Mini-Report #3

EVALUATION OF RESIDUAL THERMAL EFFECTS

Basalt Waste Isolation Project
Subtask 2.5
Numerical Evaluation of Conceptual Models

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for

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1.0 INTRODUCTION

1.1 GENERAL STATEMENT OF THE PROBLEM

The purpose of this analysis is to address the following question:

> Are thermal effects of a nuclear waste repository in basalt significant after 300 to 1000 years?

After emplacement, canisters containing nuclear waste will generate heat due to radioactive decay, causing an increase in the temperature of adjacent rocks. The initially high rate of heat generation will decrease by a factor of about 10 after 125 years from the time of emplacement (Talbot et al., 1984). Because of this substantial decrease in heat generation, the temperatures in adjacent rocks are expected to begin decreasing with time not long after canister emplacement. The purpose of calculations performed herein are to assess the magnitude of residual temperatures after 300 years when the rate of heat generation is relatively small.

1.2 RELEVANCE TO NRC

Subpart E of 10 CFR Part 60 that requires that the cumulative radionuclide flux reaching the accessible environment after permanent closure does not exceed the EPA Standard (40 CFR Part 91).

The EPA Standard addresses the cumulative flux of radionuclides across the boundary of the accessible environment over time periods of up to 10,000 years. Waste package containment and release from the Engineered Barrier System are specified such that significant releases of radionuclides do not occur until 300 to 1000 years after emplacement. Thus, if thermal effects have dissipated before this 300 to 1000 year time period, the impact of repository heat on ground water (and hence radionuclide) flux need not be considered in evaluating the EPA Standard.

1.3 RELATIONSHIP TO OTHER SITE CHARACTERIZATION/REGULATORY TASKS

In order for the BWIP site to be licenced, DOE will have to demonstrate, through performance modeling, that geologic containment will satisfy the EPA Standard. Explicit incorporation of the thermal effects on ground water flow requires that complex numerical models be used (e.g., SWIFT). These codes are time-consuming and expensive to operate, often requiring a large number of input data. For the NRC, the results of complex numerical simulations are difficult to review and update. However, if it can be demonstrated that thermal effects are negligible within the time period of the simulation, simpler numerical and/or analytical models can be utilized. In addition, it will be easier for the NRC to conduct independent analyses of repository performance as a means of evaluating DOE's results.

2.0 OBJECTIVE

The objective of this study is to perform an analysis to assess the transient temperature change in rocks near the repository resulting from variable heat generated by the waste canisters.

3.0 EVALUATION

3.1 OPERATIONAL APPROACH

The evaluation performed herein represents a conservative approach which would have a tendency to overestimate the actual temperature change. If this analysis predicts that temperature changes will be negligible after 300 years, then it can be concluded that in the real (less conservative) case, thermal effects need not be considered in post-emplacement performance modeling. If, on the other hand, the analysis predicts that thermal effects are significant, the following two options are available:

1. Additional analyses may be considered which are still conservative from the standpoint of repository conditions, but less conservative than the calculations performed herein. This will probably involve an analytical or numerical model which is considerably more complex than the one used in this study.

2. Thermal effects will have to be explicitly incorporated into post-emplacement performance modeling to evaluate the EPA Standard. This will likely require the use of sophisticated numerical models.

3.2 CONCEPTUAL MODEL

3.2.1 Framework

The repository is situated within Columbia River Basalt at a depth of about 900 meters below ground surface. Although, the layered basalt sequence contains a variety of flow structures (e.g.., interflows, flow interiors), thermal properties are considered to be relatively uniform. Thus, the layered basalt is conceptualized as a thermally homogeneous medium. Basalt above the repository represents a thermal medium of finite length, with ground surface representing a nearly constant temperature boundary. Basalt below the repository is considered to represent a semi-infinite medium.

3.2.2 Flow System

Heat flow within geologic medium is assumed to be transient, one-dimensional (both vertically upward and downward), and controled by thermal conduction. Natural and forced convection as mechanisms of heat flow are neglected. The above assumptions are considered reasonable and lend some conservativeness to this evaluation (i.e., lead to over-estimates of temperature change).

3.2.3 Repository Source Term

Heat generation in the repository as a function of time is expressed in terms of average heat flux per unit planimetric area. The initial heat flux is relatively high, since it is proportional to canister output. With time, heat generation decays in an approximately exponential manner as shown in Figure 1 (from Talbot et al, 1984; Volume 3B; page 2-10).

3.3 TECHNICAL APPROACH

3.3.1 Formal Statement Of The Problem

Given the rate of heat generation of a repository as a function of time, what is the magnitude and distribution of transient temperature changes in adjacent rocks? Will the thermal response be essentially dissipated during the 300 to 1000 year time period after emplacement?

3.3.2 Solution Techniques

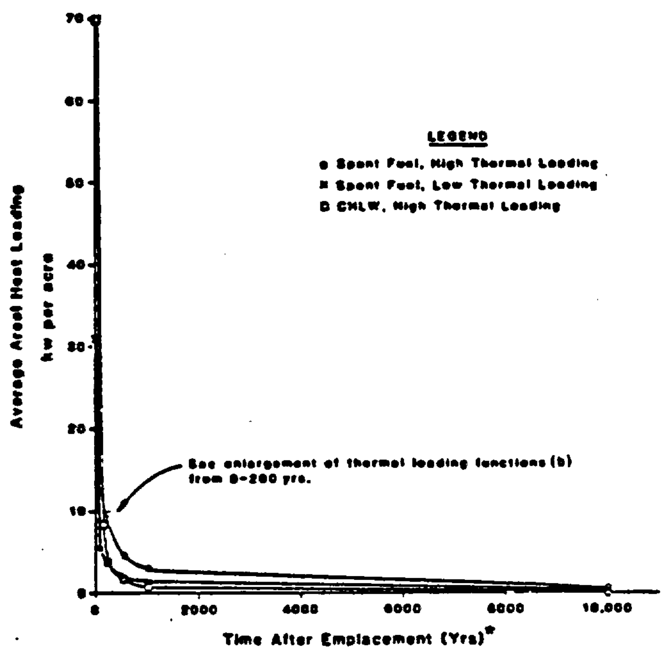
If thermal effects of the repository are assumed to be controlled only by conduction, the one-dimensional diffusion equation describes the physics of heat flow (Carslaw and Jaeger, 1959):

$$(1) \qquad \frac{\partial^2 v}{\partial x^2} = \frac{c\ ro}{K} \frac{\partial v}{\partial t}$$

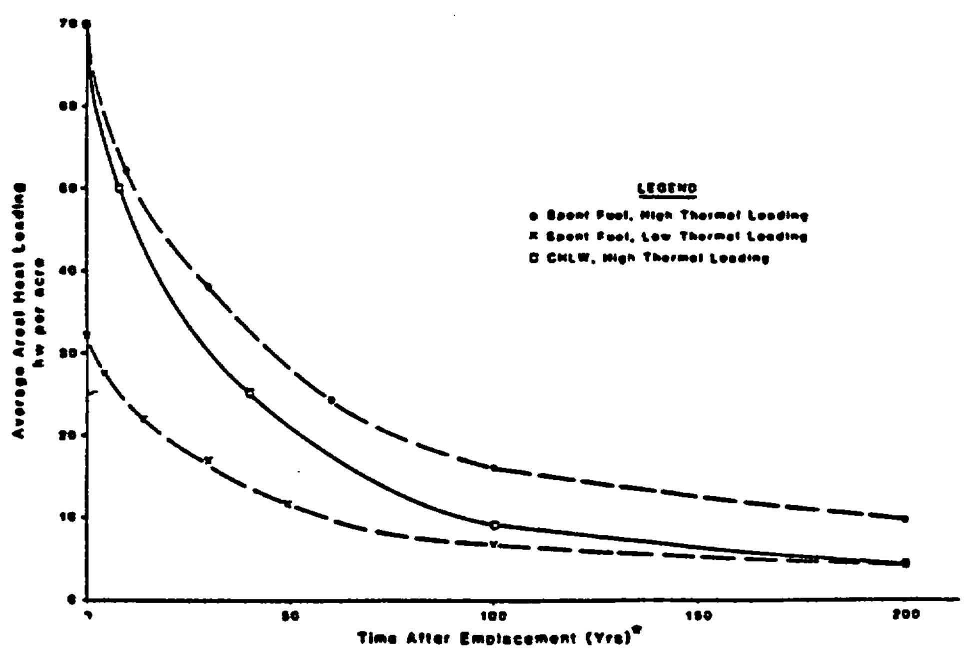
where:
- v = change in temperature
- x = vertical distance
- K = thermal conductivity
- c = heat capacity
- ro = bulk density
- t = time

FIGURE 1. BASALT REPOSITORY HEAT PRODUCTION

(From Talbot et al, 1984; Volume 3B; Page 2-10)



(a) 0 to 10,000 Years



(b) 0 to 200 Years

*Assumes instantaneous emplacement of all waste packages.

Temperature distribution within the medium is determined by solving Equation 1, subject to appropriate initial and boundary conditions.

3.3.3 Assumptions

Principal assumptions associated with analyses in this study are as follows:

1. Fractured rock is treated mathematically as a continuum.

2. Heat flow is controlled by thermal conduction. Natural and forced convection are ignored. For the purpose of this study, neglecting convection is considered reasonable and may lend a slight degree of conservativeness to the analysis (i.e., results in over-estimates of temperature change).

3. The medium is assumed to be of infinite (upward and downward) vertical extent. This assumption neglects the fact that ground surface is an approximate constant temperature boundary. However, for the purpose of this study, the assumption of an infinite medium is conservative (i.e., results in over-estimates of temperature change).

4. The rate of repository heat generation per unit area is assumed to change as a function of time in proportion to canister energy output.

5. Layered basalt is assumed to be homogeneous and isotropic with respect to thermal properties.

4.0 ANALYSIS

4.1 BASIC RELATIONSHIPS

4.4.1. Instantaneous and Time Constant Heat Source

For an instantaneous heat source of constant magnitude, which is located in an infinite one-dimensional medium (Figure 2), the following boundary and initial conditions apply:

(2) $v(x,0) = 0$; for $0 < x < \text{inf}$

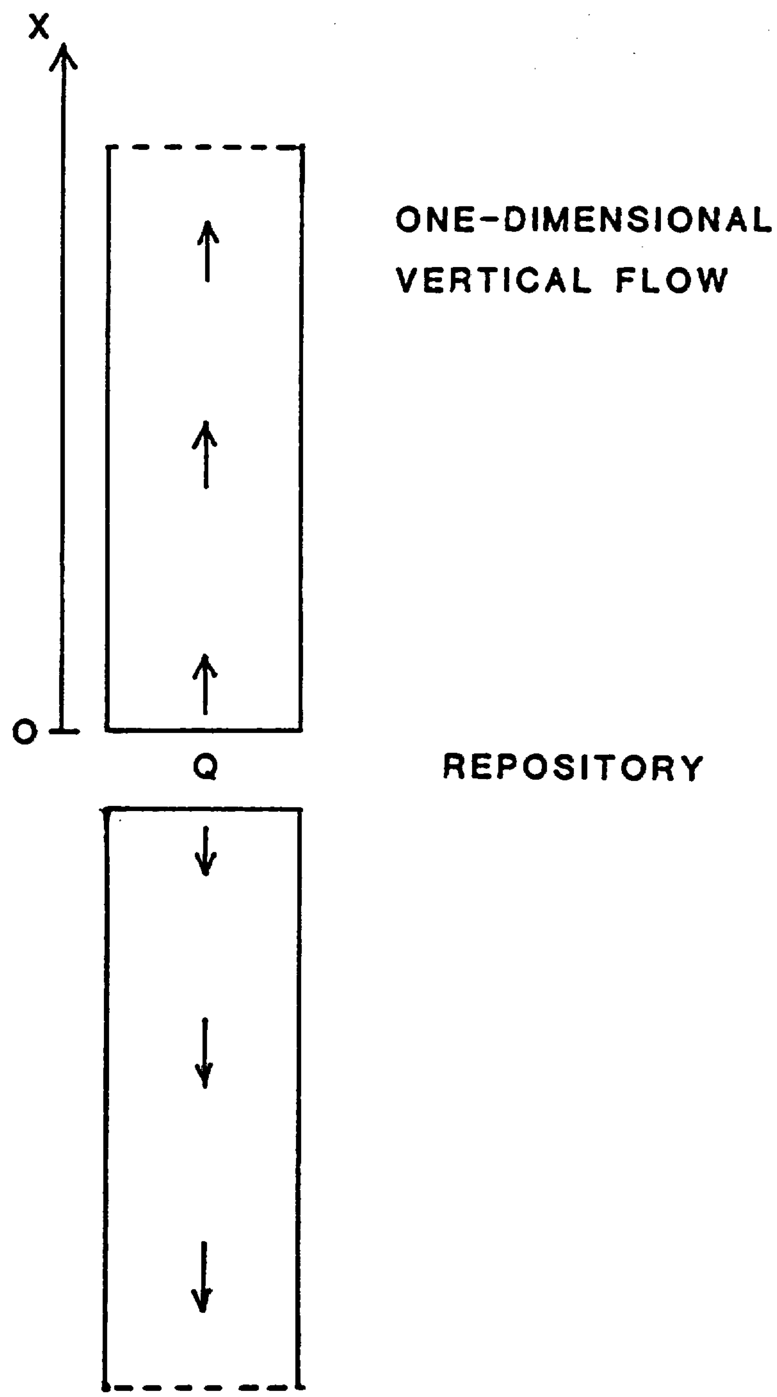
(3) $v(\text{inf},t) = 0$; for $t > 0$

(4) $\frac{dv}{dx} = \frac{(Q/2)}{K}$; for $x = 0$, $t > 0$

where: Q = constant rate of heat generated per unit area (normal to flow direction)

and "inf" implies infinity. Initial Condition 2 implies that the temperature change is zero prior to initiation of the heat source and Boundary Condition 3 indicates that negligible thermal effects occur at an infinite distance from the repository. Boundary Condition 4 defines the heat source at the repository location. Note that because of symetry, only half the flow region

FIGURE 2. ASSUMED PHYSICAL MODEL



needs to be considered in the above formulation. In this case, however, the total heat generation is divided by two as seen in Equation 4.

Solution to the boundary value problem defined by Equations 1 to 4 is given in Carslaw and Jaeger (1959; p. 75; eq. 7):

(5) $$v = \frac{Q\ x}{2\ K}\ V_D(t_D)$$

(6) $$V_D = 2\ SQR(\frac{t_D}{pi})\ exp(\frac{-1}{4\ t_D}) - erfc(\frac{1}{2\ SQR(t_D)})$$

(7) $$t_D = \frac{K\ t}{c\ ro\ x^2}$$

where: V_D = dimensionless temperature function

t_D = dimensionless time

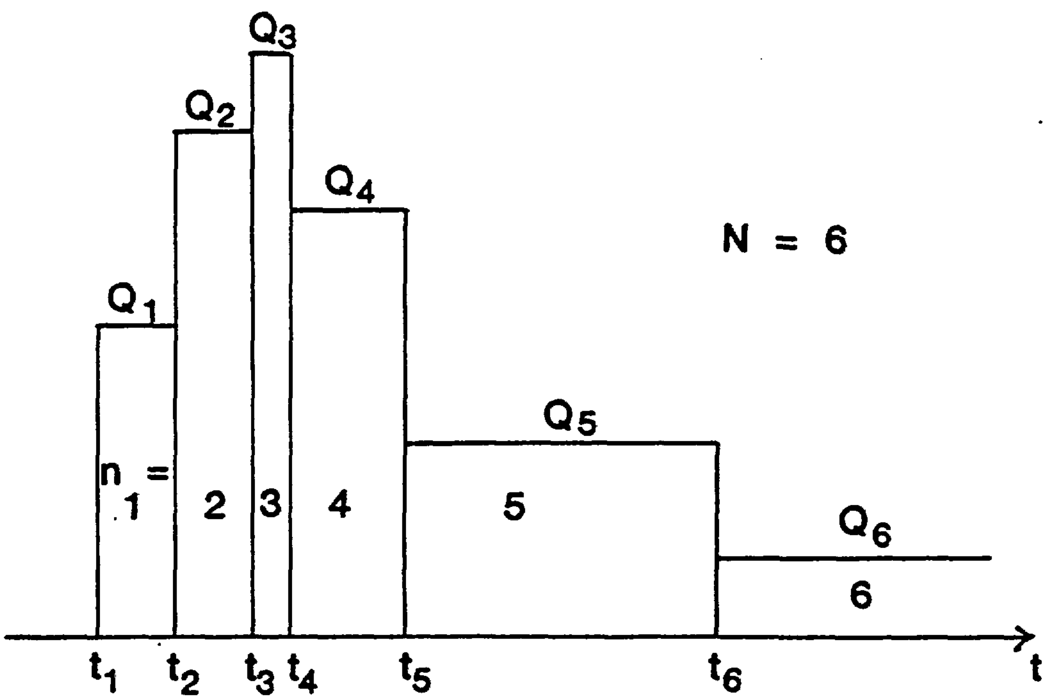
pi = 3.14159

In the above equations, "erfc" is the complimentary error function, "exp" is the exponential function, and "SQR" implies a square root.

4.1.2 Time-Varying Heat Source

The solution given in Equations 5 to 7 assumes an instantaneous and constant magnitude heat source. In order to incorporate a time-varying heat source, the basic solution can be combined with the principle of superposition. If the change in heat generation through time is approximated as a step function, as shown in Figure 3, the transient temperature change within the medium is given by:

FIGURE 3. EXAMPLE OF STEP FUNCTION



(8) $$v = \frac{x}{2\,K} \left\{ Q_1\, V_D(t_{D1}) + \sum_{n=2}^{N} (Q_n - Q_{n-1})\, V_D(t_{Dn}) \right\}$$

where:

(9) $$t_{Dn} = \frac{K\,(t - t_n)}{c\,\rho o\,x^2}$$

where: N = total number of steps in step function

t_n = time at the beginning of the nth step

t_{Dn} = dimensionless time at the beginning of the nth step

Q_n = heat generation rate during the nth step

and:

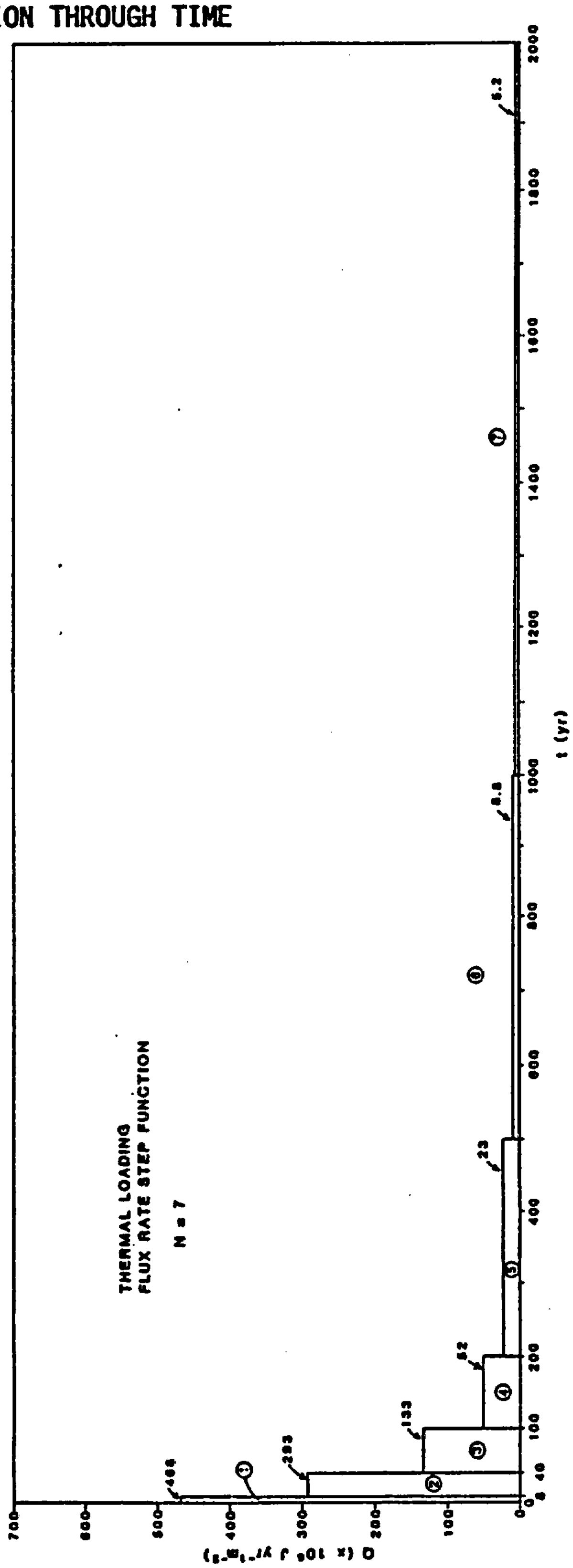
(10) if: $t < tn$; then: $V_D = 0$

In Equation 8, "SUM" represents a summation. The solution given by Equations 8 to 10 is used in Section 4.2 to evaluate thermal effects of the repository.

4.2 RESULTS

In order to evaluate the variable heat rate solution, a program has been written for the Hewlett-Packard HP-41 programable calculator which solves Equations 8 to 10. A listing of this algorithm is given in Appendix A. The variable heat step function used in the following analyses is shown in Figure 4. This function (based on Figure 1) approximates the average heat generation rate per unit area for a repository which has stored commercial

FIGURE 4. STEP FUNCTION USED TO APPROXIMATE REPOSITORY HEAT PRODUCTION THROUGH TIME



high-level nuclear waste. As shown, the initially high rate of heat production drops off dramatically after 100 years from the time of emplacement.

Thermal parameters used as input into the program are given in Roberts et al (1982; Appendix B; Table B-2). These parameters, expressed in consistent units, are summarized below:

$$K = 4.415 \times 10^{7} \ J \ m^{-1} \ yr^{-1} \ C^{-1}$$

$$c = 880 \ J \ kg^{-1} \ C^{-1}$$

$$ro = 2.86 \times 10^{3} \ kg \ m^{-3}$$

Based on the heat rate step function and thermal parameters described above, the HP 41 program has been used to determine temperature profiles at different times after waste emplacement. As shown in Figure 5, during the time period of 350 to 1000 years, substantial temperature changes are predicted in vicinity of the repository. In fact, significant temperature changes continue to persist near the repository at a time of 2000 years.

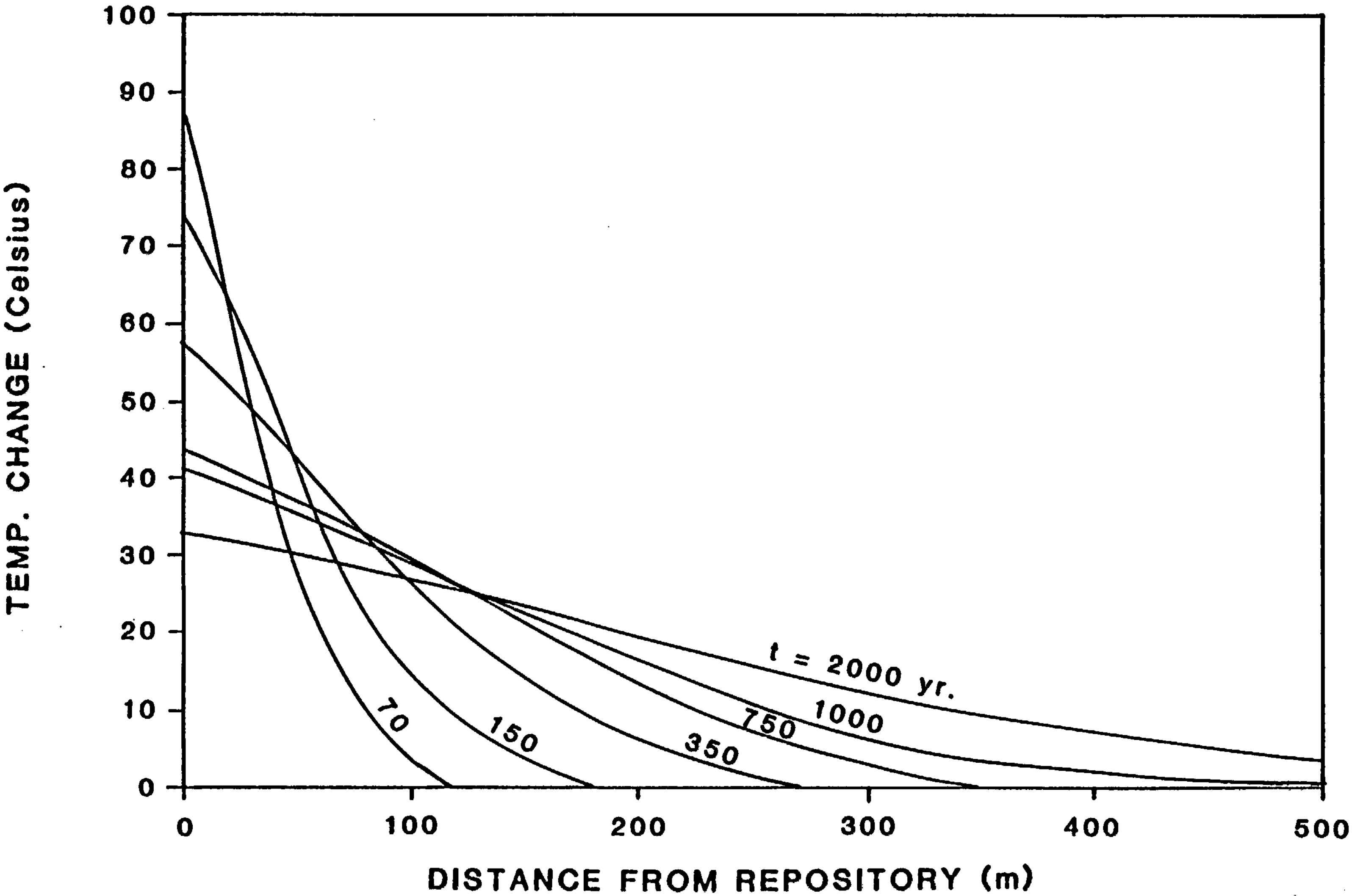


FIGURE 5. TEMPERATURE PROFILES AT VARIOUS TIMES AFTER EMPLACEMENT

5.0 CONCLUSIONS

Based on the temperature profiles in Figure 5, Terra Therma concludes that it can not necessarily be assumed that thermal effects of a repository will have dissipated during the time period of 300 to 1000 years after emplacement. As previously stated, assumptions associated with the current analysis are conservative. It is possible that less conservative analytical/numerical analyses might show that residual temperature changes are in fact less than the values predicted by the current analysis. However, unless these additional analyses prove otherwise, post-emplacement conditions used to evaluate the EPA Standard will have to consider the thermal effects of repository heat.

6.0 DISCUSSION

The analysis presented herein does not support the supposition that thermal effects can be neglected within the time period of 300 to 1000 years after emplacement. However, because the thermal parameter values are preliminary and the current analysis conservative, it might be argued that other analysis could lead to a different conclusion. Thus, Terra Therma suggests that the following evaluations be considered in the following order:

1. Develop a database for basalt thermal properties, including ranges and probable values.

2. After the database is compiled, perform a sensitivity analysis using analytical techniques described in this study.

3. If the sensitivity analysis indicates that there are possible parameter ranges for which thermal effects are negligible, site characterization activities should be directed toward determining where, within these ranges, lie the properties of basalt at BWIP.

4. If the sensitivity analysis indicates that (based on conduction) thermal effects will be significant for all parameter ranges, then less conservative analyses should be considered. In general these analyses will be more time consuming and expensive to perform. For example, less conservative evaluations might include:

- o An analysis which assumes a finite length medium where ground surface is treated as a constant temperature boundary. This can be accomplished using the same general approach of this study, but with different equations.

- o A two-dimensional analysis which can incorporate natural and forced convection as a means of dissipating repository heat. An analysis of this type may require a ground water - heat flow numerical model such as SWIFT.

If it is demonstrated that, under the above scenarios, post-emplacement temperatures are still significantly high, analyses which explicitly incorporate heat flow will need to be performed to assess the significance of thermal effects on the EPA Standard.

7.0 REFERENCES

Carslaw, H.S. and J.C. Jaeger. 1959. Conduction of Heat in Solids. Oxford University Press.

Roberts, W., et al. 1982. In Situ Test Programs Related to Design and Construction of High-Level Waste (HLW) Deep Geologic Repositories. NUREG/CR-3065.

Talbot, R. et al. 1984. Performance of Engineered Barriers in Deep Geologic Repositories for High Level Nuclear Waste (HLW). NUREG/CR-4026.

APPENDIX A: HP-41 PROGRAM LISTING

MAIN PROGRAM "VARX": EVALUATES VARIABLE FLOW RATE EQUATIONS

Direct Input: t

Memory Input:	t_n	(registers 01 - 09; t_n in register 0n)
	Q_n	(registers 11 - 19; Q_n in register 1n)
	N	(register 20)
	x	(register 21)
	K	(register 22)
	c ro	(register 23)

Note: input variables must have consistent units.

Listing:

```
LBL'VARX
'T ?
PROMPT
STO 27
0
STO 10
1.01
STO 24
LBL 01
RCL 27
RCL IND 24
-
X<=0?
GTO 05
RCL 22
*
RCL 23
/
RCL 21
X↑2
/
STO 28
SQRT
2
*
1/X
XEQ'ERF
1
```

```
-
RCL 28
4
*
CHS
1/X
E↑X
RCL 28
PI
/
SQRT
*
2
*
+
STO 25
RCL 24
1.1
X>Y?
GTO 02
X<>Y
9
+
STO 26
RCL IND 26
RCL 26
1
+
STO 26
X<>Y
CHS
RCL IND 26
+
GTO 03
LBL 02
RCL 11
LBL 03
RCL 25
*
RCL 10
+
STO 10
LBL 05
RCL 20
RCL 24
X>Y?
GTO 04
RCL 24
```

```
1
+
STO 24
GTO 01
LBL 04
RCL 10
RCL 21
*
RCL 22
/
2
/
END
```

SUBROUTINE "ERF": EVALUATES ERROR FUNCTION erf(u)

Direct Input: u

Memory Input: none

Listing:

```
LBL'ERF
X>0?
GTO 01
SF 01
CHS
LBL 01
STO 00
.0705230784
*
RCL 00
X↑2
.0422820123
*
+
RCL 00
ENTER↑
3
Y↑X
.0092705272
*
+
RCL 00
ENTER↑
4
Y↑X
```

```
.0001520143
*
+
RCL 00
ENTER↑
5
Y↑X
.0002765672
*
+
RCL 00
ENTER↑
6
Y↑X
.0000430638
*
+
1
+
ENTER↑
16
Y↑X
1/X
CHS
1
+
FS?C 01
CHS
END
```