KBS TEKNISK RAPPORT

54 :02

Groundwater movements around a repository

Thermal analyses
Part 1 Conduction heat transfer
Part 2 Advective heat transfer

Joe L Ratigan

Hagconsult AB september 1977

KÄRN - BRÄNSLE - SÄKERHET

POSTADRESS: Kärnbränslesäkerhet, Fack. 102 40 Stockholm. Telefon 08-67 95 40

GROUNDWATER MOVEMENTS AROUND A REPOSITORY

THERMAL ANALYSES
PART 1 CONDUCTION HEAT TRANSFER
PART 2 ADVECTIVE HEAT TRANSFER

Joe L Ratigan
Hagconsult AB september 1977

I slutet av rapporten har bifogats en förteckning över av KBS hittills publicerade tekniska rapporter i denna serie.

TECHNICAL REPORT 2

THERMAL ANALYSES

PART I

CONDUCTION HEAT TRANSFER

KBS-Kärnbränslesäkerhet

GROUNDWATER MOVEMENTS AROUND A REPOSITORY

Technical report 2: Thermal analyses

Part I: Conduction Heat Transfer

Hagconsult AB
in association with
Acres Consulting Services Ltd
RE/SPEC Inc.

FOREWORD

This report was prepared as one of a series of technical reports within a study of the groundwater movements around a repository for radioactive waste in the precambrian bedrock of Sweden. It was written in two parts, (I) conduction heat transfer and (II) forced convection heat transfer. This is Part I. The contract for this study was between KBS - Kärnbränslesäkerhet (Project Fuel Safety) and Hagconsult AB of Stockholm, Sweden. RE/SPEC Inc. of Rapid City, SD/USA and Acres Consulting Services Ltd of Niagara Falls, Ontario/Canada acted as subconsultants to Hagconsult AB.

The principal author of this report is Mr. Joe L. Ratigan of RE/SPEC Inc. Review was provided by Dr. Ulf E. Lindblom of Hagconsult AB and Dr. Paul F. Gnirk of RE/SPEC Inc.

The opinions and conclusions in this document are those of the author and should not be interpreted as necessarily representing the official policies or recommendations of KBS.

Stockholm August 1977

Ulf E. Lindblom
Study Director
Hagconsult AB

TABLE OF CONTENTS

		Page
1.	INTRODUCTION	1
2.	INPUT PARAMETERS AND REPOSITORY MODELLING	3
2.1	Heat Generation and Repository Layout	3
2.2	Rock Mass Properties	4
2.3	Repository Modeling	4
3.	RESULTS OF REPOSITORY LOCAL MODELS	7
4.	RESULTS OF REPOSITORY GLOBAL MODELS	11
5.	SUMMARY AND CONCLUSION	16

REFERENCES

APPENDIX: COMPARISON OF FINITE ELEMENT AND ANALYTICAL TEMPERATURE CALCULATIONS

APPENDIX: FINITE ELEMENT MODELS

LIST OF FIGURES

Figure

1. Transient heat generation for 10 year old and 40 year old high level waste

2. Tunnel and cannister details for high level waste repository

3. Layout of high level waste repository

4. Model for local repository simulation

5. Models for global repository simulation

6. Transient temperature in local repository model without ventilation

7. Transient temperature in local repository model with 30 years of ventilation

8. Comparison of thermal cycle prior to ventilation with thermal cycle after ventilation

9. Transient temperature in local repository model in axisymmetrical geometry

10. Transient temperature in local repository model for 10 year old waste

11. Transient temperature in local repository model with increased thermal conductivity

12. Temperatures through repository vertical centerline at various times for plane geometry

13. Temperature along repository plane at various times

14. Temperatures through repository vertical centerline at various times for axisymmetrical geometry

15. Temperatures through repository vertical centerline at various times at 1000 m depth

16. Transient temperature in plane global repository model at 500 m depth

17. Transient temperature in axisymmetrical repository model at 500 m depth

18. Temperature in repository plane at various times for a linear emplacement scheme

LIST OF FIGURES, (cont.)

Figure

19. Temperature 25 m above repository plane at various times for a linear emplacement scheme

20. Transient temperature in linear waste emplacement global repository model

A.1. Comparison of 40 year old high level waste characteristics with interpolation function

A.2. Comparison of finite element and analytical transient temperatures

B.1. Finite element model for local simulation

B.2. Finite element model for 500 m repository global simulation

B.3. Finite element model for 1000 m repository global simulation

B.4. Symmetric half section of finite element model for 500 m linear waste emplacement repository global analysis

THERMAL ANALYSIS OF RADIOACTIVE WASTE REPOSITORY-CONDUCTION HEAT TRANSFER

1. INTRODUCTION

In order to properly assess the ground water flow around a repository over an extended period of time, a variety of phenomenological occurences must be analyzed. One of the phenomena which is intimately coupled to the groundwater flow is the heat transfer in the rock mass and the associated transient temperature fields. The temperature fields which arise around a repository will affect the properties of the in situ groundwater, and the geometry and perhaps the chemistry of the openings which are available for the groundwater transport. The thermal perturbation of the groundwater density and viscosity will possibly result in thermally induced flow. Additionally, the temperatures will affect the rock mechanical situation such that the joint openings will close to some degree in certain locations and possibly open in others.

Unfortunately, the problem of groundwater flow is not merely coupled to the temperature in one direction. The thermally induced groundwater flow will subsequently perturb the temperature field; similarly, changes in joint openings will alter the hydraulic and thermal properties of the rock mass and therefore, will also influence the flow and temperature fields. However, the effect of the joint width changes on the rock mass thermal properties is expected to be small and is not expressly being accounted for in this study, (1)[x].

Since the analysis of the total coupled system around a repository has yet to be analyzed and the magnitude of the thermally induced flow and associated temperature field changes are not known a priori, this study is being performed in a "quasi-coupled" fashion.

x) Numbers in paranthesis refer to references at end of text.

Simply stated, the thermal analysis is divided into two distinct phases; namely, heat transfer without fluid flow and heat transfer with fluid flow. The latter will include not only heat transfer by bulk fluid flow through the repository domain, but also heat transfer from thermally induced flow.

This report is intended to present the results of the no-flow heat transfer and to provide a qualitative assessment of the thermally induced flow and the transfer associated with any groundwater flow. In this regard, the quantitative heat transfer presented in this report has been obtained under the assumption of only conductive heat transfer in the rock mass. Further heat transfer analysis within this study will therefore enable one to assess the quantitative and qualitative importance and influence of convective heat transfer and thermally induced flow within the rock mass.

2. INPUT PARAMETERS AND REPOSITORY MODELLING

2.1 Heat Generation and Repository Layout

The majority of the analysis presented in this report has been obtained with the heat generating characteristics particular to 40 year old PWR reprocessed waste which was reprocessed ten years after leaving the reactor. A description of various waste types, including the aforementioned is presented in (2). The heat generating characteristics of the waste are presented in Figure 1. Also presented in the figure is the characteristic heat generation for 10 year old PWR waste which was analyzed merely for comparative purposes.

The repository is assumed to have a capacity for accomodating 9000 tons of reprocessed waste. The high level waste is assumed to be contained in cylindrical containers as displayed in Figure 2. The containers are placed in 1 m diameter by 3 m deep drillholes excavated in the repository tunnel floors. The tunnel system is composed of 3.5 m excavations which are nearly cylindrical (see Figure 2).

The tunnels are excavated at 25 m on center and the waste packages are spaced at 4 m along the length of the tunnel. Allowing for 25 m of "buffer" space at both ends of each tunnel, forty-one 1000 m tunnels are required to allow emplacement of 9000 packages. This repository layout is graphically displayed in Figure 3.

Since the waste packages or canisters are spaced on a grid system, 4 m by 25 m, each canister has 100 square meters of area in which to conduct heat to the overlying and underlying rock mass. Therefore, the thermal flux density or gross thermal leading (GTL) can be easily calculated by dividing the canister power at emplacement by 100. For the case of 40 year old PWR reprocessed waste, the GTL is 5.25 W/m^2 or 21.25 kW/acre. It should be noted that this is a conservative GTL in comparison to those being analyzed in North America (3 and 4).

2.2 Rock Mass Properties

The rock mass thermal properties from the literature are presented in (5). However, the properties specifically utilized in this study are presented in Table 1. The thermal properties of the materials in the analysis other than the granite are also presented in Table 1. These values are nominal from the literature. Perturbations in these non-rock thermal properties have a very small influence on the subsequent rock mass temperature.

The value of the granite thermal conductivity selected for use in the analysis (2.05 W/m ^{o}C) is somewhat lower than the mean value from the literature. However, this value was selected in order to provide some degree of conservatism to the thermal analysis and to account for the generally lower conductivity of masses of rock as compared to rock samples, referred to in the literature (6). A higher value of conductivity results in lower rock mass temperatures and slightly earlier temperature peaks. Some results are presented for comparison, for an assumed granite conductivity of 3.35 W/m^2 ^{o}C.

2.3 Repository Modeling

For the purpose of assessing the groundwater flow around a repository, the mathematical modeling has been divided into two distinct regions, i.e., near field or local modeling and far field on global modeling.

The local model utilized in this study is presented in Figure 4. Several locations in the local model are labeled which will be used later in the presentation of results. The local model has been constructed by assuming symmetry at the pillar centerline and the room centerline. Obviously, this type of model assumes that the repository has an infinite number of rooms. This, of course, is not the case; however, the number of rooms is large and as will be shown, the assumption of an infinite number of rooms is a reasonable approximation due to the low horizontal temperature gradient exhibited in the global models. At the tunnel periphery two types of boundary conditions can be reasonably employed, viz., insulated or convective. In the case of an insulated periphery, no heat is allowed to be transferred through the room. In a room with stagnate air this is not the case, since the air temperature will rapidly rise to a fairly uniform level and heat will subsequently be transferred through the air. Therefore, the "insulated" boundary is a conservative assumption, since the cross sectional area available for vertical heat transfer is reduced.

In the case of a convective boundary, a film coefficient must be selected. Whereas this film coefficient is, in fact, a function of the temperature drop across the film, a low constant value can be employed in a more expedient manner to provide a reasonable simulation of the heat loss to the repository ventilation system. The boundary condition at the room periphery is examined in this study since the potential exists for different thermomechanical stress states. Subsequently, different permeabilities and flow fields may arise from the choice of the boundary condition. The film coefficient chosen for this study was 2.5 $W/m^2\ ^oC$.

Three far field or global models have been utilized in this portion of the study. These models are graphically illustrated in Figure 5. Models A and B represent repositories at 500 m and 1000 m depth, respectively. Both of these models are constructed assuming symmetry at the repository vertical centerline for both the axisymmetric and plane analysis. These models are, of course, only accurate if the repository can be assumed to be instantaneously loaded (i.e., all waste emplaced at the same time); or if the emplacement can be assumed to occur from the middle outwards in both directions simultaneously; or alternatively, if the emplacement can be assumed to begin at the outer tunnels of the repository and to proceed to the center from both ends at the same rate. For the purpose of this study, the repository models A and B are assumed to be instantaneously loaded.

Model B has been analyzed in an effort to assess the effect of repository depth on induced temperature fields. These results will be discussed in later sections of this report.

Since the repository will not, in fact, be instantaneously loaded, Model C has been constructed to analyze the simulated 30 year waste emplacement period. The emplacement in each room is not modeled; rather two rooms are emplaced with waste every 1 1/2 years, until a total of 40 rooms contain 40 year old radioactive waste.

In each global model, the boundaries other than the earth's surface have been chosen at such a distance as is required to provide insignificant influence on the repository temperatures. These distances are verified in the analysis by noting that the temperatures do not rise at these boundaries.

In both the local and global models, a geothermal gradient of $20^{\circ}C/Km$ has been utilized and the air temperature at the earth's surface is assumed to be $5^{\circ}C$.

Further sections of this report will discuss the specific results of the local and global repository models. In instances where induced groundwater flow can be quantitatively or qualitatively assessed, such an assessment is made. Analytical verification of the finite element program is also provided as an Appendix to this report.

3. RESULTS OF REPOSITORY LOCAL MODELS

Five specific local repository simulations were performed. These are summarized in Table 2. As can be seen in the table, the local model was analyzed in both axisymmetrical and plane geometry. Since the repository configuration is obviously most accurately modeled with a three-dimensional model, the two geometries are utilized to provide a reasonable approximation to the three-dimensional situation. In this regard, the axisymmetric model (wherein the canister is actually a cylinder) results in the more accurate very near field temperatures, particularly in the canister itself. The plane model provides a more realistic approximation to the pillar temperature.

Figure 6 displays the temperatures as a function of time at various locations for the local repository model in plane geometry with no ventilation and a waste age of 40 years. Several features displayed in the figure warrant discussion.

In this model, the temperature at the drillhole periphery (which is actually a trench in the plane model) peaks at 56^{o}C after 23 years. The pillar centerline temperature rises to 43^{o}C at 55 years. The horizontal thermal gradient is the significant variable in assessing local thermally induced flow, since the in situ groundwater will have a density variation from the drillhole periphery to the pillar centerline. Additionally, from a rock mechanics viewpoint, the permeability at each of these locations can be expected to be different. The maximum temperature difference (MTD) between the drillhole and the pillar centerline occurs at approximately 4 years after waste emplacement.

Therefore, assuming that thermally induced flow is merely a function of temperature changes, the flow can be expected to be greatest at this time. Further analysis during this study will provide more insight as to the correlation of MTD time with the time of maximum thermally induced flow.

It is interesting to note that even after 1000 years, the temperatures in the near field have not returned to the pre-emplacement value. However, the horizontal gradients have diminished to a negligible value and all heat conduction at this time is essentially vertical.

Figure 7 presents the near field transient history for the same situation as previously discussed with the exception that a 30-year ventilation period has been assumed. Perhaps the most interesting aspect of this figure is the illustration that with the addition of repository ventilation, each location in the near field of the canister experiences two thermal cycles. In other words, 30 years of ventilation is sufficient to remove the quantity of heat necessary to allow a heating and cooling period for both the waste canister and the rock mass. After the ventilation is terminated, the canister and the rock mass experience another heating and cooling period. However, this second cycle is of a much longer duration and as such should not be as detrimental to the rock mass as the first cycle may have been. The duration of the two thermal cycles are compared in Figure 8. In this figure, each cycle is illustrated from a common starting point in time. Perhaps, the most disadvantageous aspect of the ventilation shut down is the fact that the horizontal gradients are again increasing, thus possibly producing thermally induced flow at a much later time than was the case with the situation of no ventilation at any time (see Figure 6).

The magnitude and time of occurence of the second heating cycle peak will be shown later to be a function of the waste age and also the assumed thermal properties of the site rock mass.

The transient temperature results for the axisymmetric analysis (see Table 2) are displayed in Figure 9. In general, the temperatures in the very near vicinity of the waste package are higher than was the case with the plane models. Also, the temperatures farther away from the canister are lower with the axisymmetric analysis. The analysis presented in Figure 9 was performed to assess the temperatures in the near vicinity of the waste package. The temperatures from this model cannot be utilized without some judicious care. In particular, the canister is realistically modeled as a cylinder with a heat generation of 525 watts upon emplacement although 525 W is a conservative assumption in itself (2). However, due to the modeling (insulated boundary at a radius of 12.5 m) the resulting canister spacing is approximately 25 meters in each direction. Therefore the 4 m by 25 m canister grid system is not well represented by this model. However, the temperature results can be superposed to result in a very good approximation to the actual near field temperatures. For example, to simulate the effect of the canister 4 m from the modeled canister, the temperatures at 4 m from the modeled canister can be superposed on the temperatures resulting in the modeled canister. This process can be repeated to simulate the canisters at the 8 m and 12 m distances from the modeled canister. This process can be utilized to provide a good approximation to the temperatures since the material properties are not assumed to be temperature dependent and the boundary conditions are all homogeneous. Using this procedure the canister periphery and drillhole periphery maximum temperatures can be approximated as 77°C and 62°C, respectively, occuring at 12 years and 20 years, respectively.

In order to assess the effect of waste age on the thermal and subsequent groundwater situations, the plane model with 30 year ventilation was analyzed with 10 year old waste. The 10 year old waste is not presently an alternative; rather the waste age was chosen to accentuate the effect of varying the age of the emplaced waste. The results of this analysis are presented in Figure 10. Since the heat generation of a 10 year old waste canister is approximately twice that of 40 year old waste, the repository temperatures are considerably greater than those with the 40 year old waste. The maximum temperature rises at the drillhole periphery and pillar centerline are approximately 22°C and 4°C greater, respectively, and occur at 3 years and 10 years, respectively. These times of occurence are roughly 50 % earlier than the equivalent peak times associated with the 40 year old waste. As can be seen by comparing Figures 8 and 10, the second thermal cycle for 10 year old waste results in higher temperatures than that for 40 year old waste. It should be emphasized that the temperatures displayed in Figure 10 were obtained with the plane model and that axisymmetric modeling would result in still higher near field temperatures.

To assess the sensitivity of the induced temperature fields to a change in thermal rock properties, the plane model with 30 years of ventilation was analyzed with the rock properties given in (7). These results are illustrated in Figure 11. The thermal conductivity assumed in this simulation (3.35 W/m - $^{\circ}$C) is approximately 1.6 times greater. The temperatures for these assumed properties of granite are lower (although, not linearly) than those previously presented.

4. RESULTS OF REPOSITORY GLOBAL MODELS

Five specific global repository simulations were performed. These simulations are presented in Table 3. The instantaneous emplacement models have been examined more than the linear emplacement sequence model for economical reasons. The linear emplacement model requires approximately twice the number of degrees of freedom and the solution procedure is more lengthy due to the continual loading changes for the first 30 years of simulation.

The temperature distribution along the centerline of the repository at 500 m depth is illustrated in Figure 12 for 10,100 and 1000 years after emplacement. Even after 1000 years, a large rock mass is above the initial geothermal temperature. For this present study, the rate of rock mass temperature increase is important since this will influence the groundwater pathway (joints) width change and subsequent permeability. Therefore, it can be stated that the 40 year old waste is more advantageous than a younger waste since the rate of rock mass temperature rise is slower than that with the younger waste.

Figure 13 has been constructed to display the variation of the temperature along the repository plane at various values of time after emplacement. Early in time, there is a dramatic horizontal temperature gradient providing for the potential for thermally induced flow. Later in time the horizontal gradient is much less. Whether the early horizontal gradients are sufficient to produce any flow will be one of the subjects of further analysis within this study.

As can be seen in Figure 13, the boundaries of the global models appear to be adequately removed so that they experience no temperature rise.

Since the finite element method can merely provide approximations to the near field or far field temperatures around a repository, the input to the models which may be questionable must be examined for the resulting temperature sensitivity. In this regard, the boundary condition at the earth's surface has been examined. The physical boundary condition at the earth's surface is a convective one. However, the choice of a convective boundary condition requires the selection of a convective film coefficient, which is an additional parameter subject to constructive criticism. To analyze the effect of the choice of boundary conditions the 500 m repository model was analyzed with both a $5^{o}C$ constant temperature condition and a convective condition ($h = 2.5\ W/m^{2}\ {}^{o}C$) with atmospheric air equal to $5^{o}C$. The results of this analysis indicate the choice of the boundary condition provides for negligible change in the rock mass temperatures. In fact, the maximum difference occurs at about 700 years when the repository midplane is approximately $0.2^{o}C$ greater with the convective condition. For higher GTL's or other rock mass properties, the influence of the boundary could be expected to be greater.

In addition to the analysis of the boundary condition at the earth's surface, the global repository model was also analyzed for geometric sensitivity. Specifically, since the plane modeling indicates that the repository extent normal to the finite element model is infinite, an axisymmetric simulation was performed wherein the repository has a finite extent. The GTL for the axisymmetric analysis was equal to that for the plane analysis. The temperatures through the repository centerline at various times are displayed in Figure 14. The temperatures are very similar to those obtained with the plane modeling with the axisymmetric temperatures only slightly higher for early times and slightly lower for later times.

The plane modeling was extended for analysis of a repository at 1000 m for comparison. The temperature rises at 1000 m can be expected to be equal to those at 500 m provided that the boundary condition at the earth's surface (or equivalently, the depth of the repository) has no noticable influence on the temperature rise. (Based on these results, the above is, in fact, the case.) The temperature rises at 1000 m are very near those at 500 m (maximum difference of $1^{o}C$). The results for the 1000 m repository are briefly presented in Figure 15.

As would be expected, the transient behaviors of the global repository models are similar to that exhibited in the local analysis previously presented. However, the transient behavior of the repository global models should be observed with some scrutiny in regions very near the repository. Specifically, since the model distributes the heat generation over the entire plane of the repository (waste, pillars and rooms), the transient behavior in the plane of the repository is the integral mean of the transient behavior of every point within the plane. This can further be explained by observing Figure 16. In this figure the temperature curve identified as the repository centerline peaks at about 50 years. This, in fact, is the peak time for only a finite region of the actual repository. Some locations (near the waste packages) will peak much earlier, and some locations will peak later (pillar center, for example). The same analogy exists for the magnitude of the temperature peak.

The regions which are not very near the repository (say, more than 25 m away) are more accurate in the global model due to the symmetry assumed in the local modeling. Two characteristics displayed in Figure 16 merit discussion.

First, locations less than about 100 m from the repository have experienced the temperature peak of the thermal cycle prior to 1000 years. At 75 m below the repository centerline, the temperature peak occurs at about 700 years, whereas at 200 m below the repository centerline, the peak will not be reached until possibly 5000 years. The temperatures at locations far removed from the repository midplane (for example, at 200 m) have not yet reached their maximum values at 1000 years. However, the eventual temperatures rise at these locations can not be greater than the temperature rise at the repository midplane. Therefore, the eventual temperature rise at the 200 m location can never be greater than 18°C (temperature rise at repository plane at 1000 years) which would result in a temperature of about 36°C (18°C + pre-emplacement temperature).

The second feature displayed in Figure 16 which should be discussed is the MTD transient across the repository. The MTD is greatest at 15°C at 4 years. However, the MTD is maintained at about 10°C for an extended period of time. At 1000 years, the MTD is still at about 9^{o}C. As mentioned previously, this horizontal gradient may result in thermally induced flow. This analysis will again be the subject of further efforts within this study.

Figure 17 displays the transient behavior of the repository temperatures for the axisymmetric simulation. The fact that the repository temperatures peak higher and somewhat earlier in the axisymmetric model than in the plane model is apparent in the figure.

All of the previously discussed global models assumed instantaneous emplacement of the waste. This assumption has been previously utilized in almost every investigation performed by others. In an effort to observe the temperature field perturbation caused by the sequential emplacement of the waste, Model C (see Figure 5) was analyzed. In this repository model, 40 year old waste is emplaced in a region equivalent to 2 rooms (50 m x 3.5 m) every 1.5 years until the final repository region (1 km) has received waste. In order to accentuate the effects of emplacement, no repository ventilation was modeled.

The temperature distribution along the repository plane and 25 km above the repository plane at various times are displayed in Figure 18 and 19, respectively. As can be observed in the figures, the effect of the sequential emplacement is rather pronounced (this effect would diminish with the addition of ventilation). In this instance, a rock mass with a higher thermal diffusivity would exhibit a significantly lower emplacement effect. The horizontal temperature gradients in the repository domain are much greater in the linear emplacement than in the instantaneous emplacement simulation. Also the MTD values are much higher earlier in time. Subsequent studies of thermally induced flow should provide a better understanding of the groundwater flow induced by this situation. It is of interest to note that the horizontal temperature gradient reverses direction at about 70 years.

The transient behavior of several locations in the repository model is presented in Figure 20. After about 70 years the temperatures are nearly equal to those in the linear emplacement model (see Figure 15). However, as stated previously, the MTD is much greater during early times.

5. SUMMARY AND CONCLUSION

Conduction "baseline" thermal calculations have been completed for local near-field and global far-field temperature distributions. The effects of waste age, rock mass thermal conductivity, repository depth, repository ventilation, emplacement sequence and modeling geometry have been analyzed. These baseline results will be used in further phases of this study to analyze the effects on the rock mechanical situation and subsequent flow permeability perturbations. Additionally, the temperature fields will be utilized to assess thermally induced flow and to quantify the importance of free and forced convective heat transfer and their subsequent effects on the groundwater regime.

The temperature rises that have been observed are low in comparison to those arising in the analysis of repositories in other nations. This is mainly due to the waste age and the low GTL being investigated in Sweden. In a qualitative sense, the potential for thermally induced flow appears apparent. However, further study should quantify the magnitude of this flow.

REFERENCES

1. Lindblom, U.E., Gnirk, P.F., Charlwood, R.G. and Cherry, J.,1977, "GROUNDWATER MOVEMENTS AROUND A REPOSITORY, Phase 1. State of the art and detailed study plan", Submitted to KBS-Kärnbränsle-säkerhet, Stockholm, Sweden.

2. Ekberg, K., Kjellberg, N. and Olsson, G., 1977, "Resteffektstudier för KBS", TPM-RF-77-2246/SM-48, Submitted to KBS-Kärnbränslesäkerhet, Stockholm, Sweden.

3. Cheverton, R.D. and Turner, W.D., 1972, "Thermal Analysis of the National Radioactive Repository: Progress Through March 1972", ORNL-4789.

4. Tammemagi, H.I., 1975, "Specifications for the conceptual Design of a Radioactive Waste Repository", AECL, WNRE-260.

5. Stille, H., Burgess, A.S. and Lindblom, U.E., 1977, "GROUNDWATER MOVEMENTS AROUND A REPOSITORY, Phase 2. Technical Report 1. Geological and Geotechnical Conditions", To be submitted to KBS-Kärnbränslesäkerhet, Stockholm Sweden.

6. Beck, A., Jaeger, J.C. and Newstead, G., "The Measurement of the Thermal Conductivities of Rocks by Observations in Boreholes", Aust. J. Phys., Vol 8, No.4, pp. 286 - 296.

7. Blomquist, Roland, 1977, "Orienterande Temperaturberäkningar för slutförvaring i berg av radioaktivt avfall", TPM- RV-454, Submitted to KBS-Kärnbränslesäkerhet, Stockholm, Sweden.

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

9. Lohmander, B. and Rittsten, S., "Table of the function

$$y = e^{-x^2} \int_0^x e^{t^2} dt,$$

Kungl. Fysiogr. Sällsk. i Lund Förh., 28, 45-52 (1958).

10. Callahan, G.D. and Ratigan, J.L., "Thermoelastic Analysis of Spent fuel Repositories in Bedded and Dome Salt" May, 1977, Submitted by RE/SPEC Inc. to Office of Waste Isolation, ORNL.

TABLE 1

THERMAL PROPERTIES FOR MODELED MATERIALS

Material	K (W/m - ^{o}C)	ρ (Kg/m^3)	c (J/Kg - ^{o}C)
Granite	2.05	2800	735
Vitrified Waste	0.5	2500	735
Backfill	1.0	2800	735
Lead	28.0	12000	130

TABLE 2

SUMMARY OF LOCAL REPOSITORY SIMULATIONS

Number	Geometry	Ventilation	Waste Age (yrs)	Conductivity (W/m - ^{o}C)
1	Plane	None	40	2.05
2	Plane	to 30 yrs	40	2.05
3	Axisymmetric	None	40	2.05
4	Plane	to 30 yrs	10	2.05
5	Plane	to 30 yrs	40	3.35

TABLE 3

SUMMARY OF GLOBAL REPOSITORY SIMULATIONS

Number	Geometry	Depth (m)	Emplacement	Boundary Condition
1	Plane	500	instant[x]	Constant[xx]
2	Axisymmetric	500	instant	Convective[xxx]
3	Plane	500	instant	Convective
4	Plane	1000	instant	Convective
5	Plane	500	linear	Convective

x instant implies instantaneous emplacement

xx constant implies constant temperature at the earth's surface

xxx Convective implies a convective boundary condition at the earth's surface.

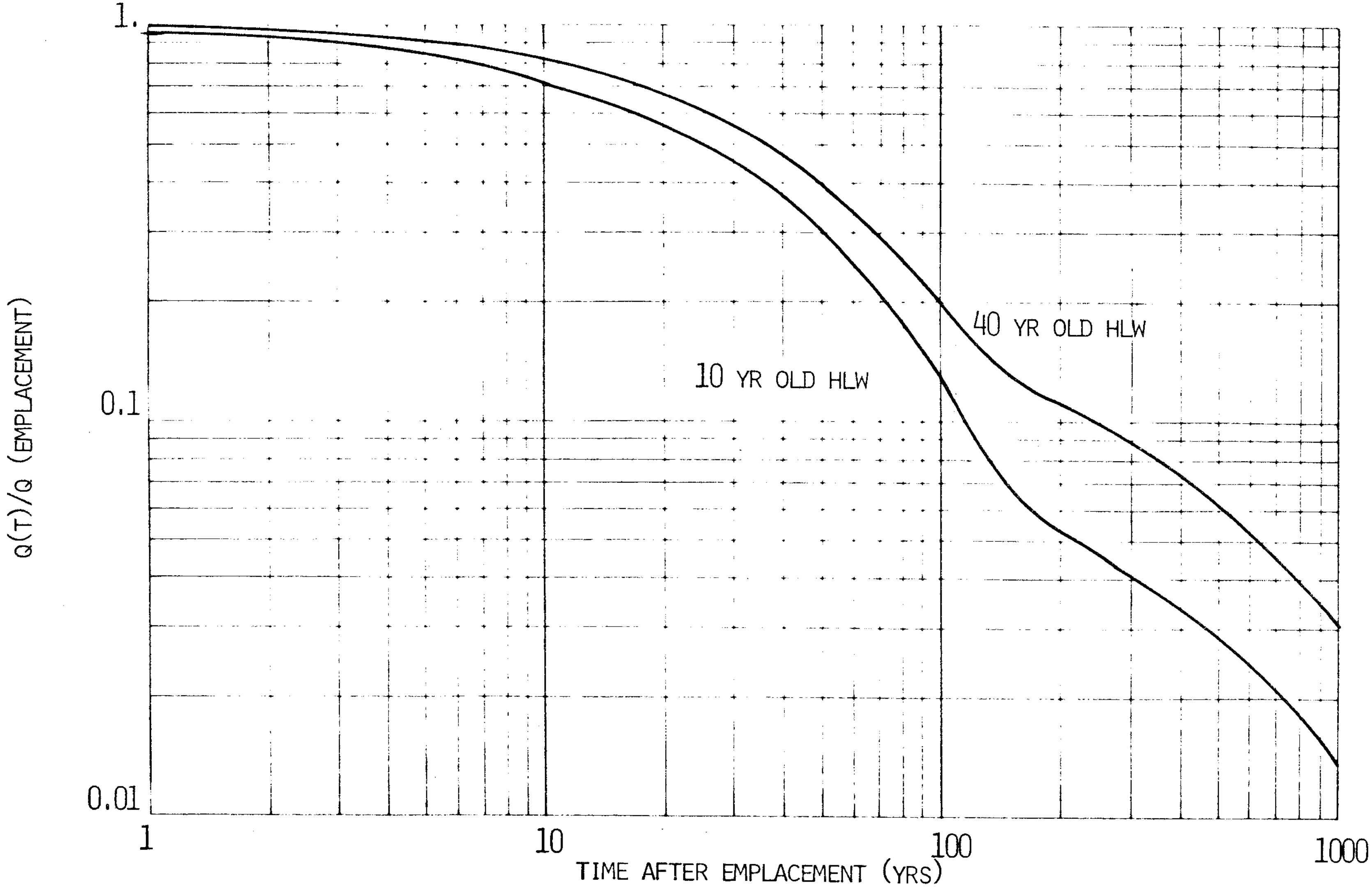


FIGURE 1. TRANSIENT HEAT GENERATION FOR 10 YEAR OLD AND 40 YEAR OLD HIGH LEVEL WASTE

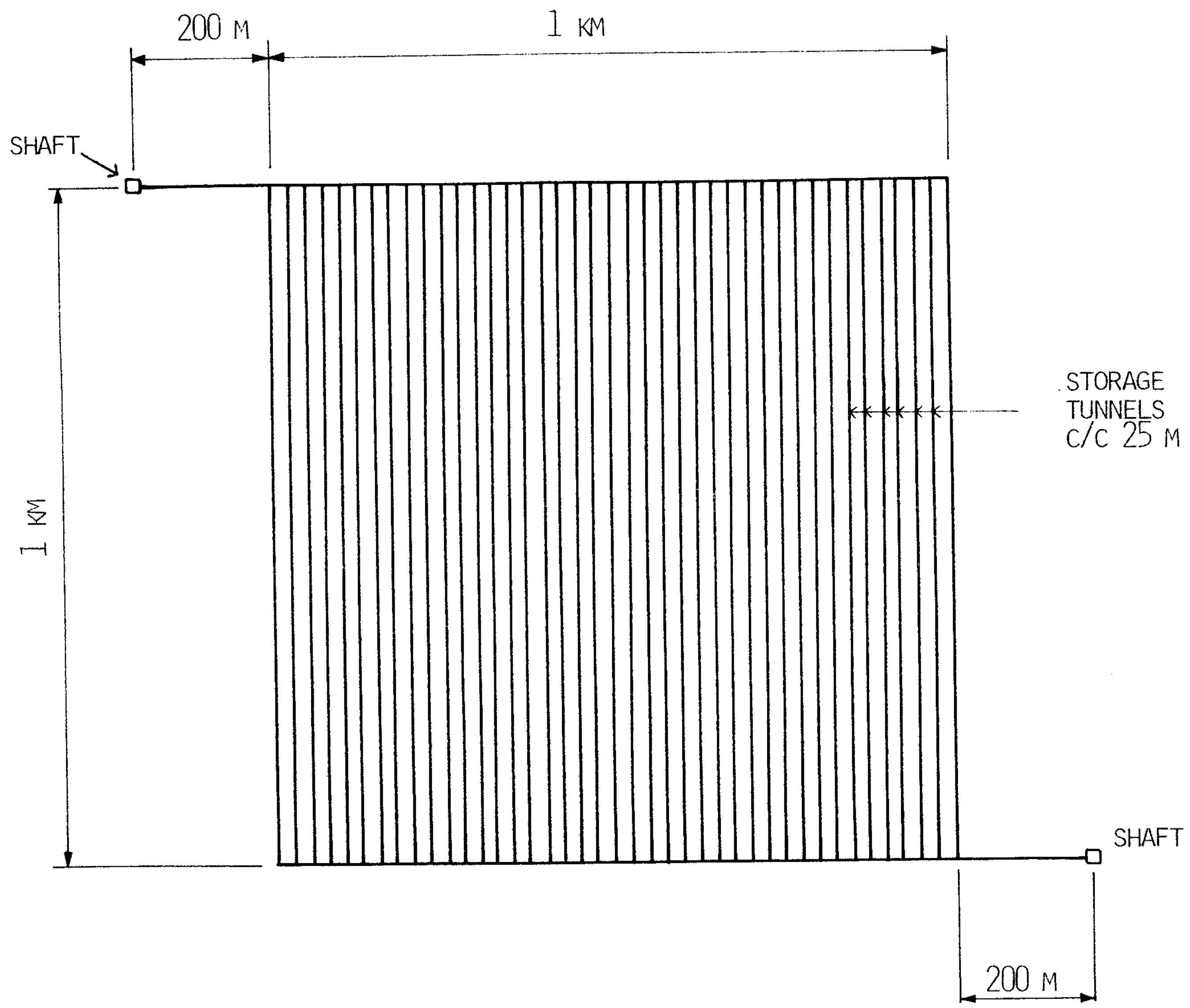


FIGURE 2. TUNNEL AND CANNISTER DETAILS FOR HIGH LEVEL WASTE REPOSITORY

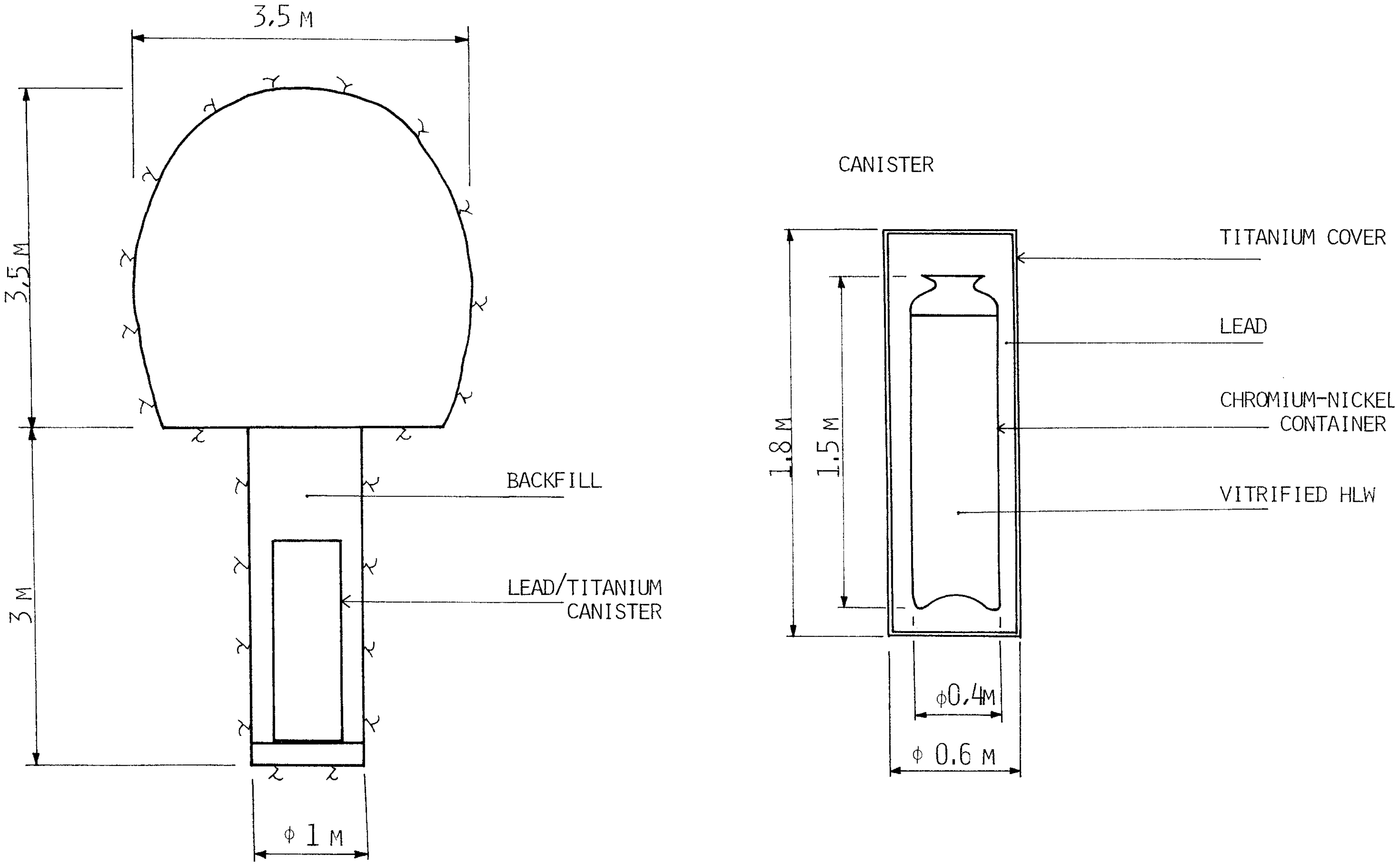


FIGURE 3. LAYOUT OF HIGH LEVEL WASTE REPOSITORY

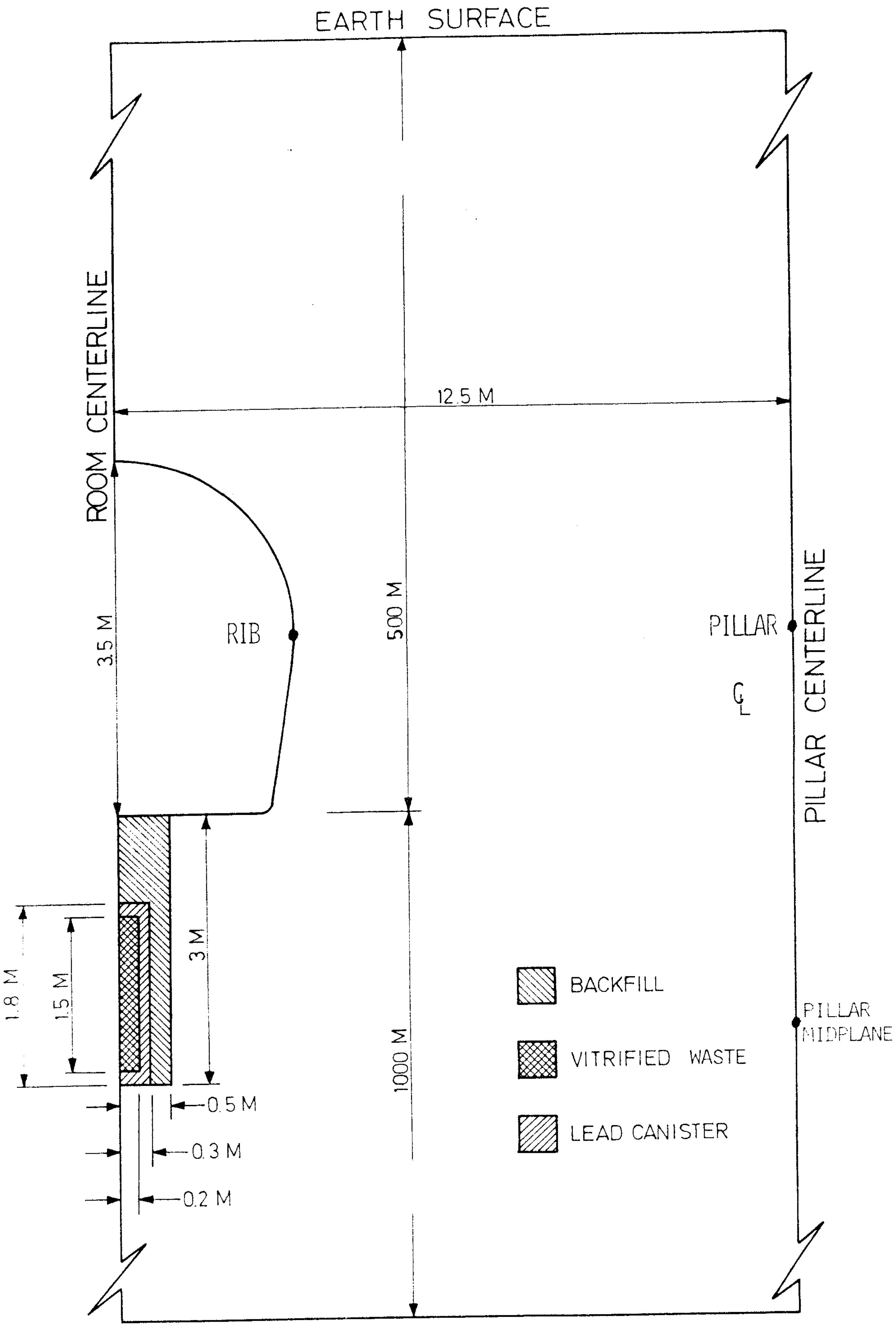


FIGURE 4. MODEL FOR LOCAL REPOSITORY SIMULATION

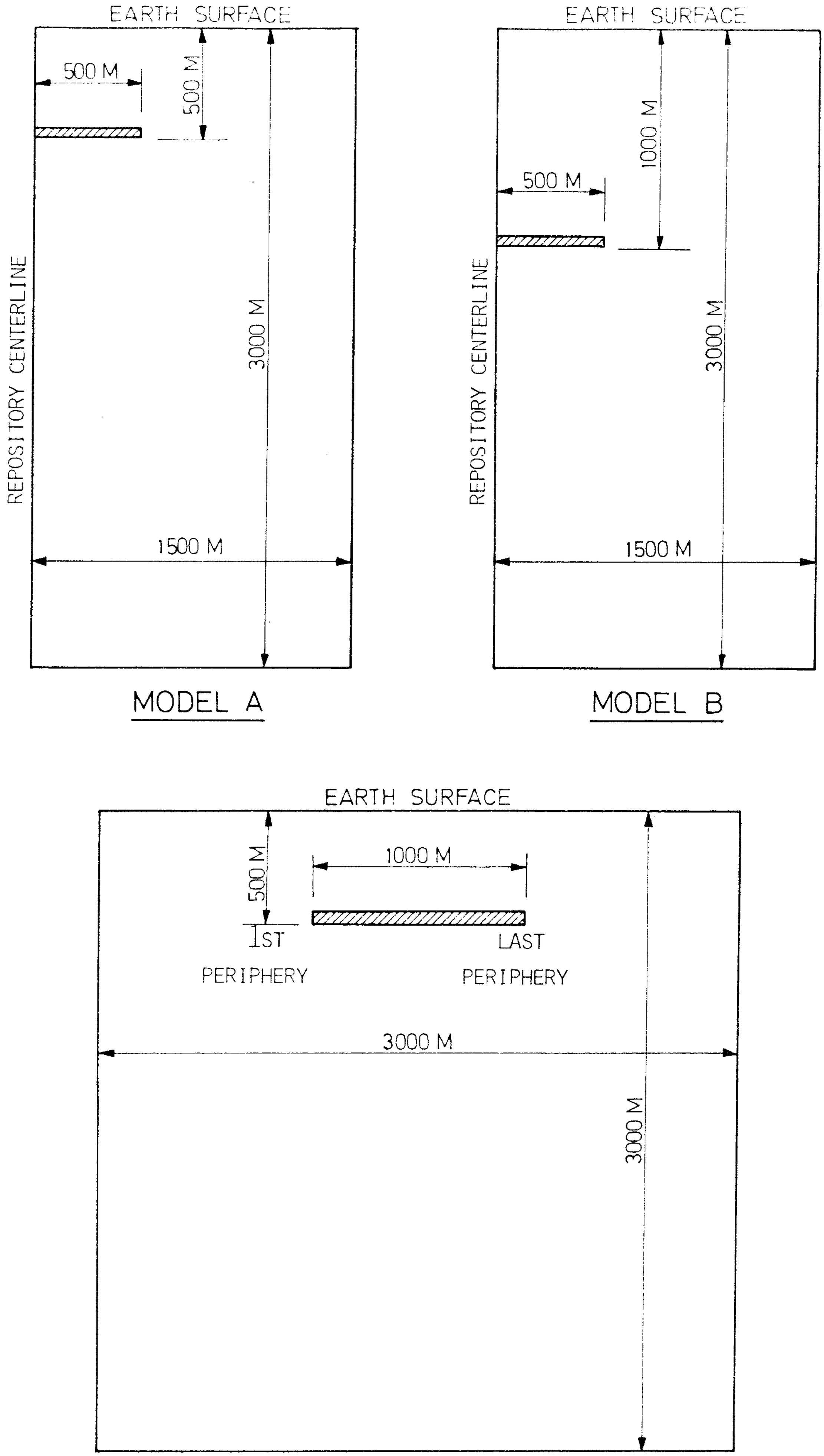


FIGURE 5. MODELS FOR GLOBAL REPOSITORY SIMULATION

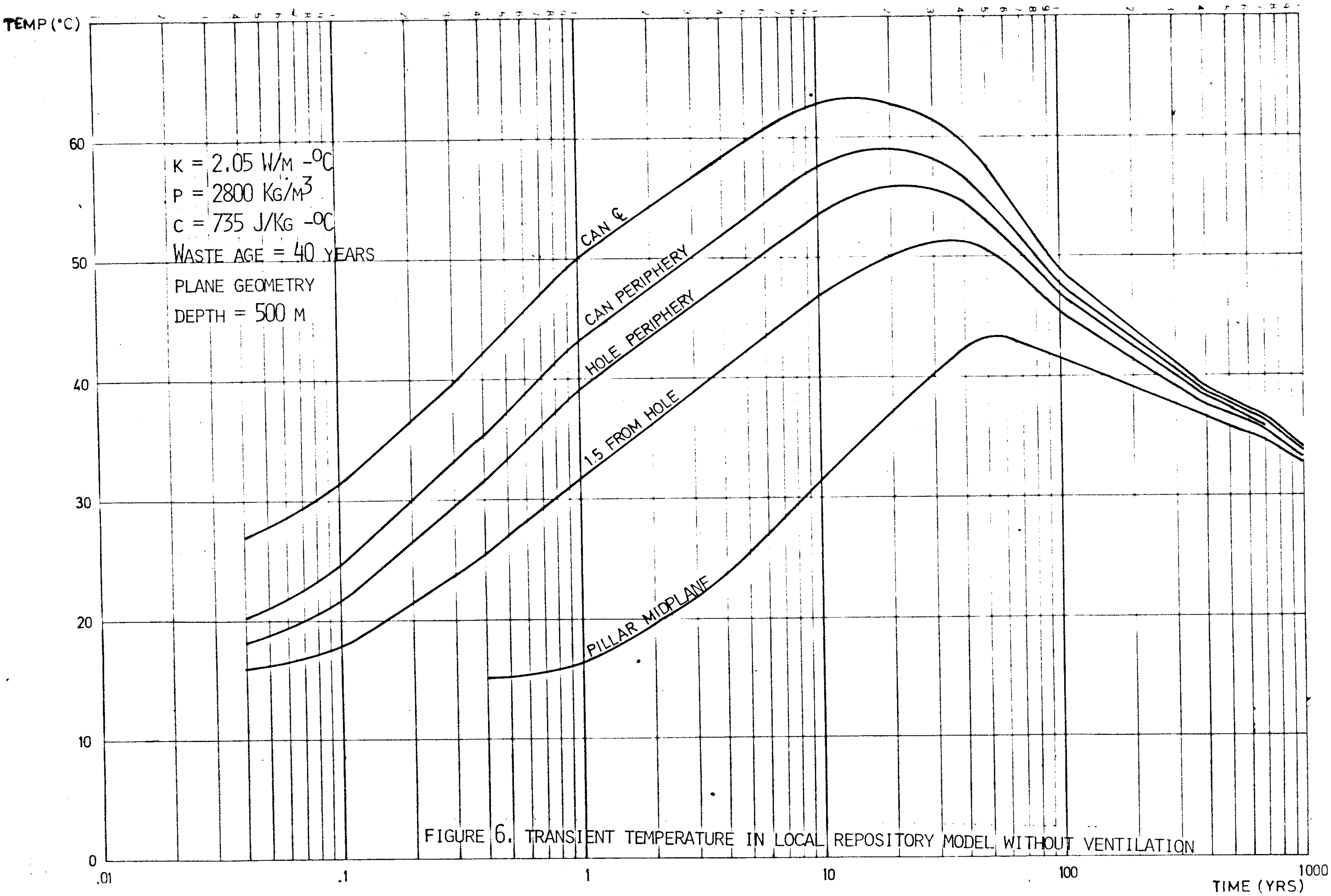


FIGURE 6. TRANSIENT TEMPERATURE IN LOCAL REPOSITORY MODEL WITHOUT VENTILATION

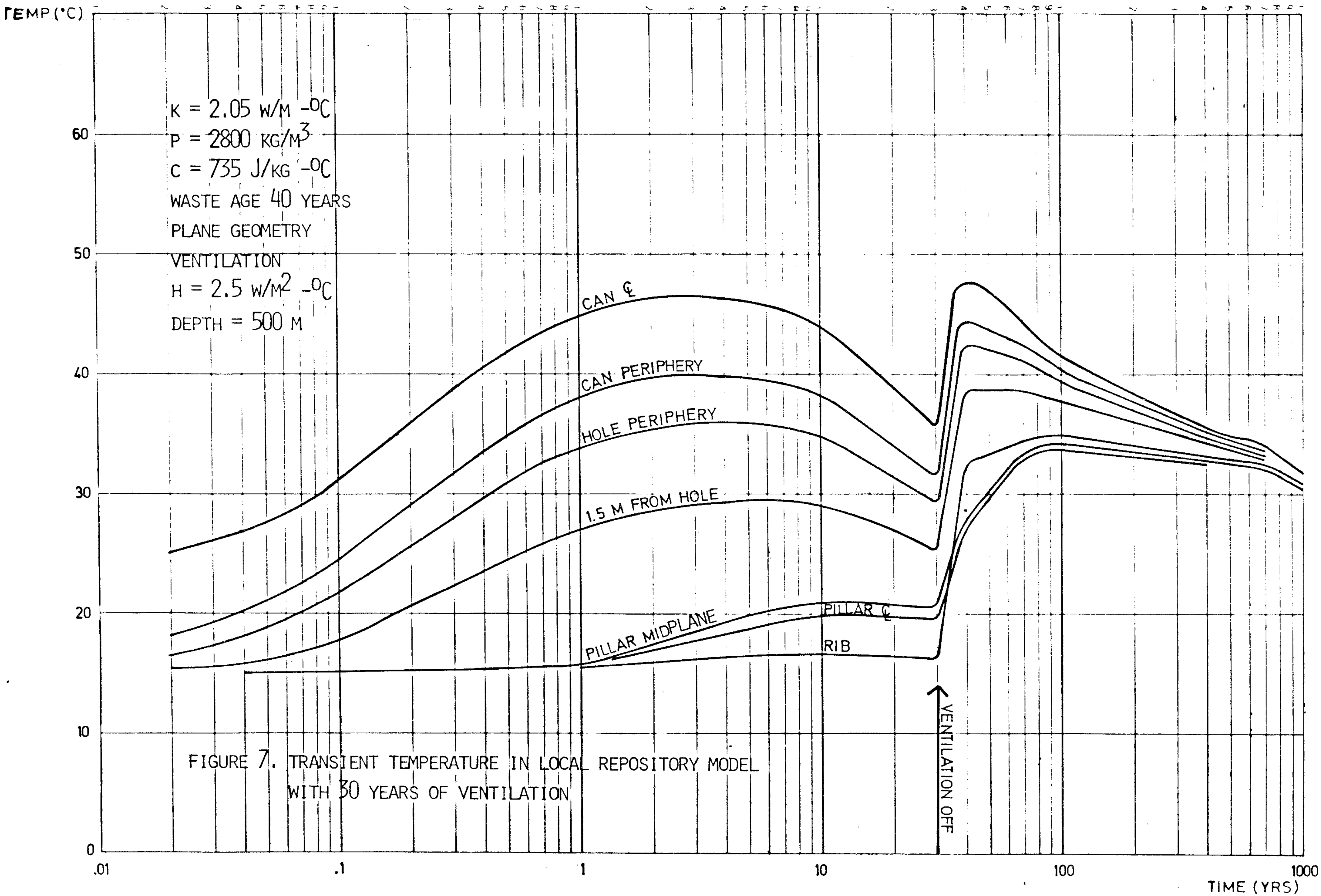


FIGURE 7. TRANSIENT TEMPERATURE IN LOCAL REPOSITORY MODEL WITH 30 YEARS OF VENTILATION

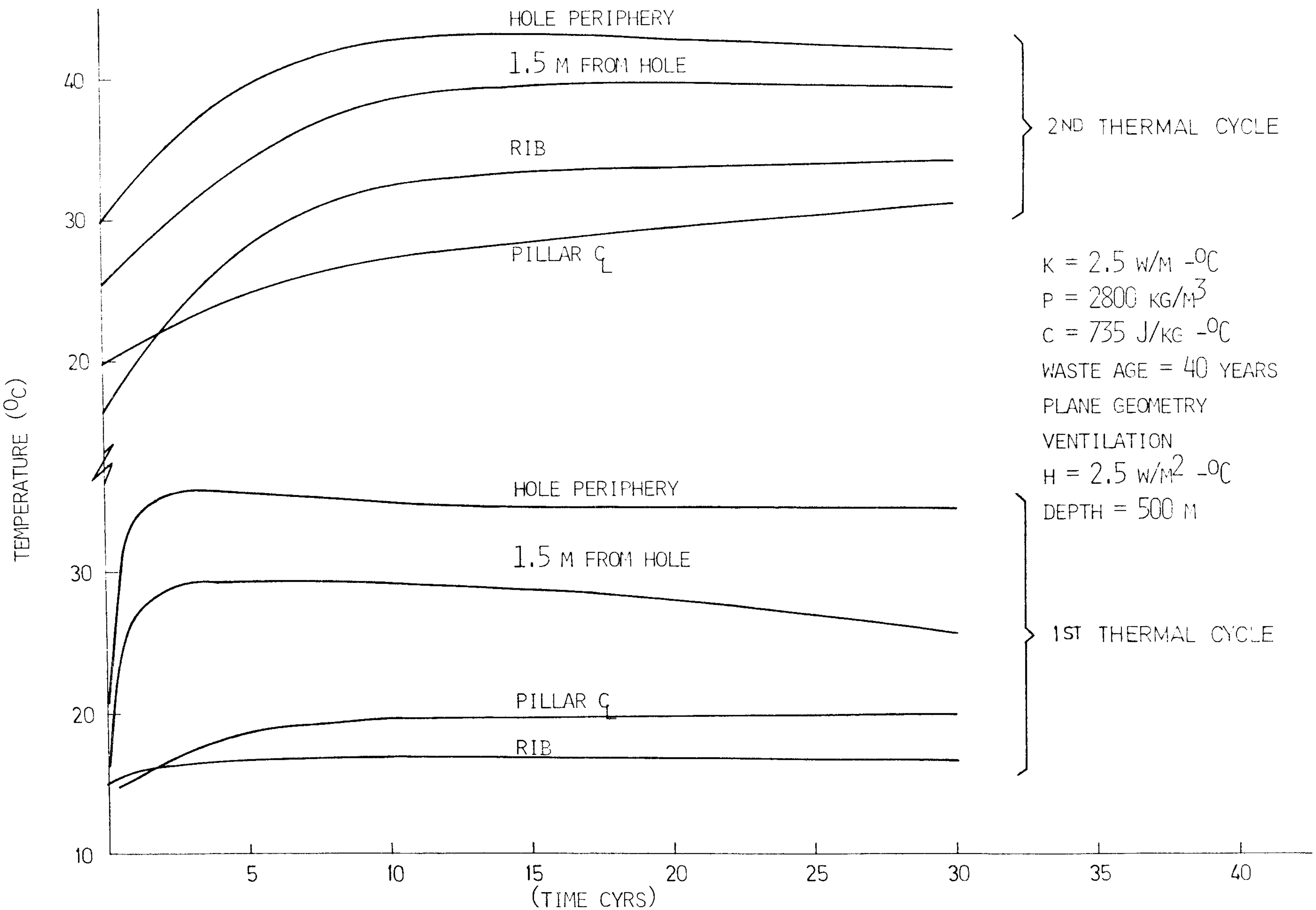


FIGURE 8. COMPARISON OF THERMAL CYCLE PRIOR TO VENTILATION WITH THERMAL CYCLE AFTER VENTILATION

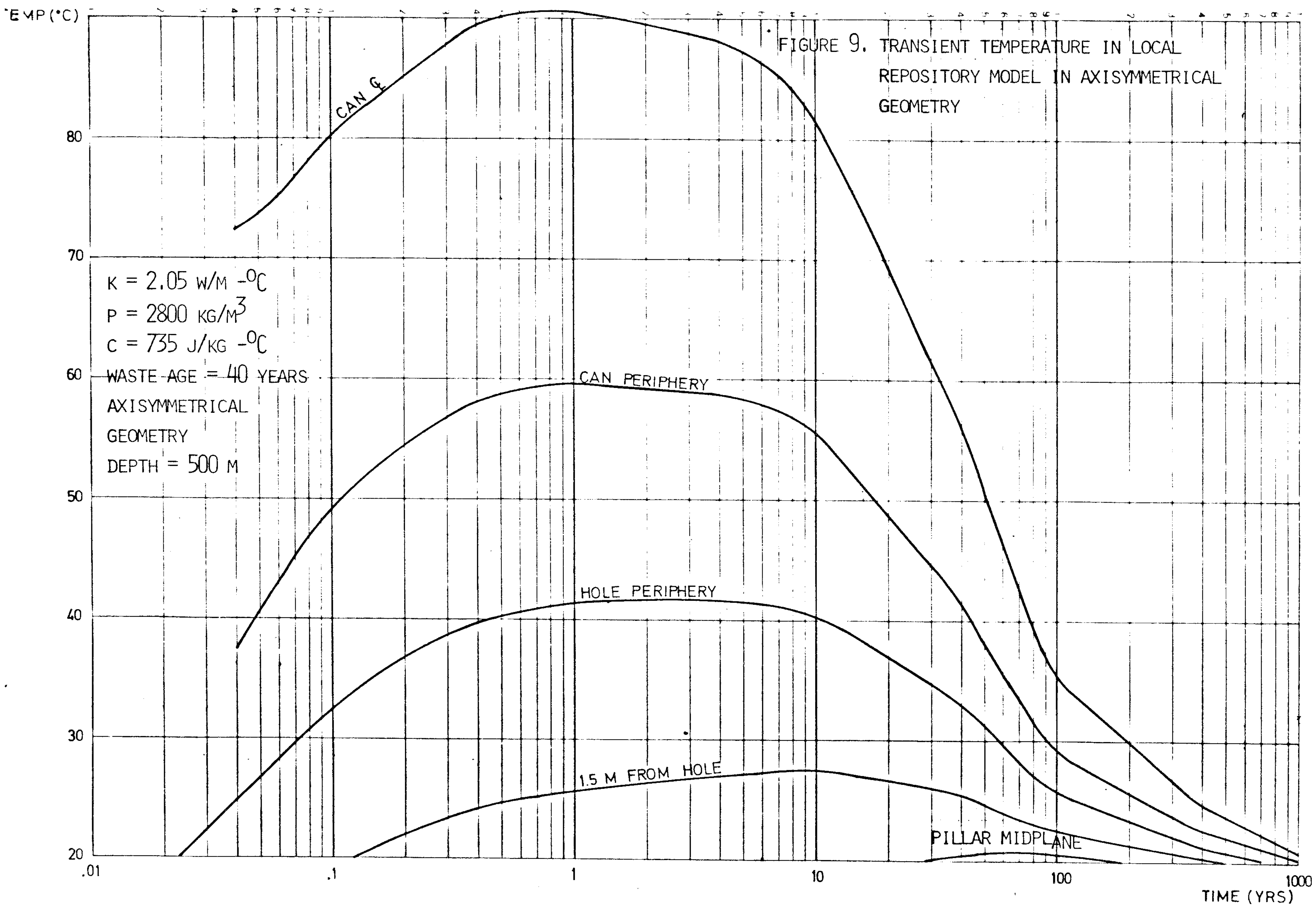


FIGURE 9. TRANSIENT TEMPERATURE IN LOCAL REPOSITORY MODEL IN AXISYMMETRICAL GEOMETRY

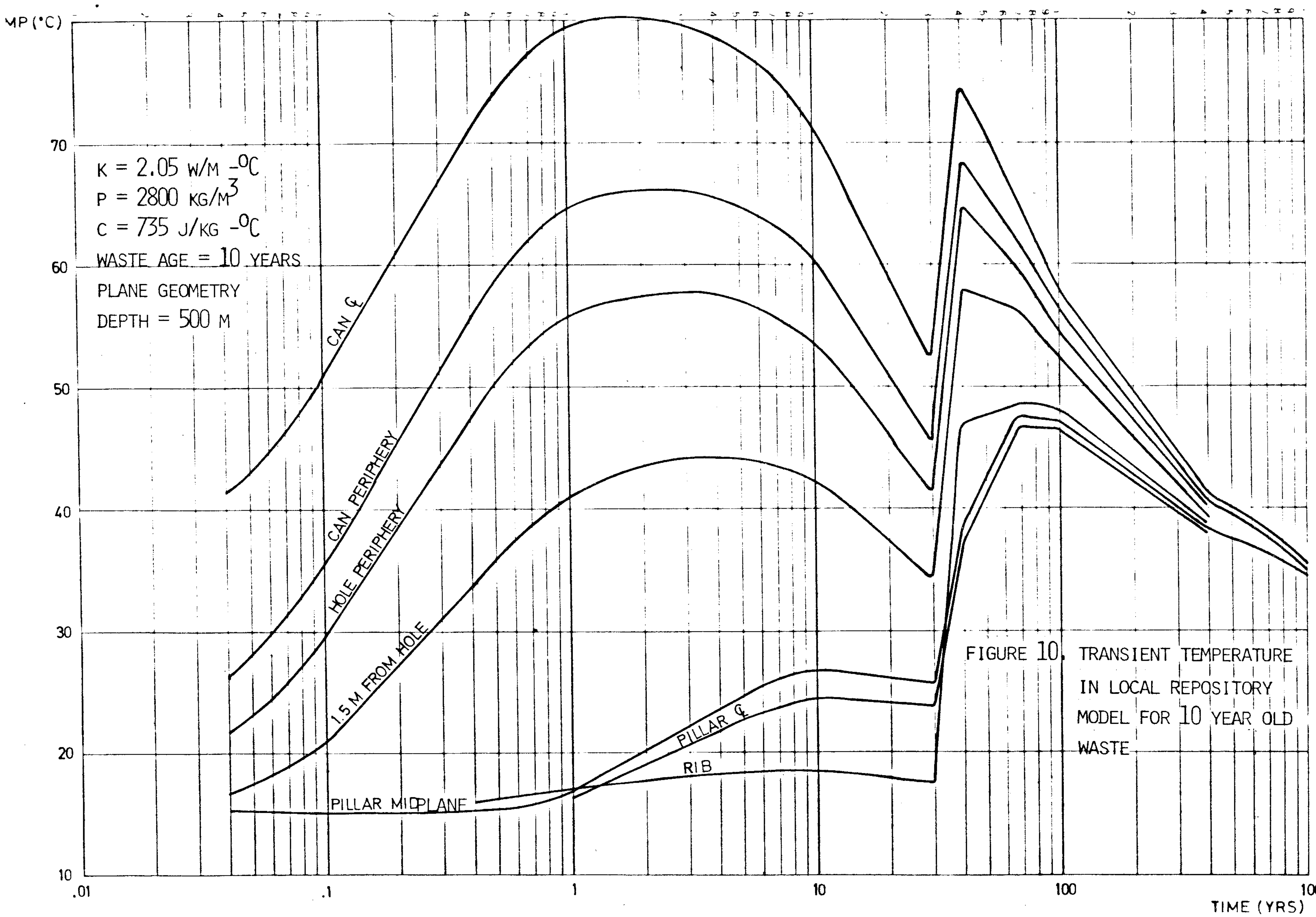


FIGURE 10. TRANSIENT TEMPERATURE IN LOCAL REPOSITORY MODEL FOR 10 YEAR OLD WASTE

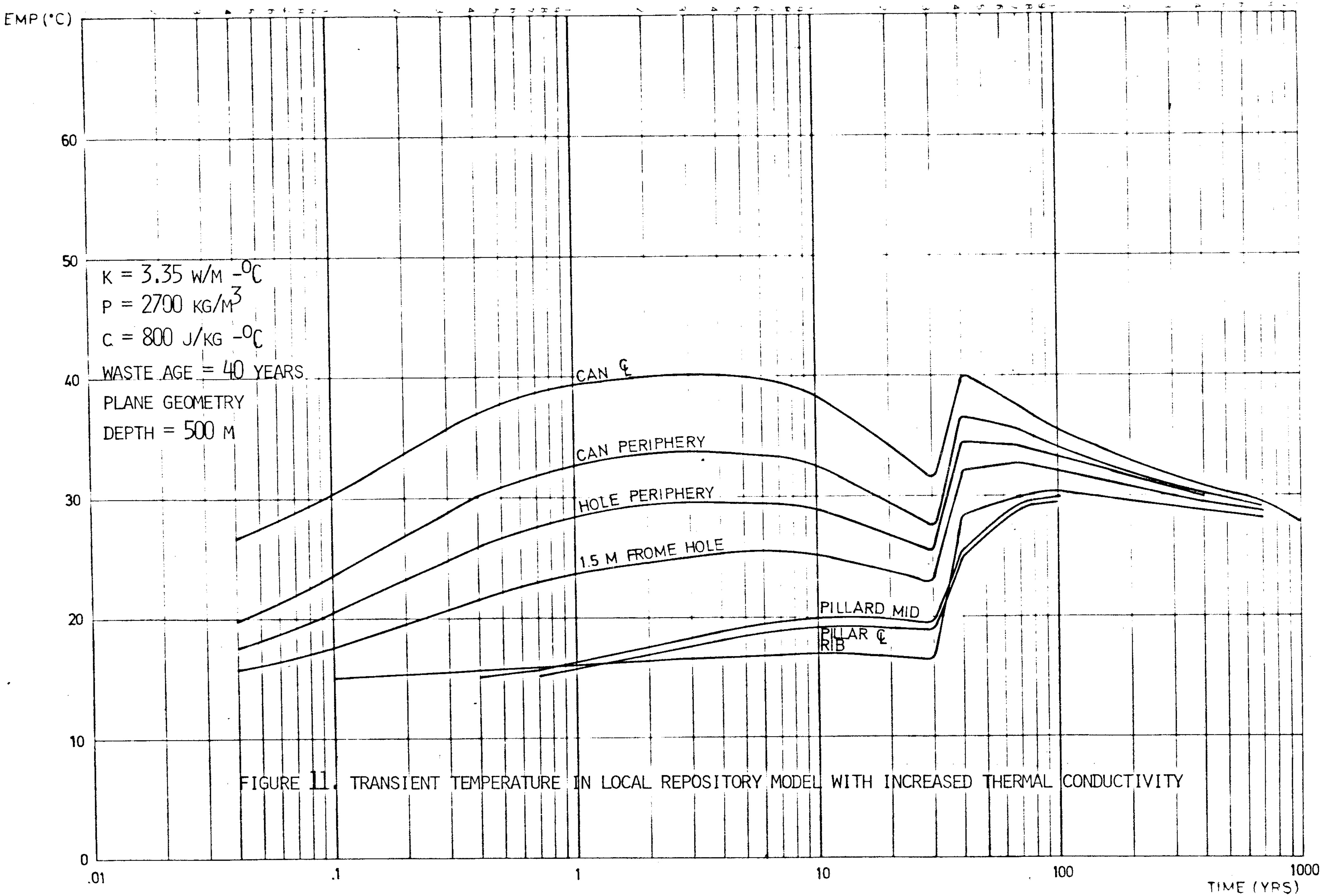


FIGURE 11. TRANSIENT TEMPERATURE IN LOCAL REPOSITORY MODEL WITH INCREASED THERMAL CONDUCTIVITY

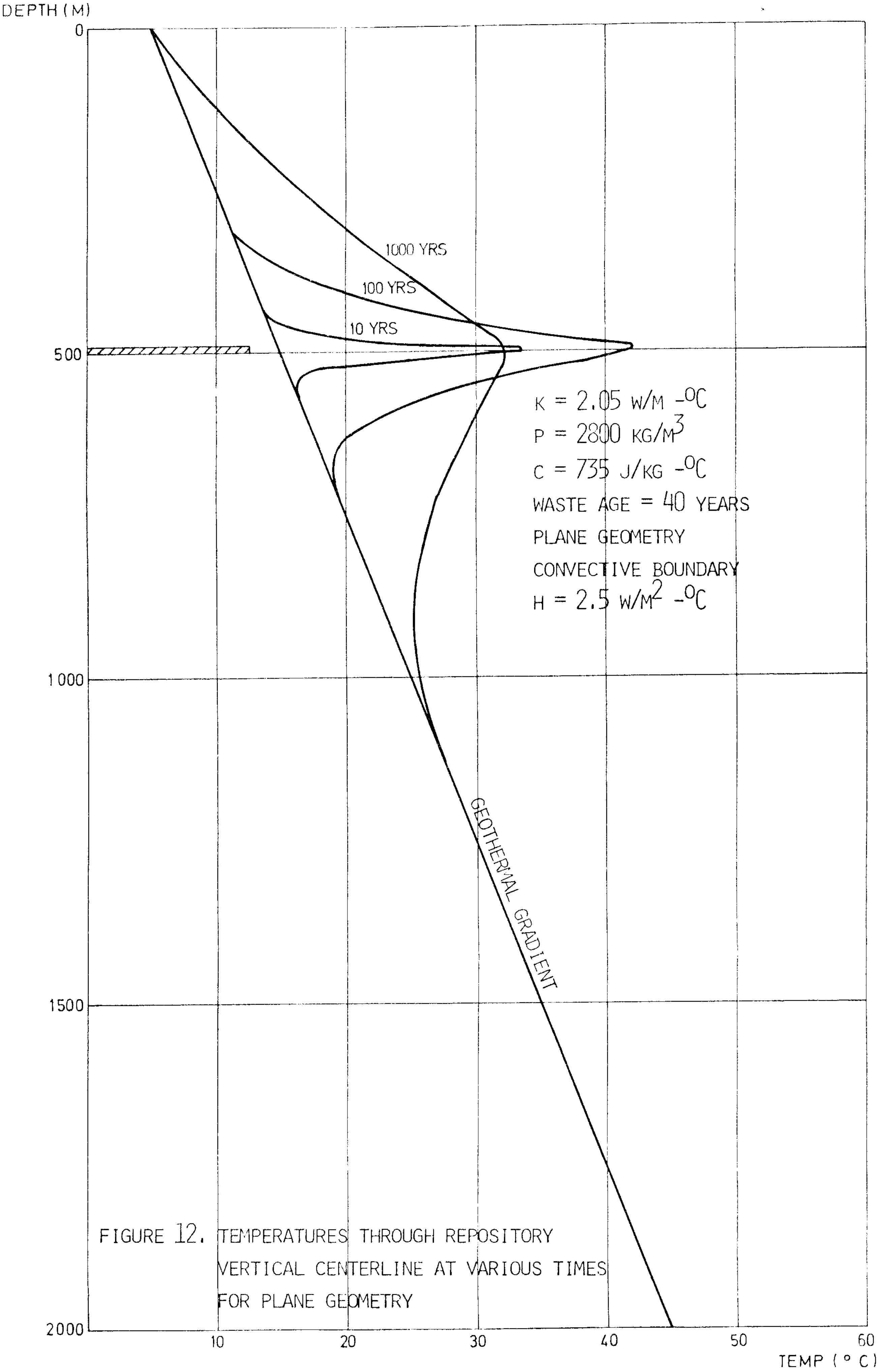


FIGURE 12. TEMPERATURES THROUGH REPOSITORY VERTICAL CENTERLINE AT VARIOUS TIMES FOR PLANE GEOMETRY

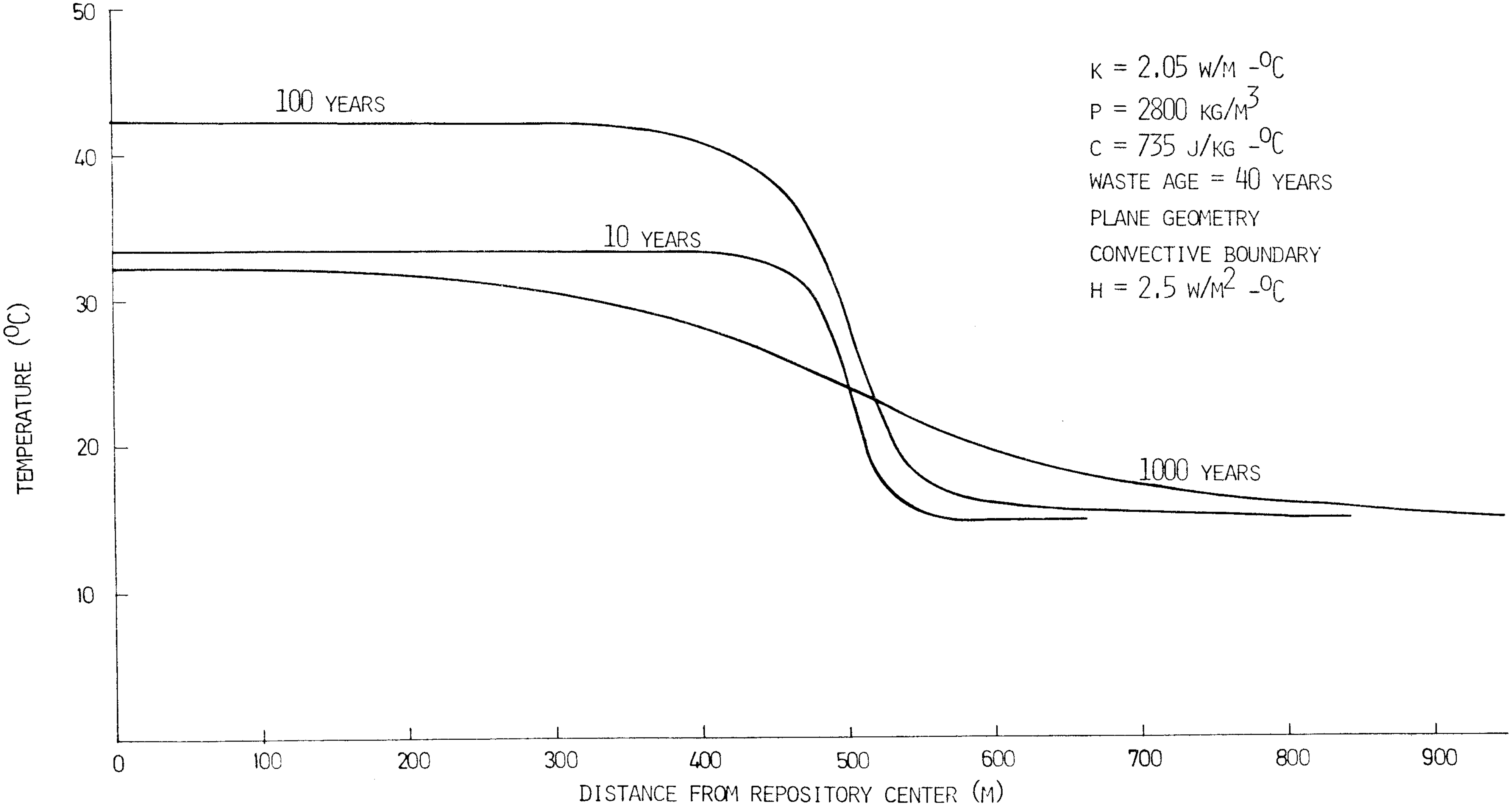


FIGURE 13. TEMPERATURE ALONG REPOSITORY PLANE AT VARIOUS TIMES

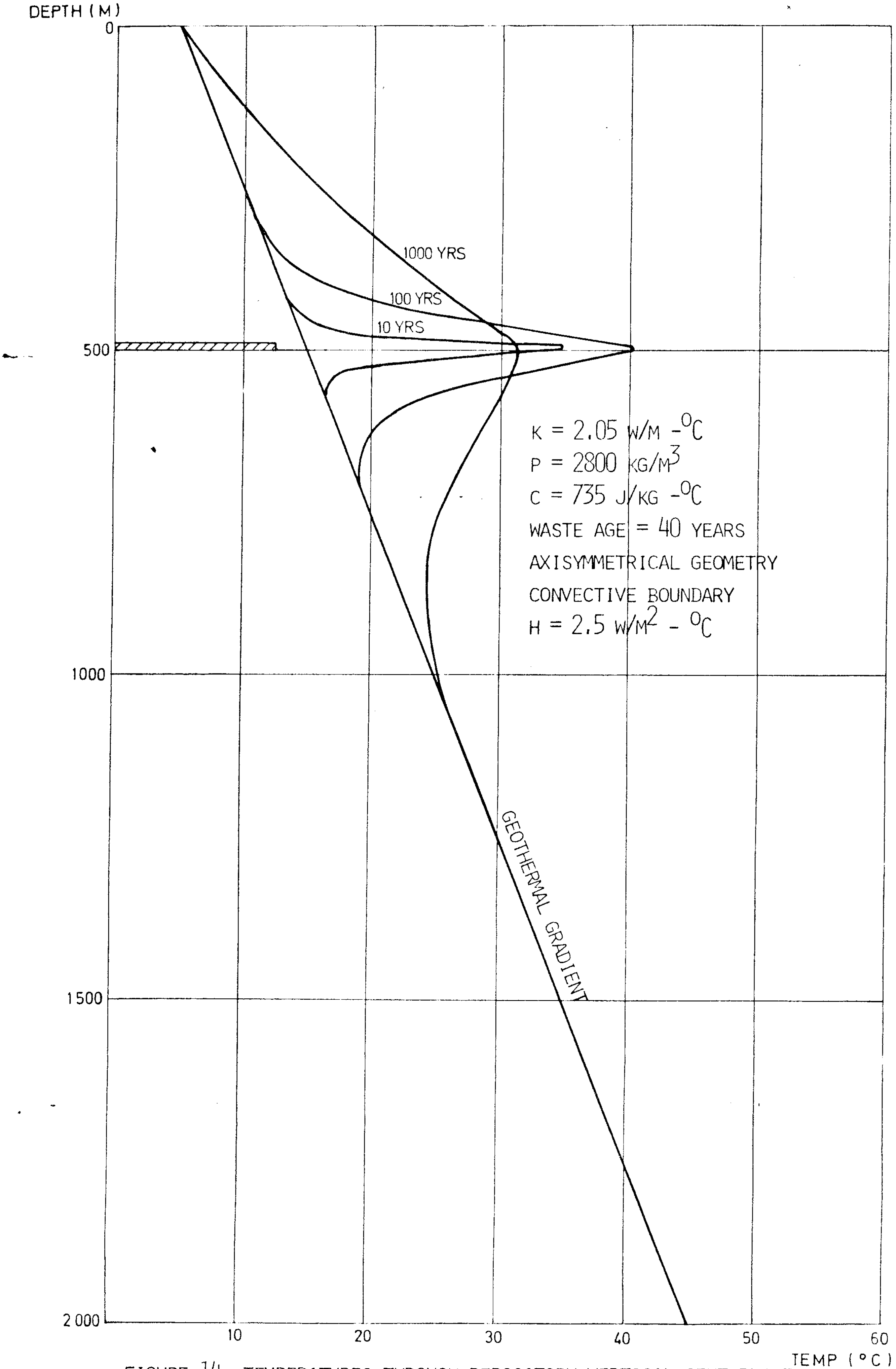


FIGURE 14. TEMPERATURES THROUGH REPOSITORY VERTICAL CENTERLINE AT VARIOUS TIMES FOR AXISYMMETRICAL GEOMETRY

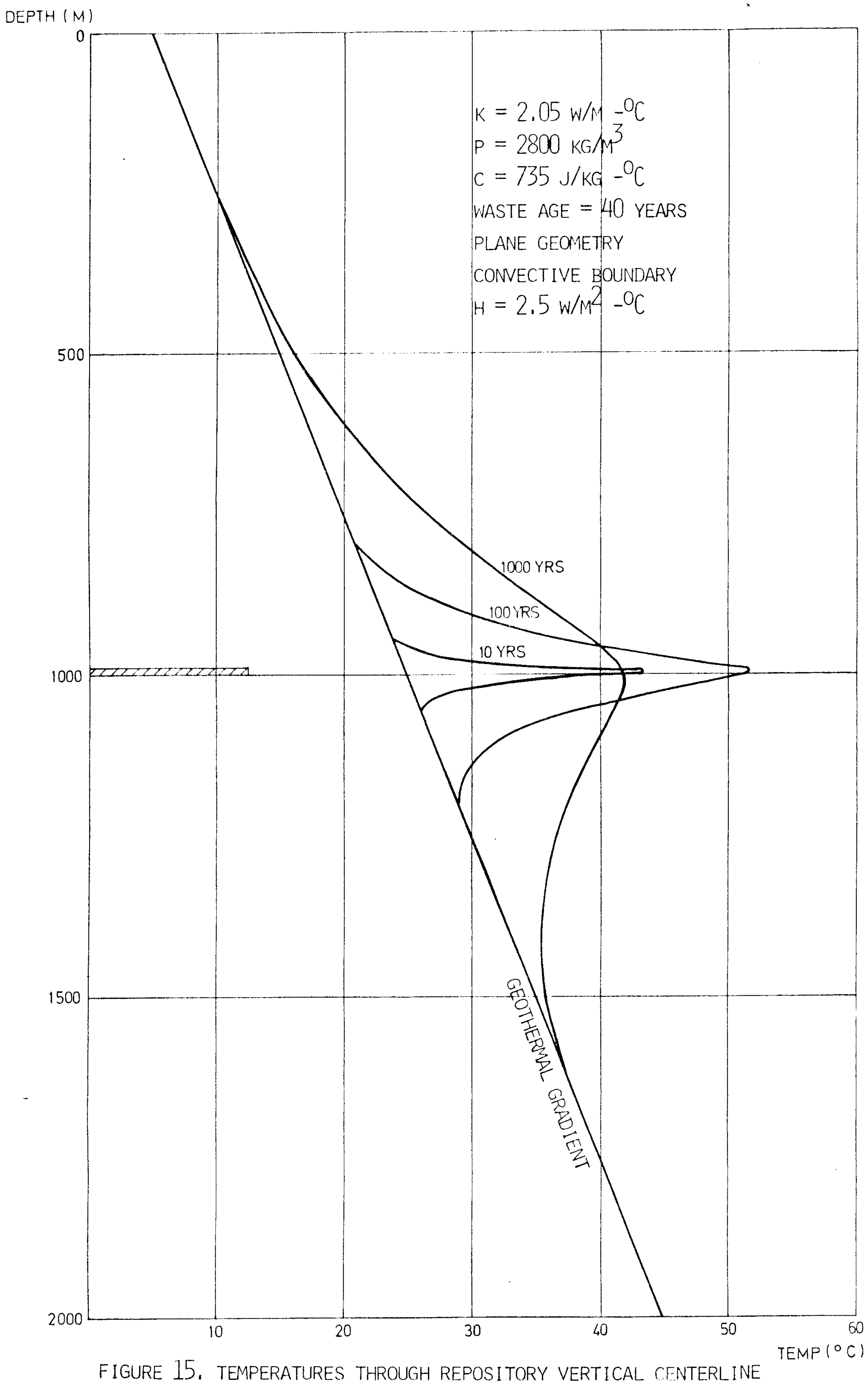


FIGURE 15. TEMPERATURES THROUGH REPOSITORY VERTICAL CENTERLINE

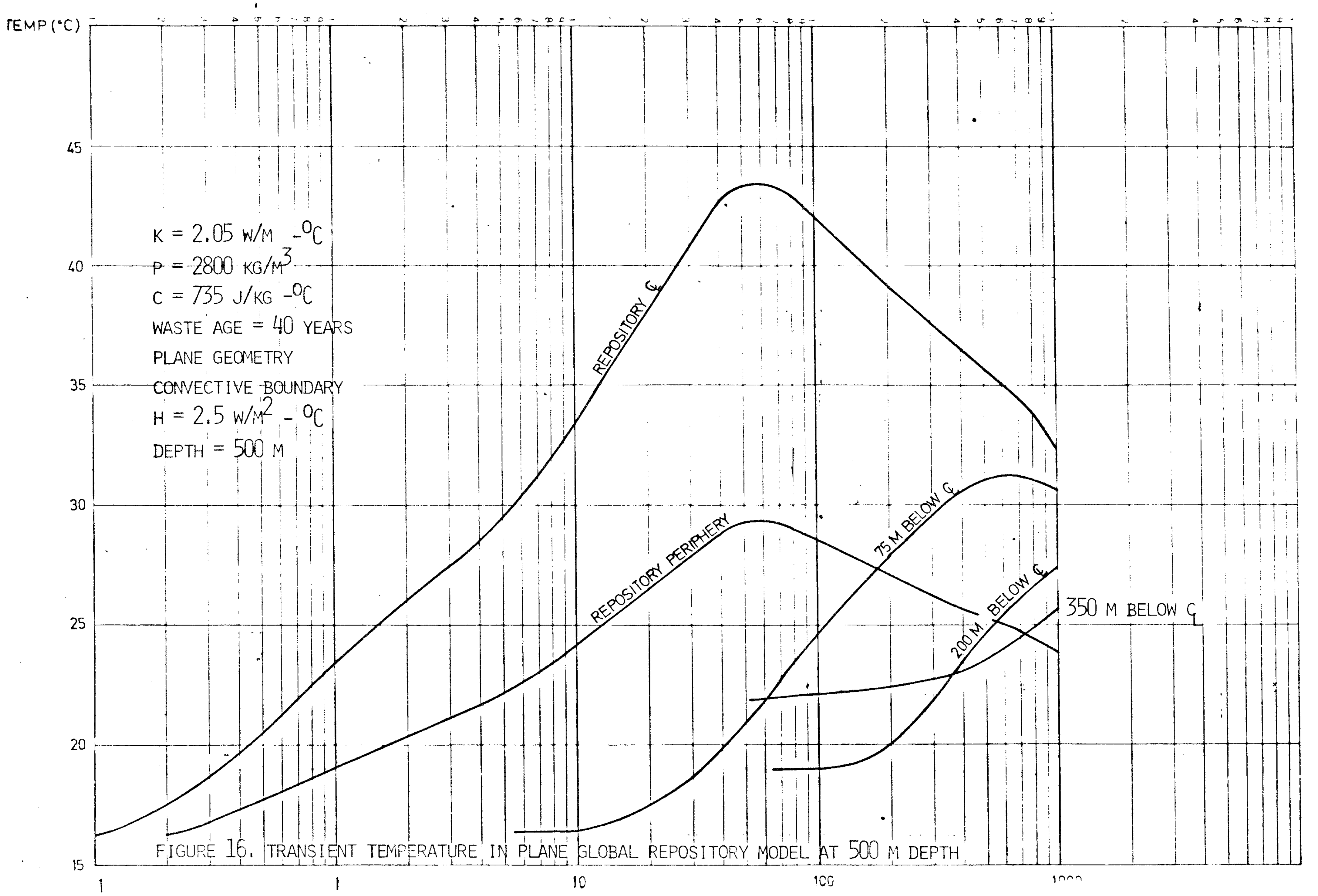


FIGURE 16. TRANSIENT TEMPERATURE IN PLANE GLOBAL REPOSITORY MODEL AT 500 M DEPTH

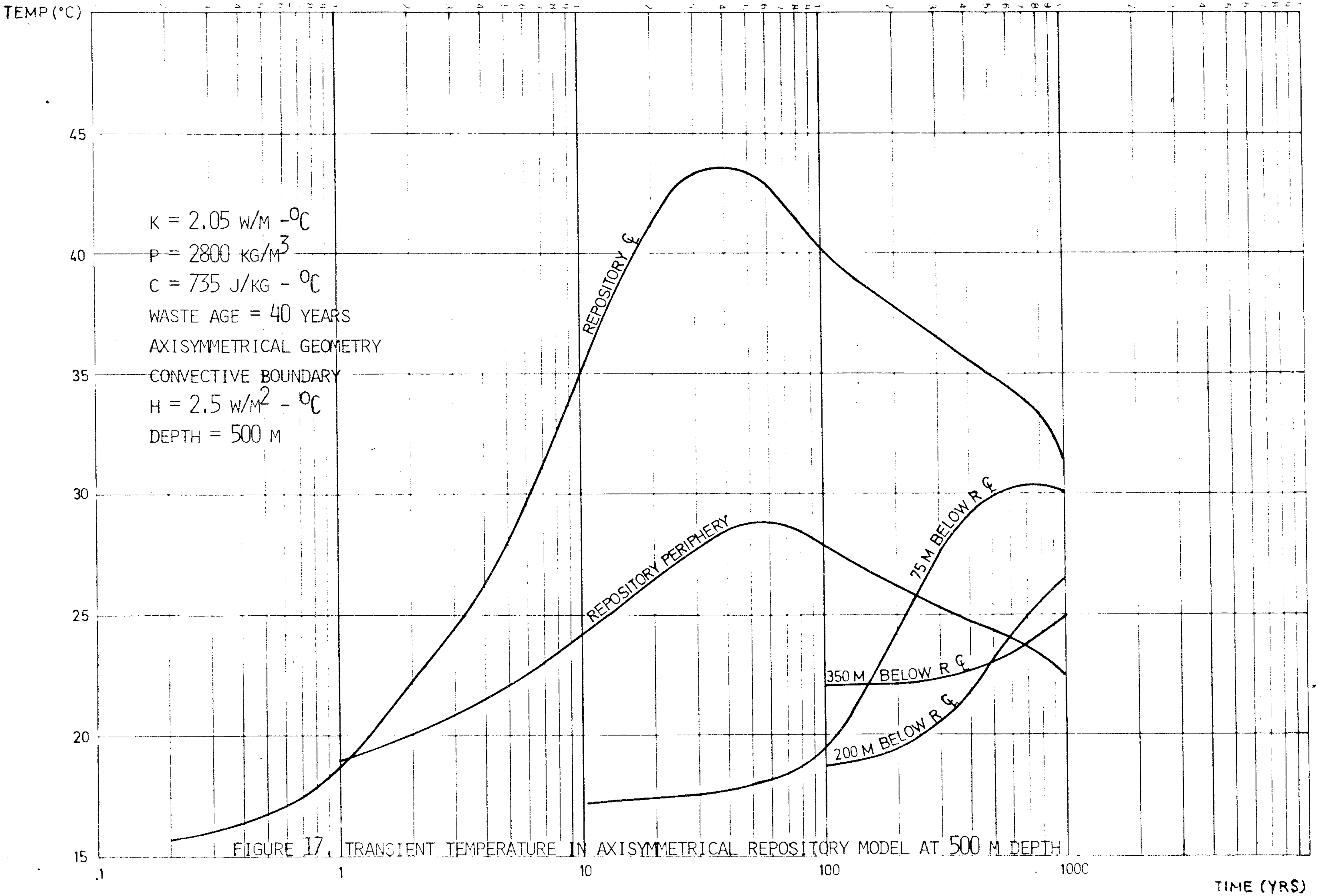


FIGURE 17. TRANSIENT TEMPERATURE IN AXISYMMETRICAL REPOSITORY MODEL AT 500 M DEPTH

TEMPERATURE IN REPOSITORY MIDPLANE

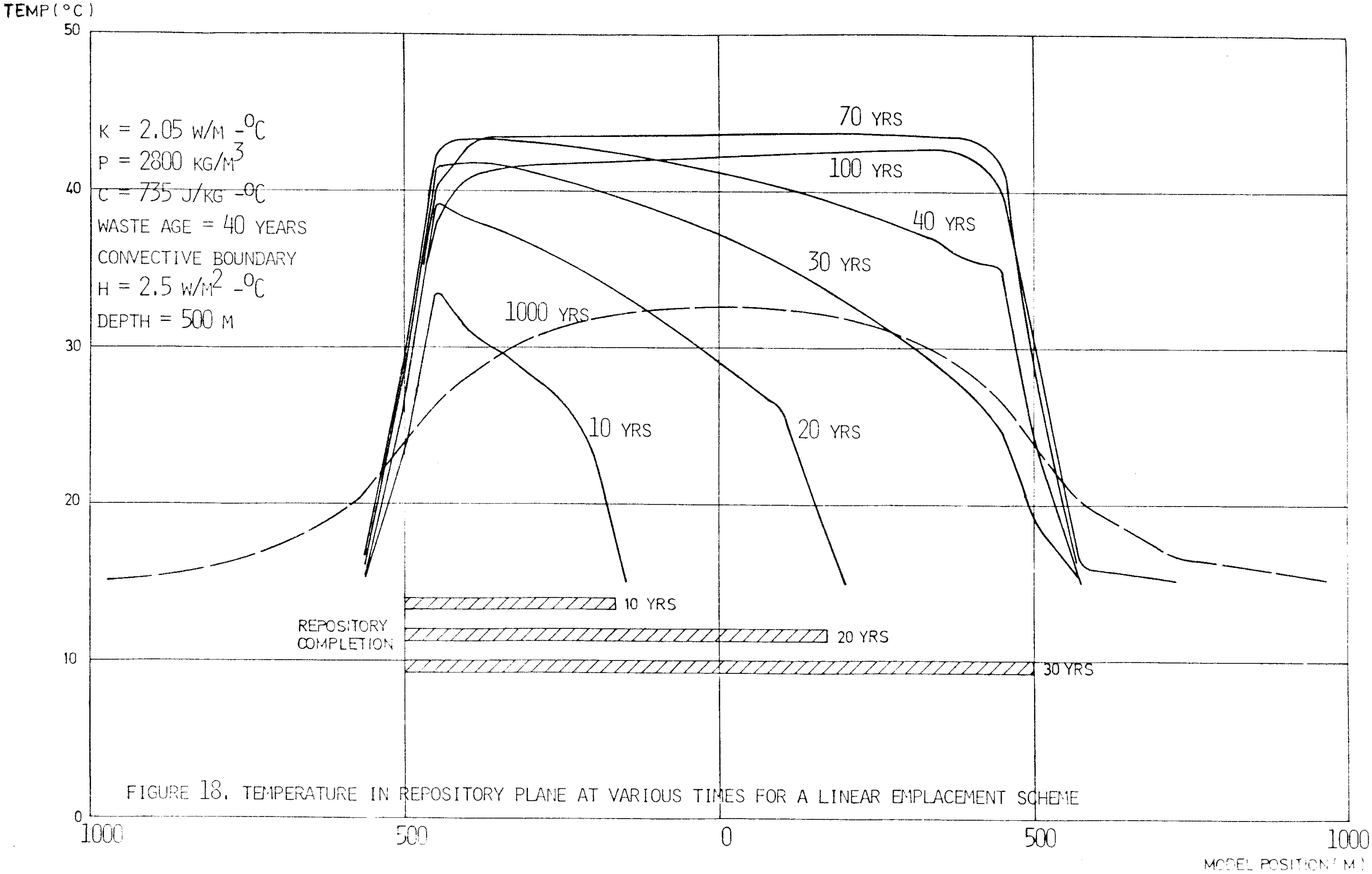


FIGURE 18. TEMPERATURE IN REPOSITORY PLANE AT VARIOUS TIMES FOR A LINEAR EMPLACEMENT SCHEME

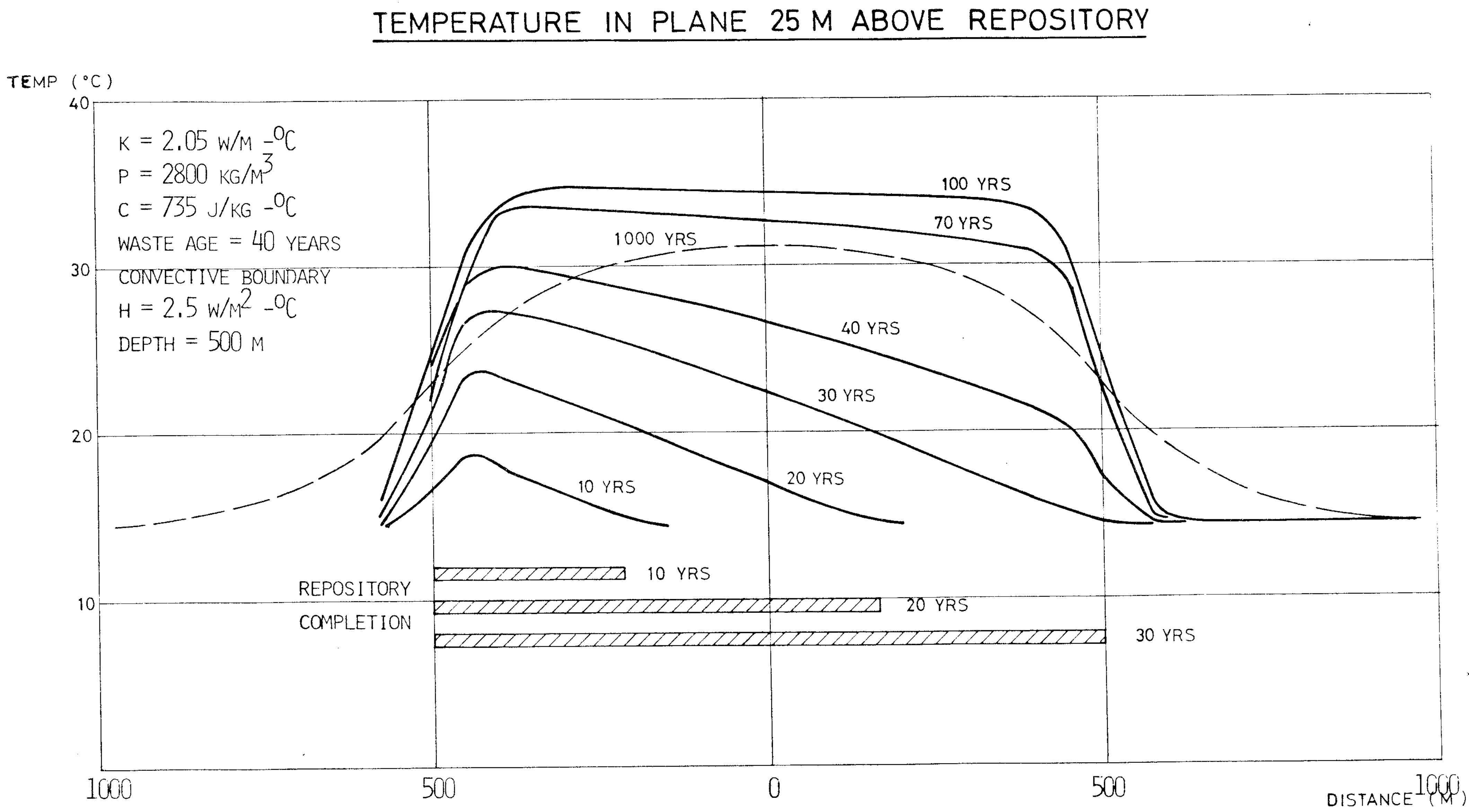


FIGURE 19. TEMPERATURE 25 M ABOVE REPOSITORY PLANE AT VARIOUS TIMES FOR A LINEAR EMPLACEMENT SCHEME.

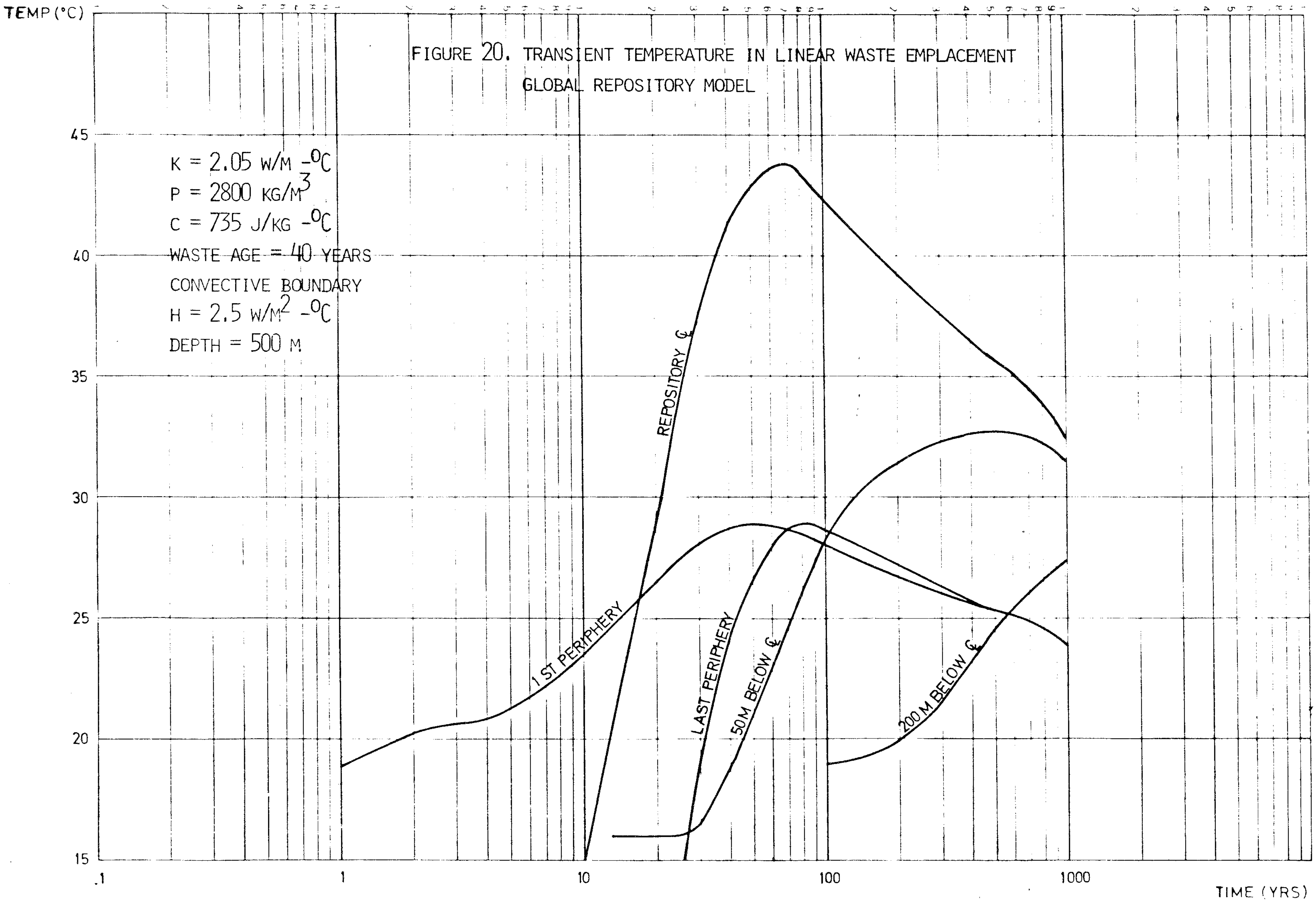


FIGURE 20. TRANSIENT TEMPERATURE IN LINEAR WASTE EMPLACEMENT
GLOBAL REPOSITORY MODEL
TEMP (°C)
K = 2.05 W/M -°C
P = 2800 KG/M3
C = 735 J/KG -°C
WASTE AGE = 40 YEARS
CONVECTIVE BOUNDARY
H = 2.5 W/M2 -°C
DEPTH = 500 M
REPOSITORY ℄
1 ST PERIPHERY
LAST PERIPHERY
50M BELOW ℄
200 M BELOW ℄
45
40
35
30
25
20
15
.1
1
10
100
1000
TIME (YRS)

A P P E N D I X

COMPARISON OF FINITE ELEMENT AND ANALYTICAL TEMPERATURE CALCULATIONS

When a numerical method is utilized for prediction of rock mass response to thermal loading, the numerical procedure should be validated for a problem with a known solution or an analytical approximation to the specific problem being addressed should be constructed. One or both of these methods should be employed to validate the numerical method since the results of any numerical method are subject to human error both in formulation and usage.

For the purposes of this study the later validation method has been utilized. In particular, the analytical solution for a plate in an infinite medium generating heat at an exponentially decaying rate has been utilized for comparison with the global model results previously discussed in this report. The derivation of the solution will not be repeated in this report; however, the salient features of the solution will be briefly described.

The temperature in an infinite medium with a plate at the origin generating heat at a time-dependent rate is given in (8) as

$$T(x,t) = \frac{Q}{2pc(\pi\alpha)^{1/2}} \int_0^t \frac{\phi(\tau)e^{-x^2/4\alpha(t-\tau)}}{(t-\tau)^{1/2}} d\tau$$

where Q = initial heat generation per unit area

ρ = density

c = specific heat capacity

α = thermal diffusivity

x = distance from plane heat source

$\phi(t) = e^{-\lambda t}$ for exponentially decaying heat generation

At $x = 0$ (midplane of repository)

$$T(t) = \frac{Q}{2pc(\pi\alpha)^{1/2}} \int_0^t e^{-\lambda\tau}(t-\tau)^{1/2}\, d\tau$$

Applying an appropriate solution procedure such as La Place transforms results in the solution

$$T(t) = \frac{Q}{K}\sqrt{\frac{\alpha}{\pi\ \lambda}}\quad D(\sqrt{\lambda t})$$

where $D(x)$ = Dawson's integral of x (9)

K = thermal conductivity

This solution has been previously reported in (10). In order to represent the heat generation of 40 year old high level waste, the waste characteristics given in this report were fit to the interploating function

$$Q(t)/Q(0) = a_1 e^{-\lambda_1 t} + a_2 e^{-\lambda_2 t}$$

By selecting λ_1 and λ_2 such that they represent 30 year and 500 year half-lives, a_1 and a_2 can be found to be 0.882 and 0.118, respectively (see Figure A.1). Therefore the solution for a plane source in an infinite medium generating heat representative of 40 year old high level waste is

$$T(t) = \frac{Q}{K}\sqrt{\frac{\alpha}{\pi}}\left[\frac{a_1}{\sqrt{\lambda_1}}\quad D(\sqrt{\lambda_1 t}) + \frac{a_2}{\sqrt{\lambda_2}}\quad D(\sqrt{\lambda_2 t})\right]$$

The results obtained through the utilization of this method are displayed in Figure A.2. Also shown in the figure are the results for the repository centerline of the finite element model A (see section 2.1).

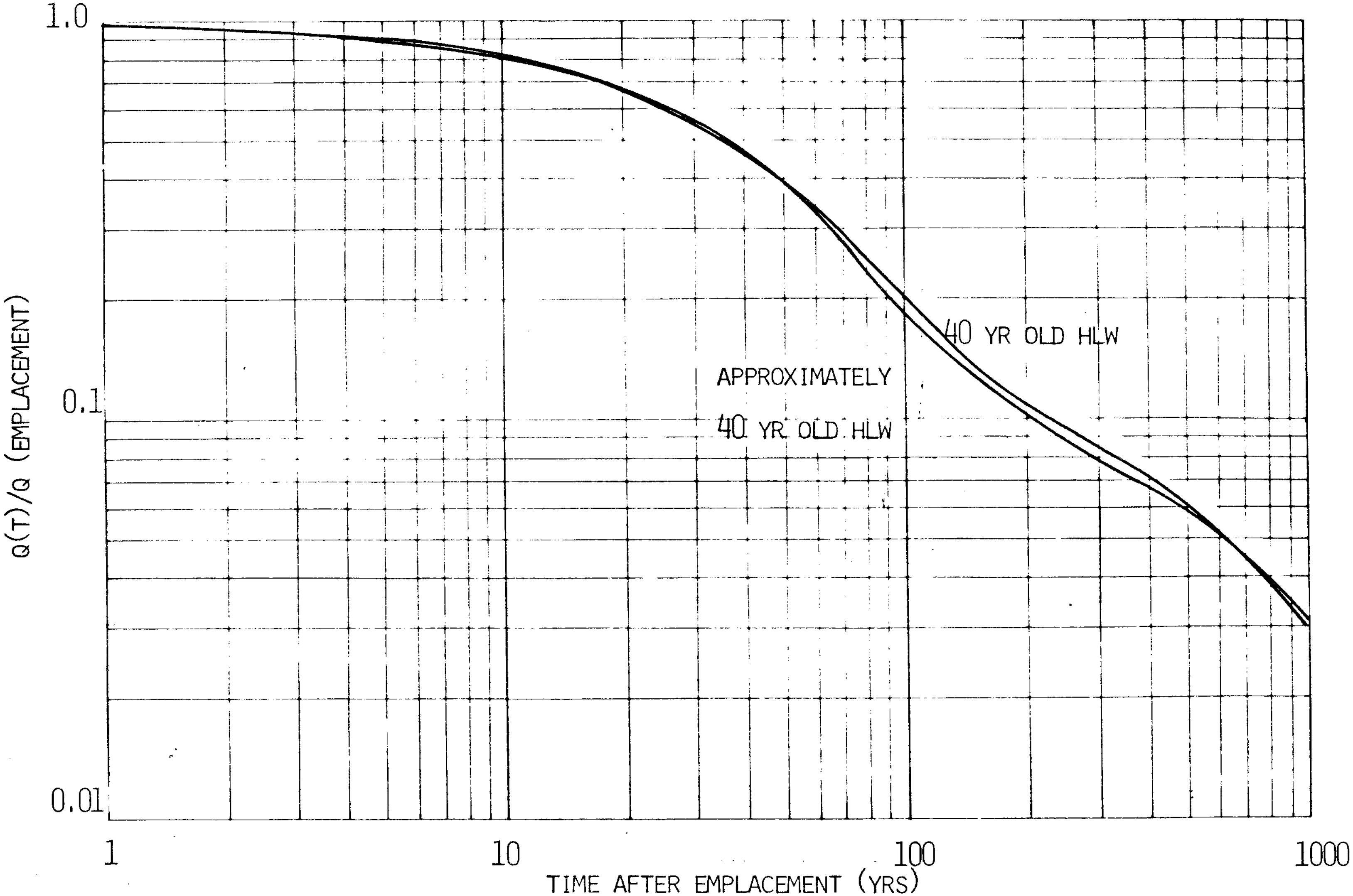


FIGURE A.1. COMPARISON OF 40 YEAR OLD HIGH LEVEL WASTE CHARACTERISTICS WITH INTERPOLATION FUNCTION

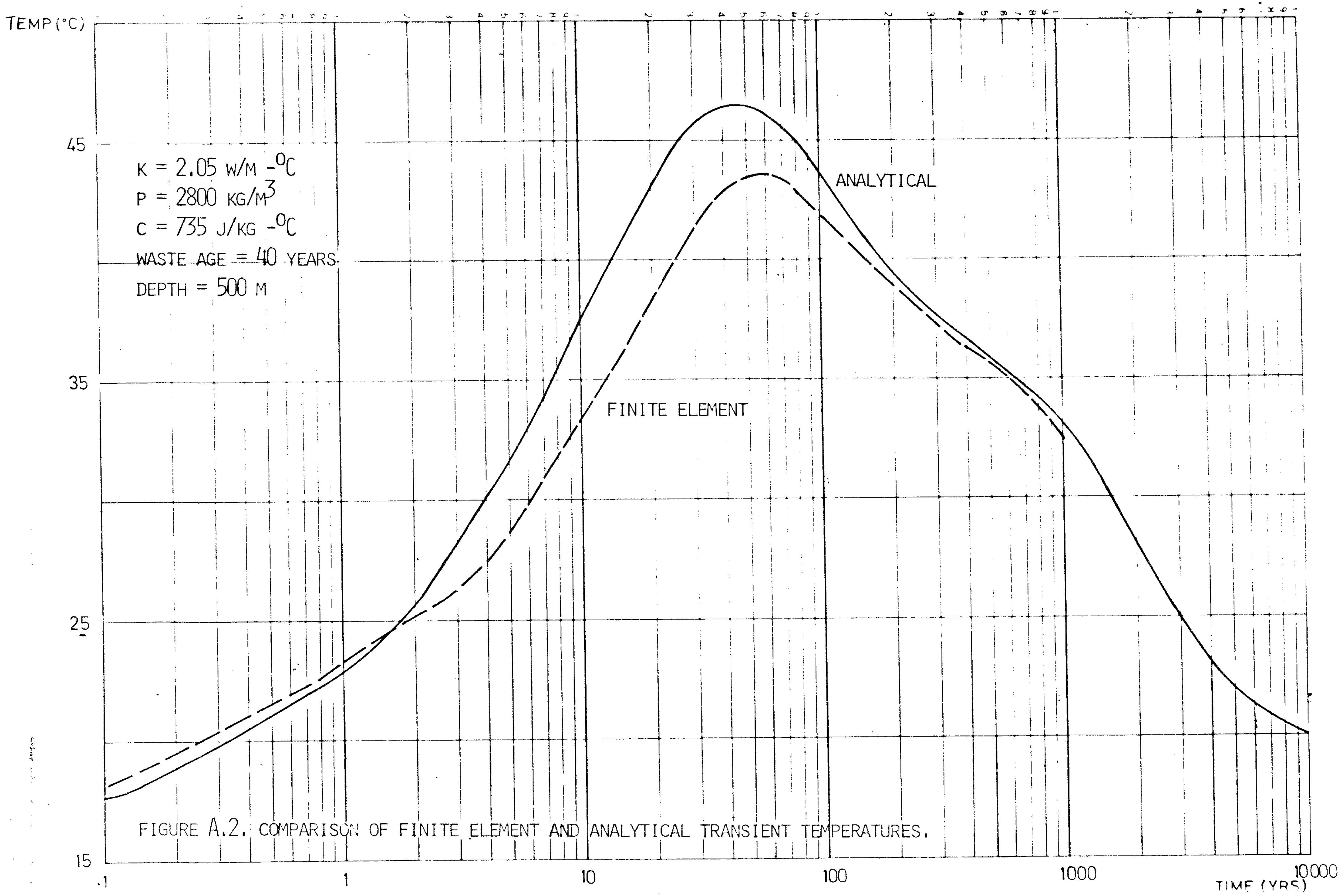
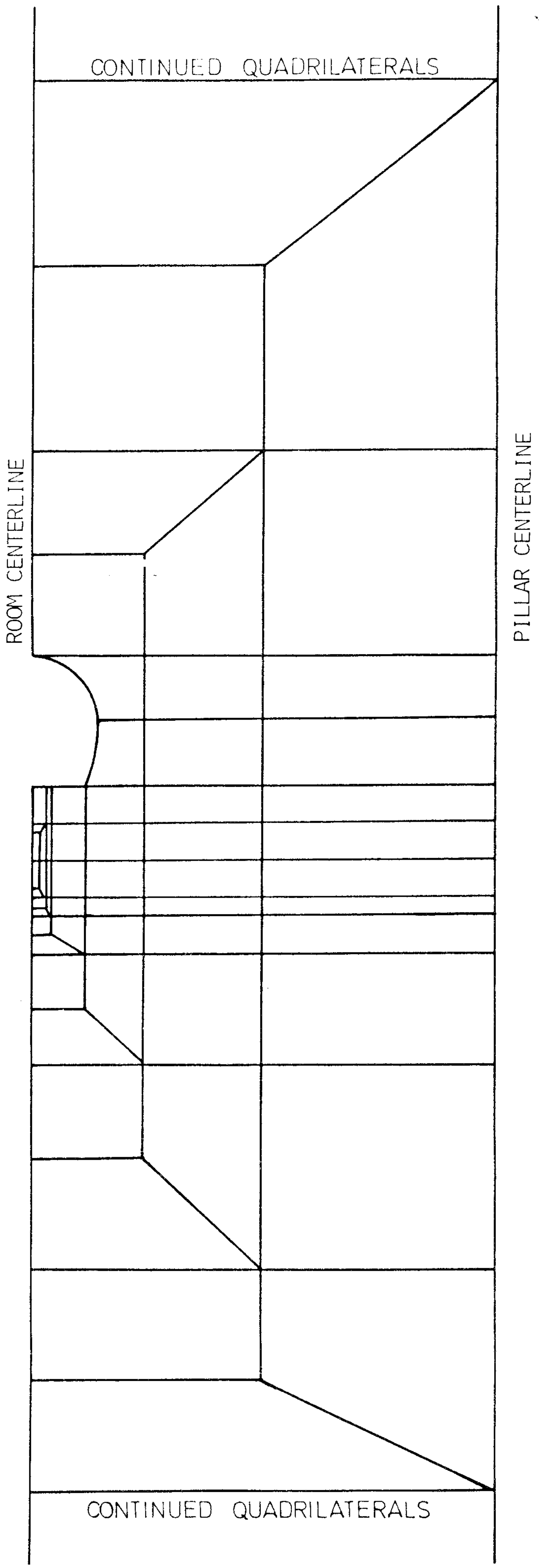


FIGURE A.2. COMPARISON OF FINITE ELEMENT AND ANALYTICAL TRANSIENT TEMPERATURES.

A P P E N D I X

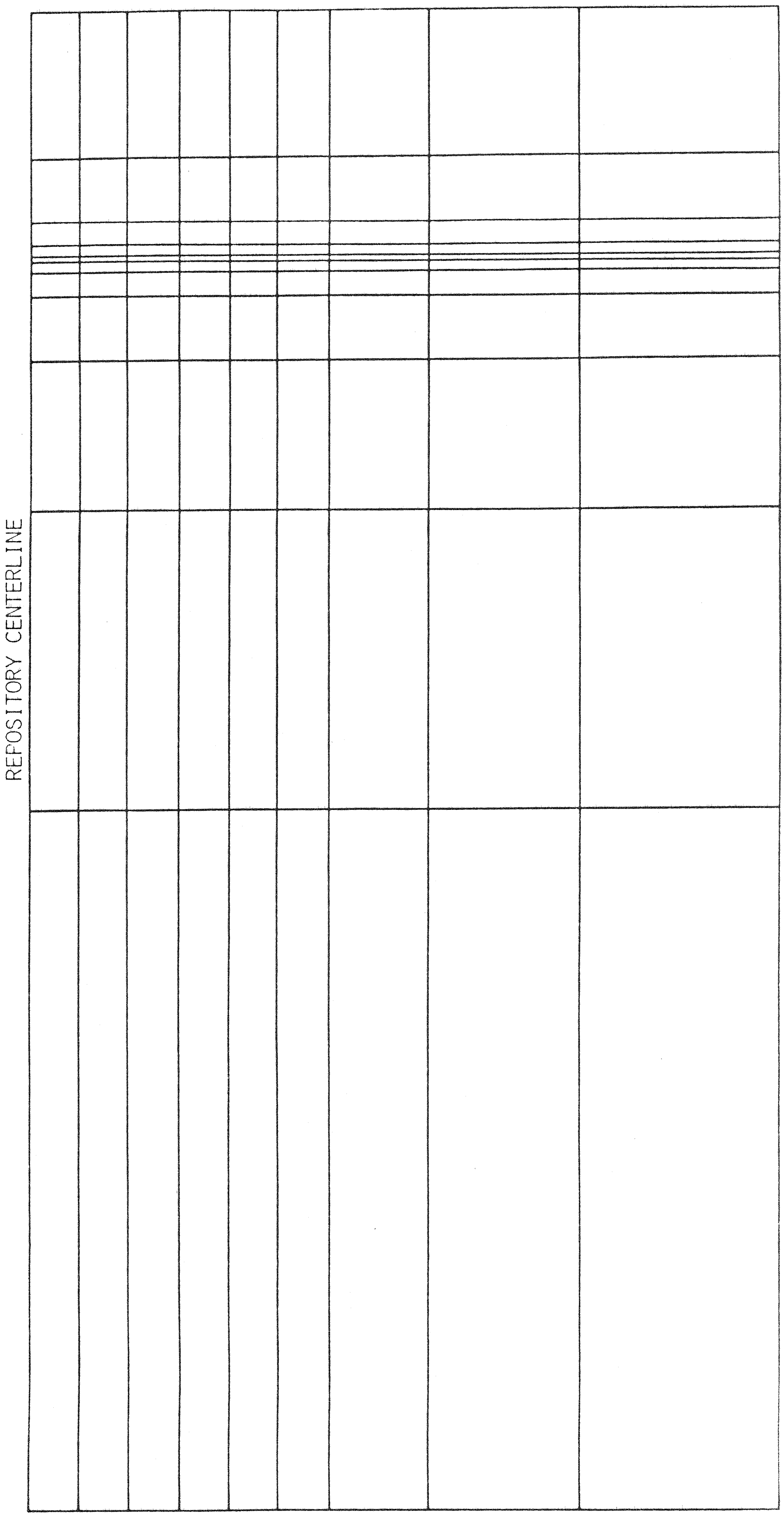
FINITE ELEMENT MODELS



NOTE:

ALL ELEMENTS ARE 8-NODED ISOPARAMETRIC QUADRILATERALS

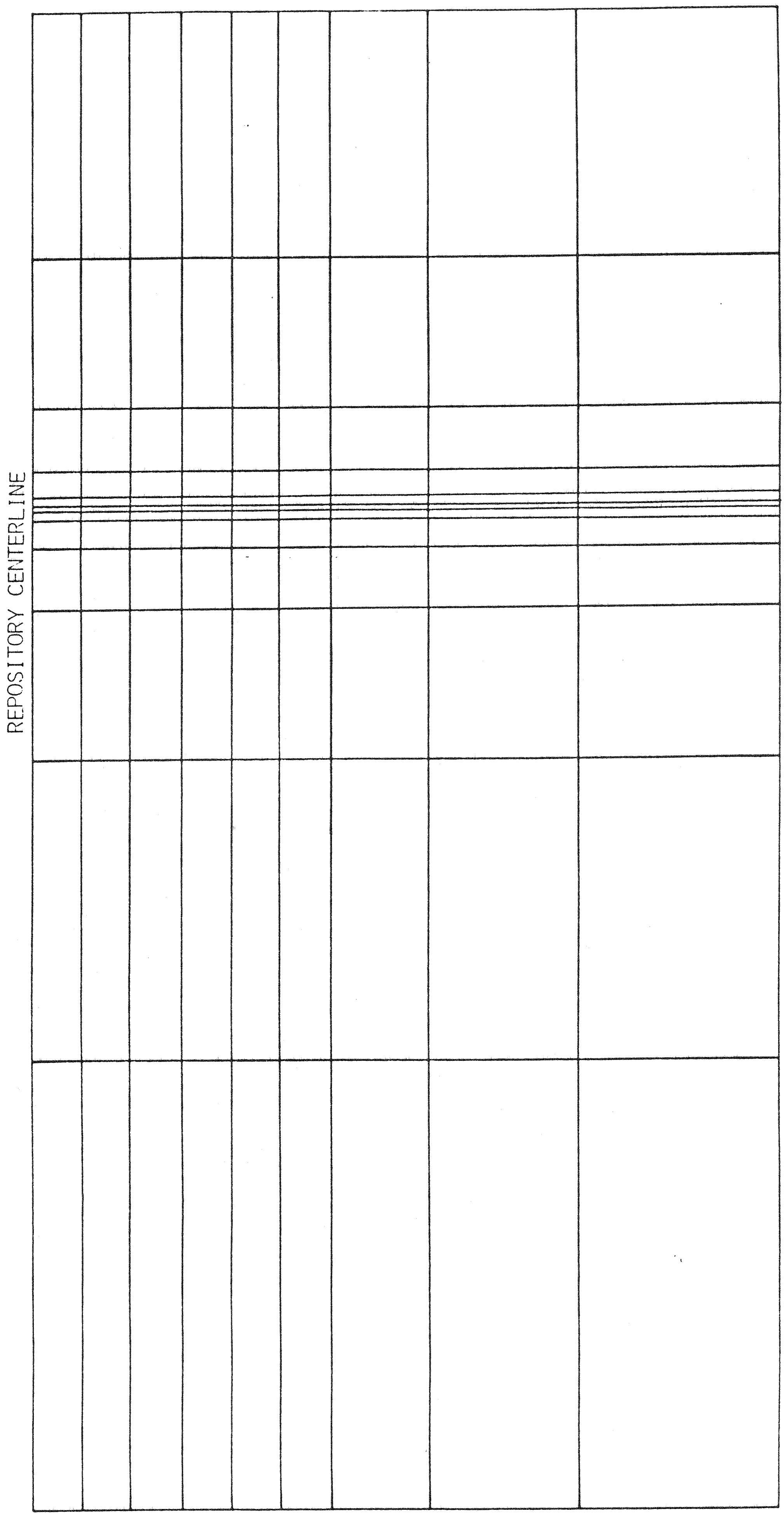
FIGURE B.1. FINITE ELEMENT MODEL FOR LOCAL SIMULATION



NOTE:

ALL ELEMENTS
ARE 8-NODED
ISOPARAMETRIC
QUADRILATERALS

FIGURE B.2. FINITE ELEMENT MODEL FOR 500 M REPOSITORY GLOBAL SIMULATION.



NOTE:

ALL ELEMENTS ARE 8-NODED ISOPARAMETRIC QUADRILATERALS

FIGURE B.3. FINITE ELEMENT MODEL FOR 1000 M REPOSITORY GLOBAL SIMULATION

NOTE:

ALL ELEMENTS ARE 8-NODED ISOPARAMETRIC QUADRILATERALS

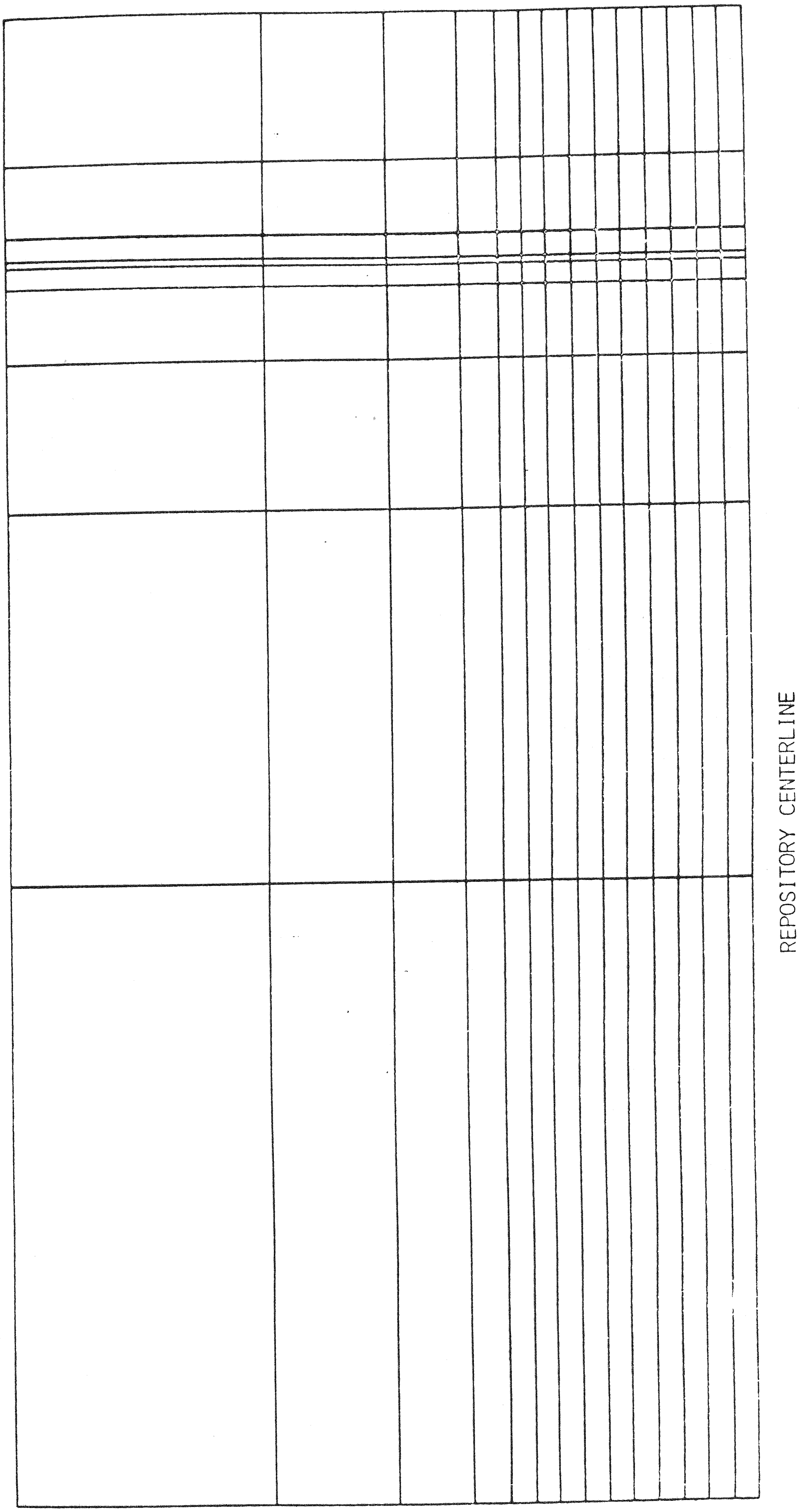


FIGURE B.4. SYMMETRIC HALF SECTION OF FINITE ELEMENT MODEL FOR 500 M LINEAR WASTE EMPLACEMENT REPOSITORY GLOBAL ANALYSIS

TECHNICAL REPORT 2

THERMAL ANALYSES

PART II

ADVECTIVE HEAT TRANSFER

KBS-Kärnbränslesäkerhet

GROUNDWATER MOVEMENTS AROUND A REPOSITORY

Phase 2. Technical report 2 Thermal Analysis - Part II: Advective Heat Transfer

Hagconsult AB
in association with
Acres Consulting Services Ltd
RE/SPEC Inc.

FOREWORD

This report was prepared as one of a series of Technical reports within a study of the groundwater movements around a repository for radioactive waste in the precambrian bedrock of Sweden. It was written in two parts, (I) conductive heat transfer and (II) advective heat transfer. This is Part II. The contract for this study was between KBS - Kärnbränslesäkerhet (Project Fuel Safety) and Hagconsult AB of Stockholm, Sweden. RE/SPEC Inc. of Rapid City, SD/USA and Acres Consulting Services Ltd of Niagara Falls, Ontario/ Canada acted as subconsultants to Hagconsult AB.

The principal author of this report is Mr. Joe L. Ratigan of RE/SPEC Inc. Review was provided by Dr. Ulf E. Lindblom of Hagconsult AB, Dr. Paul F. Gnirk of RE/SPEC Inc. and Dr. Robin G. Charlwood of Acres.

The opinions and conslusions in this document are those of the author and should not be interpreted as necessarily representing the official policies or recommendations of KBS.

Stockholm September 1977

Ulf Lindblom
Study Director
Hagconsutl AB

TABLE OF CONTENTS

		Page
1.	INTRODUCTION	1
2.	REPOSITORY MODELLING	3
3.	RESULTS OF GLOBAL SIMULATIONS	4
4.	SUMMARY AND CONCLUSION	6

REFERENCES

APPENDIX A: COMPARISON OF FINITE ELEMENT AND ANALYTICAL TEMPERATURE CALCULATIONS

APPENDIX B: FINITE ELEMENT MODEL

LIST OF FIGURES

Figure

1. Model for convective and conductive global repository simulation.

2. Transient temperature in global repository model with no regional flux.

3. Transient temperature in global repository model with regional flux of 10 q. (q = 2.(10^{-11}) m/sec).

4. Transient temperature in global repository model with regional flux of 100 q. (q = 2.(10^{-11}) m/sec).

5. Comparison of transient conduction and coupled convection and conduction with regional flux of 10 q. (q=2.(10^{-11})m/sec).

6. Comparison of transient conduction and coupled convection and conduction with regional flux of 100 q. (q=2(10^{-11})m/sec).

A.1 Comparison of Analytical and Finite Element Solutions of Convection - Diffusion Problem

B.1 Finite Element Model

LIST OF TABLES

Table

1. Thermal Properties of Repository Site Rock and Groundwater.

THERMAL ANALYSIS OF RADIOACTIVE WASTE REPOSITORY - ADVECTIVE HEAT TRANSFER

1. Introduction

Previous results within this study (1)[x] have been presented for the thermal analysis of a radioactive waste repository (2). This aforementioned analysis was performed under the assumption that the only heat transfer mode within the rock mass was that of pure conduction represented by the Fourier-Biot constitutive relation.

In water-bearing rock masses with persistant regional groundwater potential gradients, heat transfer by forced convection (an often utilized term for this is advection) will occur upon the emplacement of a radiogenic heat source. The magnitude of the heat transfer by this mode depends upon the velocity of the regional groundwater, the thermal properties of the groundwater, and the spatial and transient variation of the temperature field. The quantitative determination of the heat transfer resulting from the forced convection due to the regional groundwater flow is the single objective of this report. This objective is important in assessing whether temperature fields arising from assuming only conduction heat transfer are sufficient for temperature predictions.

It is important to determine the magnitude of the forced convective heat transfer for a variety of reasons. Specifically, the temperature fields arising in a rock mass containing heat generating radioactive waste will affect the groundwater flow by perturbing the regional flow due to; (a) the addition of flow which is thermally - induced, and; (b) the thermomechanical perturbation of the groundwater flow pathways (joints). This perturbation of the groundwater flow will subsequently alter the temperature fields which will alter the flow field and so on. This "coupling" phenomena should be accounted for if (a) the heat transfer due to forced convection is significant and/or (b) the thermomechanical perturbation of the flow pathways is significant, or (c) the heat transfer due to thermally - induced flow is of concern.

[x]Numbers in parenthesis refer to references at end of text.

In this study, the first two coupling effects are analyzed separately in order to quantify their respective importance as related to the rational prediction of groundwater movement around a repository.

The convection heat transfer can be further divided into heat transfer due to regional groundwater flow or other external mechanisms and heat transfer by natural convection due to thermally induced flow. As mentioned previously, this report is concerned with the heat transfer due to regional groundwater flow. The heat transfer and flow perturbations provided by the thermally induced flow are discussed in (3). Validation of the finite element program is provided as an appendix to this report.

2. REPOSITORY MODELING

The repository model utilized in the analysis of the convective heat transfer is displayed in Figure 1. As previously discussed in (2), the model simulates the emplacement of waste over a repository area of 1 km^2 at 500 m depth during a period of 30 years. Forty year old high level waste (4) is emplaced in a region encompassing two storage tunnels (3.5 m x 50 m) every 1.5 years, resulting in a gross thermal loading of 5.25 w/m^2.

This particular model was employed since both the repository emplacement and the regional groundwater flow do not allow for the assumption of temperature symmetry about a vertical line through the repository centerline. Even if the waste emplacement were instantaneous (symmetric), the regional groundwater flow would dictate the utilization of a model encompassing the total repository. For a more detailed discussion of the global repository model utilized in this study, the reader is refered to (2).

The thermal properties of the repository site rock and the groundwater are presented in Table 1. The additional parameter required for the analysis of the convective heat transfer, namely the regional groundwater flux, has been taken from (5). This regional flux (porosity x pore velocity), $2.(10^{-11})$ m/sec, results from an assumption of a regional horizontal groundwater flow with a permeability of 10^{-8} m/sec and a regional potential gradient of $2.(10^{-3})$. The assumptions utilized in the determination of this flux are perhaps conservative, as stated in (5). In order to more accurately quantify the convective heat transfer, the global repository previously discussed was also analyzed with regional groundwater fluxes of $2.(10^{-10})$ m/sec and $2.(10^{-9})$ m/sec. The finite element program utilized in this study employs a variable iteration, predictor and corrector initial flux vector method as discussed in (6) to account for the convective heat transfer term.

3. RESULTS OF GLOBAL SIMULATIONS

As mentioned previously, the objective of this report is to evaluate the significance of the convective heat transfer provided by the regional groundwater flow.

For the purposes of this study, the convective and conductive heat transfer has been assumed to be represented as the solution of the following differential equation with appropriate boundary conditions.

$$K_r \left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right] - \rho_\ell \, c_\ell \, q \cdot \frac{\partial T}{\partial x} + Q\ (x,\ y,\ t) = \rho_r \, C_r \, \frac{\partial T}{\partial t}$$

where

$T(x, y, t)$ = temperature
K_r = thermal conductivity of the rock
ρ_r = specific density of the rock
c_r = specific heat of the rock
ρ_ℓ = density of the groundwater
c_ℓ = specific heat of the groundwater
q = regional groundwater flux
$Q(x, y, t)$ = radiogenic heat function
t = time
x = horizontal coordinate

This equation is identical to that used in (2) with the exception of the convective term involving the regional groundwater flux.

The transient temperature arising without the convective heat transfer term at several locations in the global repository model are presented in Figure 2. These results have been previously presented in (2) for times up to 1000 years. In the development of this figure, the heat generation function utilized for analytical comparison in (2) was utilized to represent the heat generation after 1000 years.

As can be seen in Figure 2, most locations in the repository domain return to the pre-repository temperatures within about 40,000 years.

When employing the regional groundwater flux of $q = 2(10^{-11})$ m/sec and the convective heat transfer term, the resulting temperatures are within the computational accuracy of those arising in Figure 2.

In an effort to quantify the "threshold" regional groundwater flux required to produce a significant perturbation in the rock mass temperatures, simulations with 10 q and 100 q were performed. These results are presented in Figures 3 and 4, respectively. The respective times required for the repository domain to return to the virgin geothermal temperatures is approximately 30,000 years and 20,000 years. Several locations displayed in the figures are noted to experience thermal cycles of shorter duration and decreased magnitude with increasing groundwater flux (for example, 200 m below the repository (centerline).

Since the transient temperatures arising with coupled convective and conductive heat transfer are very nearly identical, Figures 5 and 6 are presented to quantify the difference in a more explicit fashion. In these figures the difference between the conduction temperatures and the coupled convection and conduction temperatures are displayed as a function of time for 10 q and 100 q. The temperature differences above the repository are similar to those below the repository.

4. SUMMARY AND CONCLUSIONS

The heat transfer due to forced convection resulting from a regional groundwater flow has been analyzed for the maximum expected flux, q of $2.(10^{-11})$ m/s and also, 10 q and 100 q. The temperature difference between assuming pure conductive heat transfer and coupled conductive and convective heat transfer was found to be negligible for a groundwater velocity of q. Analysis of groundwater flux 10 q and 100 q results in temperatures nearly identical to those predicted by conductive heat transfer for the first 100 years. The major effect provided by the convective heat transfer with groundwater flow of 10 q and 100 q was to reduce the time required for the repository domain to return to the natural geothermal gradient. The influence of the convective heat transfer could be expected to be greater for larger values of thermal flux density or for rock masses with lower thermal conductivity than that assumed in this study.

REFERENCES

1. Lindblom, U.E., Gnirk, P.F., Charlwood, R.G. and Cherry, J., 1977. "GROUNDWATER MOVEMENTS AROUND A REPOSITORY, Phase 1. State of the art and detailed study plan", Submitted to KBS-Kärnbränslesäkerhet, Stockholm, Sweden.

2. Ratigan, J.L., 1977 "GROUNDWATER MOVEMENTS AROUND A REPOSITORY, Phase 2. Technical Report 2. Thermal Analysis - Part I : Conduction Heat Transfer", Submitted to KBS - Kärnbränslesäkerhet, Stockholm, Sweden.

3. Skiba, E.S. and Charlwood, R.G., 1977 "GROUNDWATER MOVEMENTS AROUND A REPOSITORY, Phase 2. Technical Report 5. Repository Domain Groundwater Flow Analysis - Part III: Thermally Induced Flow" To be submitted to KBS-Kärnbränslesäkerhet, Stockholm, Sweden.

4. Ekberg, K., Kjellberg, N. and Olsson, G., 1977. "Resteffektstudier för KBS", TPM-RF-77-2246/SM-48, Submitted to KBS-Kärnbränslesäkerhet, Stockholm, Sweden.

5. Burgess, A.S., 1977 "GROUNDWATER MOVEMENTS AROUND A REPOSITORY, Phase 2. Technical Report 3. Regional Groundwater Flow Analyses, Part I: Initial Conditions" To be submitted to KBS-Kärnbränslesäkerhet, Stockholm, Sweden.

6. Hsu, M.B. and Nickell, R.E., "Coupled Convective and Conductive Heat Transfer by Finite Element Methods", Finite Element Methods in Flow Problems, University of Alabama Press, 1974, pp. 427 - 450.

7. Guymon, G.L., "A Finite Element Solution of the One-Dimensional Diffusion - Convection Equation," Water Resources Research 6, 1970 pp. 204 - 210.

TABLE 1

Thermal Properties of Repository Site Rock and Groundwater

Material	k ($W/m-^oC$)	ρ (Kg/m^3)	c ($J/Kg-^oC$)
Granite	2.05	2800	735
Groundwater	x	1000	4200

[x]Due to the low porosity of the site rock, the difference in the conductivities of the rock and the groundwater was not taken into account.

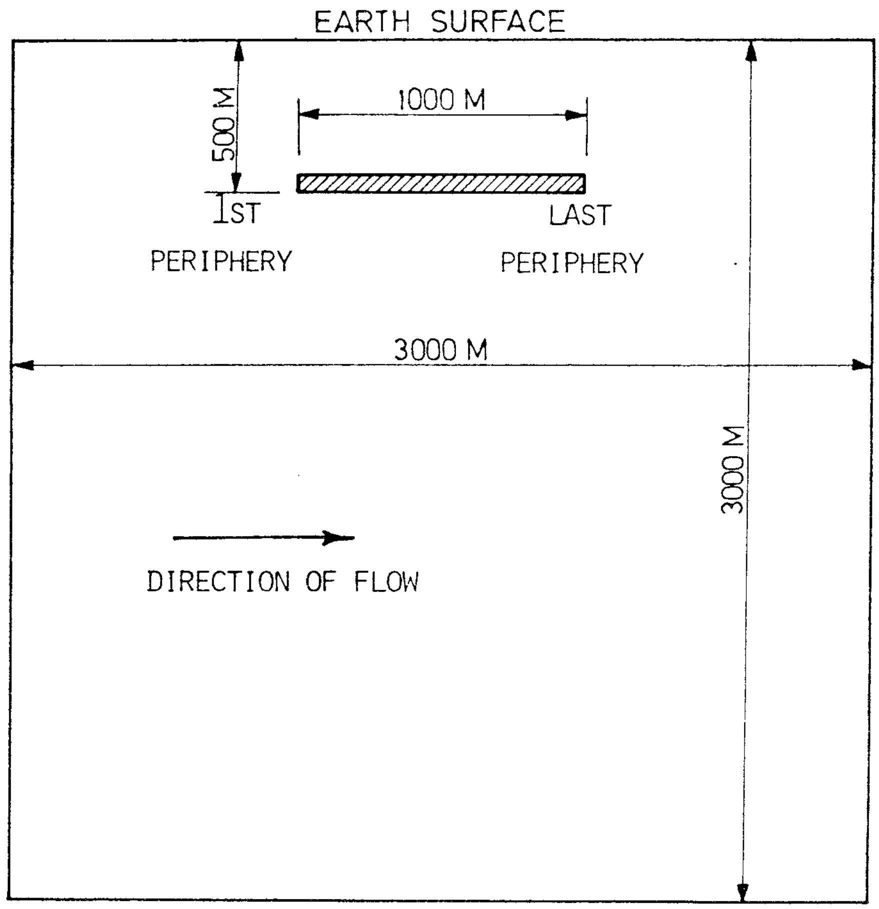


FIGURE 1 MODEL FOR CONVECTIVE AND CONDUCTIVE GLOBAL REPOSITORY SIMULATION

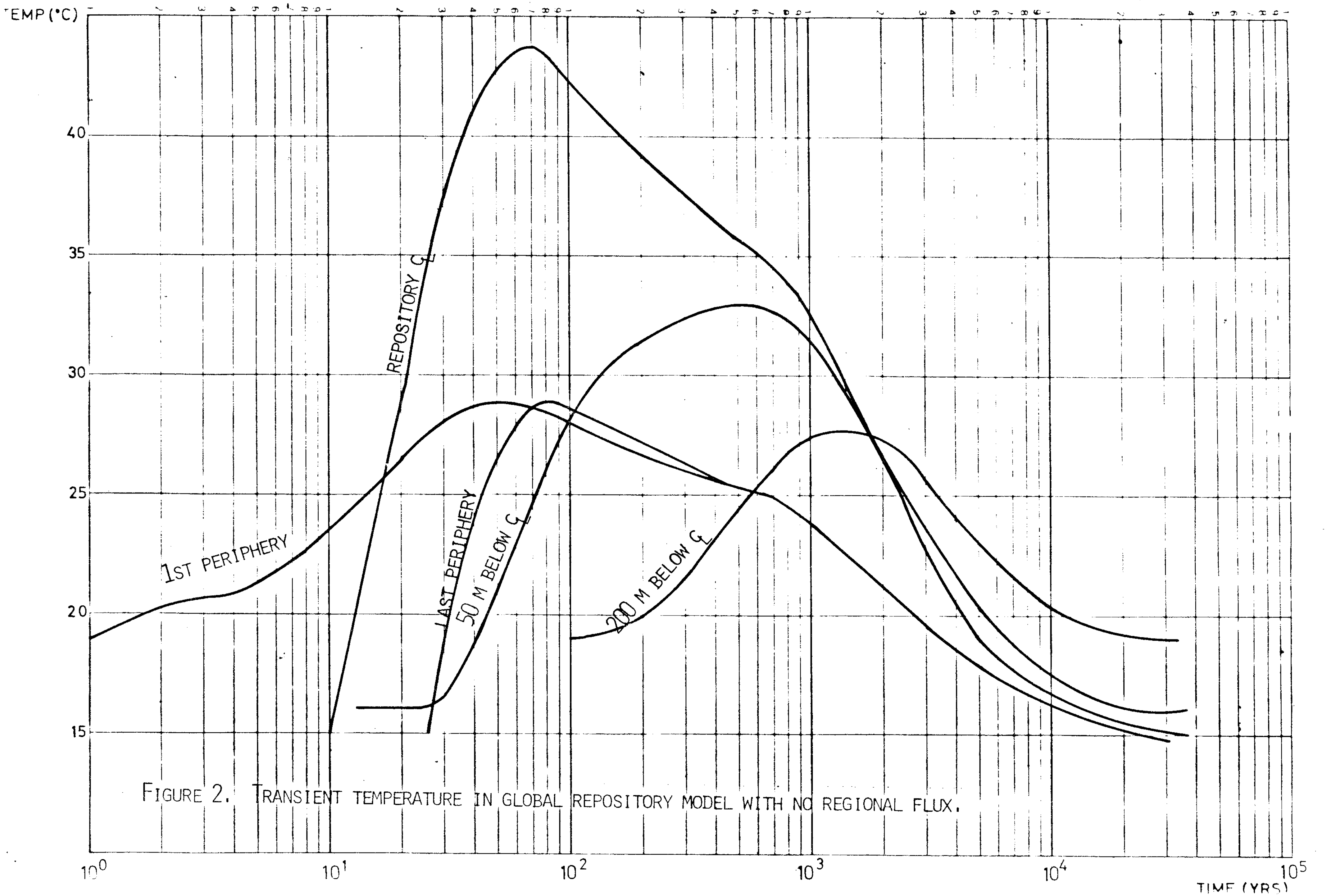


FIGURE 2. TRANSIENT TEMPERATURE IN GLOBAL REPOSITORY MODEL WITH NO REGIONAL FLUX.

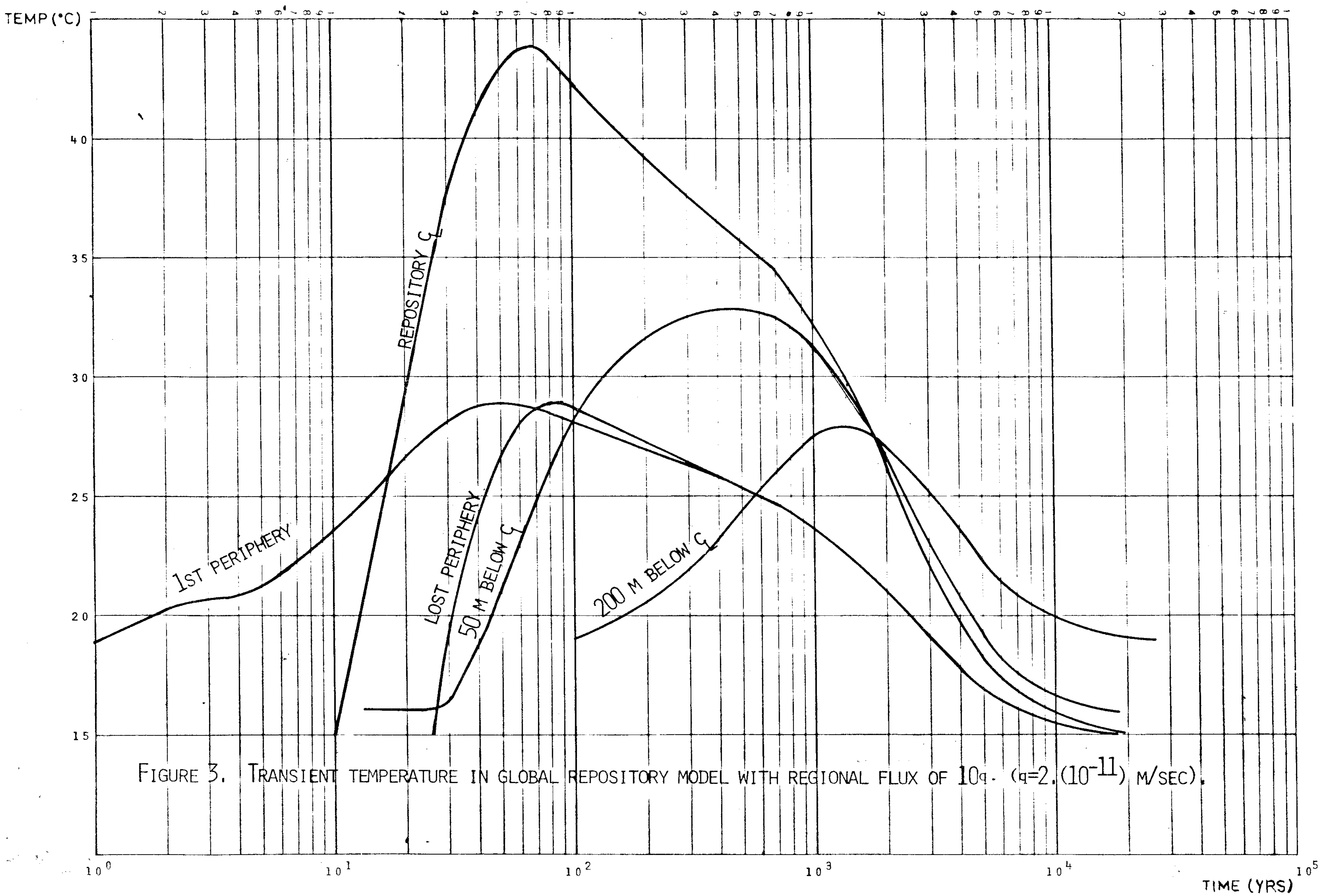


FIGURE 3. TRANSIENT TEMPERATURE IN GLOBAL REPOSITORY MODEL WITH REGIONAL FLUX OF 10q. ($q=2.(10^{-11})$ M/SEC).

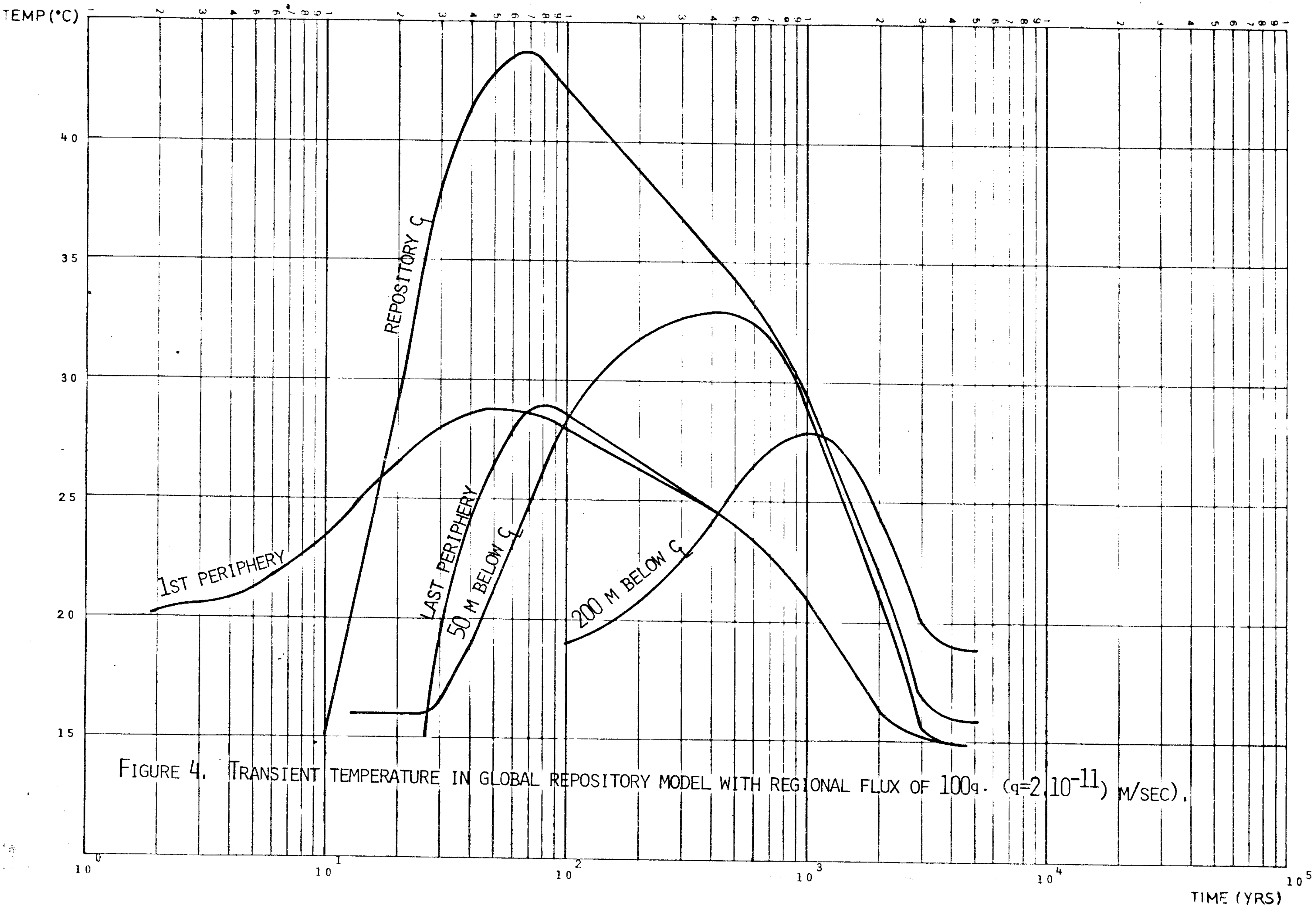


FIGURE 4. TRANSIENT TEMPERATURE IN GLOBAL REPOSITORY MODEL WITH REGIONAL FLUX OF 100q. ($q=2.10^{-11}$) M/SEC).

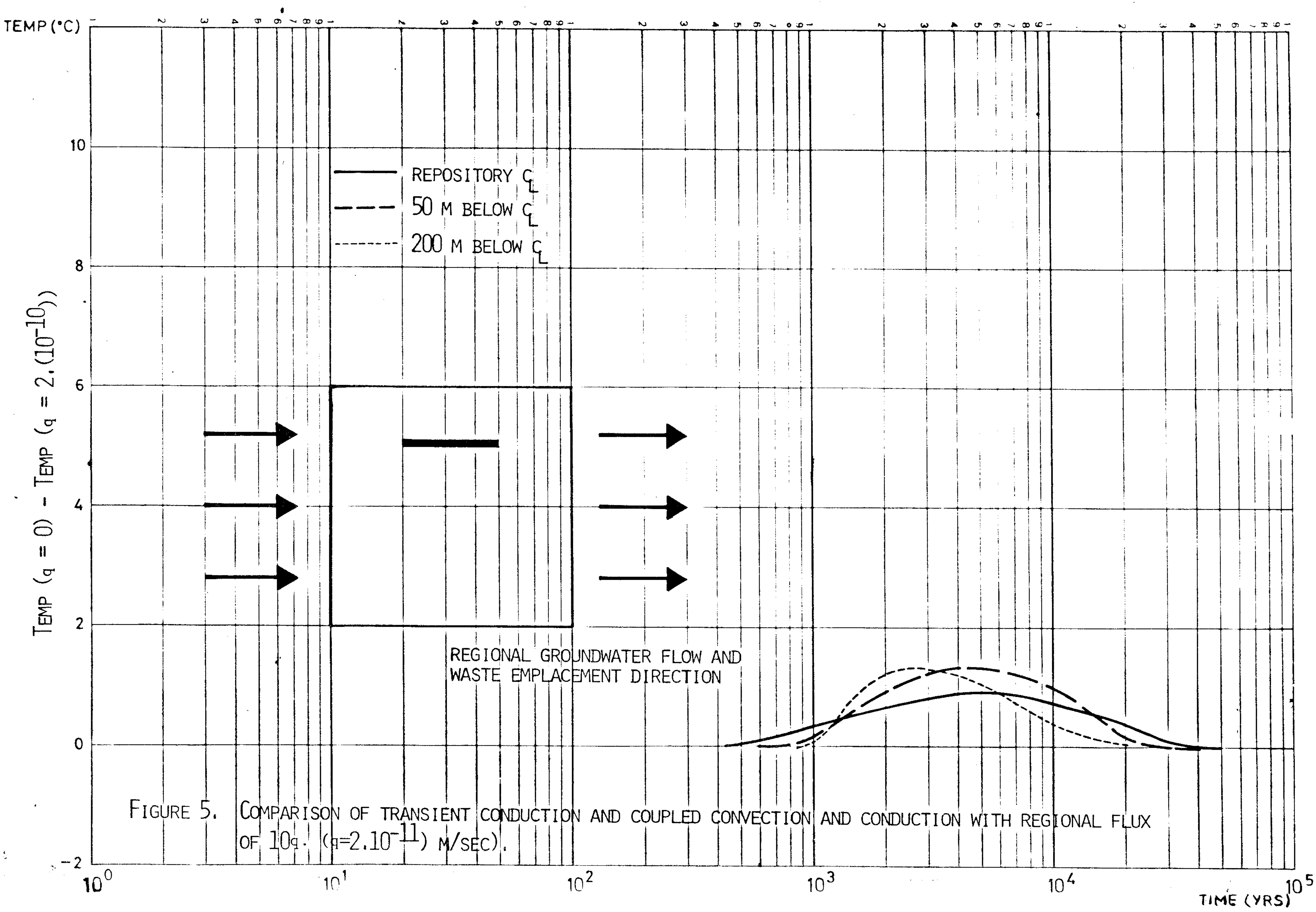


FIGURE 5. COMPARISON OF TRANSIENT CONDUCTION AND COUPLED CONVECTION AND CONDUCTION WITH REGIONAL FLUX OF $10q$. ($q = 2.10^{-11}$) M/SEC).

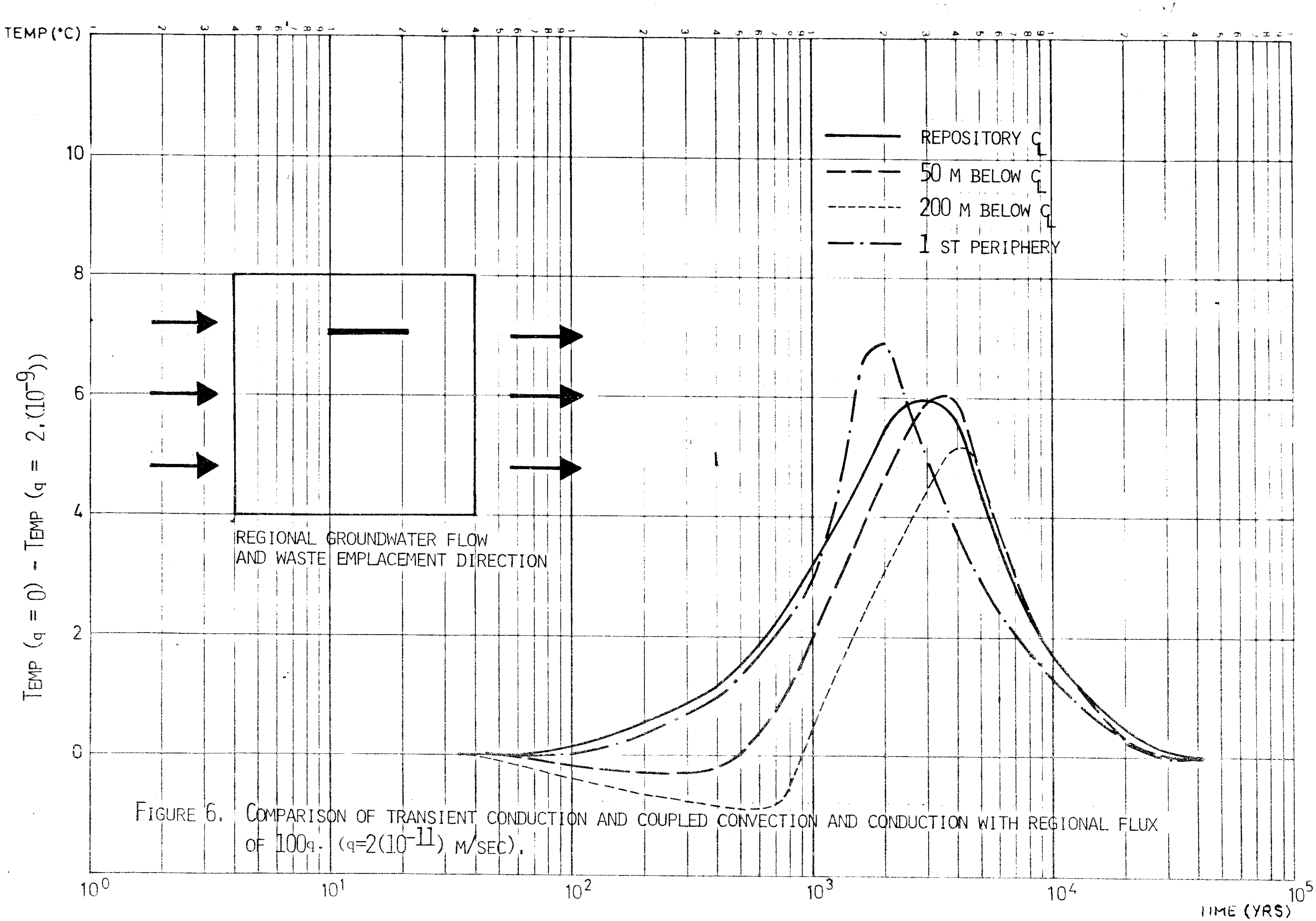


FIGURE 6. COMPARISON OF TRANSIENT CONDUCTION AND COUPLED CONVECTION AND CONDUCTION WITH REGIONAL FLUX OF 100q. ($q=2(10^{-11})$ M/SEC).

APPENDIX A

Comparison of Finite Element and Analytical temperature calculations

When a numerical method is utilized for prediction of rock mass response to thermal loading, the numerical procedure should be validated for a problem with a known solution, or an analytical approximation to the specific problem being addressed should be constructed. One or both of these methods should be employed to validate the numerical method since the results of any numerical method are subject to human error both in formulation and usage.

For the purposes of this report the former validation method has been utilized. In particular, a classical one-dimensional convective diffusion problem is analyzed (7). The differential equation, boundary and initial conditions for this problem are

$$\frac{\partial C}{\partial t} + u\,\frac{\partial C}{\partial x} = \frac{\partial}{\partial x}\left[(D\frac{\partial C}{\partial x})\right]$$

$$C(0,\ t) = C_o$$

$$C(\infty,\ t) = C(x,0) = 0$$

where

$C(x,\ t)$ = concentration of the species
u = constant velocity
D = diffusion coefficient

Taking the diffusion coefficient and boundary condition at $x = 0$ to be unity, the solution can be expressed as

$$C = \frac{1}{2}\left[\operatorname{erfc}\ (\frac{x-ut}{2\sqrt{t}}) + \exp\ (x)\ \operatorname{erfc}\ (\frac{x+ut}{2\sqrt{t}})\right].$$

where

$\operatorname{erfc}(x)$ = complimentary error function of x
$\exp\ (x) = e^x$

The analytical solution and finite element results for $c(x,t)$ are presented in Figure A.1 as a function of distance from the constant concentration boundary for $u = 0$, 1 and 10. The finite element mesh employed in this validation is also presented in this figure.

It should be noted that whereas this validation is performed for a convective diffusion concentration example, the governing differential equation is identical to the differential equation governing coupled convective and conductive heat transfer.

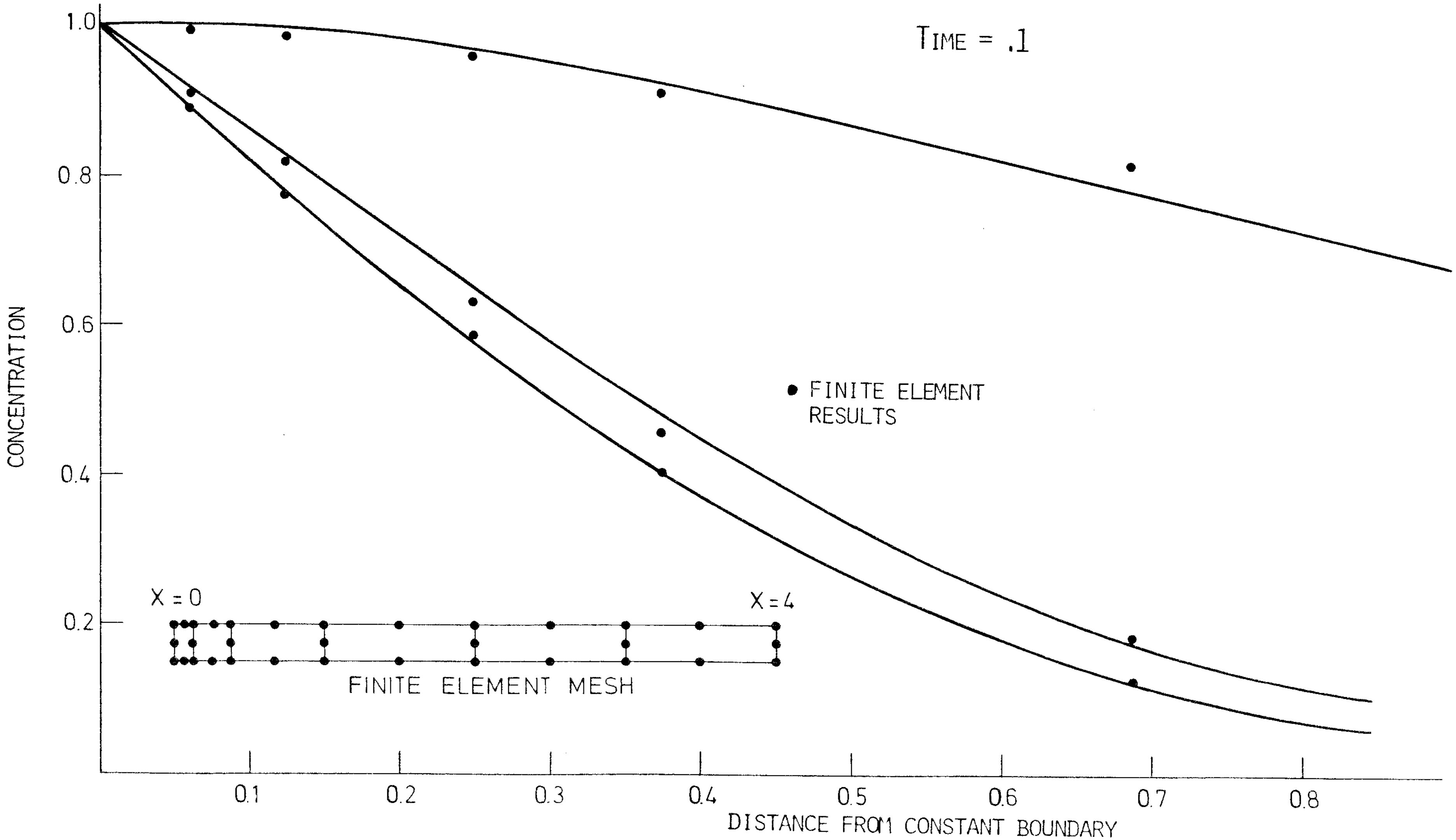


FIGURE A1. COMPARISON OF ANALYTICAL AND FINITE ELEMENT SOLUTIONS OF CONVECTION - DIFFUSION PROBLEM

A P P E N D I X B

FINITE ELEMENT MODEL

NOTE:

(1) ALL ELEMENTS ARE 8-NODED ISOPARAMETRIC QUADRILATERALS ONLY

(2) SYMMETRIC HALF SECTION OF FINITE ELEMENT MODEL REPRESENTED

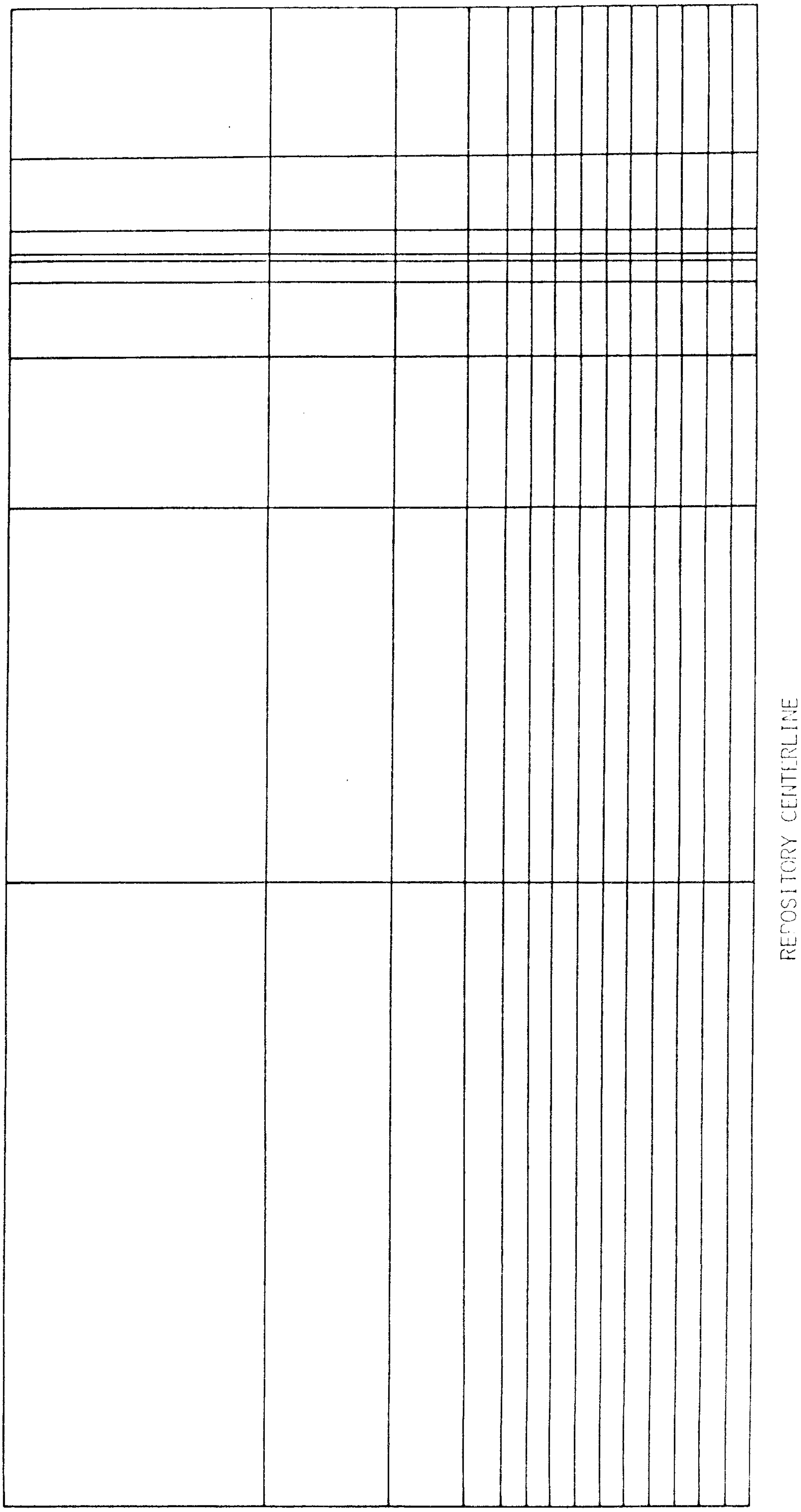


FIGURE B.1 FINITE ELEMENT MODEL

FÖRTECKNING ÖVER KBS TEKNISKA RAPPORTER

01 Källstyrkor i utbränt bränsle och högaktivt avfall från en PWR beräknade med ORIGEN
Nils Kjellbert
AB Atomenergi 77-04-05

02 PM angående värmeledningstal hos jordmaterial
Sven Knutsson
Roland Pusch
Högskolan i Luleå 77-04-15

03 Deponering av högaktivt avfall i borrhål med buffertsubstans
Arvid Jacobsson
Roland Pusch
Högskolan i Luleå 77-05-27

04 Deponering av högaktivt avfall i tunnlar med buffertsubstans
Arvid Jacobsson
Roland Pusch
Högskolan i Luleå 77-06-01

05 Orienterande temperaturberäkningar för slutförvaring i berg av radioaktivt avfall, Rapport 1
Roland Blomqvist
AB Atomenergi 77-03-17

06 Groundwater movements around a repository, Phase 1, State of the art and detailed study plan
Ulf Lindblom
Hagconsult AB 77-02-28

07 Resteffekt studier för KBS
Del 1 Litteraturgenomgång
Del 2 Beräkningar
Kim Ekberg
Nils Kjellbert
Göran Olsson
AB Atomenergi 77-04-19

08 Utlakning av franskt, engelskt och kanadensiskt glas med högaktivt avfall
Göran Blomqvist
AB Atomenergi 77-05-20

09 Diffusion of soluble materials in a fluid filling a porous medium
Hans Häggblom
AB Atomenergi 77-03-24

10 Translation and development of the BNWL-Geosphere Model
Bertil Grundfelt
Kemakta Konsult AB 77-02-05

11 Utredning rörande titans lämplighet som korrosionshärdig kapsling för kärnbränsleavfall
Sture Henriksson
AB Atomenergi 77-04-18

12 Bedömning av egenskaper och funktion hos betong i samband med slutlig förvaring av kärnbränsleavfall i berg
Sven G Bergström
Göran Fagerlund
Lars Rombén
Cement- och Betonginstitutet 77-06-22

13 Urlakning av använt kärnbränsle (bestrålad uranoxid) vid direktdeponering
Ragnar Gelin
AB Atomenergi 77-06-08

14 Influence of cementation on the deformation properties of bentonite/quartz buffer substance
Roland Pusch
Högskolan i Luleå 77-06-20

15 Orienterande temperaturberäkningar för slutförvaring i berg av radioaktivt avfall
Rapport 2
Roland Blomquist
AB Atomenergi 77-05-17

16 Översikt av utländska riskanalyser samt planer och projekt rörande slutförvaring
Åke Hultgren
AB Atomenergi augusti 1977

17 The gravity field in Fennoscandia and postglacial crustal movements
Arne Bjerhammar
Stockholm augusti 1977

18 Rörelser och instabilitet i den svenska berggrunden
Nils-Axel Mörner
Stockholms Universitet augusti 1977

19 Studier av neotektonisk aktivitet i mellersta och norra Sverige, flygbildsgenomgång och geofysisk tolkning av recenta förkastningar
Robert Lagerbäck
Herbert Henkel
Sveriges Geologiska Undersökning september 1977

20 Tektonisk analys av södra Sverige, Vättern - Norra Skåne
Kennert Röshoff
Erik Lagerlund
Lunds Universitet och Högskolan Luleå september 1977

21 Earthquakes of Sweden 1891 - 1957, 1963 - 1972
Ota Kulhánek
Rutger Wahlström
Uppsala Universitet september 1977

22 The influence of rock movement on the stress/strain situation in tunnels or bore holes with radioactive consisters embedded in a bentonite/quartz buffer mass
Roland Pusch
Högskolan i Luleå 1977-08-22

23 Water uptake in a bentonite buffer mass
A model study
Roland Pusch
Högskolan i Luleå 1977-08-22

24 Beräkning av utlakning av vissa fissionsprodukter och aktinider från en cylinder av franskt glas
Göran Blomqvist
AB Atomenergi 1977-07-27

25 Blekinge kustgnejs, Geologi och hydrogeologi
Ingemar Larsson KTH
Tom Lundgren SGI
Ulf Wiklander SGU
Stockholm, augusti 1977

26 Bedömning av risken för fördröjt brott i titan
Kjell Pettersson
AB Atomenergi 1977-08-25

27 A short review of the formation, stability and cementing properties of natural zeolites
Arvid Jacobsson
Högskolan i Luleå 1977-10-03

28 Värmeledningsförsök på buffertsubstans av bentonit/pitesilt
Sven Knutsson
Högskolan i Luleå 1977-09-20

29 Deformationer i sprickigt berg
Ove Stephansson
Högskolan i Luleå 1977-09-28

30 Retardation of escaping nuclides from a final depository
Ivars Neretnieks
Kungliga Tekniska Högskolan Stockholm 1977-09-14

31 Bedömning av korrosionsbeständigheten hos material avsedda för kapsling av kärnbränsleavfall. Lägesrapport 1977-09-27 samt kompletterande yttranden.
Korrosionsinstitutet och dess referensgrupp

32 Long term mineralogical properties of bentonite/quartz buffer substance
Preliminär rapport november 1977
Slutrapport februari 1978
Roland Pusch
Arvid Jacobsson
Högskolan i Luleå

33 Required physical and mechanical properties of buffer masses
Roland Pusch
Högskolan Luleå 1977-10-19

34 Tillverkning av bly-titan kapsel
Folke Sandelin AB
VBB
ASEA-Kabel
Institutet för metallforskning
Stockholm november 1977

35 Project for the handling and storage of vitrified high-level waste
Saint Gobain Techniques Nouvelles October, 1977

36 Sammansättning av grundvatten på större djup i granitisk berggrund
Jan Rennerfelt
Orrje & Co, Stockholm 1977-11-07

37 Hantering av buffertmaterial av bentonit och kvarts
Hans Fagerström, VBB
Björn Lundahl, Stabilator
Stockholm oktober 1977

38 Utformning av bergrumsanläggningar
Arne Finné, KBS
Alf Engelbrektson, VBB
Stockholm december 1977

39 Konstruktionsstudier, direktdeponering
ASEA-ATOM
VBB
Västerås

40 Ekologisk transport och stråldoser från grundvattenburna radioaktiva ämnen
Ronny Bergman
Ulla Bergström
Sverker Evans
AB Atomenergi

41 Säkerhet och strålskydd inom kärnkraftområdet.
Lagar, normer och bedömningsgrunder
Christina Gyllander
Siegfried F Johnson
Stig Rolandson
AB Atomenergi och ASEA-ATOM

42 Säkerhet vid hantering, lagring och transport av använt kärnbränsle och förglasat högaktivt avfall
Ann Margret Ericsson
Kemakta november 1977

43 Transport av radioaktiva ämnen med grundvatten från ett bergförvar
Bertil Grundfelt
Kemakta november 1977

44 Beständighet hos borsilikatglas
Tibor Lakatos
Glasteknisk Utveckling AB

45 Beräkning av temperaturer i ett envånings slutförvar i berg för förglasat radioaktivt avfall Rapport 3
Roland Blomquist
AB Atomenergi 1977-10-19

46 Temperaturberäkningar för använt bränsle
Taivo Tahrandi
VBB

47 Teoretiska studier av grundvattenrörelser
Preliminär rapport oktober 1977
Slutrapport februari 1978
Lars Y Nilsson
John Stokes
Roger Thunvik
Inst för kulturteknik KTH

48 The mechanical properties of Stripa granite
Graham Swan
Högskolan i Luleå 1977-09-14

49 Bergspänningsmätningar i Stripa gruva
Hans Carlsson
Högskolan i Luleå 1977-08-29

50 Lakningsförsök med högaktivt franskt glas i Studsvik
Göran Blomqvist
AB Atomenergi november 1977

51 Seismotechtonic risk modelling for nuclear waste disposal in the Swedish bedrock
F Ringdal
H Gjöystdal
E S Husebye
Royal Norwegian Council for scientific and industrial research

52 Calculations of nuclide migration in rock and porous media, penetrated by water
H Häggblom
AB Atomenergi 1977-09-14

53 Mätning av diffusionshastighet för silver i lera-sand-blandning
Bert Allard
Heino Kipatsi
Chalmers tekniska högskola 1977-10-15

54 Groundwater movements around a repository

54:01 Geological and geotechnical conditions
Håkan Stille
Anthony Burgess
Ulf E Lindblom
Hagconsult AB september 1977

54:02 Thermal analyses
Part 1 Conduction heat transfer
Part 2 Advective heat transfer
Joe L Ratigan
Hagconsult AB september 1977

54:03 Regional groundwater flow analyses
Part 1 Initial conditions
Part 2 Long term residual conditions
Anthony Burgess
Hagconsult AB oktober 1977

54:04 Rock mechanics analyses
Joe L Ratigan
Hagconsult AB september 1977

54:05 Repository domain groundwater flow analyses
Part 1 Permeability perturbations
Part 2 Inflow to repository
Part 3 Thermally induced flow
Joe L Ratigan
Anthony S Burgess
Edward L Skiba
Robin Charlwood

54:06 Final report
Ulf Lindblom et al
Hagconsult AB oktober 1977

55 Sorption av långlivade radionuklider i lera och berg
Del 1 Bestämning av fördelningskoefficienter
Del 2 Litteraturgenomgång
Bert Allard
Heino Kipatsi
Jan Rydberg
Chalmers tekniska högskola 1977-10-10

56 Radiolys av utfyllnadsmaterial
Bert Allard
Heino Kipatsi
Jan Rydberg
Chalmers tkniska högskola 1977-10-15

57 Stråldoser vid haveri under sjötransport av kärnbränsle
Anders Appelgren
Ulla Bergström
Lennart Devell
AB Atomenergi

58 Strålrisker och högsta tillåtliga stråldoser för människan
Gunnar Walinder
AB Atomenergi