract Number DE-AC01-91RW00134, Las Vegas, Nevada, December 3, 1993.

Buscheck, T.A. and J.J. Nitao, 1993: "The Analysis of Repository-Heat-Driven Hydrothermal Flow at Yucca Mountain," *Fourth International Conference on High Level Radioactive Waste Management, Las Vegas, Nevada, April 26-30, 1993*, pp 847-867. (public document)

Buscheck, T.A. and J.J. Nitao, 1992: "The Impact of Thermal Loading on Repository Performance at Yucca Mountain, Proceedings," *Third International Conference on High Level Radioactive Waste Management, Las Vegas, Nevada, April 12-16, 1992*, pp 1003-1017.

Buscheck, T.A., J.J. Nitao, and D.A. Chesnut, 1991: "The Impact of Episodic Nonequilibrium Fracture-Matrix Flow on Geological Repository Performance," *American Nuclear Society, FOCUS '91 Conference on Nuclear Waste Packaging, Las Vegas, Nevada, September 29-October 2, 1991.*

Buscheck, T.A. and J.J. Nitao, 1988: "Preliminary Scoping Calculations of Hydrothermal Flow in Variable Saturated, Fractured, Welded Tuff During the Engineered Barrier Design Test at the Yucca Mountain Exploratory Shaft Test Site," *UCID-21571, Lawrence Livermore National Laboratory, Livermore, California, November 1988.*

CFR, 1993: "Disposal of High-Level Radioactive Wastes in Geologic Repositories," *10 CFR Part 60, Office of the Federal Register, Code of Federal Regulations revised January 1, 1993.*

Danko, G., 1992: "Modeling of the Ventilation for Emplacement Drift Re-entry and Rock Drying," *University of Nevada, Reno, report submitted to DOE for publication.*

Danko, G., and P. Mousset-Jones, 1993: "Modeling of the Ventilation for Emplacement Drift Re-Entry and Rock Drying," *Fourth International Conference on High Level Waste Management, Las Vegas, Nevada, April 26-30, 1994*, pp. 590-599.

DOE, 1988a: "Site Characterization Plan," *DOE/RW-0199, Nuclear Waste Policy Act (Section 113), U.S. Department of Energy, Oak Ridge, Tennessee.*

DOE, 1988b: "Draft 1988 Mission Plan Amendment," *DOE/RW-0187, Office of Scientific and Technical Information, Oak Ridge, Tennessee, June 1988.* (HQO.880620.0022)

DOE, 1990: DOE, OCRWM, "Preliminary Estimates of the Total-System Cost for the Restructed Program: An Addendum to the May 1989 Analysis of the Total-System Life Cycle Cost for the Civilian Radioactive Waste Management Program," *DOE/RW-0295P, Washington, DC 20585, December 1990.*

DOE, 1991a: DOE, Yucca Mountain Site Characterization Project Office, "Yucca Mountain Site Description Baseline (Basis for Site Characterization Plan, Chapter 8)," *YMP/CM-0008, Revision 0, April 19, 1991.*

DOE, 1991b: U.S. Department of Energy, Yucca Mountain Site Characterization Project Office, "Conceptual Design of a Repository (Basis for Site Characterization Plan, Chapter 8)," *YMP/ CM-0009, Revision 0, April 19, 1991.*

DOE, 1991c: DOE, Yucca Mountain Site Characterization Project Office, "Waste Package Design (Basis for Site Characterization Plan, Chapter 8)," *YMP/CM-0010, Revision 0, April 19, 1991.*

DOE, 1991d: DOE, OCRWM, "Draft Mission Plan Amendment," *DOE/RW-0316P, Washington, DC 20585, September 1991.*

DOE, 1992a: "U.S. Department of Energy Radiological Control Manual," *DOE/EH-0256T, June 1992.*

DOE, 1992b: "Mined Geologic Disposal System Requirements Document, Rev 0," *DOE/RW-0404P, DOE, OCRWM, Washington, DC 20585, January 1993.*

DOE, 1992c: "The Yucca Mountain Site Characterization Project Reference Information Base," I

DOE, 1992d: U.S. Department of Energy, "Cost Estimating, Analysis, and Standardization," *Order 5700.2D, Initiated by: Office of Procurement, Assistance and Program Management, June 12, 1992.*

DOE, 1992e: "Characteristics of Potential Repository Wastes," *DOE/RW-0184-R1, Oak Ridge, Tennessee, July 1992.*

DOE, 1993a: DOE, Yucca Mountain Site Characterization Project, "Exploratory Studies Facility Technical Baseline (Vol. I and II)," *YMP/CM-0016, Revision 2, August 30, 1993.*

DOE, 1993b: DOE, Yucca Mountain Site Characterization Project, "Work Breakdown Structure Index and Dictionary - Annex II to the Project Management Plan (Vol. 1 and 2)," *YMP/CC-0001, November 11, 1993.*

DOE, 1993c: DOE, Yucca Mountain Site Characterization Project, "Yucca Mountain Site Characterization Project Cost and Schedule Baseline," *YMP/CM-0015, Revision 4, June 29, 1993.*

DOE, 1993d: "Systematic Acquisition of Site-Specific Subsurface Information," *Study Plan for Study 8.3.1.4.3.1, Revision 1, June 4, 1993. (NNA.9306070214)*

Gartling, D.K., 1982: "COYOTE - A Finite Element Computer Program for Nonlinear Heat Conduction Problems," *SAND77-1332, prepared by SNL under Contract Number DE-AC04-76DP00789* for DOE, Albuquerque, New Mexico, October 1982.

Golder Associates, Inc., 1993: "Applications of RIP (Repository Integration Program) to the Proposed Repository at Yucca Mountain: Conceptual Model and Input Data Set," pp. 923-1171, Redmond, WA.

Hertel, Jr., E.S. and E.E. Ryder, 1991: "Areal Power Density: A Preliminary Examination of Underground Heat Transfer in a Potential Yucca Mountain Repository and Recommendations for Thermal Design Approaches," *SAND89-1989,.UC-814, prepared by SNL under Contract Number DE-AC0476DP00789* with DOE, Albuquerque, New Mexico.

Holland, J.F., 1993: "The Results of Near-Field Thermal and Mechanical Calculations of Thermal Loading Schemes," *Fourth International Conference on High Level Radioactive Waste Management, Las Vegas, Nevada, April 26-30, 1993*, pp 862-873.

Johnson, C.L., 1993: *Personal Communication with C.L. Johnson, M&O, on November 19, 1993.*

King, J., 1993a: "Data Transmittal for Phase 2 Thermal Loading Study," *TRW Environmental Safety Systems, Inc., Interoffice Correspondence, VA.SE.JK.5/93.031*, prepared by CRWMS M&O under Contract Number DE-AC01-91RW00134 with DOE, Vienna, Virginia, May 24, 1993.

King, J., 1993b: "Data Transmittal for Phase 2 Thermal Loading Study," *TRW Environmental Safety Systems, Inc., Interoffice Correspondence, VA.SE.JK.10/93.125*, prepared by CRWMS M&O under Contract Number DE-AC01-91RW00134 with DOE, Vienna, Virginia, October 22, 1993.

Lin, M., M. P. Hardy, and S. J. Bauer, 1993: "Fracture Analysis and Rock Quality Designation Estimation for the Yucca Mountain Site Characterization Project," *SAND92-0449,* *UC-814, prepared by SNL for the DOE under Contract Number DE-AC04-76DP00789,* Albuquerque, New Mexico, February 1993, pp 16-28.

Lugo, M.A., 1993: *Personal Communication with M.A. Lugo, M&O, on November 22, 1993.*

McKenzie, D.G., 1993: *Personal Communication with D.G. McKenzie, M&O, on November 22, 1993.*

M&O, 1992: "System Implications of Repository Thermal Loading, Phase I Study," *prepared by the CRWMS M&O under Contract Number DE-AC01-91RW00134,* Vienna, Virginia, December 24, 1992.

M&O, 1993a: "Site Characterization Plan Thermal Goals Reevaluation," *Report B00000000-01717-5705-00005, Rev 00, prepared by the CRWMS M&O under Contract Number DE-AC01-91RW00134,* Las Vegas, Nevada, September 8, 1993. (NNA.931208.0034)

M&O, 1993b: "Yucca Mountain Site Characterization Project Engineered Barrier Design Requirements Document," *Report YMP/CM-0024, Rev 0, prepared by the CRMWS M&O under Contract Number DE-AC01-91RW00134,* Las Vegas, Nevada, July 1993.

M&O, 1993c: "Yucca Mountain Site Characterization Project Repository Design Requirements Document," *Report YMP/CM-0023, Rev 0, prepared by the CRWMS M&O Contract Number DE-AC01-91RW00134,* Las Vegas, Nevada, July 1993.

M&O, 1993d: "Waste Package Performance Allocation Study Report," *Report B00000000-01717-5705-00010, Rev 00, prepared by the CiviliaCRWMS M&O Contract Number DE-AC01-91RW00134,* Las Vegas, Nevada, September 29, 1993.

M&O, 1993e: "Emplacement Mode System Study," *Report B00000000-01717-5705-00011, Rev 00, prepared by the CRWMS M&O under Contract Number DE-AC01-91RW00134,* Las Vegas, Nevada, September 29, 1993.

M&O, 1993f: "Repository Underground Ventilation System Design Concepts," *Report B000000000-01717-5705-00003, Revision 00, prepared by the CRWMS M&O under Contract Number DE-AC01-91RW00134,* Las Vegas, Nevada, September 8, 1993.

M&O, 1993g: "Reference Description of the Civilian Radioactive Waste Management System," *(Draft), Revision 0, prepared by the CRWMS M&O,* Las Vegas, Nevada, May 28, 1993.

M&O, 1993h: "Total System Performance Assessment - II: An Evaluation of the Potential Yucca Mountain Repository," *prepared by the CRWMS M&O under Contract Number DE-AC01-91RW00134* for DOE, Las Vegas, Nevada, November 19, 1993 (Draft).

M&O, 1993i: "System Implications of Repository Thermal Loading Phase II Study" *(Preliminary Draft), prepared by the CRWMS M&O under Contract Number DE-AC01-91RW00134,* Vienna, Virginia, November 30, 1993.

M&O, 1993j: "Civilian Radioactive Waste Management System Throughput Rate Analysis," *prepared by the CRWMS M&O under Contract Number DE-AC01-91RW00134*, Systems Analysis Department, Vienna, Virginia, August 17, 1993.

M&O, 1993k: "System Architecture Study," *Report A00000000-01717-6700-00003, Rev. 0, prepared by the CRWMS M&O under Contract Number DE-AC01-91RW00134*, Systems Analysis Department, Vienna, Virginia, September 30, 1993.

McLeod, N.B. and D.C. Jones, 1992: "Evaluation of Self-Shielded Waste Packages and Multipurpose Casks in the Waste Management System," *Electric Power Research Institute, Final Draft Report JAI-362, July 1, 1992*. (NNA.930104.0049)

Nitao, J.J., 1989: "V-TOUGH - An Enhanced Version of the TOUGH Code for the Thermal and Hydrologic Simulation of Large-Scale Problems in Nuclear Waste Isolation," *UCID-21954, Lawrence Livermore National Laboratory*, Livermore, California, 1989.

NRC, 1992a: Staff Technical Position on Geologic Repository Operations Area Underground, Facility Design-Thermal Loads, *NUREG 1466, NRC, September 1992.*

NRC, 1992b: Repository Operational Criteria, *NUREG/CR-5428, NRC, June 1992.*

Nimick, F.B., 1990: "The Thermal Conductivity of Seven Thermal/Mechanical Units at Yucca Mountain, Nevada," *SAND88-1387, SNL, Albuquerque, New Mexico, January 1990.* (NNA.891213.0201)

Nimick, F.B. and J.R. Connolly, 1991: "Calculation of Heat Capacities for Tuffaceous Units from the Unsaturated Zone at Yucca Mountain, Nevada," *SAND88-3050, SNL, Albuquerque, New Mexico, May 1991*. (NNA.910308.0017)

Pruess, K., 1987: "TOUGH User's Guide," *SAND86-7104 (also NUREG/CR-4645 and LBL-20700)*, SNL, Albuquerque, New Mexico, August 1987.

Pruess, K. and Y. Tsang, 1993: "Modeling of Strongly Heat-Driven Flow Processes at a Potential High-Level Nuclear Waste Repository at Yucca Mountain, Nevada," *Fourth International Conference on High Level Radioactive Waste Management, Las Vegas, Nevada, April 26-30, 1993*, pp 568-575.

Pruess, K. and Y. Wang, 1987: "Numerical Modeling of Isothermal and Nonisothermal Flow in Unsaturated Fractured Rock - A Review," in Flow and Transport through Unsaturated Fractured Rock, D. Evans and T. Nicholson (editors), *American Geophysical Union, Geophysical Monograph 42, 1987*, pp 11-21.

Rogers, D.J., 1993: "Repository Subsurface Layout Options and ESF Interface," Report B00000000-01717-5705-00009, *Rev. 00, prepared by the CRWMS M&O under Contract Number DE-AC01-91RW00134* for DOE, Las Vegas, Nevada, December, 1993.

Rohsenow, W.M. and J.P. Hartnett, 1973: *"Handbook of Heat Transfer," McGraw-Hill*, pp 3-82 through 3-83. (published book)

Ross, B., 1992: "Temperature Scenarios for a Repository at Yucca Mountain," *Third International Conference on High Level Radioactive Waste Management, Las Vegas, Nevada, April 12-16, 1992*, pp 784-789.

Ryder, E.E., 1993: "Comparison of Predicted Far-Field Temperatures for Discrete and Smeared Heat Sources," *Fourth International Conference on High Level Radioactive Waste Management, Las Vegas, Nevada, April 26-30, 1993*, pp 841-846.

Saterlie, S.F. and M.E. Abhold, 1993: "Estimates of Repository Area Mass Loadings for Thermal Calculations," *M&O Calculation Number B00000000-01717-0200-00029-00, TRW, Las Vegas, Nevada, September 20, 1993.* (NNA.930929.0033.0034)

Sinagra, T. A. and R. Harig, 1990: "MRS System Study for the Repository," *Report SAND89-7006, prepared by SNL under Contract DE-AC0476DP00789* with DOE, Albuquerque, New Mexico, December 1990.

Smyth, J. R., 1982: "Zeolite Stability Constraints on Radioactive Waste Isolation in Zeolite-Bearing Volcanic Rocks," J*ournal of Geology, 90*, pp 195-201.

Sundberg, W.D. and R.R. Eaton, 1982. "Three-Dimensional Thermal Analysis for a Conceptual High-Level Waste Repository in Welded Tuff," *SAND81-0215, SNL, Albuquerque, New Mexico, April 1982*.

SNL, 1987: "Site Characterization Plan - Conceptual Design Report," *SAND84-2641, compiled by H.R. MacDougall, L.W. Scully, and J.R. Tillerson, Six Volumes*, SNL, Albuquerque, New Mexico, September 1987. (NN2.880902.0014-NN1.880902.0019)

TRW, 1993: "Civilian Radioactive Waste Management System Throughput Rate Analysis," *prepared by CRWMS M&O under Contract Number DE-AC01-91RW00134, TRW Environmental Safety Systems Inc., Vienna, Virginia, August 17, 1993.*

Wallin, W.E., 1993: "WP Cost Estimates Update," *TRW IOC LV.WP.WEW.6/93-135, prepared by the CRWMS M&O under Contract Number DE-AC01-91RW00134*, Las Vegas, Nevada, July 26, 1993.

Wilson, M. L., J. H. Gauthier, R. W. Barnard, G. E. Barr, H. A. Dockery, E. Dunn, R. R. Eaton, D. C. Guerin, N. Lu, M. J. Martinez, R. Nilson, C. A. Rautman, T. H. Robey, B. Ross, E. E. Ryder, A. R. Schenker, S. A. Shannon, L. H. Skinner, W. G. Halsey, J. Gansemer, L. C. Lewis, A. D. Lamont, I. R. Triay, A. Meijer, and D. E. Morris, 1994 (in press). "Total System Performance Assessment for Yucca Mountain - SNL Second Iteration (TSPA-1993)." *SAND93-2675*, SNL, Albuquerque, NM.

NNA.940329.0001