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Civilian Radioactive Waste Management System
Management & Operating Contractor

FY 93 THERMAL LOADING SYSTEMS STUDY FINAL REPORT

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DISCLAIMER

APPENDIX A

WASTE STREAM ANALYSES

A.1 INTRODUCTION

Waste stream analyses performed for repository oriented studies are composed of two distinct steps. The first step models the entire Civilian Radioactive Waste Management System (CRWMS) and tracks assemblies from "cradle" (discharge into the reactor spent fuel pools) to "grave" (emplacement in an Mined Geologic Disposal System (MGDS)). The system models currently in use have relatively high resolution towards the front end of the system (acceptance, storage, and transportation) and relatively low resolution towards the back end of the system (storage and packaging at MGDS(s) and emplacement). For this reason, models and post processors have been developed recently to examine the repository end of the system in greater detail. Therefore, the second step in the analysis focuses on various repository functions for a given (system) waste stream as it arrives at the MGDS.

The first step, the system level waste stream analysis, was performed using Waste Stream Model (WSM), CSCI: A00020025.AAXO1.0, and the second step, the repository-based analyses, used a combination of much simpler codes. This approach essentially decouples the repository from the rest of the system, with the waste stream as the integrating link between the two steps. It is important to understand that the waste stream arriving at the repository implicitly reflects all upstream system designs, schedules, and operating concepts. Thus, the waste stream may be thought of as the "fingerprint" of the system. The computational decoupling was convenient for analyzing several combinations of waste package capacities for a single system level waste stream. For this study, decoupling was appropriate, but for most system studies the entire integrated system must be considered in all scenarios.

A.2 WASTE STREAM MODELS

Figure A.1 shows the computation flow of the analyses performed for this report. The models indicated on the figure are discussed in the following sections. The system waste stream analyses only examined logistics and fuel characteristics; total system costs were not considered. The two-step process discussed above is indicated on Figure A.1. The first step, the system level waste stream analysis, is performed by WSM. The second step, the repository specific analysis, is accomplished with two models: the Waste Package And Areal Power Density (APD) Approximator (WPA3) model and the SOURCE post-processor. WPA3 is actually two independent, but linked, modules. The first packages an unpackaged (arriving) waste stream, and the second simulates emplacement. In this analysis only the first WPA3 module was used to produce the waste package inventories. SOURCE simply takes the waste package inventory and aggregates it into equivalent thermal source terms.

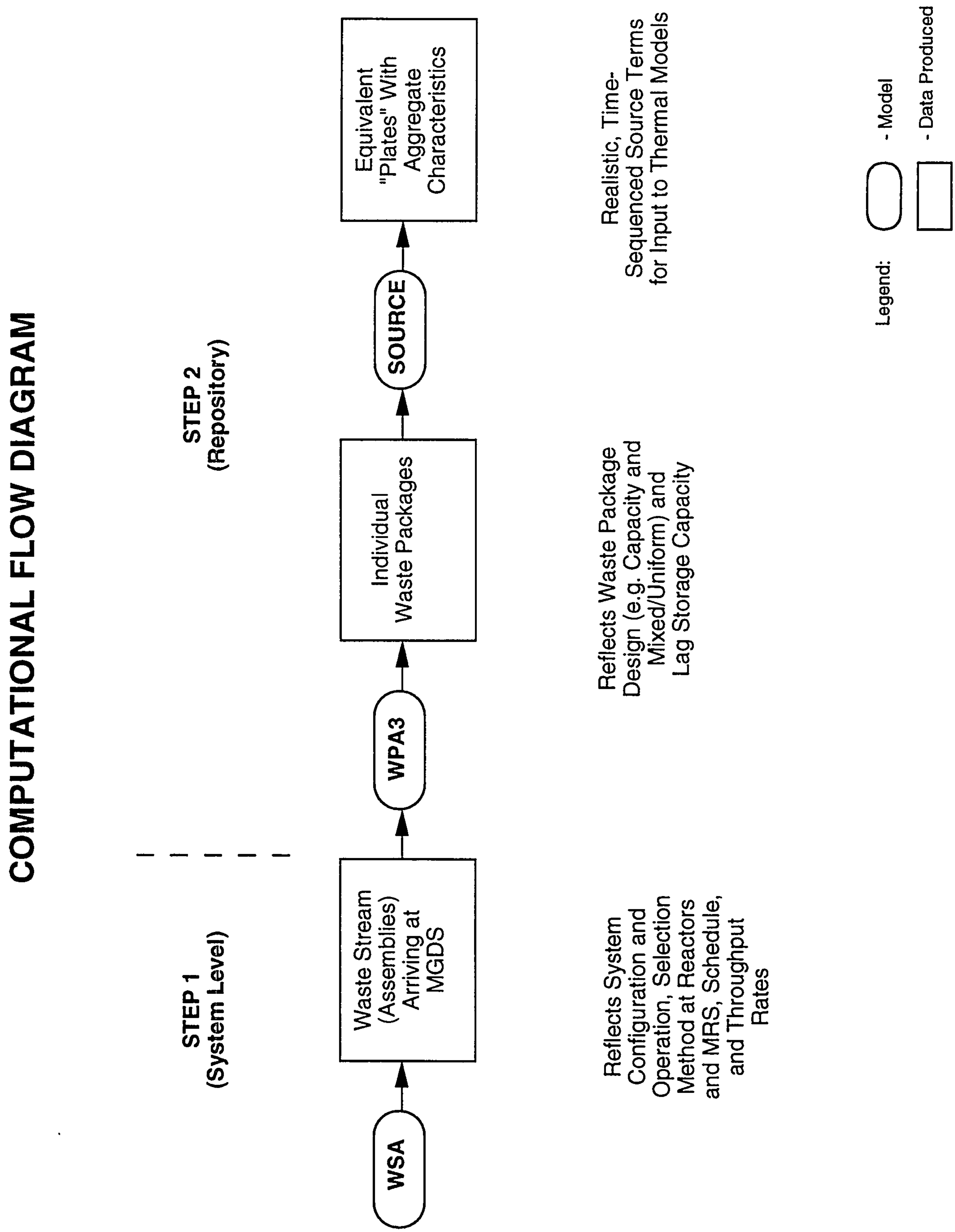

Figure A-1. Computational Flow Diagram for Phase 2 Repository Thermal Loading Study

Instantaneous heat output for a given set of fuel characteristics is the key parameter in these analyses. All models employed use the same methodology to compute this parameter (Bogart, 1992). The method exploits the latest Characteristics Database (CDB) data (DOE, 1992d) and has a high degree of resolution.

All models employed run on microcomputers under DOS or OS/2. None of the models are certified for Quality Affecting (QA) work, but the most complex of the codes, WSM, is configuration managed and very mature.

A.2.1 THE WASTE STREAM MODEL (WSM)

WSM (Andress and McLeod, 1989) simulates movement of nuclear waste through the major elements of the Civilian Radioactive Waste Management System (CRWMS) and tracks each assembly's history from discharge to arrival at the repository. WSM can characterize fuel movement and fuel containerization by fuel type, burnup, age, heat, activity, and gamma and neutron radiation dose rates. WSM can be run with or without an MRS, and packaging can be done at the MRS or the repository. Several allocation and fuel pick up strategies are available. Control and scenario parameters specify allocation rights, fuel selection rules, dry storage options, MRS flowthrough and inventory management, cask and waste package capacities, and direct shipments from western reactors (the "western strategy"). WSM does not consider defense high-level waste nor commercial high-level waste from West Valley.

WSM's strengths are: at reactor logistics, the waste acceptance process, and containerization (loading and tracking transportation casks and MPCs). WSM tracks all discharges, reactor-to-pool linkages, pool inventories, dry storage requirements, and fuel selection versus acceptance rights. Several rule-based selection options are available at both the reactor and the MRS to select fuel for shipment. A full core reserve (FCR) margin optionally can be preserved in the pools, until the last reactor discharging into that pool has shutdown. Spent fuel pool overflow is placed into onsite dry storage according to rules similar to the shipment selection rules. Fuel placed in dry storage is tracked, and pickup may be deferred until the pool is empty or until there is no five year old fuel left in the pool.

WSM tracks fuel into and out of MRS inventory on an annual basis. Incoming shipments may be flowed through, passed through, or put into storage. Flowthrough refers to receiving from-reactor rail casks at the MRS and shipping them on to the repository without opening them. These rail casks are shipped directly to the repository until repository demand for the year has been satisfied. Since all cask shipments from the MRS to the repository are by rail, assemblies from incoming truck casks are transferred to rail casks at the MRS before being shipped out; this is referred to as "passthrough." Maximizing passthrough and flowthrough minimizes inventory turnover (and therefore handlings). Conversely, characteristics-based selection at the MRS is algorithmically enforced based on user supplied rules, possibly leading to unrealistic inventory turnover when the characteristics of the incoming stream and fuel in inventory are similar. A combination of passthrough/flowthrough and characteristics based selection can also be specified.

The two main WSM components are the main sequence, selection, and containerization module and post-processor report programs. The sequence, selection, and containerization module writes a detailed spent fuel movement file which serves as the database for the report programs. The WSM output file consists of one record for each batch of fuel characterized by the following: (1) primary characteristics--burnup and enrichment; (2) primary unit measures--number of assemblies, and MTU; (3) secondary unit measures--number of casks when shipped from reactor, number of casks when shipped from the MRS (not filled for batches that are never picked up); and (4) dates of major logistic events--discharge from reactor, transferring to at-reactor dry storage, pickup from reactor, emplacement in repository. Since WSM tracks the waste stream inventories as a function of time, detailed reports are available that describe shipments, quantities, radiological characteristics, and heat output as a function of time across all CRWMS components.

WSM input data fall into two broad categories: annually updated "static" data and user-specified, scenario specific data. The first category can be further subdivided into two major areas. The first is spent fuel discharge schedules from commercial nuclear reactors, provided by the Energy Information Administration (EIA). These schedules are based on historical data gathered from the utilities on Form RW-859 and projections based on EIA models and analyses. These data are updated annually. The second area is spent fuel physical and radiological characteristics, obtained from the Characteristics Data Base (CDB). Pre-processing routines are run annually to prepare the WSM static data files from the latest EIA and CDB data. This step restructures the published EIA and CDB data into the appropriate WSM file formats.

The second category of input data, user-specified, scenario specific data, implements the many user options already discussed. They are mostly single digit parameters set by the user in the main input data file. The other key portion of user-specified data is the receipt rate schedules. The receipt rates fundamentally affect virtually all logistics. They are specified for each year in the run with a target pickup rate from waste generators and a target emplacement rate. MRS receipt and shipping rates are inferred from the pickup and emplacement rates.

A.2.2 WASTE PACKAGING WITH THE WPA3 MODEL

The Waste Package and Areal Power Density Approximator (WPA3) code (King, and Byrne, 1993) was developed initially to support the System Implications of Repository Thermal Loading Study (TRW, 1992). The purpose of the code is to compute waste package inventories and Areal Power Densities (APDs) of the filled repository for a range of system scenarios and system configurations.

WPA3 is composed of two distinct programs. The first module reads the output of WSM and loads the waste packages. The heat output (kW) of the package at the year of emplacement is calculated using the characteristics (assembly type, discharge year, burnup, and enrichment) of each assembly in the package. Those assembly characteristics are retained for each waste package, so the heat of each package can be computed for any arbitrary time following emplacement. Retaining the characteristics also allows performing any statistical analysis desired on assembly and package characteristics (King Rhodes, and Saterlie, 1994).

Several different waste package capacities can be modeled, both uniform and mixed. Mixed packages refers to waste packages containing both BWR and PWR assemblies. When mixed packages are selected, they are filled until only one type of assembly remains for the emplacement year. When this occurs, the code automatically switches to uniform packages (all BWR or all PWR) for the remainder of the assemblies in that year. When uniform packages are selected, the user has the option of selecting blending or no blending of assemblies into the packages. When no blending is selected, waste packages are filled with assemblies in the order they appear in the WSM output, and since WSM does not compute campaigns, this order is essentially random. When blending is chosen, assemblies are selected from a "lag storage" inventory to levelize the heat output across packages. The user provides the lag storage capacity in MTU. The blending scheme simply picks the hottest and coldest assemblies from a heat sorted list until the lag storage is exhausted.

The first WPA3 module also produces standard report tables. The second WPA3 module is called APD. This module simulates emplacement and computes local and total areal power densities (APDs) as a function of time. The APD module was not used in this study.

A.2.3 EQUIVALENT THERMAL SOURCE TERM GENERATION WITH SOURCE

The SOURCE code was developed as a WPA3 post-processor to add the capability to produce, track, and aggregate SNF characteristics to any level of detail in the repository and sequence the emplacement over time. Historically, physically based thermal models have used characteristically averaged, spatially homogenized, and instantaneously emplaced representations of the waste to compute repository temperatures although a number of codes such as some used by SNL an simulate emplacing waste over a period of time. Once WPA3 was developed, the ability to track explicitly the individual waste packages and the assemblies in those packages allowed thermal source terms for temperature models to be computed with much greater resolution. Recognizing the resolution limitations of thermal models and the uncertainty in rock parameters, these source terms are still useful because: 1) they are based on the best SNF discharge projections and fuel characteristics data available (CDB), 2) they reflect the upstream system configuration and operational concept (WSM) and therefore yield an integrated, system approach, 3) they capture the full characteristics variability and time-sequenced emplacement of the actual waste stream, and 4) they can be aggregated from the individual waste package level up to any arbitrary level of detail.

The primary input file is the waste package inventory file produced by WPA3. The user inputs the level of aggregation by specifying the target mass of each lumped source. Options have been added to aggregate by year and by waste package. For uniform packages, the code then accumulates BWR and PWR waste packages separately until the target mass is reached and computes mass weighted average age, burnup, and enrichment for the BWR and PWR components (the components must be kept separate because heat decay curves are fuel type specific). Also, the mass and number of waste packages each component represents is reported for tracking areal requirements. For mixed packages, the BWR and PWR assemblies are also accumulated separately, even though they are physically mixed together in the waste packages. Any leftover assemblies of one type in uniform packages are tracked and reported separately from the mixed package aggregations.

The waste package inventory file is organized by emplacement year. When aggregating, SOURCE indicates the within-year emplacement sequence of the equivalent source terms (for source masses less than the annual emplacement amount) by adding a decimal fraction to the emplacement year. The fractional years have no meaning for computing instantaneous heat output; the decay heat algorithms are not meaningful at resolutions finer than unit years. The equivalent source terms' fractional year values are intended only to indicate the within year emplacement sequence.

Since the heat decay curves are unique for any combination of fuel type, age, burnup, and enrichment, and since they are highly non-linear, there is error associated with the mass weighted averaging used to aggregate. Analyses performed during the course of past system studies have indicated that these errors are not significant for most fuel in a typical waste stream. The error seems to be worst when very old and/or very low burnup fuel is averaged with nominal fuel in significant quantities, and although non-zero amounts of fuel with these characteristics will always be present in the waste stream, their relative quantities are low compared to the 63,000 or 86,000 MTU usually considered in system scenarios. The mass weighting error introduced is deemed acceptably small, especially when the inherent errors in the heat decay curve data and reported (average) batch burnups are considered.

A.3 REFERENCES

1. Bogart, 1992. "WSA Heat Calculations," IOC, E. Bogart to W. Bailey, et al., June 19, 1992.

2. (DOE, 1992d) U. S. Department of Energy, "Characteristics of Potential Repository Wastes," DOE/RW-0184-R1, July 1992.

3. Andress, David and N. B. McLeod, 1989. "Waste Stream Analysis Model," August, 1989.

4. King, J., C. Rhodes, and J. Byrne, 1993. "Waste Package and Areal Power Density Approximator (WPA3) Computer Code," Fourth Annual International High-Level Radioactive Waste Management Conference, Las Vegas, Nevada, April 26-30, 1993.

5. TRW, 1992. Civilian Radioactive Waste Management System Management and Operating Contractor, December 24, 1992. System Implications of Repository Thermal Loading Phase I Study. TRW Environmental Safety Systems, Inc., Vienna, Virginia.

6. King, J., Rhodes, C., and S. Saterlie, 1993, "Implications of Waste Package Heat Output Distribution Resulting From Waste Stream Variability," Fifth Annual International High-Level Radioactive Waste Management Conference, Las Vegas, Nevada, May 23-25, 1994. (To be published)

Appendix B
Waste Package Design Inputs

This appendix provides information on the design inputs for the WP concepts used in the study. The WP sizes, weights, and capacities as well as some WP thermal analysis are provided. The WP Design Group provided this input in the form of IOCs to the Systems Analysis and copies of those IOCs are attached.

Interoffice Correspondence
Civilian Radioactive Waste Management System
Management & Operating Contractor

TRW

TRW Environmental Safety Systems Inc.

WBS: 1.2.2.4
QA: N/A

Subject:
Waste Package Sizes and Weights

Date:
June 14, 1993
LV.WP.RHB.06/93-112

From:
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T.W.Doering

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Distribution

In response to System Studies request at the June 4th meeting for a summary of overall dimensions and weights (including BWR and DHLW glass loadings) we enclose the following tables. This IOC completes System Studies requests for waste package dimensions and weights. For more detail than is provided here, please refer to the following previous IOC's:

March 26, 1993 (LV.WP.RHB.03/93-056)
May 11, 1993 (LV.WP.RHB.05/93-086)
May 14, 1993 (LV.WP.RHB.05/93-~~086~~91)
May 27, 1993 (LV.WP.RHB.05/93-097)

For spent nuclear fuel, three cases were defined in our March 26 IOC. Case 1 is the SCP-CDR described on page 7-25 of the "Waste Package Design (Basis for Site Characterization Plan, Chapter 8)" with a maximum loaded weight of 6.4 tonnes. Case 2 is the multi-barrier robust waste package with a 0.95 cm inner wall and Case 3 is the multi-barrier robust waste package with a 3.5 cm inner wall. Cases 2 and 3 have 2nd barrier thicknesses of 10, 20, and 45 cm.

Table 1 provides a summary of dimensions and weights for SNF. The only new information is the waste package weight when loaded with BWR's. For conversions, 1 tonne equals 1.1023 U.S. short tons.

The dimensions and weights for the high-level waste glass waste package are described in Table 2. The HLW glass canisters will be overpacked with a waste package that is optimized for their size and weight and will be compatible with transporters designed for SNF packages. The single capacity DHLW robust waste package would be compatible with transporters for the 2, 4, and 6 PWR capacity packages, the 3 DHLW package with the 12 and 16 PWR package, and the 4 DHLW package with the 21 PWR package.

Enclosures:
(1) Table 1 - Spent Nuclear Fuel W.P. Weights
(2) Table 2 - Defense High-Level Waste Packages

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File: PD-1

TABLE 1 - SPENT NUCLEAR FUEL W.P. WEIGHTS

System Study Case 1

SCP-CDR from page 7-25 of the "Waste Package Design
(Basis for Site Characterization Plan., Chapter 8)
Loaded waste package weight = 6.4 tonnes (max)

System Study Case 2
1st Barrier = 0.95 cm
2nd Barrier = 10 cm
Overall Length = 4.831 m

# of PWR's	# of BWR's	Outer Diameter (m)	Empty Weight (tonnes)	Loaded with PWR's (tonnes)	Loaded with BWR's (tonnes)
2	4	0.8389	11.34	12.90	12.62
4	6	0.9912	14.53	17.65	16.45
6	12	1.1876	18.47	23.15	22.31
12	21	1.4062	24.71	34.07	31.43
16	32	1.6367	30.17	42.65	40.41
21	40	1.7519	34.14	50.52	46.94

System Study Case 2
1st Barrier = 0.95 cm
2nd Barrier = 20 cm
Overall Length = 5.031 m

# of PWR's	# of BWR's	Outer Diameter (m)	Empty Weight (tonnes)	Loaded with PWR's (tonnes)	Loaded with BWR's (tonnes)
2	4	1.0389	23.83	25.39	25.11
4	6	1.1912	29.25	32.37	31.17
6	12	1.3876	36.15	40.83	39.99
12	21	1.6062	45.79	55.15	52.51
16	32	1.8367	54.97	67.45	65.21
21	40	1.9519	60.84	77.22	73.64

TABLE 1 - SPENT NUCLEAR FUEL W.P. WEIGHTS
(CONTINUED)

System Study Case 2
1st Barrier = 0.95 cm
2nd Barrier = 45 cm
Overall Length = 5.531 m

# of PWR's	# of BWR's	Outer Diameter (m)	Empty Weight (tonnes)	Loaded with PWR's (tonnes)	Loaded with BWR's (tonnes)
2	4	1.5389	71.00	72.56	72.28
4	6	1.6912	82.64	85.77	84.56
6	12	1.8876	97.79	102.47	101.63
12	21	2.1062	116.88	126.24	123.60
16	32	2.3367	136.34	148.82	146.58
21	40	2.4519	147.47	163.86	160.27

System Study Case 3
1st Barrier = 3.5 cm
2nd Barrier = 10 cm
Overall Length = 4.882 m

# of PWR's	# of BWR's	Outer Diameter (m)	Empty Weight (tonnes)	Loaded with PWR's (tonnes)	Loaded with BWR's (tonnes)
2	4	0.8899	14.24	15.80	15.52
4	6	1.0422	18.01	21.13	19.93
6	12	1.2386	22.71	27.39	26.55
12	21	1.4572	29.82	39.18	36.54
16	32	1.6877	36.24	48.72	46.48
21	40	1.8029	40.70	57.08	53.50

TABLE 1 - SPENT NUCLEAR FUEL W.P. WEIGHTS
(CONTINUED)

System Study Case 3
1st Barrier = 3.5 cm
2nd Barrier = 20 cm
Overall Length = 5.082 m

# of PWR's	# of BWR's	Outer Diameter (m)	Empty Weight (tonnes)	Loaded with PWR's (tonnes)	Loaded with BWR's (tonnes)
2	4	1.0899	27.59	29.15	28.87
4	6	1.2422	33.62	36.74	35.54
6	12	1.4386	41.33	46.01	45.17
12	21	1.6572	51.91	61.27	58.63
16	32	1.8877	62.10	74.58	72.34
21	40	2.0029	68.49	84.87	81.29

System Study Case 3
1st Barrier = 3.5 cm
2nd Barrier = 45 cm
Overall Length = 5.582 m

# of PWR's	# of BWR's	Outer Diameter (m)	Empty Weight (tonnes)	Loaded with PWR's (tonnes)	Loaded with BWR's (tonnes)
2	4	1.5899	77.25	78.81	78.53
4	6	1.7422	89.61	92.73	91.53
6	12	1.9386	105.68	110.36	109.52
12	21	2.1572	125.84	135.20	132.56
16	32	2.3877	146.46	158.94	156.70
21	40	2.5029	158.19	174.57	170.99

TABLE 2 - Defense High-Level Waste Packages

Four DHLW waste packages are under consideration:

Case 1: SCP-CDR described on page 7-25 of the "Waste Package Design (Basis for Site Characterization Plan, Chapter 8)"
Case 2: Multi-barrier robust waste package with 1 DHLW capacity
Case 3: Multi-barrier robust waste package with 3 DHLW capacity
Case 4: Multi-barrier robust waste package with 4 DHLW capacity

For the DHLW multi-barrier robust waste package, a single inner wall thickness o
0.9 cm was used with outer layer thicknesses of 10, 20, and 45 cm, (three case

DHLWP 2nd Barrier Thickness (cm 10
Internal WP Length (m) = 3.0084
External WP Length (m) = 3.2394

# of DHLW Cannisters	External Diameter (m)	Empty WP Weight (tonnes)	Loaded WP Weight (tonnes)	WP Heat Output (kW)
1	0.8597	7.11	10.61	0.69
3	1.6249	16.71	27.21	2.07
4	1.7914	18.84	32.84	2.76

DHLWP 2nd Barrier Thickness (cm 20
Internal WP Length (m) = 3.0084
External WP Length (m) = 3.4394

# of DHLW Cannisters	External Diameter (m)	Empty WP Weight (tonnes)	Loaded WP Weight (tonnes)	WP Heat Output (kW)
1	1.0597	16.14	19.64	0.69
3	1.8249	34.56	45.06	2.07
4	1.9914	38.79	52.79	2.76

DHLWP 2nd Barrier Thickness (cm 45
Internal WP Length (m) = 3.0084
External WP Length (m) = 3.9394

# of DHLW Cannisters	External Diameter (m)	Empty WP Weight (tonnes)	Loaded WP Weight (tonnes)	WP Heat Output (kW)
1	1.5597	51.33	54.83	0.69
3	2.3249	95.08	105.58	2.07
4	2.4914	105.30	119.30	2.76

Interoffice Correspondence
Civilian Radioactive Waste Management System
Management & Operating Contractor

TRW Environmental Safety Systems In.

WBS: 1.2.2.4
QA: N/A

Subject:
Temperatures of Drift-Emplaced Waste Packages

Date:
May 28, 1993
LV.WP.RHB.05/93-099

From:
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In response to your request for temperatures around the waste package following drift emplacement, we enclose the following information which builds on temperature results transmitted in our March 26 IOC.

At your suggestion, we generated a two-dimensional model of an infinitely long drift that is not affected thermally by adjacent drifts. By assuming a drift spacing of 200 m (656 ft), the model effectively approximates a "lone drift" because the heat front does not propagate to the next drift before the end of the 50 year life of the model.

Two waste package sizes were considered; the 21 PWR package and the 12 PWR package. These two containers represent optimum packing efficiencies and their dimensions and weights were provided in out May 27 IOC. Drift sizes of 11, 14, 18, and 25 feet diameters were assumed for both containers.

A summary of peak temperatures is tabled on the next page, and time/temperature graphs are provided on the following pages. For two cases (12 PWR with an 11 ft drift and 21 PWR with a 25 ft drift), an expanded time scale of only the first year has also been plotted. Temperatures of the waste package will actually be higher than reported here because a two-dimensional model smears the heat load over the package centerline to centerline spacing. We expect localized hot spots at the package mid-length that are not estimated here.

The results indicate that the 21 PWR package cannot be emplaced with a one meter end to end spacing without violating temperature goals for any drift diameter. Previous analyses have found that a 6 meter end to end spacing is the probable minimum. The 12 PWR package may be acceptable at the 1 m spacing, but a more detailed analysis of the waste package itself will be required. The 2-D color contour plot demonstrates that for a regular geometry, a one-dimensional (radial) analysis can adequately approximate temperatures. Hence, we believe that the one-dimensional temperature graphs from our March 26 IOC are a conservative estimate of mid-length hot spots for an individual waste package.

Although our model of the repository is detailed, we feel it is important to point out that the concept of a "lone drift" is not representative of expected conditions in the repository. Therefore, we are currently proceeding with analyses that include drift interactions for a variety of area mass loadings.

TABLE 1
Peak Temperatures Experienced by a Single Drift

WP Capacity (# of PWR's)	Drift Diameter	Maximum WP Temp.	Time of Occurrence	Max. Drift Side Temp.	Time of Occurrence
12	11 ft	259 C	8 years	190 C	10 years
"	14 ft	246 C	8 years	176 C	20 years
"	18 ft	233 C	8 years	165 C	20 years
"	25 ft	217 C	8 years	148 C	20 years
21	11 ft	422 C	8 years	305 C	10 years
"	14 ft	396 C	8 years	280 C	20 years
"	18 ft	374 C	8 years	260 C	20 years
"	25 ft	350 C	8 years	250 C	20 years

Enclosures:
Color contour of 21 PWR with 14 ft tunnel at 20 years
Temperature in Repository (10 figures)

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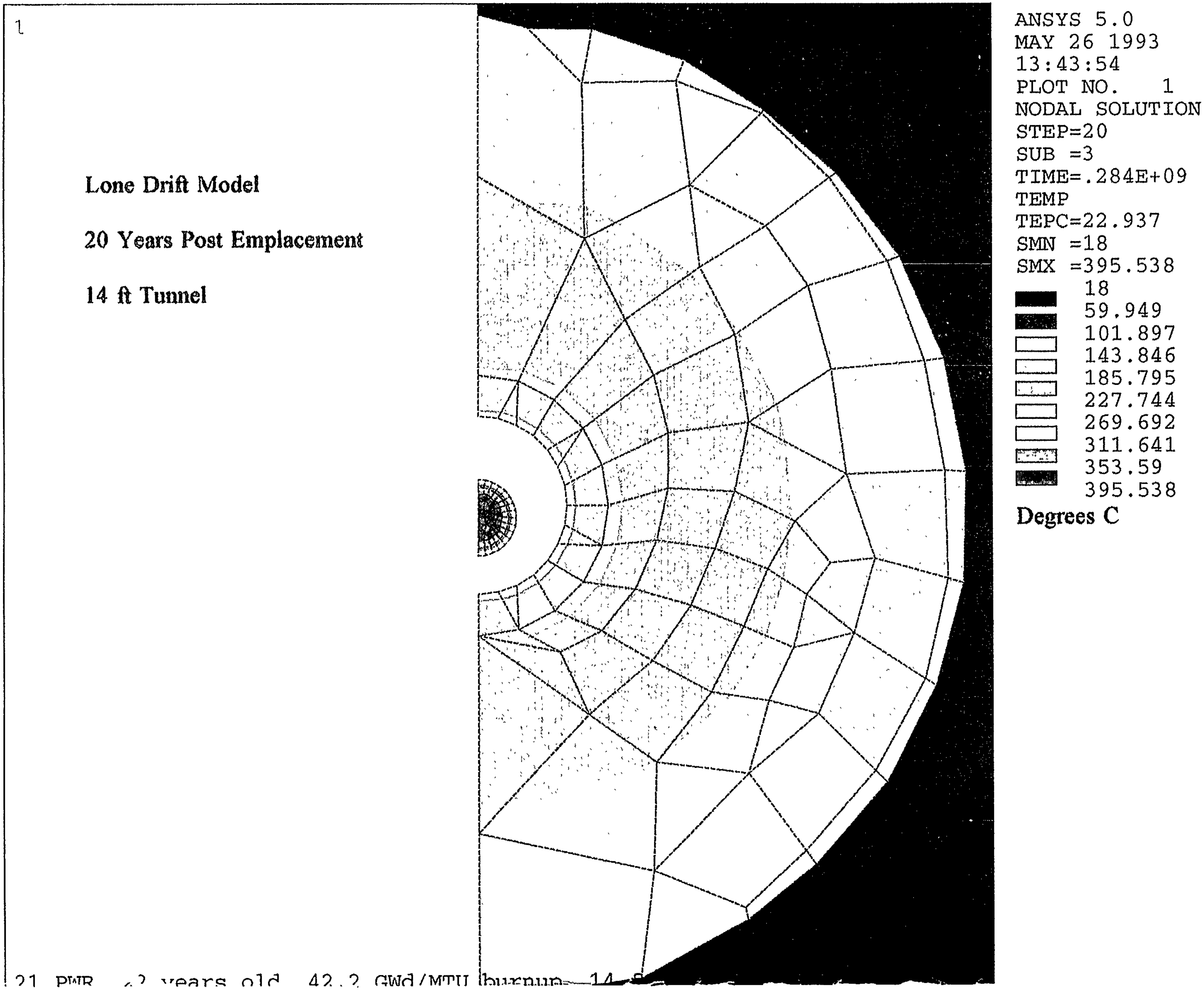
D.G.Rasmussen, TES3/423
D.J.Rogers, TES3/423
D.Stahl, TES3/423
D.A.Thomas, TES3/423
File: PD-1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Lone Drift Model
20 Years Post Emplacement
14 ft Tunnel
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MAY 26 1993
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SMX =395.538
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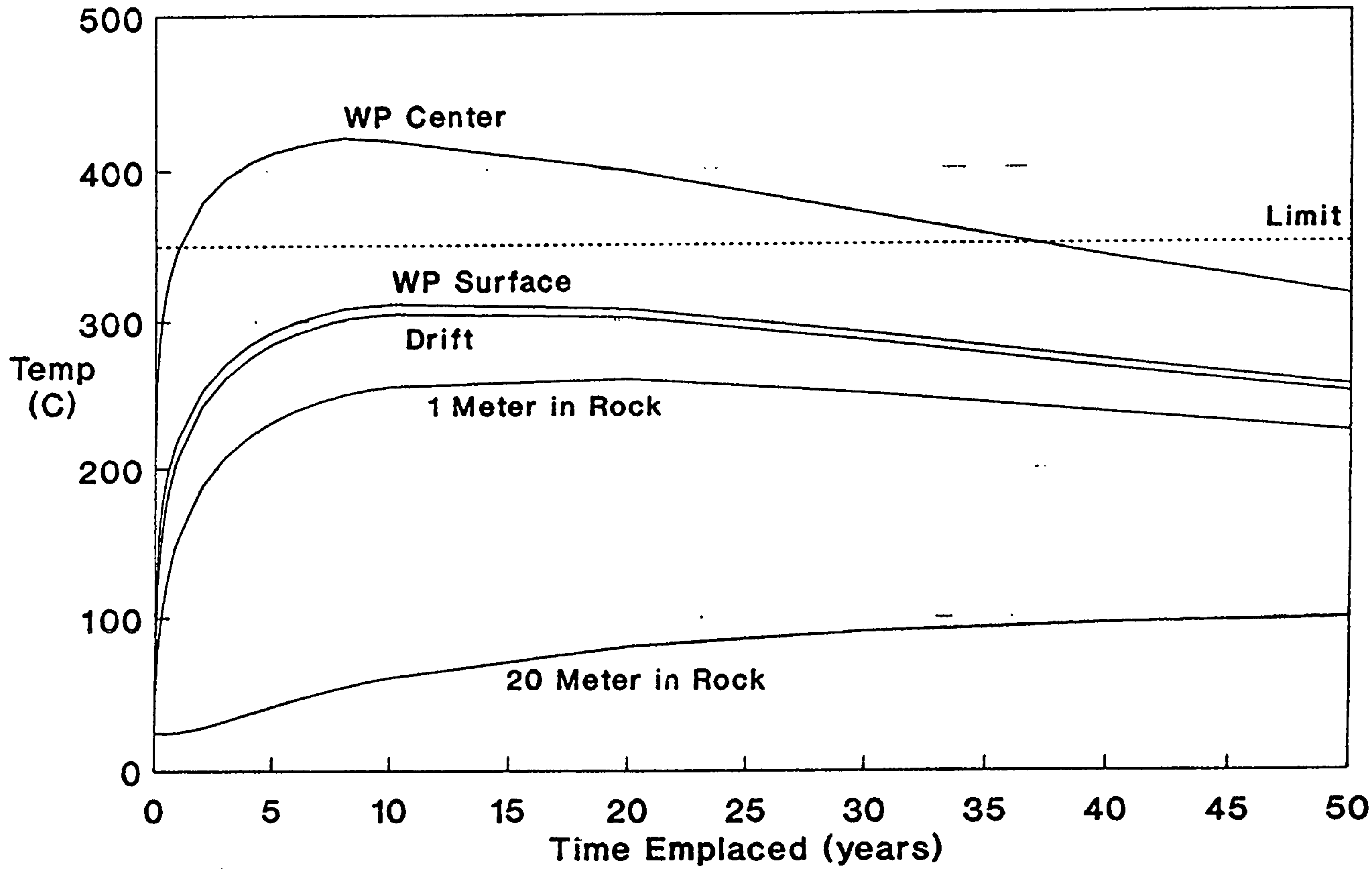
101.897
143.846
185.795
227.744
269.692
311.641
353.59
395.538
Degrees C
21 PWR years old 42.2 GWd/MTU burnup

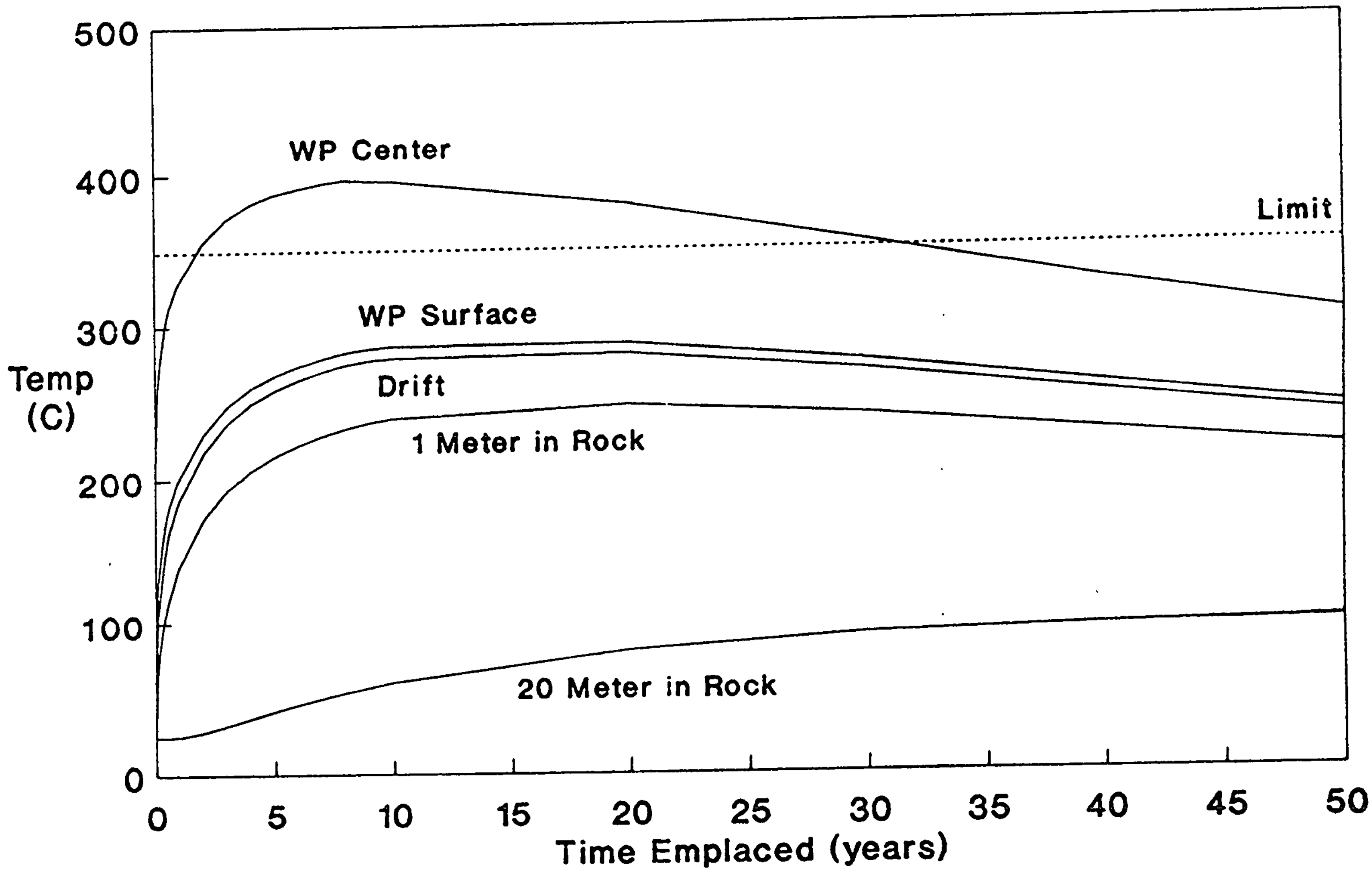
Temperature in Repository

21 PWR, Single 11 ft Drift, 1 m Spacing



22 year old fuel, 42.2 GWd/MTU burnup

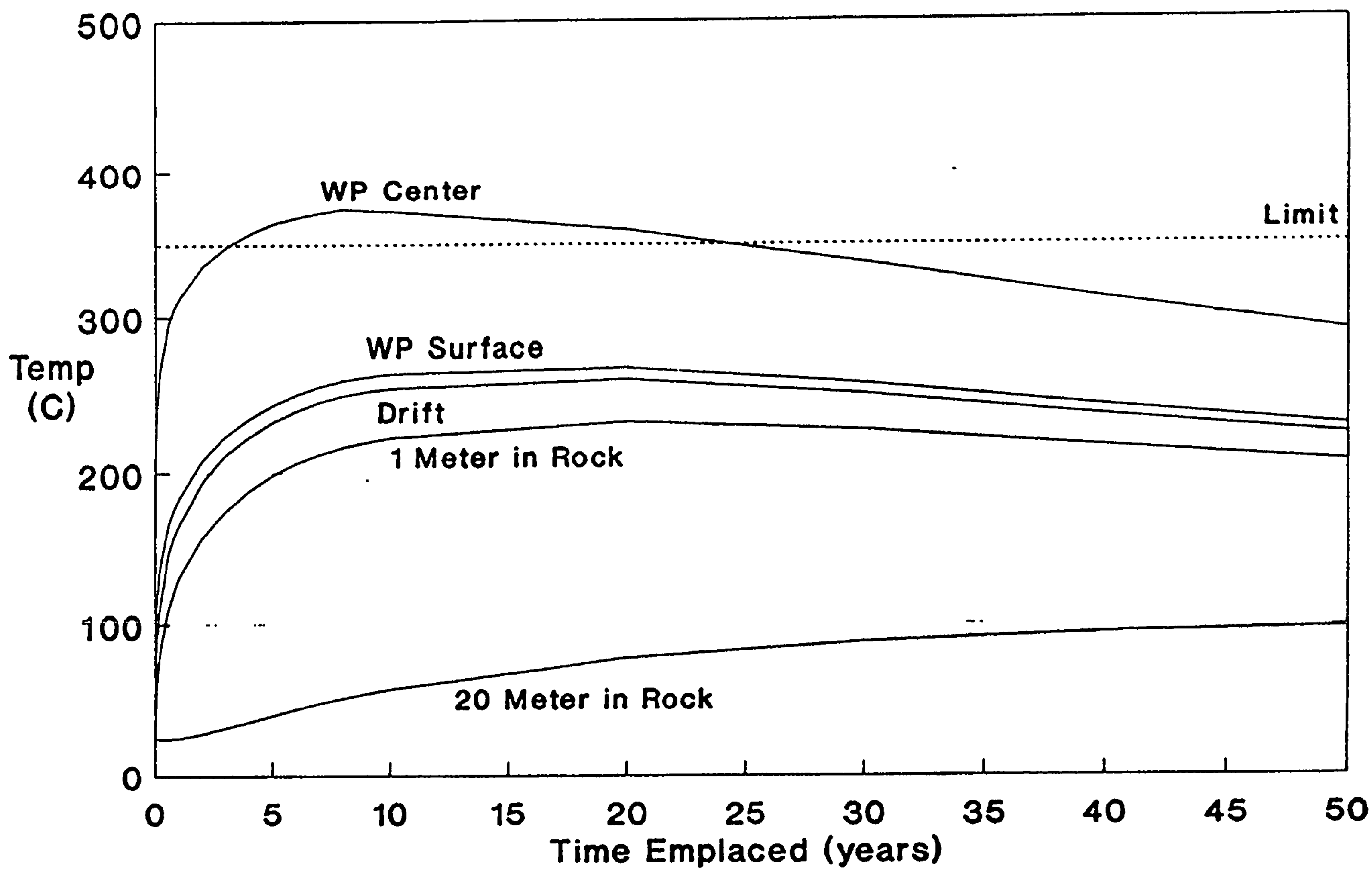
Temperature in Repository
21 PWR, Single 14 ft Drift, 1 m Spacing



22 year old fuel, 42.2 GWd/MTU burnup

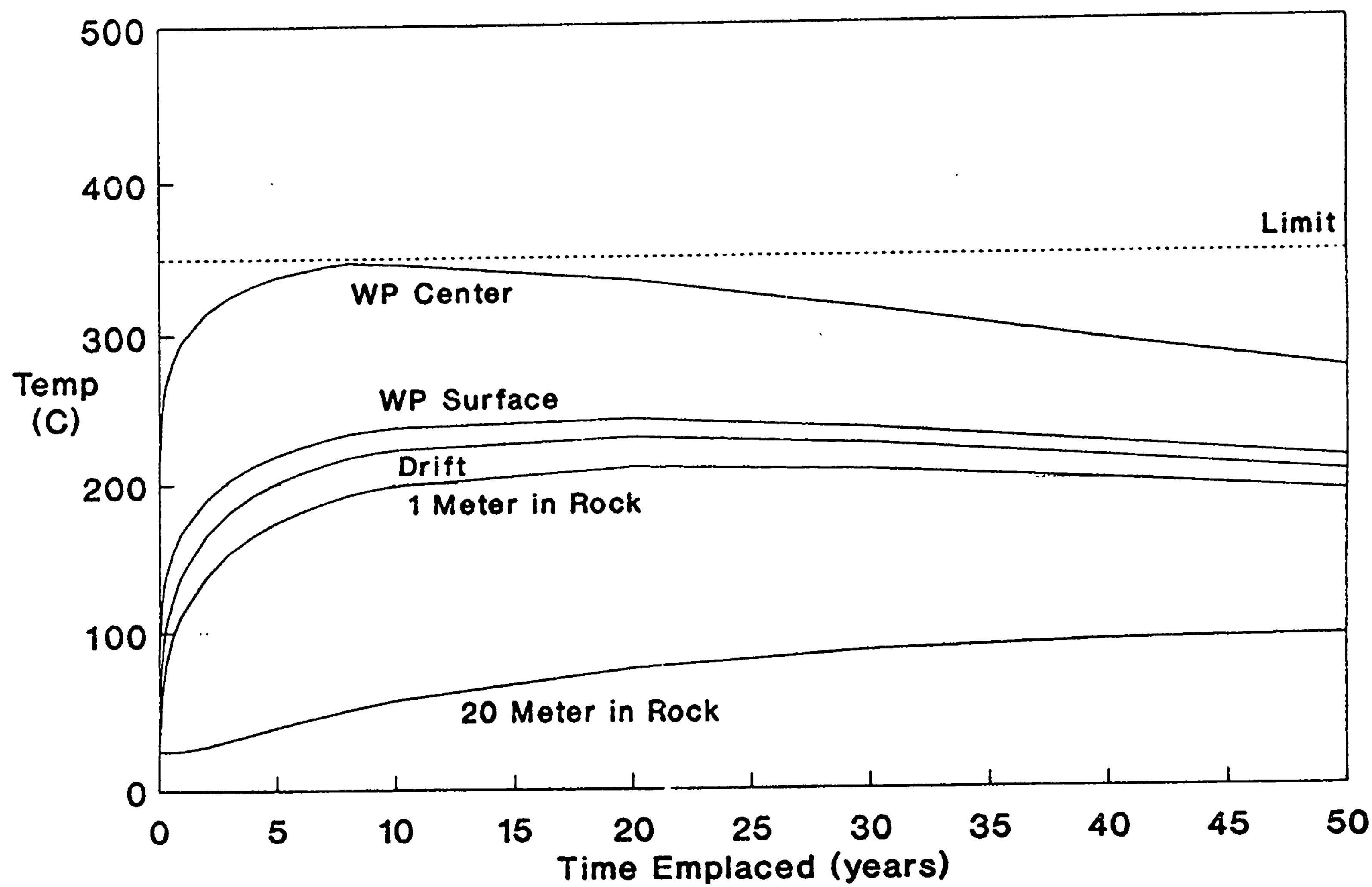
Temperature in Repository

21 PWR, Single 18 ft Drift, 1 m Spacing

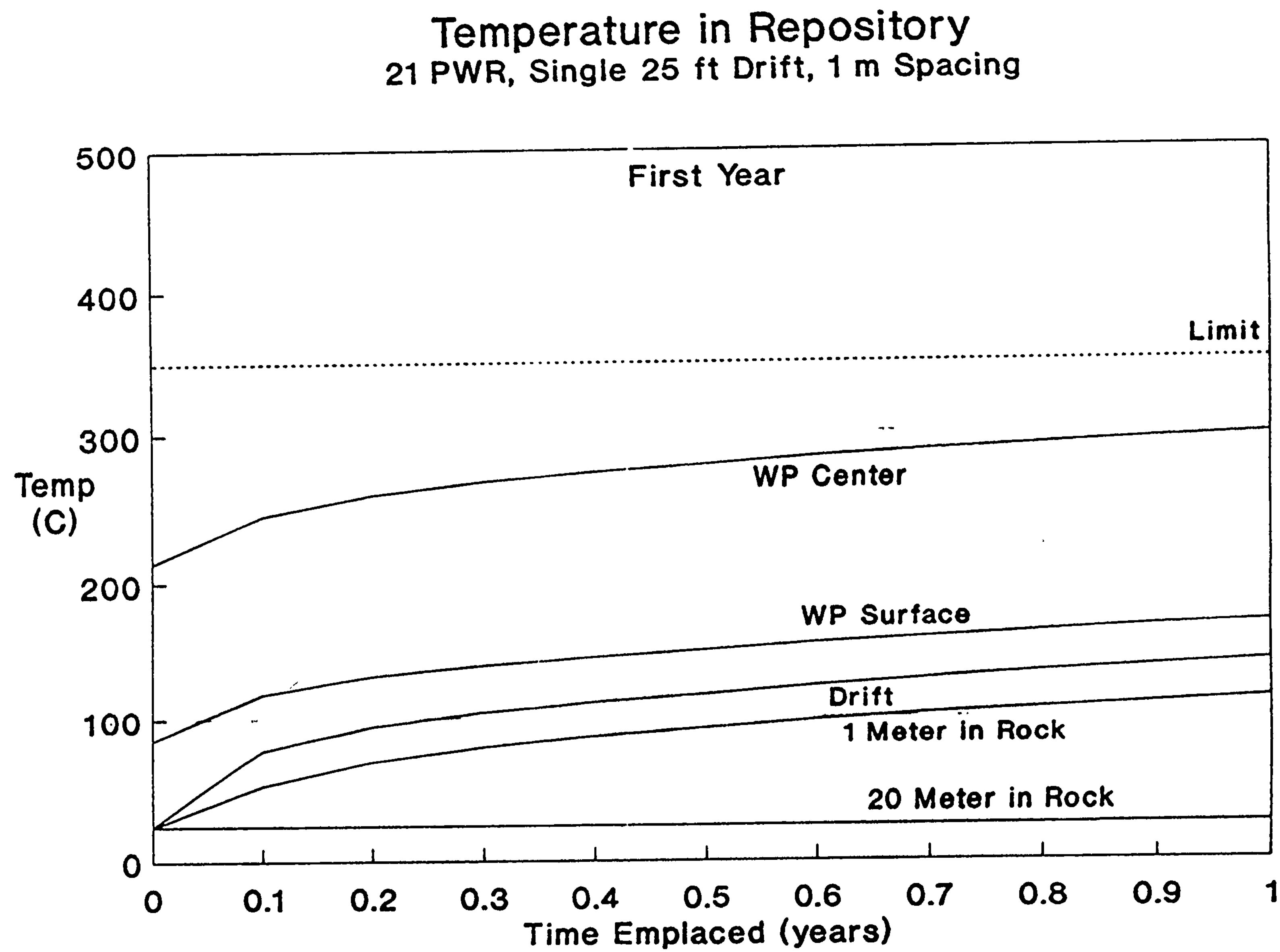


22 year old fuel, 42.2 GWd/MTU burnup

Temperature in Repository
21 PWR, Single 25 ft Drift, 1 m Spacing

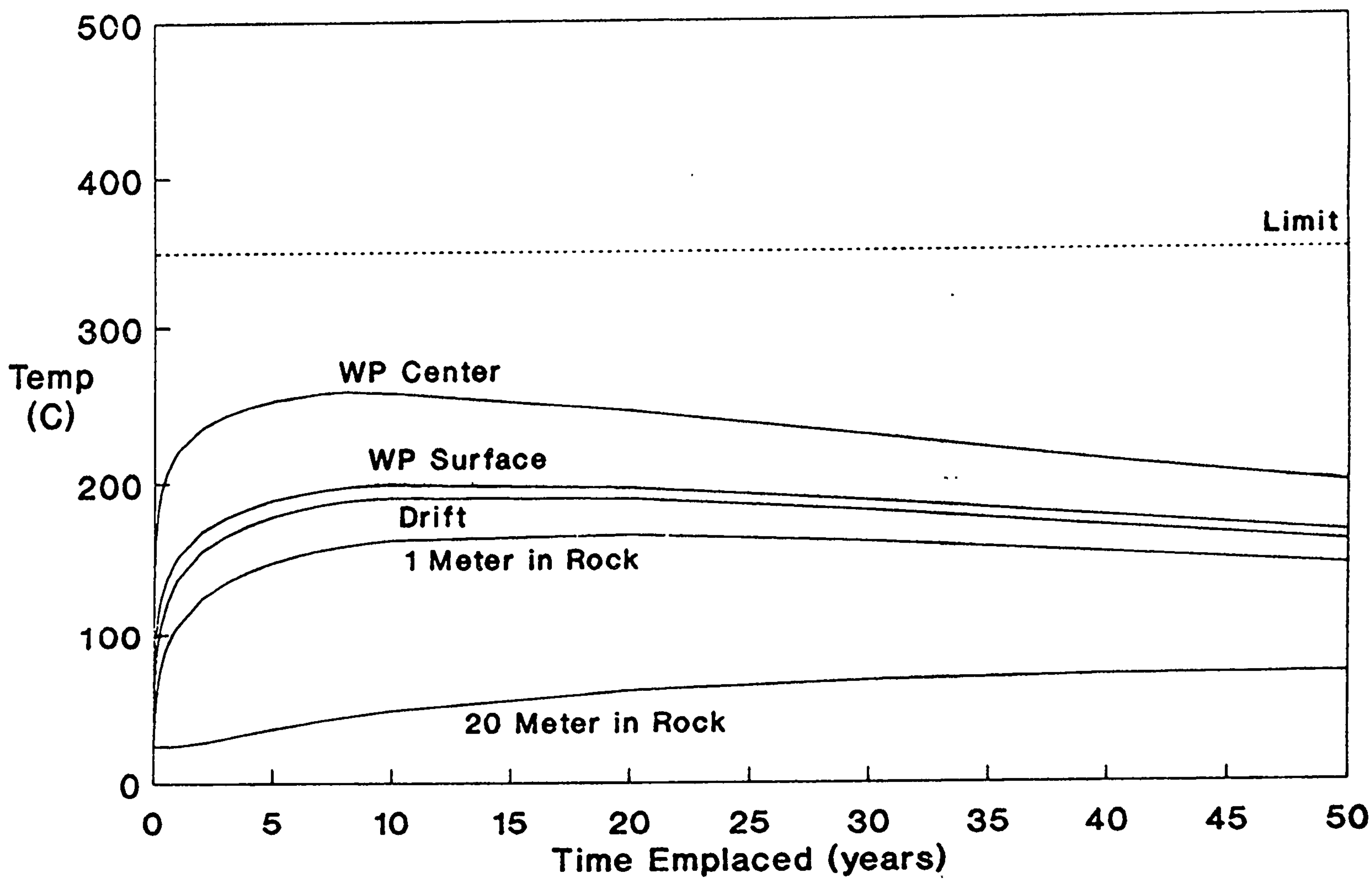


22 year old fuel, 42.2 GWd/MTU burnup



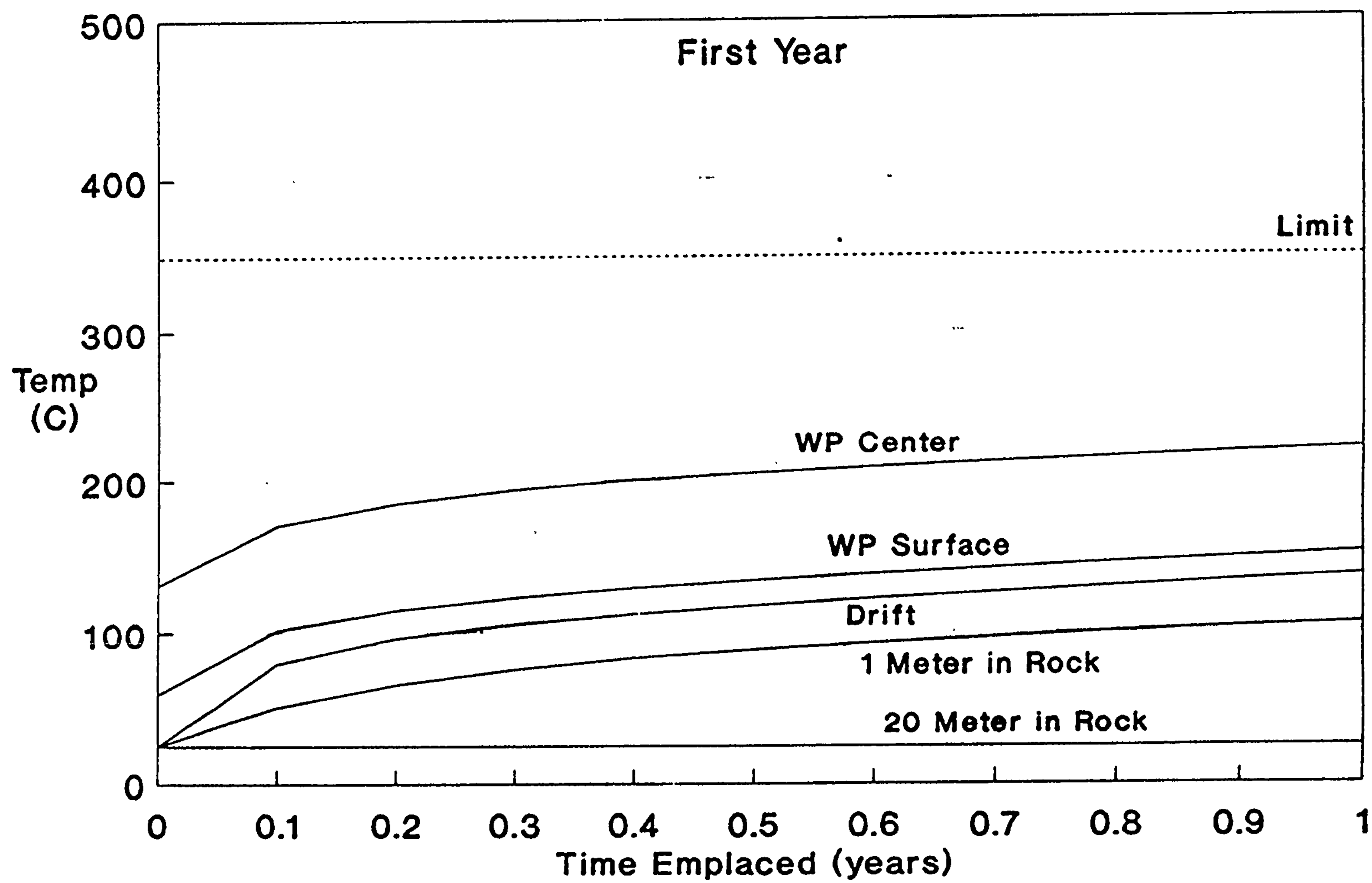
22 year old fuel, 42.2 GWd/MTU burnup

Temperature in Repository
12 PWR, Single 11 ft Drift, 1 m Spacing



22 year old fuel, 42.2 GWd/MTU burnup

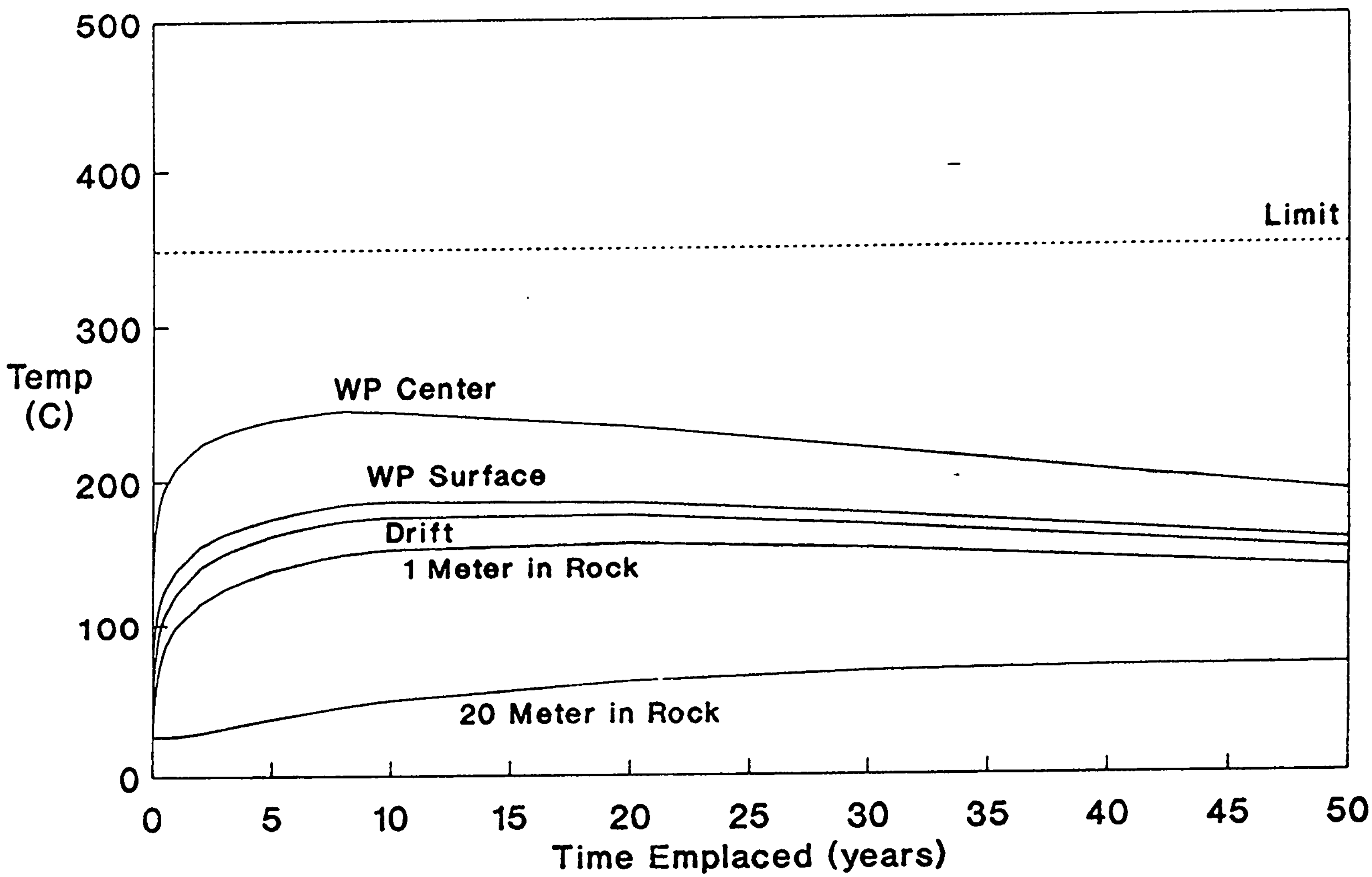
Temperature in Repository
12 PWR, Single 11 ft Drift, 1 m Spacing



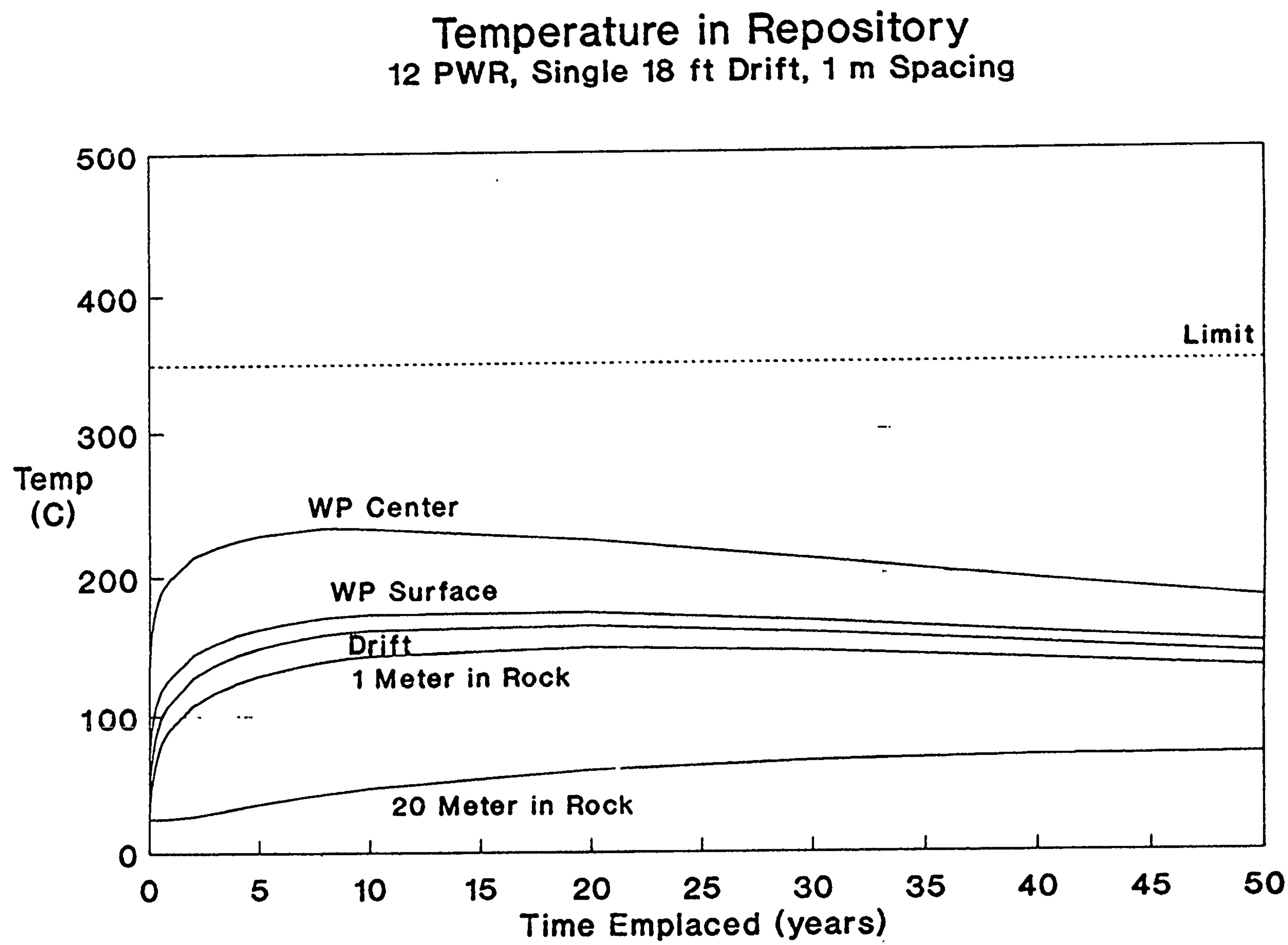
22 year old fuel, 42.2 GWd/MTU burnup

Temperature in Repository

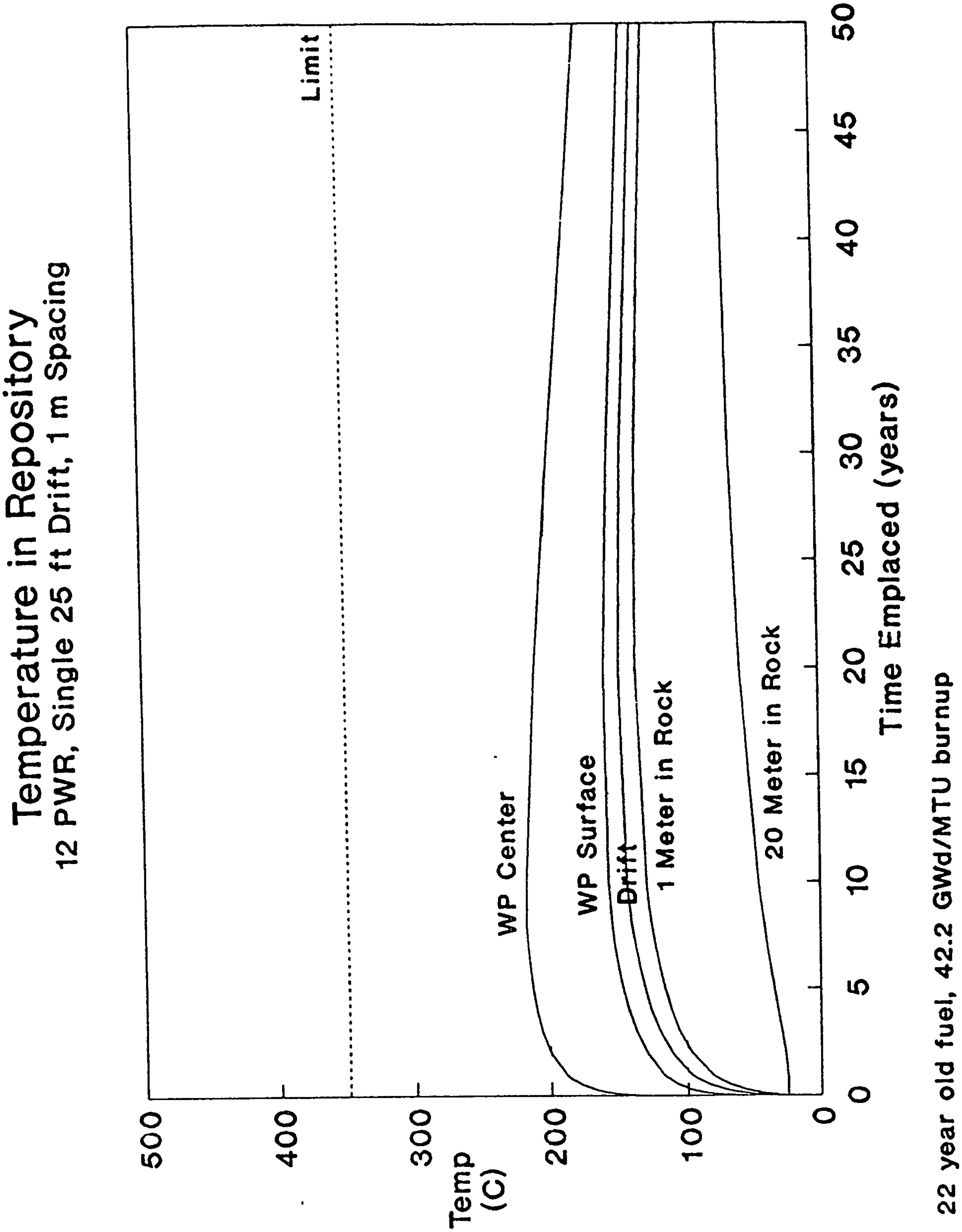
12 PWR, Single 14 ft Drift, 1 m Spacing



22 year old fuel, 42.2 GWd/MTU burnup



22 year old fuel, 42.2 GWd/MTU burnup


Temperature in Repository
12 PWR, Single 25 ft Drift, 1 m Spacing
Temp (C)
500
400
300
200
100
0
Limit
WP Center
WP Surface
Drift
1 Meter in Rock
20 Meter in Rock
0
5
10
15
20
25
30
35
40
45
50
Time Emplaced (years)
22 year old fuel, 42.2 GWd/MTU burnup

TRW Environmental
Safety Systems Inc.

WBS: 1.2.2.1
QA: N/A

Subject:	**Date:**	**From:**
Waste Package Sizes	May 11, 1993	R.H.Bahney III
Efficiencies and Weights	LV.WP.RHB.05/93-086	T.W.Doering
To:	**cc:**	**Location/Phone**
S.F.Saterlie, TES3/423	H.A.Benton, TES3/423	TES3/P102
R.Memory, TES3/423	D.Stahl, TES3/423	(702) 794-5337
J.B.Stringer, Duke(Charlotte)	R.L.Fish, TES3/423	
	D.Thomas, TES3/423	
	L.Olguin, TES3/423	
	M.Grigore, TES3/423	
	K.K.Bhattacharyya, TES3/423	
	File PD-1	

The Waste Package Design Group feels that it is necessary to define the selection of 2, 4, 12, 16, and 21 as the candidate waste package PWR capacities specified in our input to Systems Studies dated March 26, 1993. The following figures and tables demonstrate the calculated sizes and packing efficiencies of many PWR and BWR basket configurations.

For these analyses, only basket configurations that possessed ¼ symmetry were studied as asymmetric baskets are less stable and licensable. Also it was assumed that individual PWR cells are arranged in regular rows, that is: the junction between cells always forms a "+" and never a "T". Overlapping cells have been found in previous container analyses to be structurally inferior to regular arrays due to buckling of the cell wall. The basket thicknesses used here are for one burnup-credit concept and merely represent expected internal geometry.

PWR assembly packages were studied first as they are considered to be the limiting case both thermally and structurally. On Figure 3, one can see the higher efficiency of larger waste packages (no big surprise here) and the optimum configurations of 12, 21, and 24. The 24 PWR arrangement has been dropped due to thermal considerations, and the 16 has been included because the thermally optimum waste package may be between 21 and 12. The total weight per PWR emplaced is a dominant factor for smaller packages and levels off for packages holding 12 or more. The Wasted (or open) Space per PWR is less a function of waste package size than the specific basket configuration, and we see here that the 5 PWR basket may be an improvement over the 4.
The wasted space was calculated as the open corners at the edges of the basket and does not include any air space in or around the individual assemblies (the entire air space would be required for calculation of criticality during flooded conditions).

Table 1 provides a more in-depth look at the results for PWR baskets plotted on Figures 2 and 3. Here the basket dimensions are specified and the individual components of the waste package are itemized. Tables 2 and 3 represent BWR loadings with and without (respectively) their surrounding flow channels. The principal use of tables 2 and 3 is to determine how many BWR assemblies can be fit into a given PWR container.

From the following figures and tables, the optimum basket configurations for Systems Studies have been determined to be 2, 4, 12, 16, and 21. There was some confusion as to how many BWR assemblies may be fit into each of the above containers due to the consideration of BWR assemblies with and without their flow channels. For the Systems Studies evaluations it will be assumed that the BWR's are loaded with their flow channels resulting in the following correlation:

# of PWR's	# of BWR's
2	4
4	6
12	21
16	32
21	40

Enclosures:
Basket Configurations (Figure 1)
Waste Package Sizes (Figure 2)
Waste Package Efficiencies (Figure 3)
Table 1 - PWR's
Table 2 - Channeled BWR's
Table 3 - Unchanneled BWR's

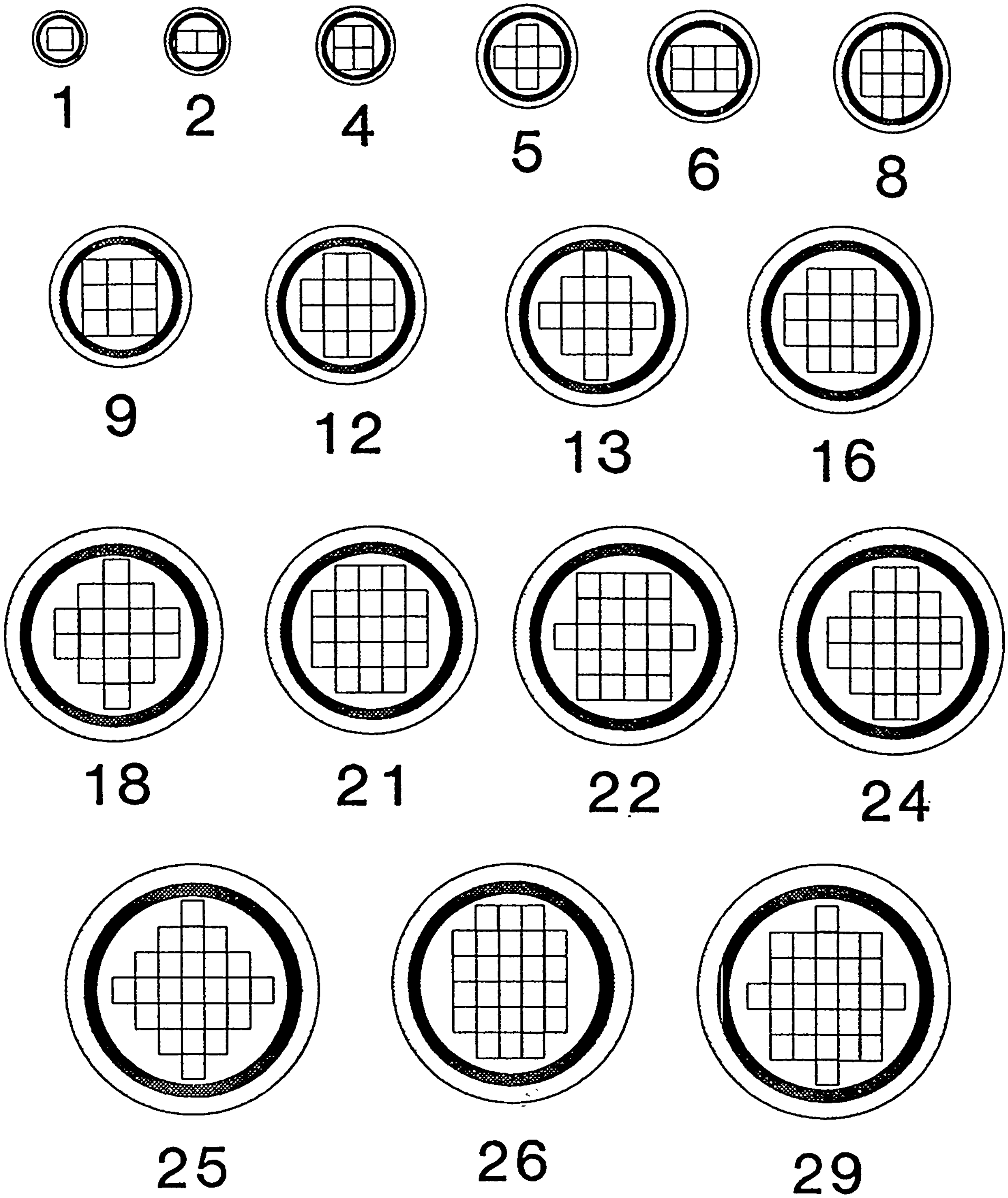


Figure 1

Basket configurations up to 100 assemblies
per waste package were analyzed

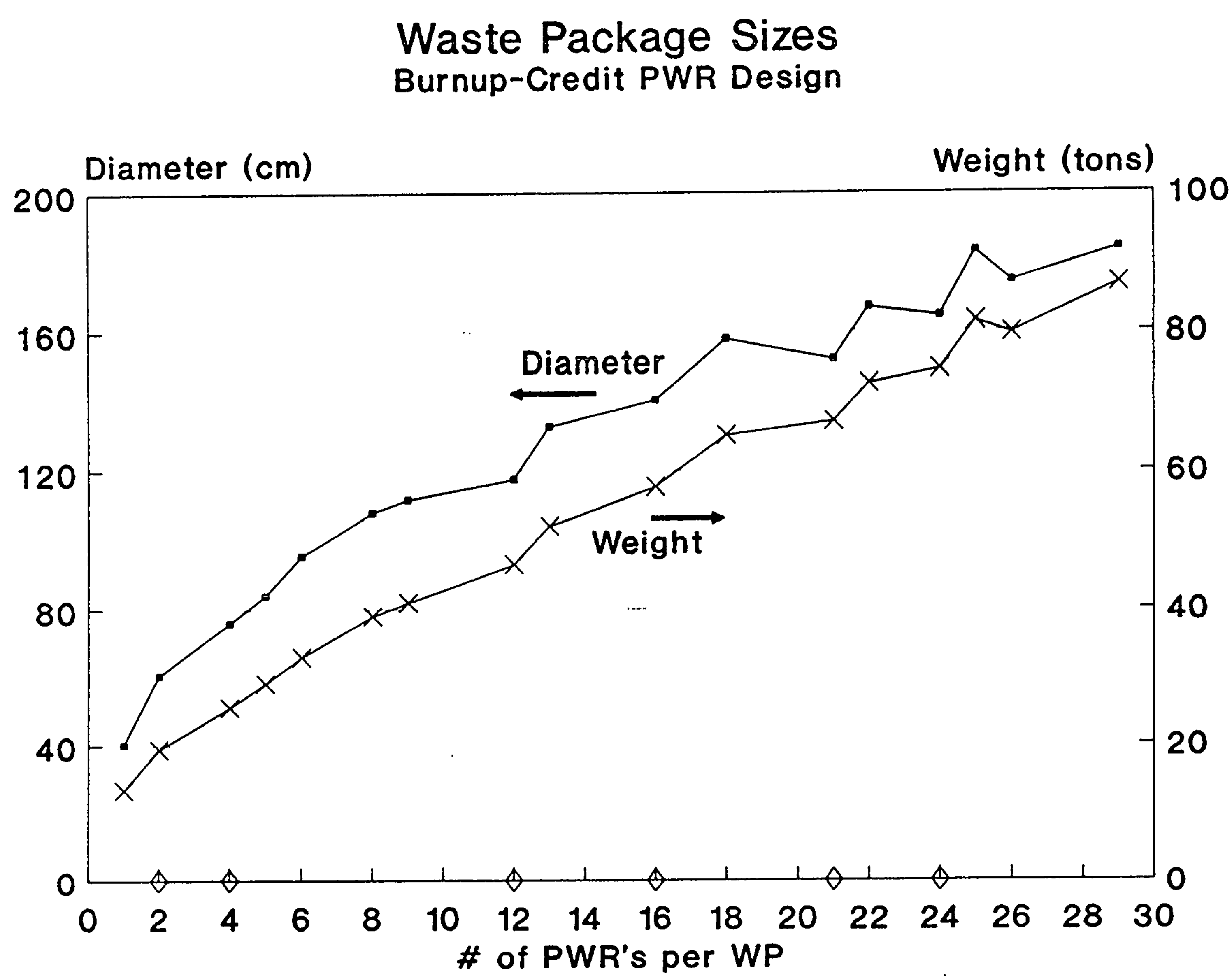

Waste Package Sizes
Burnup-Credit PWR Design
Diameter (cm)
Weight (tons)
Diameter
Weight
200
160
120
80
40
0
100
80
60
40
20
0
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
# of PWR's per WP

Figure 2

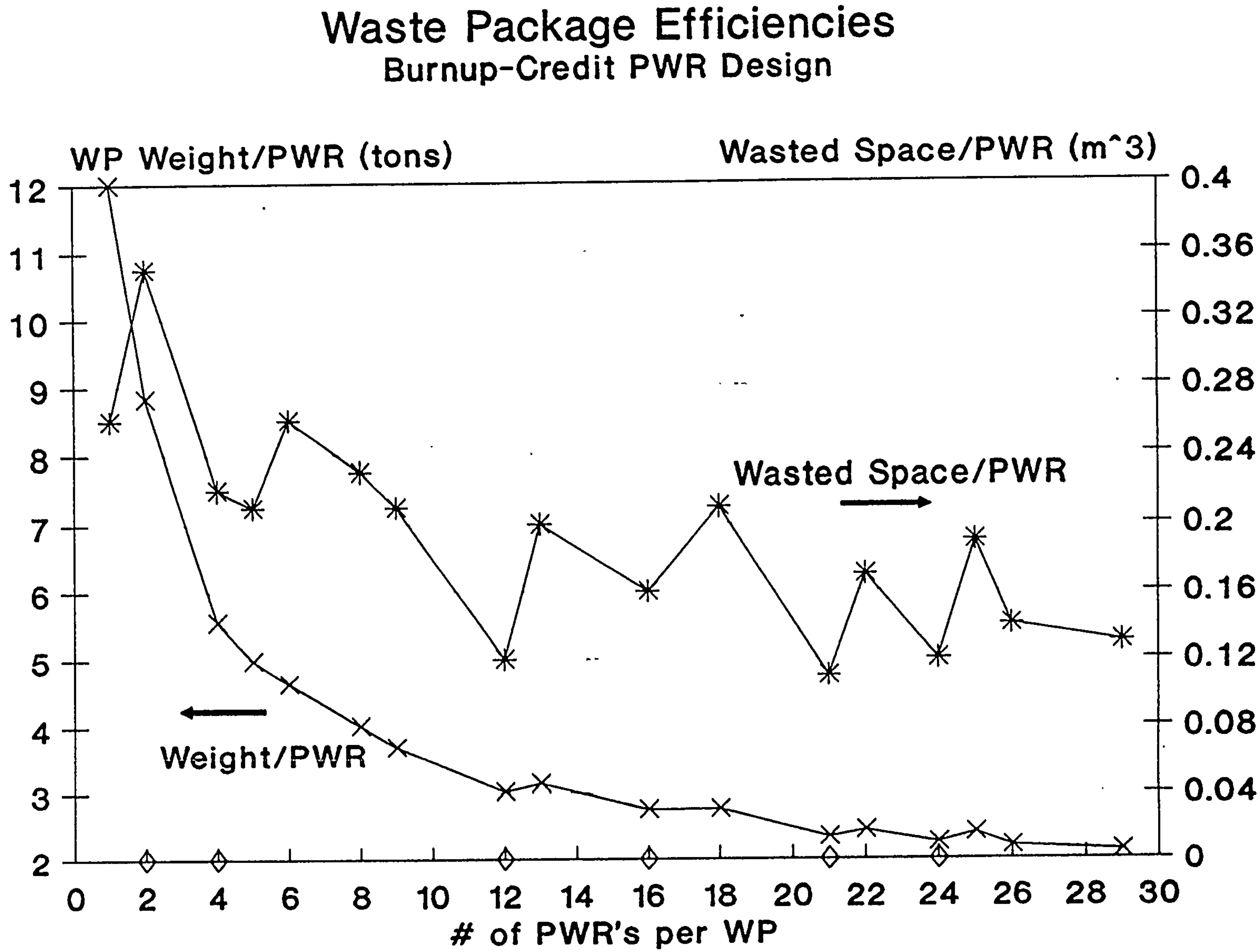

Waste Package Efficiencies
Burnup-Credit PWR Design
WP Weight/PWR (tons)
Wasted Space/PWR (m^3)
Wasted Space/PWR
Weight/PWR
12
11
10
9
8
7
6
5
4
3
2
0.4
0.36
0.32
0.28
0.24
0.2
0.16
0.12
0.08
0.04
0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
# of PWR's per WP

Figure 3

Waste Package Diameters, Efficiencies, and Weights

TABLE 1 - PWR's

Two-Layer Burnup Credit Design (Structural supports are not notched into 1st barrier)

PWR Cell Width (cm) = 22.3774 (8.81 in)
PWR Mass (kg) = 780.2
Support Wall Width (cm) = 3.0 (1.18 in)
Support Wall Density (kg/m^3) 8000.0
1st Barrier Thickness (cm) = 3.5 (1.38 in)
1st Barrier Density (kg/m^3) 8137.9
Intervening Gap (cm) = 0.6
2nd Barrier Thickness (cm) = 11.5 (4.53 in)
2nd Barrier Density (kg/m^3) 7832.0

Criticality Only Width (cm) = 1.0 (0.39 in)
Total Length of Supports (cm) 240.0 (94.5 in)

Internal WP Length (cm) = 460.0 (15.1 ft)
Overall WP Length (cm) = 491.2 (16.1 ft)

1 tonne = 1.1023 US short tons

(125 tons(s) = 113.4 tonnes)
(75 tons(s) = 68.0 tonnes)

Number of PWR's	K1	K2	KP	Internal Diameter (cm)	External Diameter (cm)	Internal Volume (m^3)	Support Basket (m^3)	Wasted Space (m^3)	Percent Wasted Space	W. Space Per PWR (m^3)	Weight of PWR's (tonnes)	Weight of Supports (tonnes)	Weight of 1st Barrier (tonnes)	Weight of 2nd Barrier (tonnes)	Empty WP Weight (tonnes)	Loaded WP Weight (tonnes)	WP Weight per PWR (tonnes)
1	1	1	4	40.13	71.33	0.58	0.10	0.26	44.0	0.26	0.78	0.76	1.90	8.65	11.31	12.09	11.31
2	1	2	6	60.79	91.99	1.33	0.16	0.71	53.2	0.35	1.56	1.32	2.85	11.86	16.03	17.59	8.01
4	2	2	8	76.02	107.22	2.09	0.28	0.89	42.5	0.22	3.12	2.23	3.58	14.31	20.12	23.24	5.03
5	1	3	12	84.07	115.27	2.55	0.37	1.03	40.3	0.21	3.90	2.98	3.98	15.63	22.58	26.48	4.52
6	2	3	10	95.66	126.86	3.31	0.39	1.53	46.3	0.26	4.68	3.15	4.55	17.56	25.26	29.94	4.21
8	1	4	14	108.29	139.49	4.24	0.53	1.86	44.0	0.23	6.24	4.26	5.20	19.71	29.16	35.40	3.65
9	3	3	12	111.91	143.11	4.52	0.55	1.90	41.9	0.21	7.02	4.43	5.38	20.33	30.14	37.17	3.35
12	2	4	16	117.52	148.72	4.99	0.74	1.49	29.8	0.12	9.36	5.90	5.68	21.31	32.88	42.24	2.74
13	1	5	20	132.95	164.15	6.39	0.83	2.56	40.1	0.20	10.14	6.64	6.49	24.04	37.17	47.31	2.86
16	2	5	18	140.57	171.77	7.14	0.94	2.51	35.2	0.16	12.48	7.54	6.90	25.41	39.85	52.33	2.49
18	1	6	22	157.84	189.04	9.00	1.08	3.77	41.9	0.21	14.04	8.65	7.86	28.58	45.08	59.12	2.50
21	3	5	20	152.09	183.29	8.36	1.19	2.33	27.8	0.11	16.38	9.54	7.54	27.51	44.59	60.98	2.12
22	4	5	22	166.71	197.91	10.04	1.26	3.71	37.0	0.17	17.16	10.10	8.36	30.24	48.69	65.85	2.21
24	2	6	24	164.31	195.51	9.75	1.38	2.85	29.2	0.12	18.72	11.01	8.22	29.78	49.02	67.74	2.04
25	1	7	28	182.86	214.06	12.08	1.47	4.85	40.2	0.19	19.50	11.76	9.28	33.32	54.36	73.86	2.17
26	3	6	22	174.27	205.47	10.97	1.44	3.54	32.3	0.14	20.28	11.55	8.79	31.67	52.00	72.29	2.00
29	5	5	28	183.69	214.89	12.19	1.65	3.86	31.7	0.13	22.63	13.21	9.33	33.48	56.02	78.64	1.93
30	2	7	26	188.47	219.67	12.83	1.67	4.25	33.1	0.14	23.41	13.38	9.61	34.41	57.40	80.80	1.91
32	4	6	24	187.16	218.36	12.66	1.74	3.55	28.0	0.11	24.97	13.91	9.53	34.15	57.60	82.56	1.80
34	5	6	26	202.43	233.63	14.80	1.85	5.12	34.6	0.15	26.53	14.83	10.44	37.15	62.42	88.94	1.84
36	1	8	30	207.96	239.16	15.63	1.99	5.34	34.2	0.15	28.09	15.94	10.77	38.25	64.96	93.05	1.80
37	3	7	28	197.21	228.41	14.05	2.01	3.52	25.0	0.10	28.87	16.11	10.13	36.12	62.35	91.22	1.69
40	4	7	30	208.70	239.90	15.74	2.17	4.35	27.6	0.11	31.21	17.39	10.82	38.40	66.60	97.81	1.67
44	6	6	32	219.58	250.78	17.42	2.38	4.91	28.2	0.11	34.33	19.03	11.48	40.60	71.10	105.43	1.62
45	5	7	28	222.49	253.69	17.88	2.38	5.14	28.8	0.11	35.11	19.01	11.66	41.19	71.86	106.97	1.60
49	1	9	36	233.13	264.33	19.64	2.65	5.70	29.0	0.12	38.23	21.22	12.32	43.38	76.92	115.15	1.57

BWR Cell Width (cm) = 15.646 (6.16 in)
BWR Mass (kg) = 320.0

Number of BWR's	K1	K2	KP	Internal Diameter (cm)	External Diameter (cm)	Internal Volume (m^3)	Support Basket (m^3)	Wasted Space (m^3)	Percent Wasted Space	W. Space Per BWR (m^3)	Weight of BWR's (tonnes)	Weight of Supports (tonnes)	Weight of 1st Barrier (tonnes)	Weight of 2nd Barrier (tonnes)	Empty WP Weight (tonnes)	Loaded WP Weight (tonnes)	WP Weight per BWR (tonnes)
1	1	1	4	30.61	61.81	0.34	0.07	0.16	46.0	0.16	0.32	0.56	1.47	7.21	9.23	9.55	9.23
2	1	2	6	45.74	76.94	0.76	0.12	0.41	54.3	0.21	0.64	0.96	2.15	9.51	12.62	13.26	6.31
4	2	2	8	56.98	88.18	1.17	0.20	0.52	44.3	0.13	1.28	1.63	2.67	11.26	15.56	16.84	3.89
5	1	3	12	62.79	93.99	1.42	0.27	0.59	41.4	0.12	1.60	2.17	2.95	12.18	17.29	18.89	3.46
6	2	3	10	71.39	102.59	1.84	0.29	0.88	47.8	0.15	1.92	2.29	3.36	13.56	19.20	21.12	3.20
8	1	4	14	80.55	111.75	2.34	0.39	1.06	45.1	0.13	2.56	3.09	3.80	15.06	21.94	24.50	2.74
9	3	3	12	83.35	114.55	2.51	0.40	1.09	43.6	0.12	2.88	3.21	3.94	15.51	22.66	25.54	2.52
12	2	4	16	87.42	118.62	2.76	0.53	0.88	31.7	0.07	3.84	4.28	4.14	16.18	24.60	28.44	2.05
13	1	5	20	98.63	129.83	3.51	0.60	1.45	41.2	0.11	4.16	4.82	4.70	18.06	27.58	31.74	2.12
16	2	5	18	104.32	135.52	3.93	0.68	1.45	36.8	0.09	5.12	5.46	4.99	19.03	29.49	34.61	1.84
18	1	6	22	116.90	148.10	4.94	0.78	2.13	43.1	0.12	5.76	6.27	5.64	21.20	33.11	38.87	1.84
21	3	5	20	112.84	144.04	4.60	0.86	1.37	29.8	0.07	6.72	6.91	5.43	20.50	32.84	39.56	1.56
22	4	5	22	123.61	154.81	5.52	0.91	2.13	38.6	0.10	7.04	7.31	6.00	22.38	35.68	42.72	1.62
24	2	6	24	121.74	152.94	5.35	1.00	1.65	30.9	0.07	7.68	7.98	5.90	22.05	35.92	43.60	1.50
25	1	7	28	135.27	166.47	6.61	1.06	2.73	41.3	0.11	8.00	8.52	6.62	24.45	39.58	47.58	1.58
26	3	6	22	129.11	160.31	6.02	1.04	2.05	34.0	0.08	8.32	8.36	6.29	23.35	38.00	46.32	1.46
29	5	5	28	136.09	167.29	6.69	1.20	2.23	33.3	0.08	9.28	9.56	6.66	24.60	40.82	50.10	1.41
30	2	7	26	139.47	170.67	7.03	1.21	2.44	34.7	0.08	9.60	9.68	6.84	25.21	41.74	51.34	1.39
32	4	6	24	138.62	169.82	6.94	1.26	2.08	30.0	0.07	10.24	10.07	6.80	25.05	41.92	52.16	1.31
34	5	6	26	149.86	181.06	8.11	1.34	2.94	36.3	0.09	10.88	10.73	7.41	27.10	45.24	56.12	1.33
36	1	8	30	153.70	184.90	8.53	1.44	3.04	35.6	0.08	11.52	11.53	7.63	27.81	46.97	58.49	1.30
37	3	7	28	145.95	177.15	7.70	1.46	2.07	26.9	0.06	11.84	11.65	7.20	26.39	45.24	57.08	1.22
40	4	7	30	154.43	185.63	8.62	1.57	2.54	29.5	0.06	12.80	12.58	7.67	27.94	48.19	60.99	1.20
44	6	6	32	162.46	193.66	9.54	1.72	2.86	30.0	0.07	14.08	13.76	8.12	29.44	51.32	65.40	1.17
45	5	7	28	164.59	195.79	9.79	1.72	3.00	30.7	0.07	14.40	13.74	8.24	29.84	51.82	66.22	1.15
49	1	9	36	172.18	203.38	10.71	1.92	3.27	30.6	0.07	15.68	15.35	8.67	31.27	55.29	70.97	1.13
52	4	8	32	170.81	202.01	10.54	1.98	2.70	25.6	0.05	16.64	15.86	8.59	31.01	55.46	72.10	1.07
56	5	8	34	180.04	211.24	11.71	2.13	3.28	28.0	0.06	17.92	17.04	9.12	32.78	58.94	76.86	1.05
57	3	9	36	180.70	211.90	11.80	2.18	3.20	27.1	0.06	18.24	17.44	9.16	32.90	59.50	77.74	1.04
60	4	9	34	187.61	218.81	12.72	2.26	3.70	29.1	0.06	19.20	18.09	9.56	34.24	61.88	81.08	1.03
61	7	7	36	188.83	220.03	12.88	2.31	3.70	28.7	0.06	19.52	18.49	9.63	34.48	62.60	82.12	1.03
62	1	10	38	190.69	221.89	13.14	2.36	3.79	28.9	0.06	19.84	18.89	9.74	34.84	63.47	83.31	1.02
66	3	10	38	198.42	229.62	14.22	2.49	4.30	30.2	0.07	21.12	19.94	10.20	36.36	66.49	87.61	1.01
68	2	10	40	193.70	224.90	13.55	2.57	3.32	24.5	0.05	21.76	20.60	9.92	35.43	65.94	87.70	0.97
69	5	9	36	196.06	227.26	13.89	2.57	3.54	25.5	0.05	22.08	20.58	10.06	35.89	66.53	88.61	0.96
70	7	8	38	202.44	233.64	14.81	2.62	4.30	29.1	0.06	22.40	20.98	10.44	37.15	68.57	90.97	0.98
71	1	11	44	209.23	240.43	15.82	2.71	5.11	32.3	0.07	22.72	21.66	10.85	38.51	71.02	93.74	1.00
74	6	9	38	205.85	237.05	15.31	2.75	4.22	27.6	0.06	23.68	22.03	10.64	37.83	70.50	94.18	0.95
76	4	10	40	204.73	235.93	15.14	2.84	3.75	24.8	0.05	24.32	22.69	10.58	37.61	70.87	95.19	0.93
78	2	11	42	211.97	243.17	16.23	2.92	4.53	27.9	0.06	24.96	23.35	11.01	39.06	73.42	98.38	0.94
80	8	8	40	215.20	246.40	16.73	2.97	4.76	28.4	0.06	25.60	23.74	11.21	39.71	74.65	100.25	0.93
81	3	11	44	216.29	247.49	16.90	3.03	4.75	28.1	0.06	25.92	24.28	11.28	39.93	75.48	101.40	0.93
82	5	10	42	212.50	243.70	16.31	3.05	4.03	24.7	0.05	26.24	24.40	11.05	39.16	74.61	100.85	0.91
86	4	11	42	222.10	253.30	17.82	3.18	4.96	27.8	0.06	27.52	25.44	11.63	41.11	78.19	105.71	0.91
88	6	10	40	221.57	252.77	17.74	3.23	4.60	25.9	0.05	28.16	25.83	11.60	41.00	78.43	106.59	0.89
89	7	9	44	216.81	248.01	16.98	3.30	3.66	21.6	0.04	28.48	26.37	11.31	40.03	77.71	106.19	0.87
92	8	9	46	228.76	259.96	18.91	3.41	5.14	27.2	0.06	29.44	27.29	12.05	42.48	81.82	111.26	0.89
96	2	12	48	230.30	261.50	19.16	3.56	4.79	25.0	0.05	30.72	28.48	12.14	42.80	83.42	114.14	0.87
97	5	11	44	229.28	260.48	18.99	3.56	4.51	23.8	0.05	31.04	28.46	12.08	42.58	83.12	114.16	0.86
100	3	12	46	234.29	265.49	19.83	3.67	4.90	24.7	0.05	32.00	29.38	12.39	43.62	85.40	117.40	0.85

Waste Package Diameters, Efficiencies, and Weights

TABLE 2 - UNCHANNELED BWR's

BWR Cell Width (cm) = 11.605 (4.57 in)
BWR Mass (kg) = 320.0

Number of BWR's	K1	K2	KP	Internal Diameter (cm)	External Diameter (cm)	Internal Volume (m^3)	Support Basket (m^3)	Wasted Space (m^3)	Percent Wasted Space	W. Space Per BWR (m^3)	Weight of BWR's (tonnes)	Weight of Supports (tonnes)	Weight of 1st Barrier (tonnes)	Weight of 2nd Barrier (tonnes)	Empty WP Weight (tonnes)	Loaded WP Weight (tonnes)	WP Weight per BWR (tonnes)
1	1	1	4	24.90	56.10	0.22	0.05	0.11	47.8	0.11	0.32	0.44	1.21	6.35	8.01	8.33	8.01
2	1	2	6	36.71	67.91	0.49	0.09	0.27	55.3	0.13	0.64	0.75	1.74	8.13	10.62	11.26	5.31
4	2	2	8	45.55	76.75	0.75	0.16	0.34	45.9	0.09	1.28	1.26	2.14	9.48	12.88	14.16	3.22
5	1	3	12	50.02	81.22	0.90	0.21	0.38	42.5	0.08	1.60	1.68	2.35	10.17	14.20	15.80	2.84
6	2	3	10	56.83	88.03	1.17	0.22	0.57	49.2	0.10	1.92	1.77	2.67	11.23	15.67	17.59	2.61
8	1	4	14	63.89	95.09	1.47	0.30	0.68	46.1	0.09	2.56	2.39	3.00	12.35	17.75	20.31	2.22
9	3	3	12	66.21	97.41	1.58	0.31	0.72	45.2	0.08	2.88	2.48	3.11	12.72	18.32	21.20	2.04
12	2	4	16	69.35	100.55	1.74	0.41	0.58	33.4	0.05	3.84	3.31	3.26	13.23	19.79	23.63	1.65
13	1	5	20	78.04	109.24	2.20	0.47	0.93	42.2	0.07	4.16	3.73	3.68	14.64	22.04	26.20	1.70
16	2	5	18	82.57	113.77	2.46	0.53	0.94	38.4	0.06	5.12	4.22	3.90	15.38	23.50	28.62	1.47
18	1	6	22	92.32	123.52	3.08	0.60	1.36	44.1	0.08	5.76	4.84	4.39	17.00	26.22	31.98	1.46
21	3	5	20	89.28	120.48	2.88	0.67	0.91	31.7	0.04	6.72	5.33	4.23	16.49	26.06	32.78	1.24
22	4	5	22	97.74	128.94	3.45	0.71	1.38	40.1	0.06	7.04	5.64	4.66	17.91	28.21	35.25	1.28
24	2	6	24	96.18	127.38	3.34	0.77	1.09	32.5	0.05	7.68	6.15	4.58	17.65	28.38	36.06	1.18
25	1	7	28	106.70	137.90	4.11	0.82	1.74	42.4	0.07	8.00	6.57	5.11	19.44	31.12	39.12	1.24
26	3	6	22	102.01	133.21	3.76	0.81	1.34	35.7	0.05	8.32	6.44	4.87	18.63	29.95	38.27	1.15
29	5	5	28	107.52	138.72	4.18	0.92	1.46	34.9	0.05	9.28	7.37	5.16	19.58	32.11	41.39	1.11
30	2	7	26	110.05	141.25	4.38	0.93	1.58	36.2	0.05	9.60	7.47	5.29	20.01	32.77	42.37	1.09
32	4	6	24	109.48	140.68	4.33	0.97	1.38	31.8	0.04	10.24	7.76	5.26	19.91	32.93	43.17	1.03
34	5	6	26	118.29	149.49	5.06	1.03	1.92	37.9	0.06	10.88	8.27	5.72	21.44	35.43	46.31	1.04
36	1	8	30	121.13	152.33	5.30	1.11	1.96	37.0	0.05	11.52	8.89	5.86	21.94	36.69	48.21	1.02
37	3	7	28	115.18	146.38	4.79	1.12	1.38	28.8	0.04	11.84	8.98	5.55	20.90	35.43	47.27	0.96
40	4	7	30	121.85	153.05	5.36	1.21	1.67	31.2	0.04	12.80	9.69	5.90	22.07	37.66	50.46	0.94
44	6	6	32	128.17	159.37	5.94	1.33	1.88	31.7	0.04	14.08	10.60	6.24	23.18	40.02	54.10	0.91
45	5	7	28	129.82	161.02	6.09	1.32	1.98	32.5	0.04	14.40	10.58	6.33	23.48	40.39	54.79	0.90
49	1	9	36	135.59	166.79	6.64	1.48	2.13	32.0	0.04	15.68	11.83	6.63	24.51	42.97	58.65	0.88
52	4	8	32	134.66	165.86	6.55	1.53	1.80	27.5	0.03	16.64	12.21	6.58	24.34	43.14	59.78	0.83
56	5	8	34	141.92	173.12	7.28	1.64	2.17	29.8	0.04	17.92	13.12	6.98	25.65	45.75	63.67	0.82
57	3	9	36	142.36	173.56	7.32	1.68	2.11	28.8	0.04	18.24	13.43	7.00	25.73	46.17	64.41	0.81
60	4	9	34	147.81	179.01	7.89	1.74	2.44	30.9	0.04	19.20	13.92	7.30	26.73	47.95	67.15	0.80
61	7	7	36	148.82	180.02	8.00	1.78	2.44	30.5	0.04	19.52	14.23	7.36	26.91	48.50	68.02	0.80
62	1	10	38	150.09	181.29	8.14	1.82	2.48	30.5	0.04	19.84	14.54	7.43	27.14	49.11	68.95	0.79
66	3	10	38	156.23	187.43	8.82	1.92	2.81	31.9	0.04	21.12	15.35	7.77	28.28	51.39	72.51	0.78
68	2	10	40	152.49	183.69	8.40	1.98	2.21	26.3	0.03	21.76	15.86	7.56	27.59	51.00	72.76	0.75
69	5	9	36	154.45	185.65	8.62	1.98	2.36	27.4	0.03	22.08	15.84	7.67	27.95	51.45	73.53	0.75
70	7	8	38	159.49	190.69	9.19	2.02	2.83	30.8	0.04	22.40	16.15	7.95	28.88	52.98	75.38	0.76
71	1	11	44	164.60	195.80	9.79	2.08	3.30	33.8	0.05	22.72	16.68	8.24	29.84	54.76	77.48	0.77
74	6	9	38	162.14	193.34	9.50	2.12	2.79	29.4	0.04	23.68	16.95	8.10	29.38	54.43	78.11	0.74
76	4	10	40	161.21	192.41	9.39	2.18	2.50	26.6	0.03	24.32	17.46	8.05	29.20	54.71	79.03	0.72
78	2	11	42	166.79	197.99	10.05	2.25	2.97	29.6	0.04	24.96	17.97	8.36	30.25	56.59	81.55	0.73
80	8	8	40	169.48	200.68	10.38	2.28	3.14	30.2	0.04	25.60	18.27	8.51	30.76	57.54	83.14	0.72
81	3	11	44	170.22	201.42	10.47	2.34	3.11	29.8	0.04	25.92	18.69	8.56	30.90	58.14	84.06	0.72
82	5	10	42	167.32	198.52	10.11	2.35	2.69	26.6	0.03	26.24	18.78	8.39	30.35	57.52	83.76	0.70
86	4	11	42	174.80	206.00	11.04	2.45	3.26	29.6	0.04	27.52	19.58	8.82	31.77	60.17	87.69	0.70
88	6	10	40	174.44	205.64	10.99	2.48	3.06	27.8	0.03	28.16	19.87	8.80	31.70	60.37	88.53	0.69
89	7	9	44	170.73	201.93	10.53	2.54	2.48	23.6	0.03	28.48	20.29	8.58	31.00	59.87	88.35	0.67
92	8	9	46	180.10	211.30	11.72	2.63	3.39	29.0	0.04	29.44	21.00	9.12	32.79	62.91	92.35	0.68
96	2	12	48	181.15	212.35	11.86	2.74	3.17	26.7	0.03	30.72	21.91	9.18	32.99	64.09	94.81	0.67
97	5	11	44	180.45	211.65	11.76	2.74	3.02	25.7	0.03	31.04	21.90	9.14	32.85	63.89	94.93	0.66
100	3		9	184.30	215.50	12.27	2.83	3.25	26.5	0.03	32.00	22.61	9.37	33.60	65.57	97.57	0.66

Interoffice Correspondence

Civilian Radioactive Waste Management System
Management & Operating Contractor

TRW Environmental
Safety Systems Inc.

WBS: 1.2.2.4
QA: N/A

Subject:
Thermal Analysis of Drift
Emplaced Waste Package

Date:
December 1, 1993
LV.WP.RHB.12/93-264

From:
R.H.Bahney III

To:
S.F.Saterlie, TES3/423

cc:
H.A.Benton, TES3/423
T.W.Doering, TES3/423
File: PD-5, TL-1

Location/Phone
TES3/P102
(702) 794-5337

A thermal analysis of a drift-emplaced 21 PWR capacity Multi-Purpose Canister with disposal container was performed in support of the M&O's thermal loading systems study. Detailed thermal analyses of waste package internal temperatures were requested for two emplacement scenarios. In both cases, waste packages are loaded with 22 year old fuel with an average burnup of 42.2 GWd/MTU. These characteristics represent averages for a youngest-fuel-first waste stream with a 10-year minimum age on waste acceptance. It should be noted that the results presented here describe temperatures in packages with an average heat load and do not address the thermal behavior in packages loaded with an above average heat load. (For example, a waste package loaded with average fuel would generate 10.23 kW; but one loaded with MPC design-basis fuel of 10 year old, 40 GWd/MTU burnup would generate 14.2 kW or 39% greater heat.)

Drift Wall Temperature histories for the two emplacement scenarios were provided by Sandia National Laboratories. These temperatures were applied as time varying boundary conditions to a detailed transient model of the MPC with disposal container. The loaded waste package has an external diameter of 1.74 m, a length of 5.11 m, and an initial heat output of 10.23 kW. The two emplacement scenarios are summarized below:

	Case 1	Case 2
Thermal Loading	111 MTU/acre	111 MTU/acre
Drift Spacing	23.30 m	20.48 m
Waste Package Spacing	14.06 m	16.00 m
Drift Diameter	7.0 m	4.3 m

Results of the 2-D evaluations of the emplaced waste package are given below. The figures on the following pages graph the temperature history of the waste package out to 1000 years for each case. Complete tabular results are enclosed as well. Drift wall temperatures reported here are taken directly from the Sandia results. It should be noted that the two cases do not provide a useful comparison between large and small drift diameters because the waste package spacing is not held constant. The table below lists the peak temperatures observed and their time of occurrence.

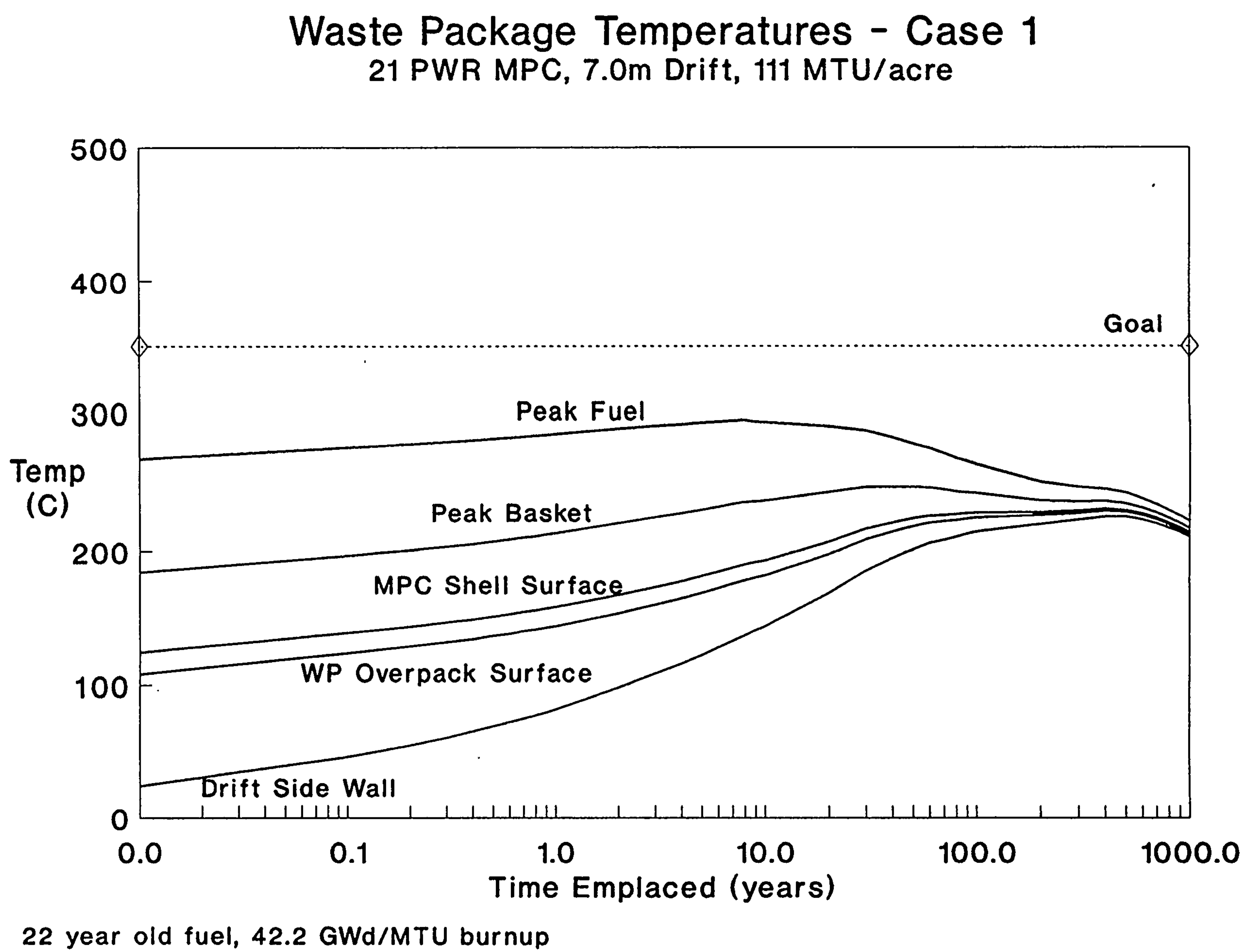
	Case 1	Case 2
Peak Clad Temperature	294°C	302°C
Peak Clad Time	8 years	8 years
Peak WP Side Temperature	230°C	234°C
Peak WP Side Time	400 years	90&400 years

Peak fuel temperatures occur within the first few years. Therefore, waste package spacing is more important for meeting the 350°C cladding limit than the drift spacing which will not have a significant effect on WP temperatures until ten or more years post-emplacement. Previous analyses indicate that a younger fuel loading (such as 10 year old) will result in higher peak temperatures which occur in the first year post-emplacement.

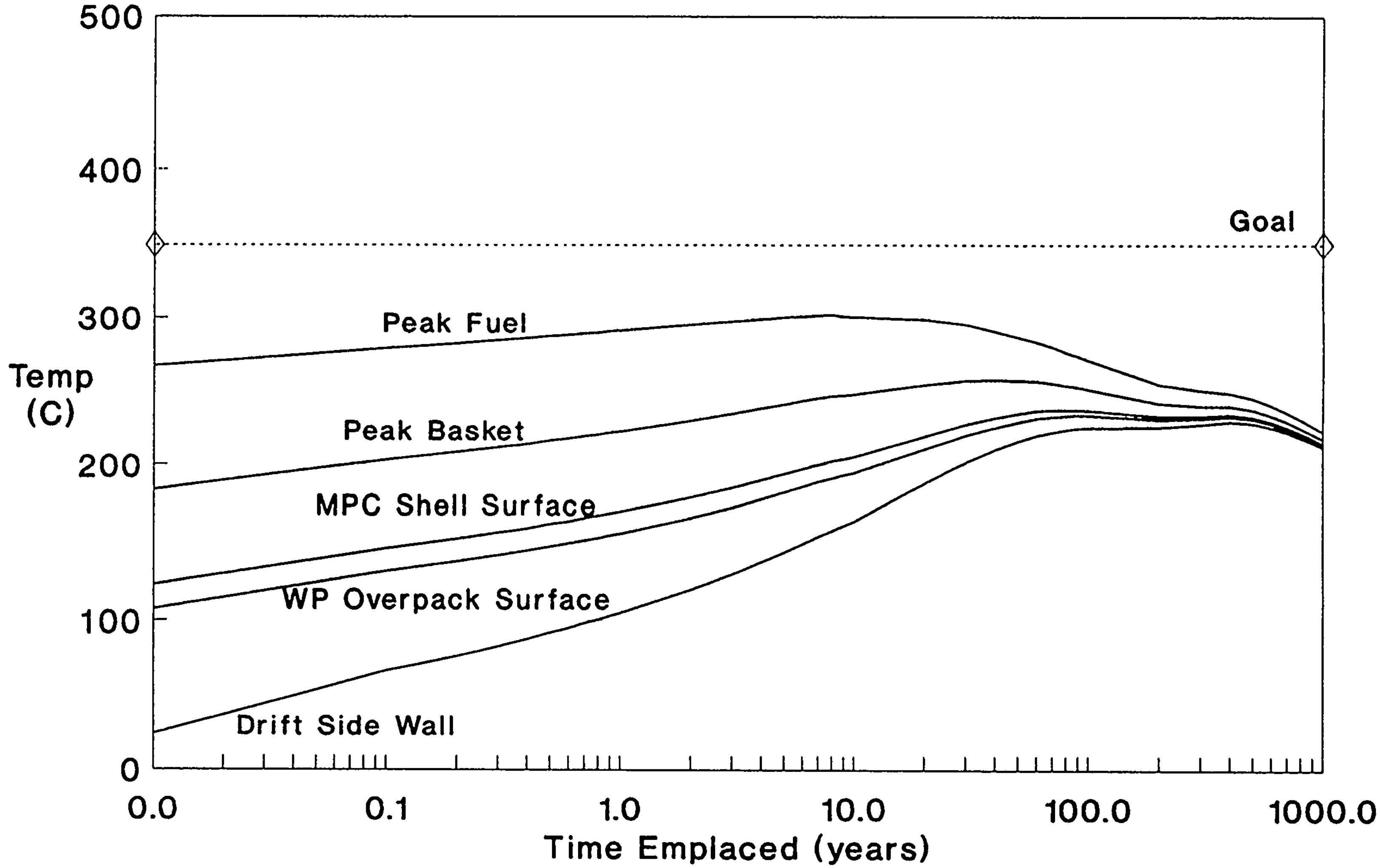
Waste package surface and drift wall temperatures reach their peak temperature around 400 years post-emplacement according to the Sandia model. The uncertainty in the time of the waste package side temperature peak for Case 2 is due to differences between the M&O waste package model and the Sandia repository model. The average drift wall temperature (predicted by Sandia) will peak at a later time (400 years) than a specific point on the wall that is directly adjacent to the waste package (90 years for the M&O model). The fluctuations observed are within the overall model uncertainty. In case 2, the waste package surface remains slightly above 230°C from 60 to 500 years.

Enclosures:
Waste Package Temperatures - Case 1 - Figure
Waste Package Temperatures - Case 2 - Figure
Waste Package Temperatures - Case 1 - Table
Waste Package Temperatures - Case 2 - Table
Drift Emplacement Geometry
Waste Package FEM Mesh Plot
Waste Package Heat Generation Rates - ANSYS Table
Drift Wall Temperature Histories - Case 1 - ANSYS Table
Drift Wall Temperature Histories - Case 2 - ANSYS Table

Concur: Hugh A. Benton
for T.W.Doering, Manager Waste Package Design


Waste Package Temperatures - Case 1
21 PWR MPC, 7.0m Drift, 111 MTU/acre
Temp
(C)
500
400
300
200
100
0
Goal
Peak Fuel
Peak Basket
MPC Shell Surface
WP Overpack Surface
Drift Side Wall
0.0
0.1
1.0
10.0
100.0
1000.0
Time Emplaced (years)
22 year old fuel, 42.2 GWd/MTU burnup

Waste Package Temperatures - Case 2
21 PWR MPC, 4.3m Drift, 111 MTU/acre



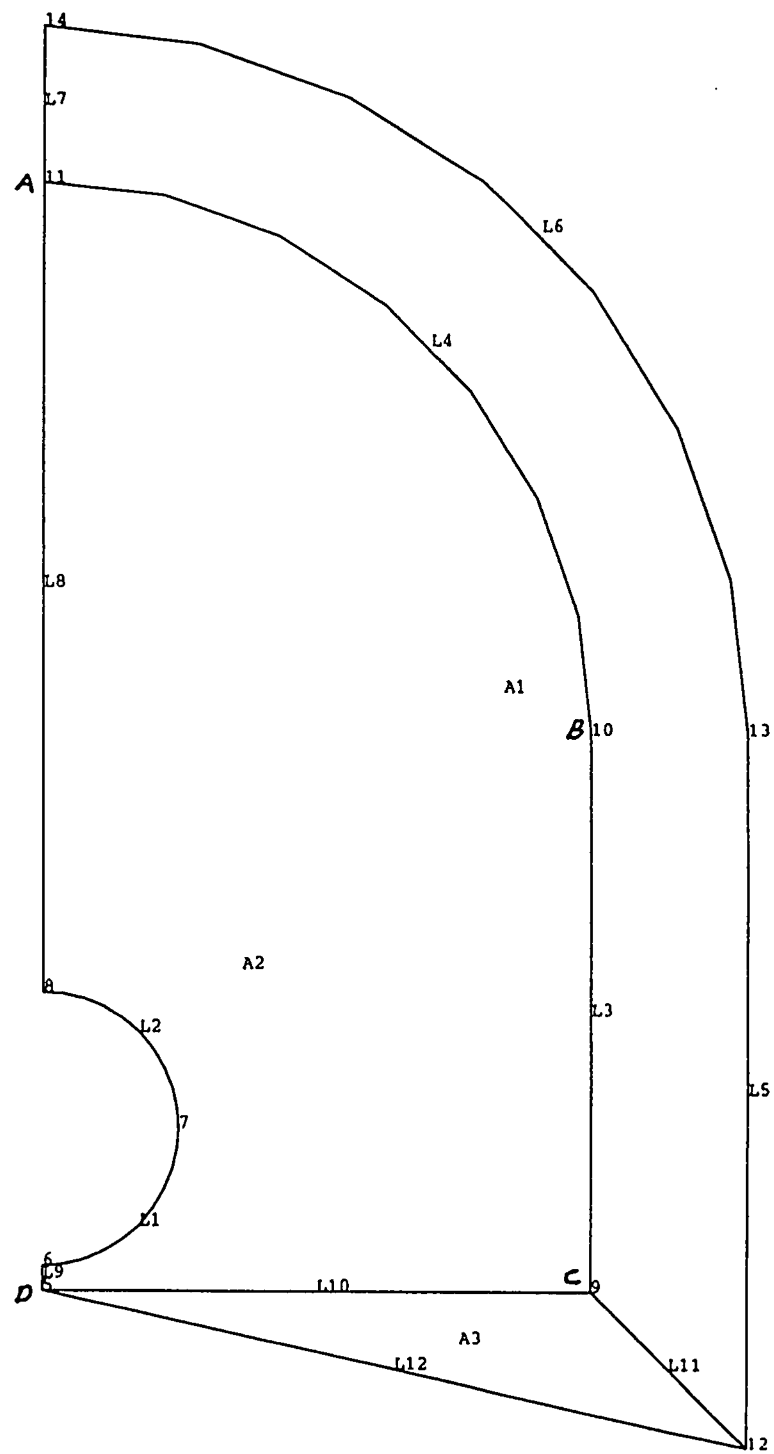
22 year old fuel, 42.2 GWd/MTU burnup

Summary of WP temperatures	R. Bahney 12-1-93	File: mpcss1
Case 1	(111 MTU/acre - 7.0 m Drift Diameter)
125 ton burnup credit 21 PWR MPC with disposal overpack : 60% Consolidated Fuel Conduct
1.1531 Peaking Factor on Assembly Heat Load	22 year old 42.2 GWd/MTU burn

Time	ANSYS FEM Temperature Results (Deg. C)				
(years)	Peak Fuel	Peak Basket	MPC Side	WP Side	Drift Wall
0	267.36	184.01	123.52	107.73	23.79
0.1	275.12	196.97	138.55	123.28	46.25
0.2	277.70	201.19	143.39	128.32	54.95
0.3	279.26	203.84	146.54	131.62	60.81
0.4	280.31	205.68	148.79	133.99	65.30
0.5	281.45	207.62	151.11	136.41	69.05
0.6	282.13	208.87	152.68	138.04	72.19
0.7	283.00	210.38	154.49	139.96	75.01
0.8	283.40	211.19	155.57	141.09	77.45
0.9	284.12	212.46	157.10	142.72	79.75
1	284.51	213.25	158.15	143.81	81.89
2	288.30	220.52	167.47	153.69	97.99
3	290.16	224.81	173.39	160.06	108.24
4	291.28	227.74	177.63	164.65	115.58
5	292.31	230.41	181.44	168.76	121.89
6	292.87	232.52	184.72	172.40	127.71
7	293.79	234.79	187.92	175.86	132.86
8	294.14	236.25	190.23	178.41	136.90
9	293.19	236.72	191.99	180.49	140.65
10	292.54	237.12	193.35	182.12	143.58
20	289.78	243.38	207.19	198.04	168.96
30	286.95	247.18	216.49	208.79	185.46
40	281.99	247.30	221.01	214.45	194.98
50	277.87	247.04	224.04	218.32	201.62
60	274.59	246.66	226.09	220.98	206.18
70	270.80	245.14	226.51	221.90	208.60
80	267.48	243.93	227.05	222.88	210.84
90	265.17	243.32	227.78	223.96	212.96
100	263.25	242.73	228.24	224.68	214.44
200	250.70	237.46	228.52	226.31	219.98
300	247.23	236.69	229.67	227.92	222.96
400	245.79	236.88	230.97	229.50	225.34
500	243.10	235.27	230.11	228.83	225.21
600	238.85	231.88	227.36	226.24	223.05
700	234.38	228.05	224.02	223.02	220.14
800	229.95	224.12	220.46	219.58	216.93
900	225.91	220.46	217.10	216.26	213.84
1000	221.89	216.71	213.56	212.81	210.50

Summary of WP temperatures R. Bahney 12-1-93 File: mpcss2
Case 2 (111 MTU/acre - 4.3 m Drift Diameter)
125 ton burnup credit 21 PWR MPC with disposal overpack : 60% Consolidated Fuel Conduct
1.1531 Peaking Factor on Assembly Heat Load 22 year old 42.2 GWd/MTU burn

Time	ANSYS FEM Temperature Results (Deg. C)				
(years)	Peak Fuel	Peak Basket	MPC Side	WP Side	Drift Wall
0	267.06	183.52	123.01	107.26	23.80
0.1	279.14	203.49	146.36	131.56	66.80
0.2	282.61	208.89	152.42	137.79	76.43
0.3	284.68	212.20	156.31	141.84	82.96
0.4	286.06	214.47	159.04	144.70	87.57
0.5	287.46	216.76	161.74	147.51	91.92
0.6	288.34	218.24	163.56	149.43	94.94
0.7	289.31	219.84	165.49	151.41	98.03
0.8	289.95	220.98	166.92	152.96	100.40
0.9	290.67	222.21	168.41	154.49	102.80
1	291.18	223.14	169.62	155.79	104.80
2	295.03	230.30	178.76	165.47	119.50
3	297.30	234.95	185.04	172.19	129.60
4	298.99	238.59	190.01	177.54	137.51
5	300.25	241.45	193.97	181.81	143.80
6	300.95	243.68	197.33	185.46	149.21
7	301.82	245.80	200.34	188.72	153.90
8	302.21	247.27	202.62	191.22	157.50
9	301.20	247.58	204.16	193.14	160.80
10	300.65	248.05	205.58	194.81	163.50
20	298.78	254.97	219.92	211.09	187.70
30	295.55	257.86	228.10	220.65	201.90
40	290.82	257.99	232.52	226.17	210.61
50	286.75	257.59	235.30	229.76	216.40
60	283.62	257.23	237.28	232.34	220.60
70	280.13	255.93	237.89	233.43	222.90
80	276.71	254.48	238.12	234.08	224.60
90	273.95	253.26	238.20	234.48	225.80
100	271.38	251.88	237.81	234.34	226.20
200	255.30	242.40	233.65	231.53	226.40
300	250.99	240.67	233.77	232.10	228.10
400	249.20	240.46	234.65	233.26	229.90
500	245.76	238.03	232.96	231.75	228.80
600	241.01	234.12	229.67	228.61	226.00
700	236.17	229.91	225.93	224.98	222.60
800	231.50	225.72	222.12	221.22	219.10
900	227.22	221.82	218.49	217.70	215.70
1000	222.99	217.85	214.75	213.97	212.10



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AREA NUM

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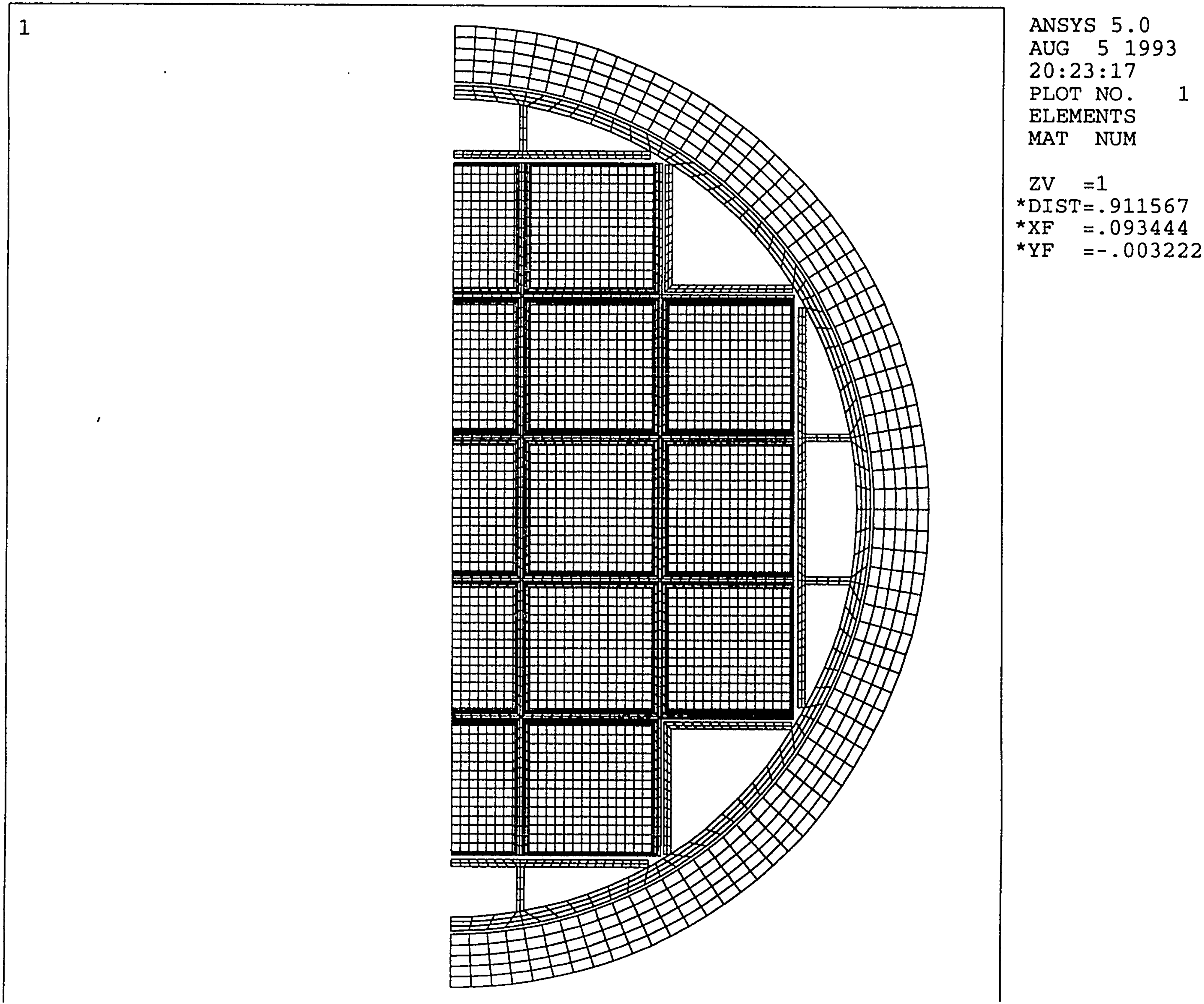
21 PWR, 22 years old, 42.2 GWd/MTU burnup, 7 m Tunnel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AUG 5 1993
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ASSY(31,1)=     123,   116.2,   110.1,   104.7,    99.9,    95.5
ASSY(37,1)=      91,    88.2,    85.7,    67.4,    56.8,    49.4
ASSY(43,1)=      43,    38.1,    34.3,    31.3,    29.1,   15.53
ASSY(49,1)=    12.8,   11.14,    9.97,    9.18,    8.55,    8.05
ASSY(55,1)=    7.63,    7.22
ASSY( 1,0)=  1.0E-6,       1,       2,       3,       4,       5
ASSY( 7,0)=       6,       7,       8,       9,      10,      15
ASSY(13,0)=      20,      25,      30,      35,      40,      45
ASSY(19,0)=      50,      55,      60,      65,      70,      75
ASSY(25,0)=      80,      85,      90,      95,     100,     110
ASSY(31,0)=     120,     130,     140,     150,     160,     170
ASSY(37,0)=     180,     190,     200,     300,     400,     500
ASSY(43,0)=     600,     700,     800,     900,    1000,    2000
ASSY(49,0)=    3000,    4000,    5000,    6000,    7000,    8000
ASSY(55,0)=    9000,   10000
ASSY(0,1)=      1.0
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/COM,   **********************************************
/COM,   ** Drift Wall Temperature Histories (SANDIA)**
/COM,   **      File name: sandia1.dat              **
/COM,   **      Aged 22 years, .428 MTU/Assy        **
/COM,   **      42.21 GWd/MTU burnup                **
/COM,   **      111.06 MTU/acre -> 126.37 kW/acre   **
/COM,   **      Df Sp = 23.3 m, WP Sp = 14.06 m     **
/COM,   **      7 m (23 ft) Drift Diameter          **
/COM,   **               TEMPA=Top of Drift         **
/COM,   **               TEMPB=Side of Drift        **
/COM,   **               TEMPC=Floor Corner         **
/COM,   **               TEMPD=Floor Center         **
/COM,   **      R.Bahney 11-30-93                   **
/COM,   **********************************************
/COM,           (Temperature time is in seconds)
TEMPA( 1,1)=   23.78,   30.57,   40.96,   45.97,   49.72,   53.05,
TEMPA( 7,1)=   55.63,   60.24,   63.83,   67.03,   69.76,   72.25,
TEMPA(13,1)=   74.47,   76.63,   78.56,   80.47,   82.20,   83.92,
TEMPA(19,1)=   85.51,   87.09,   88.57,   90.02,   91.36,   92.66,
TEMPA(25,1)=   95.75,   98.56,  100.78,  102.83,  104.87,  106.77,
TEMPA(31,1)=  108.58,  110.22,  116.58,  122.40,  127.61,  131.79,
TEMPA(37,1)=  135.56,  138.61,  141.58,  144.15,  146.77,  149.25,
TEMPA(43,1)=  151.88,  154.50,  157.17,  159.67,  162.07,  164.37,
TEMPA(49,1)=  166.63,  168.70,  170.66,  172.49,  174.22,  175.86,
TEMPA(55,1)=  177.41,  178.82,  180.14,  181.37,  186.77,  191.26,
TEMPA(61,1)=  195.04,  198.34,  203.13,  205.79,  208.25,  210.58,
TEMPA(67,1)=  212.18,  214.74,  216.10,  217.22,  218.44,  219.38,
TEMPA(73,1)=  220.25,  221.00,  221.70,  222.46,  223.16,  223.79,
TEMPA(79,1)=  224.25,  224.53,  224.62,  224.54,  224.27,  223.88,
TEMPA(85,1)=  223.39,  222.84,  222.23,  221.59,  220.90,  220.17,
TEMPA(91,1)=  219.42,  218.65,  217.86,  217.06,  216.28,  215.52,
TEMPA(97,1)=  214.78,  214.03,  213.25,  212.46,  211.64,  210.81,
TEMPA(103,1)=  209.97,
TEMPA( 1,0)= 3.156E+01, 1.578E+06, 3.156E+06, 4.734E+06, 6.312E+06,
TEMPA( 6,0)= 7.889E+06, 9.467E+06, 1.262E+07, 1.578E+07, 1.893E+07,
TEMPA(11,0)= 2.209E+07, 2.525E+07, 2.840E+07, 3.156E+07, 3.471E+07,
TEMPA(16,0)= 3.787E+07, 4.102E+07, 4.418E+07, 4.734E+07, 5.049E+07,
TEMPA(21,0)= 5.365E+07, 5.680E+07, 5.996E+07, 6.312E+07, 7.100E+07,
TEMPA(26,0)= 7.889E+07, 8.678E+07, 9.467E+07, 1.026E+08, 1.105E+08,
TEMPA(31,0)= 1.183E+08, 1.262E+08, 1.578E+08, 1.893E+08, 2.209E+08,
TEMPA(36,0)= 2.525E+08, 2.840E+08, 3.156E+08, 3.471E+08, 3.787E+08,
TEMPA(41,0)= 4.102E+08, 4.418E+08, 4.734E+08, 5.049E+08, 5.365E+08,
TEMPA(46,0)= 5.680E+08, 5.996E+08, 6.312E+08, 6.627E+08, 6.943E+08,
TEMPA(51,0)= 7.258E+08, 7.574E+08, 7.889E+08, 8.205E+08, 8.521E+08,
TEMPA(56,0)= 8.836E+08, 9.152E+08, 9.467E+08, 1.105E+09, 1.262E+09,
TEMPA(61,0)= 1.420E+09, 1.578E+09, 1.893E+09, 2.209E+09, 2.525E+09,
TEMPA(66,0)= 2.840E+09, 3.156E+09, 3.945E+09, 4.734E+09, 5.523E+09,
TEMPA(71,0)= 6.312E+09, 7.100E+09, 7.889E+09, 8.678E+09, 9.467E+09,
TEMPA(76,0)= 1.026E+10, 1.105E+10, 1.183E+10, 1.262E+10, 1.341E+10,
TEMPA(81,0)= 1.420E+10, 1.499E+10, 1.578E+10, 1.657E+10, 1.736E+10,
TEMPA(86,0)= 1.815E+10, 1.893E+10, 1.972E+10, 2.051E+10, 2.130E+10,
TEMPA(91,0)= 2.209E+10, 2.288E+10, 2.367E+10, 2.446E+10, 2.525E+10,
TEMPA(96,0)= 2.604E+10, 2.682E+10, 2.761E+10, 2.840E+10, 2.919E+10,
TEMPA(101,0)= 2.998E+10, 3.077E+10, 3.156E+10,
TEMPA(0,1)=  1.0,
TEMPB( 1,1)=   23.79,   34.23,   46.25,   50.51,   54.95,   57.95,
TEMPB( 7,1)=   60.81,   65.30,   69.05,   72.19,   75.01,   77.45,
TEMPB(13,1)=   79.75,   81.89,   83.85,   85.78,   87.51,   89.27,
TEMPB(19,1)=   90.83,   92.45,   93.90,   95.39,   96.64,   97.99,
TEMPB(25,1)=  100.98,  103.86,  106.09,  108.24,  110.17,  112.10,
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EMPB(31,1)=  113.87,  115.57,  121.89,  127.70,  132.86,  136.90,
EMPB(37,1)=  140.65,  143.58,  146.53,  149.02,  151.62,  154.04,
EMPB(43,1)=  156.69,  159.26,  161.92,  164.35,  166.74,  168.96,
EMPB(49,1)=  171.20,  173.19,  175.12,  176.85,  178.55,  180.11,
F  B(55,1)=  181.63,  182.98,  184.29,  185.46,  190.67,  194.97,
L  B(61,1)=  198.56,  201.62,  206.18,  208.60,  210.84,  212.96,
EMPB(67,1)=  214.44,  216.71,  217.90,  218.86,  219.98,  220.82,
EMPB(73,1)=  221.63,  222.29,  222.96,  223.66,  224.33,  224.90,
EMPB(79,1)=  225.34,  225.56,  225.63,  225.49,  225.21,  224.77,
EMPB(85,1)=  224.27,  223.66,  223.05,  222.36,  221.67,  220.90,
EMPB(91,1)=  220.14,  219.33,  218.54,  217.71,  216.93,  216.14,
EMPB(97,1)=  215.40,  214.61,  213.84,  213.01,  212.20,  211.34,
EMPB(103,1)=  210.50,
EMPB( 1,0)= 3.156E+01, 1.578E+06, 3.156E+06, 4.734E+06, 6.312E+06,
EMPB( 6,0)= 7.889E+06, 9.467E+06, 1.262E+07, 1.578E+07, 1.893E+07,
EMPB(11,0)= 2.209E+07, 2.525E+07, 2.840E+07, 3.156E+07, 3.471E+07,
EMPB(16,0)= 3.787E+07, 4.102E+07, 4.418E+07, 4.734E+07, 5.049E+07,
EMPB(21,0)= 5.365E+07, 5.680E+07, 5.996E+07, 6.312E+07, 7.100E+07,
EMPB(26,0)= 7.889E+07, 8.678E+07, 9.467E+07, 1.026E+08, 1.105E+08,
EMPB(31,0)= 1.183E+08, 1.262E+08, 1.578E+08, 1.893E+08, 2.209E+08,
EMPB(36,0)= 2.525E+08, 2.840E+08, 3.156E+08, 3.471E+08, 3.787E+08,
EMPB(41,0)= 4.102E+08, 4.418E+08, 4.734E+08, 5.049E+08, 5.365E+08,
EMPB(46,0)= 5.680E+08, 5.996E+08, 6.312E+08, 6.627E+08, 6.943E+08,
EMPB(51,0)= 7.258E+08, 7.574E+08, 7.889E+08, 8.205E+08, 8.521E+08,
EMPB(56,0)= 8.836E+08, 9.152E+08, 9.467E+08, 1.105E+09, 1.262E+09,
EMPB(61,0)= 1.420E+09, 1.578E+09, 1.893E+09, 2.209E+09, 2.525E+09,
EMPB(66,0)= 2.840E+09, 3.156E+09, 3.945E+09, 4.734E+09, 5.523E+09,
EMPB(71,0)= 6.312E+09, 7.100E+09, 7.889E+09, 8.678E+09, 9.467E+09,
EMPB(76,0)= 1.026E+10, 1.105E+10, 1.183E+10, 1.262E+10, 1.341E+10,
EMPB(81,0)= 1.420E+10, 1.499E+10, 1.578E+10, 1.657E+10, 1.736E+10,
EMPB(86,0)= 1.815E+10, 1.893E+10, 1.972E+10, 2.051E+10, 2.130E+10,
EMPB(91,0)= 2.209E+10, 2.288E+10, 2.367E+10, 2.446E+10, 2.525E+10,
EMPB(96,0)= 2.604E+10, 2.682E+10, 2.761E+10, 2.840E+10, 2.919E+10,
EMPB(101,0)= 2.998E+10, 3.077E+10, 3.156E+10,
EMPB(0,1)=  1.0,
EMPC( 1,1)=   23.80,   35.14,   48.53,   52.44,   57.09,   60.09,
EMPC( 7,1)=   62.89,   67.50,   71.12,   74.38,   77.07,   79.60,
EMPC(13,1)=   81.78,   84.04,   85.86,   87.90,   89.49,   91.36,
EMPC(19,1)=   92.78,   94.50,   95.81,   97.40,   98.47,   99.88,
EMPC(25,1)=  102.81,  105.71,  108.01,  110.16,  112.12,  114.01,
EMPC(31,1)=  115.83,  117.52,  123.93,  129.65,  134.79,  138.77,
EMPC(37,1)=  142.49,  145.38,  148.30,  150.76,  153.33,  155.72,
EMPC(43,1)=  158.33,  160.87,  163.51,  165.91,  168.28,  170.48,
EMPC(49,1)=  172.70,  174.67,  176.56,  178.26,  179.92,  181.47,
EMPC(55,1)=  182.97,  184.32,  185.61,  186.78,  191.93,  196.22,
EMPC(61,1)=  199.71,  202.67,  207.17,  209.53,  211.68,  213.73,
EMPC(67,1)=  215.15,  217.34,  218.46,  219.39,  220.47,  221.28,
EMPC(73,1)=  222.06,  222.72,  223.37,  224.06,  224.72,  225.29,
EMPC(79,1)=  225.71,  225.92,  225.97,  225.82,  225.52,  225.07,
EMPC(85,1)=  224.55,  223.94,  223.30,  222.61,  221.90,  221.13,
EMPC(91,1)=  220.36,  219.55,  218.74,  217.91,  217.11,  216.32,
EMPC(97,1)=  215.57,  214.78,  214.00,  213.18,  212.35,  211.49,
EMPC(103,1)=  210.64,
EMPC( 1,0)= 3.156E+01, 1.578E+06, 3.156E+06, 4.734E+06, 6.312E+06,
EMPC( 6,0)= 7.889E+06, 9.467E+06, 1.262E+07, 1.578E+07, 1.893E+07,
   C(11,0)= 2.209E+07, 2.525E+07, 2.840E+07, 3.156E+07, 3.471E+07,
   C(16,0)= 3.787E+07, 4.102E+07, 4.418E+07, 4.734E+07, 5.049E+07,
EMPC(21,0)= 5.365E+07, 5.680E+07, 5.996E+07, 6.312E+07, 7.100E+07,
EMPC(26,0)= 7.889E+07, 8.678E+07, 9.467E+07, 1.026E+08, 1.105E+08,
EMPC(31,0)= 1.183E+08, 1.262E+08, 1.578E+08, 1.893E+08, 2.209E+08,
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TEMPC(36,0)= 2.525E+08, 2.840E+08, 3.156E+08, 3.471E+08, 3.787E+08,
TEMPC(41,0)= 4.102E+08, 4.418E+08, 4.734E+08, 5.049E+08, 5.365E+08,
TEMPC(46,0)= 5.680E+08, 5.996E+08, 6.312E+08, 6.627E+08, 6.943E+08,
TEMPC(51,0)= 7.258E+08, 7.574E+08, 7.889E+08, 8.205E+08, 8.521E+08,
TEMPC(56,0)= 8.836E+08, 9.152E+08, 9.467E+08, 1.105E+09, 1.262E+09,
TEMPC(61,0)= 1.420E+09, 1.578E+09, 1.893E+09, 2.209E+09, 2.525E+09,
TEMPC(66,0)= 2.840E+09, 3.156E+09, 3.945E+09, 4.734E+09, 5.523E+09,
TEMPC(71,0)= 6.312E+09, 7.100E+09, 7.889E+09, 8.678E+09, 9.467E+09,
TEMPC(76,0)= 1.026E+10, 1.105E+10, 1.183E+10, 1.262E+10, 1.341E+10,
TEMPC(81,0)= 1.420E+10, 1.499E+10, 1.578E+10, 1.657E+10, 1.736E+10,
TEMPC(86,0)= 1.815E+10, 1.893E+10, 1.972E+10, 2.051E+10, 2.130E+10,
TEMPC(91,0)= 2.209E+10, 2.288E+10, 2.367E+10, 2.446E+10, 2.525E+10,
TEMPC(96,0)= 2.604E+10, 2.682E+10, 2.761E+10, 2.840E+10, 2.919E+10,
TEMPC(101,0)= 2.998E+10, 3.077E+10, 3.156E+10,
TEMPC(0,1)=  1.0,
TEMPD( 1,1)=   23.80,   59.25,   78.16,   78.47,   86.30,   86.80,
TEMPD( 7,1)=   91.75,   94.55,   99.85,  101.57,  105.91,  106.41,
TEMPD(13,1)=  110.21,  111.13,  113.89,  115.13,  117.24,  118.61,
TEMPD(19,1)=  120.31,  121.72,  123.33,  124.53,  125.98,  127.06,
TEMPD(25,1)=  130.14,  132.70,  135.12,  136.93,  139.06,  140.58,
TEMPD(31,1)=  142.56,  143.88,  150.09,  155.20,  160.22,  163.62,
TEMPD(37,1)=  167.23,  169.56,  172.36,  174.26,  176.70,  178.55,
TEMPD(43,1)=  181.03,  183.05,  185.56,  187.47,  189.73,  191.46,
TEMPD(49,1)=  193.58,  195.10,  196.90,  198.17,  199.76,  200.88,
TEMPD(55,1)=  202.31,  203.25,  204.47,  205.24,  209.48,  212.63,
TEMPD(61,1)=  215.42,  217.46,  220.74,  221.83,  223.22,  224.35,
TEMPD(67,1)=  225.28,  226.09,  226.50,  226.63,  227.36,  227.60,
TEMPD(73,1)=  228.19,  228.39,  228.93,  229.22,  229.81,  230.03,
TEMPD(79,1)=  230.42,  230.31,  230.36,  229.91,  229.63,  228.90,
TEMPD(85,1)=  228.41,  227.53,  226.95,  226.00,  225.35,  224.33,
TEMPD(91,1)=  223.63,  222.58,  221.85,  220.78,  220.07,  219.06,
TEMPD(97,1)=  218.39,  217.39,  216.70,  215.66,  214.93,  213.86,
TEMPD(103,1)=  213.12,
TEMPD( 1,0)= 3.156E+01, 1.578E+06, 3.156E+06, 4.734E+06, 6.312E+06,
TEMPD( 6,0)= 7.889E+06, 9.467E+06, 1.262E+07, 1.578E+07, 1.893E+07,
TEMPD(11,0)= 2.209E+07, 2.525E+07, 2.840E+07, 3.156E+07, 3.471E+07,
TEMPD(16,0)= 3.787E+07, 4.102E+07, 4.418E+07, 4.734E+07, 5.049E+07,
TEMPD(21,0)= 5.365E+07, 5.680E+07, 5.996E+07, 6.312E+07, 7.100E+07,
TEMPD(26,0)= 7.889E+07, 8.678E+07, 9.467E+07, 1.026E+08, 1.105E+08,
TEMPD(31,0)= 1.183E+08, 1.262E+08, 1.578E+08, 1.893E+08, 2.209E+08,
TEMPD(36,0)= 2.525E+08, 2.840E+08, 3.156E+08, 3.471E+08, 3.787E+08,
TEMPD(41,0)= 4.102E+08, 4.418E+08, 4.734E+08, 5.049E+08, 5.365E+08,
TEMPD(46,0)= 5.680E+08, 5.996E+08, 6.312E+08, 6.627E+08, 6.943E+08,
TEMPD(51,0)= 7.258E+08, 7.574E+08, 7.889E+08, 8.205E+08, 8.521E+08,
TEMPD(56,0)= 8.836E+08, 9.152E+08, 9.467E+08, 1.105E+09, 1.262E+09,
TEMPD(61,0)= 1.420E+09, 1.578E+09, 1.893E+09, 2.209E+09, 2.525E+09,
TEMPD(66,0)= 2.840E+09, 3.156E+09, 3.945E+09, 4.734E+09, 5.523E+09,
TEMPD(71,0)= 6.312E+09, 7.100E+09, 7.889E+09, 8.678E+09, 9.467E+09,
TEMPD(76,0)= 1.026E+10, 1.105E+10, 1.183E+10, 1.262E+10, 1.341E+10,
TEMPD(81,0)= 1.420E+10, 1.499E+10, 1.578E+10, 1.657E+10, 1.736E+10,
TEMPD(86,0)= 1.815E+10, 1.893E+10, 1.972E+10, 2.051E+10, 2.130E+10,
TEMPD(91,0)= 2.209E+10, 2.288E+10, 2.367E+10, 2.446E+10, 2.525E+10,
TEMPD(96,0)= 2.604E+10, 2.682E+10, 2.761E+10, 2.840E+10, 2.919E+10,
TEMPD(101,0)= 2.998E+10, 3.077E+10, 3.156E+10,
TEMPD(0,1)=  1.0,
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'COM,    *********************************************
'COM,    ** Drift Wall Temperature Histories (SANDIA)**
'COM,    **       File name: sandia2.dat             **
'COM,    **       Aged 22 years, .428 MTU/Assy       **
'C  ,    **       42.21 GWd/MTU burnup               **
'   ,    **       111.03 MTU/acre -> 126.34 kW/acre  **
'COM,    **       Df Sp = 20.48 m, WP Sp = 16.0 m    **
'COM,    **       4.3 m (14 ft) Drift Diameter       **
'COM,    **               TEMPA=Top of Drift         **
'COM,    **               TEMPB=Side of Drift        **
'COM,    **               TEMPC=Floor Corner         **
'COM,    **               TEMPD=Floor Center         **
'COM,    **       R.Bahney 11-30-93                  **
'COM,    *********************************************
'COM,            (Temperature time is in seconds)
'EMPA( 1,1)=   23.80,   41.25,   59.83,   63.95,   69.67,   72.96,
'EMPA( 7,1)=   76.25,   81.26,   85.24,   88.61,   91.42,   94.17,
'EMPA(13,1)=   96.24,   98.56,  100.20,  102.20,  103.50,  105.30,
'EMPA(19,1)=  106.50,  108.00,  109.30,  110.60,  111.80,  113.10,
'EMPA(25,1)=  115.80,  118.40,  121.00,  123.20,  125.40,  127.40,
'EMPA(31,1)=  129.40,  131.10,  137.60,  143.00,  147.80,  151.50,
'EMPA(37,1)=  154.90,  157.60,  160.40,  162.80,  165.40,  167.90,
'EMPA(43,1)=  170.70,  173.20,  175.80,  178.20,  180.50,  182.50,
'EMPA(49,1)=  184.60,  186.30,  187.90,  189.40,  191.00,  192.40,
'EMPA(55,1)=  193.80,  195.10,  196.30,  197.30,  202.10,  206.50,
'EMPA(61,1)=  209.70,  212.80,  217.20,  219.80,  221.70,  223.10,
'EMPA(67,1)=  223.70,  223.70,  224.00,  224.30,  224.70,  225.00,
'EMPA(73,1)=  225.50,  226.00,  226.70,  227.50,  228.10,  228.40,
'EMPA(79,1)=  228.70,  228.70,  228.60,  228.20,  227.70,  227.10,
'EMPA(85,1)=  226.50,  225.80,  225.10,  224.30,  223.50,  222.60,
'EMPA(91,1)=  221.80,  220.90,  220.00,  219.20,  218.40,  217.50,
'EMPA(97,1)=  216.70,  215.90,  215.00,  214.10,  213.30,  212.40,
'EMPA(103,1)=  211.50,
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'EMPA( 6,0)= 7.889E+06, 9.467E+06, 1.262E+07, 1.578E+07, 1.893E+07,
'EMPA(11,0)= 2.209E+07, 2.525E+07, 2.840E+07, 3.156E+07, 3.471E+07,
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'EMPA(21,0)= 5.365E+07, 5.680E+07, 5.996E+07, 6.312E+07, 7.100E+07,
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'EMPA(31,0)= 1.183E+08, 1.262E+08, 1.578E+08, 1.893E+08, 2.209E+08,
'EMPA(36,0)= 2.525E+08, 2.840E+08, 3.156E+08, 3.471E+08, 3.787E+08,
'EMPA(41,0)= 4.102E+08, 4.418E+08, 4.734E+08, 5.049E+08, 5.365E+08,
'EMPA(46,0)= 5.680E+08, 5.996E+08, 6.312E+08, 6.627E+08, 6.943E+08,
'EMPA(51,0)= 7.258E+08, 7.574E+08, 7.889E+08, 8.205E+08, 8.521E+08,
'EMPA(56,0)= 8.836E+08, 9.152E+08, 9.467E+08, 1.105E+09, 1.262E+09,
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'EMPA(86,0)= 1.815E+10, 1.893E+10, 1.972E+10, 2.051E+10, 2.130E+10,
'EMPA(91,0)= 2.209E+10, 2.288E+10, 2.367E+10, 2.446E+10, 2.525E+10,
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'EMPA(0,1)=  1.0,
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TEMPB(73,1)=  227.10,  227.40,  228.10,  228.80,  229.40,  229.60,
TEMPB(79,1)=  229.90,  229.80,  229.70,  229.20,  228.80,  228.10,
TEMPB(85,1)=  227.50,  226.70,  226.00,  225.10,  224.40,  223.40,
TEMPB(91,1)=  222.60,  221.70,  220.80,  219.90,  219.10,  218.20,
TEMPB(97,1)=  217.40,  216.50,  215.70,  214.70,  213.90,  212.90,
TEMPB(103,1)=  212.10,
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TEMPB( 6,0)= 7.889E+06, 9.467E+06, 1.262E+07, 1.578E+07, 1.893E+07,
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TEMPB(36,0)= 2.525E+08, 2.840E+08, 3.156E+08, 3.471E+08, 3.787E+08,
TEMPB(41,0)= 4.102E+08, 4.418E+08, 4.734E+08, 5.049E+08, 5.365E+08,
TEMPB(46,0)= 5.680E+08, 5.996E+08, 6.312E+08, 6.627E+08, 6.943E+08,
TEMPB(51,0)= 7.258E+08, 7.574E+08, 7.889E+08, 8.205E+08, 8.521E+08,
TEMPB(56,0)= 8.836E+08, 9.152E+08, 9.467E+08, 1.105E+09, 1.262E+09,
TEMPB(61,0)= 1.420E+09, 1.578E+09, 1.893E+09, 2.209E+09, 2.525E+09,
TEMPB(66,0)= 2.840E+09, 3.156E+09, 3.945E+09, 4.734E+09, 5.523E+09,
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TEMPB(76,0)= 1.026E+10, 1.105E+10, 1.183E+10, 1.262E+10, 1.341E+10,
TEMPB(81,0)= 1.420E+10, 1.499E+10, 1.578E+10, 1.657E+10, 1.736E+10,
TEMPB(86,0)= 1.815E+10, 1.893E+10, 1.972E+10, 2.051E+10, 2.130E+10,
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TEMPC(26,0)= 7.889E+07, 8.678E+07, 9.467E+07, 1.026E+08, 1.105E+08,
TEMPC(31,0)= 1.183E+08, 1.262E+08, 1.578E+08, 1.893E+08, 2.209E+08,
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TEMPC(76,0)= 1.026E+10, 1.105E+10, 1.183E+10, 1.262E+10, 1.341E+10,
TEMPC(81,0)= 1.420E+10, 1.499E+10, 1.578E+10, 1.657E+10, 1.736E+10,
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TEMPD(26,0)= 7.889E+07, 8.678E+07, 9.467E+07, 1.026E+08, 1.105E+08,
TEMPD(31,0)= 1.183E+08, 1.262E+08, 1.578E+08, 1.893E+08, 2.209E+08,
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TEMPD(41,0)= 4.102E+08, 4.418E+08, 4.734E+08, 5.049E+08, 5.365E+08,
TEMPD(46,0)= 5.680E+08, 5.996E+08, 6.312E+08, 6.627E+08, 6.943E+08,
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TEMPD(66,0)= 2.840E+09, 3.156E+09, 3.945E+09, 4.734E+09, 5.523E+09,
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TEMPD(81,0)= 1.420E+10, 1.499E+10, 1.578E+10, 1.657E+10, 1.736E+10,
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/
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Appendix C
Subsurface Design Inputs

The Subsurface Design Group developed some generic subsurface designs to use in the thermal loading study. The assumptions used and the details of the subsurface designs for the various emplacement modes are provided in the form of an IOC from the Subsurface Group to Systems Analysis. The IOC is attached in this appendix. Although the date on the actual IOC transmitting the information, the designs were available early in the study and were the basis used for the calculations.

Interoffice Correspondence
Civilian Radioactive Waste Management System
Management & Operating Contractor

TRW Environmental
Safety Systems Inc.

WBS: 1.2.4
QA: N/A

Subject
Generic subsurface repository concepts in Support of Thermal Loading Studies

Date
December 13, 1993
LV.SB.KKB.12/93-626

cc

From
K. K. Bhattacharyya/ KB
M. I. Grigore MG.

To
S. Saterlie

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(702)794-1872

Following is a description of the assumptions, input data, and description of the generic subsurface repository concepts developed during the FY 1993 in support of the thermal loading study.

1. **Drift size:**

- For the in-drift emplacement mode, two sizes of drifts were used: a 7.0 m diameter for the trackless waste transporter and a 4.3 m dia drift for rail type waste transporter.

- For the vertical and horizontal borehole emplacement modes, the excavated diameter of the drift was assumed to be 7.6 m

2. **Excavated longhole horizontal boreholes:**

- Drilling longhole horizontal boreholes with a maximum deviation of 76 mm/61m of hole length requires a very sophisticated and complex piece of machinery.

- Considering today's technology, a mini-tunnel boring machine (Robins Co. Mfg.) which can be driven with remote control, can excavate boreholes up to 2.4 m dia. and 190 m in length. At present this equipment is only in the prototype phase.

3. **Waste package spacing:**

- This parameter was a given by the systems group for all three form of emplacements.

4. **Emplacement Modes**

- It was assumed that waste packages containing 6 PWR or less number of spent nuclear fuel assemblies were the upper limit for emplacement in horizontal or vertical boreholes. The larger size waste packages would be emplaced in-drift.

5. Waste transportation/emplacement equipment

- The trackless transporter was assumed to be suitable for vertical and horizontal boreholes and in- drift emplacement.
- The rail haulage transporter was assumed to be suitable only for in drift emplacement.

4. Other assumed criteria.

- Areas 1 and 2 of the preliminary repository concepts (Figure 1) was considered as emplacement areas. The average lengths of drifts in the combined area was estimated to be about 1250 m.
- The excavated profiles of the ramps, perimeter, main, and the emplacement drifts for the vertical and horizontal boreholes, were assumed to be 7.6 m dia.
- In case of trackless transporter being used for the in- drift emplacement, the drift profile was assumed to be 7.0 m dia.
- For rail haulage used for the in drift emplacement, the drift was assumed to be 4.3 m dia.

5. Setback distance assumptions.

- For the in-drift emplacement mode, a 40 m setback distance was considered as an unloaded zone around the main and perimeter drifts. The set back distance is used to maintain an access drift temperature at about 50 °C during the emplacement operation.
- For the vertical boreholes emplacement mode, 20 m from the perimeter drift and 28 m setback from access drifts distances were used. For the horizontal boreholes emplacement mode, 20 m and 35 m setback distances were assumed. These set back distances were estimated from previous analyses performed by SNL and from available data from the SCP-CDR.

6. Estimates

- The number of waste packages required per drift (for in-drift emplacement mode) is the ratio between emplacement drift length and the center-to-center distance between waste packages.
- The number of emplacement drifts required is the ratio between the total packages to be emplaced and the number of packages emplaced per drift.
- The drifts spacing DS(m) is the ratio between (kW/pkg x square feet/acre) and (center-to-

center between waste package-m x kW/acre)

- Total excavated emplacement drifts is the product of the number of drifts and excavated drift length (m/drift)

- Local extraction ratio is the ratio between drift diameter (m) and drift spacing (m)

- Emplacement drift efficiency is the ratio between emplacement drift where waste is emplaced and average length of the emplacement drifts

- Heated drift area is the ratio between thermal loading (kW/acre) and emplacement drift efficiency

- Emplacement drift length is the difference between the total drift length and the total setback distance

Attachment
(1) Waste Package Emplacement in Underground
Calculation Criteria

KKB/mla

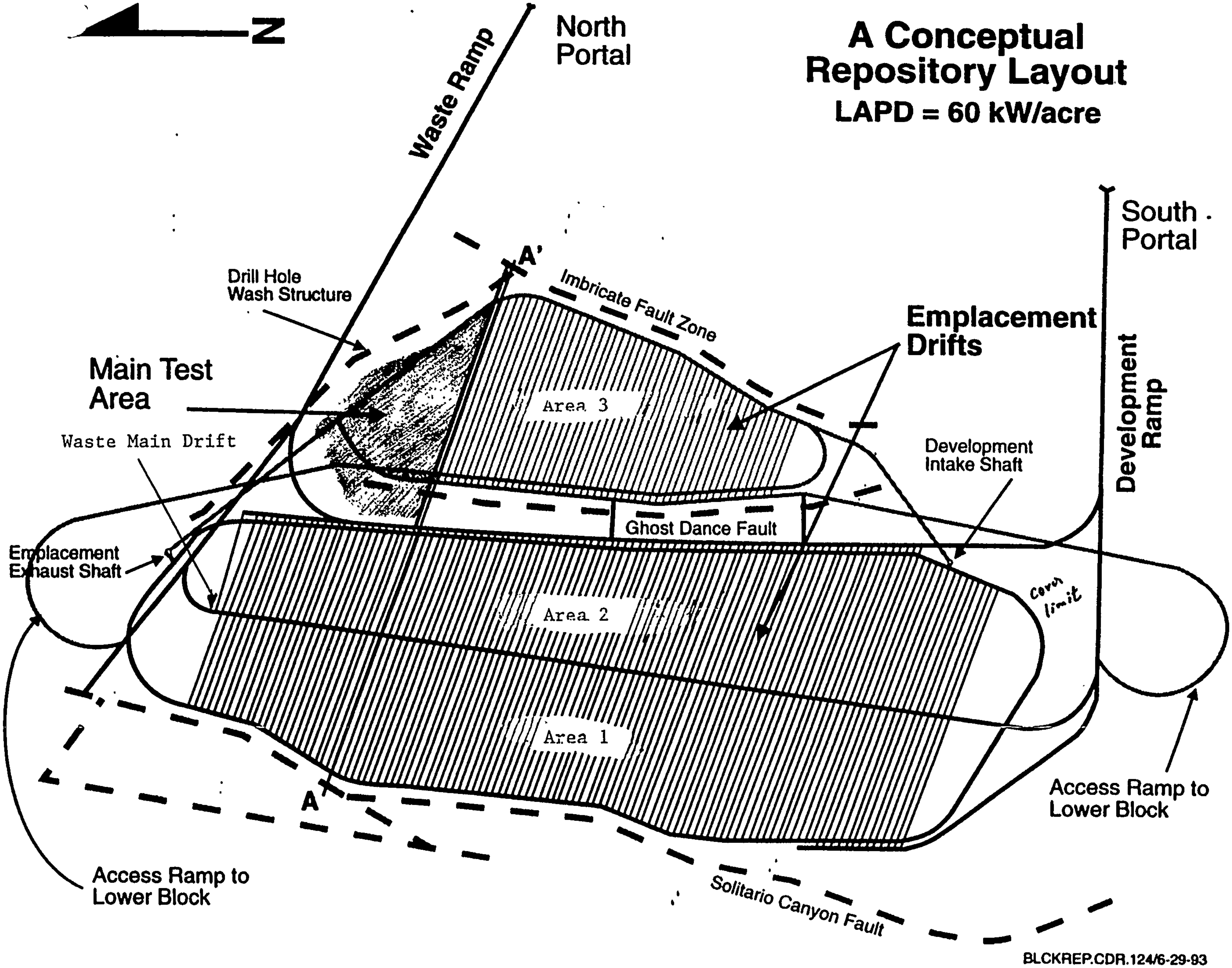


Figure 1. A Conceptual Repository Layout

Waste Package Emplacement in Under Ground

Calculation Criteria

1. GIVEN CRITERIA

O No. of PWR and BWR packages

#PWR/PKG	Mtu/PKG	kW/PKG	No. of PKGs	Total kW
6	2.57	2.89	15865	45850
12	5.14	5.78	7932	45847
21	8.99	10.12	4533	45874

#PWR/PKG	Mtu/PKG	kW/PKG	No. of PKGs	Total kW
12	2.14	1.84	10418	19169
21	3.74	3.21	5936	19055
40	7.12	6.12	3116	19070

O Fuel Characteristics at the Emplacement are:

Fuel Type	Avg. Age (Yrs)	Burnup (GWD/Mtu)	Avg. Enrichment	Total Emplaced (Mtu)	Power (kW/Mtu)
PWR	22.5	42.2	3.92	40747	1.13
BWR	23.5	32.2	3.1	22253	0.86

O Waste Emplacement Modes:

#PWR or BWR/PKG (kW/Acre)	Vertical Boreholes (kW/Acre)	Horizontal Boreholes (kW/Acre)	In-Drift (kW/Acre)
6/12	25,37,57	25,37,57	25,37,57
12/21	-	-	25,37,57,86,114
21/40	-	-	25,37,57,86,114

O Excavated Drift Diameter:

- 7.6 m dia. access drift for vertical and horizontal boreholes emplacement (for 6PWR/PKG case)
- 7.0 m dia. for In-drift emplacement mode (for 6PWR, 12PWR and 21PWR/PKG cases)

O Exacavated Borehole Charateristics:
- Vertical boreholes: 7.6 m L X 1.2 m dia.
- Short horizontal boreholes: 7.6 m L X 1.2 m dia.
- Longholes horizontal boreholes: 1.2 m dia.

O Distance between c/c of Waste Packages:
- 6.64 m (7.0 m dia. drift) for 6PWR/12BWR In-drift emplacement
- 6.64 m (4.3 m dia. drift) for 6PWR/12BWR In-drift emplacement
- 3.6 m for 6PWR/12BWR in Vertical boreholes
- 8.6 m for 6PWR/12BWR in Longholes horizontal boreholes

- 6.64 m (7.0 m dia. drift) for 12PWR/21BWR In-drift emplacement
- 6.64 m (4.4 m dia. drift) for 12PWR/21BWR In-drift emplacement

- 6.64 m (7.0 m dia. drift) for 21PWR/21BWR In-drift emplacement
- 6.64 m (7.0 m dia. drift) for 21PWR/21BWR In-drift emplacement

2. ASSUMED CRITERIA

- Repository #1 dimensions are only considered
- Repository #1 average length (c/c) = 1250 m
- Waste main drift dia. = 7.6 m
- Perimeter drifts dia. = 7.6 m
- Emplacement drift length = 1250 - (4 X 40) m = 1090 m
- Vertical and short horizontal boreholes length = 7.6 m
- Longholes horizontal boreholes length = 192 m
- For 6PWR/PKG In-drift emplacement setback distance = 20 m from c/c distance of borehole to the perimeter drift wall and 28 m from c/c of borehole to the waste main drift

- For 6PWR/PKG in longhole horizontal boreholes emplacement setback distance = 35 m from each access drift, 35 m on each side of waste main drift and 20 m from each perimeter drift

- For 6PWR/PKG in shorthole horizontal boreholes emplacement setback distance = 20 m from each perimete drift, and 35 m on both sides of waste main drift

- For 12PWR/PKG in-drift emplacement setback distance = 40 m (c/c)
- For 21PWR/PKG In-drift emplacement setback distance = 40 m (c/c)

- Equivalent outout (kW/PKG) = $\frac{(15865 \times 2.89) + (10418 \times 1.84)}{15865+10418} = 2.47$ for 6/12 PWR/BWR case

= 4.68 kW/PKG for 12/21 PWR/BWR case

= 8.49 kW/PKG for 21/40 PWR/BWR case

1.1. 6(PWR) or 12(Bwr) Case In-Drift Emplacement (7 m drift dia.)

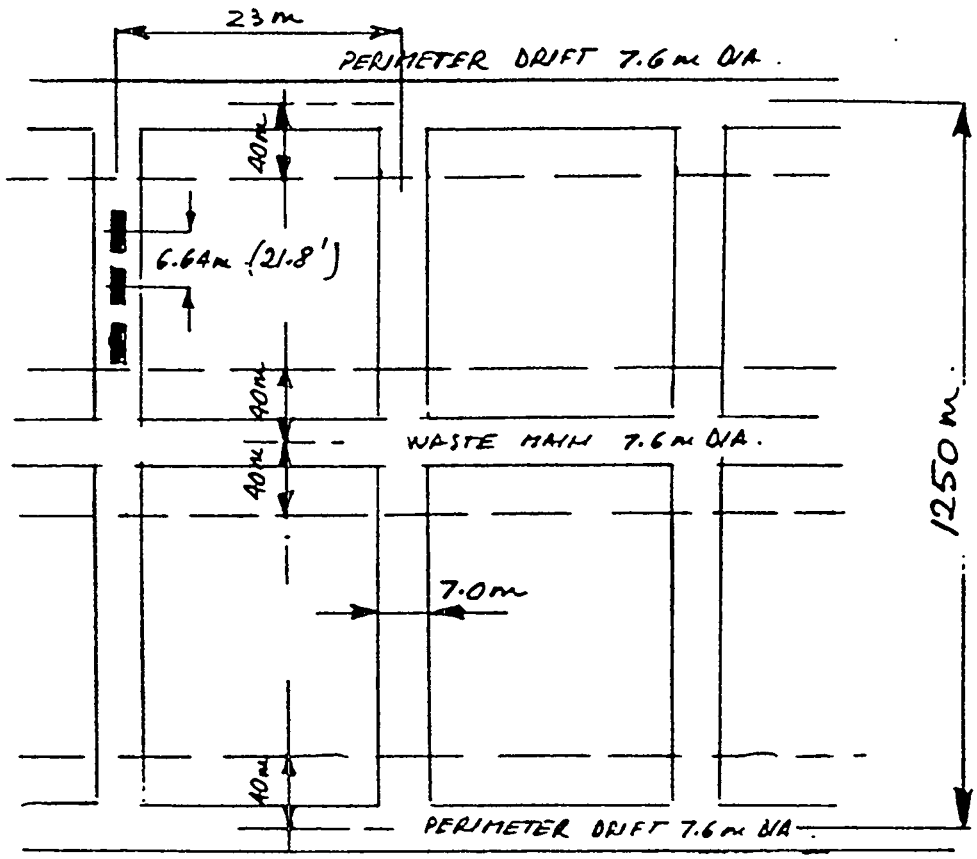
Assumed:

Kw/pkg for PWR and BWR	2.89	and	1.84
No. of PWR and BWR pkgs	15865	and	10418
15865(PWR Packs) X 2.89 kW/pkg	45850 kW		
10418 (BWR Packs) X 1.84 kW/pkg	19169 kW		
Total	65019 kW		
Perimeter drift dia. (m)	7.6		
Set back distance (m)	40		
Diameter of the access drift (m)	7		
c/c distance between waste pkgs (m)	6.64		
Average length of the repository (m)	1250		
Emplacement drift length (m)	1090		
Excavated drift length (m)	1235		
No. of waste pkgs required per drift	164		
No. of access drifts required	160		
Total emplacement length required	174400		
Total excavated drift length	197600		
Emplacement drift efficiency (%)	87		
Equivalent output (kW/pkg)	2.47		

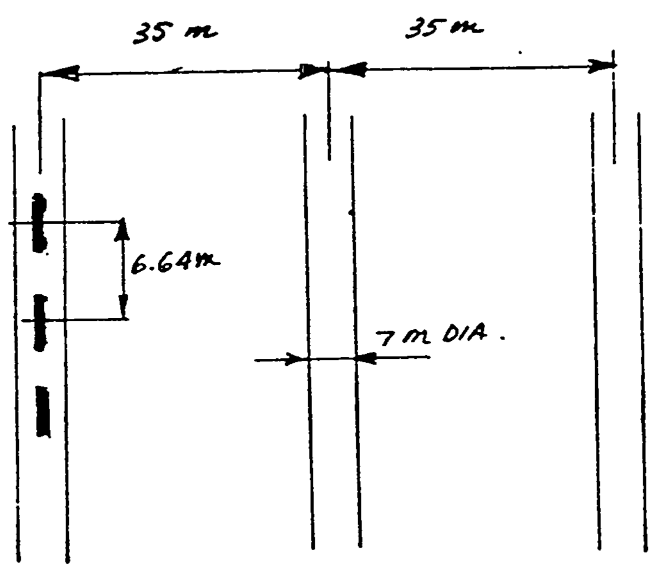
	Case 1	Case 2	Case 3
Areal power density (APD kW/Acre)	57	37	25
Local APD (LAPD kW/Acre)	66	43	29
Calculated drift spacing	23	35	52
Total drift excavated length (m)	197600	197600	197600
Excavated drift area (m2)	1383200	1383200	1383200
Local excavation ratio (%)	30	20	13
Theoretical repository area (Acre)	1141	1757	2601
Emplacement drift efficiency (%)	87	87	87
Heated drift area (kW/Acre)	66	43	29

1.0 6 (PWR) OR 12 (BWR) CASE

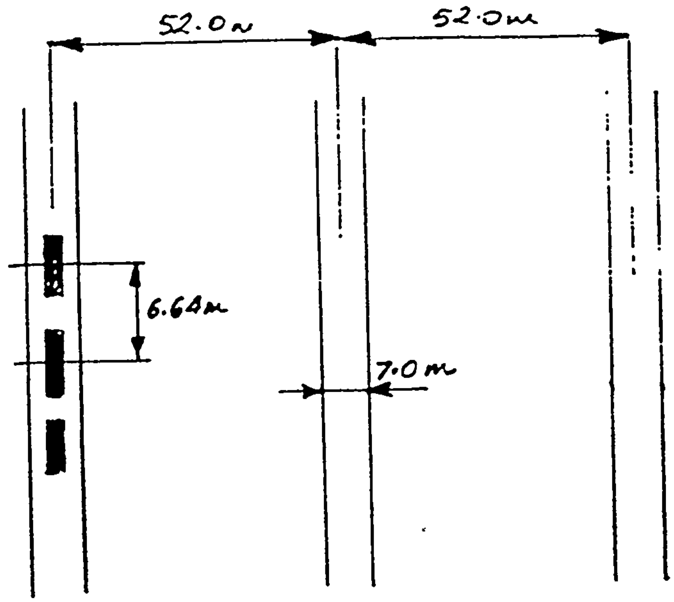
1.1.1 IN-DRIFT EMPLACEMENT AT 57 Kw/ACRE



1.1.2 IN-DRIFT EMPLACEMENT AT 40 Kw/ACRE



1.1.3 'IN-DRIFT' EMPLACEMENT AT 25 KW/ACRE



1.2. 6(PWR) or 12(Bwr) Case In-Drift emplacement (4.3m drift dia.)

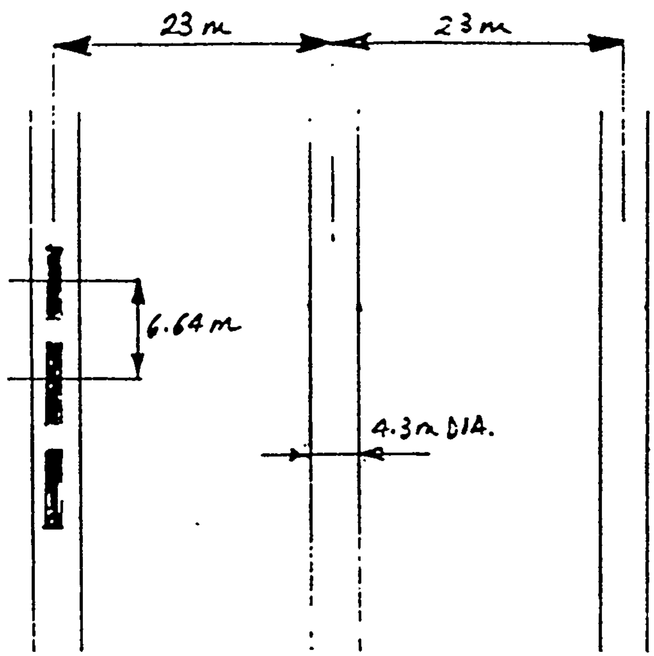
Assumed:

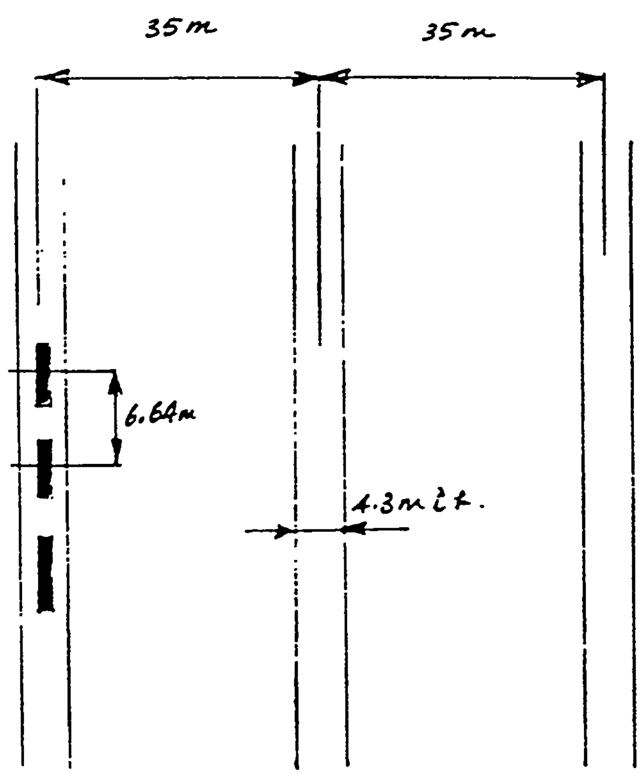
kw/pkg for PWR and BWR	2.89	and	1.84
No. of PWR and BWR pkgs	15865	and	10418
15865(PWR Packs) X 2.89 kW/pkg	45850 kW		
10418 (BWR Packs) X 1.84 kW/pkg	19169 kW		
Total	65019 kW		
Perimeter drift dia. (m)	7.6		
Set back distance (m)	40		
Diameter of the access drift (m)	4.3		
c/c distance between waste pkgs (m)	6.64		
Average length of the repository (m)	1250		
Emplacement drift length (m)	1090		
Excavated drift length (m)	1235		
No. of waste pkgs required per drift	164		
No. of access drifts required	160		
Total emplacement length required	174400		
Total excavated drift length	197600		
Emplacement drift efficiency (%)	87		
Equivalent output/pkg	2.47		

	Case 1	Case 2	Case 3
Areal power density (APD kW/Acre)	57	37	25
Local APD (LAPD kW/Acre)	66	43	29
Calculated drift spacing	23	35	52
Total drift excavated length (m)	197600	197600	197600
Excavated drift area (m2)	849680	849680	849680
Local excavation ratio (%)	19	12	8
Theoretical repository area (Acre)	1141	1757	2601
Emplacement drift efficiency (%)	87	87	87
Heated drift area (kW/Acre)	66	43	29

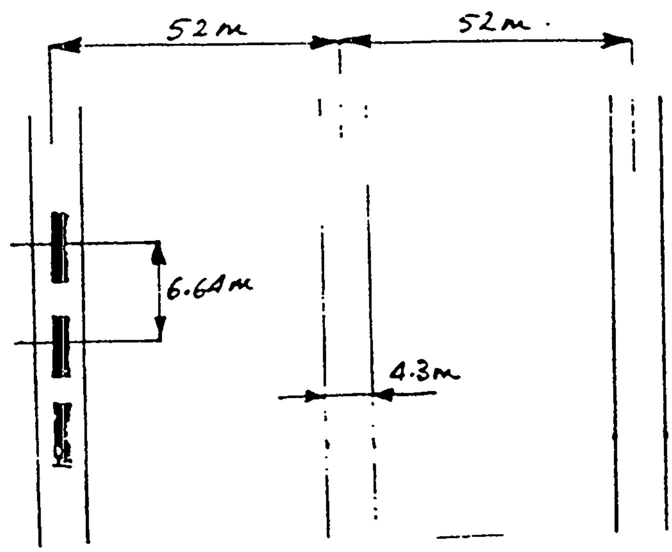
1.0 6 (PWR) OR 12 (BWR) CASE

1.2.1 IN DRIFT EMPLACEMENT AT 57 KW/ACRE





1.2.3 IN - DRIFT EMPLACEMENT AT 25 Kw /ACRE



2.1. 6(P' `) or 12(Bwr) Case Vertical Borehole Emplacement (7.6 m access drift dia.)

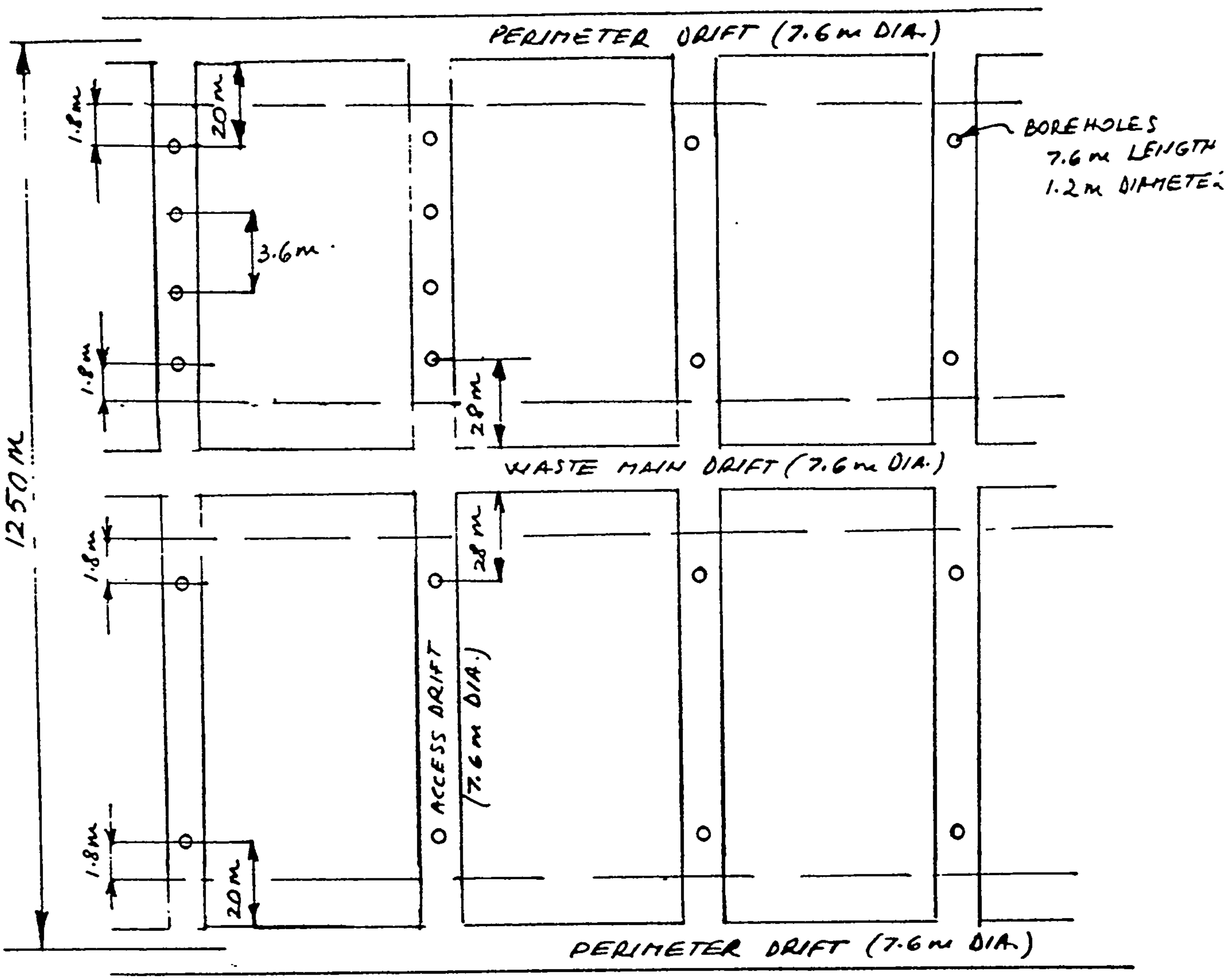
Assumed:

kw/pkg for PWR and BWR	2.89	and	1.84
No. of PWR and BWR pkgs	15865	and	10418
15865(PWR Packs) X 2.89 kW/pkg	45850 kW		
10418 (BWR Packs) X 1.84 kW/pkg	19169 kW		
Total	65019 kW		
Perimeter drift dia. (m)	7.6		
Waste main set back distance (m)	28		
Perimeter set back distance(m)	20		
Diameter of the access drift (m)	7.6		
c/c distance between boreholes (m)	3.6		
Average length of the repository (m)	1250		
Emplacement drift length (m)	1146		
Excavated drift length (m)	1235		
No. of waste pkgs required per drift	318		
No. of access drifts required	83		
Total emplacement length required	95118		
Total excavated drift length	102505		
Excavated borehole length (m)	200594		
Emplacement drift efficiency (%)	92		
Equivalent output/pkg	2.47		

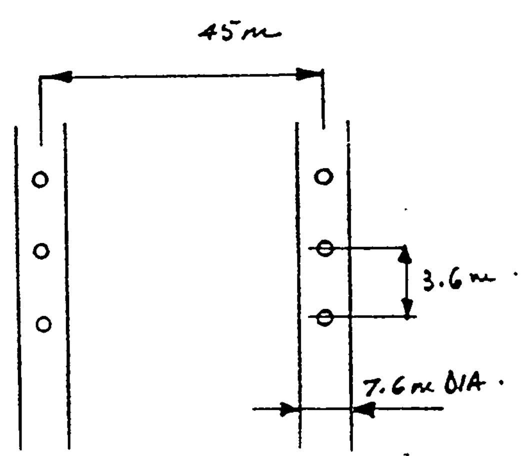
	Case 1	Case 2	Case 3
Areal power density (APD kW/Acre)	57	37	25
Local APD (LAPD kW/Acre)	62	40	27
Calculated drift spacing	45	69	103
Local excavation ratio (%)	17	11	7
Theoretical repository area (Acre)	1141	1757	2601
Emplacement drift efficiency (%)	92	92	92
Heated drift area (kW/Acre)	62	40	27

2.0 6 (PWR) OR 12 (BWR) CASE

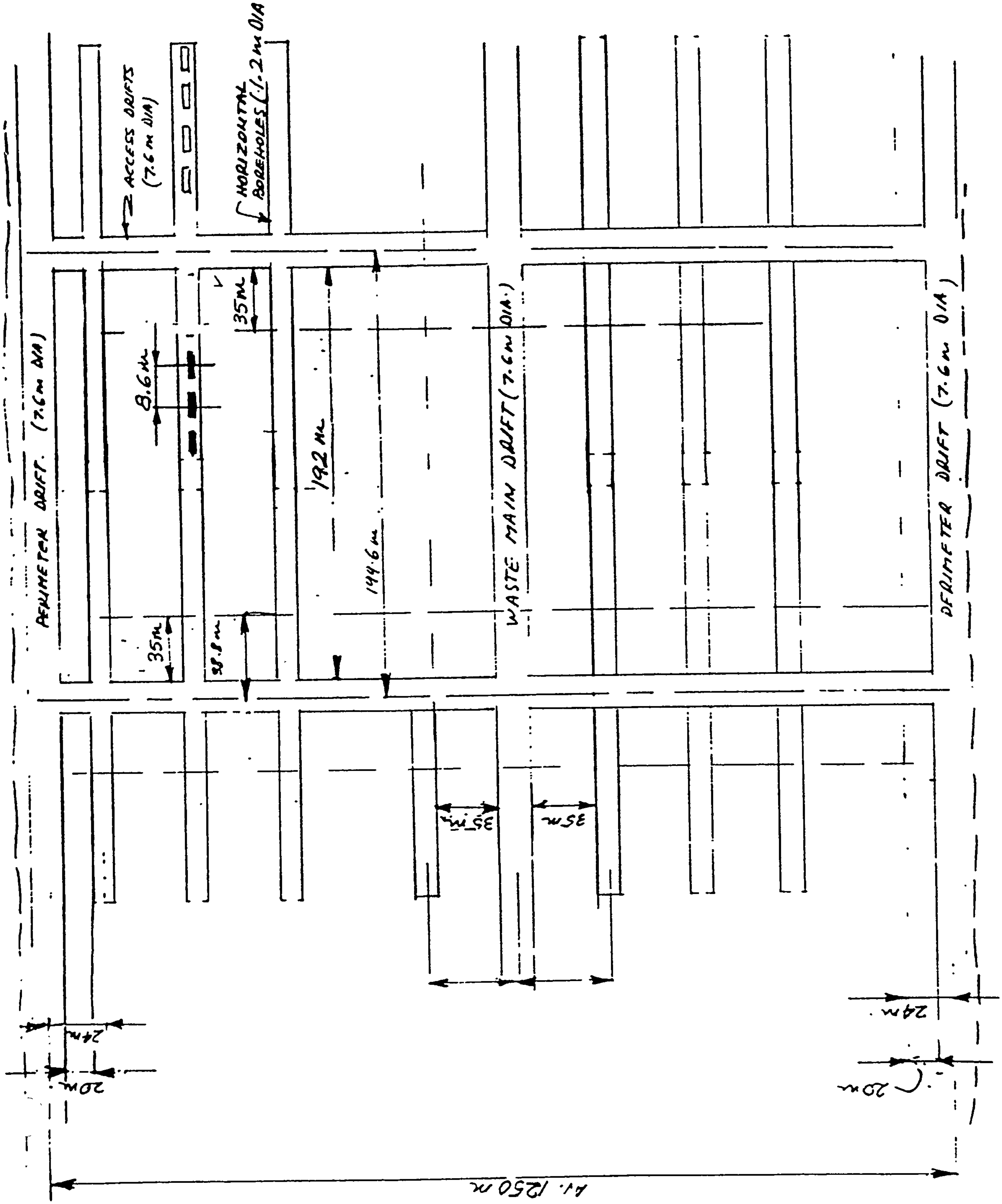
2.1 7.6 DIA ACCESS DRIFT – WASTE PACKAGES IN VERTICAL BOREHOLES EMPLACEMENT.



2.1.1 IN VERTICAL BOREHOLES EMPLACEMENT AT 57 KW/ACRE



2.0 6 (PWR) OR 12 (BWR) CASE
LONGHOLES HORIZONTAL BOREHOLES



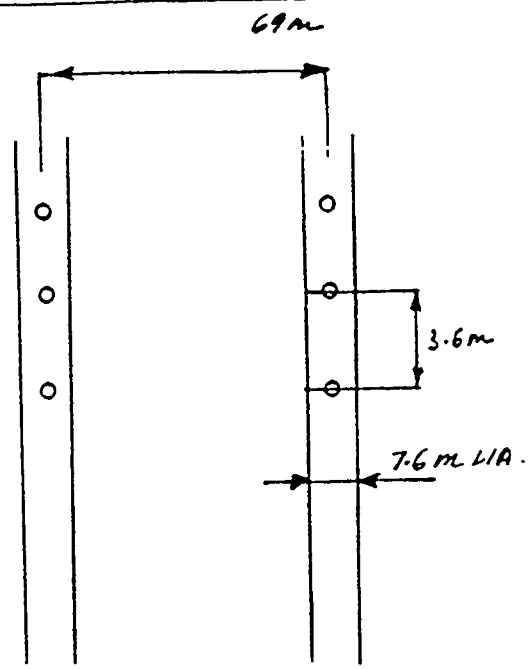
2.2. 6(PWR) or 12(Bwr) Case   Longholes horizontal borehole emplacement (7.6 m access drift dia)

Assumed:

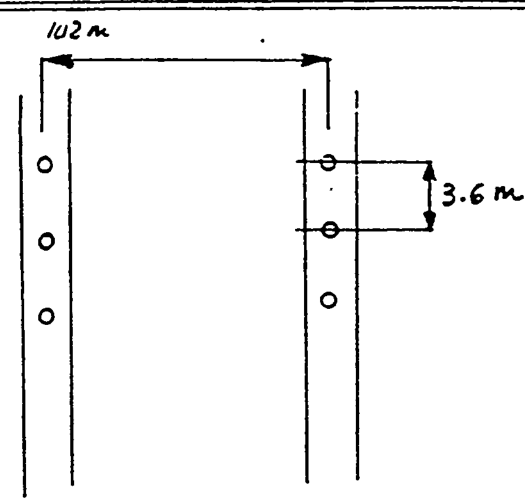
kw/pkg for PWR and BWR	2.89	and	1.84
No. of PWR and BWR pkgs	15865	and	10418
Total no. of pkgs	26283		
15865(PWR Packs) X 2.89 kW/pkg	45850 kW		
10418 (BWR Packs) X 1.84 kW/pkg	19169 kW		
Total	65019 kW		
Size of horizontal borehole (m)	192	X	1.2
Permieter drift dia. (m)	7.6		
Set back dist. from perimeter drift (m)	20		
Set back (waste main & access drift)	35 m		
Diameter of the access drift (m)	7.6		
c/c distance between pkgs (m)	8.6		
Average length of the repository (m)	1250		
Borehole excavation length (m)	192		
Borehole emplacement length (m)	122		
Access dirft emplacement length (m)	1125		
Access drift excavation length (m)	1235		
No. of waste pkgs required per hole	14		
No. of boreholes required	1877		
Borehole emplacement length (m)	228994		
Borehole excavation drift length (m)	360384		
Emplacement efficiency (%)	64		
Equivalent output (kW/pkg)	2.47		

	Case 1	Case 2	Case 3
Areal power density (APD kW/Acre)	57	37	25
Distance bet. c/c of boreholes (m)	11.4	17.6	26
Local APD (LAPD kW/Acre)	101	65	44
Local Excavation ratio (%)	4	4	4
Borehole area excavated (m2)	432461	432461	432461
Boreholes per panel	165	107	72
Excavated drifts length (m)	14079	21736	32110
Emplacement drift length (m)	12825	19800	29250
Total access drift area (m2)	107000.4	165193.6	244036
Theoretical reopository area (Acre)	1141	1757	2601
No. of access drifts required	22	36	52

2.1.2 IN VERTICAL EMPLACEMENT AT 37 KW/ACRE



2.1.3 IN VERTICAL EMPLACEMENT AT 25 KW/ACRE



2.3. 6(PWR) or 12(Bwr) Case Shortholes Horizontal Emplacement

Assumed:

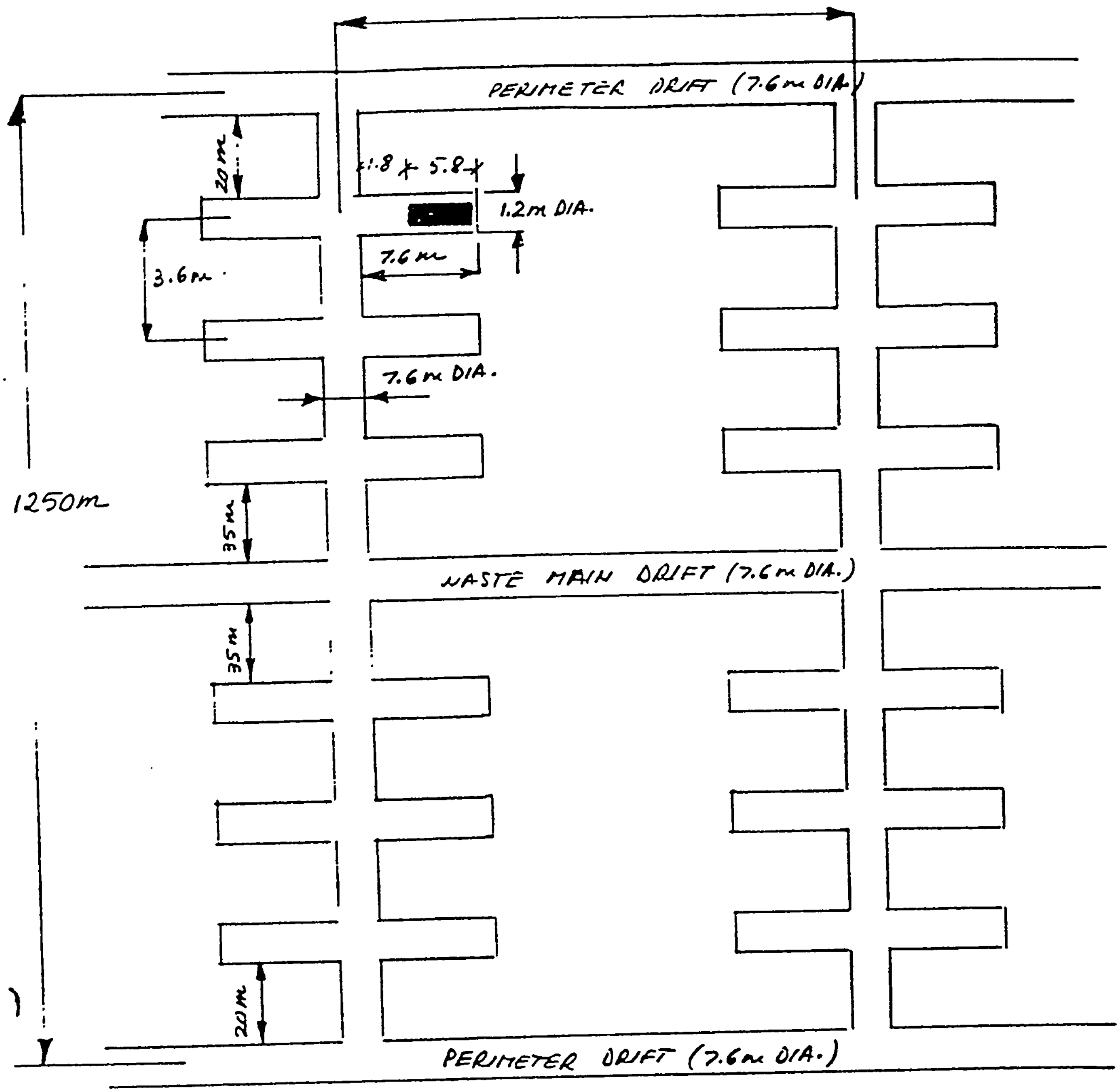
kw/pkg for PWR and BWR	2.89	and	1.84
No. of PWR and BWR pkgs	15865	and	10418
Total no. of pkgs	26283		
15865(PWR Packs) X 2.89 kW/pkg	45850 kW		
10418 (BWR Packs) X 1.84 kW/pkg	19169 kW		
Total	65019 kW		
Size of horizontal borehole (m/m)	7.6	X	1.2
Waste main drift dia (m)	7.6		
c/c Dist. bet. horizontal boreholes (m	3.6		
Permieter drift dia. (m)	7.6		
Set back dist. from perimeter drift (m)	20		
Set back dist. fm waste main drift (m)	35		
Diameter of the access drift (m)	7.6		
Average length of the repository (m)	1250		
Borehole emplacement length (m)	5.8		
Access dirft emplacement length (m)	1125		
Access drift excavation length (m)	1235		
Length of boreholes excavated (m)	199751		
Emplacement holes/ access drift	626		
Length of Boreholes emplaced (m)	152441		
Number of access drifts	42		
Emaplacement access drifts total length (m)		47250	
Excavated access drift total length (m)		51870	
Borehole efficiency (%)	76.3		
Equivalent output/pkg	2.47		

	Case 1	Case 2	Case 3
Areal power density (APD kW/Acre)	57	37	25
Number of access drifts	42	42	42
Emplacemnt access drifts length (m)	47250	47250	47250
Total excavated drift length (m)	51870	51870	51870
Access drift spacing (m)	88	135	200
Area for one panel (m2)	110000	168750	250000
Boreholes per panel	627	625	625
Emplacement efficiency (%)	63	41	28
LAPD ((kW/Acre)	90	90	89
Theoretical repository area (Acre)	1141	1757	2601

2.2 6 (PWR) OR 12 (BWR) CASE

SHORTHOLES HORIZONTAL BOREHOLES

2.3 WASTE PACKAGES EMPLACED IN SHORTHOLES HORIZONTAL BOREHOLES



3.1. 12(PWR) or 21(Bwr) Case In-Drift emplacement (7 m drift dia.)

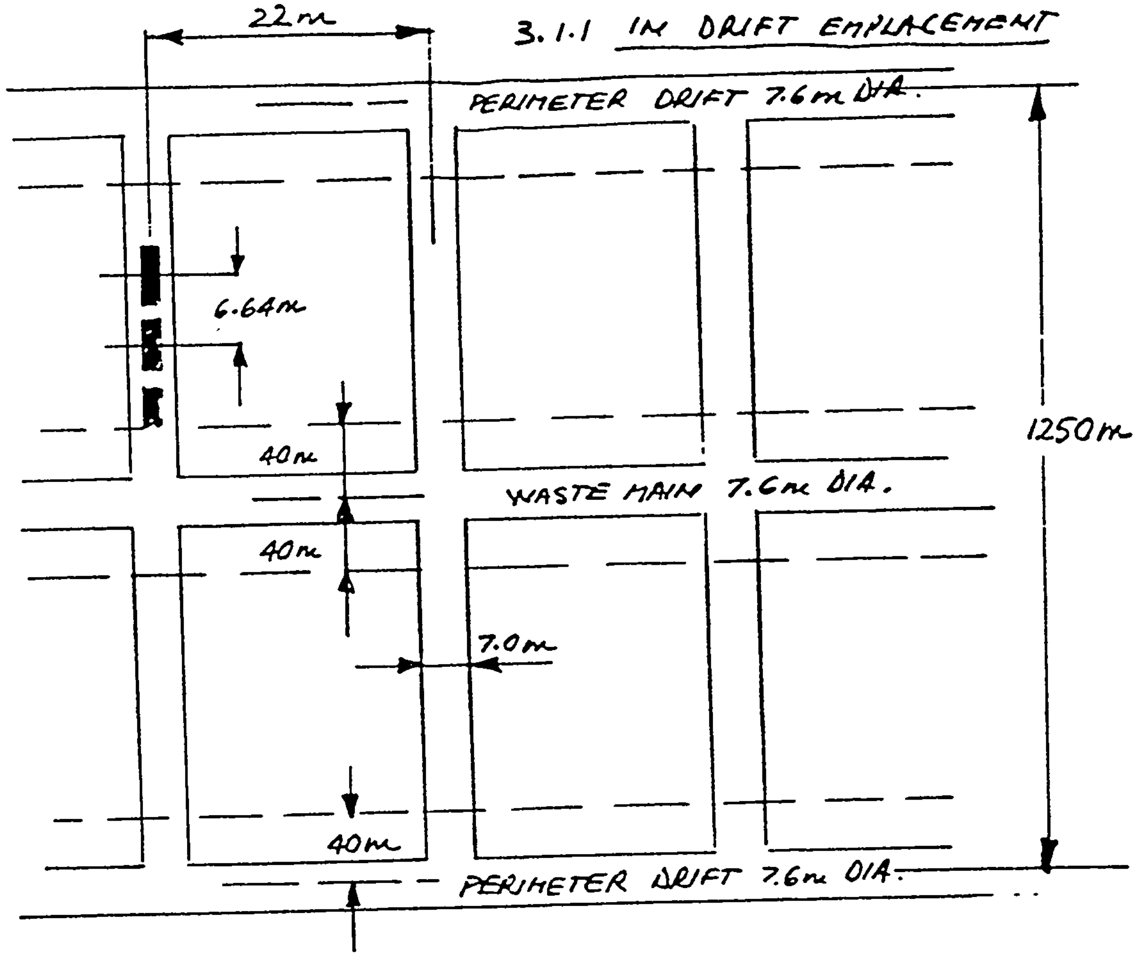
Assumed:

kw/pkg for PWR and BWR	5.78	3.21
No. of PWR and BWR pkgs	7932	5936
7932(PWR Packs) X 5.78 kW/pkg	45847	
5936 (BWR Packs) X 3.21kW/pkg	19055	
Total	64902	
Perimeter drift dia. (m)	7.6	
Set back distance (m)	40	
Diameter of the access drift (m)	7	
c/c distance between waste pkgs (m)	6.64	
Average length of the repository (m)	1250	
Emplacement drift length (m)	1090	
Excavated drift length (m)	1235	
No. of waste pkgs required per drift	164	
No. of access drifts required	85	
Total emplacement length required	92650	
Total excavated drift length	104975	
Emplacement drift efficiency (%)	87.2	
Equivalent output/pkg	4.68	

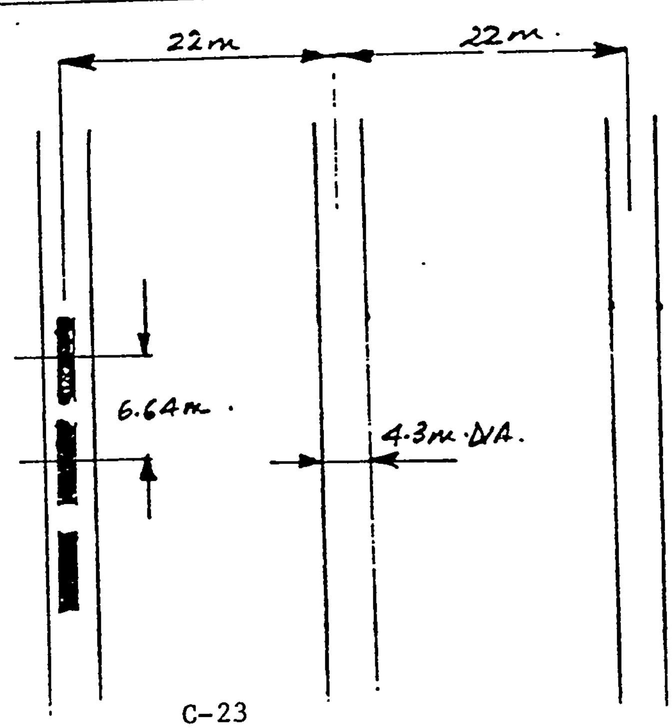
	Case 1	Case 2	Case 3	Case 4	Case 5
Areal power density (APD kW/Acre)	114	86	57	37	25
Local APD (LAPD kW/Acre)	131	99	65	42	29
Calculated drift spacing	22	29	44	68	98
Total drift excavated length (m)	104975	104975	104975	104975	104975
Excavated drift area (m2)	734825	734825	734825	734825	734825
Local excavation ratio (%)	32	24	16	10	7
Theoretical repository area (Acre)	569	755	1139	1754	2596

3.0 12 (PWR) OR 21 (BWR) IN-DRIFT EMPLACEMENT

3.1.1 IN DRIFT EMPLACEMENT



3.2.1 IN-DRIFT EMPLACEMENT AT 114 KW/ACRE



3.2. 12(PWR) or 21(Bwr) Case   In-Drift emplacement (4.3 m drift dia.)

Assumed:

kw/pkg for PWR and BWR	5.78	3.21
No. of PWR and BWR pkgs	7932	5936
7932(PWR Packs) X 5.78 kW/pkg	45847	
5936 (BWR Packs) X 3.21 kW/pkg	19055	
Total	64902	
Perimeter drift dia. (m)	7.6	
Set back distance (m)	40	
Diameter of the access drift (m)	4.3	
c/c distance between waste pkgs (m)	6.64	
Average length of the repository (m)	1250	
Emplacement drift length (m)	1090	
Excavated drift length (m)	1235	
No. of waste pkgs required per drift	164	
No. of access drifts required	85	
Total emplacement length required	92650	
Total excavated drift length	104975	
Emplacement drift efficiency (%)	87	
Equivalent output/pkg	4.68	

	Case 1	Case 2	Case 3	Case 4	Case 5
Areal power density (APD kW/Acre)	114	86	57	37	25
Local APD (LAPD kW/Acre)	131	99	66	43	29
Calculated drift spacing	22	29	43	66	98
Total drift excavated length (m)	104975	104975	104975	104975	104975
Excavated drift area (m2)	451393	451393	451393	451393	451393
Local excavation ratio (%)	20	15	10	7	4
Theoretical repository area (Acre)	569	755	1139	1754	2596

4.1. 21(P[illegible]R) or 40(Bwr) Case   In-Drift emplacement (7 m drift dia.) - Case 1

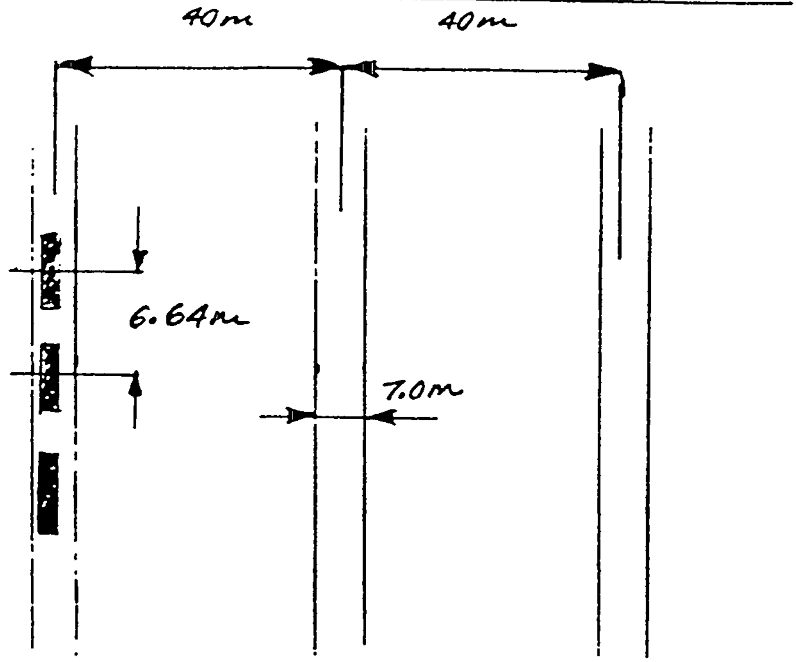
Assumed:

kw/pkg for PWR and BWR	10.12	6.12
No. of PWR and BWR pkgs	4533	3116
4533(PWR Packs) X 10.12kW/pkg	45874 kW	
3116 (BWR Packs) X 6.12 kW/pkg	19070 kW	
Total	64944 kW	
Permieter drift dia. (m)	7.6	
Set back distance (m)	40	
Diameter of the access drift (m)	7	
c/c distance between waste pkgs (m)	6.64	
Average length of the repository (m)	1250	
Emplacement drift length (m)	1090	
Excavated drift length (m)	1235	
No. of waste pkgs required per drift	164	
No. of access drifts required	47	
Total emplacement length required	51230	
Total excavated drift length	58045	
Emplacement drift efficiency (%)	87	
Equivalent output/pkg	8.49	

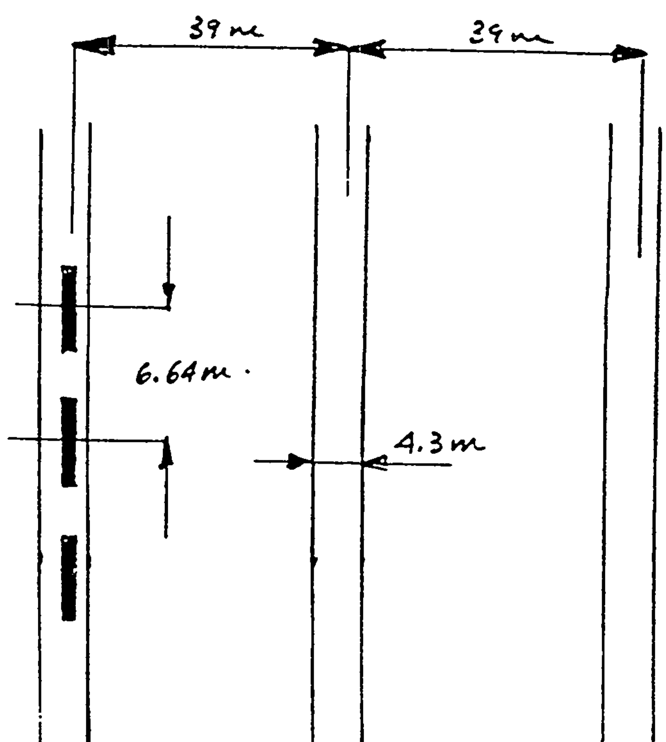
	Case 1	Case 2	Case 3	Case 4	Case 5
Areal power density (APD kW/Acre)	114	86	57	37	25
Local APD (LAPD kW/Acre)	131	99	66	43	29
Calculated drift spacing	40	52	78	120	178
Total drift excavated length (m)	58045	58045	58045	58045	58045
Excavated drift area (m2)	406315	406315	406315	406315	406315
Local excavation ratio (%)	18	13	9	6	4
Theoretical repository area (Acres)	570	755	1139	1755	2598
Emplacement drift area (m2)	358610	358610	358610	358610	358610

4.0 21 (PWR) OR 40 (BWR) CASE

4.1.1 IN-DRIFT EMPLACEMENT AT 114 KW/ACRE



4.2 4.3m DIA ACCESS DRIFT - WASTE PACKAGES IN DRIFT EMPLACEMENT



4.2. 21(PWR) or 40(Bwr) Case In-Drift emplacement (4.3 drift dia.) Case 1

Assumed:

kw/pkg for PWR and BWR	10.12	6.12
No. of PWR and BWR pkgs	4533	3116
4533(PWR Packs) X 10.12kW/pkg	45874 kW	
3116 (BWR Packs) X 6.12 kW/pkg	19070 kW	
Total	64944 kW	
Perimeter drift dia. (m)	7.6	
Set back distance (m)	40	
Diameter of the access drift (m)	4.3	
c/c distance between waste pkgs (m)	6.64	
Average length of the repository (m)	1250	
Emplacement drift length (m)	1090	
Excavated drift length (m)	1235	
No. of waste pkgs required per drift	164	
No. of access drifts required	47	
Total emplacement length required	51230	
Total excavated drift length	58045	
Emplacement drift efficiency (%)	87	
Equivalent output/pkg	8.49	

	Case 1	Case 2	Case 3	Case 4	Case 5
Areal power density (APD kW/Acre)	114	86	57	37	25
Local APD (LAPD kW/Acre)	131	99	66	43	29
Calculated drift spacing	40	52	78	120	178
Total drift excavated length (m)	58045	58045	58045	58045	58045
Excavated drift area (m2)	249594	249594	249594	249594	249594
Local excavation ratio (%)	11	8	6	4	2
Theoretical repository area (Acres)	570	755	1139	1755	2598
Emplacement drift area (m2)	220289	220289	220289	220289	220289

4.3. 21(PWR) or 40(Bwr) Case

In-Drift emplacement (7 m drift dia.) Case 2

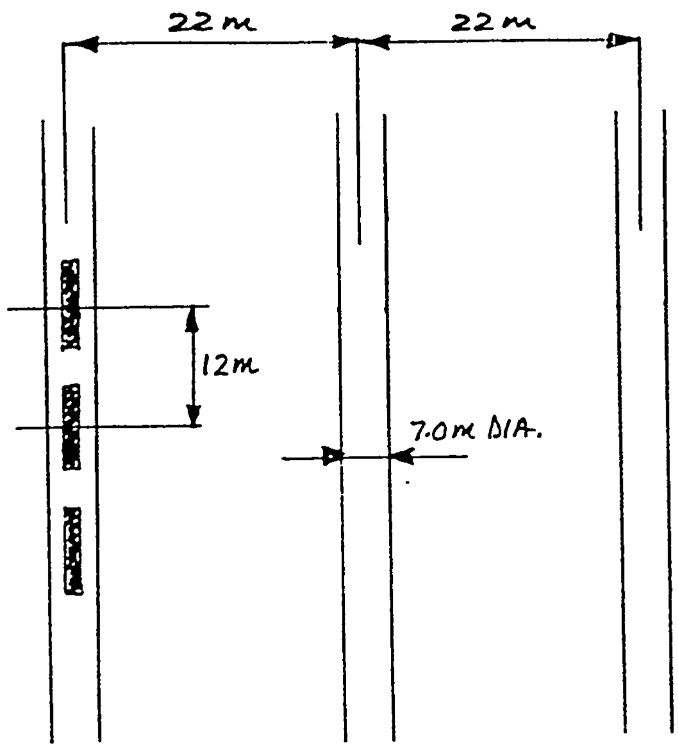
Assumed:

kw/pkg for PWR and BWR	10.12	6.12
No. of PWR and BWR pkgs	4533	3116
4533(PWR Packs) X 10.12kW/pkg	45874 kW	
3116 (BWR Packs) X 6.12 kW/pkg	19070 kW	
Total	64944 kW	
Perimeter drift dia. (m)	7.6	
Set back distance (m)	40	
Diameter of the access drift (m)	7	
c/c distance between waste pkgs (m)	12	
Average length of the repository (m)	1250	
Emplacement drift length (m)	1090	
Excavated drift length (m)	1235	
No. of waste pkgs required per drift	91	
No. of access drifts required	84	
Total emplacement length required	91560	
Total excavated drift length	103740	
Emplacement drift efficiency (%)	87	
Equivalent output/pkg	8.49	

	Case 1	Case 2	Case 3	Case 4	Case 5
Areal power density (APD kW/Acre)	114	86	57	37	25
Local APD (LAPD kW/Acre)	131	99	66	43	29
Calculated drift spacing	22	29	43	67	99
Total drift excavated length (m)	103740	103740	103740	103740	103740
Excavated drift area (m2)	726180	726180	726180	726180	726180
Local excavation ratio (%)	32	24	16	10	7
Theoretical repository area (Acres)	570	755	1139	1755	2598
Emplacement drift area (m2)	640920	640920	640920	640920	640920

1.0 21(PWR) OR 40 (BWR) CASE

4.3.1 IN-DRIFT EMPLACEMENT AT 114 KW/ACRE



4.4 21(PWR) or 40(Bwr) Case   In-Drift emplacement (4.3 drift dia.) Case 3

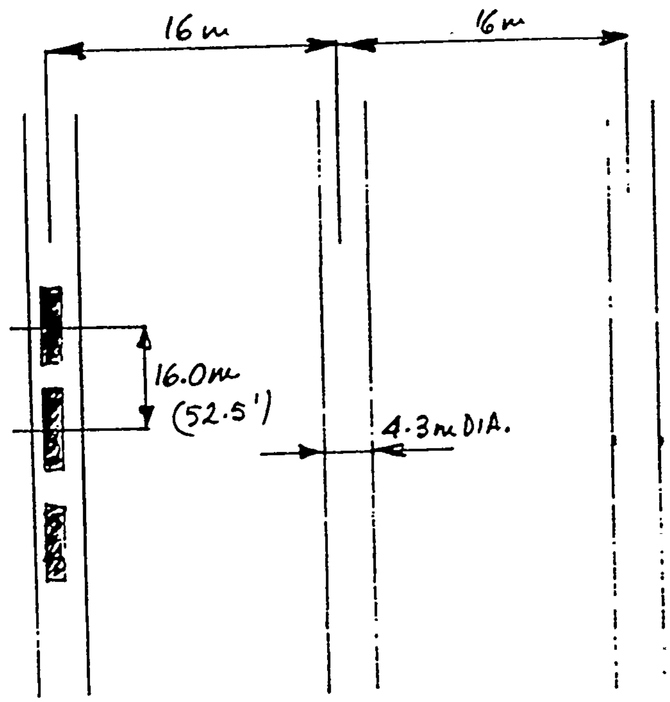
Assumed:

kw/pkg for PWR and BWR	10.12	6.12
No. of PWR and BWR pkgs	4533	3116
4533(PWR Packs) X 10.12kW/pkg	45874 kW	
3116 (BWR Packs) X 6.12 kW/pkg	19070 kW	
Total	64944 kW	
Perimeter drift dia. (m)	7.6	
Set back distance (m)	40	
Diameter of the access drift (m)	4.3	
c/c distance between waste pkgs (m)	16	
Average length of the repository (m)	1250	
Emplacement drift length (m)	1090	
Exacavated drift length (m)	1235	
No. of waste pkgs required per drift	68	
No. of access drifts required	112	
Total emplacement length required	122080	
Total excavated drift length	138320	
Emplacement drift efficiency (%)	87	
Equivalent output/pkg	8.49	

	Case 1	Case 2	Case 3	Case 4	Case 5
Areal power density (APD kW/Acre)	114	86	57	37	25
Local APD (LAPD kW/Acre)	131	99	66	43	29
Calculated drift spacing	16	22	33	50	74
Total drift excavated length (m)	138320	138320	138320	138320	138320
Exacavated drift area (m2)	594776	594776	594776	594776	594776
Local excavation ratio (%)	27	20	13	9	6
Theoretical repository area (Acres)	570	755	1139	1755	2598
Emplacement drift area (m2)	524944	524944	524944	524944	524944

1.0 21 (PWR) OR 40 (BWR) CASE

4.4.1 IN-DRIFT EMPLACEMENT AT 114 KW/ACRE



Appendix D
Thermal-Hydrologic Model Inputs

The attached information provides many of the details of the inputs used for the VTOUGH code. This information was developed by Eric Ryder of SNL based on an evaluation of the LLNL input decks during a DOE sponsored model validation effort in FY93 that involved LLNL, SNL, and others. The evaluation is fairly comprehensive and also compares the inputs against the range of values that are found in the RIB.

A Translation and Preliminary Evaluation of LLNL VTOUGH Input Decks G140RRSI and G105RRSI

prepared by

Eric Ryder
Sandia National Laboratories

March 1993

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1.0 ROCK GRAIN DENSITY

A single value of grain density is used in the LLNL calculations for all stratigraphic units. This value (2580 kg/m^3) is equal to the value for PPw reported in RIB version 3. The tables in Appendix A show that the current RIB estimates of the mean rock grain densities are similar, but the reported standard deviations do not in all cases bracket 2580 kg/m^3.

IMPACT: See Section 4.0

2.0 MATRIX POROSITY

For matrix porosity, the values used in the LLNL input decks are, in general, consistent with those reported in RIB versions 3 and 4. It is noted that the majority of the values used are not the mean values; however, the range of reported standard deviations bracket (with isolated exceptions) those values defined in the input decks.

IMPACT: See Section 4.0

3.0 GRAIN SPECIFIC HEAT

Values for grain specific heat are not reported in the RIB. Nimick and Connolly (1991) used Kopp's rule to estimate the specific heat of the solid components of the various stratigraphic units. Figure 1 is an example of the range of grain specific heats that were calculated for the sample constituents. These values are functions of temperature, with the lowest range of values reported for a temperature of 300 K being 700 to 750 J/kg-K. Examining the grain specific heats used in the LLNL input, those for PTn, CHn1v, CHn1z and PPw (422, 488, 526, and 639, respectively) are all below the 700 J/kg-K range.

IMPACT: See Section 4.0

4.0 EFFECTIVE THERMAL CAPACITANCE

In the calculation of heat transfer, it is not so much the isolated values of grain density, grain specific heat, or porosity that are important, but the combination of these values into an effective thermal capacitance of the composite material.

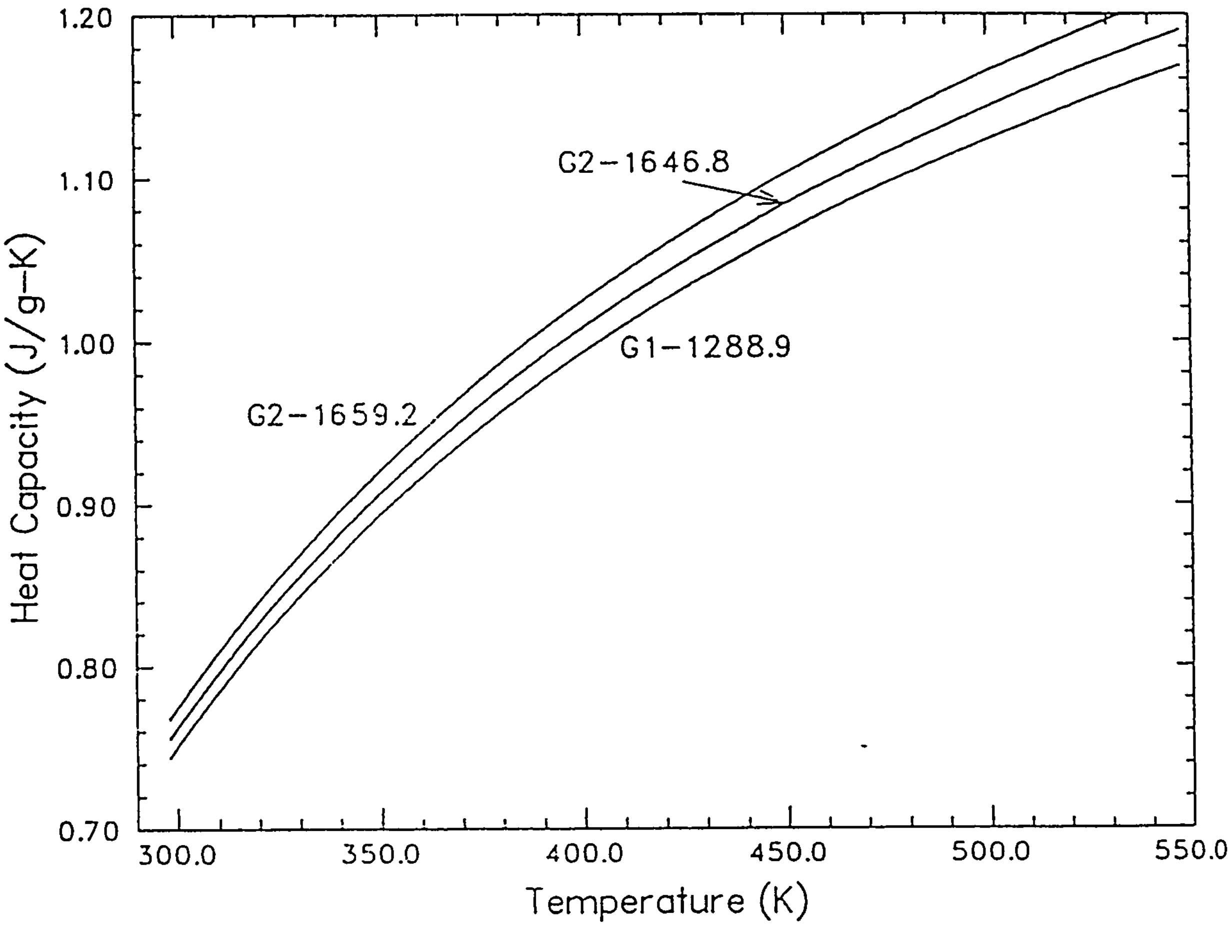

Figure 1. Heat Capacities of Solid Material for Three Samples of the Basal Vitrophyre of the Topopah Spring Member (Nimick and Connolly, 1991)

The method by which the TOUGH (Pruess, 1987) code calculates heat accumulation is as follows:

$$M = (1-\phi)(\rho c_p)_{grain} T + \phi \Sigma S_\beta \rho_\beta u_\beta \qquad (1)$$

where, ϕ is the porosity; $(\rho c_p)_{grain}$ is the rock grain thermal capacitance; T is temperature; and S_β, ρ_β, and u_β are the saturation, the density, and the internal energy of phase β, respectively. From equation 1, estimation of the specific values for the effective thermal capacitance of a rock-water mixture can be expressed as:

$$(\rho c_p)_{eff} = (1-\phi)(\rho c_p)_{grain} + \phi\ S\ (\rho c_p)_{water} \qquad (2)$$

where, $(\rho c_p)_{eff}$ is the effected thermal capacitance of the rock/water mixture and $(\rho c_p)_{water}$ is the thermal capacitance of water at an assumed temperature and pressure. For this comparison, T was assumed to be 298 K, yielding an approximate thermal capacitance for water of 4.16E6 J/m^3K.

Using the values obtained from the LLNL input decks, rock mass thermal capacitance as a function of saturation was calculated (see Table 1). The RIB item regarding thermal capacitance is fully documented in SAND88-3050 (Nimick and Connolly, 1991). The values presented in SAND88-3050 were generated based on bulk chemical analyses of 20 samples of tuffs from Yucca Mountain. To date, experimental verification of these RIB values has not been completed.

Table 2 documents RIB (version 4)thermal capacitance values for in situ saturation conditions at 25°C as well as values representing zero saturation (at an assumed temperature of 155 °C) and compares these to values presented in Table 1.

IMPACT: Because of the low sensitivity of heat conduction to small variations in heat capacity, the impact of the differences between the thermal capacitance values reported in the RIB (version 4) and those calculated using values for grain density and specific heat from the LLNL input decks is expected to be minor.

Table 1. Thermal Capacitance as a Function of Saturation (J/cm^3K)

S	TCw	PTn	TSw1	TSw2	TSw3	CHn1v	CHn1z	PPw
0.00	1.728	0.653	1.759	1.929	2.275	0.993	0.977	1.253
0.10	1.761	0.820	1.805	1.975	2.304	1.184	1.109	1.353
0.30	1.828	1.153	1.896	2.066	2.362	1.567	1.342	1.553
0.50	1.895	1.486	1.988	2.158	2.420	1.951	1.576	1.753
0.61		1.669						
0.65			2.057	2.227	2.464			
0.67	1.951							
0.70	1.961	1.819	2.080	2.250	2.479	2.334	1.809	1.953
0.9	2.028	2.153	2.171	2.341	2.537	2.177	2.042	2.153
0.91							2.038	
1.00	2.061	2.319	2.217	2.387	2.566	2.908	2.159	2.252

[double-boxed] Indicates values calculated at RIB version 4 in situ saturation levels

Table 2. RIB (version 4) Thermal Capacitance Values Compared to Calculated Values from Table 1 (J/cm^3K)

Unit	In Situ Saturation		Difference	Dry (S = 0)		Difference
	RIB	Table 1	(%)	RIB	Table 1	(%)
TCw	1.926	1.951	1.3	2.027	1.728	14.8
PTn	2.116	1.669	21.1	1.461	0.653	55.3
TSw1	1.978	2.057	4.0	1.964	1.759	10.4
TSw2	2.032	2.227	9.6	2.111	1.929	8.6
TSw3	1.844	2.464	33.6	2.449	2.275	7.1
CHn1v	2.444	2.177	10.9	1.602	0.993	38.0
CHn1z	2.603	2.038	22.7	2.742	0.997	63.6
PPw	2.65	2.252	15.0	1.65	1.253	24.1

[boxed] Indicates values from RIB version 3

5.0 THERMAL CONDUCTIVITY

The thermal conductivities presented in the LLNL input decks are defined as functions of liquid saturation. The specific relationship used is:

$$K(S_l) = K_{dry} + S_l \, (K_{wet} - K_{dry}) \quad (3)$$

where, K(S) is the effective thermal conductivity as a function of liquid saturation level S_l, K_{wet} is the saturated thermal conductivity, and K_{dry} is the dry thermal conductivity.

The RIB (version 4) only presents rock-mass thermal conductivity data for in situ saturation and dry conditions. The calculation of these values is based on the following equation:

$$K_{rm} = (1/4)\{[3(1-\phi)-1]K_o + (3\phi-1)K_f \pm [\{[3(1-\phi)-1]K_o + (3\phi-1)K_f\}^2 + 8K_oK_f]^{1/2}\} \quad (4)$$

where, K_{rm} is the calculated rock-mass thermal conductivity, ϕ is porosity, K_o is the matrix (zero porosity) thermal conductivity, and K_f is the fluid phase thermal conductivity. For partially saturated conditions, K_f is given by:

$$K_f = (1/4)\{[3(1-S)-1]K_a + (3S-1)K_w \pm [\{[3(1-S)-1]K_a + (3S-1)K_w\}^2 + 8K_aK_w]^{1/2}\} \quad (5)$$

where, S is saturation and K_a and K_w are the thermal conductivities of air and water at the temperature of interest.

Values for in situ and dry thermal conductivities presented in version 4 of the RIB were developed under the assumption that the initial in situ saturation values do not change during heating until a nominal boiling temperature of 95°C, and that all the pore water leaves the rock when the rock temperature is greater than 95°C. RIB and input deck values for in situ and dry thermal conductivities are presented in Table 3.

IMPACT: Based on the comparisons presented in Table 3, the thermal conductivity values and functional relationship defined in the input decks appear appropriate and consistent with Project practices.

Table 3. Mean RIB (version 4) Thermal Conductivity Values Compared to Calculated Values Using Equation 3 (W/mK)

Unit	In Situ Saturation		Difference (%)	Dry (S = 0)		Difference (%)
	RIB	EQN 3		RIB	EQN 3	
TCw	1.73[1] 1.59	1.66	4.0 4.4	1.64[1] 1.51	1.60	2.4 6.0
PTn	1.60[2] 0.85	0.76	52.5 10.6	1.55[2] 0.61	0.61	60.6 0.0
TSw1	1.70[1] 1.60	1.62	4.8 1.3	1.60[1] 1.50	1.55	3.1 3.2
TSw2	2.10	2.10	0.0	2.10	2.10	0.0
TSw3	1.28	1.27	0.8	1.26	1.26	0.0
CHn1v	1.20	1.16	3.3	0.84	0.84	0.0
CHn1z	1.28	1.34	4.7	≤0.56	0.56	0.0
PPw	2.00	2.00	0.0	1.35	1.35	0.0

[ ] Indicates values from RIB version 3

[1]Note: Values are presented for lithophysae poor (top value) and lithophysae rich (bottom value) formations.

[2]Note: The upper value is based on experimental results that assume a porosity lower than that expected within the repository block. The lower value is recommended for use; however, questions still exist regarding the magnitude of this value (Nimick, 1990).

As a final note regarding thermal conductivity, in SAND88-1387 (1990), Nimick discusses the establishment of 0.85 W/mK as the mean value for use at in situ conditions for PTn; however, a note of uncertainty is expressed. Specifically, there is a question regarding whether the samples from which this value was established had dried before wrapping and waxing. If this did occur, *"the value of 0.85 W/m-K would be an underestimate of the in situ thermal conductivity for Unit PTn."* This uncertainty should be resolved as samples from the NRG holes and Surface Based Drilling program are tested.

6.0 COMPUTATIONAL GRID

6.1 Spatial Grid

Table 4 documents the x- and z-locations of the integration points for the computational grids defined in the LLNL input decks. The points documented in Table 4 correspond to the points used in TOUGH's integrated finite difference solution. Using information contained in the LLNL input decks regarding distances to element interfaces, the locations of the grid lines were generated from Table 4 (see Table 5).

Table 5 also indicates what stratigraphic label was assigned to a given finite difference grid block. The locations of the stratigraphic interfaces defined in the TOUGH input decks are compared in Table 6 to the stratigraphy published in the RIB for USW-G4.

IMPACT: The impact of the defined spatial grid is unknown. In order to address the overall grid structure and spacings, a series of grid convergence runs is recommended. Regarding the z-locations of the stratigraphic units used in the LLNL calculations, based on the level of the analyses being conducted and the limitations of the TOUGH code these designations appear appropriate.

6.2 Temporal Grid

The time steps taken following emplacement are defined in the LLNL input as follows:

Start Time (yr)	End Time (yr)	Time Step (yr)
1	20	1
20	100	5
100	300	40
300	900	200
900	2,900	400
2,900	199,990	1,000

IMPACT: These temporal steps appear reasonable, however, it is noted that there is some question regarding the applicability of an areally extensive heat source at long times.

Table 4. Integration Points from LLNL Input Decks

X-CENTER (m)		Z-CENTER (m)	
20 kW/acre	114 kW/acre		
225.	75.	5.00E-31	358.9
625.	210.	7.50	361.9
950.	320.	22.15	364.9
1200.	419.25	35.80	367.9
1375.	513.5	48.80	371.4
1510.	598.5	61.35	375.4
1620.	673.5	74.95	379.4
1720.	738.5	90.00	384.35
1810.	793.5	107.5	390.2
1885.	833.5	127.5	395.6
1945.	863.5	147.5	400.6
1994.	903.5	167.5	404.25
2033.	958.5	187.5	406.55
2069.	1023.5	205.15	410.2
2115.	1098.5	235.3	415.7
2175.	1198.5	247.8	421.7
2250.	1183.5	257.8	427.7
2335.	1278.5	267.8	434.05
2430.	1388.5	276.8	441.4
2540.	1523.5	284.3	449.4
2675.	1698.5	290.8	457.4
2850.	1923.5	296.8	465.4
3075.	2198.5	302.3	474.4
3350.	2548.5	306.8	489.4
3700.	3048.5	310.8	509.4
4200.	3674.25	314.8	529.4
4900.	4400	318.3	549.4
5900.	5400	321.3	563.75
7400.	6900	324.3	569.1
9650.	9150	327.3	572.1
13,000.	12,750	330.3	578.1
15,000.	15,000	333.3	590.1
		335.8	613.1
		337.8	648.1
		339.8	693.1
		341.95	743.1
		344.25	818.1
		346.4	918.1
		348.4	1068.1
		350.4	1368.1
		352.9	1568.1
		355.9	

Table 5. Calculated Grid Block Interface Locations and Unit Designations

X (m)		Z (m)	Assigned Unit	Z (m) continued	Assigned Unit
20 kW/acre	114 kW/acre				
0	0	0		366.4	
450	150	15.0	TCw	369.4	
800	270	29.3		373.4	TSw2
1100	370	42.3		377.4	
1300	468.5	55.3	PTn	381.4	
1450	558.5	67.4		387.3	
1570	638.5	82.5		393.1	
1670	708.5	97.5		398.1	TSw3
1770	768.5	117.5		403.1	
1850	818.5	137.5	TSw1	405.4	CHn1v
1920	848.5	157.5		407.7	
1970	878.5	177.5		412.7	
2018	928.5	197.5		418.7	
2048	988.5	212.8		424.7	
2090	1058.5	227.8		430.7	
2140	1138.5	242.8		437.4	
2210	1228.5	252.8		445.4	
2290	1328.5	262.8		453.4	CHn1z
2380	1448.5	272.8		461.4	
2480	1598.5	280.8		469.4	
2600	1798.5	287.8		479.4	
2750	2048.5	293.8		499.4	
2950	2348.5	299.8		519.5	
3200	2748.5	304.8	TSw2	539.4	
3500	3348.5	308.8		559.4	
3900	4000	312.8		568.1	
4500	4800	316.8		570.1	
5300	6000	319.8		574.1	
6500	7800	322.8		582.1	
8300	10,500	325.8		598.1	
11,000	15,000	328.8		628.1	PPw
15,000		331.8		668.1	
		334.8		718.1	
		336.8		768.1	
		338.8		868.1	
		340.8		968.1	
		343.1	REPO	1168.1	
		345.4		1568.1	
		347.4			
		349.4			
		351.4			
		354.4	TSw2		
		357.4			
		360.4			
		363.4			

Table 6. Comparison between RIB Unit Contacts for USW-G4 and LLNL Layering

Unit	Location	RIB Contacts (m)	LLNL Grid (m)
UO	top base	0.0 9.1	Not Modeled
TCw	top base	9.1 36	0.0 29.3
PTn	top base	36 74	29.3 67.4
TSw1	top base	74 204	67.4 197.5
TSw2	top base	204 394	197.5 387.3
TSw3	top base	394 409	387.3 403.1
CHn1v	top base	409 415	403.1 407.7
CHn1z	top base	415 519	407.7 539.4
CHn2	top base	519 535	Not Modeled
CHn3	top base	535 545	Not Modeled
PPw	top base	545 596	539.4 1568.1
CFUn	top base	596 686	Not Modeled
BFw	top base	686 814	Not Modeled
CFMn1	top base	814 829	Not Modeled
CFMn2	top base	829 836	Not Modeled
CFMn3	top base	836 857.7	Not Modeled

7.0 MODELED HEAT SOURCE

The heat source used in the LLNL axisymmetric calculations is defined as two layers of disk/ring elements. The layers are each 2.3 m thick. Because of the multiple layers, the input deck assigns one half of the desired initial power output to each layer. For example, for the 20 kW/acre case the innermost element has a rotated surface area of 157.2 acres. To produce 20 kW/acre at emplacement, the initial power output should be approximately 3144 kW. In the input deck, this value is equally divided between the two adjacent (in the z-direction) repository elements. Figure 2 illustrates the LLNL approach to heat source definition. It is noted that when viewed along a z-normal, this approach effectively produces an overall initial loading of 20 kW/acre (since the two power outputs add in series). As viewed along an x-normal, however, there appears to be no compensation for the fact that the heat generating layers are now in parallel. Thus, along an x-normal the modeled region is only seeing a 10 kW/acre equivalent source.

IMPACT: Since the thickness of the two layers is small compared to the modeled region, the LLNL approach to heat source definition is expected to have a small impact on overall calculated responses.

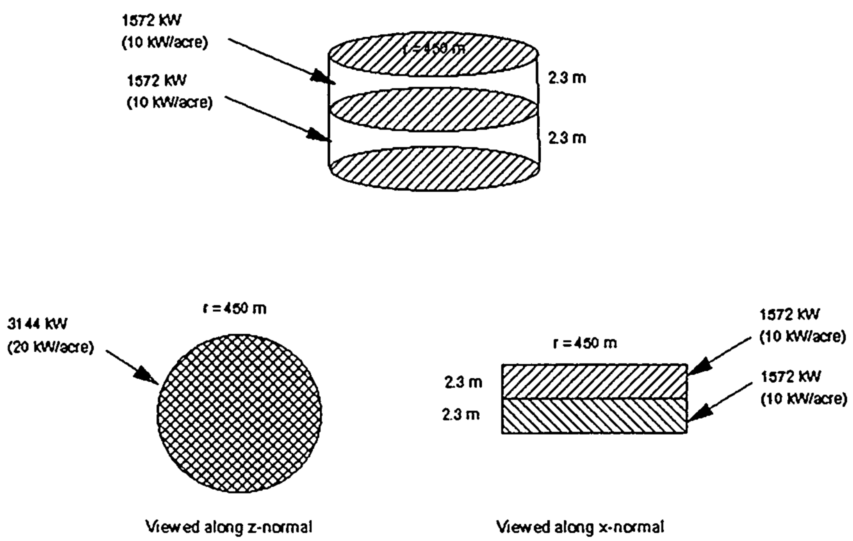

Figure 2. Heat Generating Repository Elements 1 and 13 from Input Deck G105RRS.

7.1 Waste Decay Characteristics

The decay of the heat source in the TOUGH code is handled by using tabular "look-ups" at each time step. This information was examined and appears consistent with decay characteristics for PWR-type 33 GWd/MTU spent fuel. Figure 3 is a partial representation of the LLNL decay curve (normalized to 30 years out of reactor).

IMPACT: None Identified

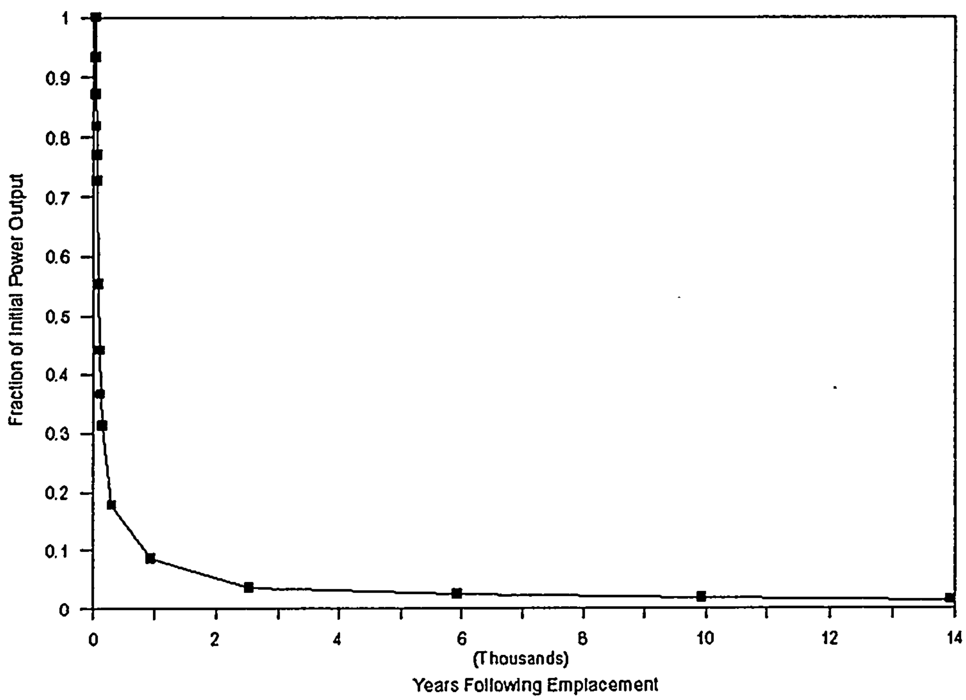

Figure 3. LLNL Decay curve Normalized to 30 years Out-of-Reactor

7.2 Areal Extent of Heat Sources

As indicated above, the definition of the overall heat-generation of the repository is made up of two layers of disk/ring elements. The overall repository areas defined for these and other calculations are documented in "*The Analysis of Repository Heat Driven Hydrothermal Flow at Yucca Mountain*," by T. Buscheck and J. Nitao (to be published in the proceedings of the 1993 International High-Level Radioactive Waste Management Conference). Table 7 is a partial reprint from Buscheck and Nitao (1993 draft).

Table 7. LLNL Modeled Repository Areas, Mass Loadings, and Areal Power Densities Assuming a 33 GWd/MTU PWR Waste Description

Areal Mass Loading (MTU/acre)	Areal Power Density (kW/acre)	Spent Fuel Age (yrs)	Modeled Area (acres)	MTU's Emplaced	Initial kW at Emplacement
27.1	20.0	30	3162	85,690	63,240
27.1	20.0	30	1747	47,344	34,940
43.5	20.0	60	1747	75,995	34,940
49.2	36.2	30	1747	85,952	63,241
49.2	57.0	10	1747	85,952	99,579
77.4	36.2	60	1747	135,218	63,241
77.4	57.0	30	1118	86,533	63,726
77.4	57.0	30	1747	135,218	99,579
124.3	57.0	60	1747	217,152	99,579
154.7	71.7	60	1747	270,261	125,260
154.7	114.0	30	559	86,477	63,726
154.7	114.0	30	1747	270,261	199,158
248.5	114.0	60	348	86,478	39,672

[ ] Indicates Values Calculated from Results Presented in Buscheck and Nitao (1993, draft)

The shaded columns in Table 7 document values that are representative of 1) the effective number of MTU's of waste emplaced--calculated as the product of columns 1 and 4 and 2) the amount of simultaneously emplaced power in kW--calculated as the product of columns 2 and 4.

7.2.1 Total MTU's Emplaced

The Mission Plan Amendment (MPA; DOE, 1988) specifies that the repository will accept 63,020 tons of spent fuel. By comparison, Table 7 indicates that (with one exception) all of the LLNL calculations exceed this limit by anywhere from 36 to 329 percent. This indicates that the heat generating areas defined in the LLNL calculations are too large.

IMPACT: See Section 8.0

7.2.2 Total Initial Power at Emplacement

As an alternate approach to evaluating the repository size representations in the LLNL calculations, the total kW at emplacement were calculated. In order to make comparisons, information regarding the heat output of a 10-, 30-, and 60-year-old 33 GWd/MTU spent fuel must be used. Table 8 documents the heat output for the three waste ages (DOE, 1992). In addition, the total number of kilowatts that would be produced by 63,020 MTU's of spent fuel are also provided. Comparing these total kW values to those calculated in Table 7, differences of 37 to 337 percent are observed (with one exception). Again, this is indicative of too large a representation of the repository in the LLNL calculations.

IMPACT: See Section 8.0

Table 8. Power Output for 33 GWd/MTU PWR Spent Fuel

Spent Fuel Age (years)	kW/MTU	Total kW Assuming 63,020 MTUs
10	1.140	71,843
30	0.723	45,563
60	0.455	28,674

8.0 IMPACT OF LLNL HEAT SOURCE DEFINITIONS

In an attempt to quantify the impact of the LLNL heat source size on the duration of the 95°C isotherm, simplified plate-source calculations were carried out. The model used allows for single or multiple heat-generating plates to be defined in a semi-infinite, homogeneous material with constant properties. The repository level was assumed to be 350 m below a constant temperature ground surface, and an initial geothermal gradient consistent with that presented in the RIB for USW-G4 was applied. Thermal conductivity and heat capacity were assumed to be 2.1 W/mK and 2.2 J/cm^3K, respectively.

8.1 Aspect Ratio = 1

For a waste age of 30-years, the combination of the MPA tonnage acceptance schedule with an areal power density of 114 kW/acre would require a plate source of approximately 400 acres. To evaluate the trends in boiling duration as this acreage is increased, runs assuming 400, 559, 1000, and 1747 acres were carried out. For this set of analyses, square plate sources were used (aspect ratio = length/width = 1). Table 10 documents the approximate times when the 95°C isotherm collapses at the center of the plate sources.

Table 10. Time to Collapse of 95°C Isotherm at Center of Modeled Repository (30-year-old waste, 114 kW/acre)

Square Plate Source Area (acres)	Time to Boiling Collapse (years)
400	6,200
559	7,000
1000	9,000
1747	10,200

It is apparent from Table 10 that LLNL's use of disk sources that are too large in relation to that which would be defined under the MPA tonnage limits may have a significant impact upon their predictions of boiling duration.

Regarding a comparison of these and LLNL results, the 10,200 year boiling duration documented in Table 10 for the 1747 acre source is essentially equivalent to the 10,685 year duration documented for the same source size in Buscheck and Nitao (1993, draft). For the 559 acre case, Buscheck and Nitao indicate a boiling duration of 11,446 years compared to a 7,000 boiling duration from Table 10. The reason for the discrepancy with the smaller source area is unclear; however, it may be partially linked to edge effects associated with overall source perimeter length. This issue is explored in the following section.

8.2 Alternate Aspect Ratios

Inherent in the use of an axisymmetric heat source representation is the minimization of source perimeter length. For example, an axisymmetric disk source of 400 acres would have a perimeter of 4,510 m. A square plate source of the same acreage would have a perimeter of 5,089 m. In order to quantify the impact of the axisymmetric model's imposed *source perimeter minimization* on boiling front duration, a series of calculations similar to those presented above were carried out. Thirty-year-old fuel was emplaced at 114 kW/acre. Plate source area was held constant at 400 acres while aspect ratios of the plate source (length/width) were varied. Table 11 documents the plate dimensions, perimeter lengths, and duration of the 95°C isotherms.

Table 11. Boiling Front Duration as a Function of Perimeter Length for 30-year-old Spent Fuel Emplaced at 114 kW/acre (plate size = 400 acres)

Length (m)	Width (m)	Perimeter (m)	95°C Duration (years)
radius = 718 m		4,510	6,900
1,272	1,272	5,089	6,200
1,472	1,100	5,143	6,000
1,619	1,000	5,238	5,850
2,313	700	6,026	4,770
3,238	500	7,475	3,550

Indicates results from axisymmetric calculations assuming the same constant thermal properties as plate source calculations.

It is obvious from Table 11 that source perimeter length has a strong impact on boiling duration. Despite the reduction in heated area requirements with increased APDs, it is unlikely that waste will be emplaced in a square or circular arrangement. Perimeter length may be further increased by the separations of waste panels across the main drift accesses or by the establishment of ventilation cross drifts.

As an example of the effect of perimeter-length increase due to panel separation, a two plate model was run assuming two 200-acre square plates (900 m by 900 m). These plates were separated by a 168 m representation of the main drift accesses and associated standoffs. The perimeter length for this model is 7,200 m. In keeping with the results presented for single plates in Table 11, the boiling isotherm collapsed at the center of the two plates approximately 4,600 years following emplacement.

IMPACT: It is argued that since the heat sources defined in the LLNL calculations are too areally extensive and that they represent minimizations of perimeter length, LLNL's predicted durations of boiling are likely to be overestimates.

9.0 RECOMMENDATIONS

Although the LLNL VTOUGH calculations could be refined to reflect evolving property values and MPA limits on waste acceptance, it is not possible for an axisymmetric model to reflect realistic waste layouts. The effects of these layouts on boiling front duration and hydrothermal interactions are important and should be addressed. It is recommended that attempts be made to incorporate more realistic heat sources in future hydrothermal flow modeling efforts.

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APPENDIX A: Tabularized Property Values from LLNL Input Decks G140RRS and G105RRS

APPENDIX A: Tabularized Property Values from LLNL Input Decks G140RRS and G105RRS

Included in this appendix are tables documenting the thermal and flow parameters used in LLNL input decks g105rrs and g140rrs. For comparison, RIB values for the same parameters are also documented.

Unit	Property	Value	RIB Value
TCw	Grain Density (kg/m^3)	2580	2500±36
	Porosity	0.08	0.107±0.051
	Absolute Permeability (m^2)	2.78E-13	See Note 3
	Saturated Thermal Conductivity (W/mC)	1.69	See Note 1
	Grain Specific Heat (c_p; J/kgC)	728	Not Available
	Dry Thermal Conductivity (W/mC)	1.60	See Note 1
	Tortuosity factor for Binary Diffusion	0.20	
Matrix	Absolute Permeability (m^2)	9.70E-19	9.89E-19
	van Genuchten alpha (Pa)	8.40E-7	8.38E-7
	van Genuchten beta	1.558	1.558
	Matrix Porosity	0.08	0.08
	Residual liquid saturation	0.0020	0.0020
Fracture	Absolute Permeability (m^2)	8.33E-10	See Note 2
	van Genuchten alpha (Pa)	1.315E-3	1.311E-4
	van Genuchten beta	4.230	4.230
	Porosity	3.33E-4	See Note 2
	Residual liquid saturation	0.0395	0.0395

NOTE 1: RIB version 4 provides Thermal Conductivity Values for *In Situ Saturation* and *Dry* Rock:

TCw	In-Situ Saturation	Dry
Lithophysae poor	1.73±0.26	1.64±0.26
Lithophysae rich	1.59±0.21	1.51±0.21

The following values are from RIB version 3 (*Saturated* and *Dry*)

Unit	Saturated	Dry
TCw	1.84±0.12	1.41±0.13

NOTE 2. The value for fracture permeability is based on the following assumptions (Buscheck and Nitao, 1988; UCID-21571):

Fracture Aperture	100.0 μm
Fracture Spacing	0.3 m

NOTE 3. Calculated as the product of Fracture Permeability and Fracture Porosity: (8.33E-10)(3.33E-4)

Unit	Property	Value	RIB Value
PTn	Grain Density (kg/m^3)	2580	2390±76
	Porosity	0.40	0.420±0.114
	Absolute Permeability (m^2)	3.17E-13	See Note 3
	Saturated Thermal Conductivity (W/mC)	0.85	See Note 1
	Grain Specific Heat (c_p; J/kgC)	422	Not Available
	Dry Thermal Conductivity (W/mC)	0.61	See Note 1
	Tortuosity Factor for Binary Diffusion	0.20	
Matrix	Absolute Permeability (m^2)	3.90E-14	3.978E-14
	van Genuchten alpha (Pa)	1.53E-6	1.53E-6
	van Genuchten beta	6.873	6.872
	Matrix Porosity	0.04	0.04
	Residual liquid saturation	0.1000	0.1000
Fracture	Absolute Permeability (m^2)	8.33E-10	See Note 2
	van Genuchten alpha (Pa)	1.315E-3	1.311E-4
	van Genuchten beta	4.230	4.230
	Porosity	3.33E-4	See Note 2
	Residual liquid saturation	0.0395	0.0395

NOTE 1: RIB version 4 provides Thermal Conductivity Values for *In Situ Saturation* and *Dry* Rock:

PTn	In-Situ Saturation	Dry
Welded, devitrified	1.60±0.11	1.55±0.06
Nonwelded or bedded	0.85±0.12	0.61±0.33

The following values are from RIB version 3 (*Saturated* and *Dry*)

Unit	Saturated	Dry
PTn	1.35±0.06	1.02±0.19

NOTE 2. The value for fracture permeability is based on the following assumptions (Buscheck and Nitao, 1988; UCID-21571):

Fracture Aperture	100.0 μm
Fracture Spacing	0.3 m

NOTE 3. Calculated as the product of Fracture Permeability and Fracture Porosity plus the Matrix Permeability: (8.33E-10)(3.33E-4) + (3.90E-14)

Unit	Property	Value	RIB Value
TSw1	Grain Density (kg/m^3)	2580	See Note 1
	Porosity	0.11	See Note 2
	Absolute Permeability (m^2)	2.78E-13	See Note 5
	Saturated Thermal Conductivity (W/mC)	1.65	See Note 3
	Grain Specific Heat (c_p; J/kgC)	766	Not Available
	Dry Thermal Conductivity (W/mC)	1.55	See Note 3
	Tortuosity Factor for Binary Diffusion	0.20	
Matrix	Absolute Permeability (m^2)	1.90E-18	1.938E-18
	van Genuchten alpha (Pa)	5.80E-7	5.79E-7
	van Genuchten beta	1.798	1.798
	Matrix Porosity	0.11	0.11
	Residual liquid saturation	0.0800	0.0800
Fracture	Absolute Permeability (m^2)	8.33E-10	See Note 4
	van Genuchten alpha (Pa)	1.315E-3	1.311E-4
	van Genuchten beta	4.230	4.230
	Porosity	3.33E-4	See Note 4
	Residual liquid saturation	0.0395	0.0395

NOTE 1: GRAIN DENSITY VARIES WITH SPATIAL LOCATION.

Location	Grain Density
UE-25a#1, USW-GU3, G4	2540±38
USW G-2	2470±43

NOTE 2: POROSITY VARIES WITH SPATIAL LOCATION.

Location	Porosity
UE-25a#1, USW-G4	0.144±0.034
USW-G2	0.059±0.027
USW GU-3	0.170±0.034

NOTE 3. RIB version 4 provides Thermal Conductivity Values for *In Situ Saturation* and *Dry* Rock:

TSw1	In-Situ Saturation	Dry
Lithophysae poor	1.70±0.3	1.60±0.3
Lithophysae rich	1.60±0.2	1.50±0.2

The following values are from RIB version 3 (*Saturated* and *Dry*)

Unit	Saturated	Dry
TSw1	1.50 (± unavailable)	0.79 (± unavailable)

NOTE 4. The value for fracture permeability is based on the following assumptions (Buscheck and Nitao, 1988; UCID-21571):

Fracture Aperture	100.0 μm
Fracture Spacing	0.3 m

NOTE 5. Calculated as the product of Fracture Permeability and Fracture Porosity: (8.33E-10)(3.33E-4)

Unit	Property	Value	RIB Value
TSw2	Grain Density (kg/m^3)	2580	2550±32
	Porosity	0.11	0.121±0.036
	Absolute Permeability (m^2)	2.78E-13	See Note 3
	Saturated Thermal Conductivity (W/mC)	2.10	See Note 1
	Grain Specific Heat (c_p; J/kgC)	840	Not Available
	Dry Thermal Conductivity (W/mC)	2.10	See Note 1
	Tortuosity Factor for Binary Diffusion	0.20	
Matrix	Absolute Permeability (m^2)	1.90E-18	1.938E-18
	van Genuchten alpha (Pa)	5.80E-7	5.79E-7
	van Genuchten beta	1.798	1.798
	Matrix Porosity	0.11	0.11
	Residual liquid saturation	0.0800	0.0800
Fracture	Absolute Permeability (m^2)	8.33E-10	See Note 2
	van Genuchten alpha (Pa)	1.315E-3	1.311E-4
	van Genuchten beta	4.230	4.230
	Porosity	3.33E-4	See Note 2
	Residual liquid saturation	0.0395	0.0395

NOTE 1: RIB version 4 provides Thermal Conductivity Values for *In Situ Saturation* and *Dry* Rock:

Unit	In-Situ Saturation	Dry
TSw2	2.10±0.2	2.1±0.2

The following values are from RIB version 3 (*Saturated* and *Dry*)

Unit	Saturated	Dry
TSw2	1.84±0.12	1.41±0.13

NOTE 2. The value for fracture permeability is based on the following assumptions (Buscheck and Nitao, 1988; UCID-21571):

Fracture Aperture	100.0 μm
Fracture Spacing	0.3 m

NOTE 3. Calculated as the product of Fracture Permeability and Fracture Porosity: (8.33E-10)(3.33E-4)

Unit	Property	Value	RIB Value
TSw3	Grain Density (kg/m^3)	2580	2400±51
	Porosity	0.07	See Note 1
	Absolute Permeability (m^2)	2.78E-13	See Note 4
	Saturated Thermal Conductivity (W/mC)	1.28	See Note 2
	Grain Specific Heat (c_p; J/kgC)	948	Not Available
	Dry Thermal Conductivity (W/mC)	1.26	See Note 2
	Tortuosity Factor for Binary Diffusion	0.20	
Matrix	Absolute Permeability (m^2)	1.50E-19	1.53E-19
	van Genuchten alpha (Pa)	4.51E-7	4.50E-7
	van Genuchten beta	2.058	2.058
	Matrix Porosity	0.07	0.07
	Residual liquid saturation	0.0800	0.0800
Fracture	Absolute Permeability (m^2)	8.33E-10	See Note 3
	van Genuchten alpha (Pa)	1.315E-3	1.311E-4
	van Genuchten beta	4.230	4.230
	Porosity	3.33E-4	See Note 3
	Residual liquid saturation	0.0395	0.0395

NOTE 1: POROSITY VARIES WITH SPATIAL LOCATION.

Location	Porosity
UE-25a#1	0.116±0.036
USW G-1, G-2,GU-3	0.032±0.014

NOTE 2: RIB version 4 provides Thermal Conductivity Values for *In Situ Saturation* and *Dry* Rock:

Unit	In-Situ Saturation	Dry
TSw3	1.28±0.10	1.26±0.10

The following values are from RIB version 3 (*Saturated* and *Dry*)

Unit	Saturated	Dry
TSw3	1.33±0.08	1.34±0.12

NOTE 3. The value for fracture permeability is based on the following assumptions (Buscheck and Nitao, 1988; UCID-21571):

Fracture Aperture	100.0 μm
Fracture Spacing	0.3 m

NOTE 4. Calculated as the product of Fracture Permeability and Fracture Porosity: (8.33E-10)(3.33E-4)

Unit	Property	Value	RIB Value
CHn1v	Grain Density (kg/m^3)	2580	2320±47
	Porosity	0.46	See Note 1
	Absolute Permeability (m^2)	3.05E-13	See Note 4
	Saturated Thermal Conductivity (W/mC)	1.20	See Note 2
	Grain Specific Heat (c_p; J/kgC)	488	Not Available
	Dry Thermal Conductivity	0.84	See Note 2
	Tortuosity Factor for Binary Diffusion	0.20	
Matrix	Absolute Permeability (m^2)	2.70E-14	2.75E-14
	van Genuchten alpha (Pa)	1.64E-6	1.63E-6
	van Genuchten beta	3.872	3.872
	Matrix Porosity	0.46	0.46
	Residual liquid saturation	0.0410	0.410
Fracture	Absolute Permeability (m^2)	8.33E-10	See Note 3
	van Genuchten alpha (Pa)	1.315E-3	1.311E-4
	van Genuchten beta	4.230	4.230
	Porosity	3.33E-4	See Note 3
	Residual liquid saturation	0.0395	0.0395

NOTE 1: POROSITY VARIES WITH SPATIAL LOCATION.

Location	Porosity
USW G-1, GU-3	0.345±0.092
USW G-4	0.146±0.032

NOTE 2: RIB version 4 provides Thermal Conductivity Values for *In Situ Saturation* and *Dry* Rock:

Unit	In-Situ Saturation	Dry
CHn1v	1.20±0.12	0.84±0.21

The following values are from RIB version 3 (*Saturated* and *Dry*)

Unit	Saturated	Dry
CHn1v	1.35±0.06	1.02±0.19

NOTE 3. The value for fracture permeability is based on the following assumptions (Buscheck and Nitao, 1988; UCID-21571):

Fracture Aperture	100.0 μm
Fracture Spacing	0.3 m

NOTE 4. Calculated as the product of Fracture Permeability and Fracture Porosity plus the Matrix Permeability: (8.33E-10)(3.33E-4) + (2.70E-14)

Unit	Property	Value	RIB Value
CHn1z	Grain Density (kg/m^3)	2580	See Note 1
	Porosity	0.28	See Note 2
	Absolute Permeability (m^2)	2.78E-13	See Note 5
	Saturated Thermal Conductivity (W/mC)	1.42	See Note 3
	Grain Specific Heat (c_p; J/kgC)	526	Not Available
	Dry Thermal Conductivity (W/mC)	0.56	See Note 3
	Tortuosity Factor for Binary Diffusion	0.20	
Matrix	Absolute Permeability (m^2)	2.00E-18	2.04E-18
	van Genuchten alpha (Pa)	3.15E-7	3.14E-7
	van Genuchten beta	1.602	1.602
	Matrix Porosity	0.28	0.28
	Residual liquid saturation	0.1100	0.1100
Fracture	Absolute Permeability (m^2)	8.33E-10	See Note 4
	van Genuchten alpha (Pa)	1.315E-3	1.311E-4
	van Genuchten beta	4.230	4.230
	Porosity	3.33E-4	
	Residual liquid saturation	0.0395	0.0395

NOTE 1: GRAIN DENSITY VARIES WITH SPATIAL LOCATION.

Location	In-Situ Saturation
UE-25a#1, USW G-4	2350±76
USW G-1	2430±34

NOTE 2: POROSITY VARIES WITH SPATIAL LOCATION.

Location	In-Situ Saturation
UE-25a#1, USW G-4	0.324±0.037
USW G-1	0.356±0.020

NOTE 3: RIB version 4 provides Thermal Conductivity Values for *In Situ Saturation* and *Dry* Rock:

Unit	In-Situ Saturation	Dry
CHn1z	1.28±0.23	≤0.56

The following values are from RIB version 3 (*Saturated* and *Dry*)

Unit	Saturated	Dry
CHn1z	1.48±0.17	1.01±0.14

NOTE 4. The value for fracture permeability is based on the following assumptions (Buscheck and Nitao, 1988; UCID-21571):

Fracture Aperture	100.0 μm
Fracture Spacing	0.3 m

NOTE 5. Calculated as the product of Fracture Permeability and Fracture Porosity: (8.33E-10)(3.33E-4)

Unit	Property	Value	RIB Value
PPw	Grain Density (kg/m^3)	2580	2580±40[1]
	Porosity	0.24	0.24±0.07[1]
	Absolute Permeability (m^2)	2.785E-13	See Note 3
	Saturated Thermal Conductivity (W/mC)	2.00	2.00±0.27[1]
	Grain Specific Heat (c_p; J/kgC)	639	Not Available
	Dry Thermal Conductivity (W/mC)	1.35	1.35±0.30 (See Note 1)
	Tortuosity Factor for Binary Diffusion	0.20	
Matrix	Absolute Permeability (m^2)	4.50E-16	4.59E-16
	van Genuchten alpha (Pa)	1.44E-6	1.44E-6
	van Genuchten beta	2.639	2.639
	Matrix Porosity	0.24	0.24
	Residual liquid saturation	0.0660	0.0660
Fracture	Absolute Permeability (m^2)	8.33E-10	See Note 2
	van Genuchten alpha (Pa)	1.315E-3	1.311E-4
	van Genuchten beta	4.230	4.230
	Porosity	3.33E-4	
	Residual liquid saturation	0.0395	0.0395

NOTE 1. These values from RIB version 3 (not contained in RIB version 4)

NOTE 2. The value for fracture permeability is based on the following assumptions (Buscheck and Nitao, 1988; UCID-21571):

Fracture Aperture	100.0 μm
Fracture Spacing	0.3 m

NOTE 3. Calculated as the product of Fracture Permeability and Fracture Porosity: (8.33E-10)(3.33E-4)

APPENDIX B: Reprint of Material Parameter Cards from LLNL Input Decks G140RRS and G105RRS

```
*g140rrs*2-D REP,flx=0.mm/y,allunts,r=848.5m,RIBver4Kth,1000msz,30yfuel,114kwAPD
ROCKS
TCw       22580.      .08           2.78e-13        0.         0.       1.69       728.
                         1.60          .2
    9       9.70e-19   8.40e-7      1.558         .08     0.0020
    9       8.33e-10  1.315e-3      4.230     3.33e-4     0.0395
PTn       22580.      .40           3.17e-13        0.         0.       0.85       422.
                         0.61          .2
    9       3.90e-14   1.53e-6      6.873         .40     0.1000
    9       8.33e-10  1.315e-3      4.230     3.33e-4     0.0395    0.120
TSw1      22580.      .11           2.78e-13        0.         0.       1.65       766.
                         1.55          .2
    9       1.90e-18   5.80e-7      1.798         .11     0.0800
    9       8.33e-10  1.315e-3      4.230     3.33e-4     0.0395
TSw2      22580.      .11           2.78e-13        0.         0.       2.10       840.
                         2.10          .2
    9       1.90e-18   5.80e-7      1.798         .11     0.0800
    9       8.33e-10  1.315e-3      4.230     3.33e-4     0.0395
REPO      22580.      .11           2.78e-13        0.         0.       2.10       840.
                         2.10          .2
    9       1.90e-18   5.80e-7      1.798         .11     0.0800
    9       8.33e-10  1.315e-3      4.230     3.33e-4     0.0395
TSw3      22580.      .07           2.78e-13        0.         0.       1.28       948.
                         1.26          .2
    9       1.50e-19   4.51e-7      2.058         .07     0.0800
    9       8.33e-10  1.315e-3      4.230     3.33e-4     0.0395
CHn1v     22580.      .46           3.05e-13        0.         0.       1.20       488.
                         0.84          .2
    9       2.70e-14   1.64e-6      3.872         .46     0.0410
    9       8.33e-10  1.315e-3      4.230     3.33e-4     0.0395   0.0610
CHn1z     22580.      .28          2.780e-13        0.         0.       1.42       526.
                         0.56          .2
    9       2.00e-18   3.15e-7      1.602         .28     0.1100
    9       8.33e-10  1.315e-3      4.230     3.33e-4     0.0395
PPw       22580.      .24          2.785e-13        0.         0.       2.00       639.
                         1.35          .2
    9       4.50e-16   1.44e-6      2.639         .24     0.0660
    9       8.33e-10  1.315e-3      4.230     3.33e-4     0.0395
frac      22580.      .90          8.333e-10        0.         0.       2.34       840.
                         1.74          .9
    7         0.7636    0.0395        1.0
   11         0.7636    0.0395    1.315e-3                  1.0     0.04
frac      22580.      .90          8.333e-10        0.         0.       2.34       840.
                         1.74          .9
    7         0.7636    0.0395        1.0
   11         0.7636    0.0395    1.315e-3                  1.0     0.04
ound      22580.      .11           4.75e-20        0.         0.       2.34       840.
                         1.74          .2
    7         0.4438    0.0001        1.0
   11         0.4438    0.0001    5.800e-7                  1.0 0.043233
eatr      21905.      .01                 0.        0.         0.      1.e03       325.
                       1.e03
    5
    1            0.          1.          2.
hole      2   1.      .99           1.0e-10         0.         0.         0.       1.e5
                         0.
    5
    1            0.          1.          2.
apfl      2 0.75      .99           1.0e-10         0.         0.       0.17       1.e3
                         0.17
```

```
   5
   1              0.        1.        2.
:adia    2 0.75     .01               0.        0.        0.    1.3750    1.e3
                      1.3750
   ,
   1              0.        1.        2.
.tm      2   1.     .99          1.0e-08        0.        0.      0.17    1.e8
                        0.17
   1              0.        0.        1.        1.
   1              0.        1.        2.

'ARAM
  24000    0 99910000010010000041          2.13E-5
        6.31152e121.E-2      1.7280e13rp  1           -9.81
                                                       1.E-7
             1.E5              .34000 23.
PTN
   0    1    0    1    1    0
TART
PCAP
   7          0.4438    0.0801      1.0
   7          0.4438    0.0801    5.8e-7    8.80e7       1.0
IMES
  17   17      1.E10 7.20000E3
    0.01 3.15576e8 9.46728e8 3.15576e9 9.46728e93.15576e106.31152e109.46728e10
.26230e111.57788e112.20903e113.15576e114.73364e116.31152e111.57788e123.15576e12
.31152e12
```

```
*g105rrs*2-DREP,flx=0.mm/y,allunts,0.86atm,RIBV4Kth,30yfl,1000msz,r=2018m,20kwAPD
ROCKS
TCw      22580.     .08          2.78e-13       0.         0.       1.69       728.
                       1.60            .2
    9       9.70e-19  8.40e-7     1.558        .08      0.0020
    9       8.33e-10  1.315e-3    4.230     3.33e-4     0.0395
PTn      22580.     .40          3.17e-13       0.         0.       0.85       422.
                       0.61            .2
    9       3.90e-14  1.53e-6     6.873        .40      0.1000
    9       8.33e-10  1.315e-3    4.230     3.33e-4     0.0395     0.120
TSw1     22580.     .11          2.78e-13       0.         0.       1.65       766.
                       1.55            .2
    9       1.90e-18  5.80e-7     1.798        .11      0.0800
    9       8.33e-10  1.315e-3    4.230     3.33e-4     0.0395
TSw2     22580.     .11          2.78e-13       0.         0.       2.10       840.
                       2.10            .2
    9       1.90e-18  5.80e-7     1.798        .11      0.0800
    9       8.33e-10  1.315e-3    4.230     3.33e-4     0.0395
REPO     22580.     .11          2.78e-13       0.         0.       2.10       840.
                       2.10            .2
    9       1.90e-18  5.80e-7     1.798        .11      0.0800
    9       8.33e-10  1.315e-3    4.230     3.33e-4     0.0395
TSw3     22580.     .07          2.78e-13       0.         0.       1.28       948.
                       1.26            .2
    9       1.50e-19  4.51e-7     2.058        .07      0.0800
    9       8.33e-10  1.315e-3    4.230     3.33e-4     0.0395
CHn1v    22580.     .46          3.05e-13       0.         0.       1.20       488.
                       0.84            .2
    9       2.70e-14  1.64e-6     3.872        .46      0.0410
    9       8.33e-10  1.315e-3    4.230     3.33e-4     0.0395     0.0610
CHn1z    22580.     .28         2.780e-13       0.         0.       1.42       526.
                       0.56            .2
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    9       8.33e-10  1.315e-3    4.230     3.33e-4     0.0395
PPw      22580.     .24         2.785e-13       0.         0.       2.00       639.
                       1.35            .2
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    9       8.33e-10  1.315e-3    4.230     3.33e-4     0.0395
frac     22580.     .90         8.333e-10       0.         0.       2.34       840.
                       1.74            .9
    7         0.7636    0.0395      1.0
   11         0.7636    0.0395  1.315e-3                  1.0      0.04
bfrac    22580.     .90         8.333e-10       0.         0.       2.34       840.
                       1.74            .9
    7         0.7636    0.0395      1.0
   11         0.7636    0.0395  1.315e-3
        1.0     0.04
bound    22580.     .11          4.75e-20       0.         0.       2.34       840.
                       1.74            .2
    7         0.4438    0.0001      1.0
   11         0.4438    0.0001  5.800e-7                  1.0 0.043233
heatr    21905.     .01                0.       0.         0.     1.e03       325.
                     1.e03
    5
    1              0.          1.        2.
bhole    2   1.     .99           1.0e-10       0.         0.         0.     1.e5
                       0.

    5
    1              0.          1.        2.
gapfl    2 0.75     .99           1.0e-10       0.         0.       0.17      1.e3
                       0.17
    5
    1              0.          1.        2.
radia    2 0.75     .01                0.       0.         0.     1.3750      1.e3
                     1.3750

    5
```

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atm       2   1.      .99            1.0e-08        0.        0.       0.17     1.e8
                              0.17
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    1             0.        1.        2.

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START
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6.31152e111.57788e123.15576e12
```

Appendix E
Near-Field Calculations

This appendix outlines the calculations that were done by SNL in support of the Thermal Loading Study. The SNL Work Agreement for the effort is included. This work agreement provides the definition of the problem, the thermal properties used, and the calculation methodology. Additionally, a more extensive set of plots of the near-field calculations is also provided.

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Near-Field Thermal Analyses in Support of the M&O's FY93 Thermal Loading Systems Study

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1.0 INTRODUCTION

Using the nonlinear finite element code COYOTE (Gartling, 1982), near-field thermal analyses were performed in support of the Yucca Mountain Site Characterization Project's Management and Operating (M&O) contractor's 1993 thermal loading systems study . These analyses assumed that the inventory of spent fuel expected at the potential repository could be adequately represented by the decay characteristics of 22.5-year-old, pressurized-water reactor (PWR) spent fuel with an average burnup of 42.2 giga-Watt days per metric ton of uranium (GWd/MTU). These values for waste characteristics are consistent with averages reported for a Youngest Fuel First (YFF) waste stream in which no spent fuel younger than 10 years out-of-reactor is accepted for disposal (i.e., a YFF(10) scenario).

Areal mass loadings (AMLs) ranging from 24 to 111 MTU/acre were examined in combination with two drift diameters and three waste package designs. As requested by the M&O, emplacement drifts were assumed to remain open (unbackfilled) for the entire modeled time frame of 1000 years. Prior to a description of the heat source strengths and layouts, a discussion of intact-rock thermal properties will be presented.

1.1 INTACT ROCK THERMAL PROPERTIES

For this set of analyses, a layered stratigraphy was assumed. The layers were considered uniform in thickness over the entire modeled region. Contact points for the various units were obtained from published information for drillhole USW G-4. Table 1 documents the distance from the surface to the contact between units (as measured vertically downward from the surface), as well as the modeled thermal conductivity and heat capacitances for each unit. The values for unit depth, heat capacitance, and thermal conductivity are consistent with values published in the Project's Reference Information Base (RIB). It is noted that the temperature-dependent heat capacitances defined in Table 1 should result in predicted profiles that are consistent with those that would be calculated by coupled hydrothermal codes.

1.2 RADIATION HEAT TRANSFER

It was assumed that the emplacement drifts remain open and unventilated for the modeled time frame. Gartling et al. (1981) showed that radiation heat transfer in a closed drift is an order of magnitude greater than convective heat transfer in a typical SCP-type emplacement drift. Because of this, radiation was considered the dominant heat transfer mechanism in the open emplacement drifts.

In order to model radiation heat transfer, a *drift equivalent* conductive material with a conductivity of 20 W/mK and a thermal capacitance of 0.001 J/cm^{3}K was defined for the open air space of the emplacement drift. This *drift equivalent* material mimics through conduction the radiative flux across the open air space (St. John, 1987).

Table 1. Assumed Thermal Properties and Contact Depths of Stratigraphic Units

				Heat Capacitance (J/cm^{3}K)		
Unit	Upper Contact (m)	Lower Contact (m)	Thermal Conductivity (W/mK)	94°C≥T	94°C<T≤114°C	114°C<T
TCw	0	36.0	1.65	2.0313	9.3748	2.0979
PTn	36.0	74.1	0.85	2.2286	29.3110	1.5236
TSw1	74.1	204.2	1.60	2.0775	12.2655	2.0219
TSw2	204.2	393.5	2.10	2.1414	10.4768	2.1839
TSw3	393.5	409.3	1.28	2.0530	4.5193	2.5535
CHn1v	409.3	414.5	1.20	2.5651	35.3680	1.6702
CHn1z	414.5	518.5	1.28	2.6709	35.3854	2.2835
CHn2	518.5	535.2*	1.30	2.5512	22.3349	1.9599

*Note: For the regions below CHn2, property values are not available in the RIB. Therefore, CHn2 properties were assumed to persist below 535.2 m.

1.3 HEAT SOURCE GEOMETRY AND CHARACTERISTICS

1.3.1 Waste Package

Three waste packages were investigated in this study. All three were assumed to be 4.912 m in length and have diameters consistent with capacities of 6, 12, and 21 PWR assemblies. Specifically, waste package diameters of 1.27 m (6 PWR), 1.49 m (12 PWR), and 1.83 m (21 PWR) were modeled.

1.3.2 Spent Fuel Characteristics

The thermal decay characteristics of spent nuclear fuel were represented by a six-term exponential of the following form:

$$P(t) = \sum_{i=1}^{6} a_i \exp(-b_i t) \qquad (1)$$

where, P(t) is the thermal power output in Watts per MTU, a_i and b_i are fitted constants and t is time since discharge from the reactor. The fitted coefficients for the six-term exponential decay curve used to represent the 42.2 GWd/MTU PWR spent fuel are listed in Table 2. These coefficients are normalized to 22.5 years out-of-reactor. The data used in the exponential fitting were obtained from the Characteristics Data Base (DOE, 1992).

Table 2. Normalized Thermal Decay Coefficients for 42.2 GWd/MTU, PWR-Type Waste

i	a_i	b_i (yr^{-1})
1	0.02068	0.21903E-5
2	0.14450	0.13263E-2
3	0.13185	0.61814E-2
4	0.01238	0.12091E-1
5	0.67719	0.23888E-1
6	0.01340	0.111839

1.3.3 Initial Power Output of Source

The power output for 22.5-year-old, 42.2 GWd/MTU, PWR-type spent fuel was calculated to be 1.126 kW/MTU. Using the YFF(10) emplacement schedule provided by the M&O (King, 1993), an average PWR assembly weight of 0.428 MTU can be calculated. Average initial power outputs and MTUs for the three waste package designs considered in this study are documented in Table 3.

Table 3. Calculated Initial Canister Power Outputs and MTU/package

Number of PWR Assemblies per Package	Initial Power Output (kW/package)	MTU/Package
6	2.89	2.568
12	5.78	5.136
21	10.12	8.986

1.4 REPOSITORY LAYOUTS

It has been proposed that the emplacement drifts will be developed using a tunnel boring machine (TBM). This mining method would result in a circular cross-section for the emplacement drifts. Two options for the diameter of the circular openings were examined in this study, 7.0 m and 4.3 m.

The assumed emplacement mode for these analyses was *in drift*. In-drift emplacement is a concept that assumes that the waste will not be emplaced in boreholes, but instead will be placed horizontally on the emplacement drift floors. For the purposes of this analysis, it was assumed that the waste packages line up axially, and that the centerlines of the package arrays lie in the emplacement drift's vertical plane of symmetry (see Figure 1).

As shown in Figure 1, it was assumed that the floor of the emplacement drifts will undergo an additional mining sequence after the TBM to provide a level emplacement surface. The bottom of the waste package was assumed to be 0.152 m above the excavated floor to account for the separation caused by resting

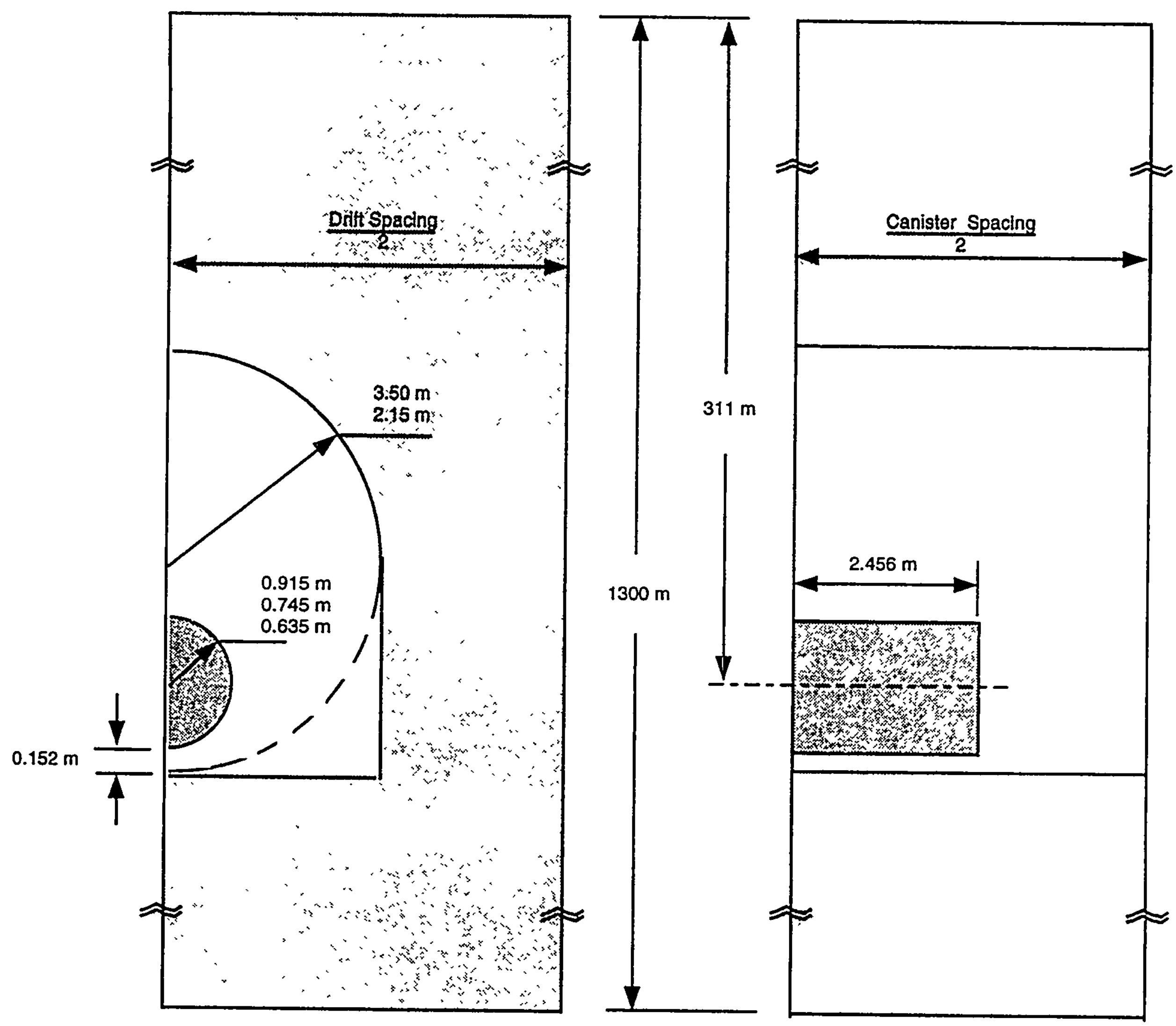

Figure 1. Cross-Sectional Views of Three-Dimensional COYOTE model

brackets anticipated to hold the waste packages. The depth of burial as measured to the centerlines of the waste packages was assumed to be 311 m, with the modeled region extending down to a depth of 1300 m.

Areal mass loading is a surrogate designation of repository thermal loading that is consistent with areal power density (APD). AML is often used to represent thermal loading because it remains constant through time, whereas APD decreases in time as a function of the waste decay characteristics. For this study, AMLs of 24, 36, 55, 83, and 111 MTU/acre were proposed for consideration.

In defining the actual combinations of drift and canister spacings (layouts) to be examined, two approaches were adopted: the *constant drift spacing* approach and the *cost minimization* approach.

1.4.1 Constant Drift Spacing Approach

The first approach--*constant drift spacing*--assumes that the drift spacing is constant as defined by a 30% extraction ratio (23.3 m for a 7-m diameter drift and 14.3 m for a 4.3-m diameter drift), and canister spacing is adjusted to meet AML goals. Tables 4 through 9 document the possible combinations of drift and canister spacings that were calculated using this approach to layout definition.

It was possible to narrow the 30 layouts documented in Tables 4 through 9 by applying the following two screening criteria:

1. Because it was assumed that the waste packages line up axially, if a calculated canister spacing is less than 4.912 m (the assumed length of a canister) this represents an unrealistic layout of packages,

2. If a calculated canister spacing is significantly greater than the drift spacing defined by the 30% extraction ratio limit, this represents an inefficient layout that is not considered viable.

Layouts that were not considered viable based on these two screening criteria are identified in Tables 4 through 9 by shaded boxes and were not analyzed in this investigation.

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

Assemblies per Package	Areal Mass Loading (MTU/acre)	Drift Spacing (m)	Canister Spacing (m)
21	111	23.3	14.06
21	83	23.3	18.80
21	55	23.3	28.38
21	36	23.3	43.35
21	24	23.3	65.03

Table 5. 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)
12	111	23.3	8.04
12	83	23.3	10.75
12	55	23.3	16.22
12	36	23.3	24.78
12	24	23.3	37.17

Table 6. Required Canister and Drift Spacings for a 7-m Diameter Drift and a 6 PWR Package

Assemblies per Package	Areal Mass Loading (MTU/acre)	Drift Spacing (m)	Canister Spacing (m)
6	111	23.3	4.02
6	83	23.3	5.37
6	55	23.3	8.11
6	36	23.3	12.39
6	24	23.3	18.58

Table 7. Required Canister and Drift Spacings 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)
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 8. Required Canister and Drift Spacings 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)
12	111	14.3	13.09
12	83	14.3	17.51
12	55	14.3	26.42
12	36	14.3	40.38
12	24	14.3	60.56

Table 9. Required Canister and Drift Spacings 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)
6	111	14.3	6.55
6	83	14.3	8.76
6	55	14.3	13.21
6	36	14.3	20.19
6	24	14.3	30.28

1.4.2 *Cost Minimization* Approach

A second approach to layout definition was also adopted for this study. Specifically, a *cost minimization* approach defines a layout by minimizing the number of mined emplacement drifts by setting the package-to-package spacing constant and adjusting drift spacing to meet AML goals. Specific canister spacings were provided by the M&O and are documented along with the corresponding drift spacings in Tables 10 through 15.

It is noted that for the *cost minimization* approach, layouts were not considered viable if the calculated drift spacing was less than that defined by a 30% extraction ratio limit (i.e., 23.3 m for a 7-m diameter drift and 14.3 m for a 4.3-m diameter drift). Layouts that were not considered viable are identified by shaded boxes in Tables 10 through 15 and were not analyzed in this study.

Table 10. 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)
21	111	27.30	12.0
21	83	36.51	12.0
21	55	55.10	12.0
21	36	84.18	12.0
21	24	126.27	12.0

Table 11. 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)
12	111	28.20	6.64
12	83	37.71	6.64
12	55	56.92	6.64
12	36	86.95	6.64
12	24	130.43	6.64

Table 12. 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)
6	111	14.10	6.64
6	83	18.85	6.64
6	55	28.46	6.64
6	36	43.48	6.64
6	24	65.22	6.64

Table 13. Required Drift Spacings for a 4.3-m Diameter Drift and a 21 PWR Package Assuming a Constant Canister Spacing of 16 m

Assemblies per Package	Areal Mass Loading (MTU/acre)	Drift Spacing (m)	Canister Spacing (m)
21	111	20.48	16.0
21	83	27.38	16.0
21	55	41.32	16.0
21	36	63.14	16.0
21	24	94.70	16.0

Table 14. Required Drift Spacings for a 4.3-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)
12	111	28.20	6.64
12	83	37.71	6.64
12	55	56.92	6.64
12	36	86.95	6.64
12	24	130.43	6.64

Table 15. Required Drift Spacings for a 4.3-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)
6	111	14.10	6.64
6	83	18.85	6.64
6	55	28.46	6.64
6	36	43.48	6.64
6	24	65.22	6.64

1.5 BOUNDARY AND INITIAL CONDITIONS

The modeled emplacement drifts are assumed to be one drift in an infinite series of simultaneously emplaced drifts. Using symmetry, the vertical boundaries shown in Figure 1 were modeled as adiabatic surfaces. At the ground surface, a constant temperature of 18°C was assumed. At the lower boundary, a constant temperature of 52.5°C was imposed. These values of constant temperature are consistent with values published in the RIB. The model was allowed to reach thermal equilibrium prior to the emplacement of waste.

2.0 RESULTS

When examining the results of any model, it is important to keep the assumptions and limitations of the model firmly in mind. For these analyses, the primary limitation is that dictated by the symmetry boundary formulation. This imposes the assumption of an infinite array of packages described by a single set of waste characteristics. Further, the geologic structure is constrained to a uniform layering. Quantification of the impacts of these assumptions has yet to be completed. However, for the purposes of this discussion, the infinite extent assumption does introduce significant uncertainty in the late time (greater than 500 year) results. For this reason, results obtained for times greater than 500 years will not be discussed, since they are likely overestimates of what would be predicted for a more realistic finite-extent repository model.

Taking into account the limitations of the model, results from the near-field analyses were only compared to thermal goals defined for three locations: the drift wall, one-meter radially into the drift wall, and the TSw2/TSw3 interface. Discussions of the predictions for these locations and how they compare to applicable thermal goals will be presented separately for analyses defined using the *constant drift spacing* and the *cost minimization* approaches.

2.1 RESULTS FOR *CONSTANT DRIFT SPACING* APPROACH

2.1.1 Drift Wall Temperature

There currently exists a thermal goal for the emplacement drift wall to limit peak temperatures to below 200°C . For the *constant drift spacing* approach, it was found that only one of the cases defined in Tables 4 through 9 exceeded this temperature limit. Producing a peak drift wall temperature of 207°C, this case assumed an AML of 111 MTU/acre, a 21 PWR waste package capacity, and a 7-m drift diameter. Closely approaching the 200°C goal, the case defined by a 111 MTU/acre AML, a 12 PWR package and a 7 m drift diameter produced a peak wall temperature of 199°C. Table 16 documents the peak drift wall temperatures predicted for all of the cases analyzed using the *constant drift spacing* approach.

Looking beyond the 200°C thermal goal, there has been recent interest in the possibility of creating a *below boiling repository.* Only three cases were found to produce drift wall temperatures below 97°C at all times: the 36 and 24 MTU/acre cases defined for a 6 PWR package and a 7 m drift and the 36 MTU/acre case defined by a 6 PWR package and a 4.3 m drift. The key to these below boiling cases can not be singularly linked to AML, but instead are likely due primarily to the smaller capacity waste package. To illustrate this, a 12 PWR waste package emplaced at 36 MTU/acre in a 7 m drift was found to produce peak wall temperatures of 103°C.

Table 16. Peak Drift Wall Temperatures Predicted for Cases Defined Using *Constant Drift Spacing* Approach

PWR Assemblies per Package	Drift Diameter (m)	Drift Spacing (m)	Canister Spacing (m)	Areal Mass Loading (MTU/acre)	Time to Peak (years)	Peak Drift Wall Temperature (C)
21	7.0	23.3	14.06	111	50	207
21	7.0	23.3	18.80	83	40	157
21	7.0	23.3	28.38	55	23	141
12	7.0	23.3	8.04	111	60	199
12	7.0	23.3	10.75	83	50	157
12	7.0	23.3	16.22	55	35	126
12	7.0	23.3	24.78	36	40	103
6	7.0	23.3	5.37	83	60	152
6	7.0	23.3	8.11	55	50	119
6	7.0	23.3	12.39	36	60	95
6	7.0	23.3	18.58	24	50	74
12	4.3	14.3	13.09	111	70	197
12	4.3	14.3	17.51	83	50	158
6	4.3	14.3	6.55	111	70	191
6	4.3	14.3	8.76	83	70	150
6	4.3	14.3	13.21	55	60	117
6	4.3	14.3	20.19	36	60	96

It is noted that because of the geometrically eccentric relationship between the waste package and the emplacement drift, drift wall temperatures are not uniform around the entire drift perimeter. The magnitudes of the temperature variations along the drift perimeter were investigated by comparing predictions for four points along the surface of the modeled emplacement drift (see Figure 2). It is noted that these four points are located in the vertical plane of symmetry that includes the waste package's centerpoint. Table 17 documents the ranges of peak temperature differences around the emplacement drift wall calculated for the various combinations of WP capacity and drift diameter defined in Tables 4 through 9.

In all cases, the hottest temperatures are predicted for that point on the drift floor that is directly below the center of the waste package (point 4). The coolest temperatures are predicted for the drift crown (point 1). The peak temperature differences shown in Table 17 were obtained by comparing histories for these two points.

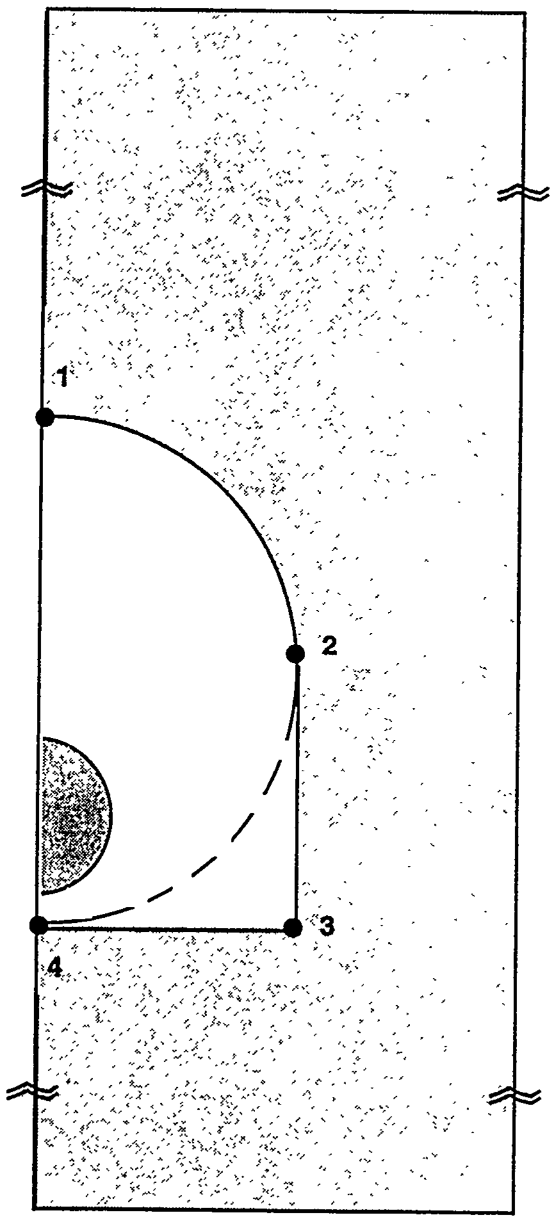

Figure 2. Location of Sampling Points on Emplacement Drift Wall

Examining the peak temperature differences reported in Table 17, several trends are observed. First, as the waste package capacity decreases, the magnitude of the temperature differences decreases. The key to this trend is the reduction in individual waste package power output corresponding to the decrease in waste package capacity. A second trend of decreasing drift temperature variations with decreased drift diameter is also evident. This trend can be related to the decrease in geometric eccentricity between the package and drift that accompanies the reduction in drift diameter.

Table 17. Ranges of Peak Temperature Differences for Analyses Defined in Tables 4 through 9

WP Capacity	Drift Diameter (m)	Range of Peak Temperature Differences Around Drift Perimeter (°C)
21	7	20 to 30
12	7	12 to 16
6	7	6 to 8
12	4.3	8 to 11
6	4.3	4 to 6

2.1.2 One-Meter Radial Temperatures

In addition to the drift wall temperature limit of 200°C, there also exists a thermal goal of keeping temperatures at locations one-meter radially into the rock wall to less than 200°C . By definition, if the drift wall temperature goal is met, the one-meter goal is met. Thus, the only case of concern is that defined for the 21 PWR package, 7-m diameter drift, and loading of 111 MTU/acre. The peak wall temperature directly below the waste package is predicted to be 207°C, thus it is possible that a location one meter directly below this point may approach or exceed the 200°C goal. However, this violation would be highly localized. Taking a point one meter radially outward from the sidewall of the drift as more representative, no violations of the 200°C temperature goal were identified for any of the cases analyzed from Tables 4 through 9.

2.1.3 TSw2/TSw3 Interface Temperatures

There currently exists a goal at the TSw2/TSw3 stratigraphic interface to limit temperatures to below 115°C. Examining the interface temperature histories for the cases defined in Tables 4 through 9, four cases were identified as exceeding the 115°C limit. Documented in Table 18, all of the cases that exceeded the TSw2/TSw3 thermal goal were defined with an AML of 111 MTU/acre. The times to the initial violations of the 115°C goal occur between 450 to 475 year years following waste emplacement, within the 500-year time frame of applicability for the near-field model.

Table 18. Summary of Cases Defined by *Constant Drift Spacing* Approach that Violated Thermal Goal for TSw2/TSw3 Interface

AML (MTU/acre)	Waste Package Capacity	Drift Diameter (m)	Canister Spacing (m)	Drift Spacing (m)	Time to Violation of TSw2/TSw3 Thermal Goal (years)
111	21 PWR	7.0	14.06	23.3	475
111	12 PWR	7.0	8.04	23.3	475
111	12 PWR	4.3	13.09	14.3	450
111	6 PWR	4.3	6.55	14.3	475

2.2 RESULTS FOR *COST MINIMIZATION* APPROACH

2.2.1 Drift Wall Temperatures

Four cases from those defined using the *cost minimization* approach were found to produce drift wall temperatures in excess of 200°C. Specifically, all of the 111 MTU/acre cases examined violated the proposed drift wall temperature goal. Peak drift wall temperatures produced for the 111 MTU/acre cases ranged from 203°C to 213°C. Documentation of the predicted peak drift wall temperatures obtained for the cases defined using the *cost minimization* approach can be found in Table 19.

With respect to a *below boiling repository,* only one case (24 MTU/acre, 6 PWR waste package, 7-m diameter drift) was found to produce drift wall temperatures that never exceeded 97°C. The reason for this is the basic premise of the *cost-minimization* approach: *maximize the number of canisters within a given drift to minimize the number of drifts that need to be constructed.* When this is done, the canister-to-canister interactions within a given emplacement drift increase, resulting in increased near-field temperatures that are not linked to repository or local AML.

As discussed in Section 2.1.1, predicted drift wall temperatures are not uniform around the entire perimeter of the emplacement drift. The maximum differences in drift wall temperatures (defined as the maximum difference in temperature predictions between the drift crown and the floor directly beneath the center of the waste package) were calculated for each of the 27 cases examined from Tables 10 through 15. Table 20 documents the ranges of maximum temperature differences calculated for given combinations of waste package capacity and drift diameter.

Table 19. Peak Drift Wall Temperatures Predicted for Cases Defined Using *Cost Minimization* Approach

PWR Assemblies per Package	Drift Diameter (m)	Drift Spacing (m)	Canister Spacing (m)	Areal Mass Loading (MTU/acre)	Time to Peak (years)	Peak Drift Wall Temperature (C)
21	7.0	27.30	12.0	111	50	210
21	7.0	36.51	12.0	83	22	181
21	7.0	55.10	12.0	55	19	167
21	7.0	84.18	12.0	36	13	163
21	7.0	126.27	12.0	24	13	163
12	7.0	28.20	6.64	111	50	204
12	7.0	37.71	6.64	83	27	173
12	7.0	56.92	6.64	55	21	159
12	7.0	86.95	6.64	36	15	154
12	7.0	130.43	6.64	24	15	154
6	7.0	28.46	6.64	55	45	122
6	7.0	43.48	6.64	36	35	104
6	7.0	65.22	6.64	24	18	93
21	4.3	20.48	16.0	111	45	213
21	4.3	27.38	16.0	83	21	182
21	4.3	41.32	16.0	55	19	167
21	4.3	63.14	16.0	36	11	160
21	4.3	94.70	16.0	24	10	159
12	4.3	28.20	6.64	111	50	213
12	4.3	37.71	6.64	83	22	188
12	4.3	56.92	6.64	55	18	176
12	4.3	86.95	6.64	36	13	173
12	4.3	130.43	6.64	24	13	173
6	4.3	18.85	6.64	83	60	153
6	4.3	28.46	6.64	55	35	128
6	4.3	43.38	6.64	36	28	111
6	4.3	65.22	6.64	24	14	103

As with the cases defined for the constant drift spacing approach, peak drift wall temperature differences for the *cost minimization* approach display the trends of decreasing magnitudes with decreasing waste package capacity and decreasing drift diameter. Because the *cost minimization* approach is predicated on constant canister spacing, a third trend of increased peak temperature differences with decreasing AML is observed that was not seen for the cases discussed in Section 2.1.1. Thus, unlike the values in Table 17, the range of values presented in Table 20 can be interpreted with a direct correlation to AML. Specifically, the highest value of peak temperature difference corresponds in every case to an AML of 24 MTU/acre and the smallest value of peak temperature difference corresponds to the highest AML evaluated for the given combination of waste package capacity and drift diameter (see Tables 10 through 15 for the range of AML values analyzed).

Table 20. Ranges of Peak Temperature Differences for Analyses Defined in Tables 10 through 15

WP Capacity	Drift Diameter (m)	Range of Peak Temperature Differences Around Drift Perimeter (°C)
21	7	21 to 36
12	7	14 to 24
6	7	8 to 12
21	4.3	18 to 30
12	4.3	12 to 19
6	4.3	5 to 10

2.2.2 One-Meter Radial Temperatures

For all of the Table 10 through 15 cases examined, no violations of the 200°C temperature goal were identified for a location defined one meter radially into the sidewall of the drift. It is likely, however, that a small region of rock one meter below the centerpoint of the waste package does achieve peak temperatures of 200°C for all of the 111 MTU/acre cases defined in Tables 10 through 15. The significance of localized regions exceeding 200°C is unknown.

2.2.3 TSw2/TSw3 Interface Temperatures

Examining the TSw2/TSw3 interface temperature histories, all of the 111 MTU/acre cases defined using the *cost minimization* approach to repository layout violated the 115°C thermal goal (see Table 21). These violations occurred between 450 and 475 years following emplacement, within the assumed 500-year time frame of applicability for the model.

Table 21. Summary of Cases Defined by *Cost Minimization* Approach that Violated Thermal Goal for TSw2/TSw3 Interface

AML (MTU/acre)	Waste Package Capacity	Drift Diameter (m)	Canister Spacing (m)	Drift Spacing (m)	Time to Violation of TSw2/TSw3 Thermal Goal (years)
111	21 PWR	7.0	12.0	27.30	475
111	12 PWR	7.0	6.64	28.20	475
111	21 PWR	4.3	16.0	20.48	475
111	12 PWR	4.3	6.64	28.20	450

3.0 DISCUSSION

In general, layouts generated using the *cost minimization* approach produce near-field temperatures that are greater than those predicted for *equivalent* cases defined using the *constant drift spacing* technique. Temperature predictions for the two methods at equivalent locations show the impact of increased canister-to-canister interactions inherent in the *cost minimization* approach to layout definition. Because of the large drift spacings assumed by many of the *cost minimization* layouts, the predicted thermal profiles are marked by depressions between drifts. The impacts of these depressions is currently unknown. It may be that these regions would become preferential drainage zones for any condensate; however, thermal-mechanical-chemical processes must be evaluated prior to making this claim.

Of the eight cases analyzed at 111 MTU/acre, 5 produced drift wall temperatures that exceed the current thermal goal of 200°C. Since the remaining three 111 MTU/acre cases were within 10°C of the drift wall thermal goal, it is reasonable to conclude that 111 MTU/acre (approximately 99 kW/acre) represents a loading that is pushing the upper bound of what is currently considered acceptable. This conclusion is consistent with previous analyses (e.g., Hertel and Ryder, 1991) that indicated a local thermal loading of 100 kW/acre represents an approximate upper limit for the potential repository.

4.0 REFERENCES

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Appendix F
Far-Field Calculations

This appendix outlines the calculations that were done by LLNL in support of the Thermal Loading Study. This appendix was written by LLNL and provides information on the assumptions used, the calculation methodology, and a more extensive set of results. The majority of the inputs used in the V-TOUGH calculations are defined in this report in Appendix D.

Appendix F

I. Introduction

This hydrothermal modeling study was carried out in support of the ongoing thermal loading systems study. The models used in this study are similar to those used in preceding studies.[1-5]The initial stage of this work is being included as an Appendix to the 1993 version of the thermal loading systems study report. This Appendix includes a comprehensive set of figures describing the simulated thermo-hydrological behavior of the various thermal loading scenarios and cases considering a wide range of thermo-hydrological properties. However, at this stage of the reporting we have only included a preliminary discussion of the analysis. Subsequent reports[6,7] will discuss the analysis in more detail than is possible at this time.

As in past work,[2-5] we use the term Areal Mass Loading (AML) as a synonym for thermal loading conditions. Therefore, a high thermal loading case is referred to as a high-AML case and a low thermal loading case is referred to as a low-AML case. For a given burnup [expressed as megawatt-days per metric ton of initial heavy metal (MWd/MTU)], the most useful macroscopic thermal loading parameter in analyzing long-term thermal performance is the AML [expressed in metric tons of uranium per acre (MTU/acre)]. Generally, early temperature performance (including the peak temperature, T_{peak}) is sensitive to the age of spent nuclear fuel (SNF), while the duration of the boiling period, t_{bp}, and post-boiling-period thermal performance are determined by the AML and are insensitive to SNF age. Consequently, we prefer using AML to identify the thermal loading conditions rather than the Areal Power Density [(APD) expressed in kW/acre].

II. Discussion of Numerical Models, Physical Data, and Assumptions

II.A V-TOUGH Hydrothermal Flow Code

All hydrothermal calculations in this study were carried out using the V-TOUGH (vectorized transport of unsaturated groundwater and heat) code.[8] V-TOUGH is Lawrence Livermore National Laboratory's enhanced version of the TOUGH code, which was developed at Lawrence Berkeley Laboratory by Pruess.[9] V-TOUGH is a multidimensional numerical simulator capable of modeling the coupled transport of water, vapor, air, and heat in fractured porous media. Our models include boiling and condensation effects, the convection of latent and sensible heat, and thermal radiation.

II.B Equivalent Continuum Model

Because of the impracticality of discretely accounting for all of the fractures at Yucca Mountain, it was necessary to account for fractures using the equivalent continuum model (ECM). The assumption of capillary pressure and thermal equilibrium between fractures and matrix allows the fracture and matrix properties to be pore-volume-averaged into an equivalent medium. The bulk porosity, ϕ_b, bulk saturation, S_b, and bulk hydraulic conductivity, K_b, of the equivalent medium are given by:

$$\phi_b = \phi_f + (1 - \phi_f)\phi_m \tag{1}$$

$$S_b = \frac{S_f\phi_f + S_m(1 - \phi_f)\phi_m}{\phi_f + (1 - \phi_f)\phi_m} \tag{2}$$

$$K_b = K_m(1 - \phi_f) + K_f\phi_f \tag{3}$$

where ϕ_m, S_m, ϕ_f, and S_f are the porosity and saturation of the matrix and fractures, respectively, and K_m and K sub roman f are the hydraulic conductivities of the matrix and fractures. Because of the small K_m in the unsaturated zone (UZ), K_b is almost completely dominated by K_f and ϕ_f for most fracture spacings and permeabilities.

II.C Thermo-Hydrological Properties

All major hydrostratigraphic units in the UZ at Yucca Mountain are included in the models.[10,11] The hydrostratigraphic profile employed here has been used in previous modeling studies.[2,12] The wet and dry thermal conductivity, K_{th}, data were obtained from the RIB.[13] In this study we use the RIB Version 4 K_{th} values. We assume the steady-state liquid saturation profile obtained for a net recharge flux of 0 mm/yr, which yields a repository horizon saturation of 68%.[12]

For the primary suite of calculations, a uniform fracture permeability is assumed. Because the bulk permeability, k_b is dominated by the fracture permeability, this yields a k_b distribution that is nearly uniform. The reference case assumes a bulk permeability, k_b, of 2.8 x 10^{-13}m^2 (280 millidarcy), which is equivalent to three 100-µm fractures per meter. The sensitivity of boiling and dry-out performance to k_b was examined by considering the following values of k_b: 1 millidarcy (three 15-µm fractures per meter), 10 millidarcy (three 33-µm fractures per meter), 84 millidarcy (three 68-µm fractures per meter), 1 darcy (three 153-µm fractures per meter), 10 darcy (three 330-µm fractures per meter), 40 darcy (one 781-µm fracture per meter), and 84 darcy (one 1000-µm fracture per meter).

For all of the cases which are labeled as having a bulk permeability, k_b, of 280 millidarcy, k_b is 280, 320, 280, 280, 280, 310, 280, and 280 millidarcy in the TCw, PTn, TSw1, TSw2, TSw3, CHnv, CHnz, and PPw, respectively. The value of k_b in the PTn and CHnv is somewhat larger than in the other units because the matrix permeability, k_m is relatively large (reference Figure 3). For large k_b (greater than 1 darcy), the contribution of k_m is relatively small, even in the PTn and CHnv.

Regarding the presumption than the PTn and CHn units are relatively unfractured and therefore have a very small k_b the jury is still out. Chesnut has analyzed the C-Well data and found that the mode of the k_b distribution in the CHn is between 200 and 300 millidarcy. It is not unreasonable to expect that the PTn would have a similar k_b as the CHn. It should be stressed that our current knowledge of the k_b distribution is limited at best and that it is crucial that we understand the sensitivity of thermo-hydrological performance over a wide range of conditions.

Consequently, we have been considering a wide range of k_b and cases of layered k_b. For example, we have considered cases where k_b in the PTn and CHn is substantially less than in the TSw units.

II.D Initial and Boundary Conditions

The vertical temperature, T, distribution in the models is initialized to correspond to the nominal geothermal gradient in the region. The atmosphere at the ground surface is represented by a constant-property boundary, with T and gas-phase pressure, p_g, fixed at 13°C and 0.86 atm, respectively. The relative humidity at the ground surface is also fixed so that it is in thermodynamic equilibrium with the initial saturation conditions at the top of the TCw unit. Therefore, under initial (ambient) saturation and temperature conditions there is no mass flux of water vapor between the atmosphere and upper TCw.

In previous work, [2] it was assumed that because of the large fracture permeability, buoyant convective mixing in the saturated zone (SZ) results in it acting as a heat sink. The large k_b and storativity of the SZ were also assumed to result in the water table being at a fixed depth. For the drift-scale calculations reported here, we also assume that the water table has a fixed depth (z = 568.1 m) and a constant temperature (31°C). The constant-temperature water table assumption causes the water table to act as a heat sink. Because this model does not explicitly model hydrothermal flow in the SZ, it is called the "UZ" model. In comparing the UZ model with the UZ-SZ model, which is described below, we found that, for the first 1000 yr, repository temperatures are insensitive to the treatment of heat flow at the water table.[3,4] Because the primary use of the drift-scale model is to examine sub-repository-scale, thermo-hydrological behavior during the first 1000 yr, the constant-temperature water table assumption does not significantly affect the interpretation of our results. The initial temperature and saturation at the repository horizon in the UZ model are 23.3°C and 68%, respectively.

The manner in which the vertical liquid saturation profiles were arrived at is described in other reports (Buscheck et al. 1991; Buscheck and Nitao, 1992; Buscheck and Nitao, 1993). Buscheck and others (1991) modeled infiltration in Yucca Mountain using a one-dimensional steady-state ECM. On the basis of that model, the observed range in saturation at the repository horizon corresponds to a range in recharge flux of approximately -0.005 to 0.05 mm/yr. The vertical liquid saturation distribution corresponds to zero recharge flux, which corresponds to gravity-capillary equilibrium. This profile results in a liquid saturation of 68 % at the repository horizon. Because of the relatively small capillarity of the high-k_m PTn and CHnv units (where k_m is the matrix permeability), the high capillary suction potential of their neighboring units causes them to be nearly drained to near-residual saturation (resulting in the appearance of "saturation anomalies"). Buscheck and Nitao (1992, 1993b) also considered recharge fluxes of 0.045 and 0.132 mm/yr, resulting in saturations at the repository horizon of 85 and 95 %, respectively. Because of the relatively small k_m of the TSw2 and TSw2, the saturations profile within those units is quite sensitive to variations in recharge flux. Because of its large k_m the CHnv can sustain the steady-state flux at small saturations. The saturation profiles in the CHnz and PPw are less sensitive to variations in the steady-state recharge flux.

Saturation values obtained form the Reference Information Base (RIB) have been compared with the vertical liquid saturation profile (Buscheck et al, 1991). While zero recharge flux results in a liquid saturation of about 10 percent for the PTn and CHnv, the RIB reports mean saturation values of 61 to 91 percent, respectively. Obviously, significant recharge fluxes are able to reach the high-k_m units without affecting the saturation of the neighboring low-k_m units. Non-equilibrium fracture flow through the TCw, TSw1, TSw2, and TSw3, is a likely explanation for the inconsistency between the measured saturation data and the saturation profile predicted by the one-dimensional, steady-state ECM. The discrepancy between the apparent near-zero recharge flux to the low-k_m units and the apparent large flux to the high-k_m units can also be partially resolved by mechanisms that remove water from the vadose zone. These mechanisms may include vapor flow (Thorstenson et al. 1989) as well as lateral liquid flow along high-k_m units such as the PTn and CHnv. The capacity of these mechanisms may be considerably in excess of what is currently required to provide a net zero flux at the repository horizon.

We conducted our repository-scale calculations with an unsaturated zone/saturated zone (UZ-SZ) model that explicitly includes hydrothermal flow in the upper 1000 m of the SZ. Conductive and convective heat flow, including buoyancy flow, are modeled in the SZ. Because the RIB[13] lacks thermal property and hydrologic data below the PPw unit (the lower-most hydrostratigraphic unit in our UZ model), we assumed that the PPw was applicable to the upper 1000 m of the SZ (down to the lower boundary of the UZ-SZ model). The lower boundary of the UZ-SZ model has a constant temperature of 53.5°C and a fixed pressure corresponding to the hydrostatic pressure and temperature profile of the upper 1000 m of the SZ. The initial temperature and saturation at the repository horizon in the UZ-SZ model are 23.5°C and 67.7%, respectively.

II.E Repository-Scale Models

In conducting our modeling studies, we have represented the repository at several different scales. The repository-scale models assume radial symmetry about the center of the repository and represent the repository as a disk-shaped heat source with a uniformly distributed thermal load over the heated area of the repository. Because of their radial symmetry, these models assume a really uniform thermo-hydrological properties. Layered heterogeneity (i.e., property variability that occurs in the vertical direction) can be represented by these models. We modeled repository areas of 570, 744, 1139, 1755, and 2598 acres. For 63,000 MTU of SNF, these repository areas correspond to Areal Mass Loadings (AMLs) of 110.5, 83.4, 55.3, 35.9, and 24.4 MTU/acre. The repository-scale models are well suited for representing mountain-scale behavior, such as mountain-scale, buoyant, gas-phase convection. These models employ a relatively fine gridblock spacing at the outer perimeter of the repository in order to more accurately account for the effect of edge-cooling. We assume a Youngest Fuel First (YFF) SNF receipt scenario with a 10-yr cutoff for the youngest fuel. This waste receipt scenario is referred to as YFF(10). We account for, in yearly increments, the emplaced inventory of boiling water reactor (BWR) WPs, containing 40 assemblies WP, and pressurized water reactor (PWR) WPs, containing 21 assemblies per WP. The waste receipt schedule was determined by King and others. For the 110.5-MTU/acre case, we considered the following values of k_b: 1, 10, 84, and 280 millidarcy; and 1, 10, 40, and 84 darcy. For the 24.4-, 35.9-, 55.3-, and 83.4-MTU/acre cases, the following values of k_b were considered: 280 millidarcy, 1, 10, 40, and 84 darcy.

II.F Sub-Repository-Scale Models

Because it areally averages the thermal load, the repository-scale model cannot represent differences in temperature and saturation behavior within (1) the pillars (i.e., the rock separating neighboring emplacement drifts), (2) the emplacement drifts, or (3) the WPs themselves. The drift-scale model is a two-dimensional cross-sectional model that explicitly represents the details of the WPs and emplacement drifts in the plane orthogonal to the drift axes. This model is useful in representing details of thermo-hydrological behavior at the drift (or sub-repository) scale. We are interested in the detailed temperature distribution within and in the immediate vicinity of the emplacement drifts. We are also interested in how sub-repository-scale, buoyant, gas-phase convection (which is driven by temperature differences between the drifts and pillars) affects vapor and condensate flow and thermal performance. To take advantage of symmetry, the drift-scale model assumes an infinite repository with uniformly spaced emplacement drifts. The assumption of an infinite repository area is applicable to the interior of the repository, which is not affected by cooling at the edge. This region includes most of the repository area during at least the first 1000 yr.

We modeled several emplacement scenarios with the drift-scale model. For the YFF(10) emplacement scenario with 4533 21-PWR WPs and 3116 40-BWR WPs, the center-to-center spacing between emplacement drifts is 99 m. For the YFF(10) emplacement scenario with 7932 12-PWR WPs and 5936 21-BWR WPs, the center-to-center drift spacing is 56.58 m. The drift-scale model represents a symmetry element from the symmetry plane down the center of the WP to the symmetry plane in the pillar between neighboring drifts. The thermal load is axially averaged along the axis of the drift. The WP has a cross section of 1.6x1.6 m and is located in the center of an emplacement drift that is 4.8 m height by 6.0 m wide. This drift cross section is reasonably representative of a circular drift with a 7-m diameter. The drifts are assumed to remain open; therefore, heat flow from the WP surface to the drift wall occurs as thermal radiation, convection, and conduction. The drift scale model can represent heterogeneity that occurs at the scale of the drifts.

Heterogeneity that occurs at a larger scale is represented by a third model, which we call the cross-sectional uniform heat flow (CSUHF) mode. Like the drift-scale model, the CSUHF model assumes an infinite repository, thereby enabling it to take advantage of symmetry. The CSUHF can represent the detailed thermo-hydrological behavior that results from spatially varying thermal loading conditions. For example, the CSUHF is useful in representing relatively large unheated portions of the repository, such as the area adjacent to the main access drift. We modeled a scenario in which the main access drift is 8 m wide and is located 40 m from the nearest heated region of the repository.

III. Discussion of Analysis for the Repository-Scale Model

III.A Vertical Temperature and Saturation Profiles

With the use of the repository-scale model, we modeled 28 cases, including 5 AMLs, and 8 different values of bulk permeability, k_b. All cases were modeled for a minimum of 100,000 yr. Rather than presenting the vertical temperature and saturation profiles for all 28 cases, a detailed examination of the profiles is done for the suite of 280-millidarcy cases. In previous work,[4,5] we found that the threshold bulk permeability where mountain-scale, buoyant, gas-phase convection begins to dominate moisture movement is about 1 darcy. Below this threshold, the effects of boiling tend to dominate the effects of buoyant gas-phase convection. We did not choose to focus on the 280-millidarcy suite of cases because 280 millidarcy is considered to be the most likely value of k_b; rather, the impact of boiling behavior on moisture movement can be more readily discerned if it is not competing with the influence of mountain-scale, buoyant, gas-phase convection. A detailed examination of the impact of that convection on thermo-hydrological performance is covered in following sections.

The vertical temperature and saturation profiles are given for three different radial distances from the repository center. The first value of r (r = 0 m) corresponds to the center of the repository. The second value of r corresponds to the radial position that encloses 50% of the repository. This position is representative of "average" conditions within the repository because half of the WPs are inside of this radial position. The third value of r corresponds to the radial position that encloses 95% of the repository. The third radial position is a good representation of conditions at the repository edge (or perimeter) because only 5% of the WPs lie outside of this position. In this report, we refer to the radial location within the repository with respect to percentage of the repository area enclosed by that radial location. Therefore, a radial position of 0% corresponds to the repository center, while a radial position of 100% corresponds to the outer perimeter.

Figures 1 through 4 show the vertical temperature and saturation profiles for the 110.5-MTU/acre case at various times for the first 100,000 yr after emplacement. Notice that the thermal and dry-out performance is very similar for the 0 and 50% radial positions of the repository (Figures 1a-c and 3a-c) and that edge cooling affects at least the outer 5% of the repository. The flattening of the temperature profile at the nominal boiling temperature, T_b, (≈96°C) corresponds to two-phase flow effects, which result from condensate drainage. The effects are described in more detail in other reports.[2-5] Dry-out due to boiling results in a 200- to 300-m-thick dry-out zone for the inner 50% of the repository. Edge cooling substantially reduces the vertical extent of dry-out. The outer edge of the repository drops below boiling at about 2000 yr (Figure 1d), while the center remains above T_b for more than 7000 yr (Figure 2a). Temperatures for the entire repository have declined to below T_b within 10,000 yr; however, a large zone of sub-ambient saturations persists long after that (Figures 4a-c). The edge of the repository re-wets back to ambient saturation within 50,000 yr, while the center remains below ambient saturation for more than 100,000 yr (Figures 4d-f).

Figures 5 through 8 show the vertical temperature and saturation profiles for the 83.4-MTU/acre case. Notice that the thermal and dry-out performance is similar to that of the 110.5-MTU/acre case, except that the vertical and temporal extent of boiling and dry-out effects is less. The dry-out zone persists for more than 50,000 yr at the center of the repository and for about 20,000 yr at the repository edge.

Figures 9 through 12 show the vertical temperature and saturation profiles for the 55.3-MTU/acre case. Notice that the thermal and dry-out performance is similar to the 83.4-MTU/acre case, except that the vertical and temporal extent of boiling and dry-out effects are substantially less. For the 55.3-MTU acre case, temperatures as the outer 5% of the repository never exceed T_b. Consequently, the outer repository edge undergoes very little dry-out. The dry-out zone persists for about 30,000 yr at the center of the repository.

Figures 13 through 16 show the vertical temperature profiles for the 35.9- and 24.4-MTU/acre cases. Notice that the repository-scale model does not predict temperatures to exceed T_b indicating that averaged temperature conditions throughout the repository remain below T_b. However, as will be discussed later, local temperatures around the emplacement drift may be well above T_b for WPs containing a large number of SNF assemblies. Because of the absence of boiling conditions in the repository-scale model, and because 280 millidarcy is below the threshold where mountain-scale, buoyant, gas-phase convection results in significant moisture movement, the 24.4- and 35.9-MTU/acre cases show a minor change in saturation relative to ambient conditions. Therefore, we did not provide the vertical saturation profiles for these two cases.

Notice that temperatures at the 0% and 50% radial positions are similar (Figures 13-16). This similarity is due to the relatively large size of the repository (1755 and 2598 acres), which results in edge cooling effects not penetrating to the inner half of the repository. For the 110.5-MTU/acre case, the effects of edge cooling penetrate to the inner half of the repository within 1000 yr (Figure 1c). For the 83.4- and 55.5 MTU/acre cases, the effects of edge cooling penetrate to the inner half of the repository within 2000 yr (Figures 5d and 9d).

III.B Temperature and Saturation Histories in the Repository

As in the previous section, we perform a detailed examination of the suite of 280-millidarcy cases. The temperature and saturation histories at various locations in the repository are shown for the 110.5-, 83.4-, and 55.3-MTU/acre cases (Figures 17-19). Peak temperatures, T_{peak}, occur within the first 120 yr. Notice that edge cooling effects do not penetrate to the inner 75% of the repository in the first 120 yr; consequently, T_{peak} is about the same for the inner 75% of the repository (Figure 17a). For example, T_{peak} is 187.2°C at the repository center and 186.0°C at the 75% radial position. Edge cooling effects reduce T_{peak} for the outer 25% of the repository relative to the center. Notice that edge cooling effects penetrate into the center of the repository, resulting in a decrease in the duration of boiling, t_{bp}, even for the 12.5% radial position relative to the 0% radial position. At the outer edge of the repository, T_{peak} is only 112.4°C.

Liquid saturation in the repository remains below ambient conditions long after boiling conditions have ceased for most of the repository. The inner 75% of the repository remains below ambient saturation for at least 100,000 yr (Figure 17b). The inner 99% of the repository remains below ambient saturation for at least 10,000 yr, while the outer 1% re-wets nearly back to ambient saturation within 5000 yr (Figure 17d).

The temperature and liquid saturation histories for the 83.4-MTU/acre case are similar to those of the 110.5-MTU/acre case, except that the duration of boiling and sub-ambient liquid saturation conditions is less (Figure 18). The inner 75% of the repository shows a similar T_{peak} (146°C). At the outer edge, T_{peak} is only 97.8°C. Most of the repository re-wets back to ambient saturation within 100,000 yr. Edge cooling effects cause the outer 1% of the repository to never undergo significant dry-out (Figure 18d).

The duration of boiling and sub-ambient liquid saturation conditions are substantially less for the 55.5-MTU/acre case than for the 83.4-MTU/acre case. Temperatures in the outer 3% of the repository never exceed T_b, and T_{peak} at the outer edge of the repository is only 74.7°C. Liquid saturations for the inner half of the repository re-wet back to ambient conditions in about 30,000 yr. Between the 50% and 75% radial positions, liquid saturations re-wet back to ambient conditions in about 20,000 yr. At the 84% radial position, re-wetting takes about 10,000 yr. At the 90% radial position, re-wetting takes about 2000 yr. At the 94% radial position, re-wetting takes about 700 yr. At the 97% radial position, re-wetting takes about 150 yr, and dry-out never occurs for the outer 3% of the repository.

For the 35.9- and 24.4-MTU/acre cases, T_{peak} is 85.7 and 65.7°C, respectively, for the inner 75% of the repository. Edge cooling results in T_{peak} at the other repository edge being 58.2 and 47.8°C for the 35.9- and 24.4-MTU/acre cases, respectively.

Figure 22 shows the duration of the boiling period, t_{bp}, as a function of radial position for the 110.5-, 83.4-, and 55.5-MTU/acre cases and all of the values of bulk permeability, k_b, considered. The influence of edge cooling is very evident. Notice the effect that increasing k_b has on decreasing t_{bp}. Mountain-scale, buoyant, gas-phase convection begins to significantly cool repository temperatures for $k_b >> 1$ darcy. For $k_b \leq 1$ darcy, t_{bp} is insensitive to k_b. Notice that the sensitivity of t_{bp} to k_b increases with decreasing AML.

We also calculated the area-weighted boiling period duration, $\bar{t}_{bp}$ for the 110.5, 83.4-, and 55.5-MTU/acre cases (Figure 23). For the 110.5-MTU/acre case, $\bar{t}_{bp}$ is 5466, 5515, 5446, 5286, 4990, 3891, and 3227 yr for the 1-, 10-, and 280-millidarcy cases and the 1-, 10-, 40-, and 84-darcy cases, respectively. For the 83.4-MTU/acre case, $\bar{t}_{bp}$ is 3391, 3108, 2402, 2056, and 1592 yr for the 280-millidarcy case and the 1-, 10-, 40-, and 84-darcy cases, respectively. For the 55.3-MTU/acre case, $\bar{t}_{bp}$ is 1424, 1363, 928, 375, and 164 yr for the 280-millidarcy case and the 1-, 10-, 40-, and 84-darcy cases, respectively. The cooling effect that mountain-scale, buoyant, gas-phase convection has on $\bar{t}_{bp}$ increases with decreasing AML. Consequently, the 110.5-MTU/acre case is least sensitive to this effect. For the 110.5-MTU/acre, 1-darcy case, this cooling effect reduces $\bar{t}_{bp}$ by 2.9% relative to the 280-millidarcy case, while for the 83.4- and 55.3-MTU/acre cases, $\bar{t}_{bp}$ is reduced by 8.3 and 4.3%, respectively. For the 83.4-MTU/acre, 10-darcy case, $\bar{t}_{bp}$ is reduced by 17.5% relative to the 280-millidarcy case, while for the 83.4- and 55.3-MTU/acre cases, the reduction is 29.2 and 34.9%, respectively. For the 110.5-MTU/acre, 40-darcy case, $\bar{t}_{bp}$ is reduced by 28.6% relative to the 280-millidarcy case, while for the 83.4- and 55.3-MTU/acre cases, the reduction is 39.4 and 73.7%, respectively. For the 110.5-MTU/acre, 84-darcy case, $\bar{t}_{bp}$ is reduced by 40.7% relative to the 280-millidarcy case, while for the 83.4- and 55.3-MTU/acre cases, the reduction is 53.1 and 88.5%, respectively.

III.C Mountain-Scale Moisture Redistribution

We compared the net buildup of liquid water above the repository, ΔV_l, for all of the thermal loads and k_b cases (Figures 24 and 25). For the high-k_b, high-AML cases (10, 40, and 84 darcy; 83.4 and 110.5 MTU/acre), there is a very early peak in ΔV_l that occurs at about 500 to 800 yr (Figures 24c-e, 25d and e), coinciding with the maximum vertical extent of boiling conditions. After the initial peak, ΔV_l quickly declines, with a trough occurring at around 3000 yr, coinciding with the maximum vertical extent of dry-out. For the 110.5-MTU/acre case, ΔV_l declines to nearly zero (Figures 24c-e). For the 83.4-MTU/acre case, the trough is less pronounced as ΔV_l stays well above zero. For the 55.3-MTU/acre case, there is no trough, and the increase in ΔV_l is uninterrupted. After the trough occurs in the 83.4- and 110.5-MTU/acre cases, the increase in ΔV_l resumes until a second peak in ΔV_l occurs at around 20,000 to 30,000 yr. For 10, 40, and 84 darcy, the 55.3, 83.4, and 110.5-MTU/acre cases undergo the same initial rate of increase in ΔV_l until 500 yr, when the 110.5-MTU/acre case reaches its initial peak and 800 yr, when the 83.4-MTU/acre case reaches its initial peak (Figures 24c-e). This initial peak is related to the interaction of the heat-pipe effect and mountain-scale, buoyant, gas-phase convection.

It is important to note that ΔV_l is always greater in the 55.3- and 83.4-MTU/acre cases than in 110-MTU/acre case. We plot the maximum ΔV_l (called ΔV_l^{max}) for all of the AMLs and values of k_b considered (Figure 26). For the 55.3-MTU/acre case, ΔV_l^{max} is 1.5, 1.3, 2.4, 2.6, and 2.5 times greater than in the 110.5-MTU/acre case for 280 millidarcy, 1, 10, 40, and 84 darcy, respectively. For the 83.4-MTU/acre case, ΔV_l^{max} is 1.5, 1.7, 1.4, 1.4, and 1.5 times greater than in the 110.5-MTU/acre case for 280 millidarcy, 1, 10, 40, and 84 darcy, respectively. To the first order, for the above-boiling case, ΔV_l^{max} is proportional to the repository area. Therefore, ΔV_l^{max} decreases with increasing AML. For the 110.5-MTU/acre case and $k_b \leq$ 10 millidarcy, ΔV_l is always negative (i.e., there is a net decrease in liquid saturation). Consequently, if the large-scale connected k_b is small enough, mountain-scale, buoyant, gas-phase convection does not result in a liquid water buildup above the repository.

For 280 millidarcy, ΔV_l^{max} for the 24.4- and 35.9-MTU/acre cases is 26 and 34% of ΔV_l^{max} for the 110.5-MTU/acre case; however, ΔV_l^{max} for the latter case is relatively small to begin with. For 10 darcy, ΔV_l^{max} for the 24.4- and 35.9-MTU/acre cases is 50 and 105% of ΔV_l^{max} for the 110.5-MTU/acre case. For 40 darcy, ΔV_l^{max} for the 24.4- and 35.9-MTU/acre cases or is 1.7 and 2.9 times greater than in the 110.5-MTU/acre case. For 84 darcy, ΔV_l^{max} for the 24.4- and 35.9-MTU/acre cases is 2.8 and 3.4 times greater than in the 110.5-MTU/acre case. Therefore, for low k_b, the sub-boiling cases result in less net liquid water buildup than in the 110.5-MTU/acre case. However, for high k_b, the sub-boiling cases result in substantially greater ΔV_l than in the 110.5-MTU/acre case. To the first order, for high k_b, ΔV_l^{max} is proportional to the repository area. Therefore, the total amount of liquid water buildup above the repository decreases with increasing AML.

IV. Discussion of Analysis for the Sub-Repository-Scale Models

IV.A Temperature History in the Vicinity of the Emplacement Drift

The preceding analysis is representative of averaged thermo-hydrological behavior in the repository. In order to investigate the details of thermo-hydrological behavior in the vicinity of WPs, it is necessary to use sub-repository-scale models. We start with the drift-scale model. Figure 27 shows the temperature history on the waste package (WP) surface and in the rock 0.75 m above the center of the drift ceiling for an AML of 24.4 MTU/acre and two different WP scenarios. The first scenario assumes a repository with 4533 21-PWR WPs and 3116 40-BWR WPs, with a 99-m spacing between emplacement drifts. The second scenario assumes a repository with 7932 21-PWR WPs and 5936 40-BWR WPs, with a 56.58-m spacing between emplacement drifts. The heat output from an individual WP is ramped up in the same fashion as in the repository-scale model rather than instantaneously turning on the full-power equivalent of an individual WP. We represent the heat output from the WP in the drift-scale model by using the heating curve from the repository-scale model and multiplying by N^{-1}, where N is the number of WPs. Therefore the heat output from the WP in our drift-scale model is representative of the composite heating of all of the WPs as they are brought into the repository and the predicted temperature buildup is somewhat more gradual than that of an actual WP.

For the 21-PWR/40-BWR scenario, the local temperatures around the emplacement drift are substantially higher than in the repository-scale model (Figure 27a). The rock immediately above the emplacement drift is above the nominal boiling point, T_b, for 131 yr with a peak temperature of 118°C. The peak WP surface temperature is 144°C. The repository-scale model predicted a peak temperature of 65.7°C. For the 12-PWR/21-BWR scenario, the local temperatures around the emplacement drift are substantially less than in the 21-PWR/40-BWR scenario, but greater than predicted by the repository-scale model (Figure 27b). The rock immediately above the emplacement drift reaches a peak temperature of 84.8°C, while the peak WP surface temperature is 103.3°C.

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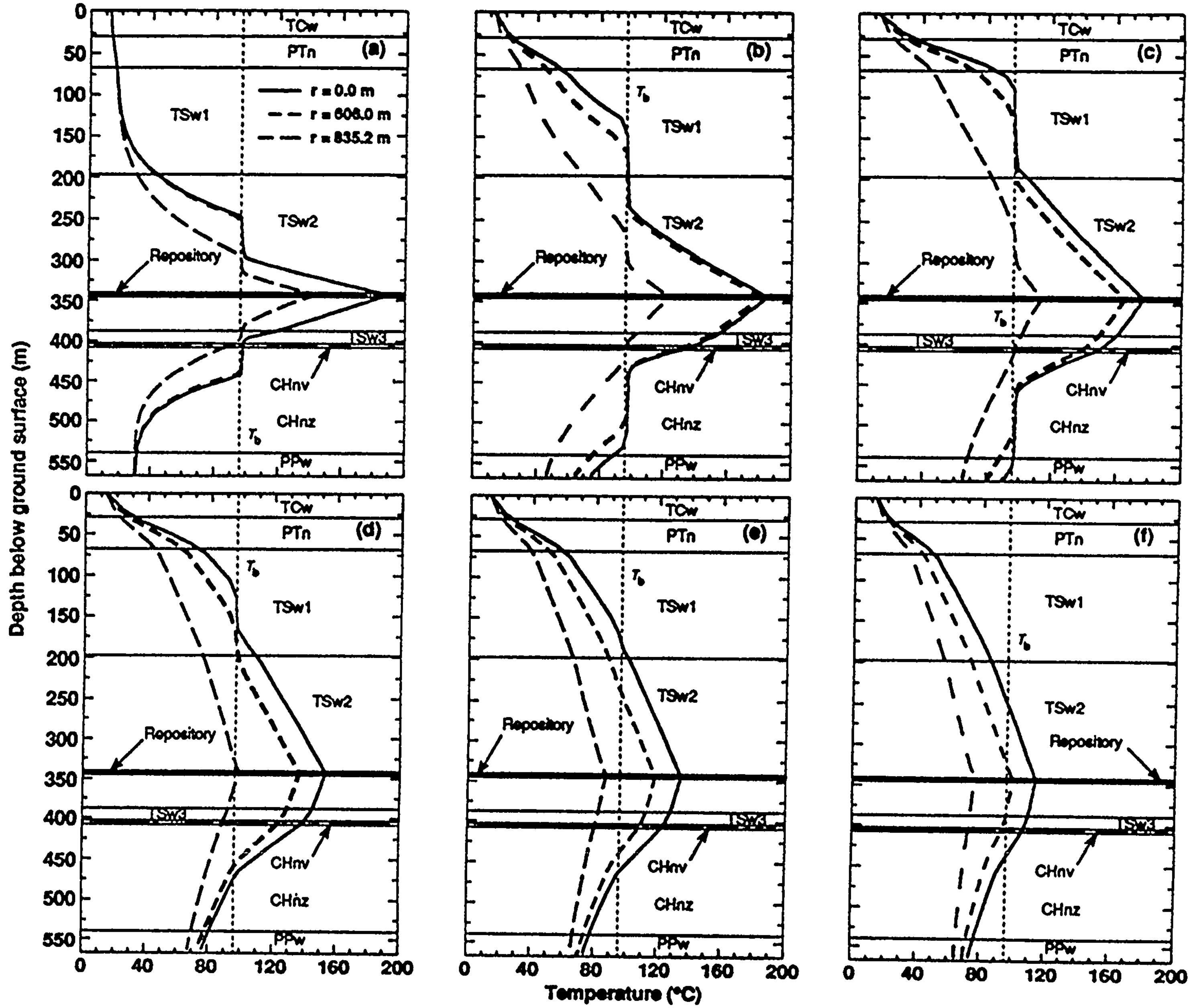


Figure 1. Vertical temperature profiles at various radial distances, r, from repository centerline for an AML of 110.5 MTU/acre at (a) t = 121 yr, (b) t = 453 yr, (c) t =1000 yr, (d) t = 2000 yr, (e) t = 3000 yr, and (f) t = 5000 yr.

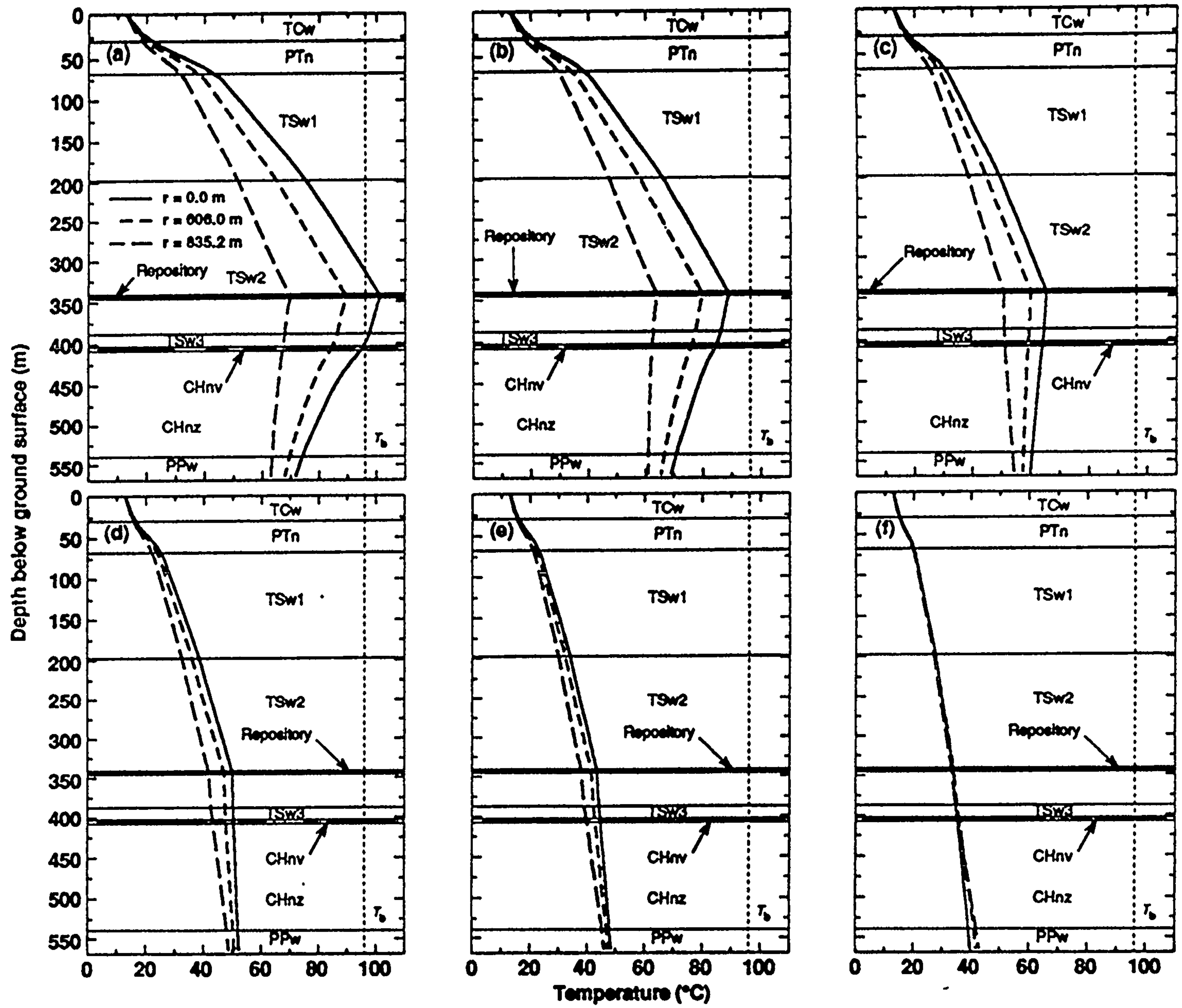


Figure 2. Vertical temperature profiles at various radial distances, r, from repository centerline for an AML of 110.5 MTU/acre at (a) t = 7000 yr, (b) t = 10,000 yr, (c) t = 20,000 yr, (d) t = 36,000 yr, (e) t = 50,000 yr, and (f) t = 100,000 yr.

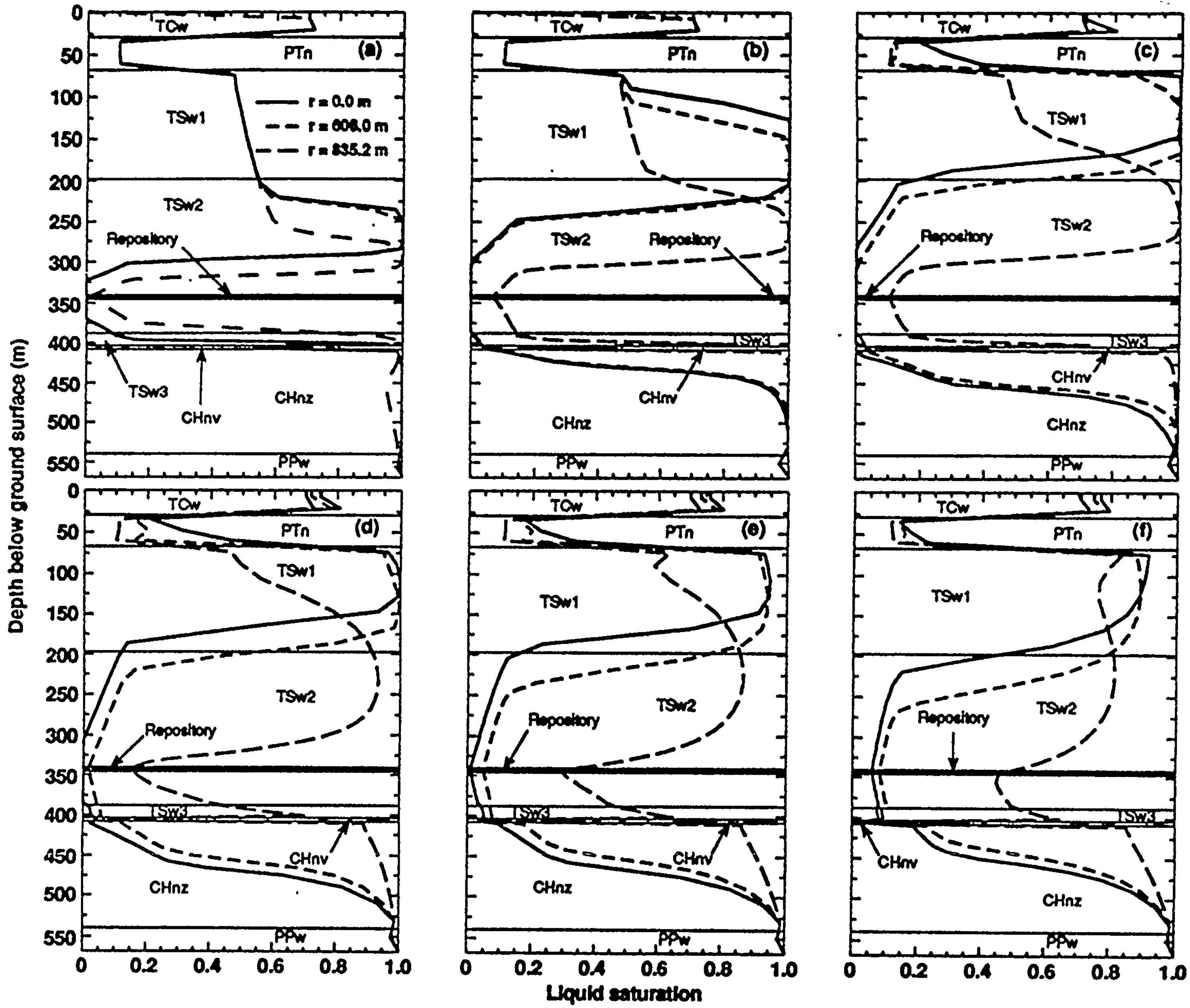


Figure 3. Vertical liquid saturation profiles at various radial distances, r, from repository centerline for an AML of 110.5 MTU/acre at (a) t = 121 yr, (b) t = 453 yr, (c) t = 1000 yr, (d) t = 2000 yr, (e) t = 3000 yr, and (f) t = 5000 yr.

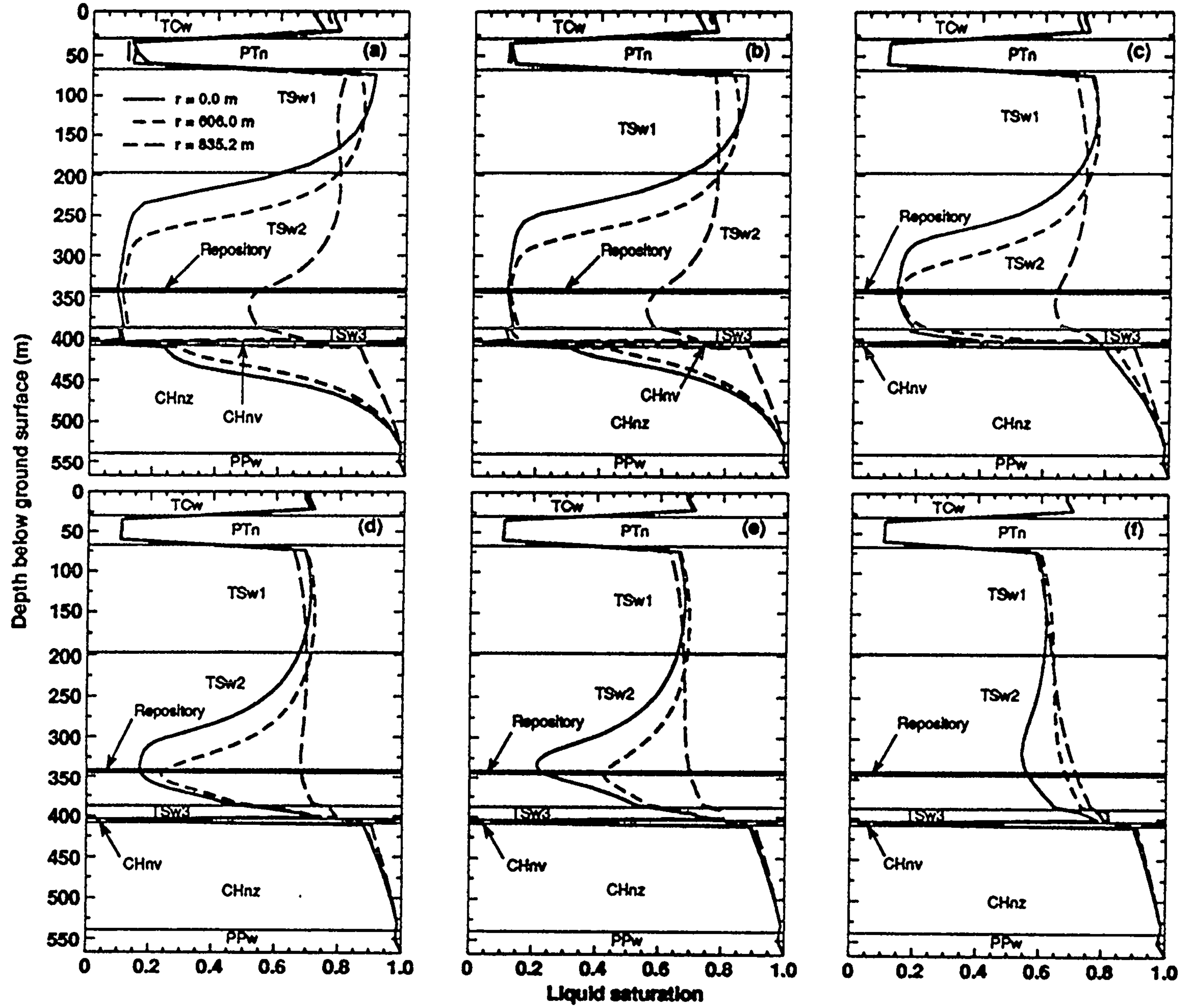


Figure 4. Vertical liquid saturation profiles at various radial distances, r, from repository centerline for an AML of 110.5 MTU/acre at (a) t = 7000 yr, (b) t = 10,000 yr, (c) t = 20,000 yr, (d) t = 36,000, (e) t = 50,000 yr, and (f) t = 100,000 yr.

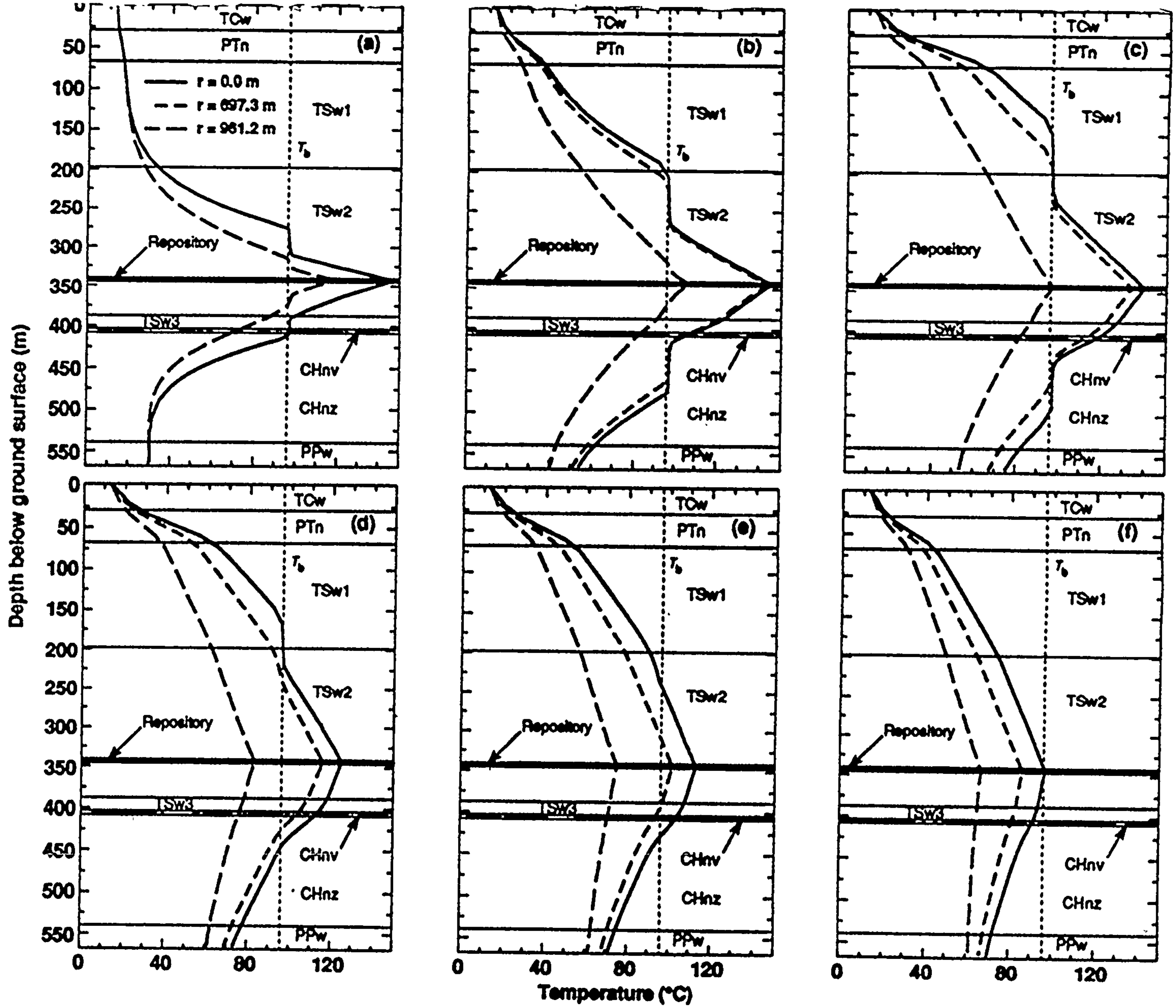


Figure 5. Vertical temperature profiles at various radial distances, r, from repository centerline for an AML of 83.4 MTU/acre at (a) t = 120 yr, (b) t = 451 yr, (c) t = 1000 yr, (d) t = 2000 yr, (e) t = 3000 yr, and (f) t = 5000 yr.

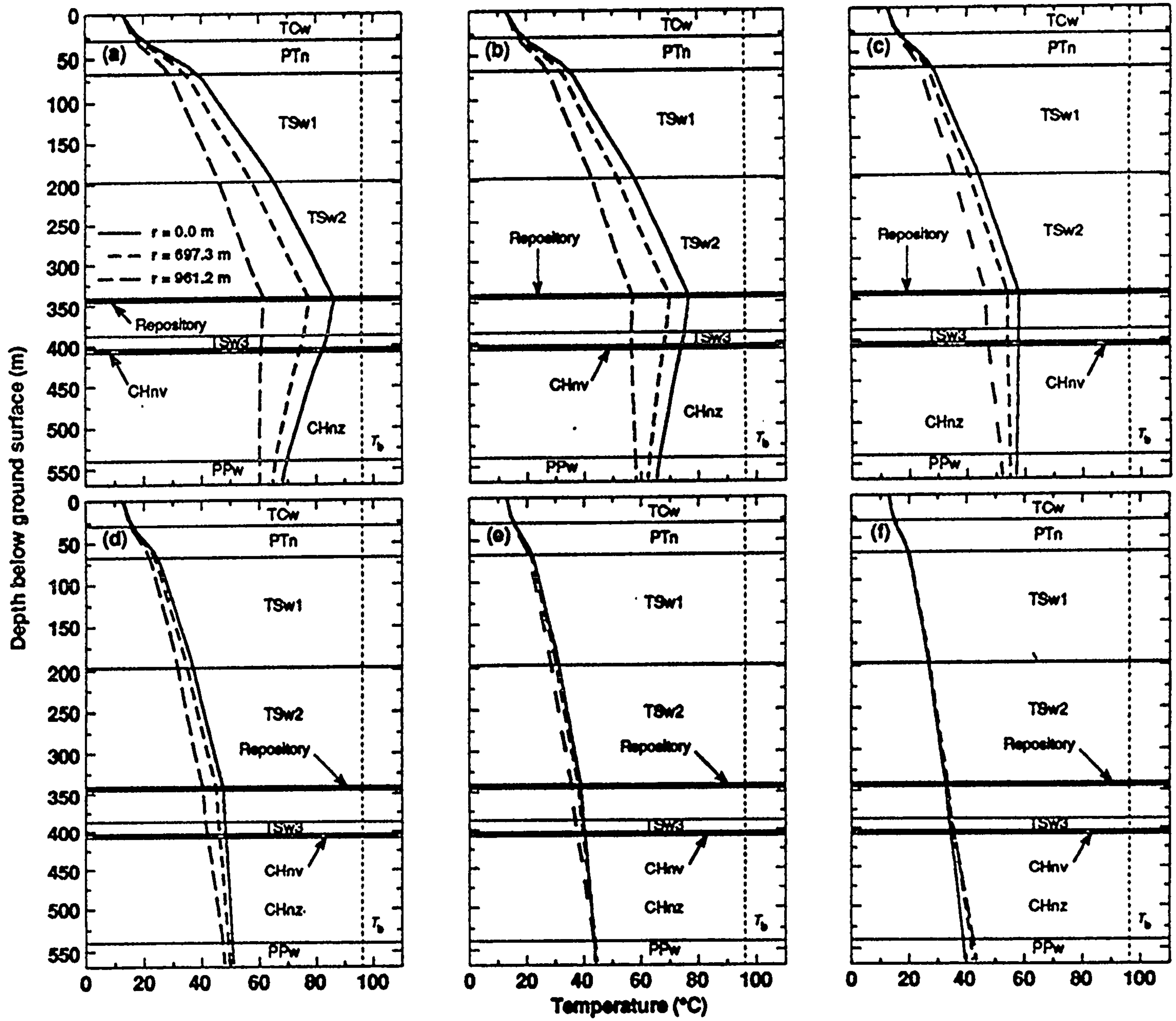


Figure 6. Vertical temperature profiles at various radial distances, r, from repository centerline for an AML of 83.4 MTU/acre at (a) t = 7000 yr, (b) t = 10,000 yr, (c) T = 20,000, (d) t = 33,000 yr, (e) t = 50,000 yr, and (f) t = 100,000 yr.

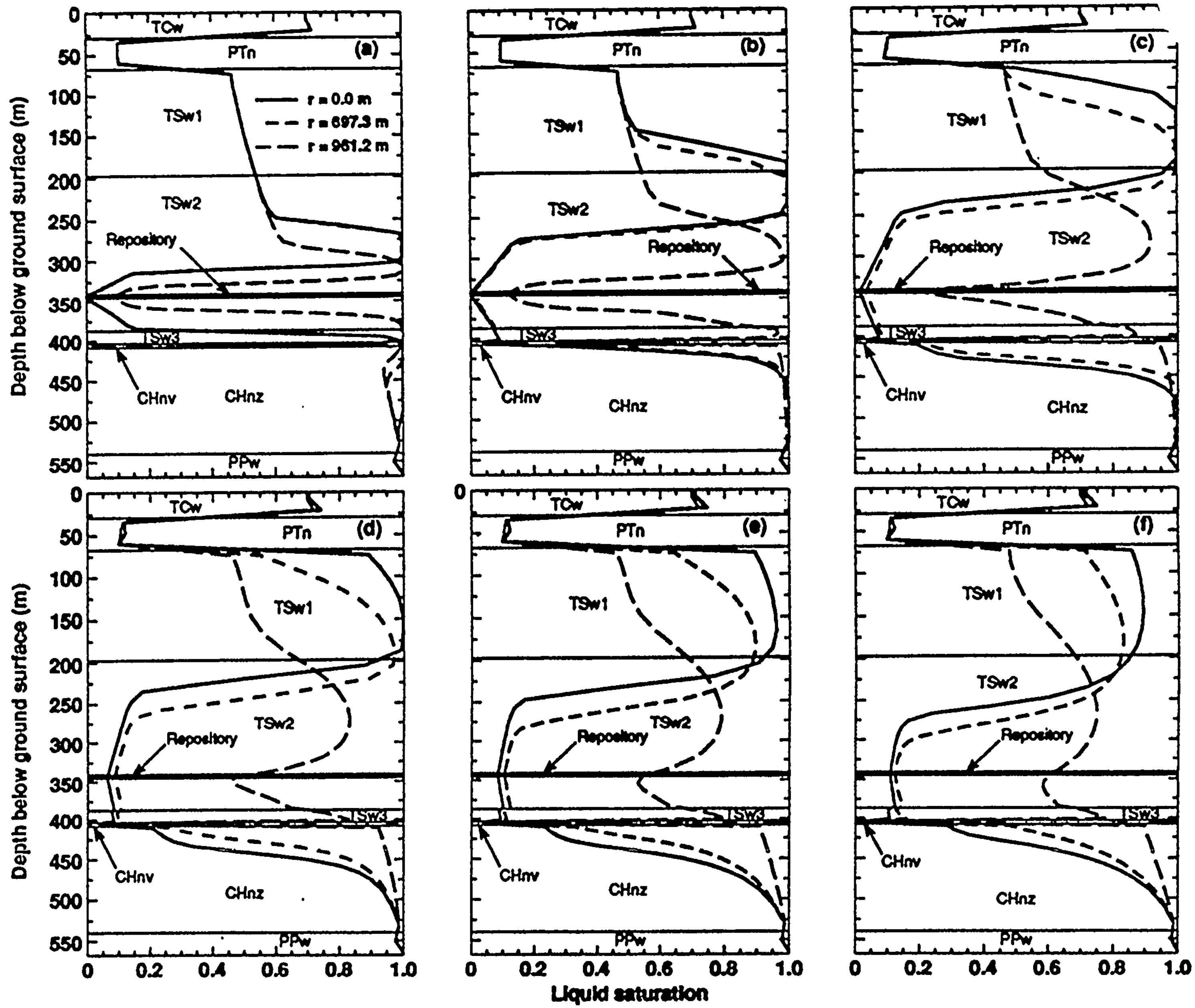


Figure 7. Vertical liquid saturation profiles at various radial distances, *r*, from repository centerline for an AML of 83.4 MTU/acre at (a) t = 120 yr, (b) t = 451 yr, (c) t 1000 yr, (d) t = 2000 yr, (e) t = 3000 yr, and (f) t = 5000 yr.

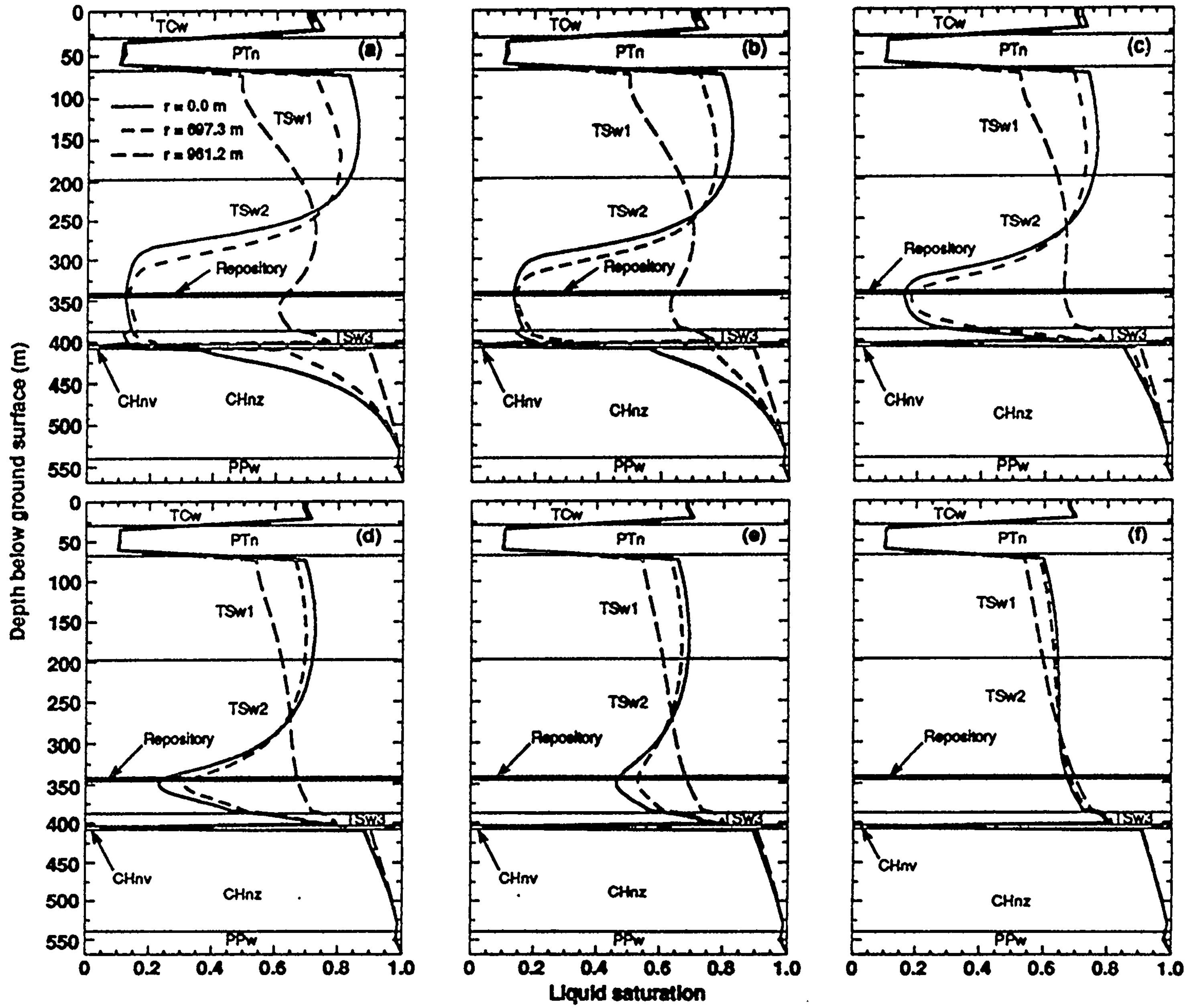


Figure 8. Vertical liquid saturation profiles at various radial distances, *r*, from repository centerline for an AML of 83.4 MTU/acre at (a) t = 7000 yr, (b) t = 10,000 yr, (c) t = 20,000 yr, (d) t = 33,000, (e) t = 50,000 yr, and (f) t = 100,000 yr.

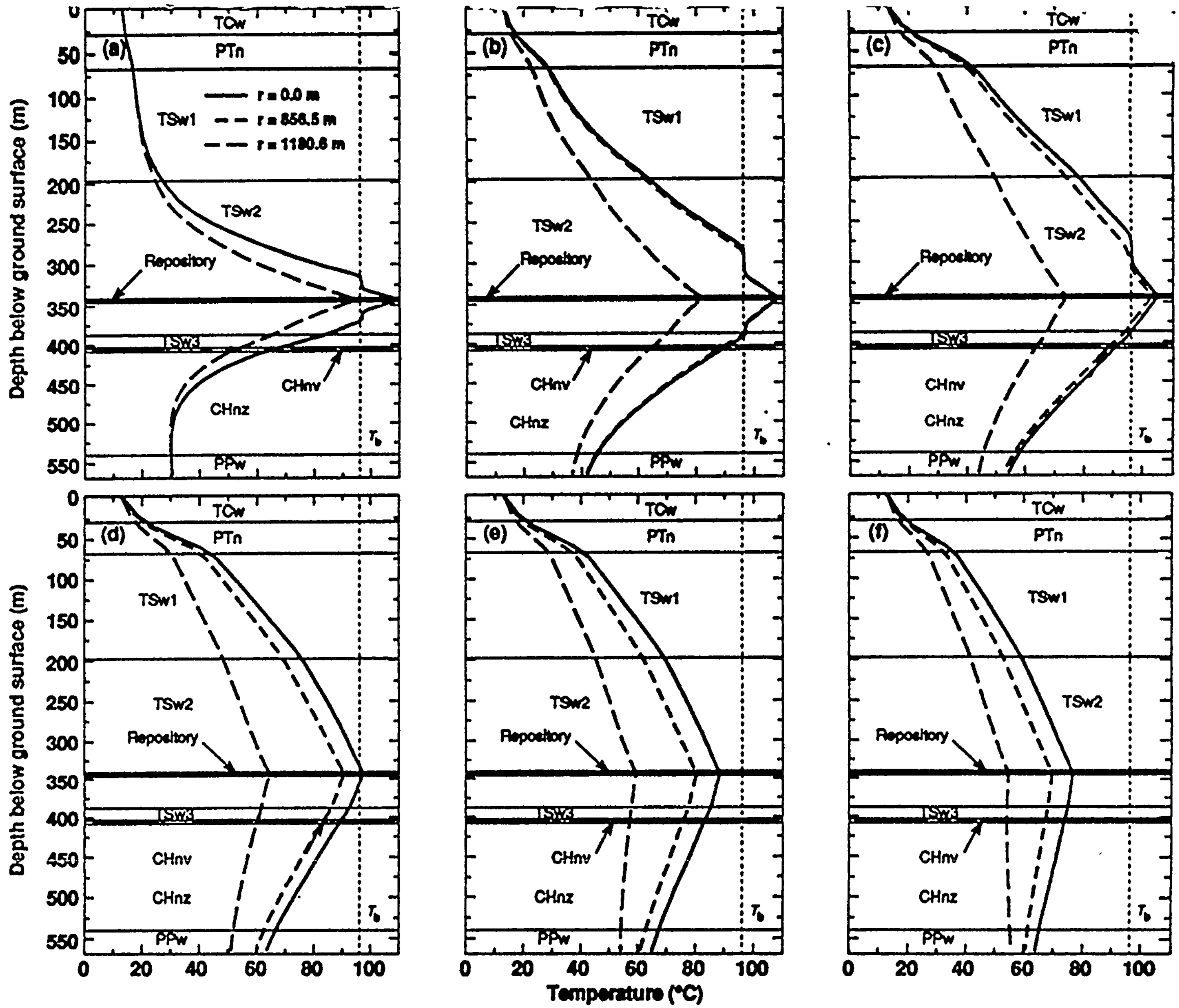


Figure 9. Vertical temperature profiles at various radial distances, r, from repository centerline for an AML of 55.3 MTU/acre at (a) t = 122 yr, (b) t = 497 yr, (c) t = 1000 yr, (d) t = 2000 yr, (e) t = 3000 yr, and (f) t = 5000 yr.

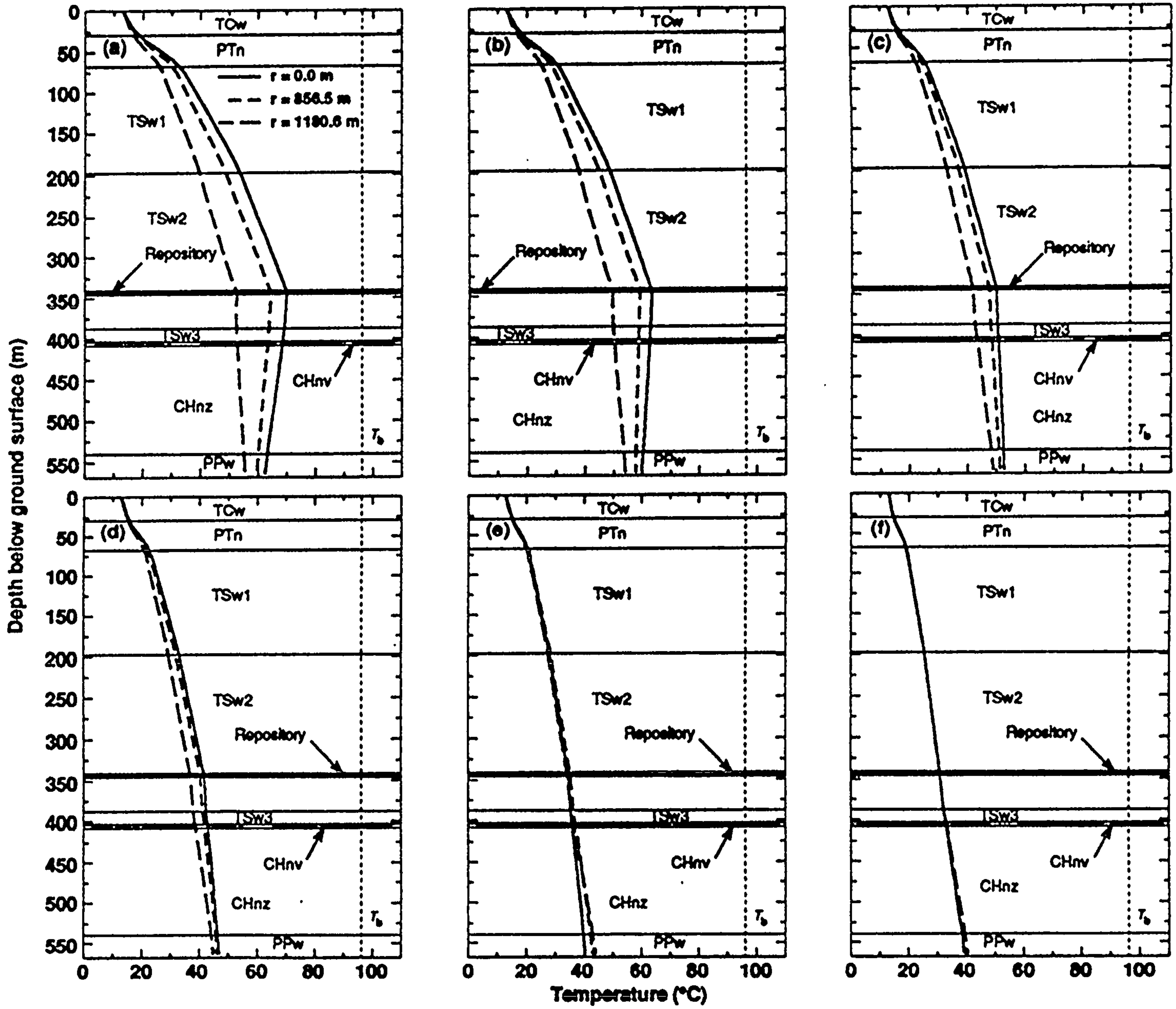


Figure 10. Vertical temperature profiles at various radial distances, r, from repository centerline for an AML of 55.3 MTU/acre at (a) t = 7000 yr, (b) t = 10,000 yr, (c) t = 20,000 yr, (d) t = 36,000 yr, (e) t = 50,000 yr, and (f) t = 100,000 yr.

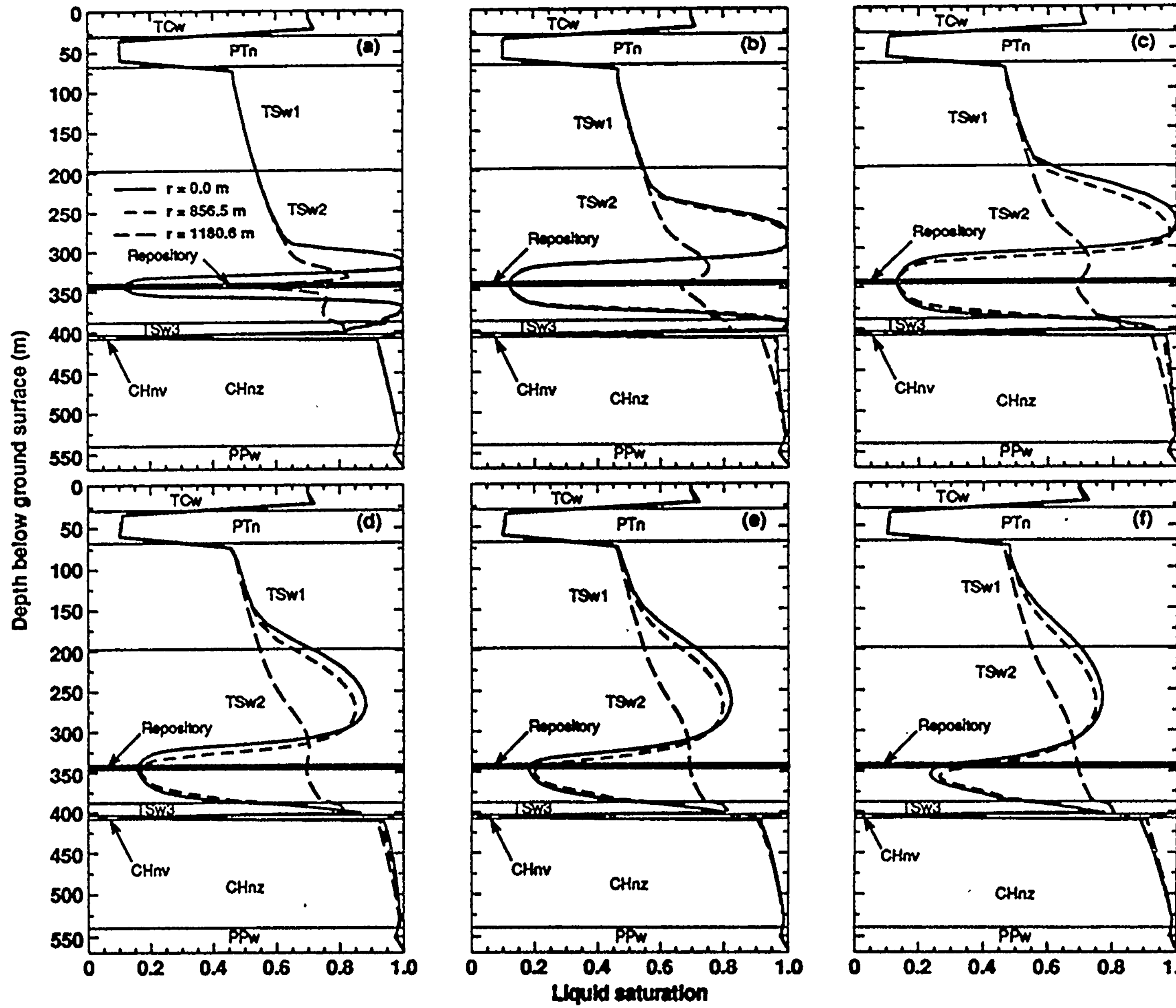


Figure 11. Vertical liquid saturation profiles at various radial distances, r, from repository centerline for an AML of 55.3 MTU/acre at (a) t = 122 yr, (b) t = 497 yr, (c) t = 1000 yr, (d) t = 2000 yr, (e) t = 3000 yr, and (f) t = 5000 yr.

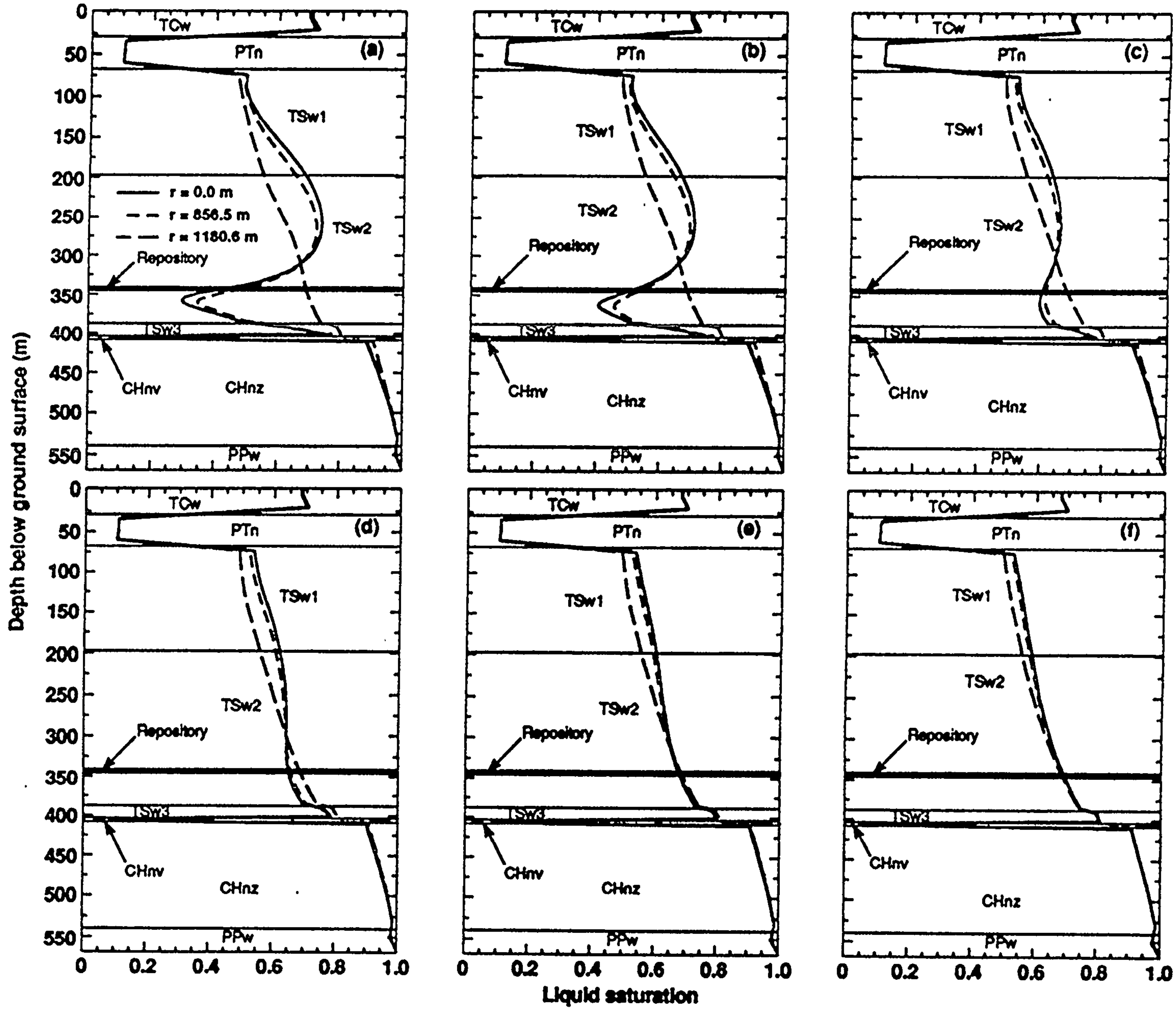


Figure 12. Vertical liquid saturation profiles at various radial distances, r, from repository centerline for an AML of 55.3 MTU/acre at (a) t = 7000 yr, (b) t = 10,000 yr, (c) t = 20,000 yr, (d) t = 31,000 yr, (e) t = 50,000 yr, and (f) t = 100,000 yr.

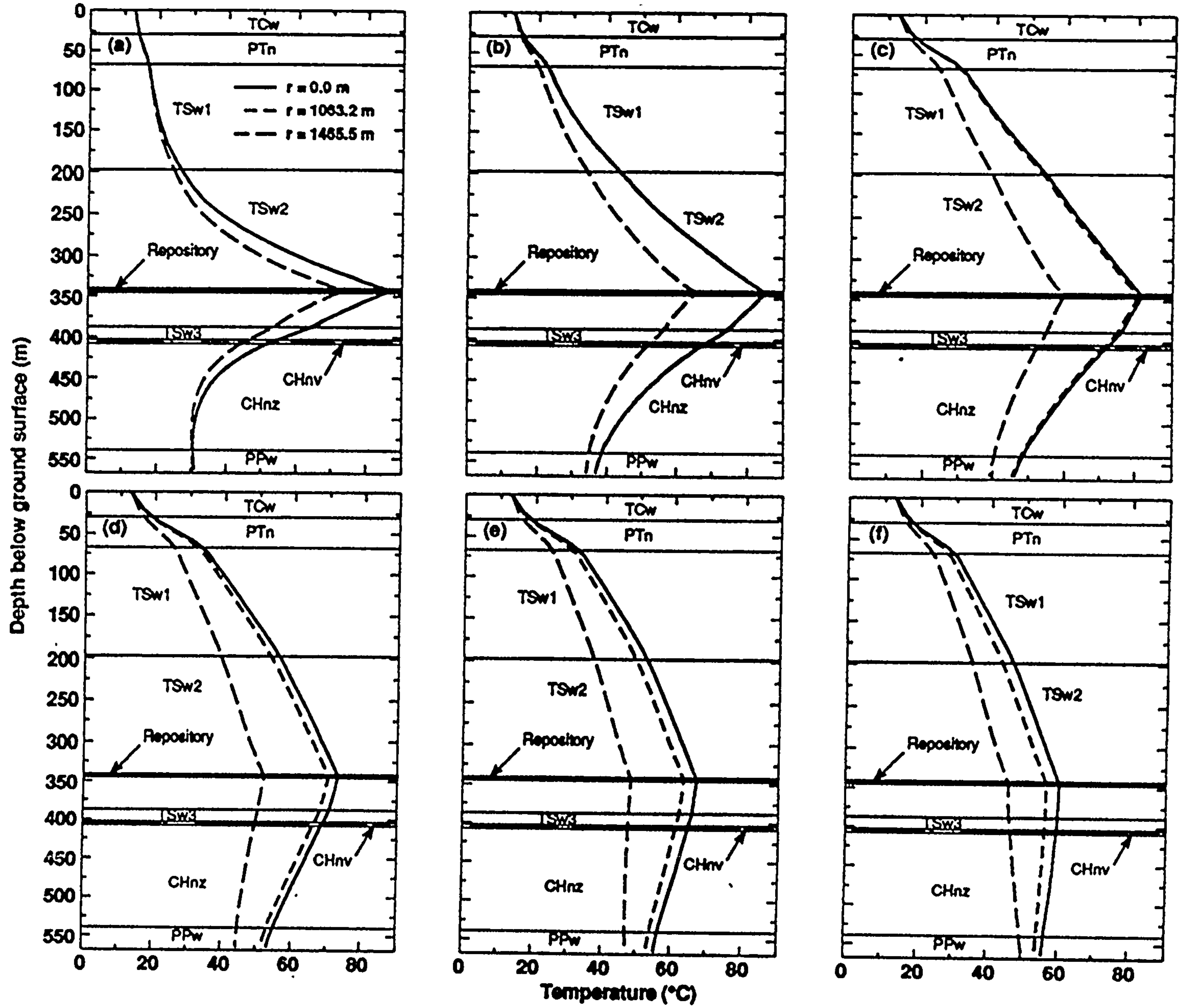


Figure 13. Vertical temperature profiles at various radial distances, r, from repository centerline for an AML of 35.9 MTU/acre at (a) $t = 143$ yr, (b) $t = 447$ yr, (c) $t = 1000$ yr, (d) $t = 2000$ yr, (e) $t = 3000$ yr, and (f) $t = 5000$ yr.

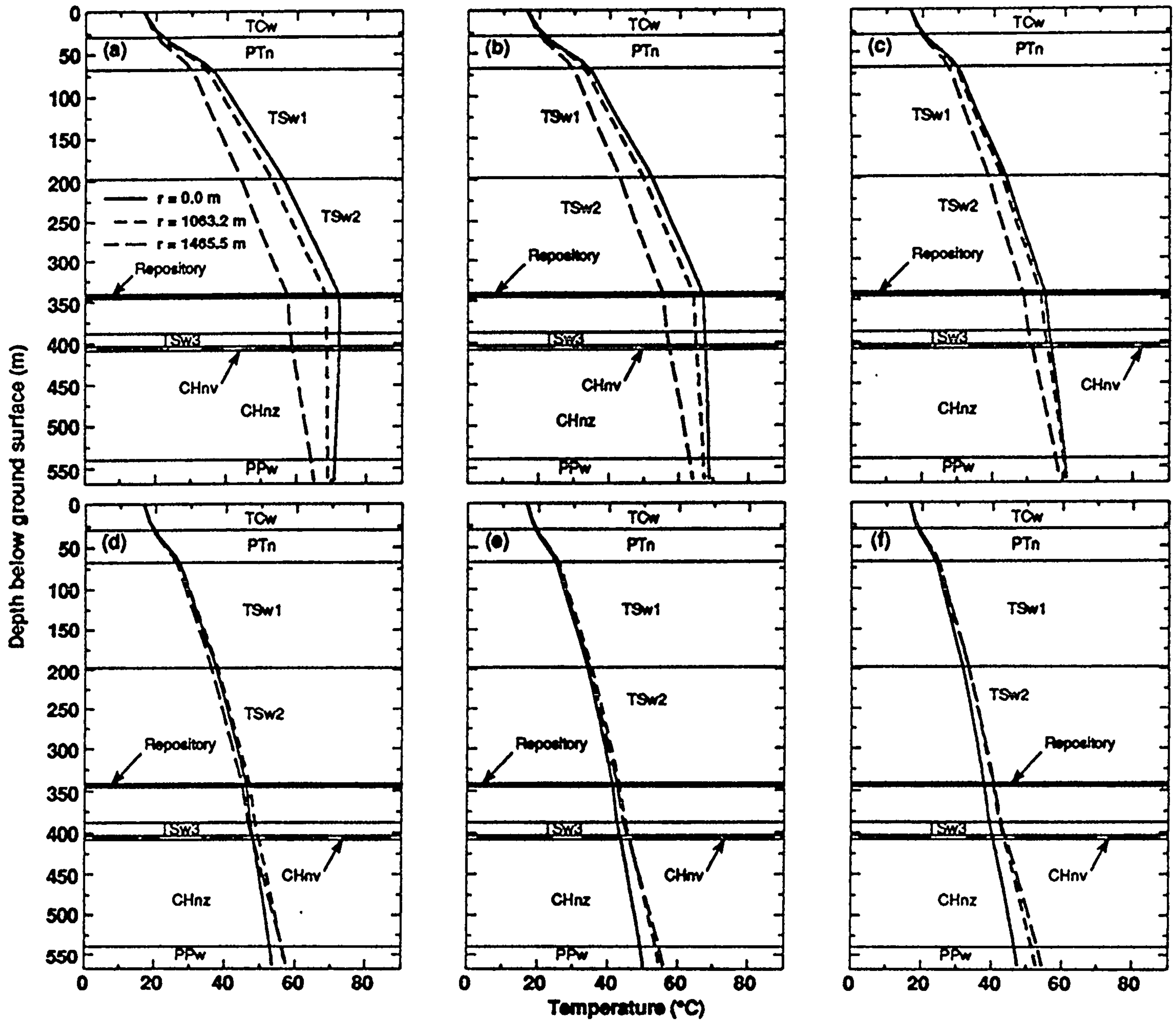


Figure 14. Vertical temperature profiles at various radial distances, r, from repository centerline for an AML of 35.9 MTU/acre at (a) $t = 7000$ yr, (b) $t = 10{,}000$ yr, (c) $t = 20{,}000$ yr, (d) $t = 32{,}000$ yr, (e) $t = 50{,}000$ yr, and (f) $t = 100{,}000$ yr.

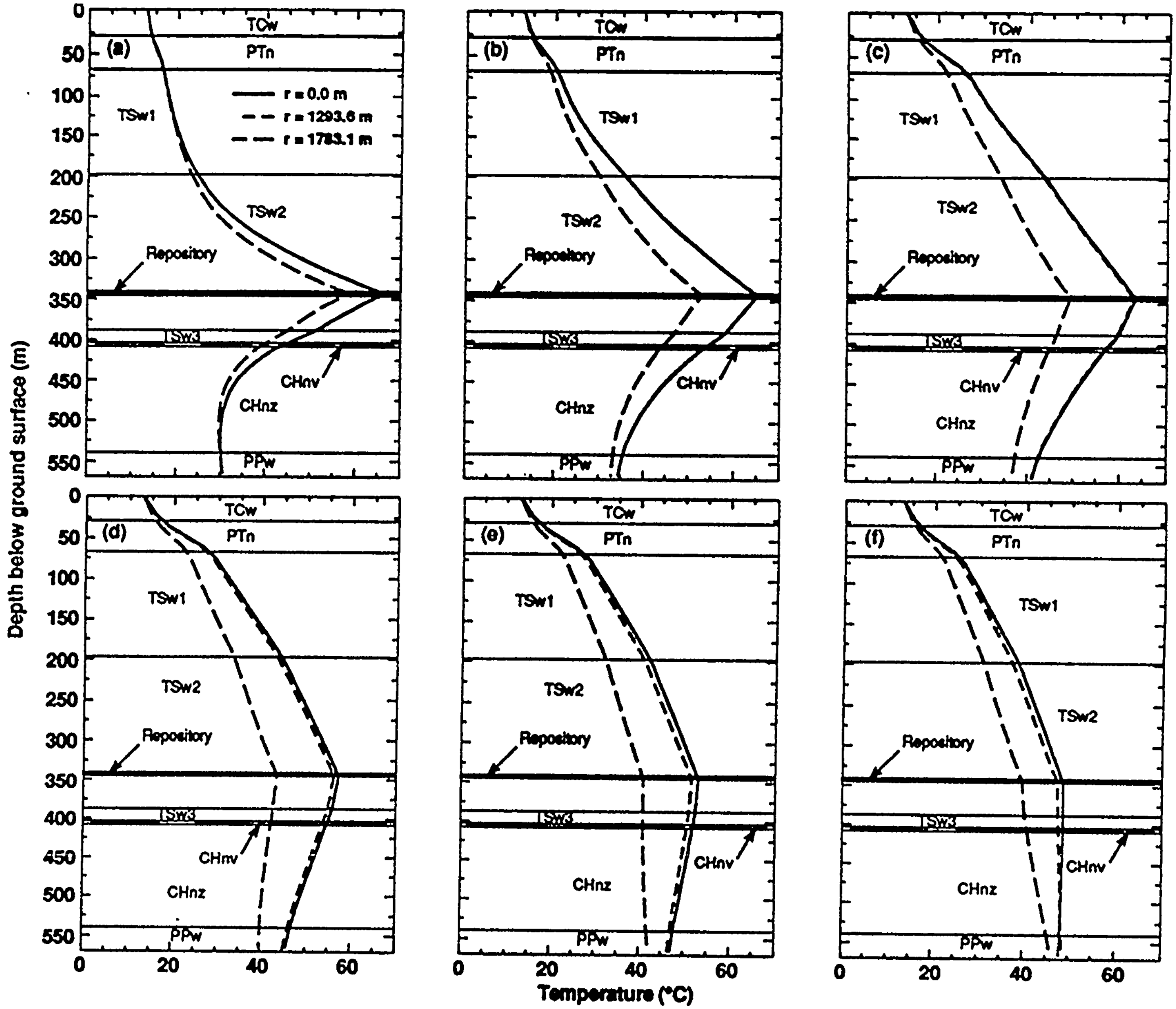


Figure 15. Vertical temperature profiles at various radial distances, r, from repository centerline for an AML of 24.2 MTU/acre at (a) t = 145 yr, (b) t = 435 yr, (c) t = 1000 yr, (d) t = 2000 yr, (e) t = 3000 yr, and (f) t = 5000 yr.

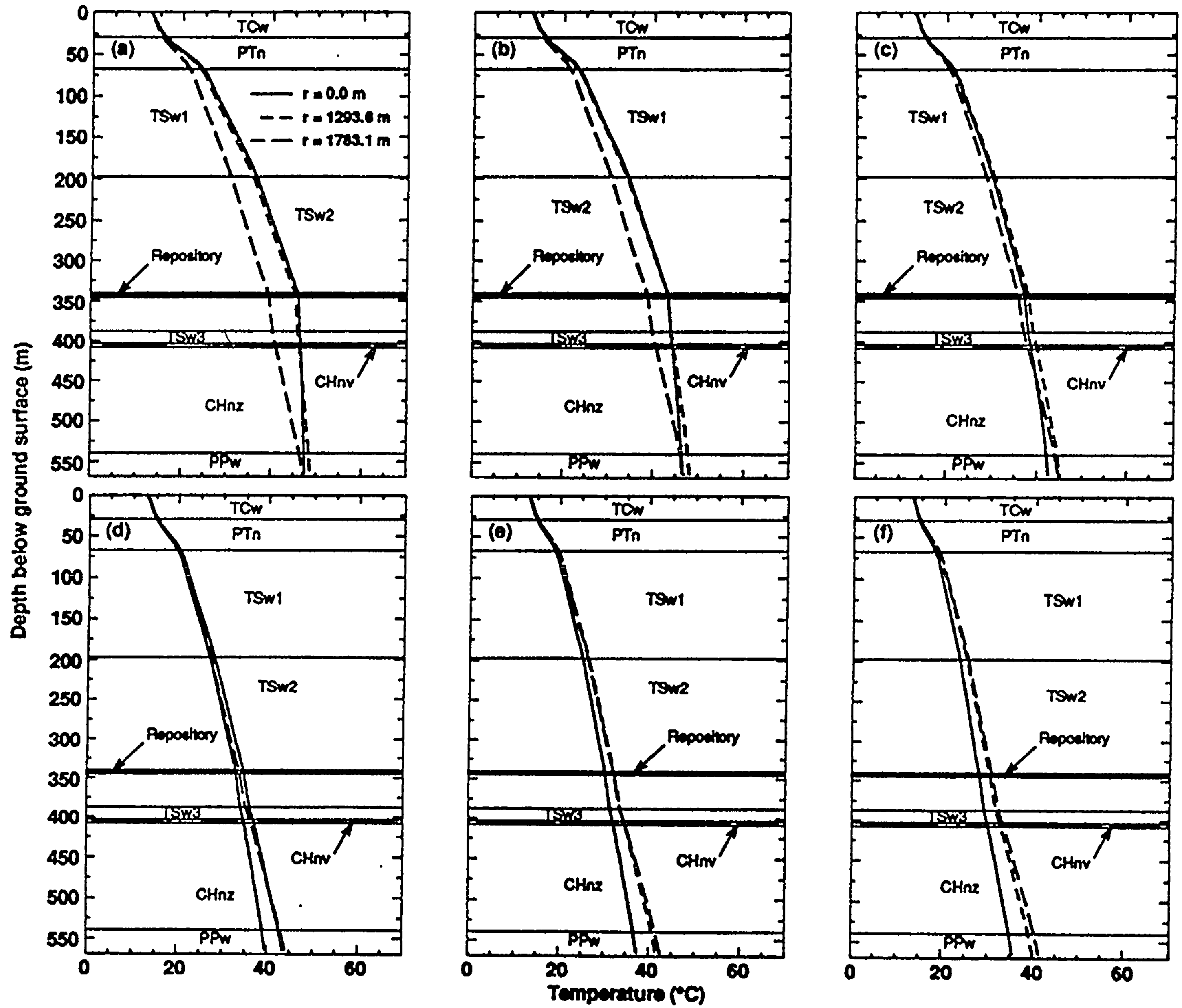


Figure 16. Vertical temperature profiles at various radial distances, r, from repository centerline for an AML of 24.2 MTU/acre at (a) t = 7000 yr, (b) t = 10,000 yr, (c) t = 20,000 yr, (d) t = 30,000 yr, (e) t = 50,000 yr, and (f) t = 100,000 yr.

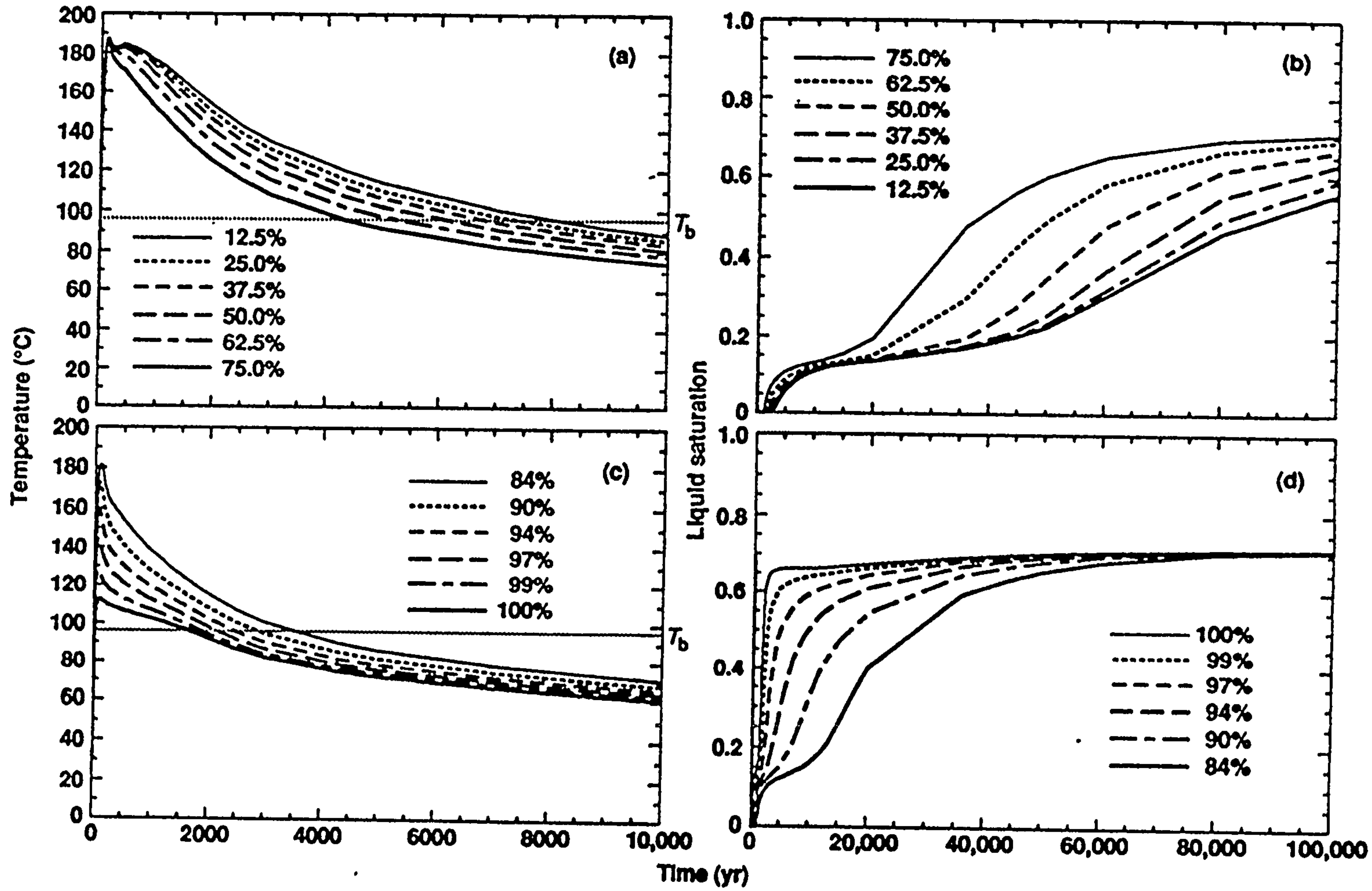


Figure 17. Temperature history (a and c) and liquid saturation history (b and d) at various repository locations relative to the repository center for an AML of 110.5 MTU/acre. The locations are identified as the percentage of the repository area enclosed, with 0% corresponding to the repository center, and 100% corresponding to the outer perimeter of the repository.

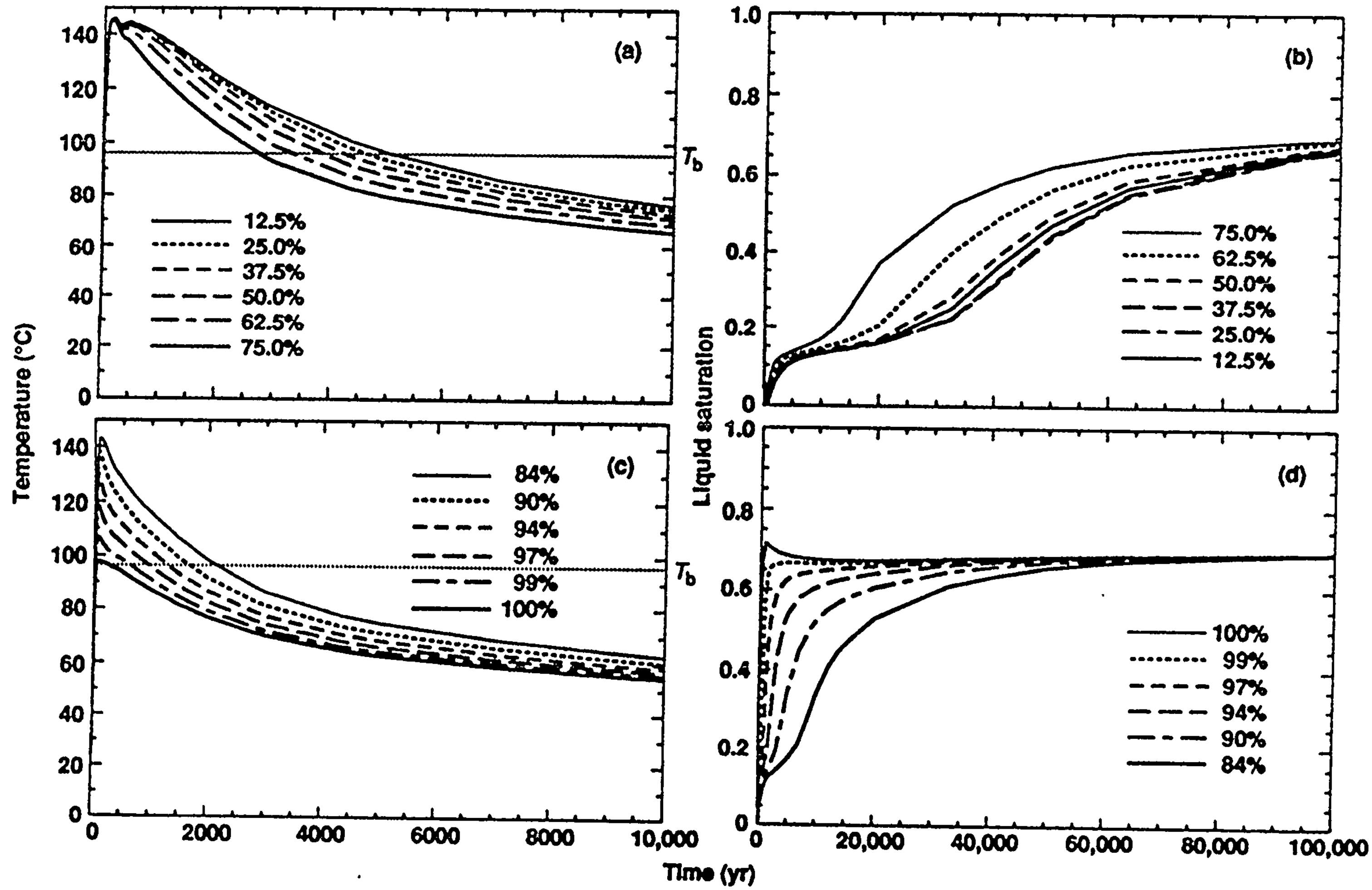


Figure 18. Temperature history (a and c) and liquid saturation history (b and d) at various repository locations relative to the repository center for an AML of 83.4 MTU/acre. The locations are identified as the percentage of the repository area enclosed, with 0% corresponding to the repository center, and 100% corresponding to the outer perimeter of the repository.

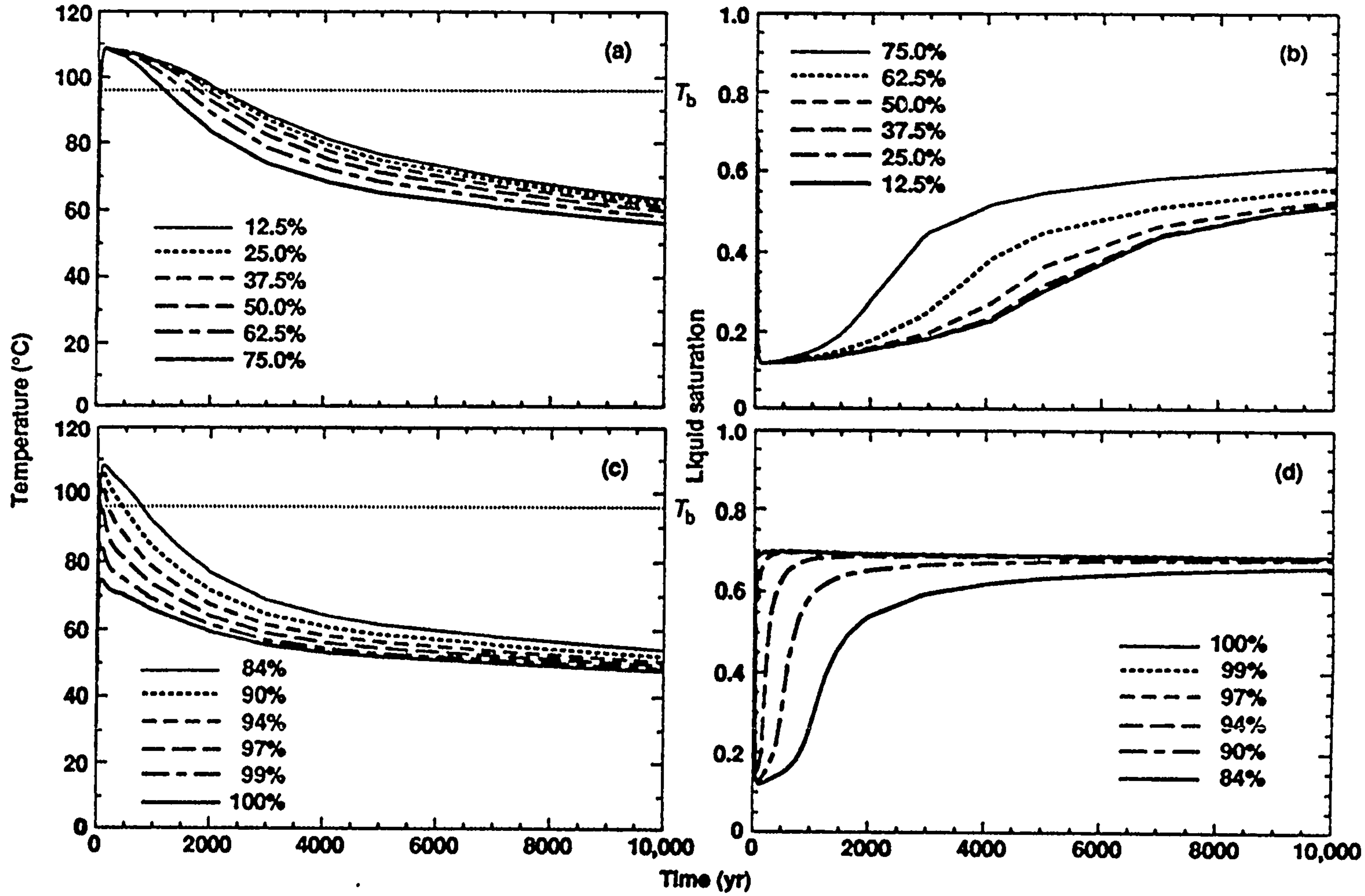


Figure 19. Temperature history (a and c) and liquid saturation history (b and d) at various repository locations relative to the repository center for an AML of 55.3 MTU/acre. The locations are identified as the percentage of the repository area enclosed, with 0% corresponding to the repository center, and 100% corresponding to the outer perimeter of the repository.

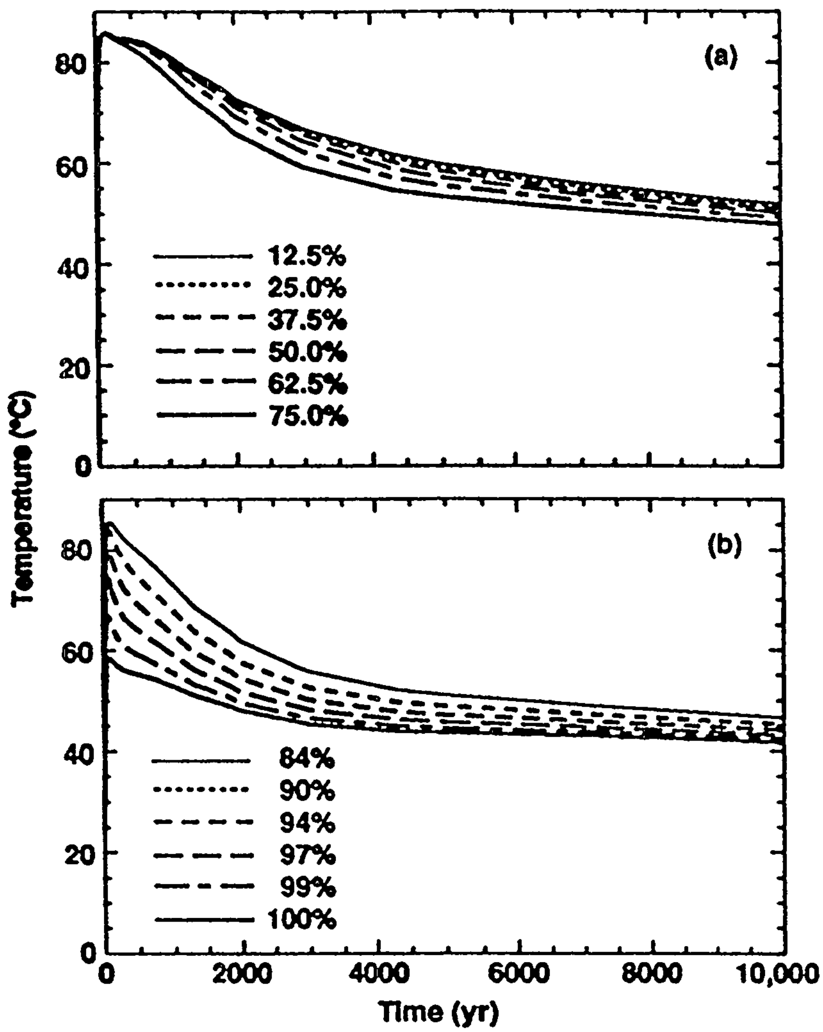


Figure 20. Temperature history at various repository locations relative to the repository center for an AML of 35.9 MTU/acre. The locations are identified as the percentage of the repository area enclosed, with 0% corresponding to the repository center, and 100% corresponding to the outer perimeter of the repository.

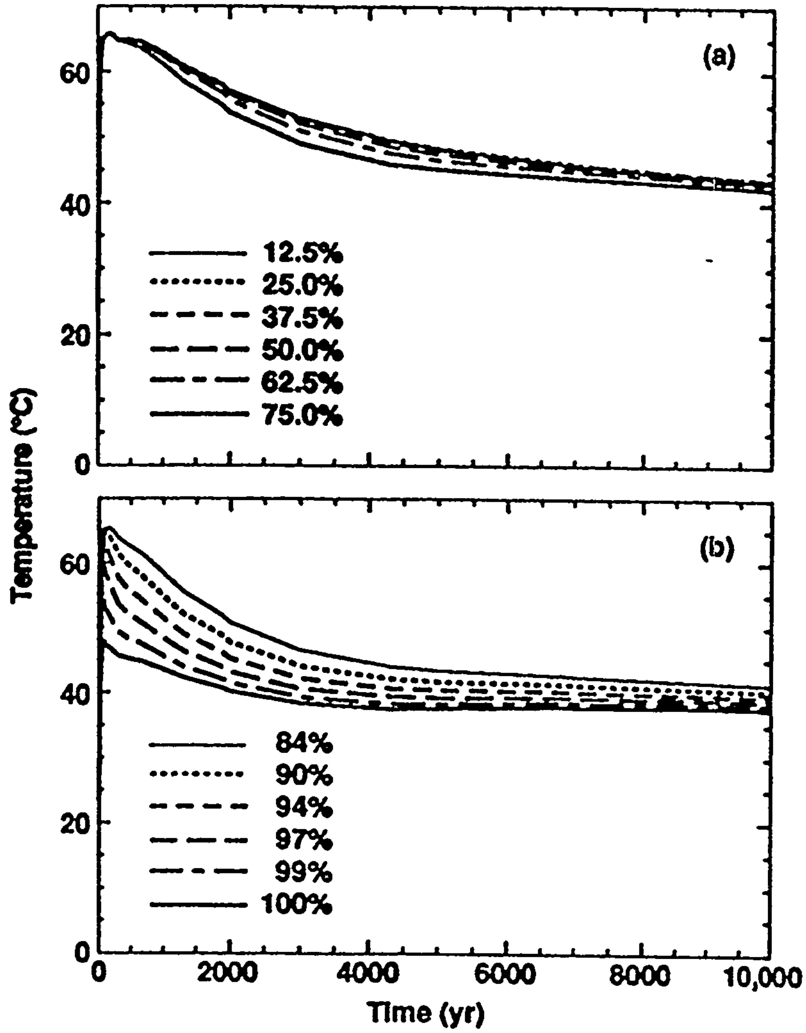


Figure 21. Temperature history at various repository locations relative to the repository center for an AML of 24.2 MTU/acre. The locations are identified as the percentage of the repository area enclosed, with 0% corresponding to the repository center, and 100% corresponding to the outer perimeter of the repository.

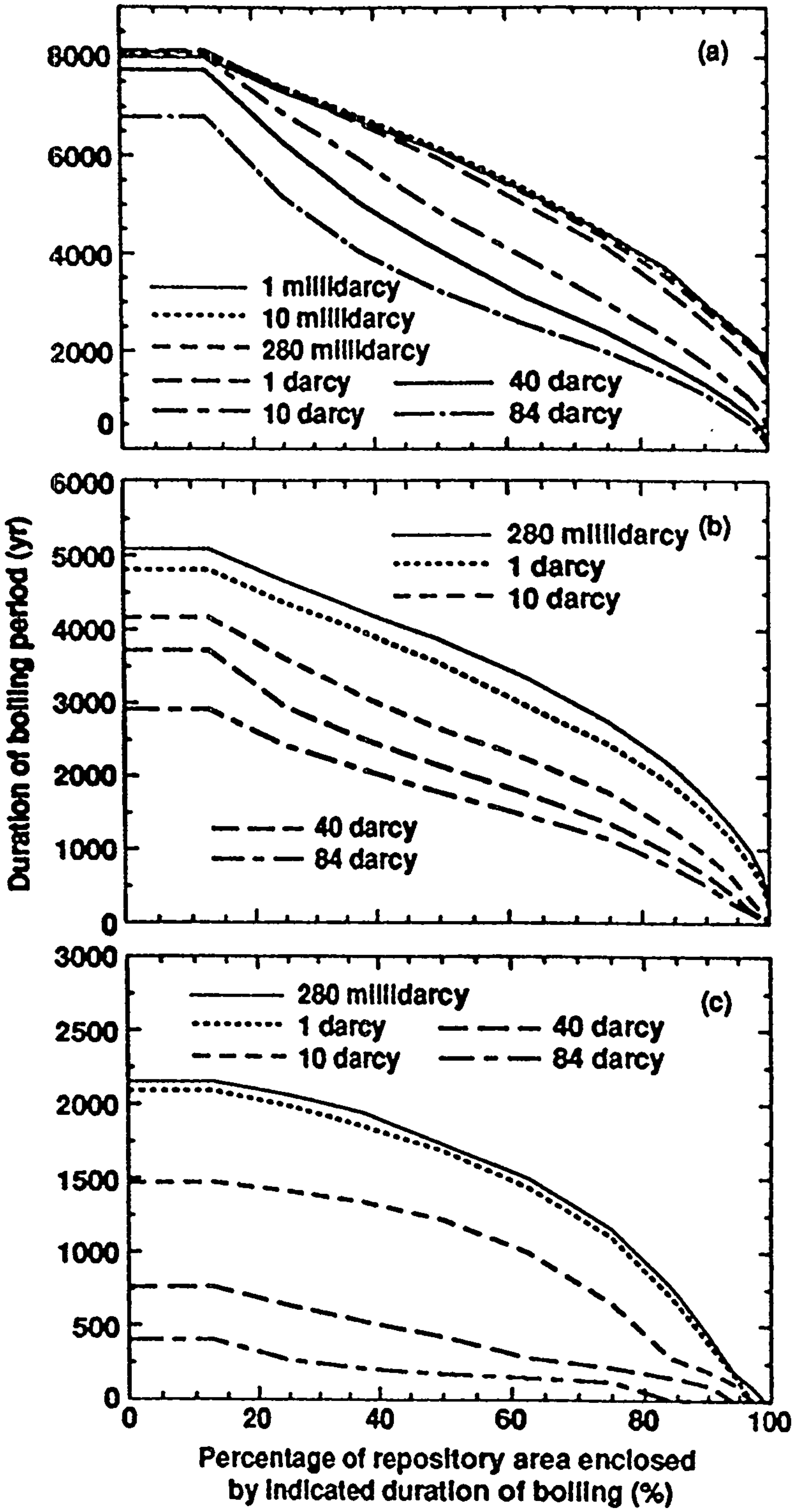


Figure 22. Duration of the boiling period at various repository locations relative to the repository center for AMLs of (a) 110.5 MTU/acre, (b) 83.4 MTU/acre, and (c) 55.3 MTU/acre. The locations are identified as the percentage of the repository area enclosed, with 0% corresponding to the repository center, and 100% corresponding to the outer perimeter of the repository.

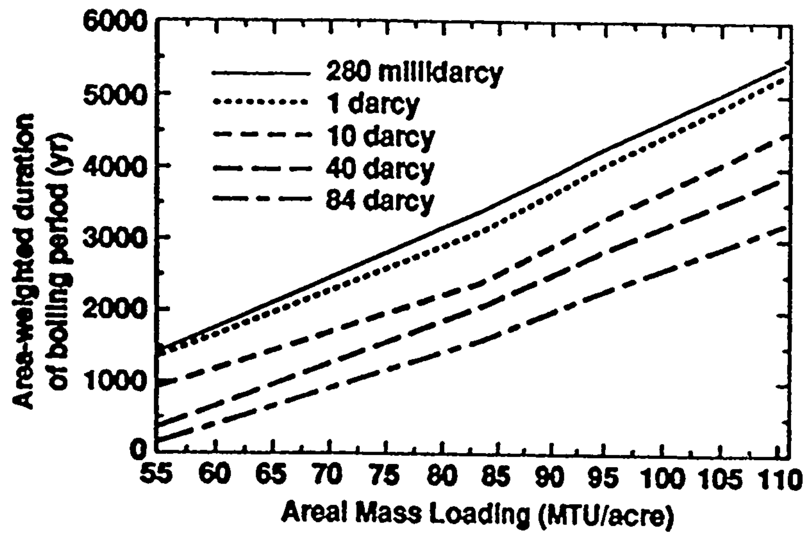


Figure 23. Area-weighted duration of the boiling period as a function of Areal Mass Loading, AML, for various values of bulk permeability, k_b.

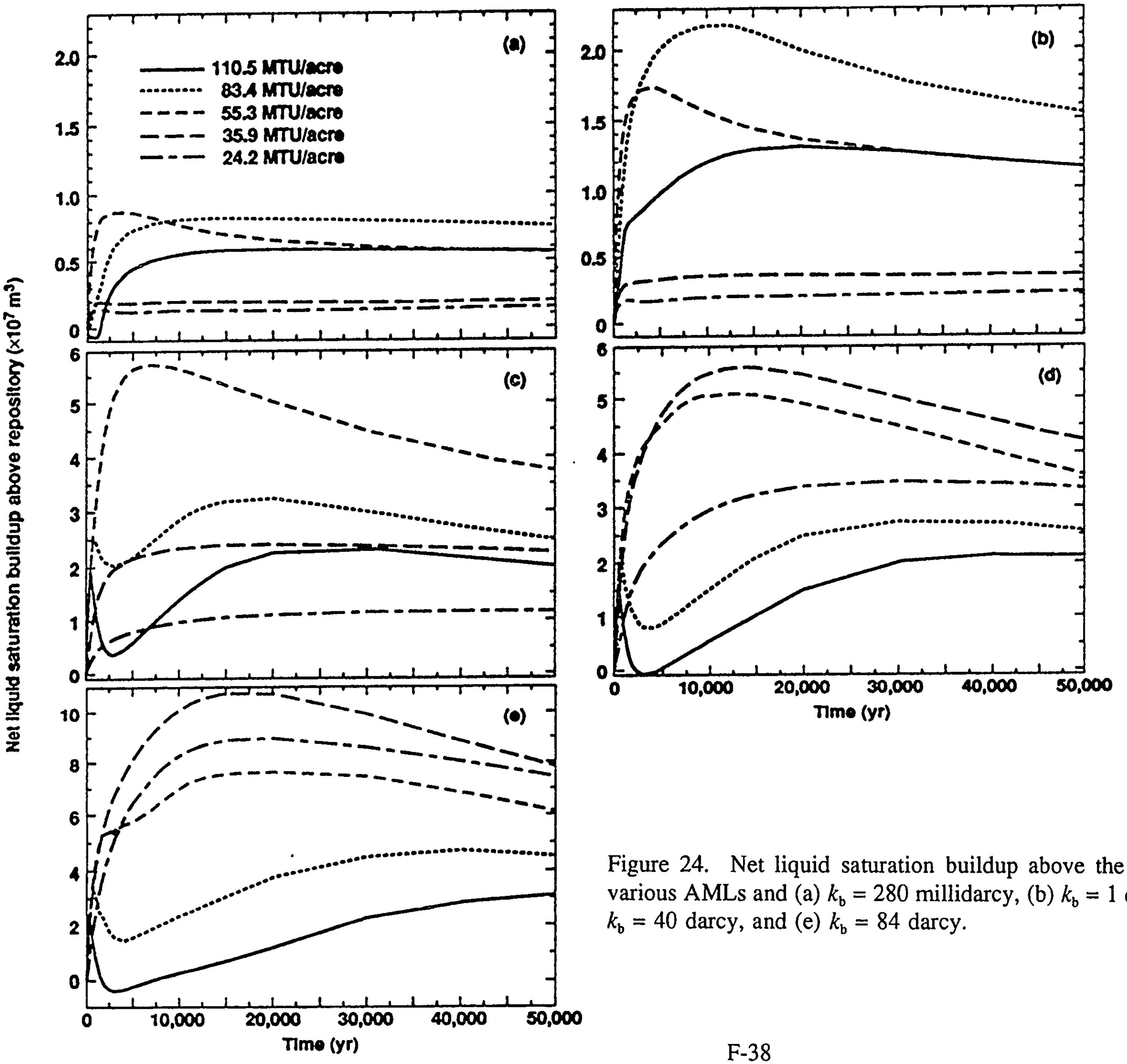


Figure 24. Net liquid saturation buildup above the repository versus time for various AMLs and (a) k_b = 280 millidarcy, (b) k_b = 1 darcy, (c) k_b = 10 darcy, (d) k_b = 40 darcy, and (e) k_b = 84 darcy.

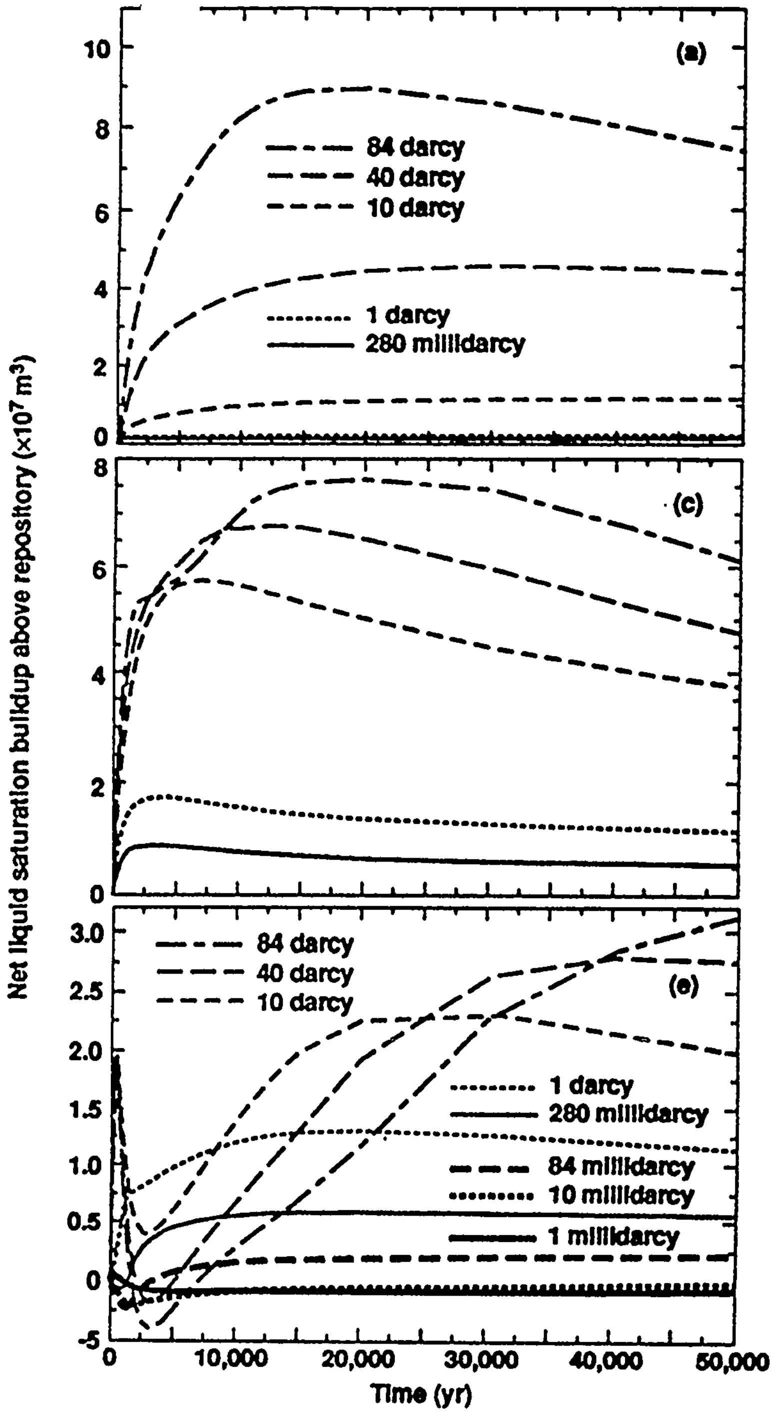


Figure 25. Net liquid saturation buildup above the repository versus time for various values of bulk permeability, k_b, and AMLs of (a) 24.2 MTU/acre, (b) 35.9 MTU/acre, (c) 55.3 MTU/acre, (d) 83.4 MTU/acre, and (e) 110.5 MTU/acre.

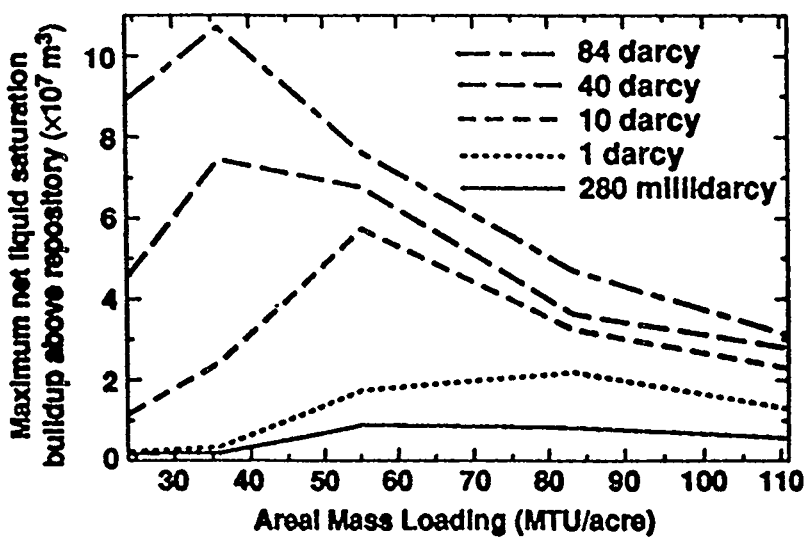


Figure 26. Maximum net liquid saturation buildup above the repository as a function of Areal Mass Loading, AML, for various values of bulk permeability, k_b.

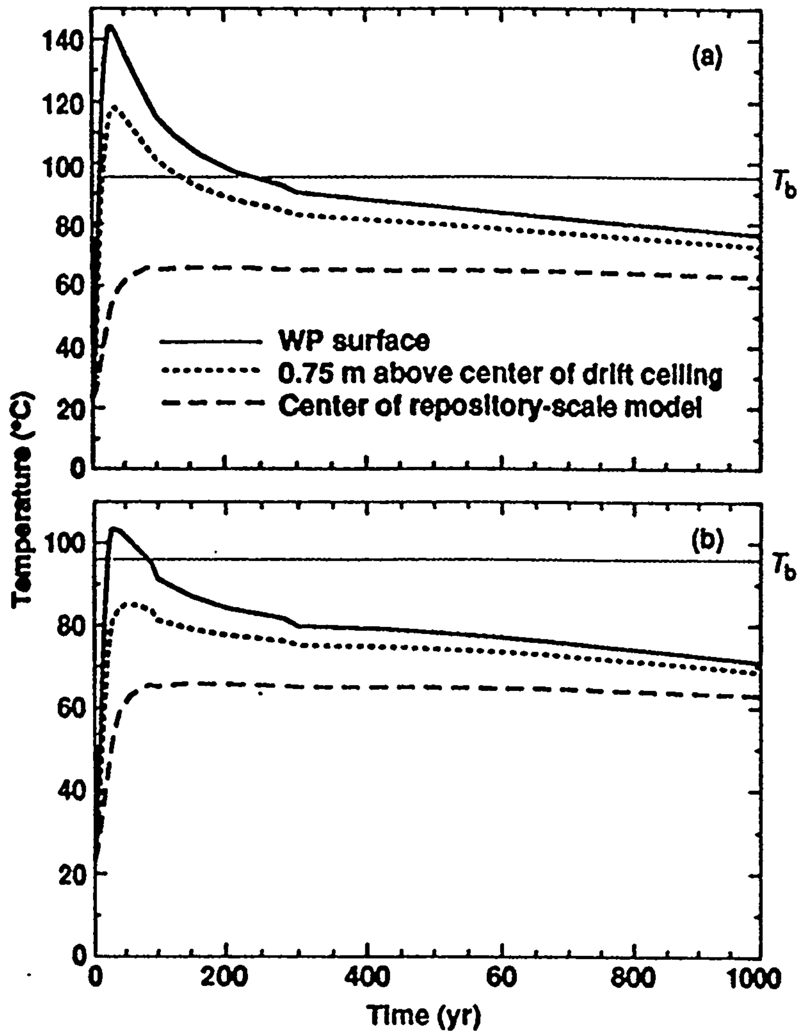


Figure 27. Temperature history on waste package (WP) surface and in the rock 0.75 m above the center of the drift ceiling for an AML of 24.4 MTU/acre. (a) For repository containing 4533 21-PWR WPs and 3116 40-BWR WPs and a center-to-center drift spacing of 99 m. (b) For repository containing 7932 12-PWR WPs and 5936 21-BWR WPs and a center-to-center drift spacing of 56.58 m.

Appendix G
Reliability of Electronics as a Function of Temperature

Introduction

A small study was done in support of the Thermal Loading Study to determine the reliability of electronic equipment as a function of temperature. The details of this study are reported in this appendix.

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. If the repository concept relies on the use of electronic equipment, such as radiation monitors, alarm systems, communications systems, the reliability of this equipment will be affected by the temperature environment. If the temperature is high enough, active cooling may be necessary to allow for a reasonable maintenance schedule.

A survey of the reliability of electronic parts as a function of temperature was undertaken. The approach taken was not to determine the state of the art in temperature endurance, but to provide an indication of what reasonable and available technology could endure. The reliability of electronic piece parts and monolithic circuits that are intended for high-temperature application were included in the survey only for parts in common use. A fundamental limitation on reliability prediction is on the extension of data from known systems to a new application. The analysis methodology chosen does not determine the reliability of electronic systems, but indicates the expected dependance on temperature by extrapolating from low level data on piece-parts.

This analysis was not performed according to quality assurance procedures. It is intended for the sole purpose of suggesting further quality assured work to validate the concept and approach of this study.

Method

The method used was taken from the Military Handbook for the Reliability Prediction of Electronic Equipment, MIL-HDBK-217E.[1] A number of common assumptions were adopted for all of the electronic parts investigated:

Environment	=	Ground Fixed
Quality Class	=	Class B
Learning Class	=	Established Parts

[1]Military Handbook Reliability Prediction of Electronic Equipment, MIL-HDBK-217E, October 27, 1986.

In addition a number of specific assumptions were adopted for each part type. These assumptions were not intended to determine a "worst case" for temperature reliability, but instead were formulated to indicate representative performance for temperature tolerant parts intended for a high temperature environment. For example, where power or current stress adversely affects reliability, the lowest stress within the range of validity was used. Similarly, the highest temperature rated parts were included for comparison whenever data was available for more than one temperature rating. Parts not in common use may be available that out-perform the parts chosen for examination. However, it is likely that these parts are not used in the type and kind of equipment that is readily available for the current application, and would not be usable without a specialized development program.

Rather than reproduce the equations and data used here, which can be quite lengthy and involved, the reader is referred to the appropriate section of reference 1. The specific assumptions used by part type are summarized below:

<u>Discrete Transistors</u>

Part Type: Group 1
Power Stress: 0.1
Reference: Table 5.1.3.1-7 through 5.1.3.1-10.

<u>Discrete Diodes</u>

Part Type: Group IV
Current Stress: 0.1
Reference: Table 5.1.3.4-7 and 5.1.3.4-8

<u>Monolithic Bipolar</u>

Part Type: Hermetic DIP with solder or welded seal, Eutectic DIE Attach., < 22 Pins
Power Dissipation : 1 Watt
Theta jc : 30 C/watt
Reference: Section 5.1.2.1 et. seq.

<u>Linear Devices</u>

Part Type: Hermetic DIP with solder or welded seal, Eutectic DIE Attach, < 22 Pins
Power Dissipation: 1 Watt
Theta jc : 30 C/watt
Reference: Section 5.1.2.2 et. seq.

<u>MOS Digital Microprocessor</u>

Part Type: PMOS, NMOS, HMOS, Hermetic, 40 Pin
Power Dissipation : 1 Watt
Theta jc : 25 C/watt

Reference: Section 5.1.2.3 et. Seq.

CMOS Dynamic Ram

Part Type: CMOS, Hermetic, 12 VDD, 22 Pin
Power Dissipation: 0.2 Watt
Theta jc : 30 C/Watt
Reference: Section 5.1.2.4. et. Seq.

Discrete Components

Part Type: Resistor: composition, wire wound; Capacitor: 150 C max, 170 C max
Power Stress : 0.1
Reference : Tables 5.1.6.1-4, 5.1.7.1-13, 5.1.6.4-4, 5.1.7.1-21

Hybrid Interconnections

Type: Bimetal: Gold-Aluminum; Single metal: Al-Al, Gold-Gold, Solder
Reference: Table 5.1.2.9-3

Motors

Type: 1 HP or less
Reference: Table 5.1.9.1-1

Results

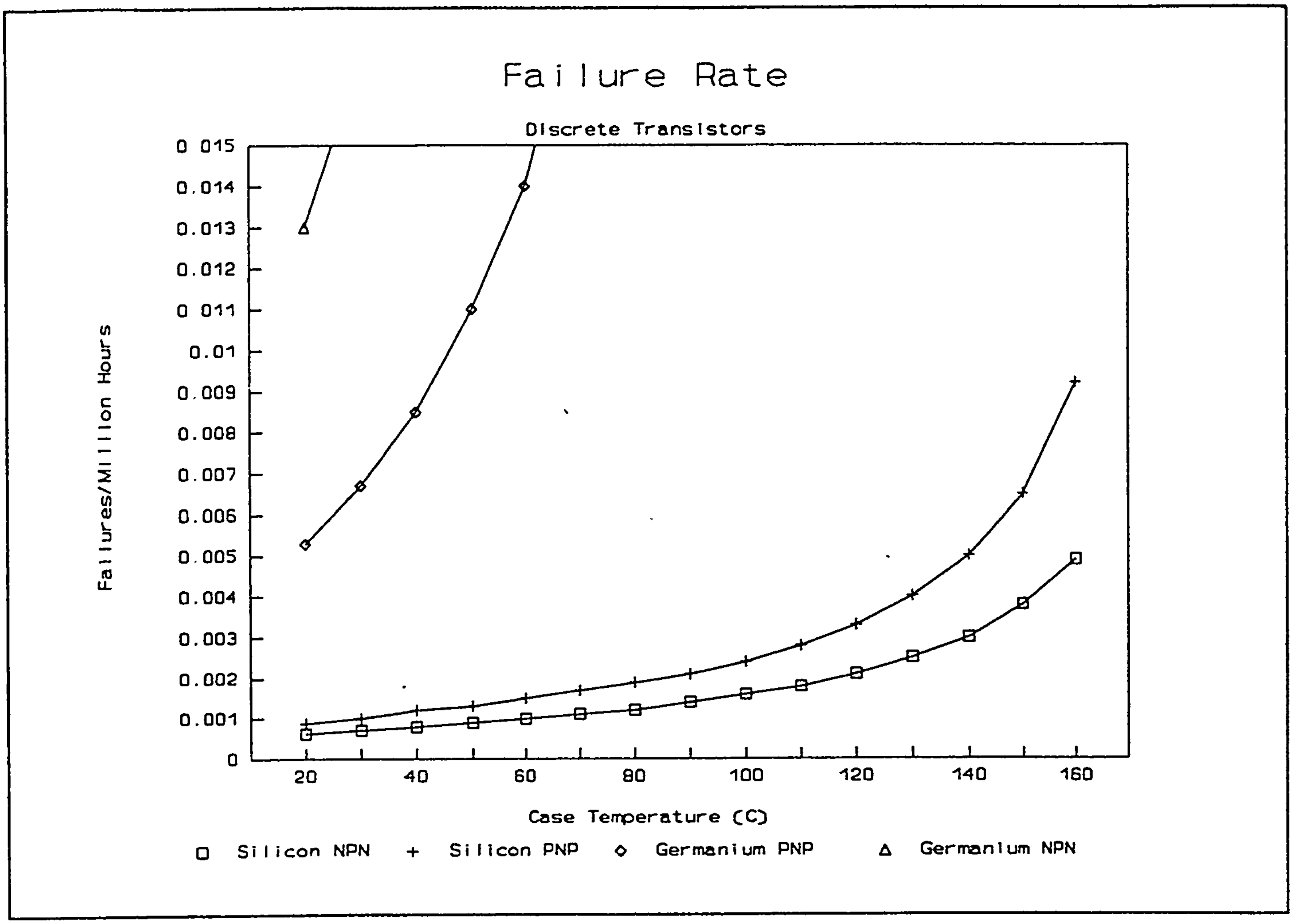
The failure rate of electronic components as a function of temperature is shown in Figures 1 through 8. Figure 9 shows the characteristic lifetime of motor components as a function of temperature. It can be observed that the failure rates are very sensitive to temperature, especially so for temperatures above about 80 °C. All types of electronic components exhibit extremely high failure rates above about 160 °C. In addition, the characteristic lifetime of motors degrades rapidly above 70 °C to the point that failures can be expected to occur almost monthly at temperatures above 140 °C.

Recommendations

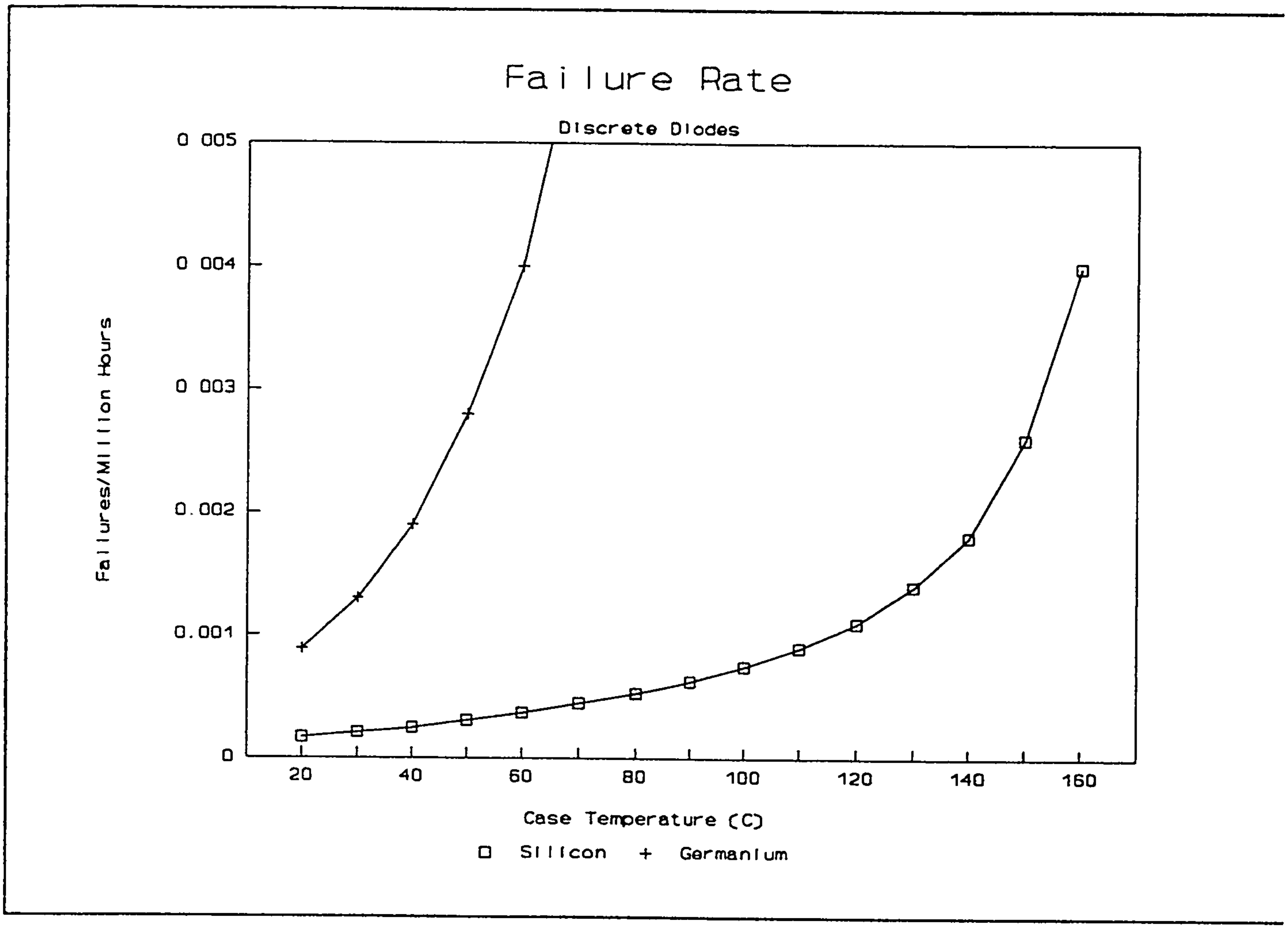
1. Operational concepts should be developed for all thermal loading options. Particular attention should be paid to electronic system maintenance for systems forced to operate above 80 °C.

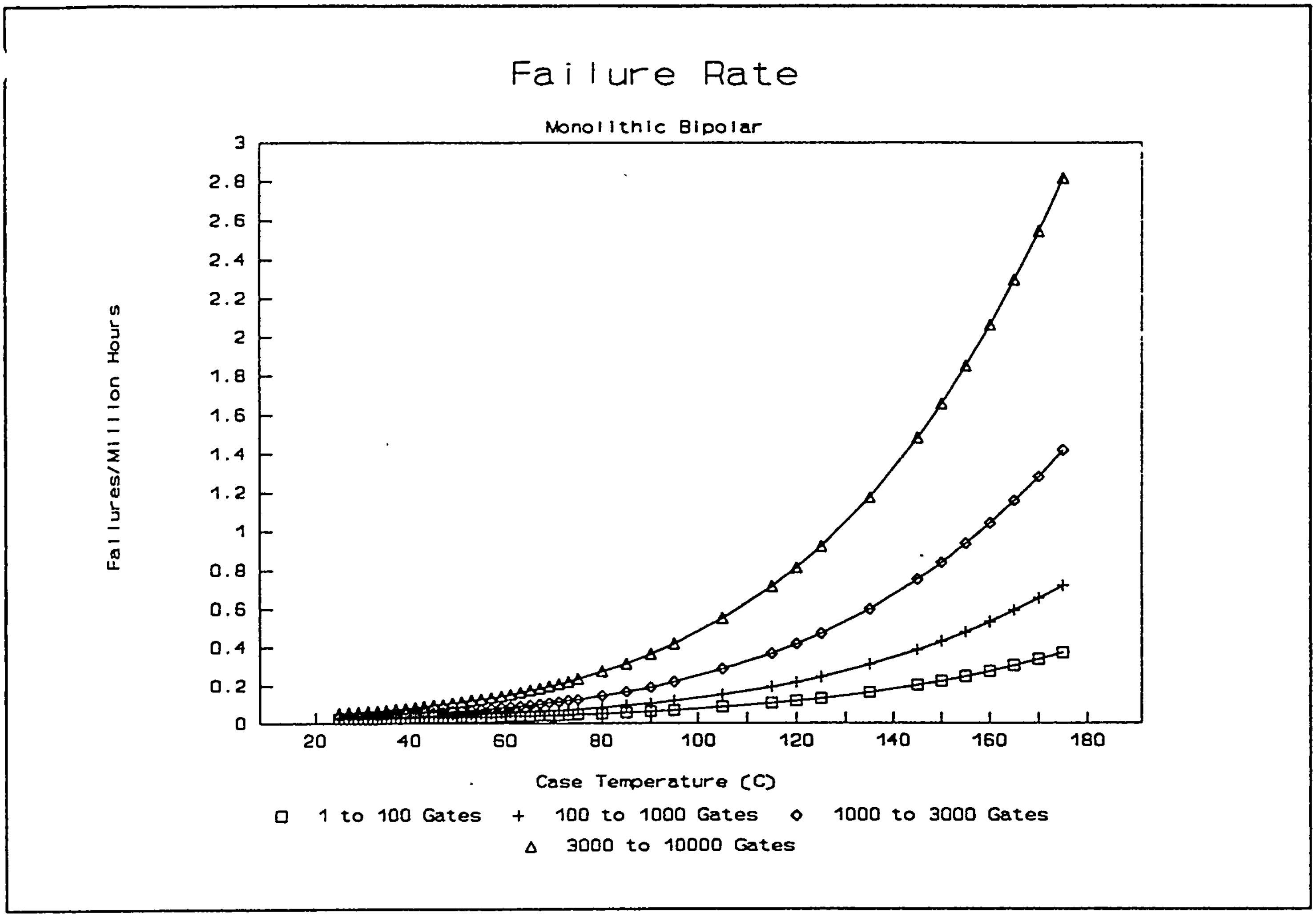
2. Options which require electronic systems to perform above 160 °C should not be considered unless active cooling (air conditioning, freon-type cooling loop, etc.) of those systems is employed.

3. A review of electronic system reliability at elevated temperatures, as opposed to the piece-part approach taken here, should be undertaken to define the capability of reasonable and available technology for the current application. It is likely, owing to the complexity of electronic systems, that the absolute upper temperature bound of 160 °C recommended above will prove to be too high.

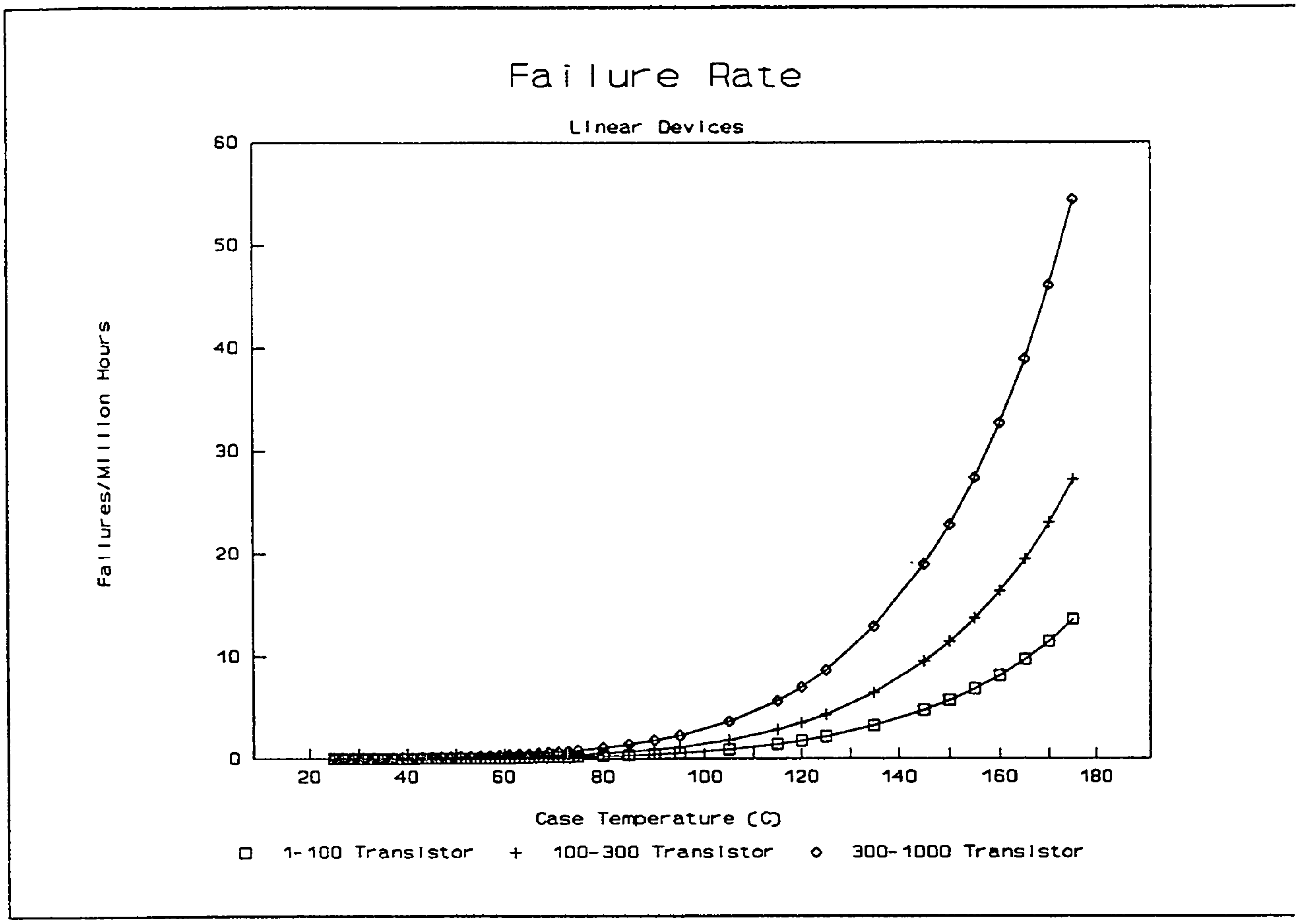


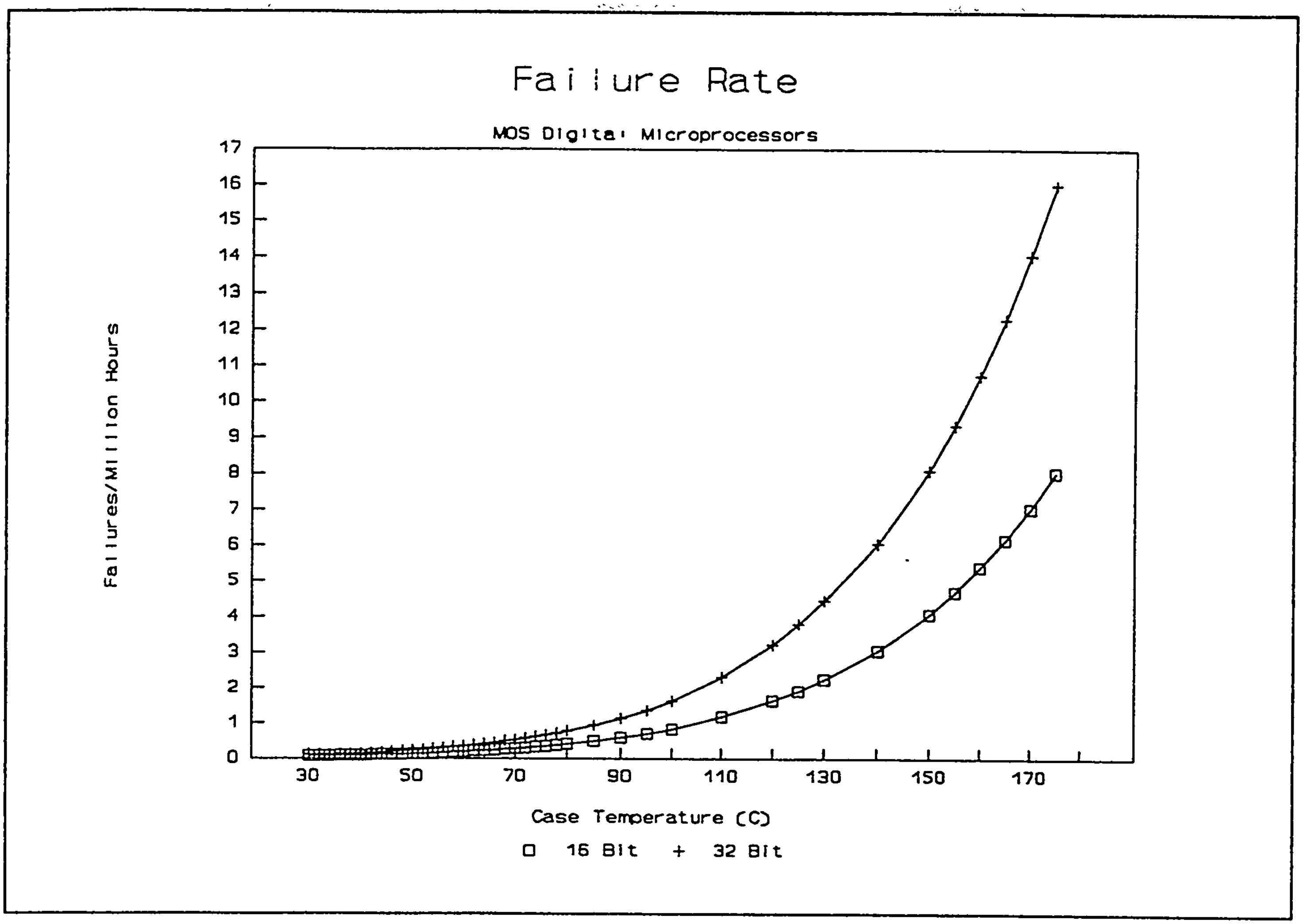
Failure Rate
Discrete Transistors
Failures/Million Hours
0 015
0.014
0.013
0.012
0 011
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
20
40
60
80
100
120
140
160
Case Temperature (C)
Silicon NPN
Silicon PNP
Germanium PNP
Germanium NPN


Failure Rate
Discrete Diodes
Failures/Million Hours
0.005
0.004
0.003
0.002
0.001
0
20
40
60
80
100
120
140
160
Case Temperature (C)
Silicon
Germanium

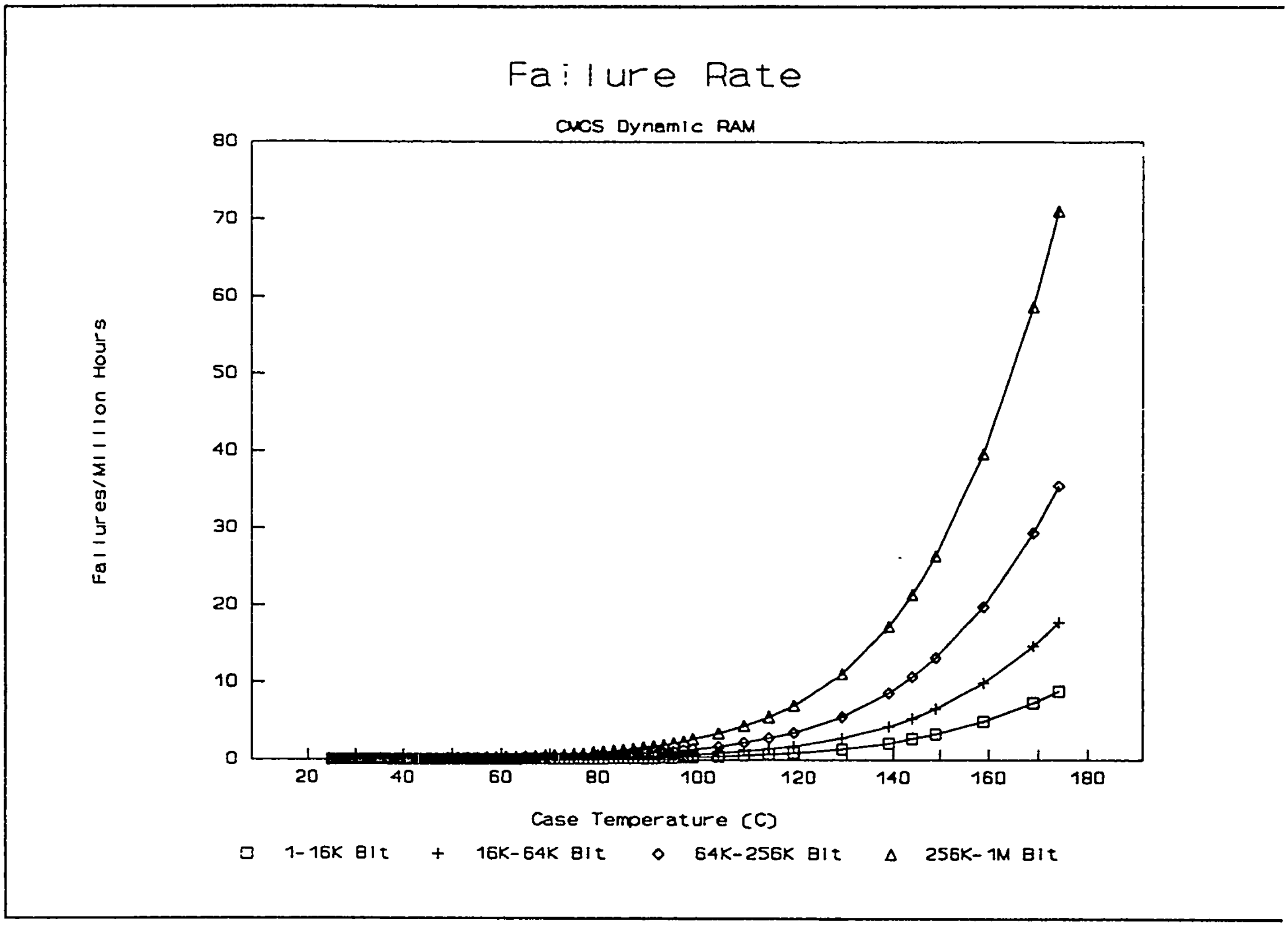


Failure Rate
Monolithic Bipolar
Failures/Million Hours
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
20
40
60
80
100
120
140
160
180
Case Temperature (C)
1 to 100 Gates
100 to 1000 Gates
1000 to 3000 Gates
3000 to 10000 Gates

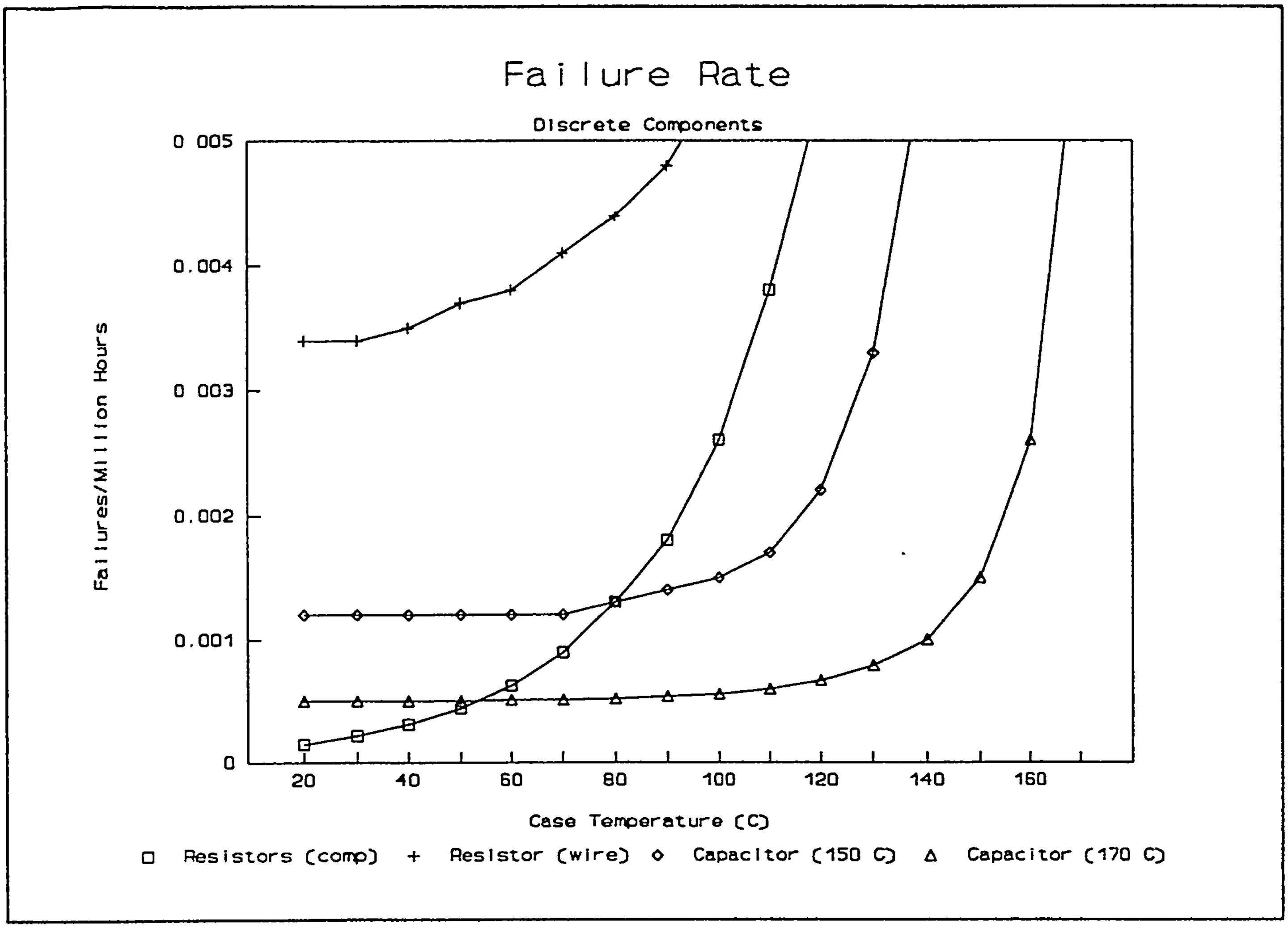

Failure Rate
Linear Devices
Failures/Million Hours
60
50
40
30
20
10
0
20
40
60
80
100
120
140
160
180
Case Temperature (C)
1-100 Transistor
100-300 Transistor
300-1000 Transistor



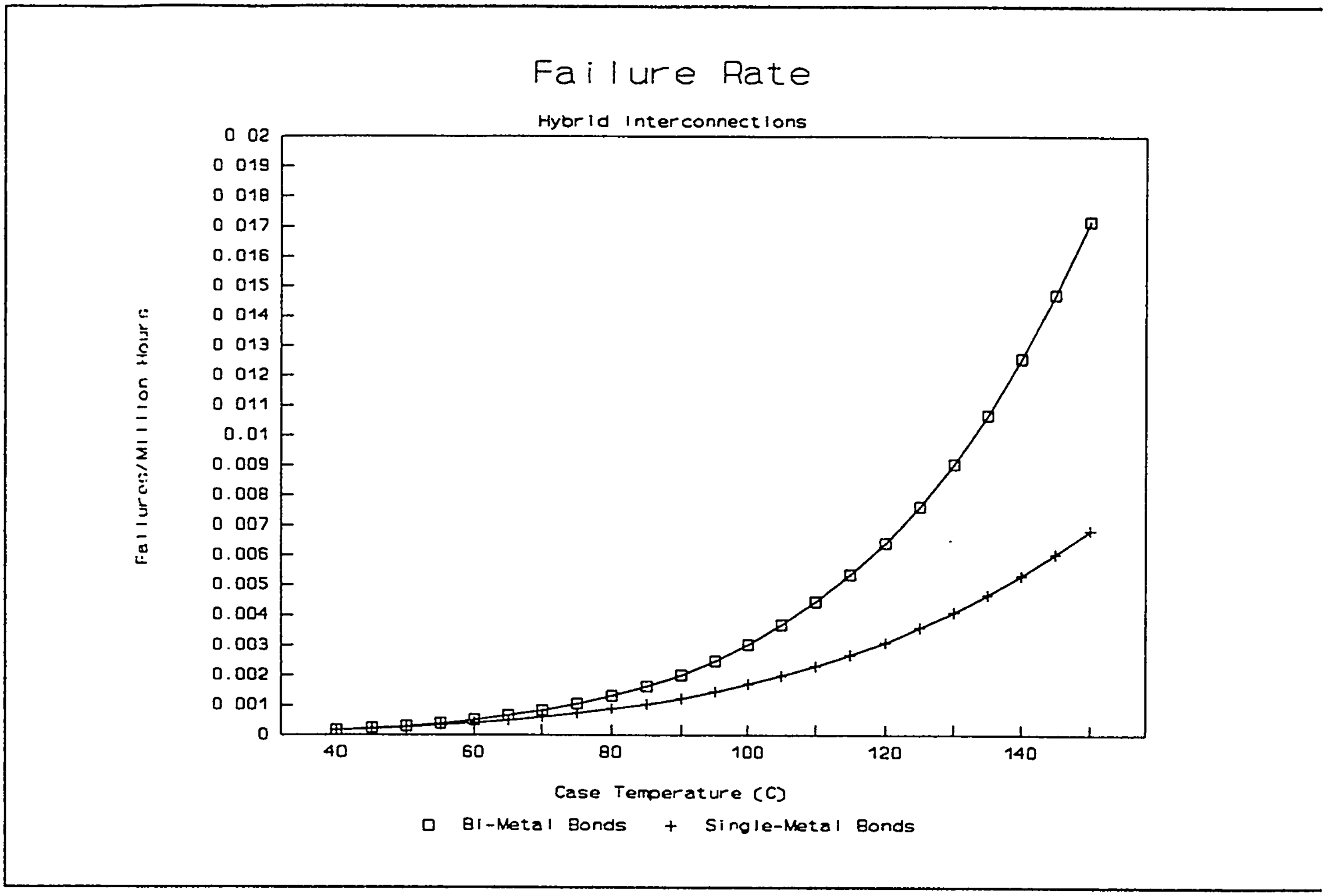
Failure Rate
MOS Digital Microprocessors
Failures/Million Hours
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
30
50
70
90
110
130
150
170
Case Temperature (C)
□ 16 Bit + 32 Bit

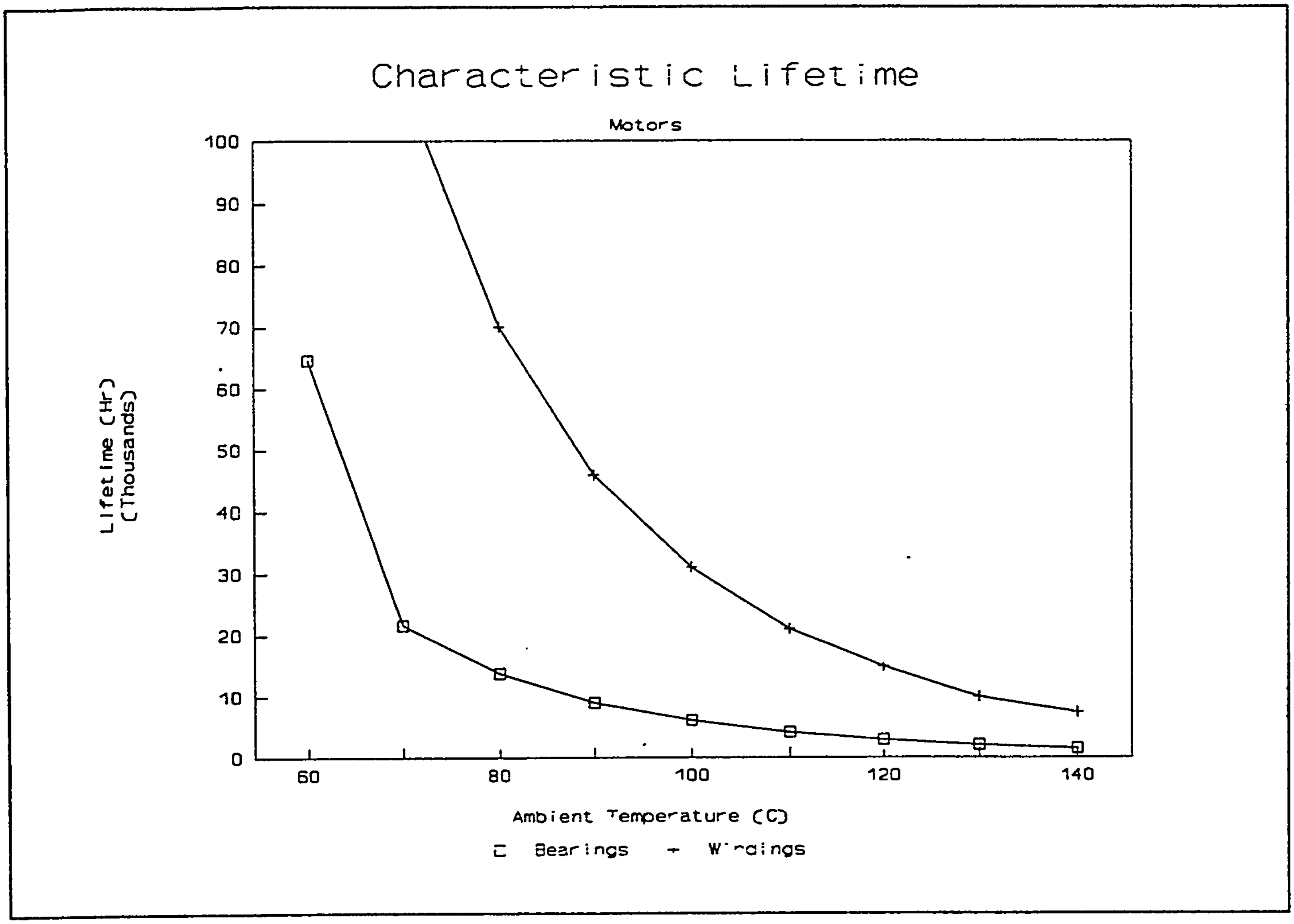


Failure Rate
CMOS Dynamic RAM
Failures/Million Hours
80
70
60
50
40
30
20
10
0
20
40
60
80
100
120
140
160
180
Case Temperature (C)
1-16K Bit
16K-64K Bit
64K-256K Bit
256K-1M Bit



Failure Rate
Discrete Components
Failures/Million Hours
0 005
0.004
0 003
0.002
0.001
0
20
40
60
80
100
120
140
160
Case Temperature (C)
Resistors (comp)
Resistor (wire)
Capacitor (150 C)
Capacitor (170 C)


Failure Rate
Hybrid Interconnections
Failures/Million Hours
0 02
0 019
0 018
0 017
0.016
0 015
0 014
0 013
0 012
0 011
0.01
0.009
0.008
0 007
0.006
0.005
0.004
0.003
0.002
0 001
0
40
60
80
100
120
140
Case Temperature (C)
Bi-Metal Bonds
Single-Metal Bonds



Characteristic Lifetime
Motors
100
90
80
70
60
50
40
30
20
10
0
Lifetime (Hr)
(Thousands)
60
80
100
120
140
Ambient Temperature (C)
Bearings
Windings

APPENDIX H

COST ANALYSIS DETAILS

Cost Analysis Details for the Yucca Mountain Site Characterization Project Cost Impacts Due to Thermal Loading

Justification of Cost Basis

The following excerpt from the Yucca Mountain Site Characterization Project Cost and Schedule Baseline (YMP/CM-0015) [DOE, (1993a)] summarizes the mission of the Yucca Mountain Site Characterization Project:

- Conduct site characterization to determine the geologic conditions at Yucca Mountain.
- Use data collected to evaluate site suitability of the site and to conduct performance assessments.
- Use data collected to prepare the waste package and repository designs in sufficient detail to support the license application.
- Prepare license application for submittal to NRC, if Yucca Mountain is found suitable as a potential repository site.

The Project technical, cost and schedule baselines were developed to support the Project mission. The Yucca Mountain Site Characterization Project Cost and Schedule Baseline document provides the planned work scopes required to satisfy the technical baseline. The major milestone in the Project schedule baseline is Project completion in October 2001 with the submittal of license application. The Total Project Cost (TPC) is reported as $6,319,337,000 in year of expenditure dollars.

Detailed Groundrules and Assumptions by Third Level WBS:

A key assumption described earlier in sections 3.5 and 3.6 of Volume I 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. 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.

1.2.1 Systems Engineering:
  a. No impact is assumed.

1.2.2 Waste Package:
  a. No impact is assumed.

1.2.3 Site Investigations:
  a. The Systematic Drilling (SD) program is modified based on the thermal loading decision. Table H-1 provides the emplacement areas for the desired AMLs.
  b. Each SD borehole is used to support unsaturated zone (UZ) testing.

c. For the purpose of costing and scheduling, as assumption on the thermal loading strategy will me made at the end of fiscal year 1994. The altered SD program is compatible schedule-wise with the existing SD program; the completion of any SD boreholes and associated UZ program activities is by FY 2000, in accordance with the Mission 2001 schedule. The Mission 2001 schedule has a more detailed schedule for the drilling program than the project cost and schedule baseline but has the same project completion date.

d. The area investigated in the SD program should be considered as the larger of the emplacement area and the areal extent of the boiling front based on the far-field thermal analysis performed in support of the Thermal Loading Study (see Table H-2 and Appendix F).

Table H-1 - Emplacement Areas for Desired AMLs

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

Table H-2 - Areal Extent of Boiling Front for Desired AMLs

AML (MTU/acre)	Areal Extent of Boiling Front (acre)
24	2598
36	1755
55	1139
83	755
111	583

e. The number of SD boreholes required is to be in the same proportion, boreholes/unit area, as currently planned (e.g., 12 SD borehole for the 1600 acres of the repository block [DOE, (1993b)].

f. The actual area required for the repository is larger than the above emplacement areas and areal extent of boiling front. The baseline repository area is approximately 1420 acres [DOE, (1991)]. With 1139 acres required for emplacement, there is approximately 281 acres set aside for subsurface common and support facilities, etc.

g. A fixed area, 180 acres, will be set aside as part of the repository block for uncertainty in the usable area. The fixed area is the difference between the 1600 acres in the repository block and the baseline repository area, 1420 acres. It is assumed that the repository block area required, due to uncertainty, is the same for all thermal loadings as in the baseline. Table H-3 describes the repository block area and the number of SD boreholes assumed in the SD program for each of the desired thermal loadings.

Table H-3 - Repository Block Areas and SD Boreholes for Desired AMLs

AML (MTU/acre)	Area Investigated (acre)	Common and Support Area (acre)	Uncertainty Area (acre)	Repository Block Area (acre)	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

h. Unsaturated-zone (UZ) percolation studies will require funding at a level of 0.5 million FY 94 $ per SD borehole to allow procurement, calibration, and installation of down hole equipment; air-permeability testing; and acquisition of instrument shelters. A flat rate of 0.3 million FY 94 $ per year will be required for monitoring of any and all additional boreholes [Rousseau, (1993)].

i. The productivity of the LM-300 drilling rigs is two boreholes/year [M&O, (1993a)].

j. One year of lead time is required for procurement of all LM-300 type drill rigs.

k. The total cost of each LM-300 drill rig is estimated at 6.49 million FY 94 $ [Pritchett, (1993)].

l. The major portion of the unit cost for an SD borehole of 4.71 million FY 94 $ is based on Table H-4 [St. Clair, (1993)].

Table H-4 - WBS 1.2.3 Elements Grouped by Priority and Functional Program
(Thousands of FY 94 $)

WBS	SCP Number	Title	Participant	Funding	Comments
		1.2.3 Site Investigations Total Priorities 1-4		**59000**	
Programs: Priority 1: ESF DESIGN SUPPORT			Priority 1 Total:	**22565**	
Two Deep Boreholes (Systematic Drilling Program)			Subtotal:	**9418**	
1.2.3.2.2.2.1	8.3.1.4.3.1	Systematic Acq. of Site Specific Subsurface Info.	SNL	455	
1.2.3.2.2.2.2	8.3.1.4.3.2	3-D Rock Charact. Models	SNL	302	
1.2.3.5.1		Sample Management Facility	REECo	233	2/3 of Support
1.2.3.5.1		Sample Management Facility	TMSS	2000	2/3 of Support
1.2.3.5.2.1	8.3.1	Common-to-Drilling Support	REECo	2487	2/3 of Support
1.2.3.5.2.2	8.3.1	Engineering, Design and Drilling	RSN	1333	2/3 of Support
1.2.3.5.2.2	8.3.1	Engineering, Design and Drilling	T&MSS	400	2/3 of Support
1.2.3.5.2.2	8.3.1	Engineering, Design and Drilling	LLNL	25	
1.2.3.5.3.17	8.3.1.4.3.1	Geostatistical Drillholes	REECo	1500	
1.2.3.5.3.23		Access & Pad Construction	REECo	266	
1.2.3.9.3		Test Interference Evaluations	M&O	167	2/3 of Support
1.2.3.9.4		Tracers, Fluids and Materials	M&O	100	2/3 of Support
1.2.3.9.4		Tracers, Fluids and Materials	EG&G	33	2/3 of Support
1.2.3.9.6		Field Test Coordinator Support	USBR	117	2/3 of Support
Four Ramp Boreholes (Soil & Rock Properties)			Subtotal:	**4735**	
1.2.3.2.6.2.1	8.3.1.14.2.1	Surface Fac. Explor. Program	SNL	220	
1.2.3.2.6.2.2	8.3.1.14.2.2	Surface Fac. Lab Tests & Material Prop.	SNL	71	
1.2.3.2.6.2.3	8.3.1.14.2.3	Surface Fac. Field Tests & Char. Meas.	SNL	425	
1.2.3.5.1		Sample Management Facility	REECo	117	1/3 of Support
1.2.3.5.1		Sample Management Facility	TMSS	1000	1/3 of Support
1.2.3.5.2.1	8.3.1	Common-to-Drilling Support	REECo	1243	1/3 of Support
1.2.3.5.2.2	8.3.1	Engineering, Design and Drilling	RSN	667	1/3 of Support
1.2.3.5.2.2	8.3.1	Engineering, Design and Drilling	T&MSS	200	1/3 of Support
1.2.3.5.3.20	8.3.1.14.2.1	Surface Facilities Drillholes	REECo	450	1/3 of Support
1.2.3.5.3.23		Access & Pad Construction	REECo	134	1/3 of Support
1.2.3.9.3		Test Interference Evaluations	M&O	83	1/3 of Support
1.2.3.9.4		Tracers, Fluids and Materials	M&O	50	1/3 of Support
1.2.3.9.4		Tracers, Fluids and Materials	EG&G	17	1/3 of Support
1.2.3.9.6		Field Test Coordinator Support	USBR	58	1/3 of Support
Stratigraphy/Structure for ESF Design Support			Subtotal:	**1955**	
1.2.3.2.2.1.1	8.3.1.4.2.1	Vert. and Lat. Dist. of Strat. Units in Site	USGS	300	
1.2.3.2.2.1.2	8.3.1.4.2.2	Structural Features Within the Site Area	USGS	350	
1.2.3.2.8.4.2	8.3.1.17.4.2	Loc. & Rec. of Flt. Near Prosp. Surf. Facil.	USGS	110	
1.2.3.5.2.4		Title III Engineering For SBT	M&O	15	
1.2.3.5.3.22	8.3.1.17.4.8	In Situ Strs. Drlhle. & Tsts., & Qua. Flt.	REECo	100	
1.2.3.9.5		3-D Site Model	M&O	450	
1.2.3.9.5		3-D Site Model	EG&G	630	
Laboratory Testing of ESF and Borehole Samples			Subtotal:	**2282**	
1.2.3.2.7.1.1	8.3.1.15.1.1	Lab. Thermal Properties	SNL	880	
1.2.3.2.7.1.2	8.3.1.15.1.2	Lab. Thermal Expansion Testing	SNL	332	
1.2.3.2.7.1.3	8.3.1.15.1.3	Lab. Determin. of Mech. Prop. of Intact	SNL	470	
1.2.3.2.7.1.4	8.3.1.15.1.4	Lab. Determ. of the Mech. Prop. of	SNL	600	
Geophysics			Subtotal:	**780**	
1.2.3.11.1		Borehole Geophysical Logging	RSN	580	
1.2.3.11.3		ESF Geophysics	LLNL	200	
Coordination and Planning			Subtotal:	**3395**	
1.2.3.1		Coordination and Planning	M&O	1800	
1.2.3.1		Coordination and Planning	T&MSS	920	
1.2.3.1		Coordination and Planning	SNL	225	
1.2.3.1		Coordination and Planning	USGS	450	

m. Laboratory testing of the SD borehole samples will cost 0.75 million FY 94 $ per borehole [Datta, (1993)].

n. Site Investigations Coordination and Planning cost deltas will be applied at 15 percent of the total altered SD program cost delta. This is based on the Table H-4 for Priority 1 activities [St. Clair, (1993)]

1.2.4 Repository:

a. No impact is assumed.

1.2.5 Regulatory:

a. The impact is indeterminate, but no impact is assumed. Both the M&O Performance Assessment and Modeling group and Regulatory and Licensing group feel that the cost will increase as the uncertainty in total system performance increases [Nelson, (1993)] and [Weaver, (1993)]. The impact of thermal loading on total system performance uncertainty is not fully understood.

1.2.6 Exploratory Studies Facility (ESF):

a. Any Exploratory Studies Facility (ESF) 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 <u>processes</u> will be adequately addressed with currently planned excavations, and <u>features</u> will be investigated with surface-based techniques [Johnson, (1993)]. Another idea suggested it would be difficult to license an expanded repository area without an examination of the extent of the potential repository area [McKenzie, (1993)]. A compromise position offered by the Regulatory & Licensing group [Lugo, (1993)] stated that the current ESF design resolves the NRC concerns and that the idea that no additional or reduced drifting is necessary was reasonable, but suggested that additional drifting in the expansion areas could be done contingently 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 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 of this issue and a more detailed examination of this issue will be needed at a later date.

1.2.7 Test Facilities:

a. The cost of one mile of road per SD borehole for drilling access [Datta, (1993)] will be estimated at 0.3 million FY 94 $ per mile of construction and maintenance [McKinnon, (1993)]. 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. Also, they may be slightly over estimated since there is a small cost for roads in the 1.2.3 element already.

b. Minimal facilities delta costs are expected due to the small variation in work scope required at the site.

1.2.8 (Reserved)

a. No work is performed in this element.

1.2.9 Project Management

a. No impact is assumed.

1.2.10 Financial/Technical Assistance:

a. No impact is assumed.

1.2.11 Quality Assurance (QA):

a. No impact is assumed.

1.2.12 Information Management:

a. No impact is assumed.

1.2.13 Environment, Safety and Health:

a. Additional land access, if needed, would be obtained at minimal project cost [Jacobs, (1993)]. Environment, safety and health cost impacts are minimal [McCann, (1993)]. The impact on the Terrestrial Ecosystems program is at most a 10% increase from the current baseline ($3 million) program for the lower than baseline thermal loading cases [Ostler, (1993)].

1.2.14 Institutional:

a. No impact is assumed.

1.2.15 Support Services:

a. No impact is assumed.

Analysis Details:

The costs from the identified WBS areas, 1.2.3, 1.2.7 and 1.2.13, are described below.

WBS 1.2.3 Site Investigation Costs:

The number of drill rigs required for each thermal loading will be identified. Since over five full years of drilling is possible for each LM-300 before FY 2000, each LM-300 drill rig procured could drill approximately 10 SD holes. Based on this information, only one additional drill rig will be required for the 24 and 36 MTU/acre thermal loadings at a cost of $6.49 million. No reduction in the number of drill rigs can be justified for the 83 and 111 MTU/acre thermal load cases.

The total fixed cost per SD borehole is summarized in Table H-5 below.

Table H-5 - Total Fixed Cost per SD Borehole

Cost Description	Costs (Millions of FY 94 $)
Drilling	4.71
Laboratory Testing	0.75
UZ Percolation Studies	0.50
Total	**5.96**

The cost of monitoring UZ boreholes was estimated at 0.3 million FY 94 $ per year. At five years for drilling possible, a hole drilled in the first possible year will cost $1.5 million, a hole drilled in the second possible year will cost $1.2 million, etc. For the 24 MTU/acre thermal loading case, eleven additional SD boreholes are required. A total of 31 additional years of monitoring is assumed for this case at $0.3 million per year for a total delta cost of $9.3 million. For the 36 MTU/acre thermal loading, five additional SD boreholes are required. A total of 21 additional years of monitoring is assumed for a total delta cost of $6.3 million. For the 83 MTU/acre thermal loading case, three less SD boreholes are required. A total of four less years of monitoring is assumed for this case for a total delta cost of $1.2 million. For the 111 MTU/acre thermal loading case, four less SD boreholes are required. A total of six less years of monitoring is assumed for this case for a total delta cost of $1.8 million.

The WBS 1.2.3 related delta costs by thermal loading are summarized below in Table H-6.

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

AML (MTU/acre)	Delta Number of SD Bore-holes Required	LM-300 Drill Rig Cost (Millions of FY 94 $)	Fixed SD Borehole Cost (Millions of FY 94 $)	UZ Monitoring Cost (Millions of FY 94 $)	Subtotal (Millions of FY 94 $)	Coordination and Planning (Millions of FY 94 $)	Total 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)

WBS 1.2.7 Test Facilities Costs:

The cost of roads to access the SD boreholes is the main cost impact identified in this WBS element. Table H-7 provides the delta costs for the desired AMLs.

WBS 1.2.13 Environment, Safety and Health Costs:

The cost of the Terrestrial Ecosystems program is the main cost impact identified in this WBS element. Table H-8 provides the delta costs for the desired AMLs.

Table H-7 - WBS 1.2.7 Test Facilities Delta Cost for Desired AMLs

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

Table H-8 - WBS 1.2.13 Environment, Safety and Health Delta Cost for Desired AMLs

AML (MTU/acre)	Terrestrial Ecosystems Cost (Millions of FY 94 $)	Total Delta Cost (Millions of FY 94 $)
24	0.3	0.3
36	0.3	0.3
55	0	0
83	0	0
111	0	0

Table H-9, "ESAAB Approved Baseline", provides the baseline costs in constant FY 91 dollars. The total project cost in FY 91 dollars is $5,685,291,000. In order to put the total project cost in FY 94 $, it was escalated using the escalation rates from Table H-10. The baseline cost in

Table H-9 - ESAAB Approved Baseline
(Thousands of FY 91 $)

Includes Capital Equipment

WBS	PRIOR	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	FUTURE	TOTAL
1.2	1068125	340067	603801	597210	581946	579019	491178	442547	381103	326755	261989	11551	5685291
1.2.1	80935	41426	42885	43216	42434	40344	38185	35326	30919	24901	18041	912	439524
1.2.2	84657	22021	29140	29277	27784	27663	22104	13627	8116	3938	2453	2339	273119
1.2.3	287151	114367	139467	133352	108902	94785	74343	54587	43750	31930	29422	1336	1113392
1.2.4	92565	26425	28421	28080	30803	31832	46260	45351	44775	39043	34740	2661	450956
1.2.5	83698	24700	24721	27760	26864	28885	30204	31291	32858	33465	37094	518	382058
1.2.6	106039	19823	121396	87816	128074	130752	72612	70607	37194	26500	2000	0	802813
1.2.7	23733	6000	37011	55256	40520	39392	31008	28700	26800	23200	1850	0	313470
1.2.8	1285	196	195	195	194	195	195	265	265	265	264	0	3514
1.2.9	243042	70249	77292	89584	75097	84151	83233	74180	73398	65426	63938	3690	1003280
1.2.10	65020	14860	103273	102674	101274	101020	93034	88613	83028	78087	72187	95	903165

Table H-10 Escalation Rates February 1993 Update

Index for 1992$		Index for 1993$	ENERGY RESEARCH & NUCLEAR	Index for 1994$	FOSSIL	CONSERVATION SOLAR	DEFENSE PROGRAMS, EM & GENERAL CONSTRUCTION
	1976		6.1		6.0	5.7	5.2
	1977		6.2		6.3	6.0	6.0
	1978		7.1		7.3	6.8	7.3
	1979		9.1		9.6	9.1	8.9
	1980		9.7		10.1	10.7	9.7
	1981		9.2		9.4	9.1	8.1
	1982		6.8		6.6	6.5	6.3
	1983		3.0		2.6	2.9	3.1
	1984		2.4		2.2	2.4	2.4
	1985		2.1		1.9	2.0	1.6
1.187	1986	1.217	1.3	1.255	0.6	1.3	1.1
1.165	1987	1.193	1.9	1.232	1.8	1.8	1.8
1.120	1988	1.147	4.0	1.185	4.7	4.0	3.2
1.075	1989	1.101	4.2	1.137	4.4	4.5	3.2
1.045	1990	1.071	2.8	1.106	2.3	2.9	2.3
1.018	1991	1.042	2.7	1.077	2.2	2.7	2.2
1.000	1992	1.024	1.8	1.058	1.3	1.6	1.2
	1993	1.000	2.4	1.033	2.3	2.4	1.9
	1994		3.3	1.000	3.3	3.2	2.5
	1995		3.6		3.6	3.6	3.0
	1996		3.7		3.7	3.6	3.2
	1997		3.7		3.7	3.6	3.4
	1998		3.6		3.6	3.5	3.3
	1999		3.6		3.6	3.5	3.2
	2000		3.8		3.8	3.7	3.3
	2001		3.9		3.8	3.8	3.3
	2002		3.9		3.8	3.8	3.5

constant FY 94 dollars is $6,123,058,000 (1.077 inflation factor or index, [Yurow, (1993)]. Typically the prior costs are not escalated, but for this study the cost basis was used as a reference point from which delta costs were added to indicate the magnitude of the changes. The analysis developed delta costs from this baseline in 1994 constant year dollars for different assumed thermal loadings of the potential repository. These cost deltas and total project costs are summarized in Table H-11 below.

Table H-11 - Site Characterization Delta Cost and Total Project Cost for Desired AMLs

AML (MTU/acre)	Baseline Cost (Millions of FY 94 $)	Delta Costs (Millions of FY 94 $)	Total Project 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

Cost Analysis Details for the Repository Life Cycle Cost Impacts Due to Thermal Loading

Justification of Cost Basis

Except for the Yucca Mountain Site Characterization Project, the Program Cost and Schedule Baseline (PCSB) (DOE/RW-0253) [DOE, (1992)] does not control the cost of the First Repository Life Cycle Costs (LCC) as a baseline. The First Repository Life Cycle Costs that are not baselined include the Engineering and Construction, Emplacement Operations, Caretaker Operations, and the Decommissioning and Closure phases of the life cycle. The Yucca Mountain Site Characterization Project portion of the First Repository Life Cycle is referred to as the Development and Evaluation (D&E) phase and the remainder is referred to as post-D&E. The PCSB states "OCRWM regularly prepares costs estimates that extend beyond the end of the baseline. The source for all such cost estimates is the most recent approved Total System Life Cycle Cost (TSLCC) analysis performed in conjunction with the annual fee adequacy assessment." Case 4 of the MRS System Study for the Repository, (SAND89-7006) [SNL, (1990)], was the basis for the repository input to the last officially published TSLCC report, "Analysis of the Total System Life Cycle Cost for the Civilian Radioactive Waste Management Program," (DOE/RW-0236) [DOE, (1989a)], and its addendum "Preliminary Estimates of the Total-System Cost for the Restructured 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) [DOE, (1990)]. Although not formally incorporated into the technical baseline, the changes of the potential repository made in Case 4 of the MRS System Study for the Repository have been recommended for use in TSLCC exercises by the DOE. Therefore, these costs were used as a cost basis for the Thermal Loading Study. The schedule assumptions for the reference case were based on the Addendum to the 1989 TSLCC which used the guidance in the "Report to Congress on Reassessment of the Civilian Radioactive Waste Management Program," (DOE/RW-0247) [DOE, (1989b)].

Analysis Details

The cost data for Figure 6-1 of the report were taken from the Waste Package Performance Allocation Study report [M&O, (1993b)] but escalated to FY 94 $ from FY 93 $. The escalation factor of 1.033 was applied to the cost estimates from the referenced report to obtain the cost data for Figure 6-1. Table H-10, Escalation Rates February 1993 Update, [Yurow, (1993)] contains the escalation rates used for the escalation of all dollars from previous estimates that were created in a different base year. The column entitled Energy Research & Nuclear was used for the escalation rates. The escalation rate for the year 1994 is 3.3. This is the percentage of increase that should be applied to escalate an estimate from FY 93 $ to FY 94 $. The cost data for Figure 6-2 is provided in the following Tables H-12 through H-45 in the row entitled Subsurface Excavations. The cost data for Figure 6-3 was just the combination of the Yucca Mountain Site Characterization Project cost estimates and one of the Repository LCC (post-D&E) estimates.

The Repository LCC Summaries provided in Tables H-12 through H-45 utilize values from the cost basis for areas that were not determined to vary with the design parameters considered. The costs that were updated in this analysis are based on cost estimates provided by the M&O Repository Surface Design, Repository Subsurface Design, and Waste Package Development groups. Details of the cost inputs provided to support this study can be found in references: [Bali, (1993)], [Bhattacharyya and Rasmussen, (1993)] and [Wallin (1993)]. The method that was used to assemble these cost inputs was described in more detail in the Cost Data Appendix of the Waste Package Performance Allocation Study [M&O, (1993b)].

Table H-12 Repository LCC (post-D&E) for Cost Basis

Cost Basis	**Repository LCC (post-D&E) Millions of 1994 $**					
	Engineering & Construction	**Emplacement Operations**	**Caretaker Operations**	**Closure**	**Decommissioning**	**Total**
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$488.78	$2,073.49	$261.46	$51.84	$40.42	$2,915.99
Shafts/Ramps - Underground	$77.70	$17.42	$18.87	$4.36	$0.00	$118.35
Subsurface Excavations	$179.20	$1,139.76	$58.62	$145.32	$0.00	$1,522.89
Underground Service Systems	$124.73	$863.31	$233.79	$195.30	$0.00	$1,417.13
Waste Package Fabrication	$0.00	$1,511.30	$10.36	$0.00	$0.00	$1,521.66
Total Repository	$1,413.25	$5,747.00	$633.83	$418.25	$95.78	$8,308.12

Table H-13 Repository LCC (post-D&E) for Case 0

Case 0	Repository LCC (post-D&E) Millions of 1994 $					
	Engineering & Construction	Emplacement Operations	Caretaker Operations	Closure	Decommissioning	Total
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$355.32	$2,397.15	$261.46	$51.83	$40.42	$3,106.18
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$1,217.62	$1,117.54	$58.63	$235.10	$0.00	$2,628.88
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$2,895.37	$18.56	$0.00	$0.00	$2,913.93
Total Repository	$2,319.32	$7,453.61	$644.92	$515.67	$95.78	$11,029.31

Table H-14 Repository LCC (post-D&E) for Case 1 (HLW Cost Not Included in Subsurface Excavations)

Case 1	Repository LCC (post-D&E) Millions of 1994 $					
	Engineering & Construction	Emplacement Operations	Caretaker Operations	Closure	Decommissioning	Total
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$397.16	$2,519.07	$261.46	$51.83	$40.42	$3,269.94
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$925.90	$756.01	$58.63	$186.21	$0.00	$1,926.75
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$5,523.84	$28.16	$0.00	$0.00	$5,552.00
Total Repository	$2,069.45	$9,842.46	$654.52	$466.79	$95.78	$13,129.01

Table H-15 Repository LCC (post-D&E) for Case 2 (HLW Cost Not Included in Subsurface Excavations)

Case 2	Repository LCC (post-D&E) Millions of 1994 $					
	Engineering & Construction	Emplacement Operations	Caretaker Operations	Closure	Decommissioning	Total
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$397.16	$2,519.07	$261.46	$51.83	$40.42	$3,269.94
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$875.44	$740.08	$58.63	$177.09	$0.00	$1,851.24
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$5,523.84	$28.16	$0.00	$0.00	$5,552.00
Total Repository	$2,018.98	$9,826.53	$654.52	$457.67	$95.78	$13,053.50

Table H-16 Repository LCC (post-D&E) for Case 3 (HLW Cost Not Included in Subsurface Excavations)

Case 3	Repository LCC (post-D&E) Millions of 1994 $					
	Engineering & Construction	Emplacement Operations	Caretaker Operations	Closure	Decommissioning	Total
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$397.16	$2,519.07	$261.46	$51.83	$40.42	$3,269.94
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$839.82	$728.83	$58.63	$170.65	$0.00	$1,797.93
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$5,523.84	$28.16	$0.00	$0.00	$5,552.00
Total Repository	$1,983.36	$9,815.29	$654.52	$451.23	$95.78	$13,000.19

Table H-17 Repository LCC (post-D&E) for Case 4 (HLW Cost Not Included in Subsurface Excavations)

Case 4	Repository LCC (post-D&E) Millions of 1994 $					
	Engineering & Construction	Emplacement Operations	Caretaker Operations	Closure	Decommissioning	Total
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$397.16	$2,519.07	$261.46	$51.83	$40.42	$3,269.94
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$1,007.37	$2,121.87	$58.63	$128.97	$0.00	$3,316.84
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$5,523.84	$28.16	$0.00	$0.00	$5,552.00
Total Repository	$2,150.91	$11,208.33	$654.52	$409.55	$95.78	$14,519.10

Table H-18 Repository LCC (post-D&E) for Case 5 (HLW Cost Not Included in Subsurface Excavations)

Case 5	Repository LCC (post-D&E) Millions of 1994 $					
	Engineering & Construction	Emplacement Operations	Caretaker Operations	Closure	Decommissioning	Total
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$397.16	$2,519.07	$261.46	$51.83	$40.42	$3,269.94
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$846.34	$2,068.95	$58.63	$99.87	$0.00	$3,073.79
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$5,523.84	$28.16	$0.00	$0.00	$5,552.00
Total Repository	$1,989.89	$11,155.41	$654.52	$380.45	$95.78	$14,276.05

Table H-19 Repository LCC (post-D&E) for Case 6 (HLW Cost Not Included in Subsurface Excavations)

Case 6	Repository LCC (post-D&E) Millions of 1994 $					
	Engineering & Construction	Emplacement Operations	Caretaker Operations	Closure	Decommissioning	Total
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$397.16	$2,519.07	$261.46	$51.83	$40.42	$3,269.94
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$731.33	$2,031.15	$58.63	$79.08	$0.00	$2,900.19
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$5,523.84	$28.16	$0.00	$0.00	$5,552.00
Total Repository	$1,874.87	$11,117.61	$654.52	$359.66	$95.78	$14,102.45

Table H-20 Repository LCC (post-D&E) for Case 7 (HLW Cost Not Included in Subsurface Excavations)

Case 7	Repository LCC (post-D&E) Millions of 1994 $					
	Engineering & Construction	Emplacement Operations	Caretaker Operations	Closure	Decommissioning	Total
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$397.16	$2,519.07	$261.46	$51.83	$40.42	$3,269.94
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$622.09	$2,120.74	$58.63	$152.85	$0.00	$2,954.31
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$5,523.84	$28.16	$0.00	$0.00	$5,552.00
Total Repository	$1,765.63	$11,207.20	$654.52	$433.43	$95.78	$14,156.57

Table H-21 Repository LCC (post-D&E) for Case 8 (HLW Cost Not Included in Subsurface Excavations)

Case 8	Repository LCC (post-D&E) Millions of 1994 $					
	Engineering & Construction	Emplacement Operations	Caretaker Operations	Closure	Decommissioning	Total
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$397.16	$2,519.07	$261.46	$51.83	$40.42	$3,269.94
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$573.45	$2,105.39	$58.63	$144.06	$0.00	$2,881.52
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$5,523.84	$28.16	$0.00	$0.00	$5,552.00
Total Repository	$1,716.99	$11,191.84	$654.52	$424.64	$95.78	$14,083.78

Table H-22 Repository LCC (post-D&E) for Case 9 (HLW Cost Not Included in Subsurface Excavations)

Case 9	Repository LCC (post-D&E) Millions of 1994 $					
	Engineering & Construction	Emplacement Operations	Caretaker Operations	Closure	Decommissioning	Total
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$397.16	$2,519.07	$261.46	$51.83	$40.42	$3,269.94
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$539.12	$2,094.55	$58.63	$137.85	$0.00	$2,830.15
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$5,523.84	$28.16	$0.00	$0.00	$5,552.00
Total Repository	$1,682.66	$11,181.01	$654.52	$418.43	$95.78	$14,032.40

Table H-23 Repository LCC (post-D&E) for Case 10 (HLW Cost Not Included in Subsurface Excavations)

Case 10	**Repository LCC (post-D&E) Millions of 1994 $**					
	Engineering & Construction	**Emplacement Operations**	**Caretaker Operations**	**Closure**	**Decommissioning**	**Total**
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$397.16	$2,519.07	$261.46	$51.83	$40.42	$3,269.94
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$1,507.07	$2,148.50	$58.63	$262.33	$0.00	$3,976.52
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$5,523.84	$28.16	$0.00	$0.00	$5,552.00
Total Repository	$2,650.62	$11,234.96	$654.52	$542.91	$95.78	$15,178.78

Table H-24 Repository LCC (post-D&E) for Case 11 (HLW Cost Not Included in Subsurface Excavations)

Case 11	Repository LCC (post-D&E) Millions of 1994 $					
	Engineering & Construction	Emplacement Operations	Caretaker Operations	Closure	Decommissioning	Total
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$397.16	$2,519.07	$261.46	$51.83	$40.42	$3,269.94
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$1,458.43	$2,133.14	$58.63	$253.54	$0.00	$3,903.74
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$5,523.84	$28.16	$0.00	$0.00	$5,552.00
Total Repository	$2,601.98	$11,219.60	$654.52	$534.11	$95.78	$15,106.00

Table H-25 Repository LCC (post-D&E) for Case 12 (HLW Cost Not Included in Subsurface Excavations)

Case 12	Repository LCC (post-D&E) Millions of 1994 $					
	Engineering & Construction	Emplacement Operations	Caretaker Operations	Closure	Decommissioning	Total
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$397.16	$2,519.07	$261.46	$51.83	$40.42	$3,269.94
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$1,424.10	$2,122.31	$58.63	$247.33	$0.00	$3,852.36
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$5,523.84	$28.16	$0.00	$0.00	$5,552.00
Total Repository	$2,567.64	$11,208.76	$654.52	$527.91	$95.78	$15,054.62

Table H-26 Repository LCC (post-D&E) for Case 13 (HLW Cost Not Included in Subsurface Excavations)

Case 13	Repository LCC (post-D&E) Millions of 1994 $					
	Engineering & Construction	Emplacement Operations	Caretaker Operations	Closure	Decommissioning	Total
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$373.26	$2,454.11	$261.46	$51.83	$40.42	$3,181.08
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$438.86	$1,193.65	$58.63	$112.39	$0.00	$1,803.53
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$4,485.54	$15.86	$0.00	$0.00	$4,501.40
Total Repository	$1,558.50	$9,176.85	$642.22	$392.97	$95.78	$11,866.33

Table H-27 Repository LCC (post-D&E) for Case 14 (HLW Cost Not Included in Subsurface Excavations)

Case 14	**Repository LCC (post-D&E) Millions of 1994 $**					
	Engineering & Construction	**Emplacement Operations**	**Caretaker Operations**	**Closure**	**Decommissioning**	**Total**
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$373.26	$2,454.11	$261.46	$51.83	$40.42	$3,181.08
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$390.22	$1,178.29	$58.63	$103.60	$0.00	$1,730.74
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$4,485.54	$15.86	$0.00	$0.00	$4,501.40
Total Repository	$1,509.86	$9,161.50	$642.22	$384.18	$95.78	$11,793.54

Table H-28 Repository LCC (post-D&E) for Case 15 (HLW Cost Not Included in Subsurface Excavations)

Case 15	**Repository LCC (post-D&E) Millions of 1994 $**					
	Engineering & Construction	**Emplacement Operations**	**Caretaker Operations**	**Closure**	**Decommissioning**	**Total**
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$373.26	$2,454.11	$261.46	$51.83	$40.42	$3,181.08
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$355.26	$1,167.26	$58.63	$97.28	$0.00	$1,678.43
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$4,485.54	$15.86	$0.00	$0.00	$4,501.40
Total Repository	$1,474.90	$9,150.46	$642.22	$377.86	$95.78	$11,741.23

Table H-29 Repository LCC (post-D&E) for Case 16 (HLW Cost Not Included in Subsurface Excavations)

Case 16	**Repository LCC (post-D&E) Millions of 1994 $**					
	Engineering & Construction	**Emplacement Operations**	**Caretaker Operations**	**Closure**	**Decommissioning**	**Total**
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$373.26	$2,454.11	$261.46	$51.83	$40.42	$3,181.08
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$333.98	$1,160.54	$58.63	$93.44	$0.00	$1,646.58
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$4,485.54	$15.86	$0.00	$0.00	$4,501.40
Total Repository	$1,453.62	$9,143.75	$642.22	$374.02	$95.78	$11,709.39

Table H-30 Repository LCC (post-D&E) for Case 17 (HLW Cost Not Included in Subsurface Excavations)

Case 17	Repository LCC (post-D&E) Millions of 1994 $					
	Engineering & Construction	Emplacement Operations	Caretaker Operations	Closure	Decommissioning	Total
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$373.26	$2,454.11	$261.46	$51.83	$40.42	$3,181.08
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$323.34	$1,157.18	$58.63	$91.51	$0.00	$1,630.66
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$4,485.54	$15.86	$0.00	$0.00	$4,501.40
Total Repository	$1,442.98	$9,140.39	$642.22	$372.09	$95.78	$11,693.46

Table H-31 Repository LCC (post-D&E) for Case 18 (HLW Cost Not Included in Subsurface Excavations)

Case 18	Repository LCC (post-D&E) Millions of 1994 $					
	Engineering & Construction	Emplacement Operations	Caretaker Operations	Closure	Decommissioning	Total
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$373.26	$2,454.11	$261.46	$51.83	$40.42	$3,181.08
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$909.00	$1,208.39	$58.63	$170.55	$0.00	$2,346.58
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$4,485.54	$15.86	$0.00	$0.00	$4,501.40
Total Repository	$2,028.65	$9,191.60	$642.22	$451.13	$95.78	$12,409.38

Table H-32 Repository LCC (post-D&E) for Case 19 (HLW Cost Not Included in Subsurface Excavations)

Case 19	Repository LCC (post-D&E) Millions of 1994 $					
	Engineering & Construction	Emplacement Operations	Caretaker Operations	Closure	Decommissioning	Total
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$373.26	$2,454.11	$261.46	$51.83	$40.42	$3,181.08
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$863.40	$1,194.00	$58.63	$162.31	$0.00	$2,278.34
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$4,485.54	$15.86	$0.00	$0.00	$4,501.40
Total Repository	$1,983.05	$9,177.20	$642.22	$442.89	$95.78	$12,341.14

Table H-33 Repository LCC (post-D&E) for Case 20 (HLW Cost Not Included in Subsurface Excavations)

Case 20	Repository LCC (post-D&E) Millions of 1994 $					
	Engineering & Construction	Emplacement Operations	Caretaker Operations	Closure	Decommissioning	Total
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$373.26	$2,454.11	$261.46	$51.83	$40.42	$3,181.08
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$826.92	$1,182.49	$58.63	$155.72	$0.00	$2,223.75
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$4,485.54	$15.86	$0.00	$0.00	$4,501.40
Total Repository	$1,946.57	$9,165.69	$642.22	$436.30	$95.78	$12,286.56

Table H-34 Repository LCC (post-D&E) for Case 21 (HLW Cost Not Included in Subsurface Excavations)

Case 21	Repository LCC (post-D&E) Millions of 1994 $					
	Engineering & Construction	Emplacement Operations	Caretaker Operations	Closure	Decommissioning	Total
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$373.26	$2,454.11	$261.46	$51.83	$40.42	$3,181.08
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$804.12	$1,175.29	$58.63	$151.60	$0.00	$2,189.64
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$4,485.54	$15.86	$0.00	$0.00	$4,501.40
Total Repository	$1,923.77	$9,158.49	$642.22	$432.18	$95.78	$12,252.44

Table H-35 Repository LCC (post-D&E) for Case 22 (HLW Cost Not Included in Subsurface Excavations)

Case 22	Repository LCC (post-D&E) Millions of 1994 $					
	Engineering & Construction	Emplacement Operations	Caretaker Operations	Closure	Decommissioning	Total
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$373.26	$2,454.11	$261.46	$51.83	$40.42	$3,181.08
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$793.48	$1,171.93	$58.63	$149.67	$0.00	$2,173.71
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$4,485.54	$15.86	$0.00	$0.00	$4,501.40
Total Repository	$1,913.13	$9,155.13	$642.22	$430.25	$95.78	$12,236.52

Table H-36 Repository LCC (post-D&E) for Case 23 (HLW Cost Not Included in Subsurface Excavations)

Case 23	Repository LCC (post-D&E) Millions of 1994 $					
	Engineering & Construction	Emplacement Operations	Caretaker Operations	Closure	Decommissioning	Total
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$370.33	$2,433.72	$261.46	$51.83	$40.42	$3,157.76
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$499.93	$885.65	$58.63	$126.83	$0.00	$1,571.05
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$3,709.53	$12.57	$0.00	$0.00	$3,722.10
Total Repository	$1,616.64	$8,072.45	$638.93	$407.41	$95.78	$10,831.22

Table H-37 Repository LCC (post-D&E) for Case 24 (HLW Cost Not Included in Subsurface Excavations)

Case 24	Repository LCC (post-D&E) Millions of 1994 $					
	Engineering & Construction	Emplacement Operations	Caretaker Operations	Closure	Decommissioning	Total
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$370.33	$2,433.72	$261.46	$51.83	$40.42	$3,157.76
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$451.86	$870.48	$58.63	$118.15	$0.00	$1,499.12
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$3,709.53	$12.57	$0.00	$0.00	$3,722.10
Total Repository	$1,568.57	$8,057.28	$638.93	$398.73	$95.78	$10,759.29

Table H-38 Repository LCC (post-D&E) for Case 25 (HLW Cost Not Included in Subsurface Excavations)

Case 25	Repository LCC (post-D&E) Millions of 1994 $					
	Engineering & Construction	Emplacement Operations	Caretaker Operations	Closure	Decommissioning	Total
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$370.33	$2,433.72	$261.46	$51.83	$40.42	$3,157.76
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$417.81	$859.74	$58.63	$111.99	$0.00	$1,448.17
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$3,709.53	$12.57	$0.00	$0.00	$3,722.10
Total Repository	$1,534.52	$8,046.53	$638.93	$392.57	$95.78	$10,708.34

Table H-39 Repository LCC (post-D&E) for Case 26 (HLW Cost Not Included in Subsurface Excavations)

Case 26	**Repository LCC (post-D&E) Millions of 1994 $**					
	Engineering & Construction	**Emplacement Operations**	**Caretaker Operations**	**Closure**	**Decommissioning**	**Total**
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$370.33	$2,433.72	$261.46	$51.83	$40.42	$3,157.76
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$395.78	$852.78	$58.63	$108.01	$0.00	$1,415.20
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$3,709.53	$12.57	$0.00	$0.00	$3,722.10
Total Repository	$1,512.49	$8,039.58	$638.93	$388.59	$95.78	$10,675.37

Table H-40 Repository LCC (post-D&E) for Case 27 (HLW Cost Not Included in Subsurface Excavations)

Case 27	Repository LCC (post-D&E) Millions of 1994 $					
	Engineering & Construction	Emplacement Operations	Caretaker Operations	Closure	Decommissioning	Total
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$370.33	$2,433.72	$261.46	$51.83	$40.42	$3,157.76
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$383.76	$848.99	$58.63	$105.84	$0.00	$1,397.22
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$3,709.53	$12.57	$0.00	$0.00	$3,722.10
Total Repository	$1,500.48	$8,035.79	$638.93	$386.42	$95.78	$10,657.39

Table H-41 Repository LCC (post-D&E) for Case 28 (HLW Cost Not Included in Subsurface Excavations)

Case 28	Repository LCC (post-D&E) Millions of 1994 $					
	Engineering & Construction	Emplacement Operations	Caretaker Operations	Closure	Decommissioning	Total
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$370.33	$2,433.72	$261.46	$51.83	$40.42	$3,157.76
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$898.39	$832.44	$58.63	$169.28	$0.00	$1,958.75
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$3,709.53	$12.57	$0.00	$0.00	$3,722.10
Total Repository	$2,015.11	$8,019.24	$638.93	$449.86	$95.78	$11,218.92

Table H-42 Repository LCC (post-D&E) for Case 29 (HLW Cost Not Included in Subsurface Excavations)

Case 29	Repository LCC (post-D&E) Millions of 1994 $					
	Engineering & Construction	Emplacement Operations	Caretaker Operations	Closure	Decommissioning	Total
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$370.33	$2,433.72	$261.46	$51.83	$40.42	$3,157.76
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$850.33	$817.27	$58.63	$160.60	$0.00	$1,886.82
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$3,709.53	$12.57	$0.00	$0.00	$3,722.10
Total Repository	$1,967.04	$8,004.07	$638.93	$441.17	$95.78	$11,147.00

Table H-43 Repository LCC (post-D&E) for Case 30 (HLW Cost Not Included in Subsurface Excavations)

Case 30	**Repository LCC (post-D&E) Millions of 1994 $**					
	Engineering & Construction	**Emplacement Operations**	**Caretaker Operations**	**Closure**	**Decommissioning**	**Total**
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$370.33	$2,433.72	$261.46	$51.83	$40.42	$3,157.76
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$814.27	$805.89	$58.63	$154.08	$0.00	$1,832.88
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$3,709.53	$12.57	$0.00	$0.00	$3,722.10
Total Repository	$1,930.99	$7,992.69	$638.93	$434.66	$95.78	$11,093.05

Table H-44 Repository LCC (post-D&E) for Case 31 (HLW Cost Not Included in Subsurface Excavations)

Case 31	Repository LCC (post-D&E) Millions of 1994 $					
	Engineering & Construction	Emplacement Operations	Caretaker Operations	Closure	Decommissioning	Total
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$370.33	$2,433.72	$261.46	$51.83	$40.42	$3,157.76
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$793.24	$799.25	$58.63	$150.28	$0.00	$1,801.41
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$3,709.53	$12.57	$0.00	$0.00	$3,722.10
Total Repository	$1,909.96	$7,986.05	$638.93	$430.86	$95.78	$11,061.58

Table H-45 Repository LCC (post-D&E) for Case 32 (HLW Cost Not Included in Subsurface Excavations)

Case 32	Repository LCC (post-D&E) Millions of 1994 $					
	Engineering & Construction	Emplacement Operations	Caretaker Operations	Closure	Decommissioning	Total
Management and Integration	$331.91	$32.35	$31.44	$19.64	$8.14	$423.47
Site Preparation	$210.94	$109.38	$19.30	$1.79	$47.22	$388.63
Surface Facilities	$370.33	$2,433.72	$261.46	$51.83	$40.42	$3,157.76
Shafts/Ramps - Underground	$78.80	$12.17	$13.19	$3.30	$0.00	$107.46
Subsurface Excavations	$782.73	$795.94	$58.63	$148.38	$0.00	$1,785.67
Underground Service Systems	$124.74	$889.65	$242.34	$204.02	$0.00	$1,460.76
Waste Package Fabrication	$0.00	$3,709.53	$12.57	$0.00	$0.00	$3,722.10
Total Repository	$1,899.44	$7,982.73	$638.93	$428.96	$95.78	$11,045.85

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Appendix I
Geochemistry

Preliminary Evaluation of Geochemical Effects of Various Repository Thermal Loads

The evaluations included in this report are very preliminary and should be considered as equivalent to the results of an elicitation session. An attempt has been made to answer questions in spite of insufficient data. Rigorous documentation of statements in the report has been omitted because the time available was insufficient to check existing references.

<u>Geochemical Processes of Concern</u>

This preliminary assessment concentrates on three general geochemical processes. First, mineral dehydration is the loss of internal water from zeolites, clays, and volcanic glass. This process is probably a largely reversible process for these phases although the loss of water over periods of year may be partly irreversible and may cause irreversible structural changes in zeolites and clays (Bish, 1990; Vaniman and others, in press). It is not known that such changes have any effect on the sorptive characteristics of the minerals. The contraction of the crystal structures accompanying dehydration of the affected minerals may cause irreversible changes in bulk hydraulic properties.

The second process in crystallization of volcanic glass to a secondary mineral assemblage. The term "zeolitization" is used in the thermal effects charts as a generic description of the various zeolite-clay-silica mineral assemblages that typify low- and moderate-temperature alteration of rocks containing silicic volcanic glass. In nonwelded tuffs, this process causes a reduction in hydraulic conductivity (Loeven, 1993) due perhaps to secondary-mineral cementation. In welded tuffs, the process ins expected to causes a reduction in porosity, but the effects on hydraulic conductivity are more difficult to predict because fracture flow is an important component of overall conductivity.

The third process is recrystallization of clinoptilolite-silica (e.g., opal-CT) mineral assemblages to analcime-quartz assemblages. The reaction also liberates water. Thermal conditions under which this reaction might occur have been estimated from illite-smectite geothermometry of the zeolite-bearing rocks (Bish and Aronson, 1993). Analcime has less sorptive capacity for some radionuclides than clinptilolite. The reaction involves a volume reduction of about 22% (i.e., the product minerals are denser than the reactant minerals), but it is unclear how these changes would affect the bulk hydrologic properties. A mineralogic volume reduction should result in increased porosity, and the recrystallization would change the distribution and connectivity of pores. These predicted changes cannot be translated into expected changes of hydraulic conductivity. Most analcime-bearing rocks at Yucca Mountain are poor hydraulic-property analogs for alteration of the CHnz because they have experienced compaction and alteration in the saturated zone at depths of 3000 ft. (914 m) or more (Bish and Chipera, 1989).

The following list summarizes the general geochemical concerns for each functional stratigraphic unit:

PTn: glass dehydration (partially reversible), zeolitization (irreversible)

Repository Horizon: little or no mineralogic effects

TSw3: glass dehydration (partially reversible), zeolitization (irreversible)

CHnv: glass dehydration (partially reversible), zeolitization (irreversible)

CHnz: zeolite dehydration (partially reversible), zeolite recrystallization (irreversible)

Effects on Retardation

T he approach being taken to mineral sorption coefficients at LANL is the highly conservative "minimum K_d" approach. Sorption values for the least sorptive minerals will be utilized in retardation calculations. Under this approach, a change in mineralogy (e.g., zeolitization of volcanic glass) or in mineralogic property (e.g., a change in the oxidation sate of iron in a mineral) brought about by repository-induced processes may affect sorptive properties but is not necessarily factored into current retardation calculations. However, rock alternation resulting in mineralogic changes may also be reflected by a change in available mineral surface area, and this change may need to be taken into account in retardation calculations. There may also be changes in hydraulic conductivity as a result of alteration. For example, the zeolitization of volcanic glass can result in a volume increase of as much as 24% (Levy and Valentine, in press). Secondary-mineral sealing of fracture and matrix porosity as a result of the volume increase is tentatively identified as an enhancement of retardation. However, other changes during alteration, such as dissolution and new fracturing, could counteract the effects of mineral sealing; therefore, the overall effect on retardation is uncertain. LANL is in the process of collecting mineral-specific data; the present assessment emphasizes changes in surface area and hydraulic conductivity in evaluating possible repository thermal effects.

Effects of Mineral Dehydration on the Heat Budget

There are no zeolites or other hydrous minerals in the repository horizon (343 m) itself, beyond trace quantities (<1%). Therefore, no effects on heat or liquid saturation calculations from mineral dehydration at the repository horizon ar expected. The hydrous phases closest to the repository horizon are expected. The hydrous phases closest to the repository are the clays, zeolites, and glass below the repository in the devitrified-vitric transition zone (TSw2-TSw3 boundary). This zone does not have a fixed thickness or constant hydrous mineral content, but overall, glass is the most abundant and predictable and predictable constituent. Glass contains about 4 weight percent water in non-natural state core samples. LANL has experimental data for glass (powdered Topopah Spring vitrophyre) dehydration rates at various temperatures, but all at room relative humidity. Under these conditions, at least some dehydration occurs within a few years even at temperatures below 100°C (Vaniman and others, in press). Uncertainties associated with the in situ dehydration process include the effects of pore water (and water vapor saturation as opposed to "liquid saturation") and the lengthier diffusion pathways that the expelled water must take. The water held in glass probably is at least twice the content of pore water in the vitrophyre; therefore, whatever the contribution of the vitrophyre might be in mediating temperature increase just below the repository, factoring in glass dehydration could increase that contribution several-fold. It might be helpful to produce plots of temperature and saturation profiles for time less than 120 years (peak temperature for 110/ MTU/ac case).

Glass and zeolite-bearing moderately and nonwelded tuffs further down (CHnv and CHnz) may have more of an effect on temperatures below the repository after 120 years. During the first 120 years or more (up to 454 years perhaps, based on the 110 MTU/ac model output), the liquid saturation is this interval increases, making it less likely that dehydration of hydrous minerals would occur (the issue of phase changes will be discussed separately). But, some time between 120 and 454 years, the liquid saturation falls to or below the original ambient saturation and stays below for >1000 years. Under these conditions, mineral dehydration is likely, but the effect on the repository heat budget requires further calculations to estimate. It is likely that the enthalpy of dehydration of zeolites in this interval will make a significant contribution to the heat budge.t

Mineral dehydration may be a negligible concern for temperature moderation in the 24 MTU/ac case because the model results (not included) show little or no change in liquid saturation (relatively high in most of the geologic section) from ambient conditions and peak temperatures well below boiling. Under these conditions, simple dehydratinof existing hydrous minerals may be minimal.

<u>Major Uncertainties</u>

The following are only a few examples of either uncertainties or information needs:

1. data on energetics and kinetics of zeolite dehydration and transformation (recrystallization).

2. effects of existing lateral stratigraphic variation, in particular the differences between sections where CHnv is thick (west) and this (east).

3. mineralogic alteration will probably increase the heterogeneity of all rock properties.

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36 MTU/Ac

Functional Unit	Primary Concerns	Primary Repository Effects	Mineralogic Processes: Effect on Retardation		
			Dehydration	Zeolitization	Other
PTn	Hydrologic Barrier	T_{max} ~ 17-55 °C (Central) ~ 15-25 (Boundary) No saturation change	Not expected	Minor, local: no effect	-
Repository Horizon	-	T_{max} ~ 70-85 Negligible change in ambient sat.	-	-	-
TSW3	Retardation	T_{max} ~ 63-65 (Central) ~ 47 (Boundary) Negligible change in ambient sat	Possible: minor	Possible: minor	-
CHn_v	Retardation	T_{max} ~ 63 (Central) ~ 47 (Boundary) Negligible change in ambient saturation	Not expected	Possible: possible enhanced retardation	-
Z	Retardation	T_{max} ~ 52-63 (Central) ~ 47 (Boundary) Negligible change in ambient saturation	Not expected	-	-

24 MTU/Ac

Functional Unit	Primary Concerns	Primary Repository Effects	Mineralogic Processes: Effect on Retardation		
			Dehydration	Zeolitization	Other
PTn	Hydrologic Barrier	T_{max} ~ 30 °C No saturation change	Not expected	No expected	-
Repository Horizon	-	T_{max} ~ 66 Negligible change in ambient sat.	Not expected	-	-
TSW3	Retardation	T_{max} ~ 60 No saturation change	Not expected	Possible: slight retardation increase?	-
CHn_v	Retardation	No saturation change	Not expected	-	-
Z	Retardation	No saturation change	Not expected	-	-

55 MTU/Ac

Functional Unit	Primary Concerns	Primary Repository Effects	Mineralogic Processes: Effect on Retardation		
			Dehydration	Zeolitization	Other
PTn	Hydrologic Barrier	T_{max} ~ 18-45 °C (Central) No saturation change	Not expected	Minor, local: no effect	-
Repository Horizon	-	T_{max} ~ 108 dehydration predominates	-	-	-
TSW3	Retardation	T_{max} ~ 68-100 (Central) ~ 65-90 (Boundary) early full saturation in central part, return to ambient	Not expected	Possible: minor	-
CHn_v	Retardation	T_{max} ~ 65-68 Early slight increase from ambient saturation (High)	Not expected	Probable: possible enhanced retardation	-
Z	Retardation	T_{max} ~ 55-68 (Central) ~ 55-65 (Boundary) Early sl. increase from ambient (High)	Not expected	-	-

83 MTU/Ac

Functional Unit	Primary Concerns	Primary Repository Effects	Mineralogic Processes: Effect on Retardation		
			Dehydration	Zeolitization	Other
PTn	Hydrologic Barrier	T_{max} ~ 30 -60°C little or no change in ambient saturation	Possible: no effect o retardation	Not expected	-
Repository Horizon	-	T_{max} ~ 147 dehydration predominates	-	-	-
TSW3	Retardation	T_{max} - 110-125 (Central) - 60-90 (Boundary) early near-saturation	Probable, after early times effects unknown	Probable: changes in fracture porosity surface area. Effects on retardation unknown	-
CHn_v	Retardation	T_{max} ~ 110(Central) ~ 80 (Boundary) early near-saturation	Probable reversible dehydration.: no long-term effects	Probable: possible enhanced retardation	-
Z	Retardation	T_{max} ~ 90-110 (Central) ~ 60-75 (Boundary) Partial dehydration. below central rep.; little change at boundaries	Little or no dehydration?: effects probably minimal	-	-

111 MTU/Ac

Functional Unit	Primary Concerns	Primary Repository Effects	Mineralogic Processes: Effect on Retardation		
			Dehydration	Zeolitization	Other
PTn	Hydrologic Barrier	T_{max} ~ 95°C increased saturation	Possible in upper part: no effect	Probable: effect uncertain	Increased channeling of recharge water
Repository Horizon	-	T_{max} ~ 190 °C rock dehydration	-	-	-
TSW3	Retardation	T_{max} ~- 160 (Central) ~ 100 (Boundary) dehydration predominates	Probable: effect unknown	Possible in first 100 Yr, concentrated near bound and flow paths: possible enhancement of retardation	-
CHn_v	Retardation	T_{max} ~ 145 (Central) ~ 100 (Boundary) early full sat. dehydration. below center, increased sat. below bound.	Probable: irreversible changes in hydrologic properties	Possible in first 100 Yr, concentrated near bound and flow paths: possible enhancement of retardation	-
Z	Retardation	Most of section >100° for > 500 Yr early full sat. dehydration. below center, incr. sat. below boundaries	Probable: irreversible changes in hydrologic properties	-	Possible Clinoptilolite + OPAECT -> analcime + quartz: effects uncertain.

Appendix J
Areas of Uncertainty In Thermal Loading

Several areas of uncertainty were identified in the Systems Study and in the subsequent comments by the document reviewers. This appendix summarizes those specific uncertainties. However, there has been little or no adequate parametric analysis to indicate the degree of importance of many of these parameters and the range where changes in these parameters would result in significant changes in performance. This parametric study needs to be done and some of that work will be attempted in a follow-on study. The following list of items has been identified as uncertainties although this should not be taken as a complete list:

1. Bulk Permeability - The measure of this and the scale for the various stratigraphic units will determine the hydrologic flow and is of particular concern if permeabilities are greater than about 1 Darcy

2. The extent and degree to which nonequilibrium fracture flow occurs

3. The fracture size, number, and connectivity in the mountain

4. The extent and duration (both spatial and temporal) of the dry out region that occurs as a result of heating

5. The degree and time scales over which conduction dominates and whether or not convection is important at various thermal loadings

6. The thermo-mechanical properties of the rock

7. The degree to which ventilation can be employed to mitigate preclosure effects and remove moisture from the mountain

8. The percolation flux needs to be known and the changes that may occur as a function of climate change

9. The spatial heterogenieties that exist for many of the parameters mentioned such as permeability, fracture density, etc.

10. What thermal goal should be applied to the Paintbrush tuff member

11. Establishment of the container corrosion resistance for various thermal loads and water chemistries that might occur in the potential repository

12 The degree to which silica mobilization and precipitation occur and may influence the hydrology of the mountain at various thermal loads

13. Spent nuclear fuel variability, power output and radioactivity

14. Performance monitoring issues - where, what data rate, and what instruments

15. A reevaluation of the thermal goals is needed

16. Geochemistry alterations as a function of thermal load - such issues as zeolite dehydration and transformation, mineralogic alteration of rock properties

17. Cost of various subcomponents of the system as a function of thermal load.