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Impact of a repository on permafrost development during glaciation advance

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ABSTRACT

The study concerns the development of permafrost during the initial phase of a glaciation period in an area in Sweden, where a generic repository for spent nuclear fuel of type KBS-3 was assumed be located 600 m below the ground surface. The bedrock was assumed to consist of granite which could be superposed by till. An aim of the study was to assess, by calculations, if prerequisites could be developed for a forced ground water flow from an adjacent lake, past the repository and then up to an un-frozen ground surface above the repository. Results from computer calculations, carried out with a finite element program for a total simulation period of 10 000 years, and with varied assumptions regarding final mean air temperature 5 000 years ahead, indicated that permafrost development will be about the same in the ground immediately above the repository as in surrounding ground, and that conditions for the mentioned ground water flow could prevail during less than 10 years. It was also indicated that the impact on permafrost development in a zone with anomalous heat generation would be insignificant in comparison with the impact from a repository.

SUMMARY

This study concerns the development of permafrost during the initial phase of a glaciation period in an area with a repository for spent nuclear fuel.

The aim of the study has been to assess, by calculations:

i) time histories for permafrost development with varied air temperature decrease rates,

ii) if the ground over the repository can be un-frozen while at the same time permafrost has developed in the surroundings and an adjacent lake is not completely frozen,

iii) if till layers in the ground surface will have an insulating effect,

iv) if permafrost development will be similar in an area with natural anomalous heat generation as in an area with a repository.

Adverse conditions could hypothetically be developed with conditions according to item ii) above. Then, lake water could possibly be transported as ground water past the repository and up to the un-frozen ground above the repository, thereby reducing the lengths of the flow paths to the shortest physically possible, and possibly increasing the groundwater flow rates, cf. Fig. 1.1.

Assumptions

The considered time for the permafrost to develop in the study was set to 10 000 years ahead from now.

The Finnsjön area in northern Uppland in Sweden was considered as a site for a generic repository in the study, cf. Fig. 3.1.

The bedrock at the site was assumed to consist of granite. For some calculations the granite was superposed by a two metre thick layer of till. The ground water surface was then located in the midst of this till layer.

The repository was of type KBS-3, located 600 m below the ground surface and with a total number of 5 300 canisters stored. The incipient average heat generation from the spent fuel in each canister was equal to 1 066 W at the time of deposition.

Thermal coefficients for till, granite, and lake water were assumed. The effect of latent heat was regarded for till and lake water but was assumed negligible for the bedrock for the purpose of this study.

A temperature gradient of 13° C/km on the average in the ground was assumed. For areas with natural anomalous radioactive heat generation a temperature gradient of 20° C/km was considered.

Based on assumptions regarding possible future air temperature decreases and a certain temperature difference between the air and ground surface temperatures, three separate ground surface temperature decrease rates were regarded for the repository area with surroundings, viz. from +6° C to -3° C, -5° C and -7° C, respectively, during 5 000 years ahead from now, and constant temperature thereafter, cf. Fig. 3.5.

Computer runs

The heat propagation in the ground was simulated with a computer program with trade mark Solvia, a finite element program.

A part of the earth's crust was modelled. In order to keep the amount of computer time at a reasonable level, a two-dimensional, axi-symmetric geometrical model was generated and used for the simulations. The model was given an extension in the radial direction of 5 000 m and in the vertical direction of 4 000 m, cf. Fig. 4.1.

The repository was modelled as a circular slab with a radius that corresponds to the repository area, viz. 528 m. A lake, with a width of 750 m and a depth of 15 m, was assumed to be located 1 250 m from the repository centre.

Five primary computer runs, denominated Cases A to E, were carried out. Cases A to D included heat generation from the repository, and were carried out with a geothermal gradient of 13° C/km. Case E did not include heat generation from a repository, and was carried out with a geothermal gradient of 20° C/km in part of the model, corresponding to an assumed zone with natural anomalous radioactive heat generation, and with a geothermal gradient of 13° C/km in the remaining part, cf. Fig. 4.3. The final temperatures after 5 000 years were -3° C, -5° C, -7° C, -5° C and -5° C for Cases A, B, C, D and E, respectively. Case D included two till strata on the ground surface.

Calculated temperatures

The results of the temperature calculations for Cases A to E are presented in Appendices 1 to 5 to this Report with plots which show the spatial temperature distributions for selected times.

A number of temperature time histories were also elaborated for selected FE-mesh nodes, cf. Figs 5.1 to 5.5. These nodes were located:

- above the repository:
  * on level -0.5 m, node # 468,
  * on level -2.0 m, node # 522,

- between the repository and the lake:
  * on level -0.5 m, node # 496,
  * on level -2.0 m, node # 538,

- below the lake, node # 448:
  * on level -15.0 m (lake bottom), node # 448,
  * on level -22.5 m, node # 679,

- between the repository and the model extreme vertical border line:
  * on level -0.5 m, node # 1 202.

Checks were carried out for verification of the size of the geometrical model, and of the time for permafrost to develop as well as for freezing the lake completely, cf. Appendix 6.

Discussion

Scrutiny of the temperature time histories for the studied Cases A to C, cf. Figs 5.1 to 5.3, shows that:

- the upper ground between the repository and the lake will freeze slightly before the upper ground above the repository will freeze; the time difference varies very roughly from about 10 years for Case A to about 5 years for Case C,

- the upper ground above the repository will freeze well before the ground close to the lake bottom will freeze; the time difference is roughly about 650 years for Case A, about 550 years for Case B and some 500 years for Case C,

- the ground under the lake close to the lake bottom will freeze before all water in the lake has frozen, i.e. before all latent heat in the lake has been transferred.

Scrutiny of the temperature time history for the studied Case D, i.e. Case B with the addition of a layer of till, cf. Fig. 5.4, and comparison with Case B indicate that:

- the layer of till on the ground surface will have an insulating effect,

- the till layer will delay the freezing of the upper ground above and around the repository with about 175 years,

- the till will delay the freezing of the ground under the lake close to the lake bottom with nearly about 125 years,

- conditions are otherwise comparable with those for Case B.

Scrutiny of the temperature time history for the studied Case E, i.e. Case B but without repository and including a zone with anomalous heat generation, cf. Fig. 5.5, and comparison with Case B indicate that:

- the upper ground above the zone with anomalous heat generation will freeze slightly before the same area for Case B; the time difference is about 15 years.

The anomalous heat generation does not significantly increase the temperatures above those for the adjacent area with normal heat generation. The reason why the repository in Case B increases the ground temperatures much more than the area with anomalous heat generation in Case E can be explained by a comparison of the respective heat flows. The heat transfer from the repository is substantially larger than the additional heat transfer from the zone with anomalous heat generation during the initial approx. 1 000 years after deposition. Thereafter, the repository will have lost its importance as a heat source.

Conclusions

The temperature calculations showed that:

- the ground over the repository will not stay un-frozen significantly longer than ground in the surrounding area,

- the time during which water from the lake, by inverted siphon action, could possibly communicate with un-frozen ground above the repository, while the upper ground in between these two areas is frozen, is less than 10 years,

- a till layer on the ground surface will have an insulating effect but will not change the behaviour described in the above two paragraphs,

- the impact on permafrost development from a zone with anomalous natural heat generation is insignificant in comparison with the impact from a repository.

1. INTRODUCTION

Next glaciation period has been predicted to appear in some 5 000 years, see Ref. (1). During the initial phase of such a glaciation period, permafrost will develop.

The ground in a repository area will, due to heat generation from the spent fuel, be warmer than the surrounding ground. This heating can delay permafrost development above the repository.

An adverse situation during a glaciation period could possibly develop if permafrost has settled generally in the repository surroundings while at the same time:

- the ground directly above the repository site proper is un-frozen due to local heating,
- a lake in the repository area has not been frozen solid due to the latent heat in the lake water.

During such circumstances, water can hypothetically be transported as ground water from the lake, by seepage into the ground, past the repository and up to the un-frozen ground above the repository, thereby reducing the lengths of the flow paths to the shortest physically possible, and possibly increasing the groundwater flow rates, see Figure 1.1.

In order to get a view of the development of permafrost in a repository area during a coming permafrost advance, SKB AB commissioned VBB VIAK AB to carry out theoretical calculations. These calculations as well as the outcomes are addressed in this report.

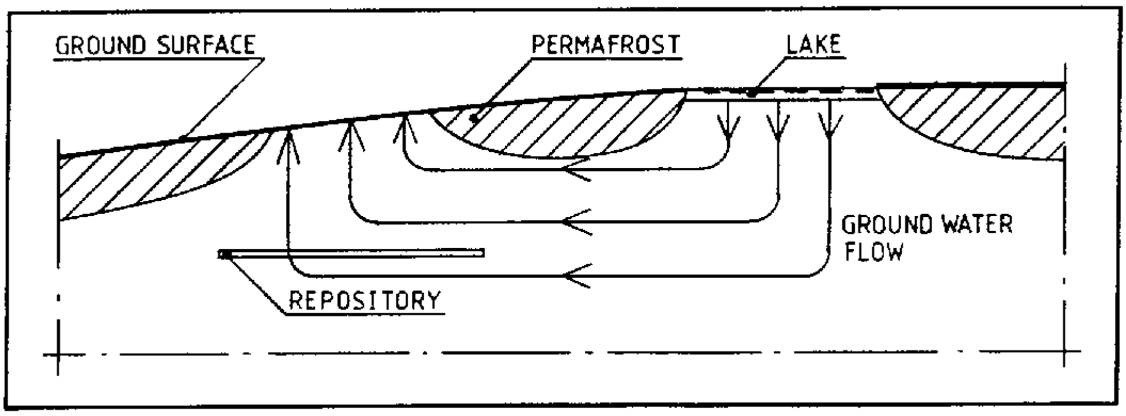

Figure 1.1 Hypothetical ground water flow during permafrost advance.

2. SCOPE OF THE STUDY

The aim of the study has primarily been to establish:

- time histories for permafrost development with varied air temperature decrease rates,
- if the ground over the repository can be un-frozen while at the same time permafrost has developed in the surroundings and an adjacent lake is not frozen solid,
- if a till layer in the ground surface will have an insulating effect,
- if permafrost development will be similar in an area with natural anomalous heat generation as in an area with a repository.

The computational analysis was only taken to 10 000 years after present (A.P.).

3. ASSUMPTIONS

3.1 Geographical area description

The Finnsjön area in northern Uppland has been used as a site for a generic repository in the study. The location of the repository for spent fuel has been described elsewhere, for example in Ref. (2). See also Figure 3.1.

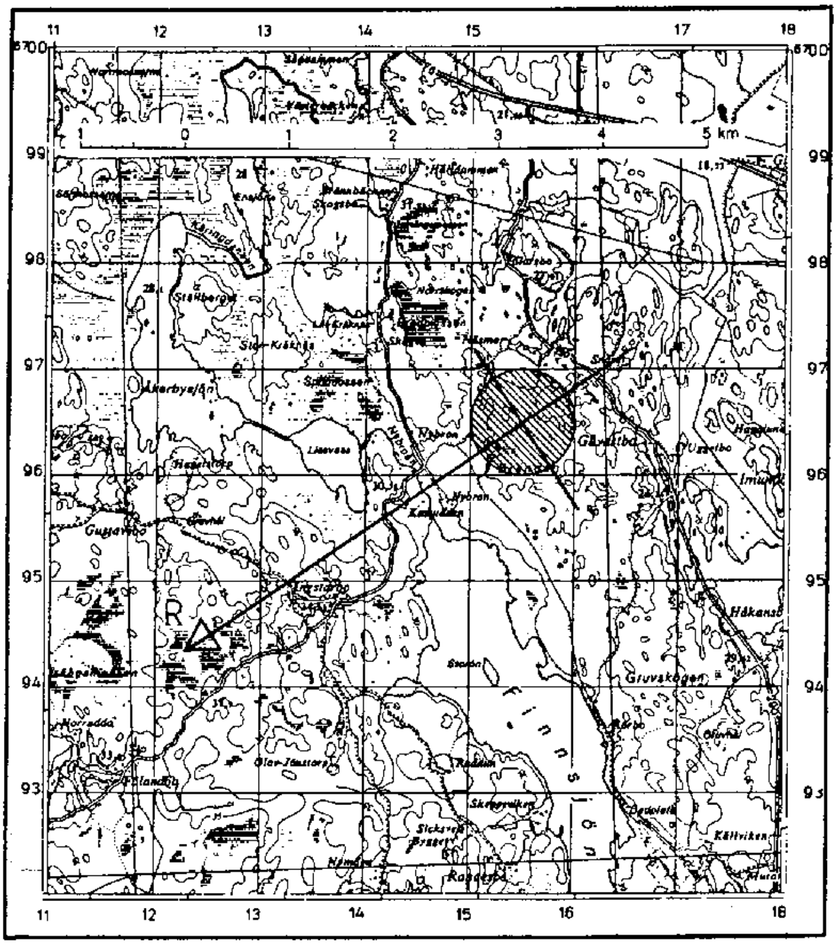

Figure 3.1 The Finnsjön area. The approximate location of a generic repository is indicated with the shaded area.

A system of lakes, including lake Finnsjön, extends like a band in an approximate SE-NW direction to the south-west of the repository. The distance from the repository centre to a lake shore is about 1 250 m. A characteristic lake width is about 750 m. The water depth in the lake system is assumed to be about 15 m on the average.

3.2 Geology

The bedrock has been assumed consist of granite. For some calculations the granite was assumed superposed by a layer of till with a thickness of two metres. The ground water table was then located in the midst of this till layer.

3.3 Repository characteristics

General repository characteristics according to Ref. (2) have been adopted for the study. Thus:

- the repository is of type KBS-3 and located 600 m below the ground surface,
- a total number of 5 300 canisters is stored,
- the repository spatial requirement resembles 5 830 canister positions, i.e. the number of canisters increased by 10%,
- the centre distance between canisters in a drift is 6.0 m and between drifts 25.0 m, respectively.

The canister length is 4.5 m. The initial average heat generation from the spent fuel in one canister has been assumed equal to 1 066 W when all canisters have been placed, cf. Ref. (3). Thus:

- the repository area is 874 500 m^2,
- the repository volume is 3 935 250 m^3,
- total initial average heat generation is 5.65 MW,
- initial average specific heat generation from the repository is 1.436 W/m^3.

The spent fuel heat decay according to Ref.(4) and Ref. (3) was assumed for the study. The relative heat generation decay function is shown in Figure 3.2.

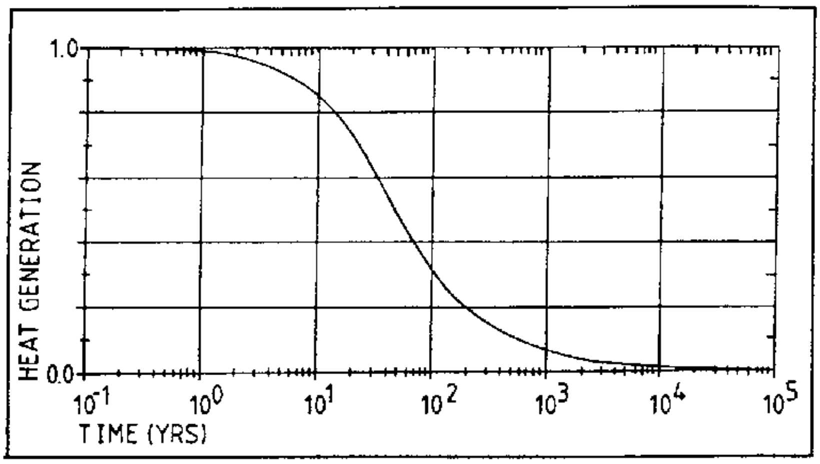

Figure 3.2 Relative spent fuel heat generation decay.

3.4 Thermal coefficients

Thermal coefficients for till, bedrock, assumed to consist of granite, and lake water were gathered from Refs (5), (6) and (7). The coefficients are compiled in Table 3.1.

	Cond. (W/m,°C)	S.H. (MJ/m^3,°C)	L.H. (MJ/m^3)
Till above gwt: - un-frozen - frozen	 1.2 1.0	 2.5 2.0	 50
Till below gwt: - un-frozen - frozen	 2.0 2.5	 4.0 2.1	 75
Lake: - water - ice	 0.6 2.1	 4.2 2.2	 330
Bedrock	3.3	2.1	-

Table 3.1 Thermal coefficients used in the study. Cond.=conductivity, S.H.=specific heat, L.H.=latent heat, gwt= ground water table.

The effect of latent heat in bedrock was assumed negligible for the purpose of this study.

The till was assumed to have the following physical properties:

- dry density 1 700-1 900 kg/m^3,
- porosity 30%,
- water content 5-7%,
- saturation degree:
  * above gwt approx. 30%,
  * below gwt 100%.

The thermal coefficient values for till were conservatively selected in order to obtain distinct indications from the calculations of the till's insulating ability. The choice was also motivated by the complicated processes that will take place when ice develops in the ground.

3.5 Geothermal gradient

A temperature gradient of 13° C/km on the average in the bedrock was assumed for the Finnsjön area in accordance with Ref. (8). For areas with natural anomalous radioactive heat generation, a temperature gradient of 20° C/km on the average in the bedrock was assumed, see Ref (9).

3.6 Air temperature variation

The future variation of air temperature has been estimated by studying and comparing, c.f. Figure 3.3:

- the Astronomical Climate Index (ACLIN) for the last glacial cycle and the projected climate of the next 60 000 years, see Ref. (1),

- The Generalized Northern Hemisphere air temperature trends based on mid-latitude sea-surface temperature, pollen records and worldwide sea-level records, see Ref. (10).

The ACLIN model shows that present interglacial conditions are gradually changing to glacial conditions with a maximum occurring in 23 000 years. However, there should be a cold peak already in 5 000 years. The next warm deglaciation will occur between 70 000 and 80 000 years ahead from now, with an optimum in 75 000 years.

The estimate of future air temperature has been based on a comparison between the ACLIN values and the air temperature of the past 125 000 years. The total temperature variation of the past is about 10° C. The

ACLIN cycles seem to be of the same magnitude in the future as in the past which indicates an air temperature decrease of about 10° C up to the next glacial.

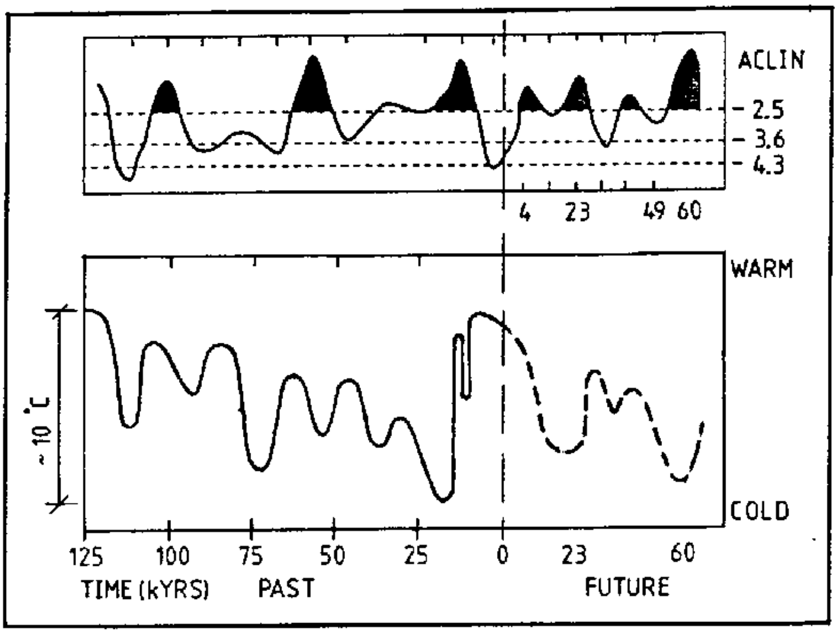

Figure 3.3 The ACLIN projected climate of past and future years (upper graph) and the generalized Northern Hemisphere air temperature trends (lower graph).

At present, the mean annual air temperature within the actual area is +6.6° C. For the study it has been assumed that the air temperature will decrease regularly from +6.6° C to -4° C, -6° C and -8° C in 5 000 years and thereafter remain constant up to 23 000 years, see Figure 3.4. An air temperature decrease down to -6° C or -8° C should be on the conservative side.

Possible greenhouse effects on future temperatures have not been considered in this study.

3.7 Ground surface temperature

Climate is the most important factor influencing the ground surface temperature. Of all climatic factors, air temperature is the most readily measured and most directly related to ground heat loss or heat gain. Observations in Sweden and other countries indicate a relation between mean annual air and ground temperatures.

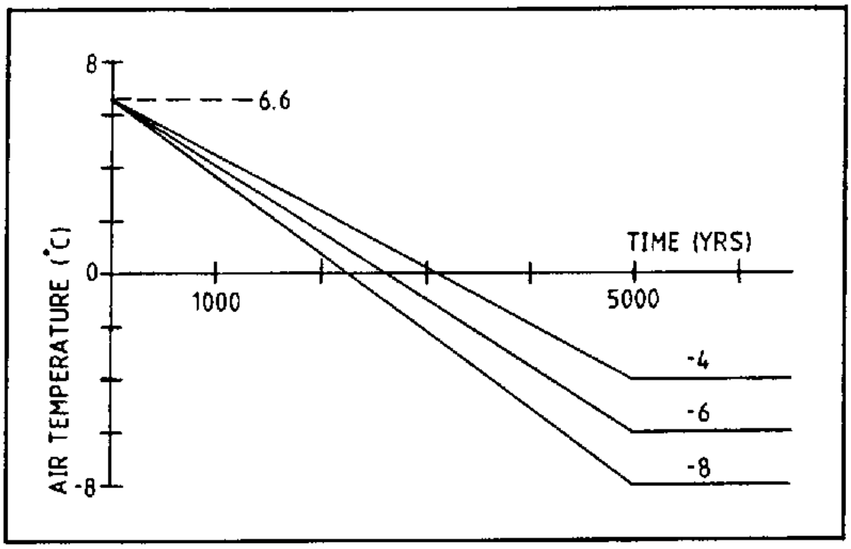

Figure 3.4 Air temperature adopted for the study.

There is, however, a certain temperature difference, sometimes by many degrees. The difference varies from place to place and is caused by factors other than air temperature. Factors which seem particularly influential are net radiation, vegetation, winds, snow cover, topographic features, surface water and groundwater conditions.

In Sweden the ground condition is normally influenced by annual variations down to a depth of 10 to 15 m. Below this depth the temperature increases steadily as mentioned above in sub-Section 3.5.

An accurate prediction of mean annual ground surface temperature by calculations, i.e. by heat transfer calculations, is a rather complicated exercise due to the many factors which have an influence on the exchange regime between air and ground. In this study, the present ground surface temperature has instead been estimated from measurements in boreholes. According to Ref. (8), the ground surface temperature at Finnsjön is +5.8° C à +5.9° C, or 0.7° C à 0.8° C lower than the mean annual air temperature. A future regular air temperature decrease is foreseen. After a certain initial period, the surface ground temperature will probably be higher than the air temperature. The difference is estimated to be of the same magnitude as the present or about 1° C.

Based on the assumption regarding air temperature decreases outlined in the preceding section and the temperature difference of 1° C mentioned above, three separate ground surface temperature decreases have been regarded for this study, viz. from +6° C to -3° C, -5° C and

-7° C, respectively, for the repository area with surroundings. These decreases are exhibited in Figure 3.5.

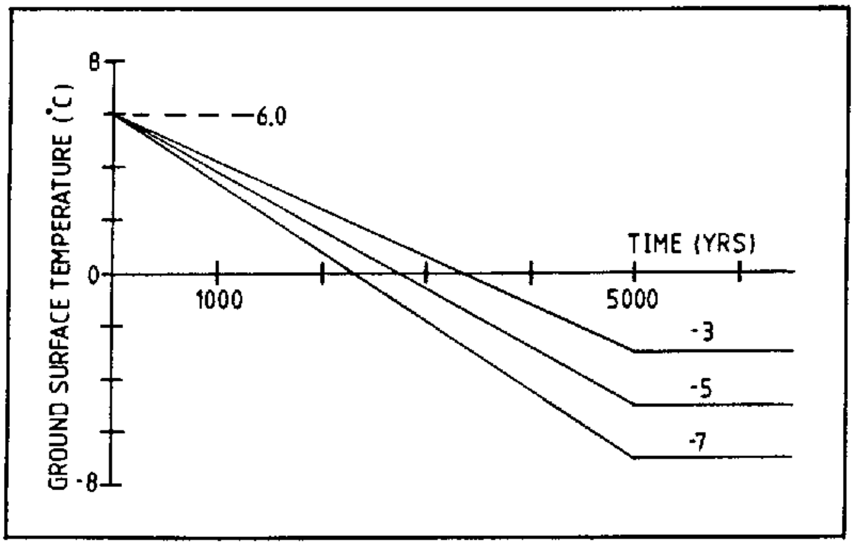

Figure 3.5 Ground surface temperature adopted for the study.

4. COMPUTER RUNS

4.1 Software and hardware

The heat propagation in the ground was simulated with a computer program with trade mark Solvia. Program Solvia is a finite element program. The program includes a program package called Solvia-Temp, which was used for this study. Solvia-Temp can be used for steady state and transient heat transfer analyses.

The program runs were carried out with a personal computer.

4.2 Computer model

A part of the earth's crust was modelled. In order to keep the amount of computer time at a reasonable level, a two-dimensional model was generated and used for the simulations.

An axi-symmetric geometrical model was built up with its vertical centre line through the middle of the repository. The axi-symmetric model was assumed to more accurately represent the heat output from the repository to the surrounding ground than a plane model would do.

The model was given an extension in radial direction of 5 000 m and in downward direction of 4 000 m. The radial extension was selected such that the temperatures along the extreme vertical border line would not be impacted by the presence of the repository and the lake. In the same way, the extension downwards was set such that no temperature changes would occur along the lower horizontal border line during the time span considered.

The repository was modelled as a circular slab and with a radius that corresponds to the repository area, viz. 528 m.

4.3 Finite element mesh

The model's finite element, FE-, mesh is shown in Figures 4.1 and 4.2. In order to best model the heat flows, a finer mesh was used from a level below the repository and upwards. For the same reason, eight node elements, instead of four node elements, were used in that area.

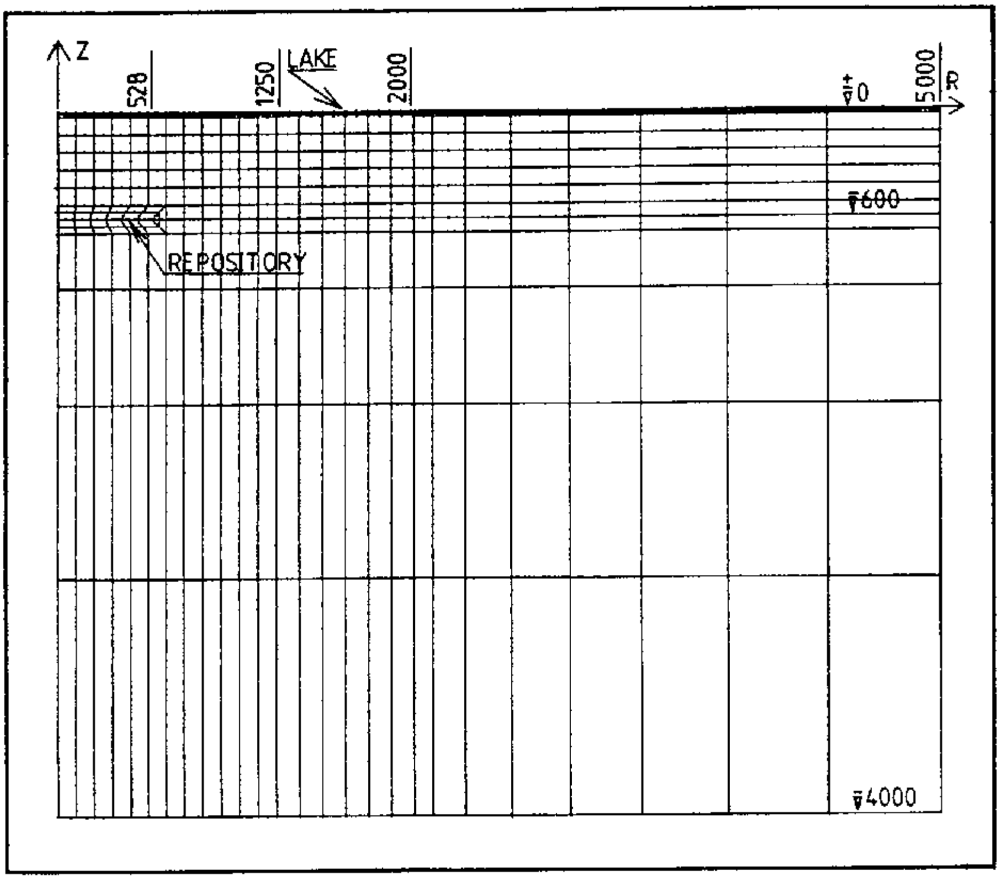

Figure 4.1 Finite element mesh.

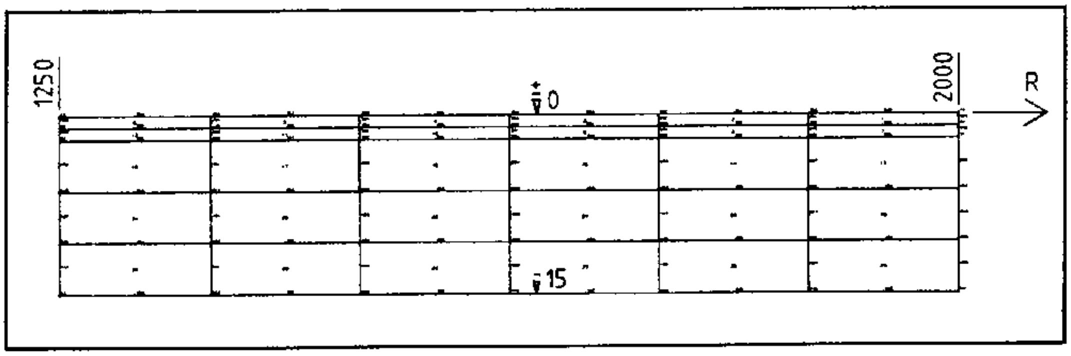

Figure 4.2 Finite element mesh, details.

4.4 Run schedule

Five primary computer runs, denominated Case A to Case E, were carried out, see Table 4.1. Cases A to D included the heat generation from a repository, and were carried out with a geothermal gradient of 13° C/km. Case E did not include heat generation from a repository, but was carried out with a geothermal gradient of 20° C/km in part of the model, corresponding to a zone with natural anomalous radioactive heat generation, and with a geothermal gradient of 13° C/km in the remaining part, c.f. Figure 4.3.

Case	Repository (Y/N)	Till (Y/N)	Final ground surface temp. (°C)
A	Y	N	-3
B	Y	N	-5
C	Y	N	-7
D	Y	Y	-5
E	N	N	-5

Table 4.1 Scheme for primary computer runs. Case E includes a geothermal inhomogeneity.

In addition, a number of runs were carried out for purposes of validation and verification.

4.5 Time steps

The computer calculations comprised three parts for each of the Cases A to E, viz.:

- static calculation for time 0 in order to get the incipient temperature in each model node,
- transient calculations from time 0 to 200 years with a relatively short time step of approx. 10 years, during which period the repository heat generation change is relatively fast,
- transient calculations from time 200 to 10 000 years with a time step of approx 100 years.

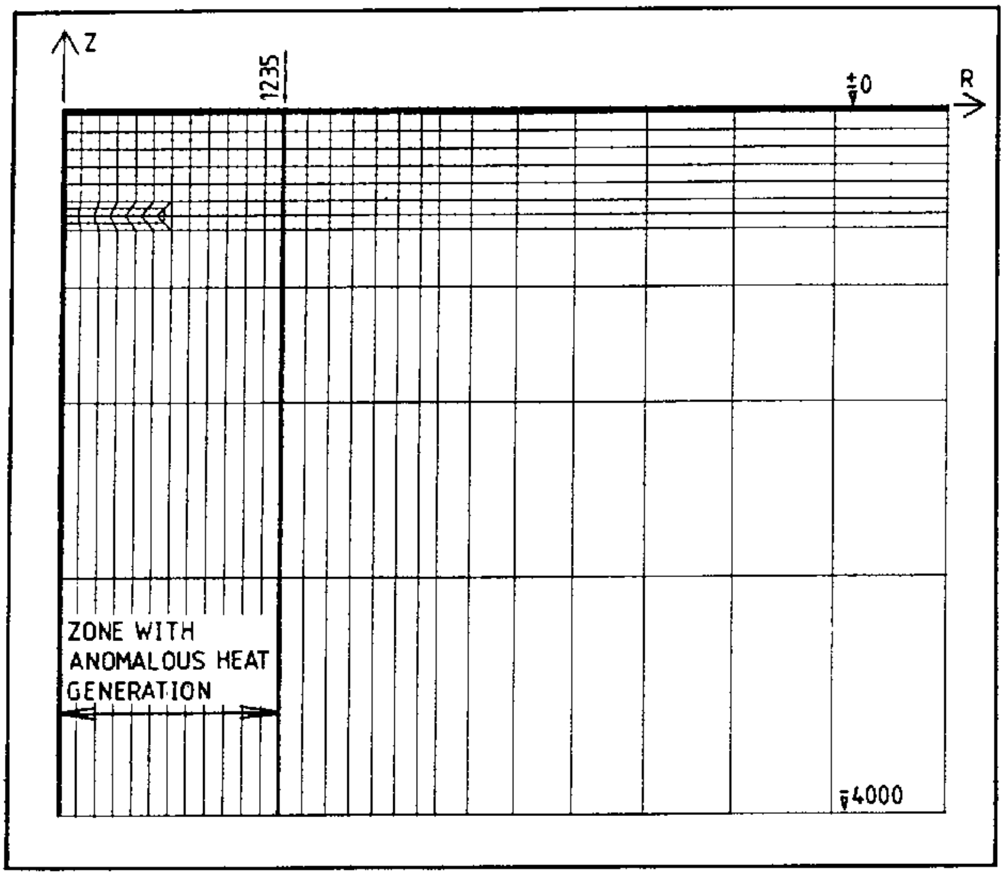

Figure 4.3 Zone with geothermal inhomogeneity.

During the third type of calculation mentioned above, it was necessary to decrease the time step during periods when temperature changes were fast. Such changes occurred when latent heats in the lake and the till were set free. Time steps as small as one year could then be required.

4.6 Boundary values

In the computer model, the temperature close to the ground followed the description given in sub-section 3.7. This temperature was transferred to the model's ground and lake surfaces by a superposed layer of dummy material. The dummy material was given a high thermal conductivity, 100 W/m,°C, and a low specific heat, 0.02 MJ/m^3,°C, in order to get immediate response in the ground and lake surfaces to imposed temperature changes.

The temperature along the lower horizontal border line of the model was kept constant and equal to 58° C if the geothermal gradient was 13° C/km and equal to 86° C if the geothermal gradient was 20° C/km.

The surface generated by the extreme vertical border line was assumed to be completely insulated, i.e. no heat was transferred radially across this surface.

The z-axis was a symmetry line.

The repository generated the heat corresponding to the assumed incipient heat generation multiplied with the assumed heat generation decay function that have been described in sub-section 3.3. The repository was given a thermal conductivity of 0.5 W/m,°C and a specific heat of 3.3 MJ/m^3,°C.

5. CALCULATED TEMPERATURES

5.1 Presentation of results

5.1.1 Temperature distribution plots

The results of the temperature calculations for Cases A to E are presented in Appendices 1 to 5 with plots which show the spatial temperature distributions for selected times. These times are approx.:

- 0 years,
- 200 years,
- 1 000 years,
- 2 000 years,
- 4 000 years,
- 6 000 years,
- 8 000 years,
- 10 000 years.

5.1.2 Time histories

A number of temperature time histories have been produced for selected FE-mesh nodes. These nodes were located:

- above the repository, radial distance equal to 303.8 m:
  * on level -0.5 m, node # 468,
  * on level -2.0 m, node # 522,

- between the repository and the lake, radial distance equal to 928.8 m:
  * on level -0.5 m, node # 496,
  * on level -2.0 m, node # 538,

- below the lake, node # 448, radial distance equal to 1 625.0 m:
  * on level -15.0 m (lake bottom), node # 448,
  * on level -22.5 m, node # 679,

- between the repository and the model extreme vertical border line, radial distance equal to 3301.0 m:
  * on level -0.5 m, node # 1 202.

The temperature time histories pertaining to Cases A to E are shown in Figures 5.1 to 5.5, respectively.

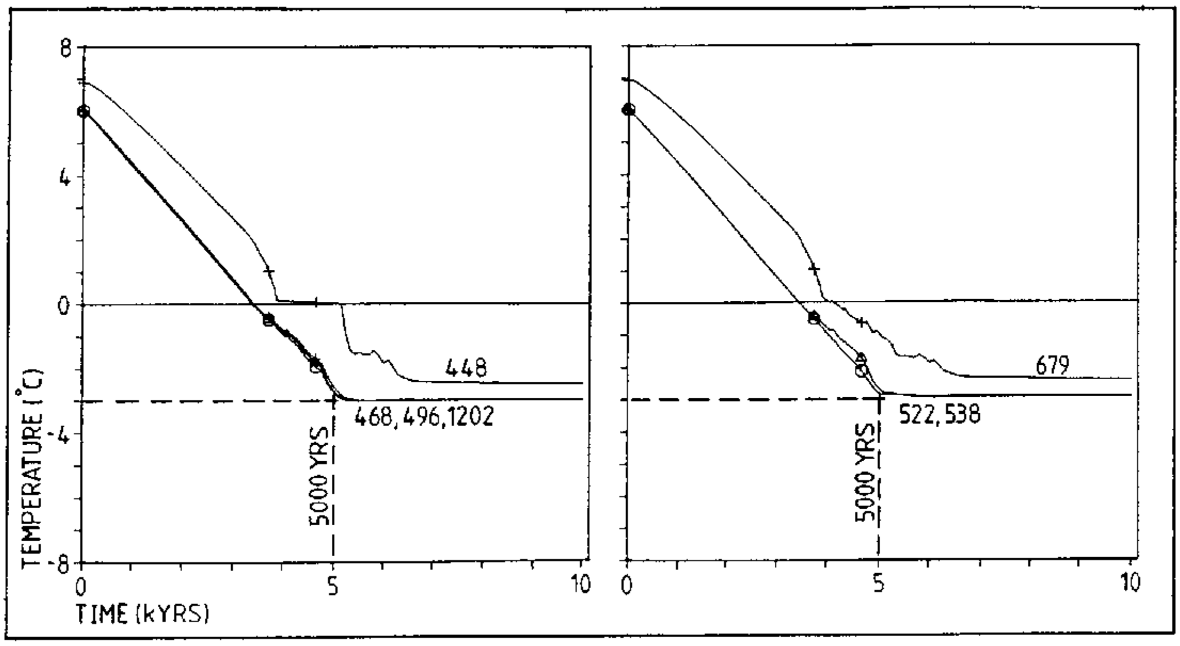

Figure 5.1 Temperature time history for Case A.

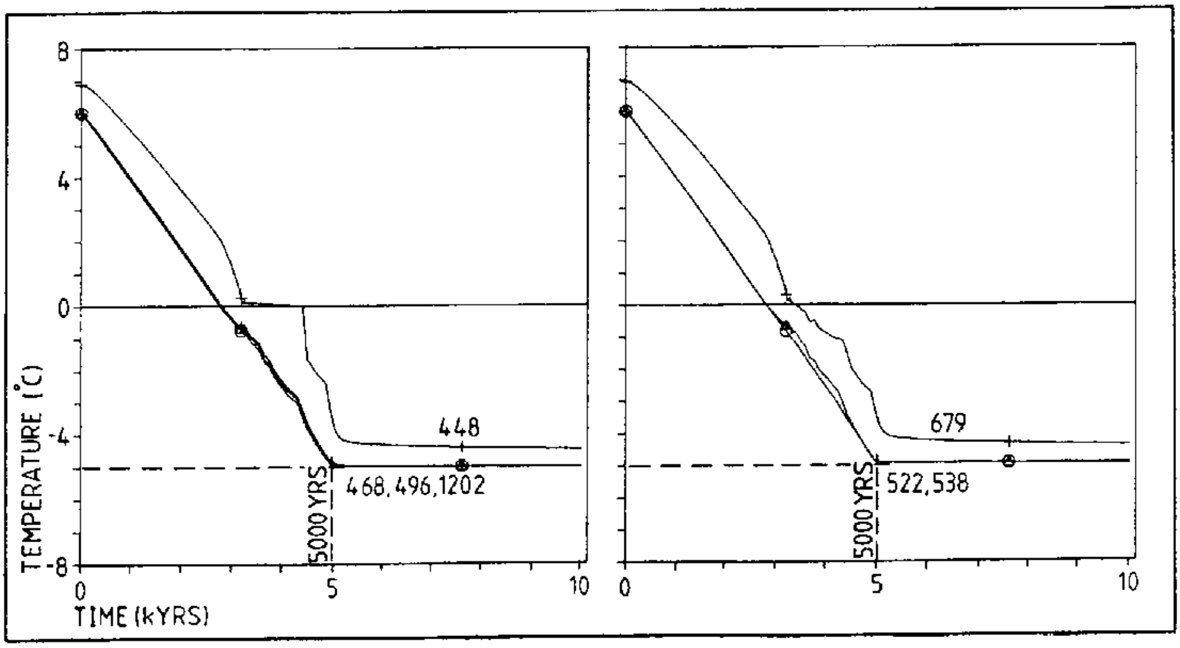

Figure 5.2 Temperature time history for Case B.

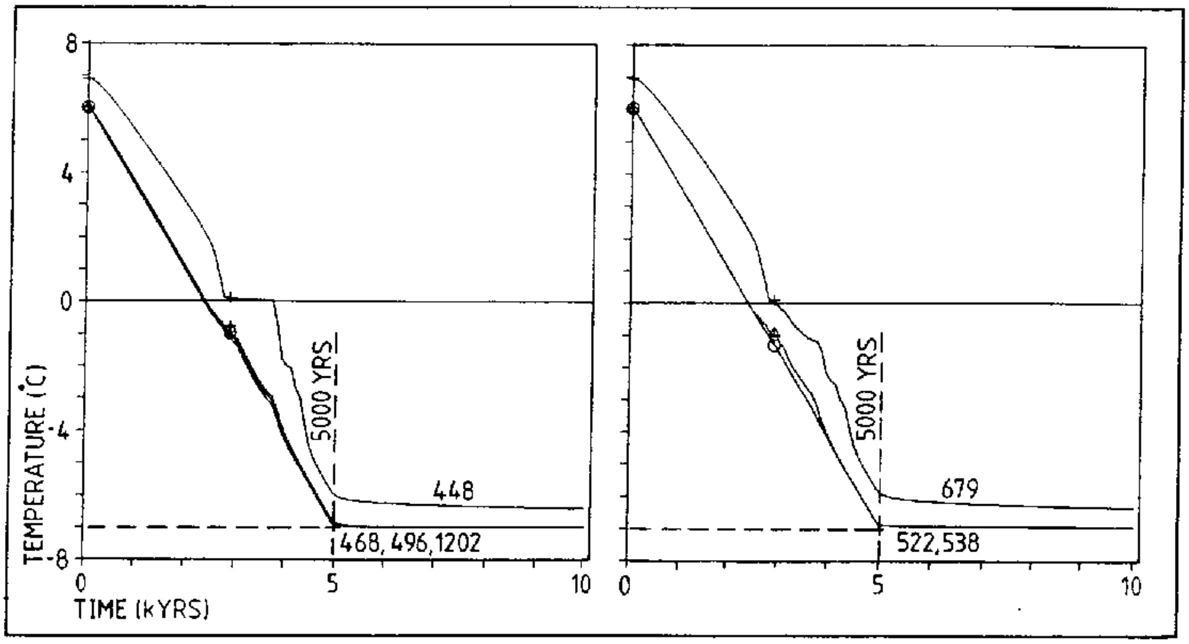

Figure 5.3 Temperature time history for Case C.

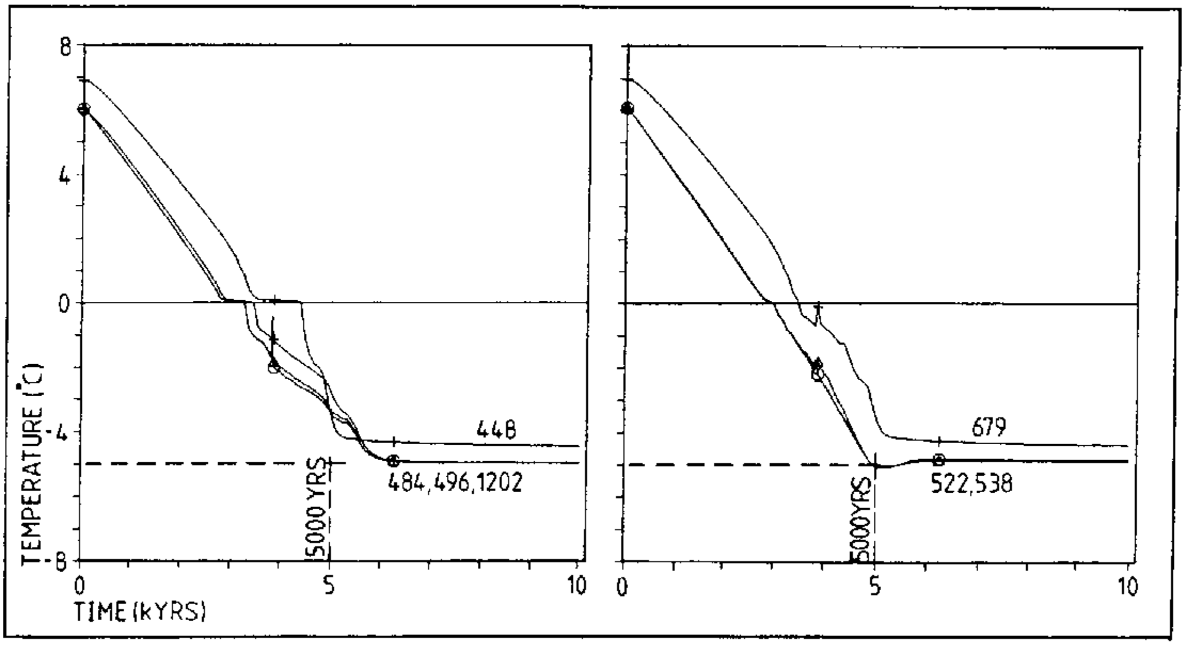

Figure 5.4 Temperature time history for Case D.

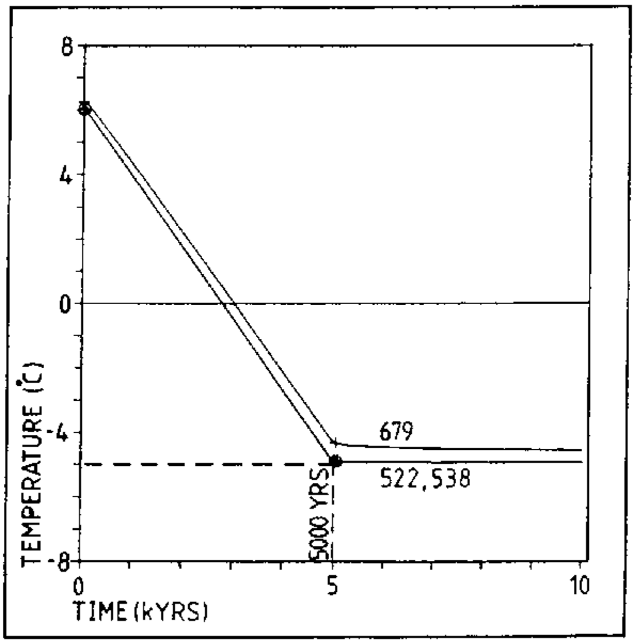

Figure 5.5 Temperature time history for Case E.

5.2 Verification of results

Three checks have been carried out, viz.:

- check of the size of the geometrical model,
- comparison of the results from calculations with the program Solvia and manual calculations as regards:
  * permafrost development as function of time,
  * time for freezing a lake completely.

The verifications are described in Appendix 6.

6. DISCUSSION

6.1 Introduction

Below will be discussed differences in time for permafrost to develop between various positions in the ground. These time differences have been related to:

- node # 522 above the repository on level -2.0 m,
- node # 538 between the repository and the lake on level -2.0 m,
- node # 679 below the lake close to the lake bottom on level -17.5 m.

These nodes were found to be more feasible for reliable calculation of relatively small time differences than the nodes closer to the model top interfaces.

The choice of representative nodes is also motivated by the condition that the lake bottom, as represented by node # 448 in the model, will freeze later than the underlying strata, c.f. the time histories for nodes # 448 and # 679 on Figure 5.1 to 5.4. If the ground below the lake is frozen, water seepage from the lake will be hampered.

6.2 Cases A to C

Scrutiny of the temperature time histories for the studied Cases A to C, see also Figures 5.1 to 5.3, shows that:

- the upper ground between the repository and the lake, i.e. node # 538, will freeze slightly before the upper ground above the repository, i.e. node # 522, will freeze; the time difference varies very roughly from some 10 years for Case A to some 5 years for Case C,
- the upper ground above the repository, i.e. node # 522, will freeze well before the ground close to the lake bottom, i.e. node # 679, will freeze; the time difference is roughly some 650 years for Case A, some 550 years for Case B and some 500 years for Case C,
- the ground under the lake close to the lake bottom, i.e. node # 679, will freeze before all water in the lake has frozen, i.e. before all latent heat in the lake has been transferred.

The differences in time for permafrost to develop between the positions represented by nodes # 522 and # 538, and by nodes # 522 and # 679, have been plotted as function of the respective assumed air temperature decrease rates, see Figures 6.1 and 6.2.

6.3 Case D

Scrutiny of the temperature time history for the studied Case D, i.e. Case B with the addition of a layer of till, see also Figure 5.4, and comparison with Case B indicates that:

- the layer of till on the ground surface will have an insulating effect,
- the till layer will delay the freezing of the upper ground above and around the repository, i.e. nodes # 522 and 538, with nearly about 175 years,
- the till will delay the freezing of the ground under the lake close to the lake bottom, i.e. node # 679, with nearly about 125 years,
- conditions are otherwise comparable with those for Case B.

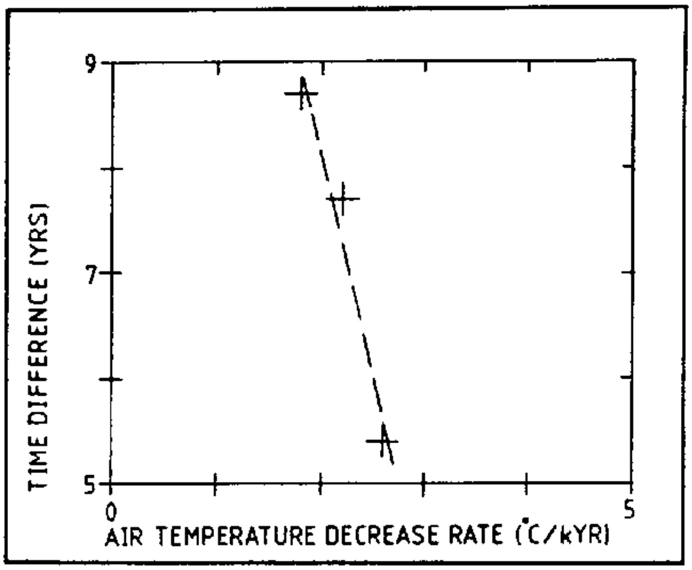

Figure 6.1 Difference in time for permafrost to develop between two positions represented by nodes # 522 (above repository) and # 538 (between repository and lake) as function of the respective assumed air temperature decrease rates. Node # 538 will freeze first.

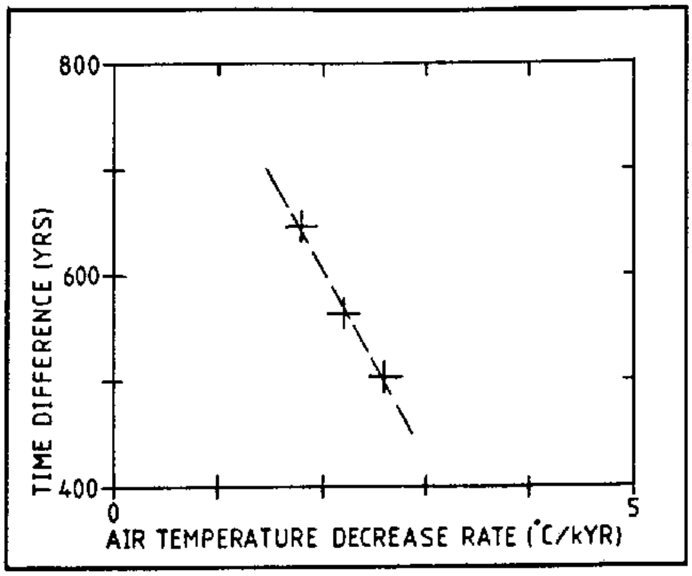

Figure 6.2 Difference in time for permafrost to develop between two positions represented by nodes # 522 (above repository) and # 679 (below lake) as function of the respective assumed air temperature decrease rates. Node # 522 will freeze first.

6.4 Case E

Scrutiny of the temperature time history for the studied Case E, i.e. Case B but without repository and including a zone with anomalous heat generation, see also Figure 5.5, and comparison with Case B indicates that:

- the upper ground above the anomaly, i.e. node # 522, will freeze slightly before the same area for Case B; the time difference is about 15 years.

The temperature distribution plots for Case E, see Appendix 5, show that the isopleths are rather horizontal on levels above the 'repository' level. Thus, the anomalous heat generation does not significantly increase the temperatures above those for the adjacent area with normal heat generation.

The reason why the repository in Case B increases the ground temperatures much more than the area with anomalous heat generation in Case E can be explained by a comparison of the respective heat flows. Thus:

- the specific heat flow from the area with normal heat generation is 3.3*13/1000 W/m^2, i.e. 0.043 W/m^2, and from the area with anomalous heat generation 3.3*20/1000 W/m^2, i.e. 0.066 W/m^2; consequently, the additional specific heat flow due to the anomalous heat generation is 0.023 W/m^2,

- the zone with anomalous heat generation has been considered for a circular area with a radius of 2 000 m; consequently, the additional heat flow due to the anomalous heat generation is 290 kW,

- the heat generation from the studied repository is initially 5650 kW; this heat has decreased to 4 800, 2 225, 390 and 290 kW after 10, 100, 1 000 and 1230 years, respectively.

From the above can be concluded that the heat transfer from the repository is substantially larger than the additional heat transfer from the zone with anomalous heat generation during the initial approx. 1 000 years after deposition. Thereafter, the repository will have lost its importance as a heat source. This behaviour is supported by the temperature distribution plots, which indicate that the isotherms no longer ascend after some 1 000 years for Cases A to D.

7. CONCLUSIONS

The temperature calculations have shown that:

- the ground over the repository will not stay un-frozen significantly longer than ground in the surrounding area,

- the time during which water from the lake could possibly communicate with un-frozen ground above the repository, while the upper ground in between these two areas is frozen, is less than 10 years,

- a till layer on the ground surface will have an insulating effect but will not change the general behaviour described in the above two paragraphs,

- the impact on permafrost development from a zone with anomalous natural heat generation is insignificant in comparison with the impact from a repository.

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(10) Osterkamp, T.E., Response of Alaskan permafrost to climate, Proc. Fourth International Conference on Permafrost, Fairbanks, Alaska, 1983.

(11) Code of practice for design and construction (Bygg del 1), Ch. 143:75, 3rd ed., Stockholm 1961.

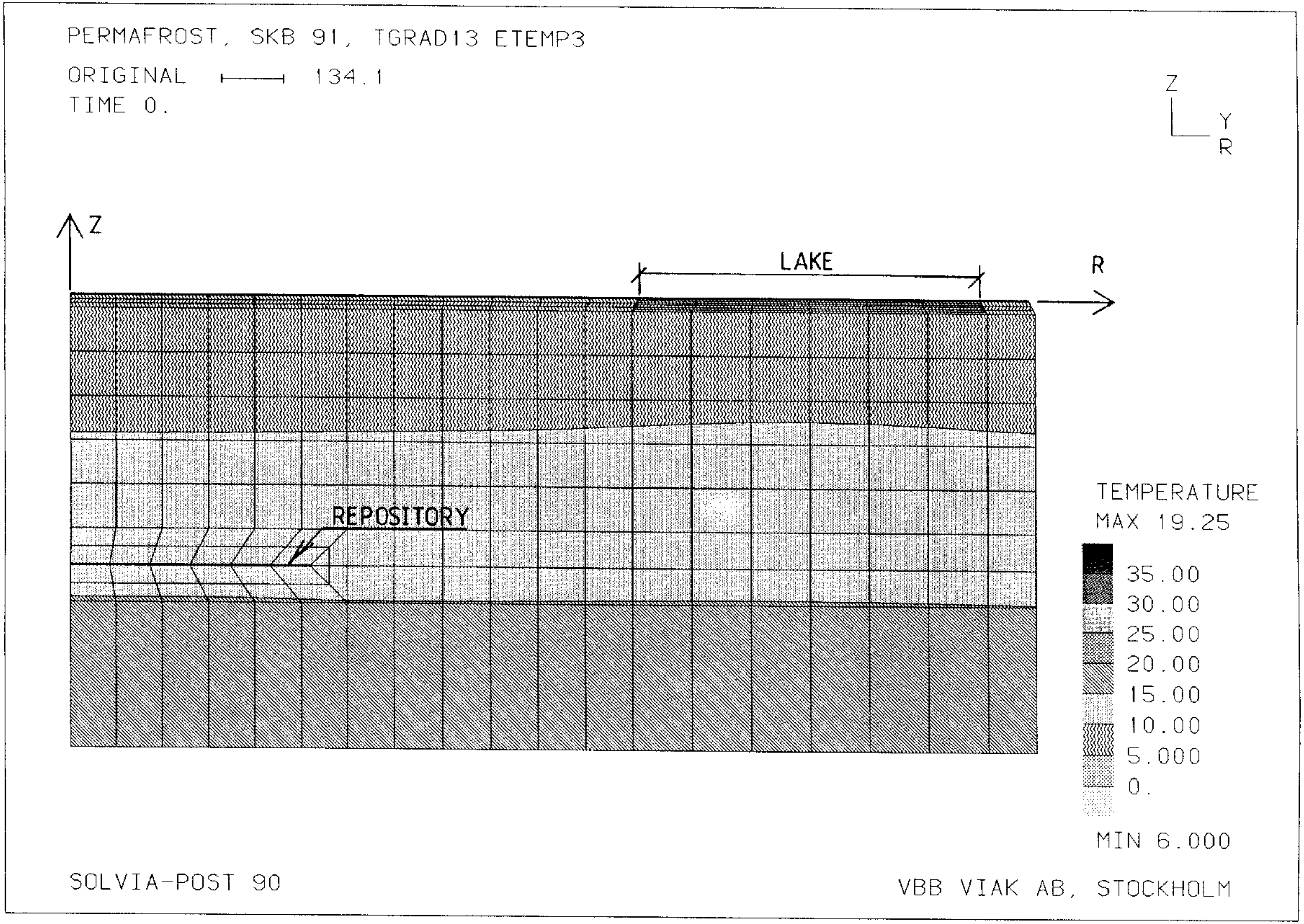
APPENDIX 1

TEMPERATURE DISTRIBUTIONS FOR CASE A

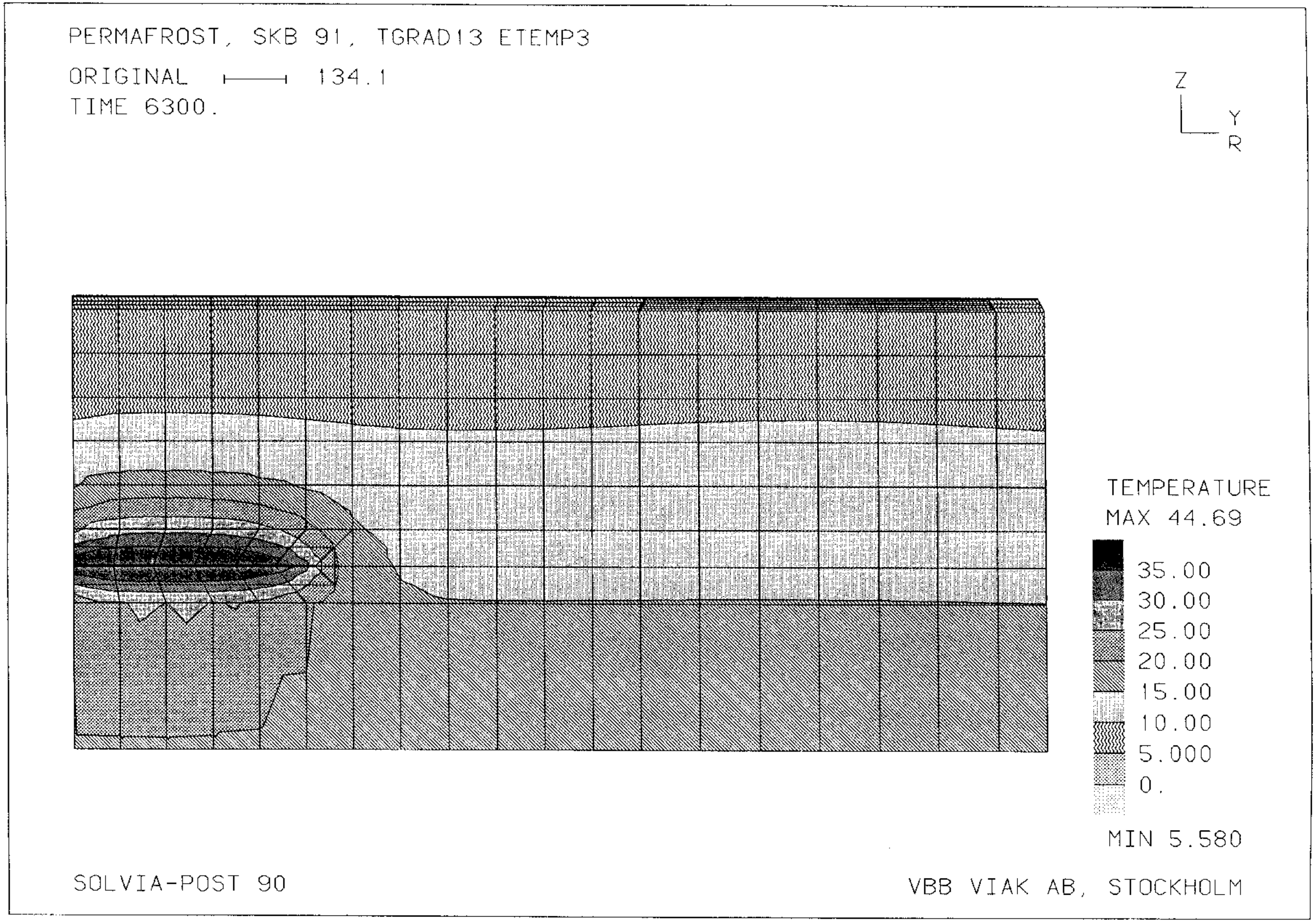
The case is described in Section 4.5.

Times given on the following isotherm plots are expressed in megaseconds, Ms. In the following list, these times are translated into years.

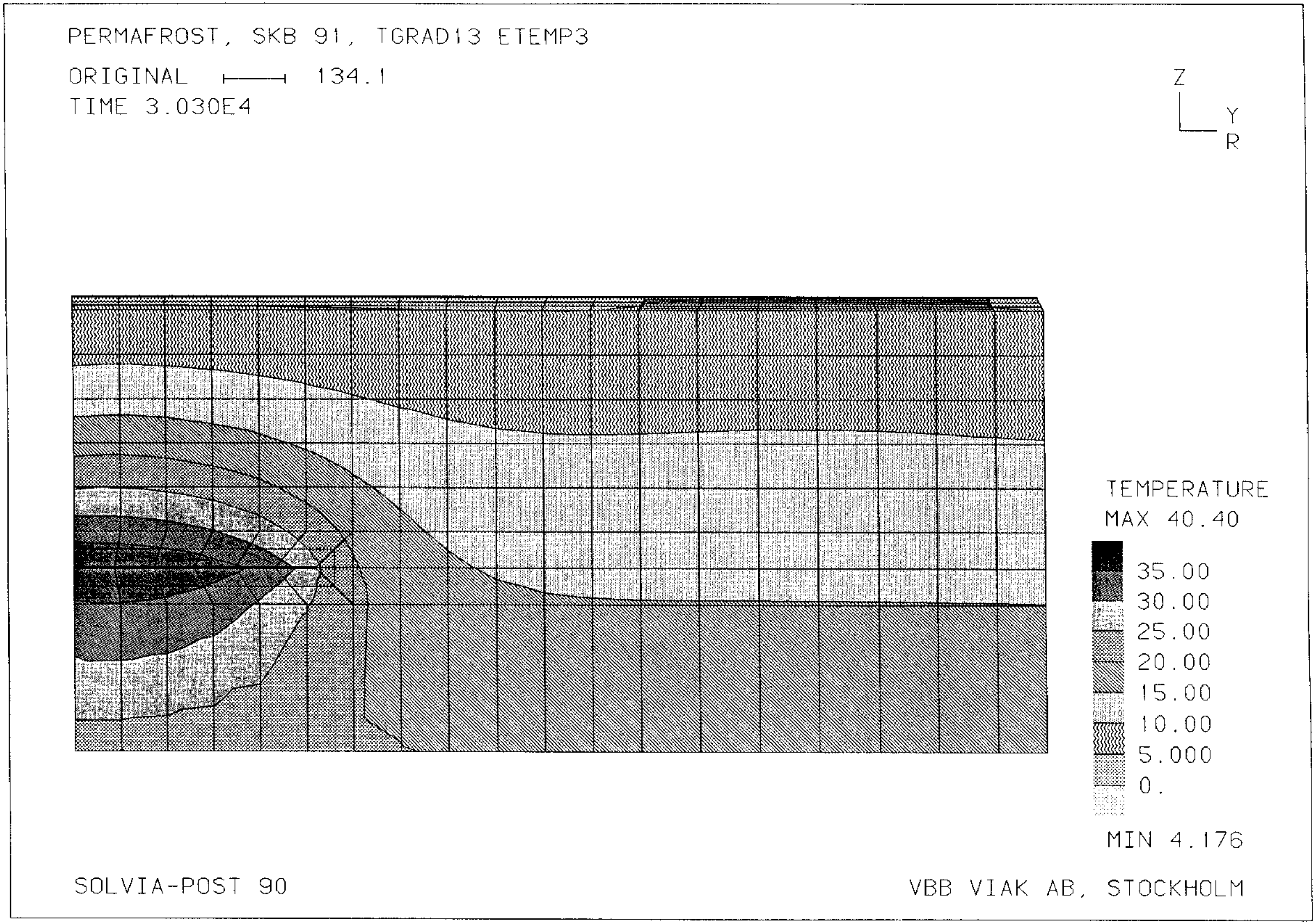
Page #	Time (Ms)	Time (yrs)
1	0	0
2	6300	200
3	3.030E4	961
4	6.330E4	2 007
5	1.260E5	3 995
6	1.899E5	6 022
7	2.529E5	8 019
8	3.159E5	10 017



APPENDIX 1, P. 1



APPENDIX 1, P. 2



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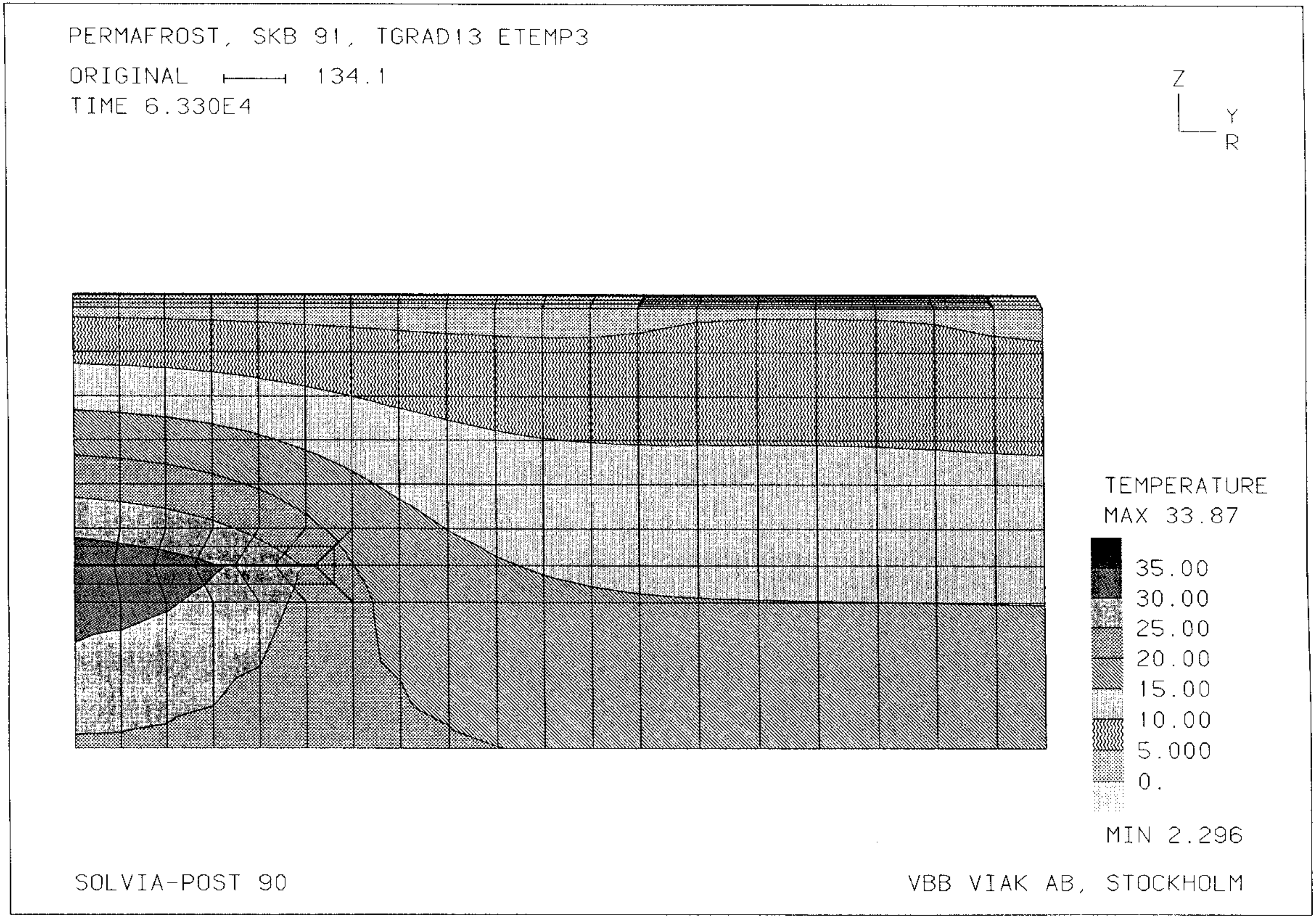
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R
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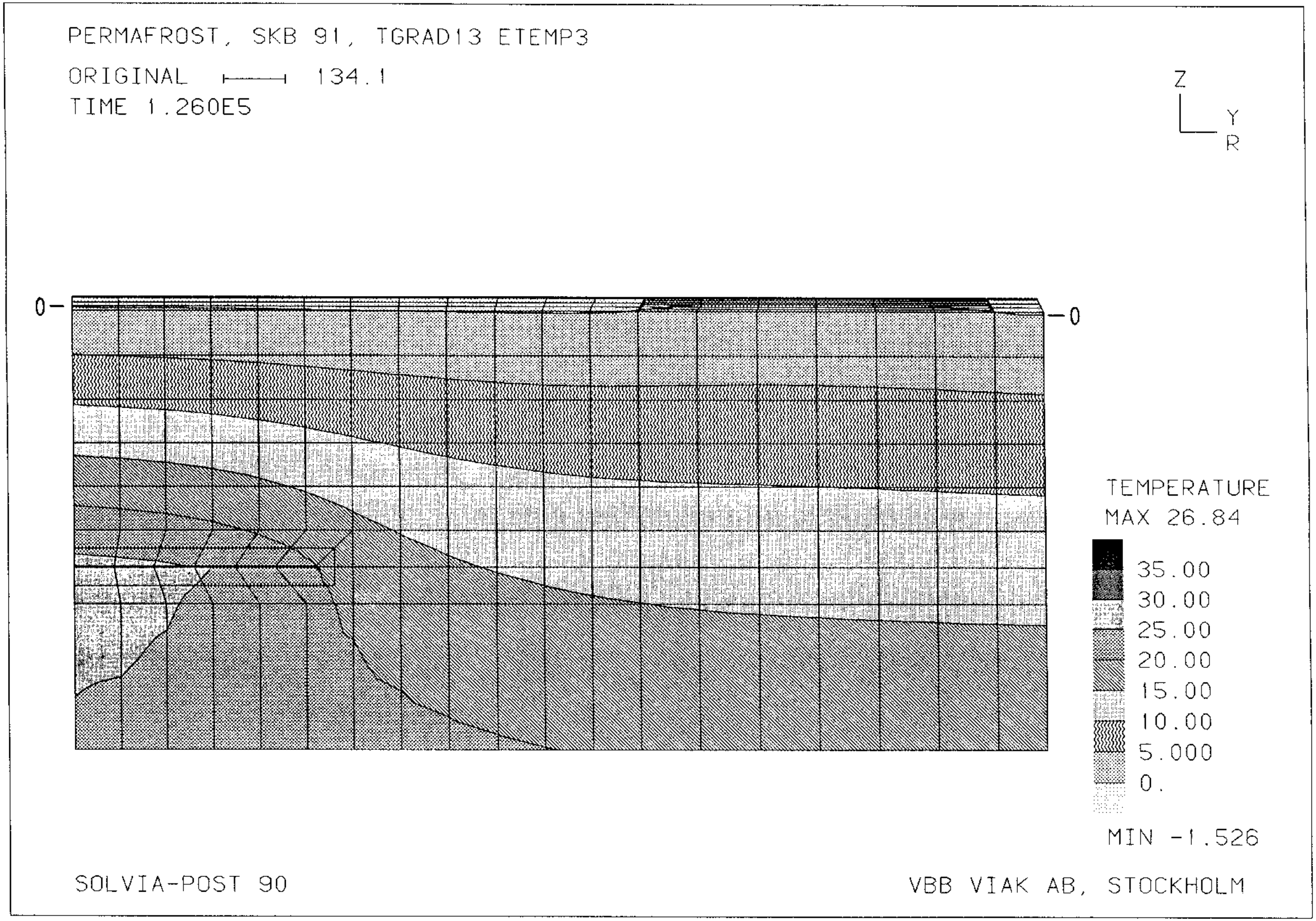
20.00
15.00
10.00
5.000
0.
MIN 2.296
SOLVIA-POST 90
VBB VIAK AB, STOCKHOLM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Z
Y
R
0
0
TEMPERATURE
MAX 26.84
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15.00
10.00
5.000
0.
MIN -1.526
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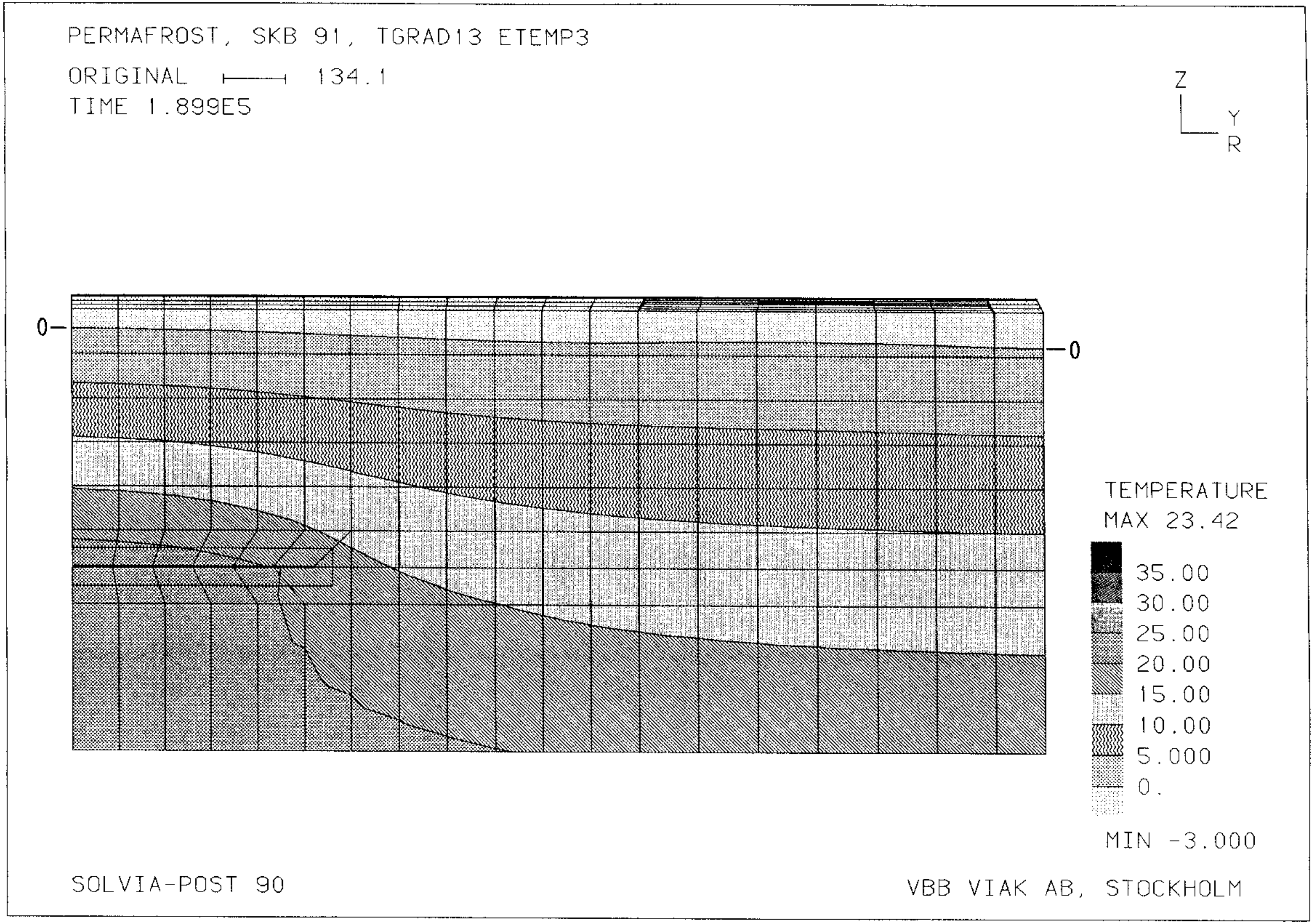

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Y
R
0
0
TEMPERATURE
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20.00
15.00
10.00
5.000
0.
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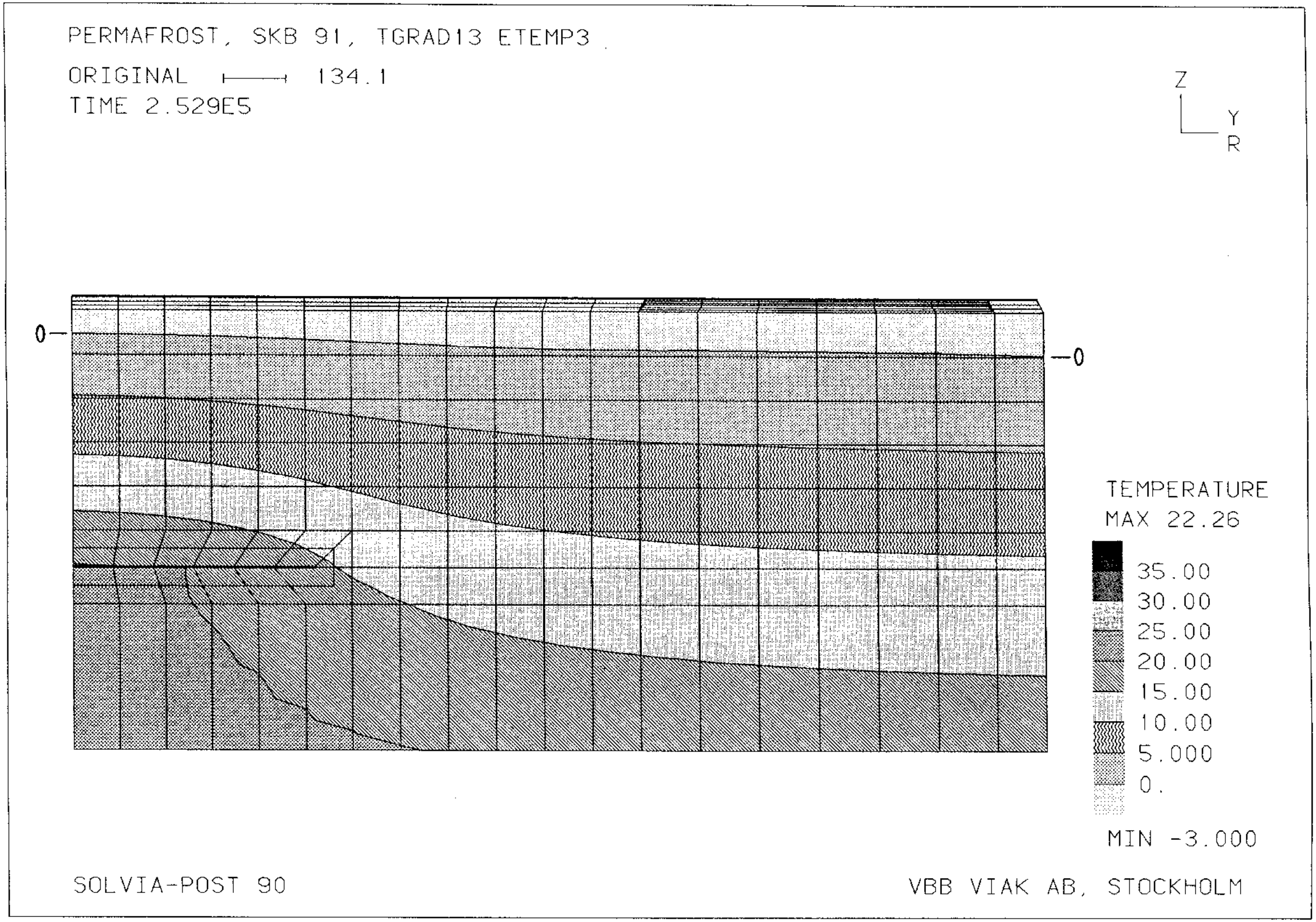

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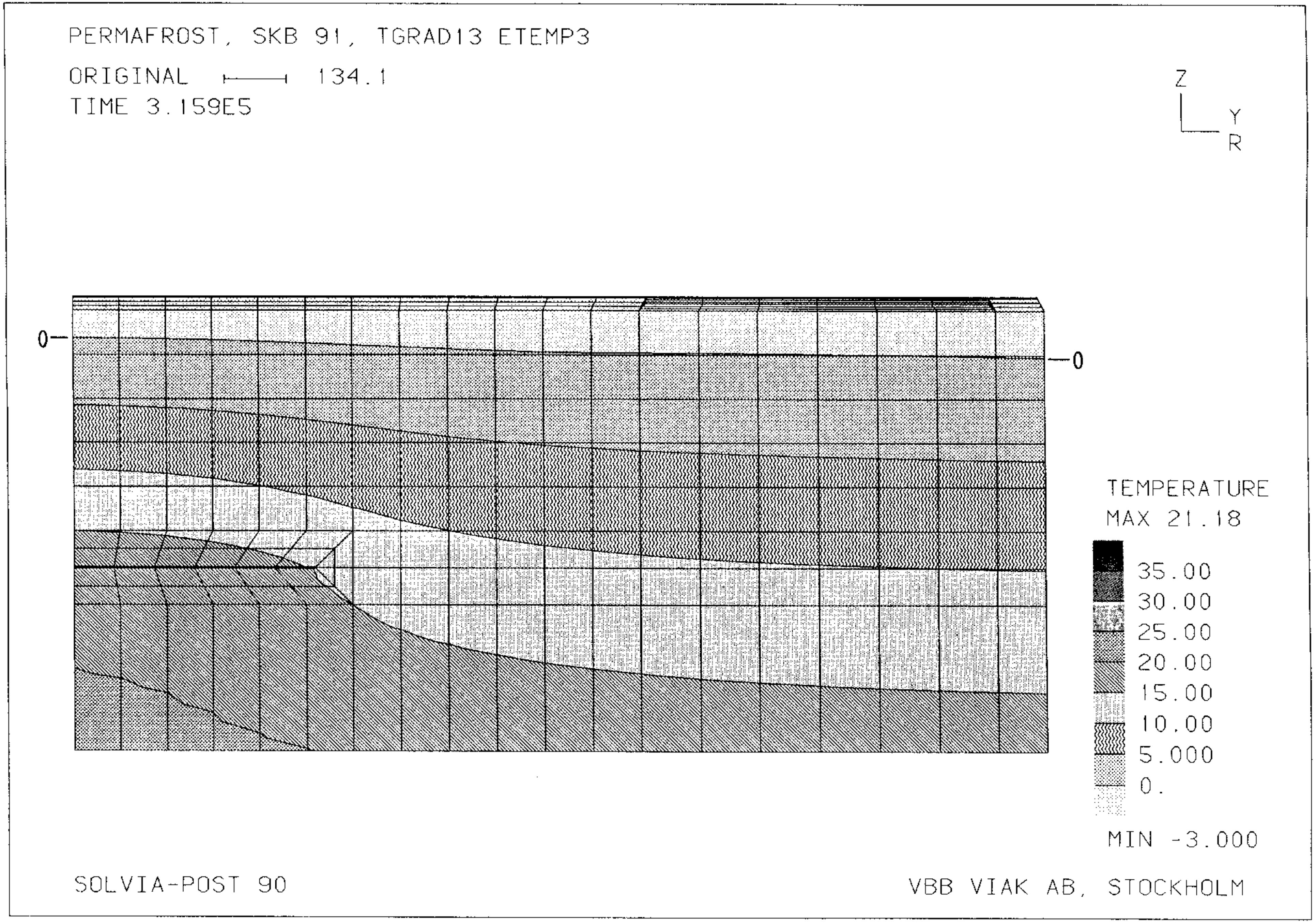
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TIME 3.159E5
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Y
R
0
0
TEMPERATURE
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25.00
20.00
15.00
10.00
5.000
0.
MIN -3.000
SOLVIA-POST 90
VBB VIAK AB, STOCKHOLM

APPENDIX 2

TEMPERATURE DISTRIBUTIONS FOR CASE B

The case is described in Section 4.5.

Times given on the following isotherm plots are expressed in megaseconds, Ms. In the following list, these times are translated into years.

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4	6.330E4	2 007
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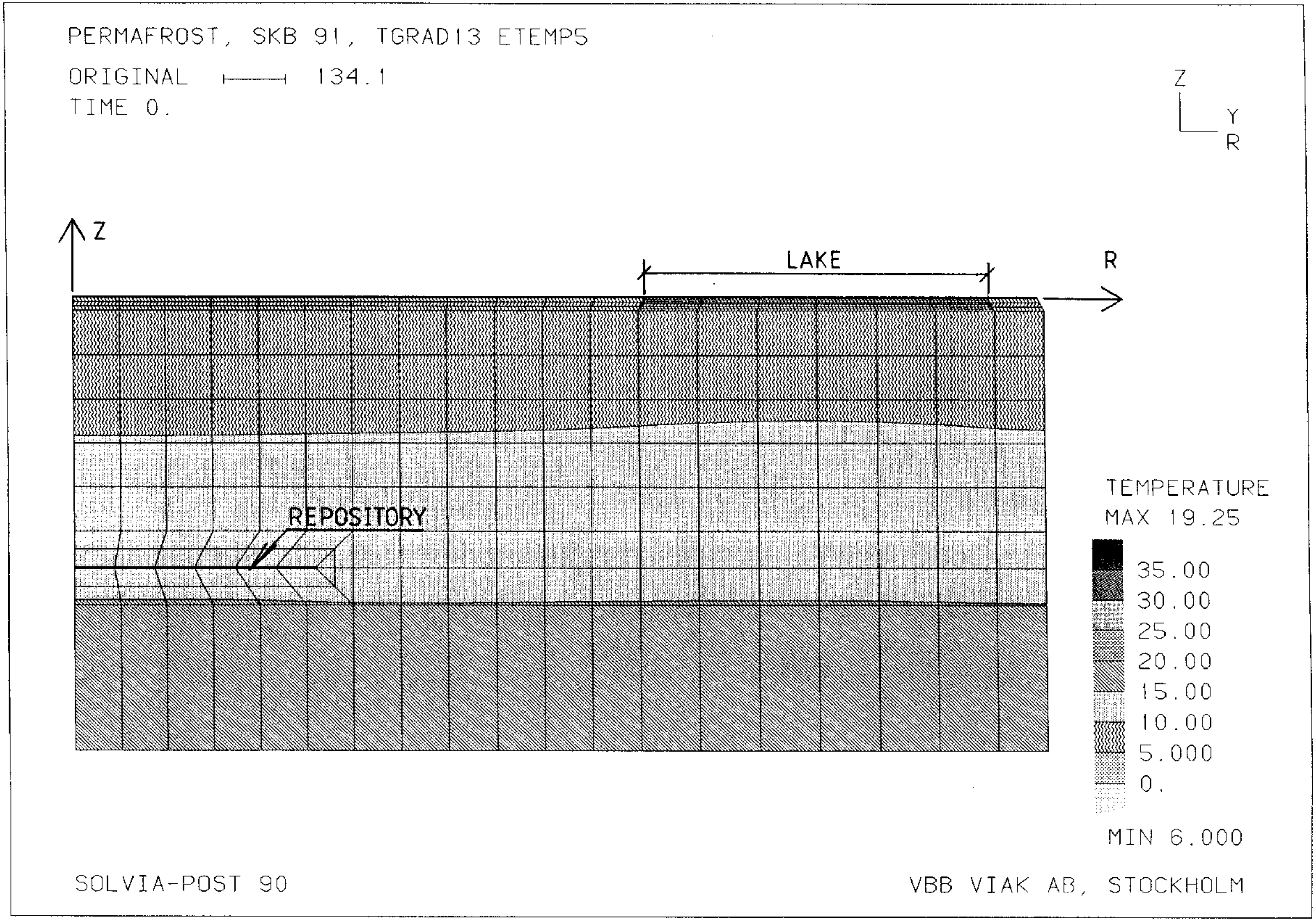
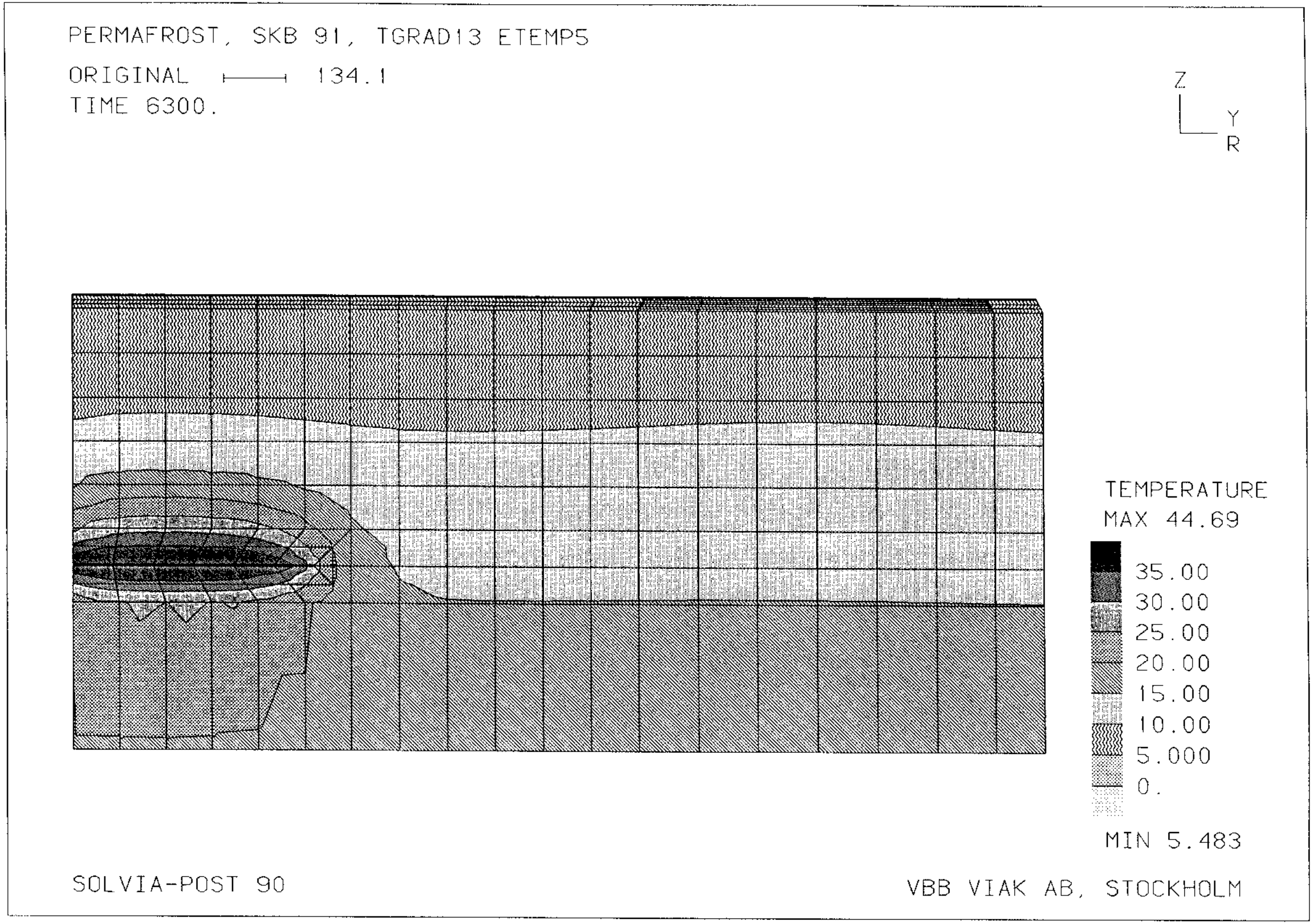
7	2.535E5	8 038
8	3.165E5	10 036



APPENDIX 2, P. 1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R
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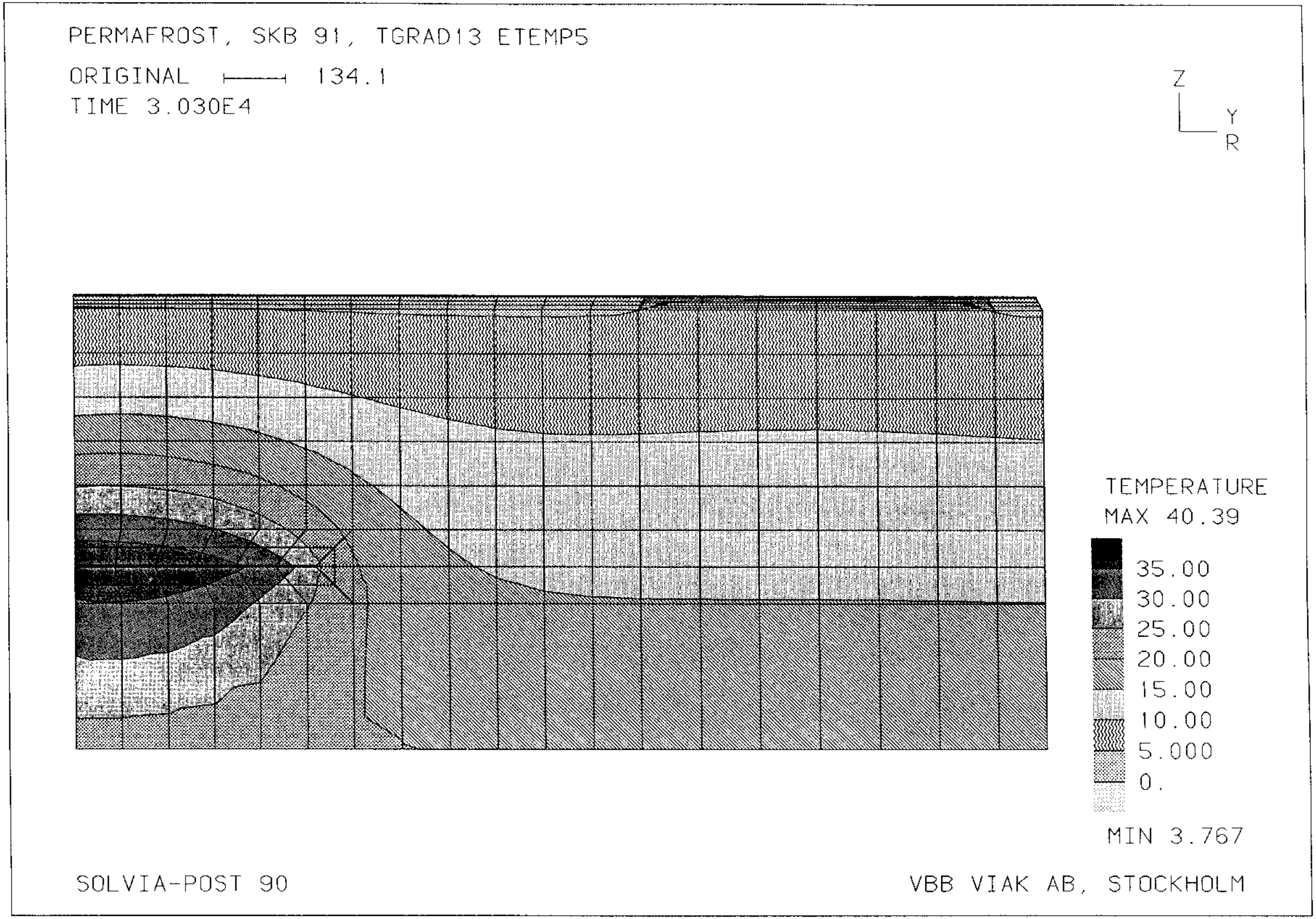
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Y
R
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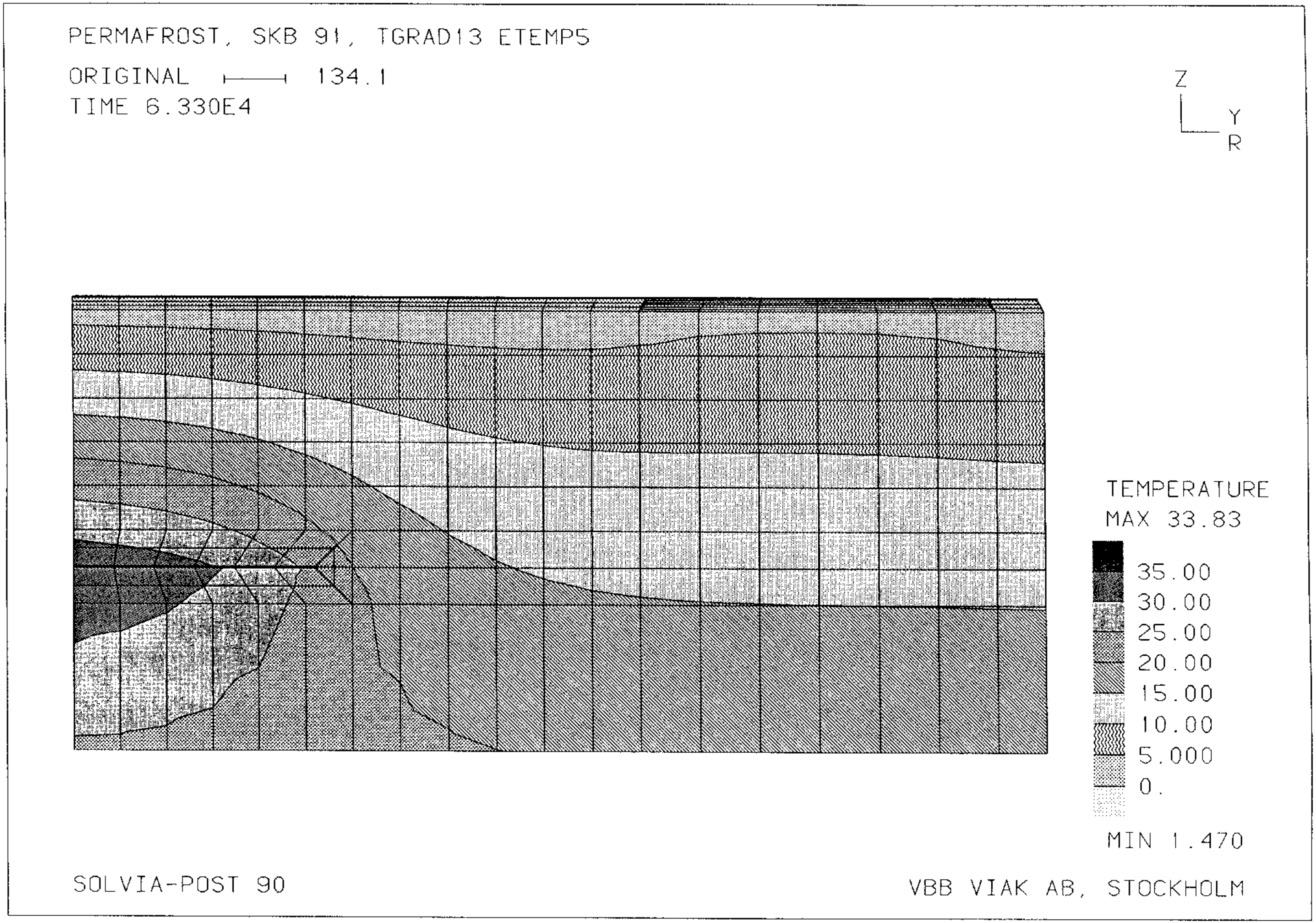
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Y
R
TEMPERATURE
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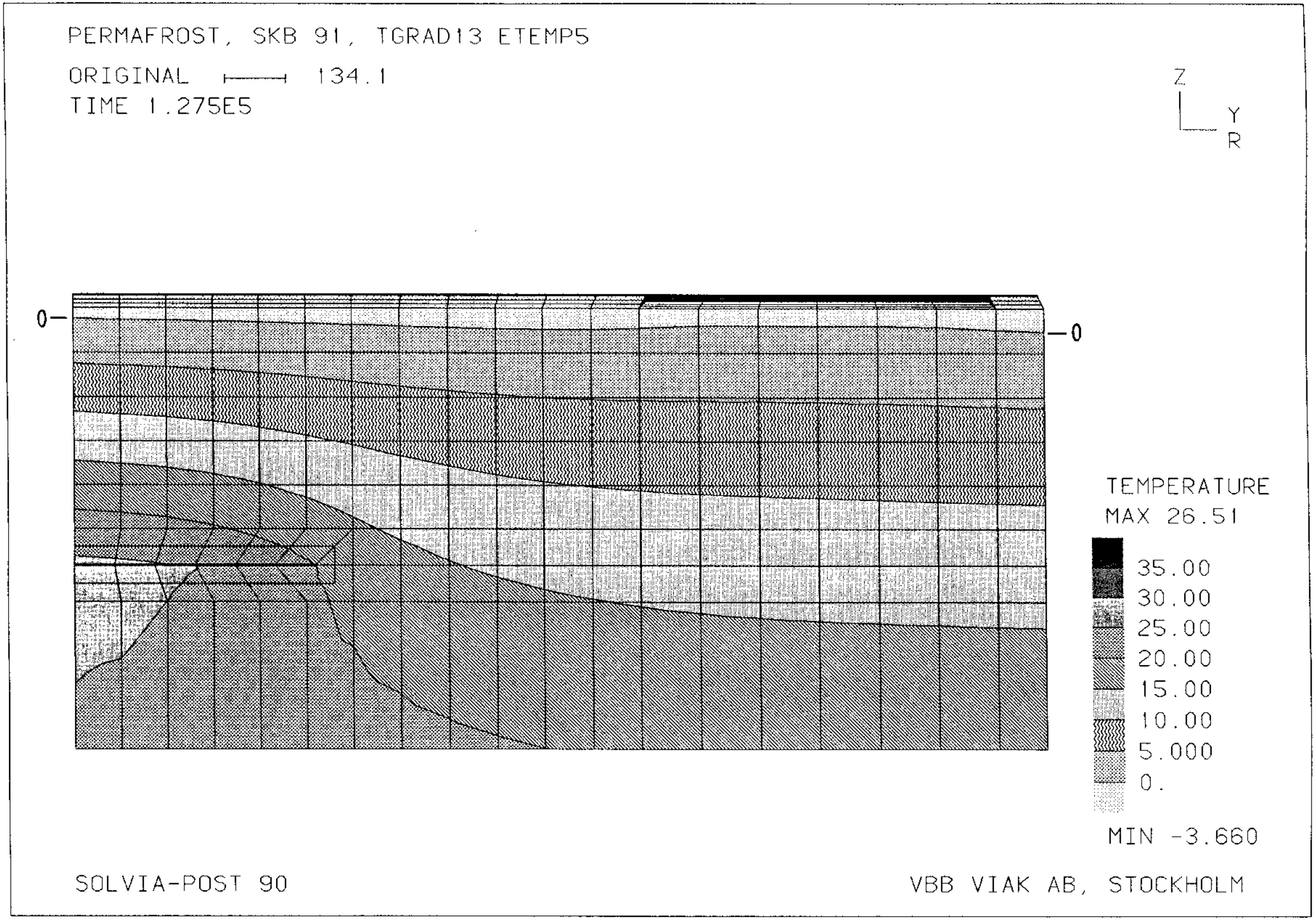
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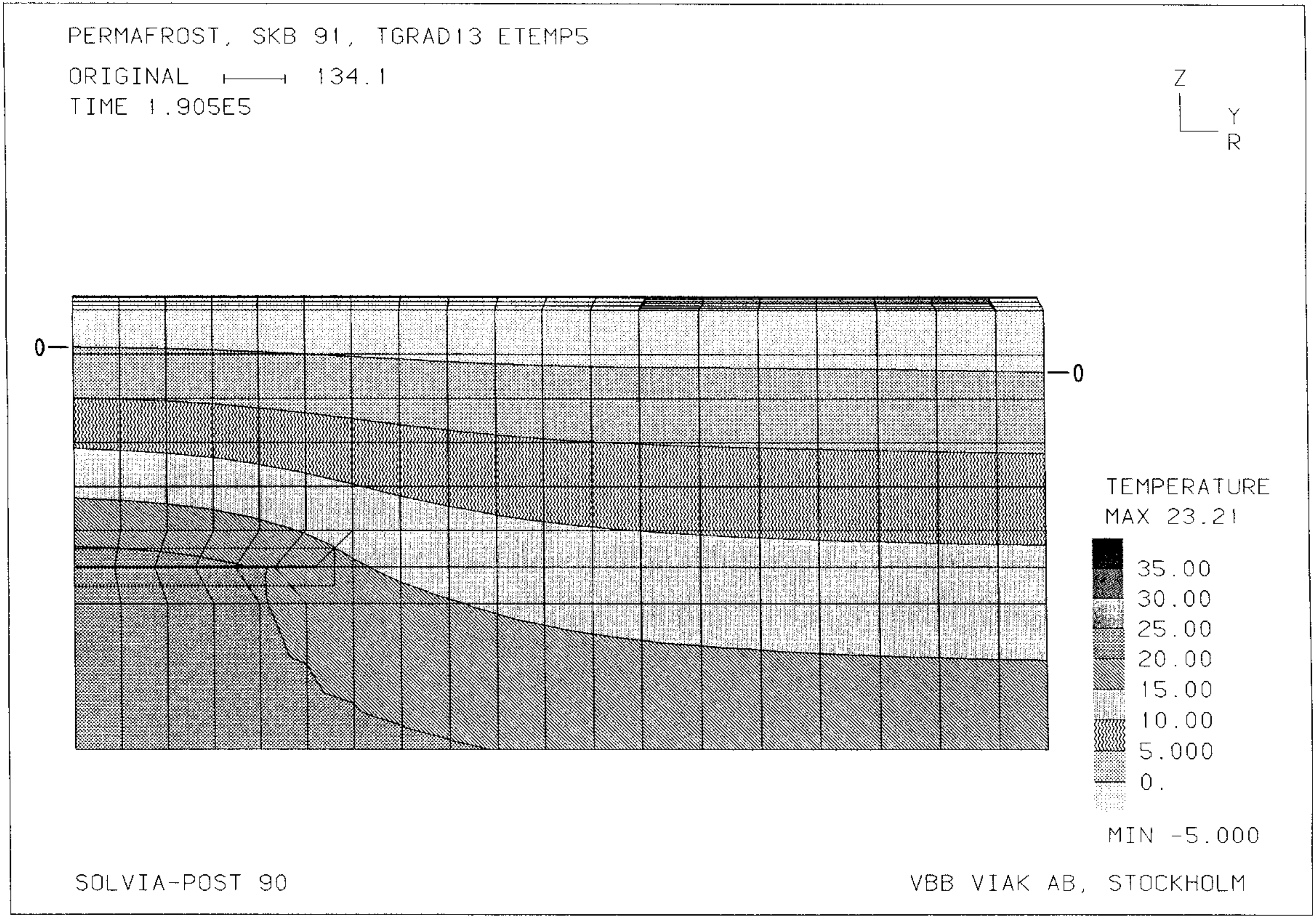
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R
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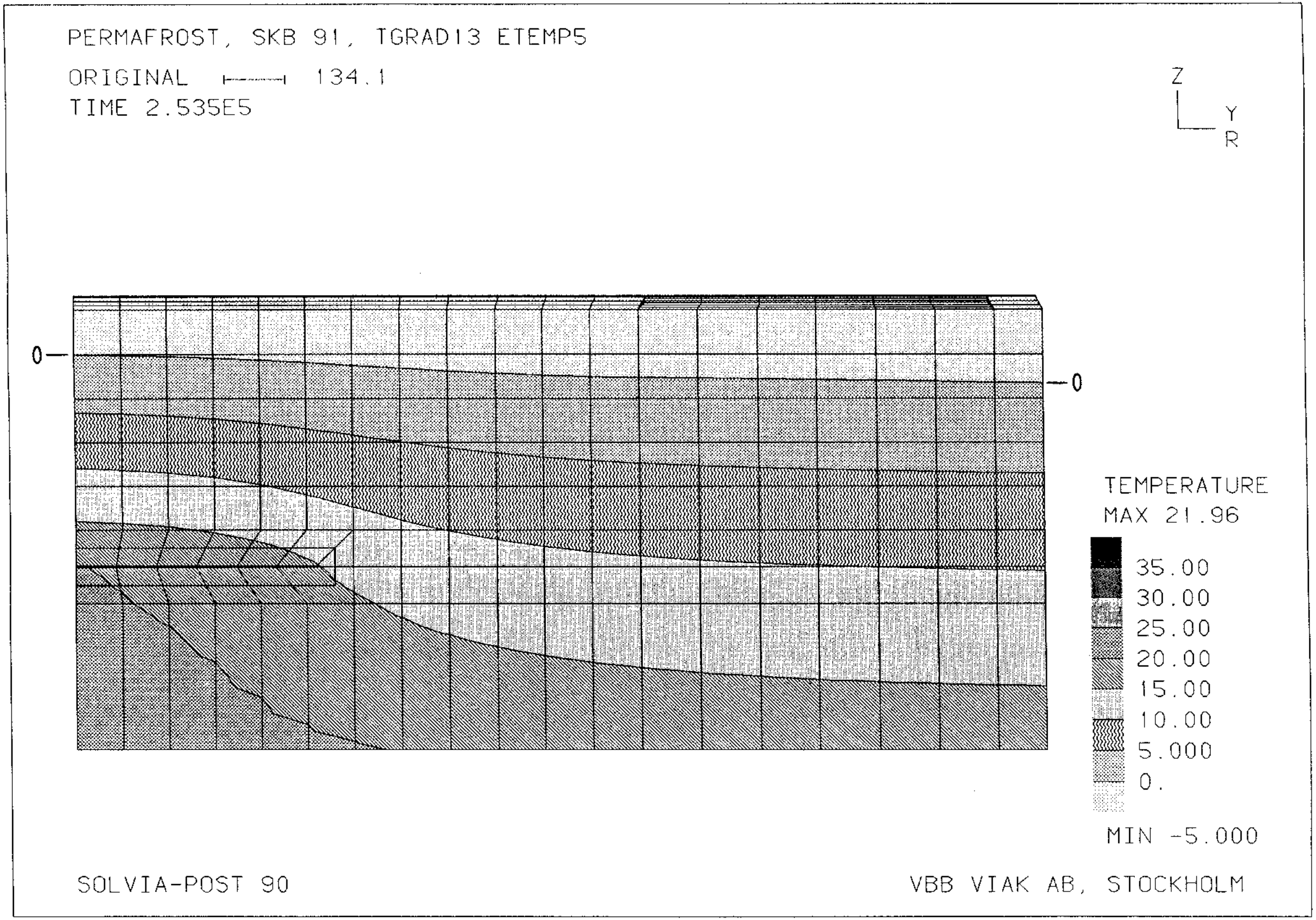
VBB VIAK AB, STOCKHOLM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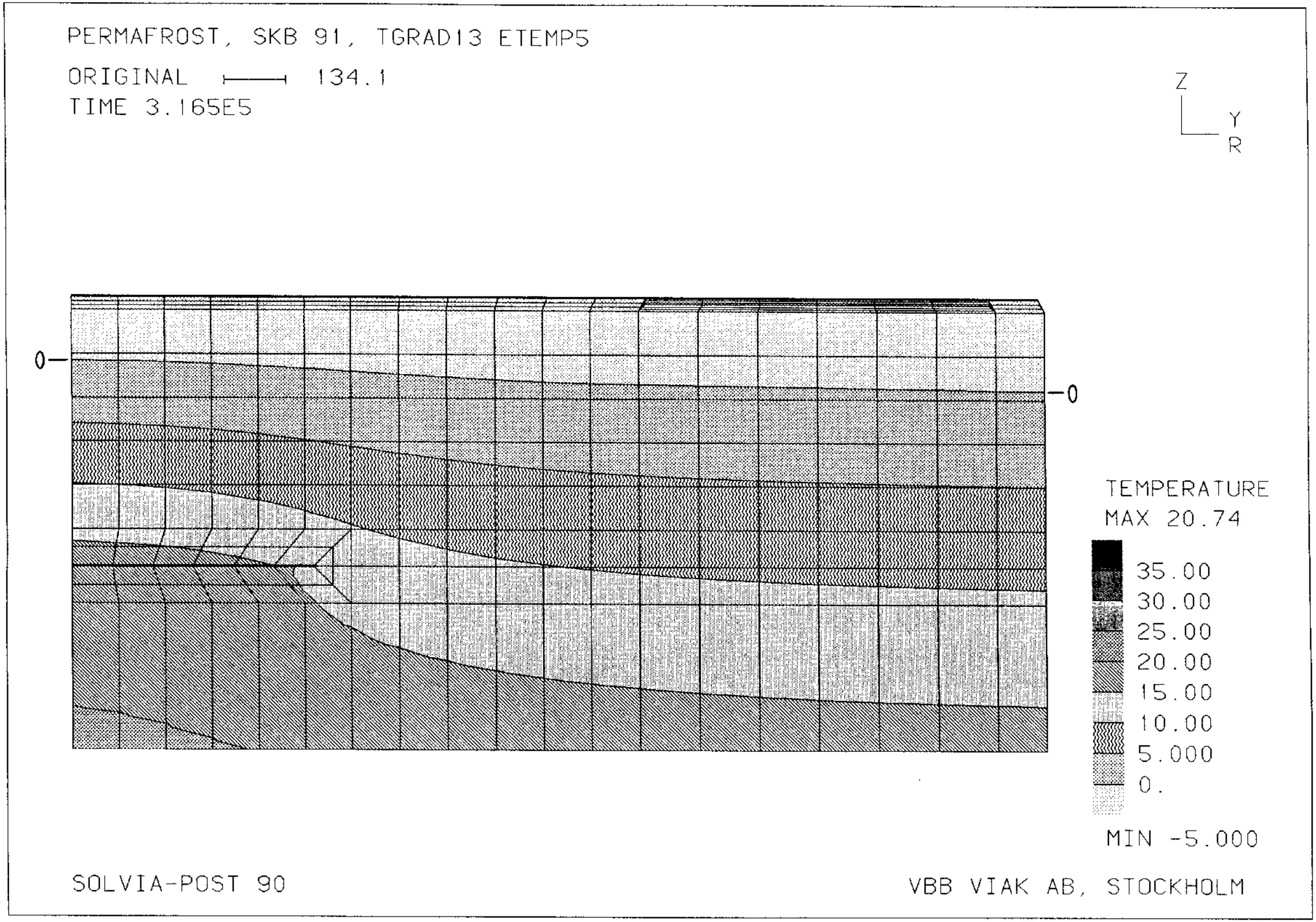
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SOLVIA-POST 90
VBB VIAK AB, STOCKHOLM

APPENDIX 3

TEMPERATURE DISTRIBUTIONS FOR CASE C

The case is described in Section 4.5.

Times given on the following isotherm plots are expressed in megaseconds, Ms. In the following list, these times are translated into years.

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4	6.330E4	2 007
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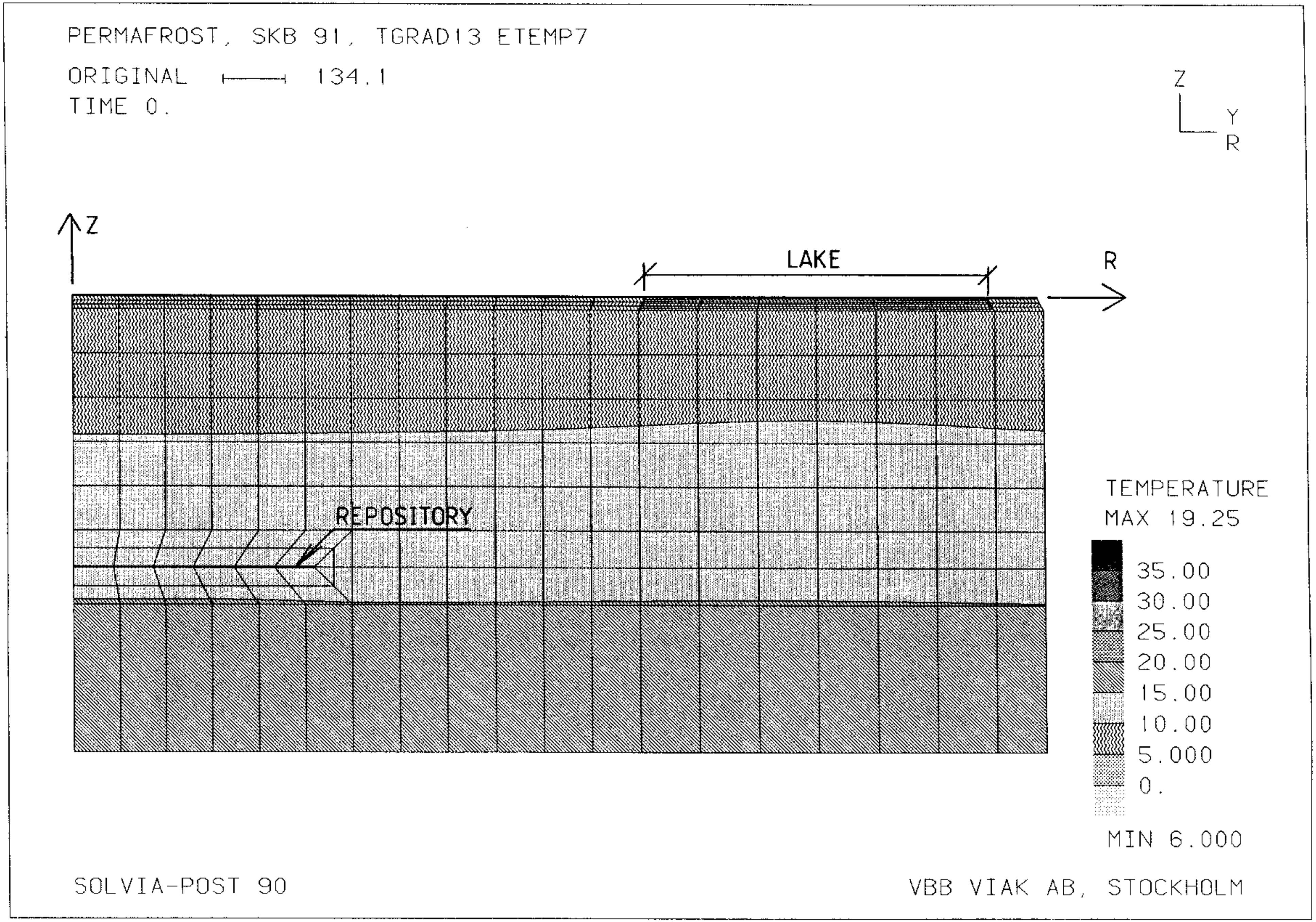
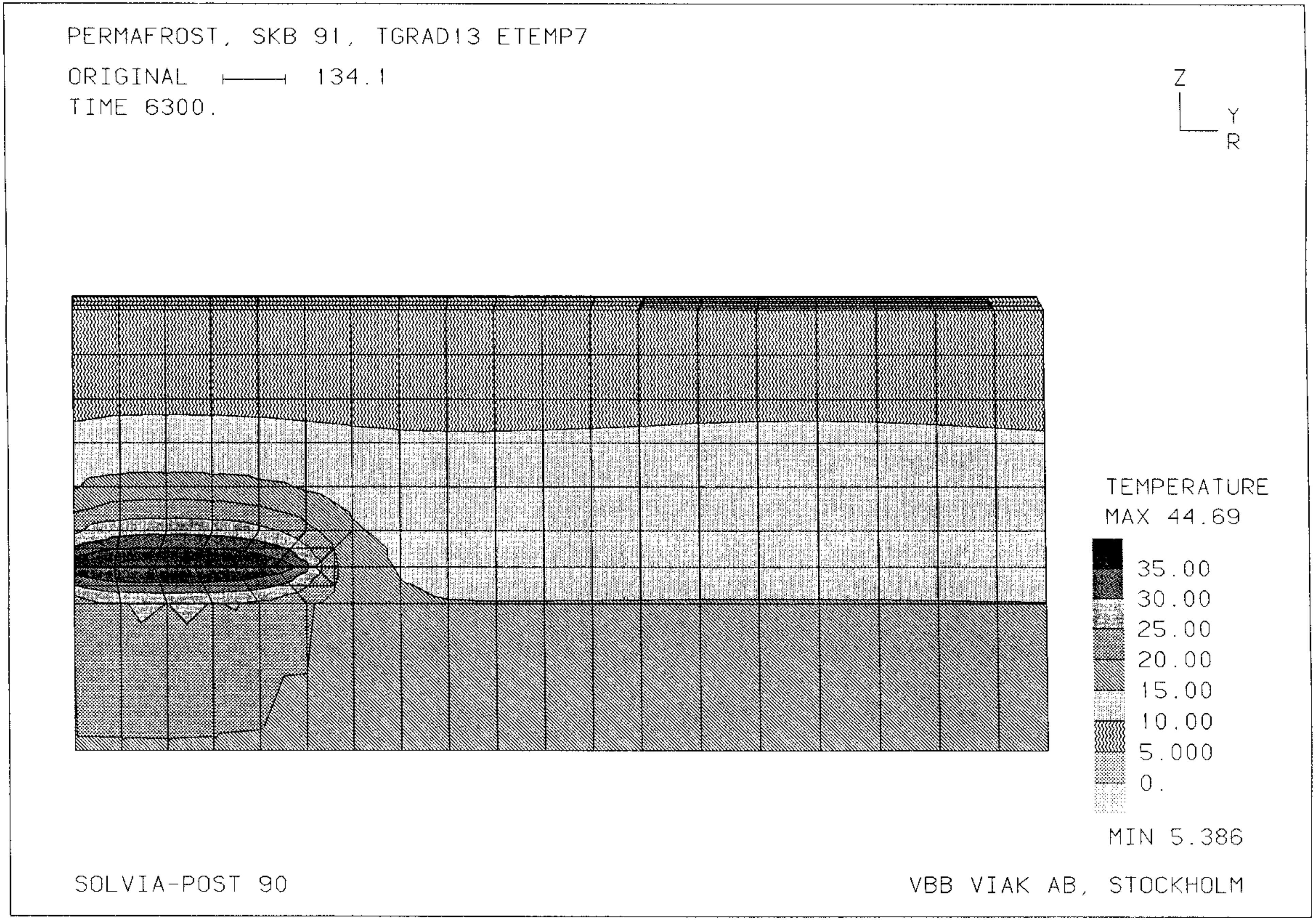


APPENDIX 3, P. 1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R
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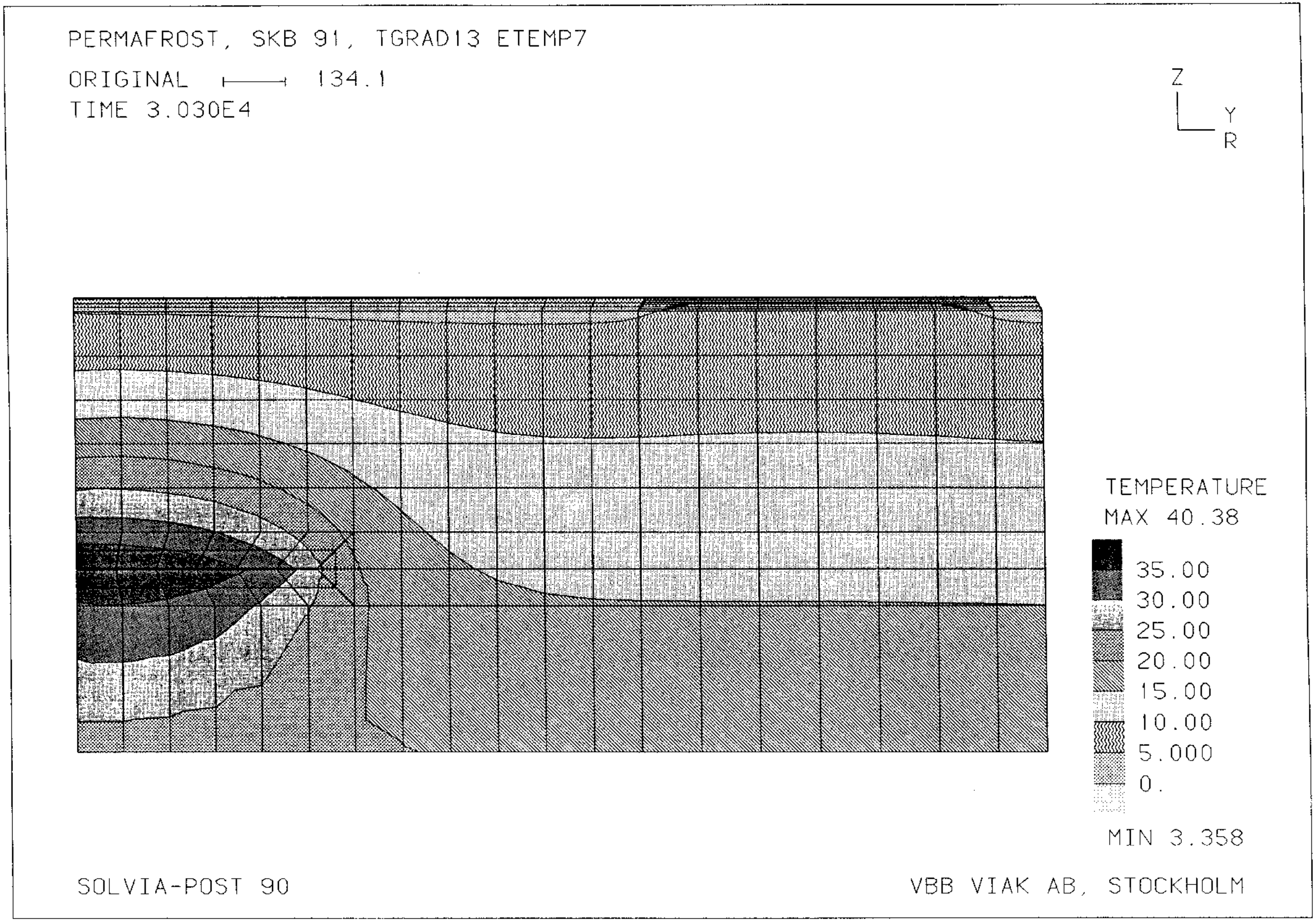
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20.00
15.00
10.00
5.000
0.
MIN 3.358
SOLVIA-POST 90
VBB VIAK AB, STOCKHOLM

PERMAFROST, SKB 91, TGRAD13 ETEMP7

ORIGINAL ⊢—⊣ 134.1

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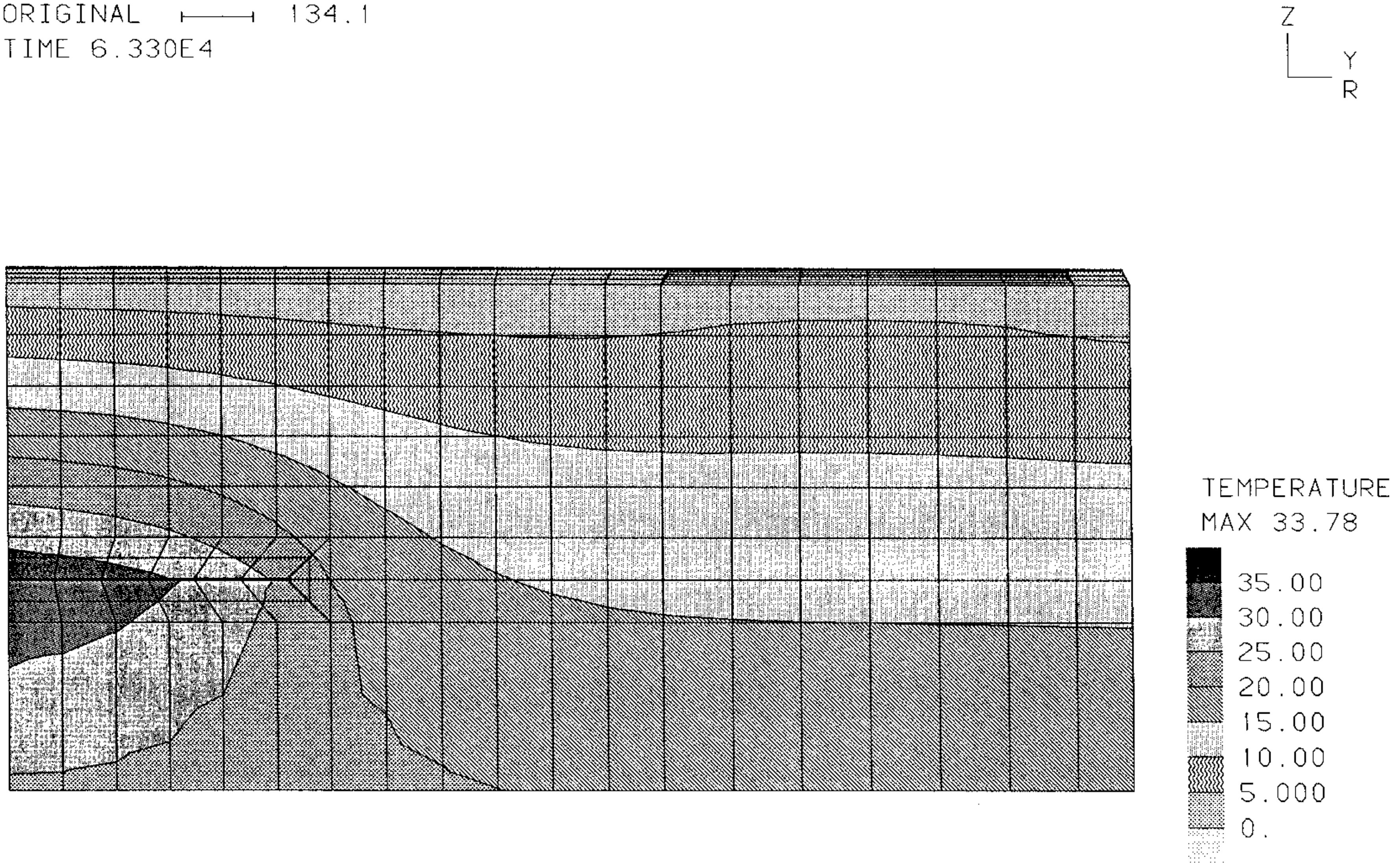

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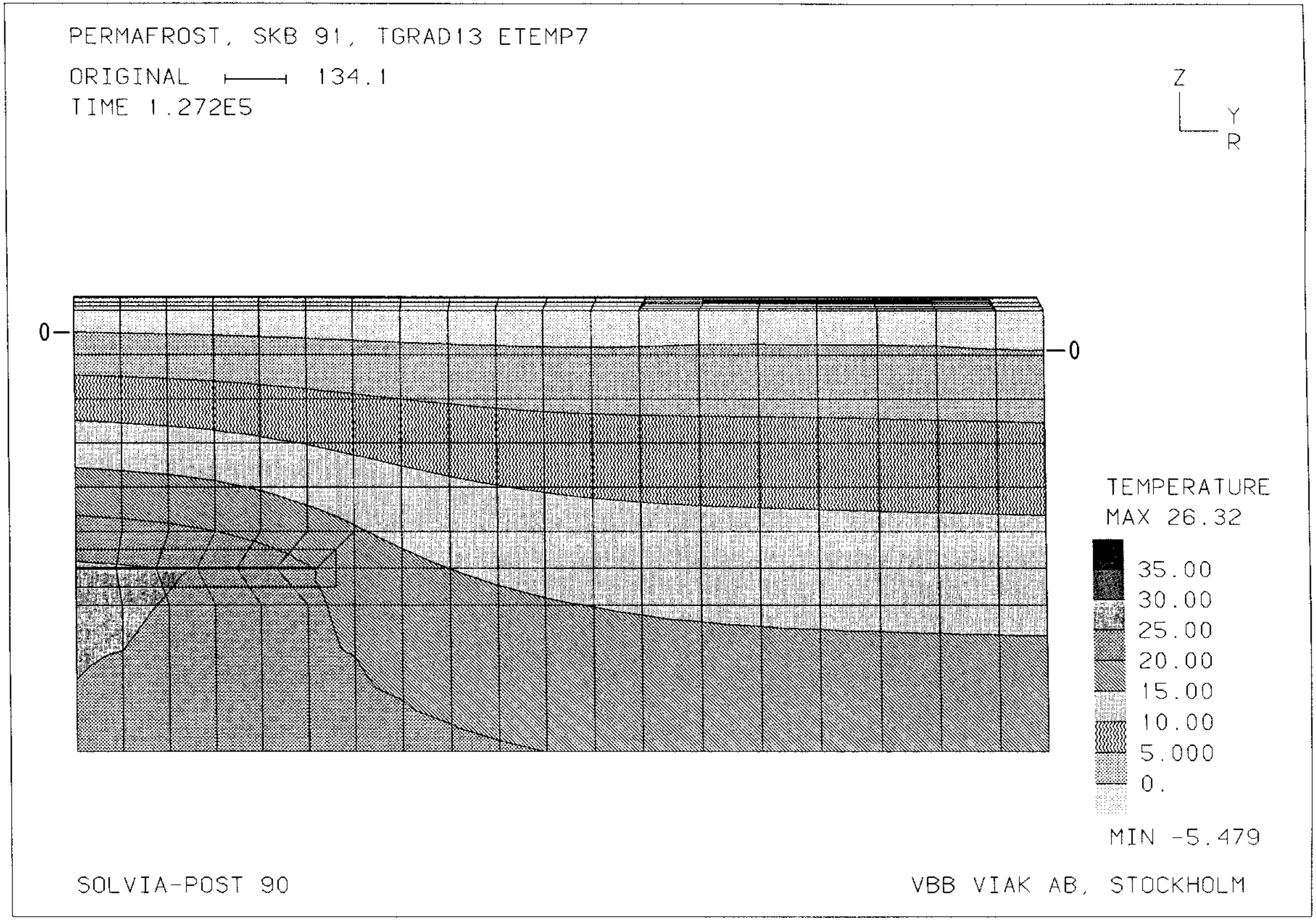
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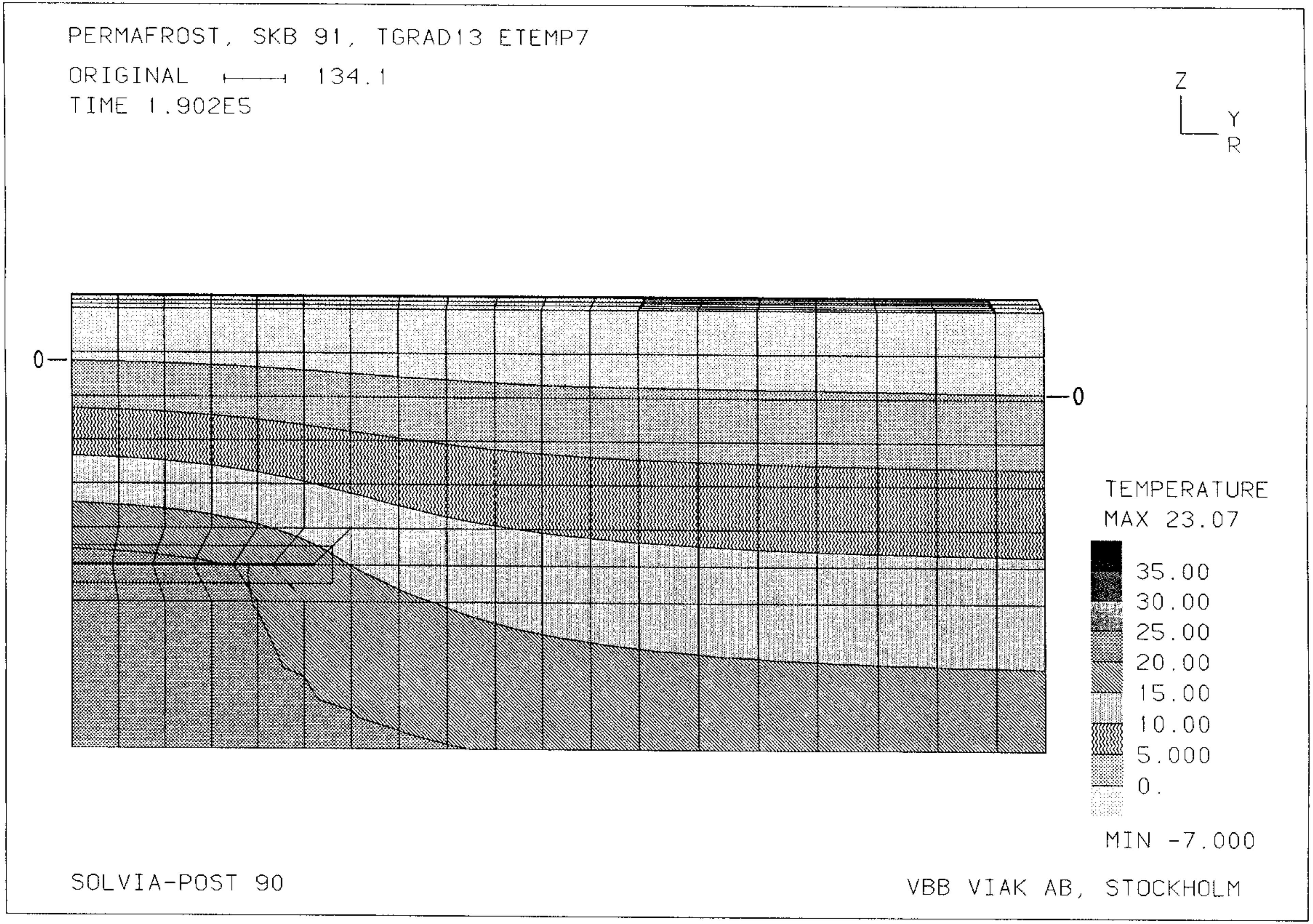
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R
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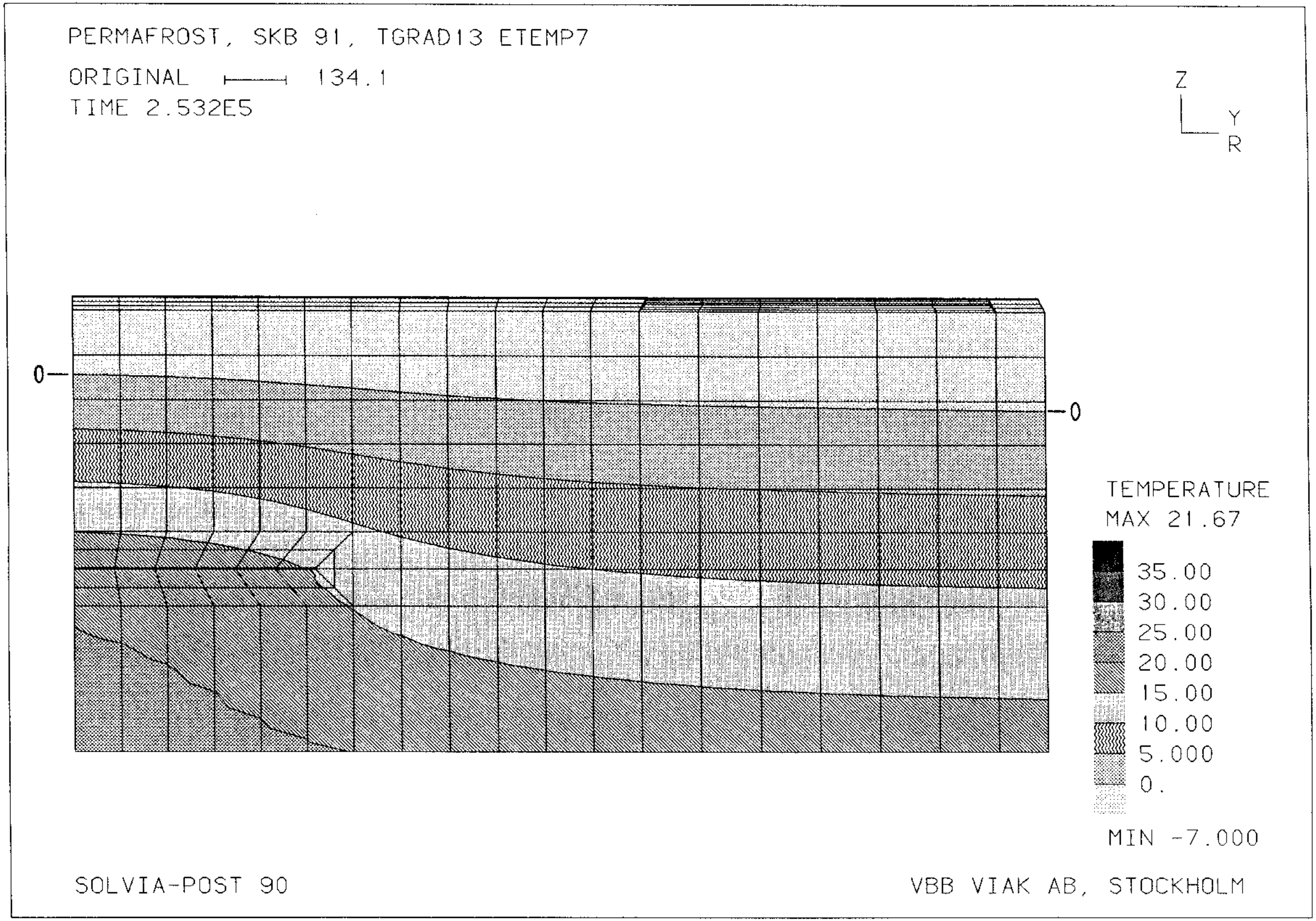
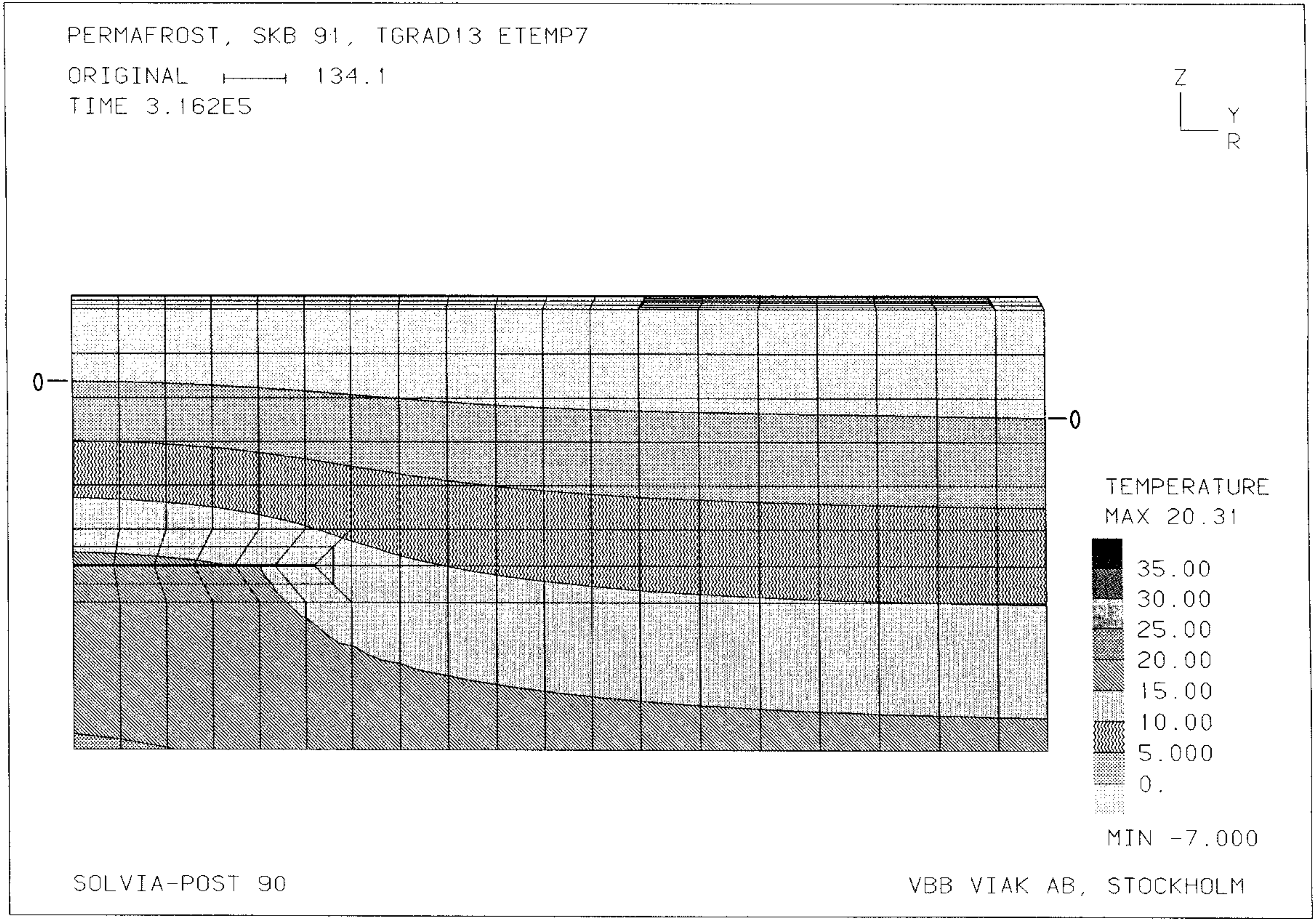


APPENDIX 3, P. 7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TIME 3.162E5
Z
Y
R
0
0
TEMPERATURE
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30.00
25.00
20.00
15.00
10.00
5.000
0.
MIN -7.000
SOLVIA-POST 90
VBB VIAK AB, STOCKHOLM

APPENDIX 4

TEMPERATURE DISTRIBUTIONS FOR CASE D

The case is described in Section 4.5.

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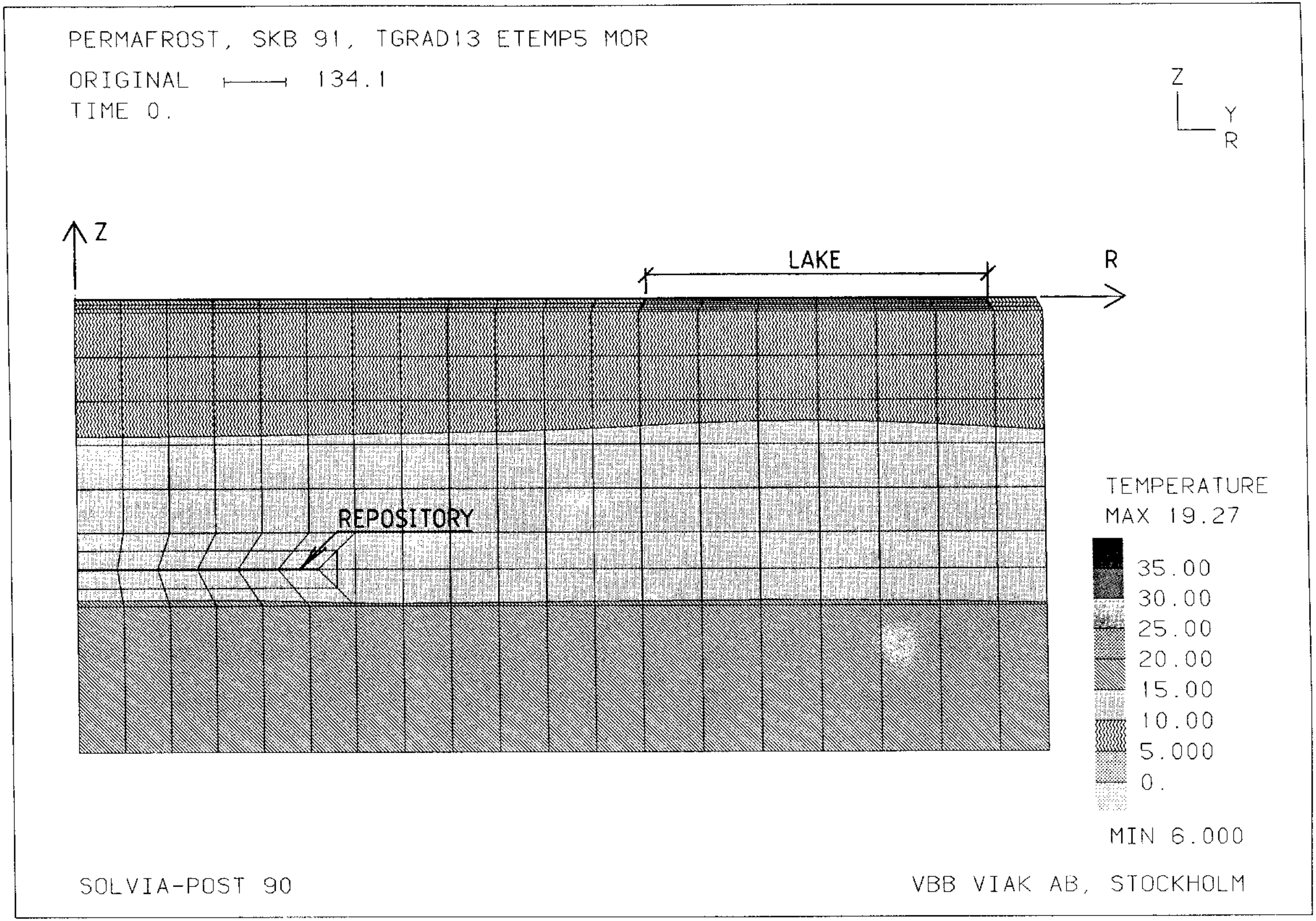
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Z
Y
R
Z
LAKE
R
REPOSITORY
TEMPERATURE
MAX 19.27
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5.000
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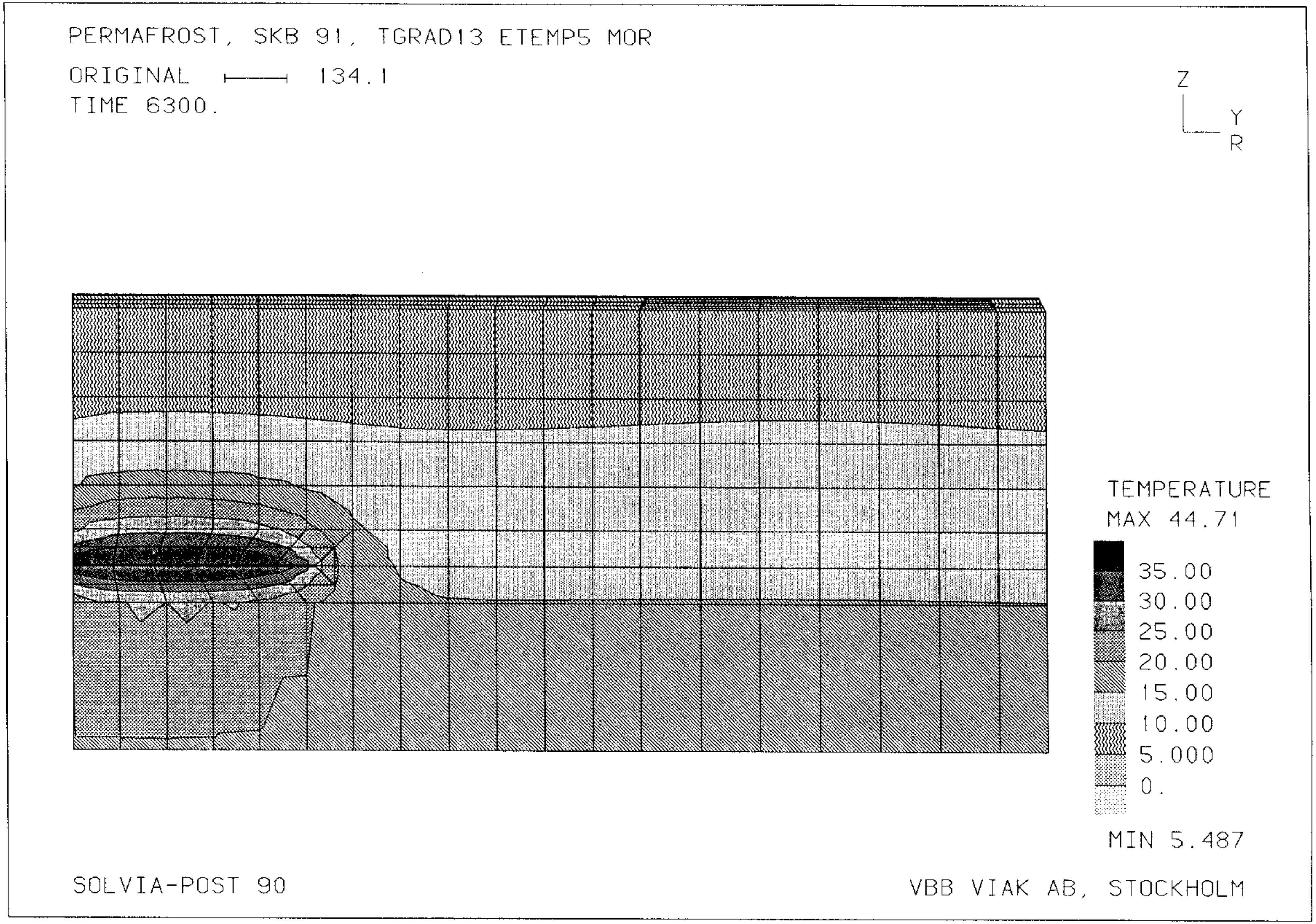
MIN 6.000
SOLVIA-POST 90
VBB VIAK AB, STOCKHOLM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Y
R
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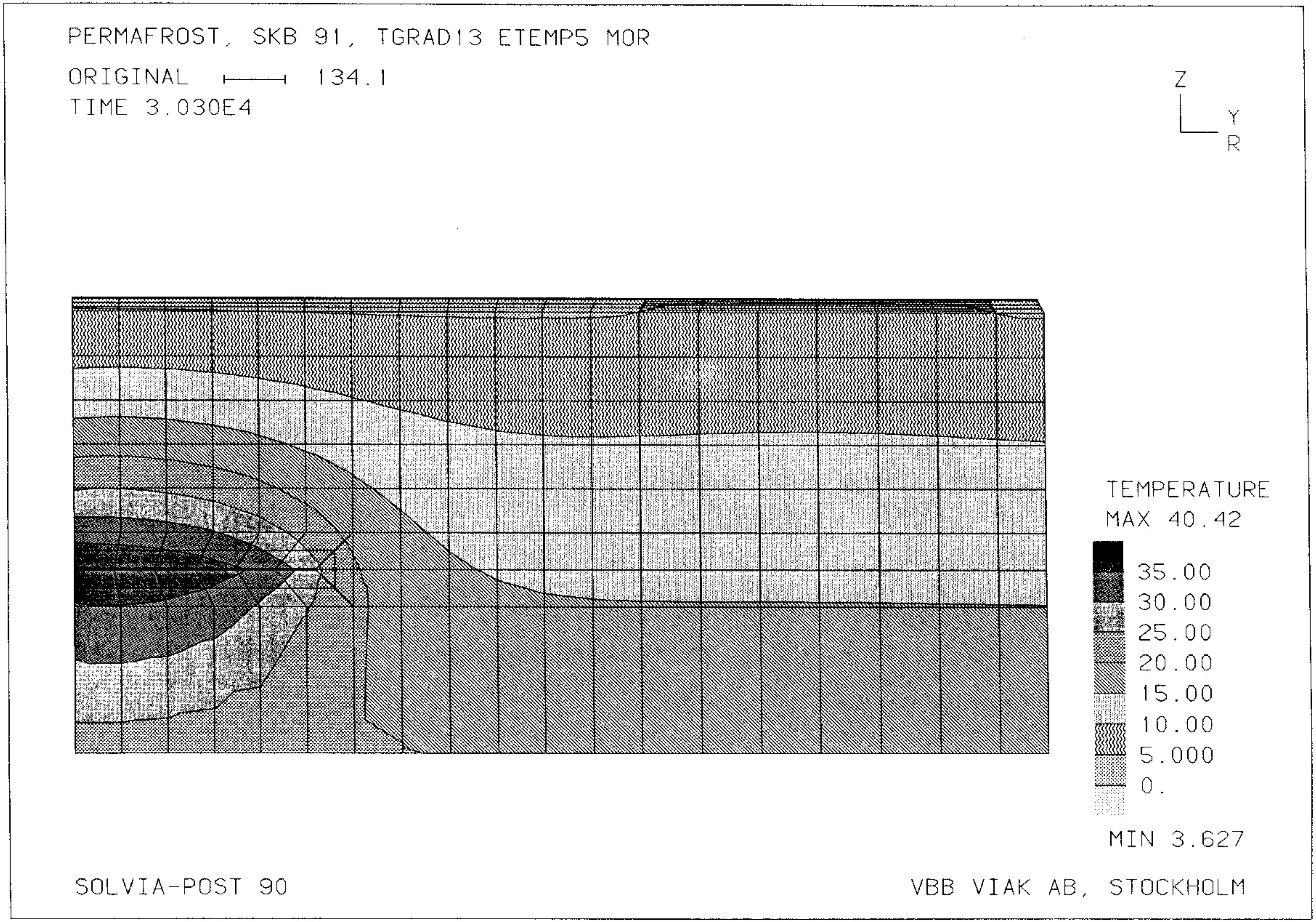
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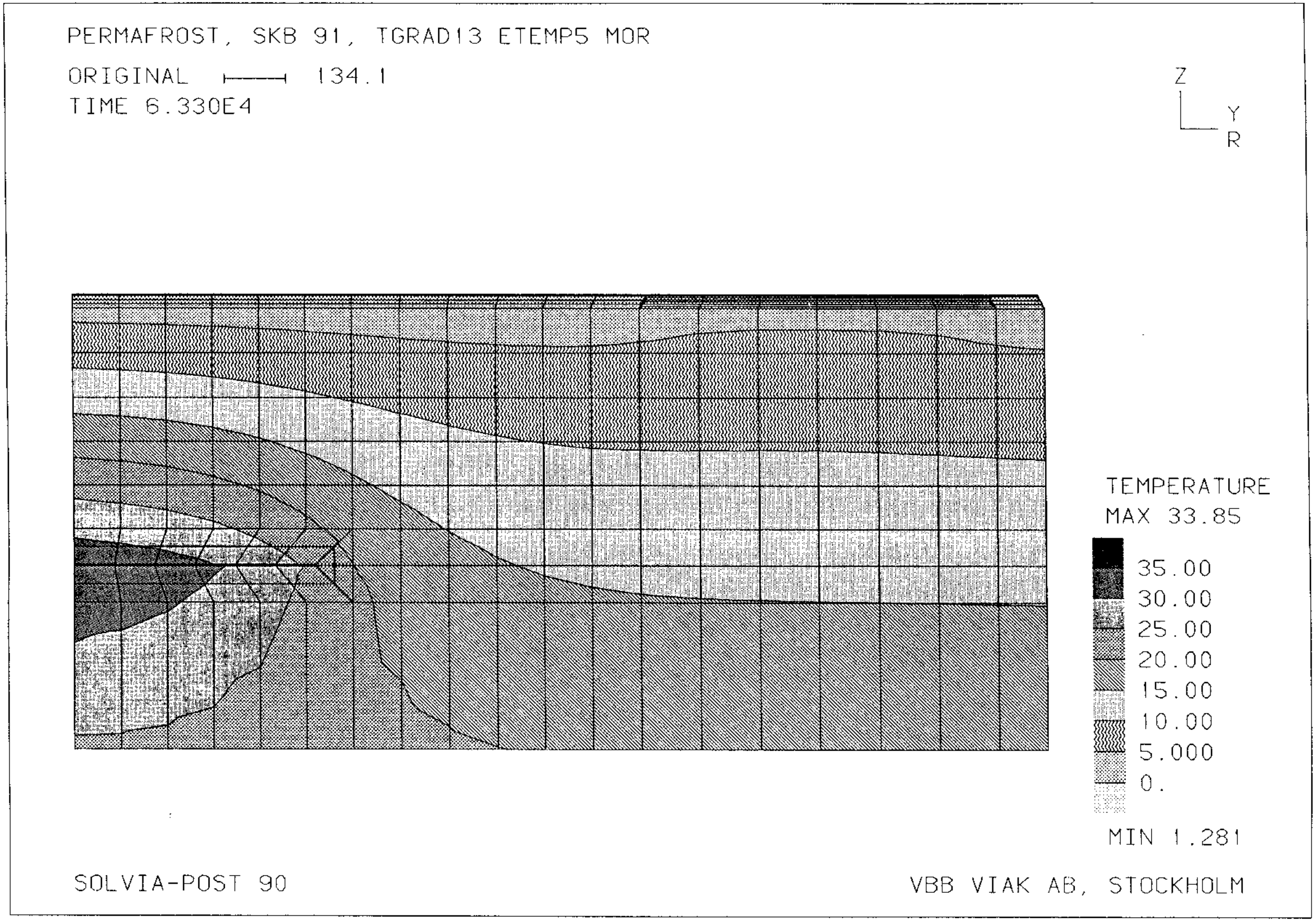
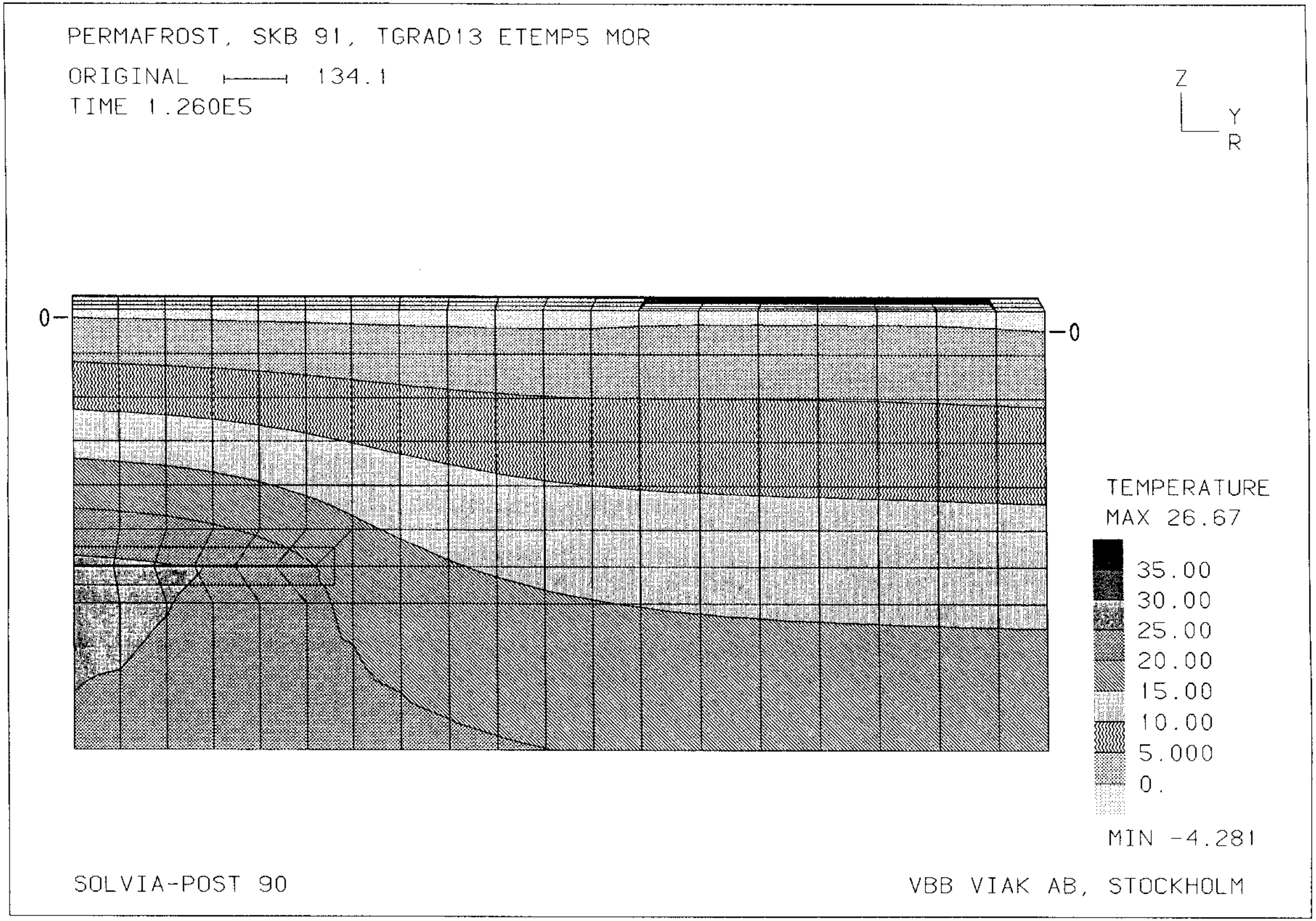


APPENDIX 4, P. 4



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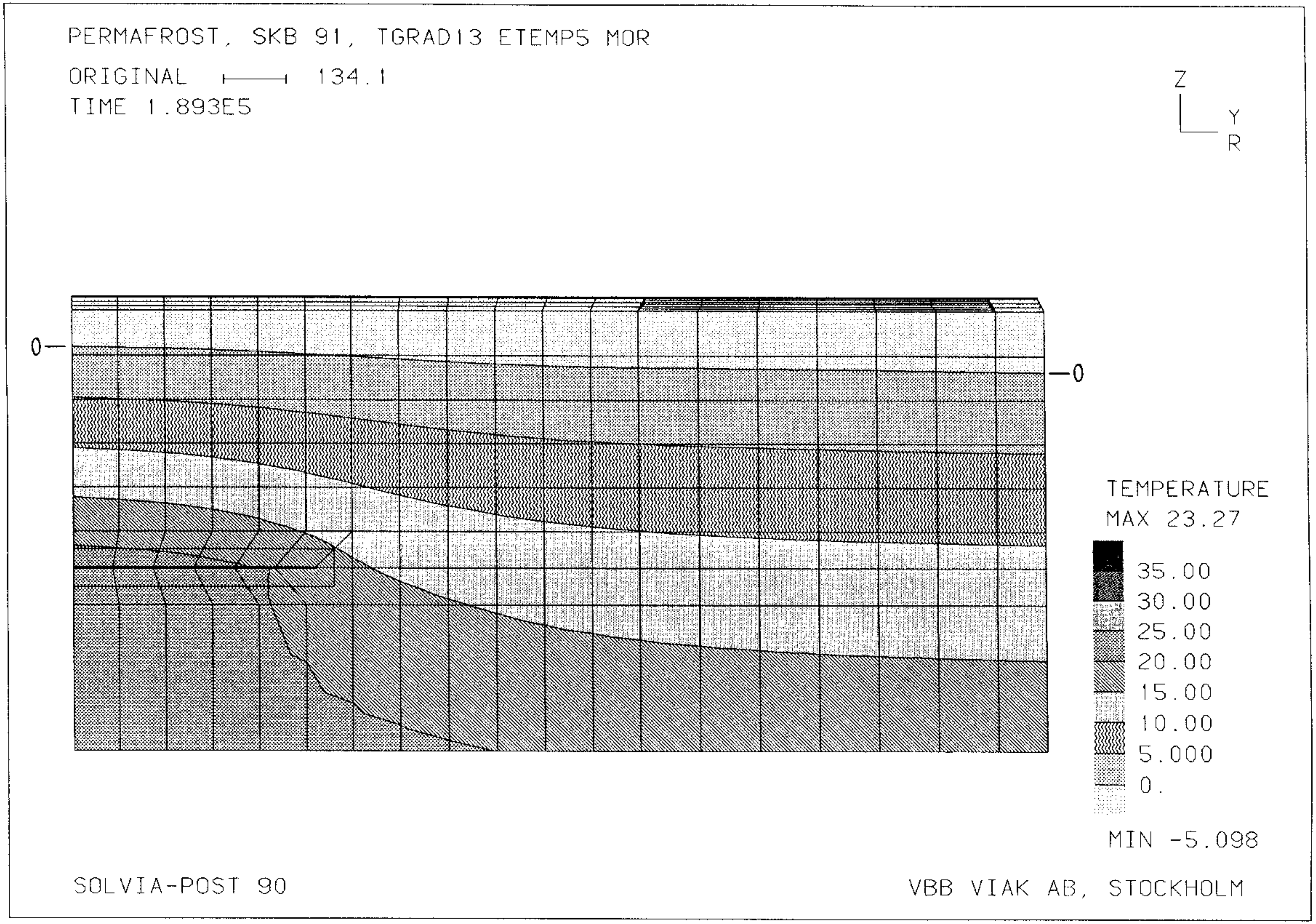
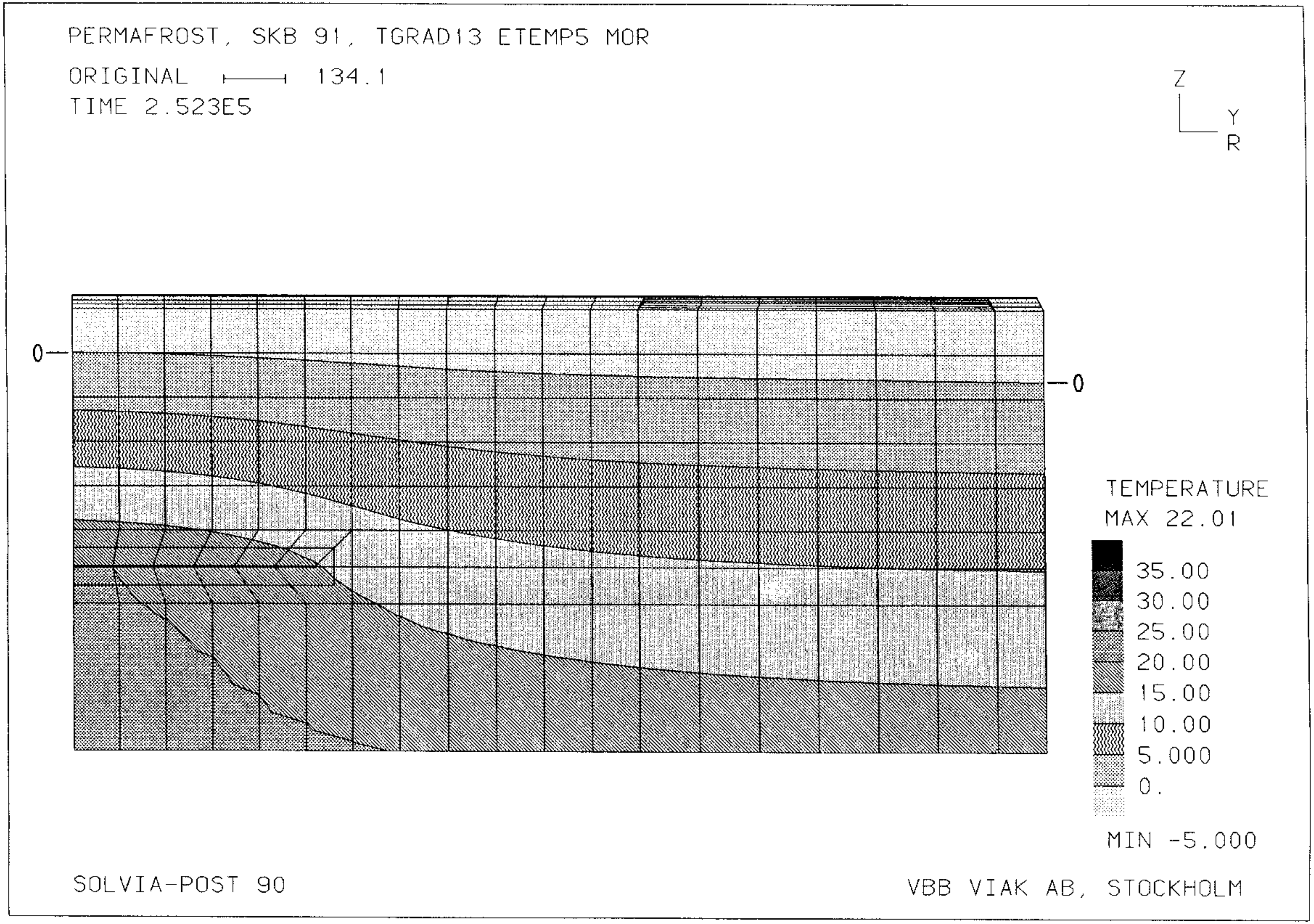

PERMAFROST, SKB 91, TGRAD13 ETEMP5 MOR
ORIGINAL 134.1
TIME 1.893E5
Z
Y
R
0
0
TEMPERATURE
MAX 23.27
35.00
30.00
25.00
20.00
15.00
10.00
5.000
0.
MIN -5.098
SOLVIA-POST 90
VBB VIAK AB, STOCKHOLM



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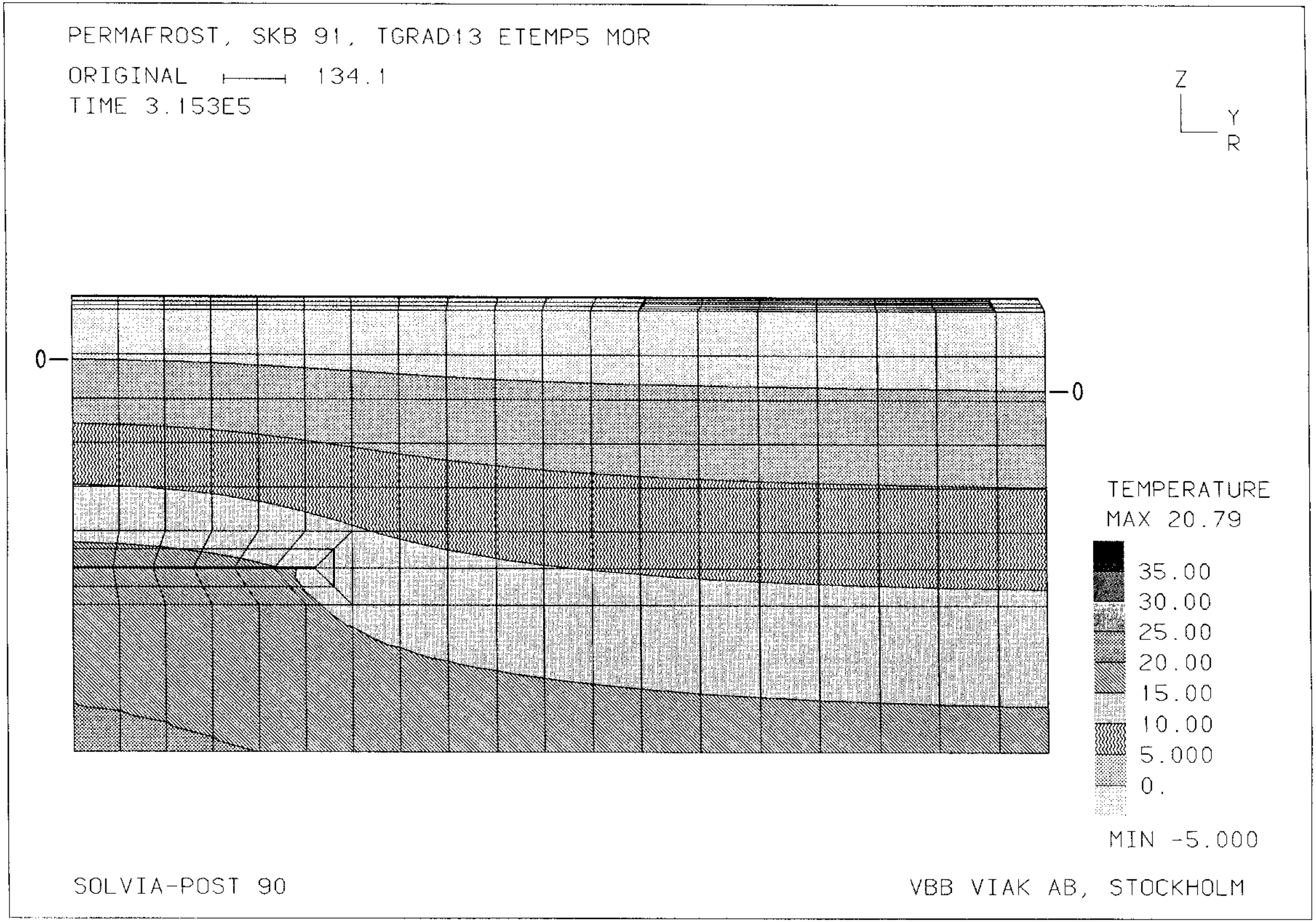

PERMAFROST, SKB 91, TGRAD13 ETEMP5 MOR
ORIGINAL 134.1
TIME 3.153E5
Z
Y
R
0
0
TEMPERATURE
MAX 20.79
35.00
30.00
25.00
20.00
15.00
10.00
5.000
0.
MIN -5.000
SOLVIA-POST 90
VBB VIAK AB, STOCKHOLM

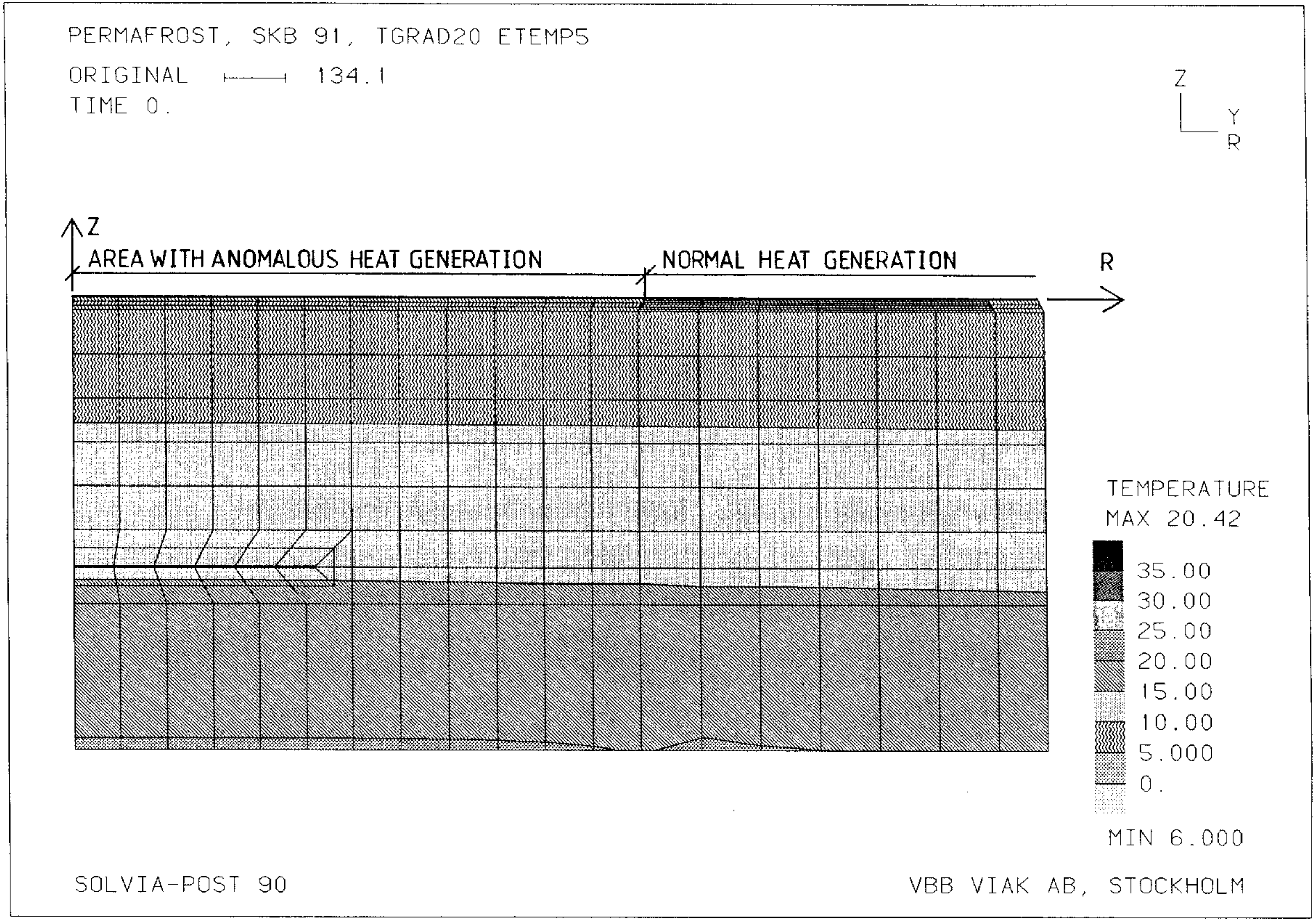
APPENDIX 5

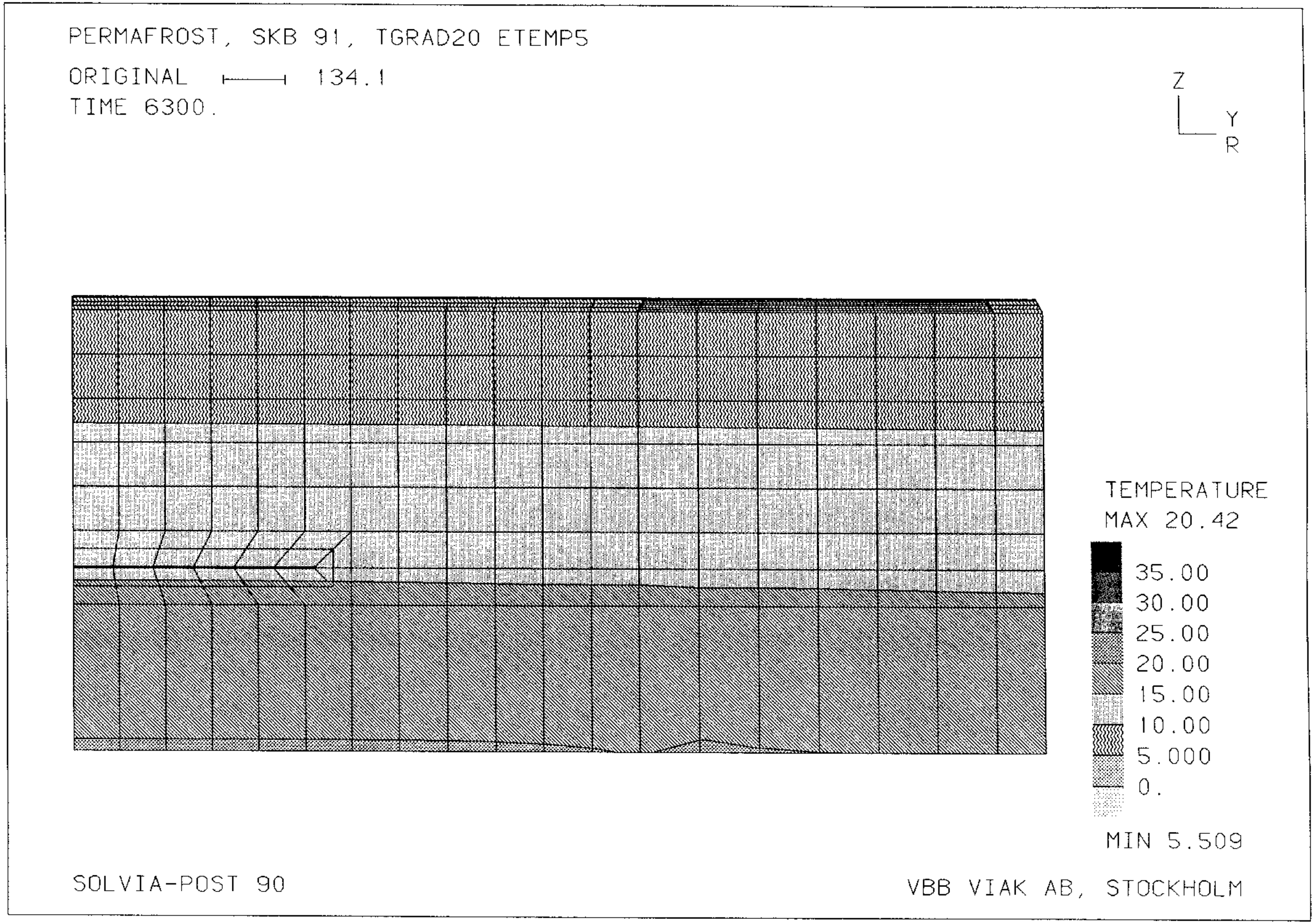
TEMPERATURE DISTRIBUTIONS FOR CASE E

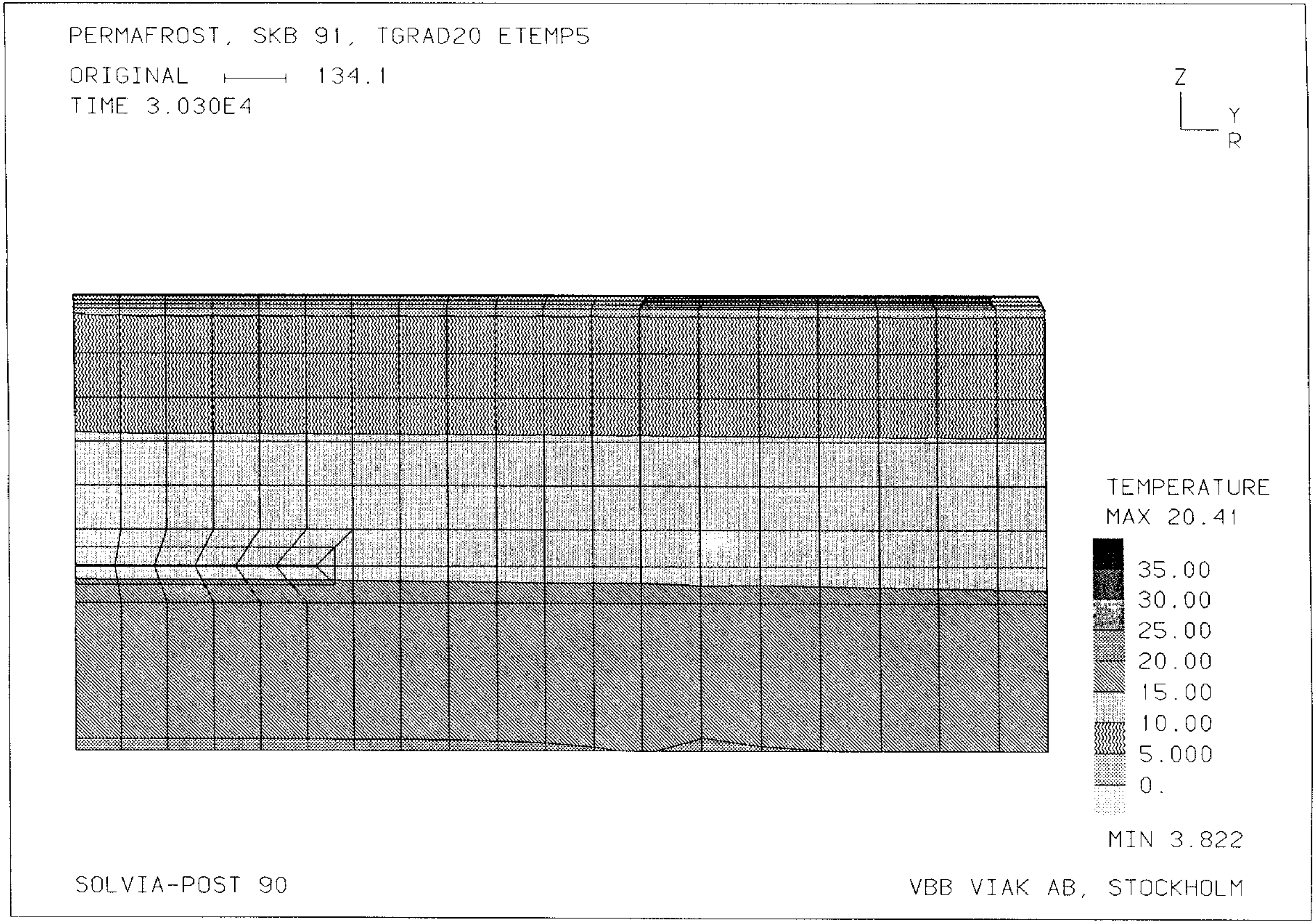
The case is described in Section 4.5.

Times given on the following isotherm plots are expressed in megaseconds, Ms. In the following list, these times are translated into years.

Page #	Time (Ms)	Time (yrs)
1	0	0
2	6300	200
3	3.030E4	961
4	6.330E4	2 007
5	1.263E5	4 005
6	1.899E5	6 022
7	2.529E5	8 019
8	3.159E5	10 017


PERMAFROST, SKB 91, TGRAD20 ETEMP5
ORIGINAL 134.1
TIME 0.
Z
Y
R
Z
AREA WITH ANOMALOUS HEAT GENERATION
NORMAL HEAT GENERATION
R
TEMPERATURE
MAX 20.42
35.00
30.00
25.00
20.00
15.00
10.00
5.000
0.
MIN 6.000
SOLVIA-POST 90
VBB VIAK AB, STOCKHOLM


PERMAFROST, SKB 91, TGRAD20 ETEMP5
ORIGINAL 134.1
TIME 6300.
Z
Y
R
TEMPERATURE
MAX 20.42
35.00
30.00
25.00
20.00
15.00
10.00
5.000
0.
MIN 5.509
SOLVIA-POST 90
VBB VIAK AB, STOCKHOLM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ORIGINAL 134.1
TIME 3.030E4
Z
Y
R
TEMPERATURE
MAX 20.41
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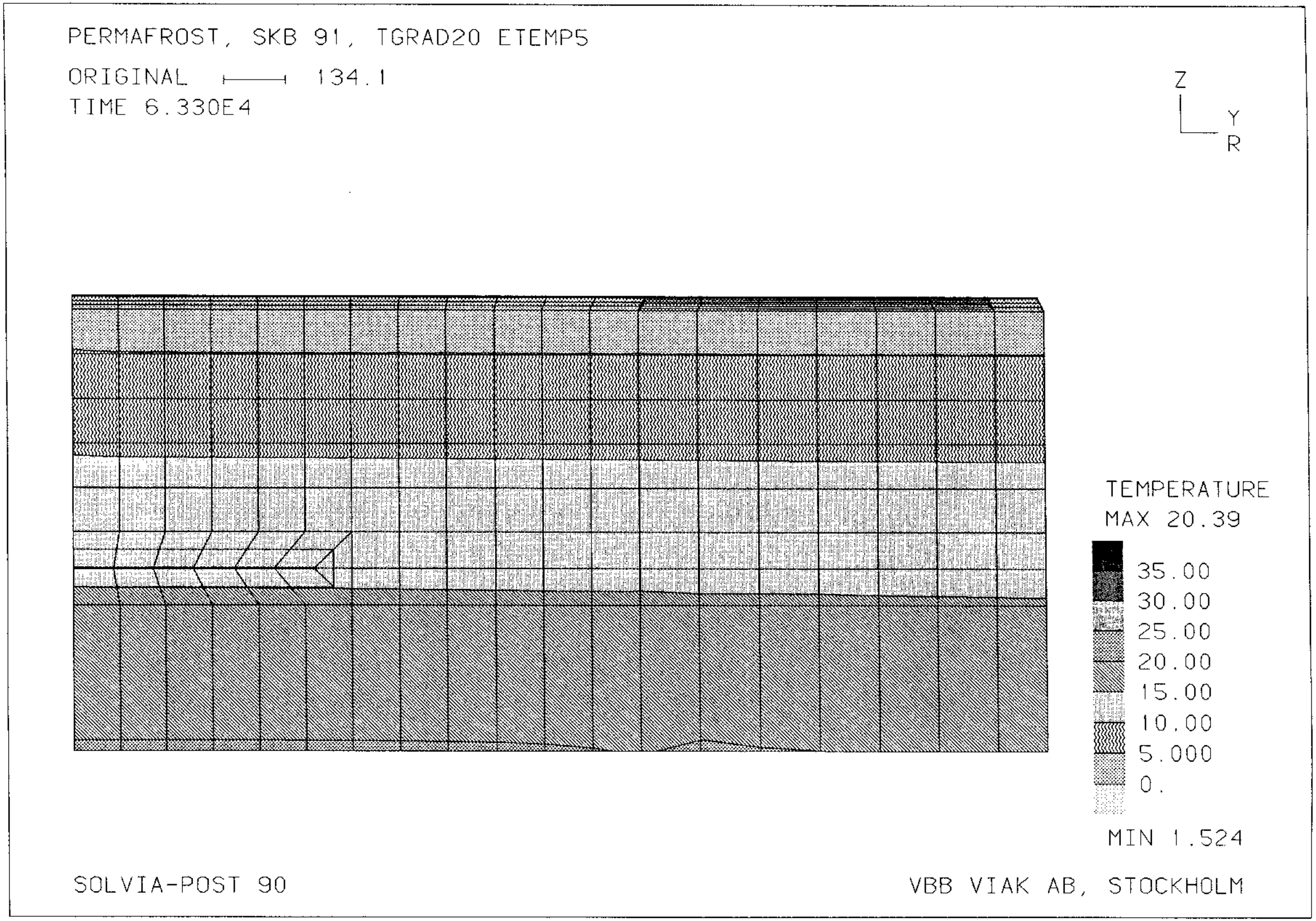
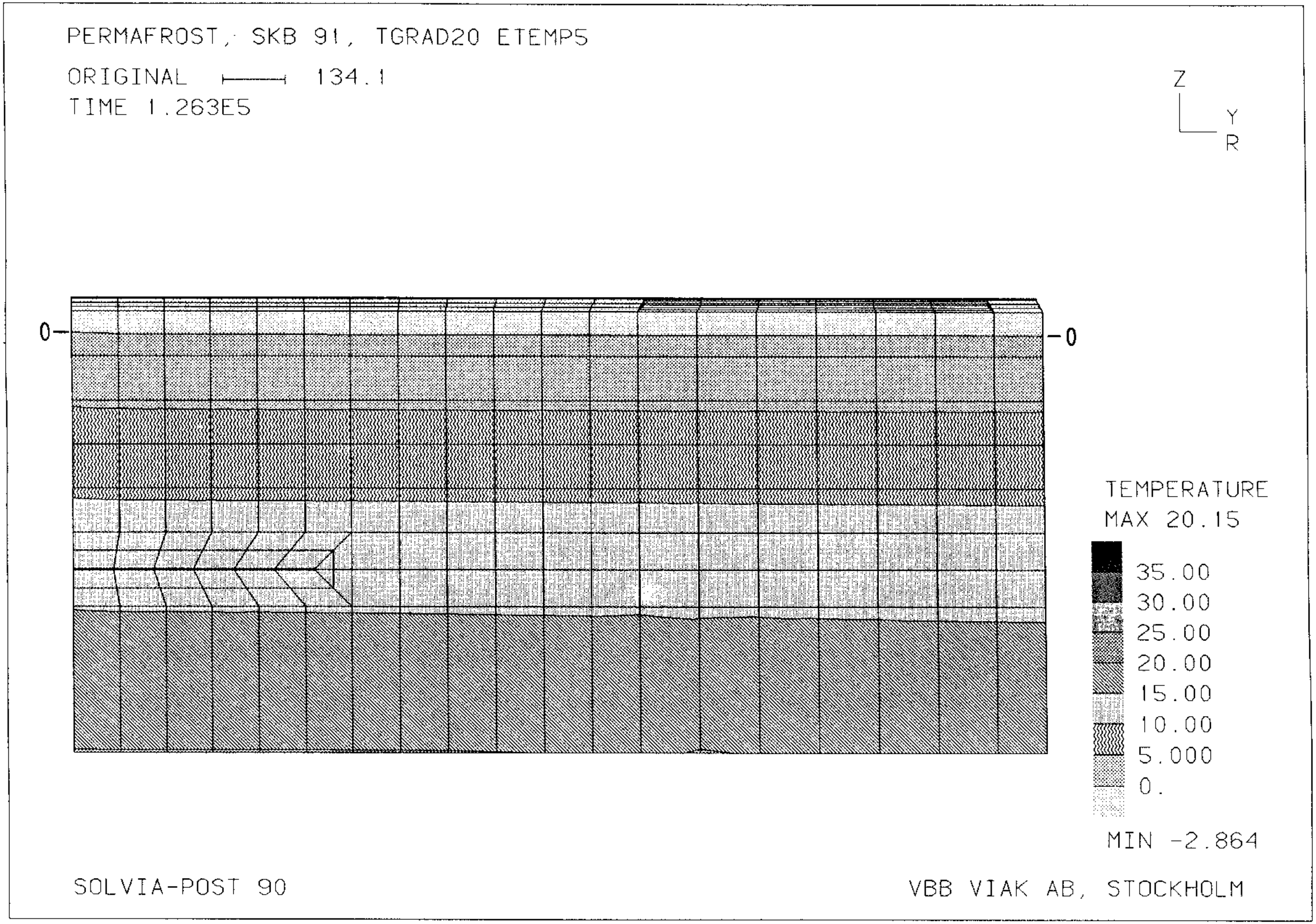
30.00
25.00
20.00
15.00
10.00
5.000
0.
MIN 3.822
SOLVIA-POST 90
VBB VIAK AB, STOCKHOLM


PERMAFROST, SKB 91, TGRAD20 ETEMP5
ORIGINAL 134.1
TIME 6.330E4
Z
Y
R
TEMPERATURE
MAX 20.39
35.00
30.00
25.00
20.00
15.00
10.00
5.000
0.
MIN 1.524
SOLVIA-POST 90
VBB VIAK AB, STOCKHOLM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ORIGINAL 134.1
TIME 1.263E5
Z
Y
R
0
0
TEMPERATURE
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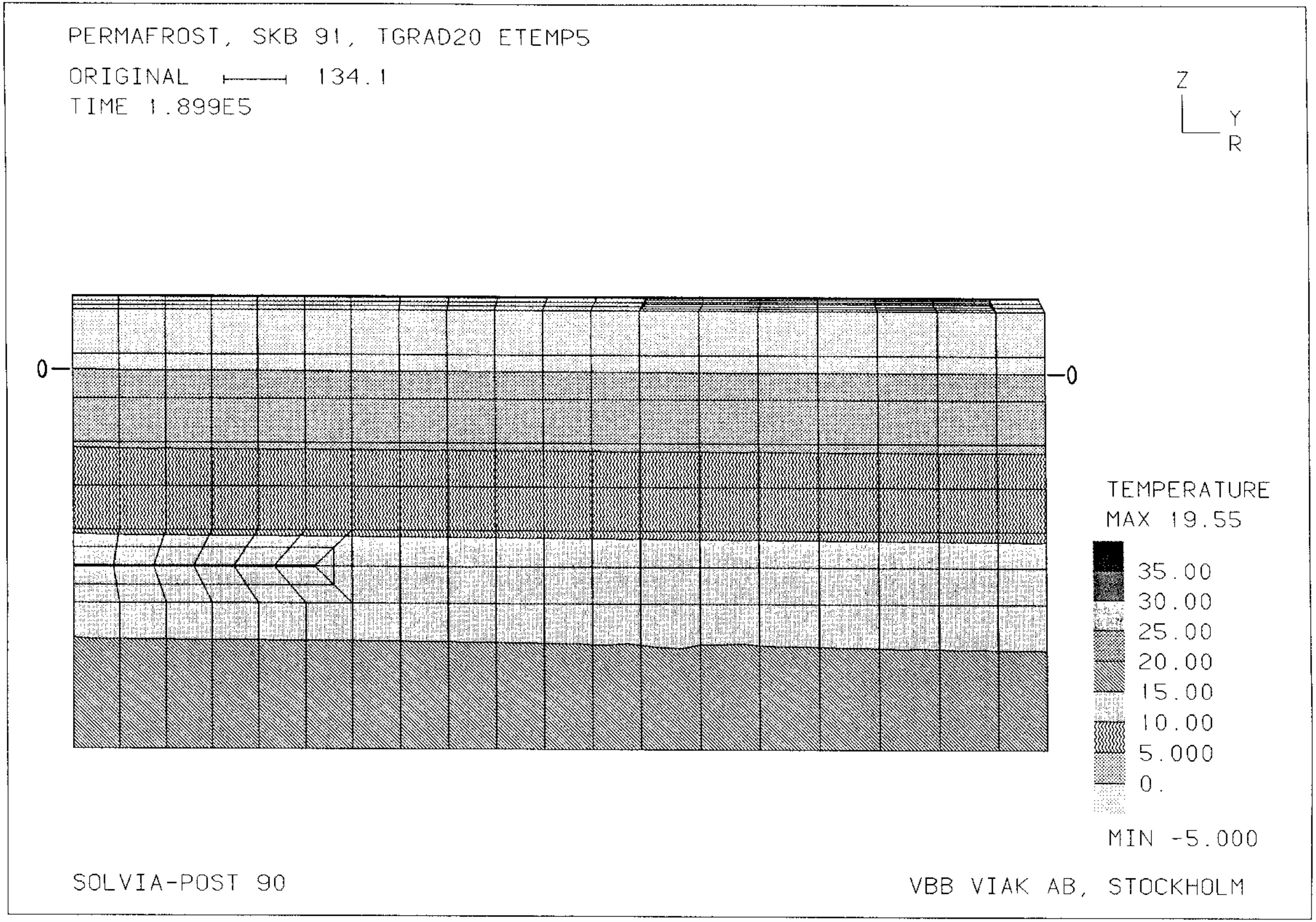
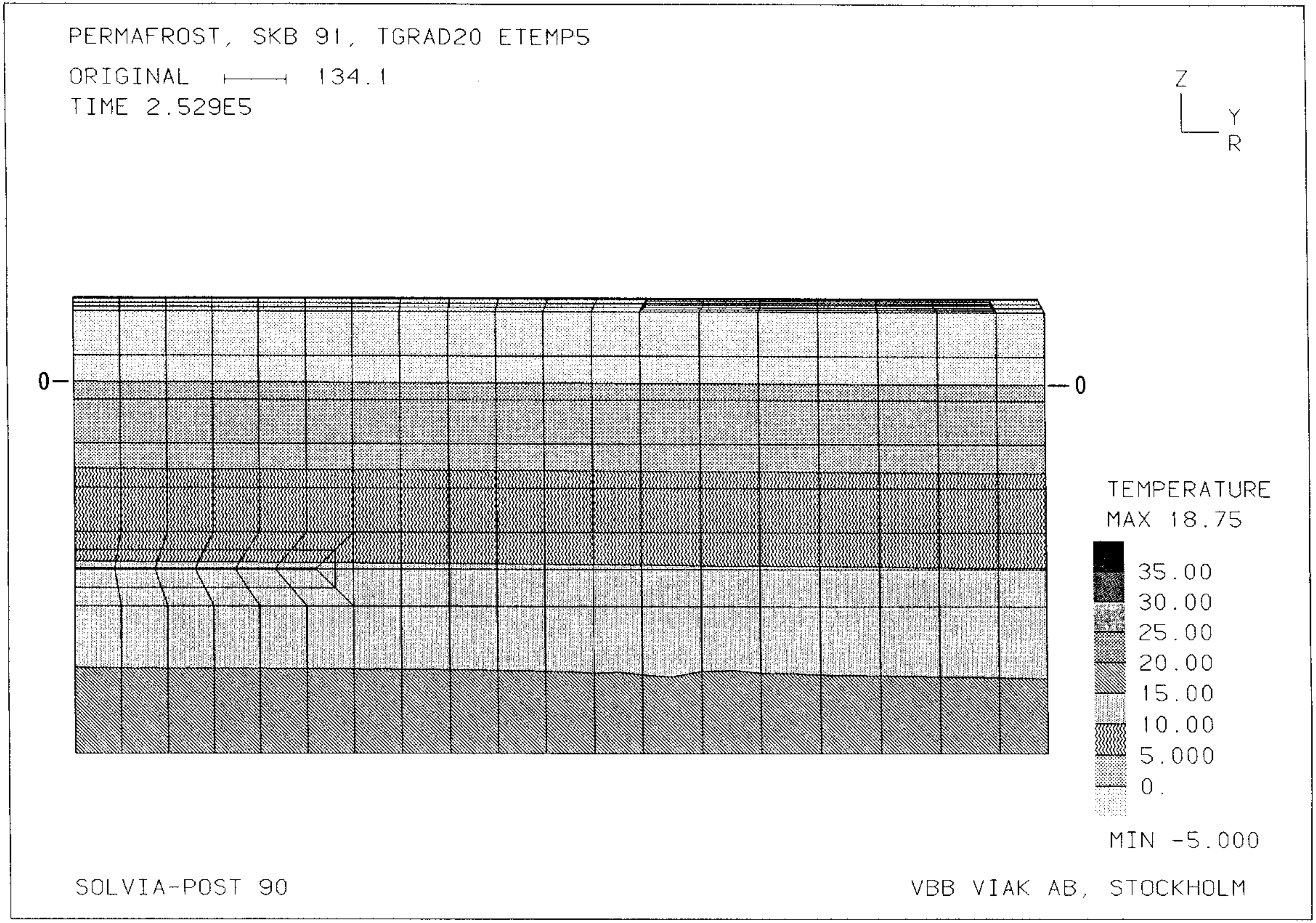
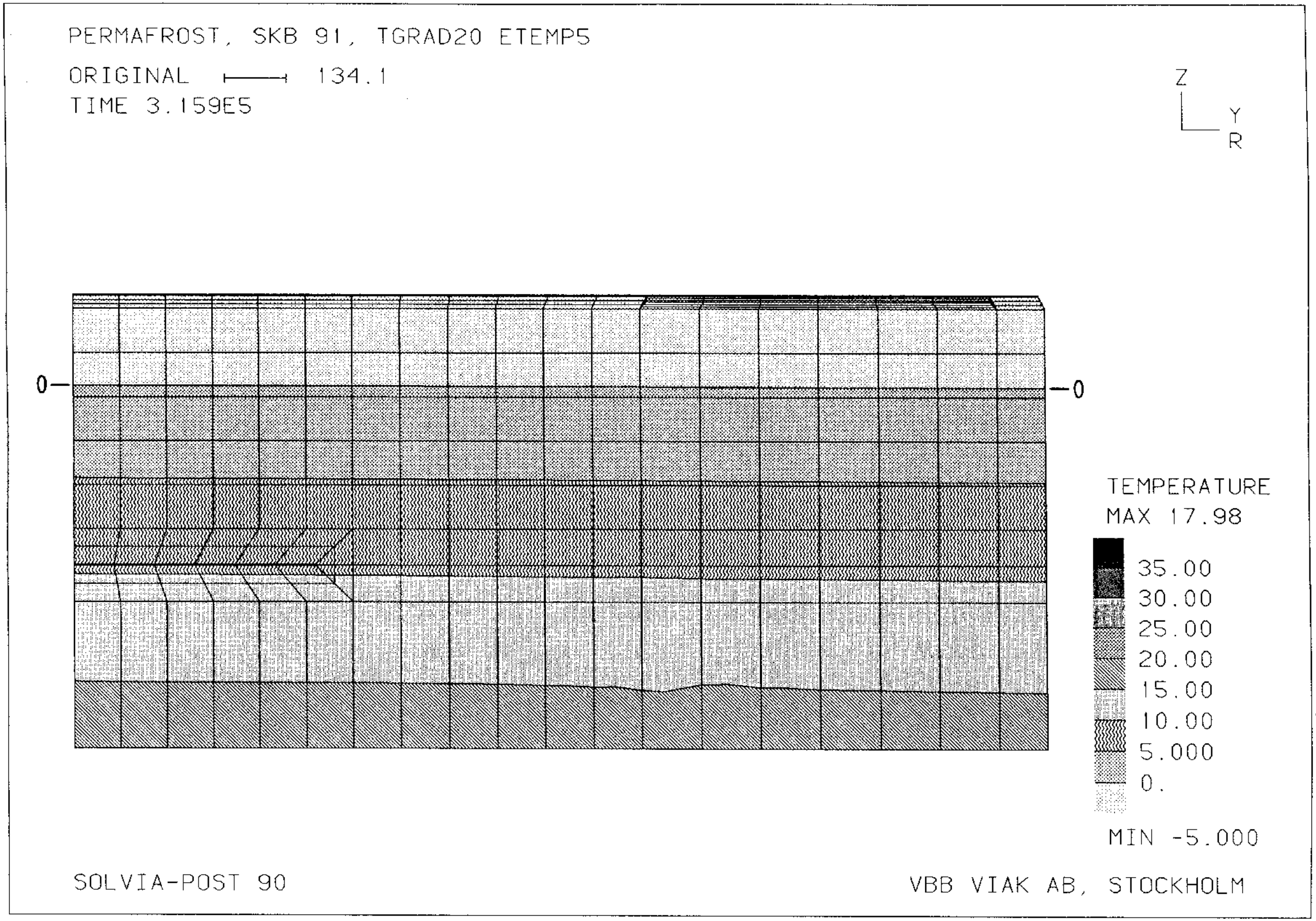
30.00
25.00
20.00
15.00
10.00
5.000
0.
MIN -2.864
SOLVIA-POST 90
VBB VIAK AB, STOCKHOLM


PERMAFROST, SKB 91, TGRAD20 ETEMP5
ORIGINAL 134.1
TIME 1.899E5
Z
Y
R
0
0
TEMPERATURE
MAX 19.55
35.00
30.00
25.00
20.00
15.00
10.00
5.000
0.
MIN -5.000
SOLVIA-POST 90
VBB VIAK AB, STOCKHOLM


PERMAFROST, SKB 91, TGRAD20 ETEMP5
ORIGINAL 134.1
TIME 2.529E5
Z
Y
R
0
0
TEMPERATURE
MAX 18.75
35.00
30.00
25.00
20.00
15.00
10.00
5.000
0.
MIN -5.000
SOLVIA-POST 90
VBB VIAK AB, STOCKHOLM


PERMAFROST, SKB 91, TGRAD20 ETEMP5
ORIGINAL 134.1
TIME 3.159E5
Z
Y
R
0
0
TEMPERATURE
MAX 17.98
35.00
30.00
25.00
20.00
15.00
10.00
5.000
0.
MIN -5.000
SOLVIA-POST 90
VBB VIAK AB, STOCKHOLM

APPENDIX 6

VERIFICATION OF RESULTS

Table of Contents

1. GEOMETRICAL MODEL SIZE

The extension of the model in the radial and vertical directions should be such that:

- the vertical temperature distribution is uniform for radial distances beyond the model boundary,
- the temperature is constant during the time period considered along the lower model boundary.

That these conditions were fulfilled was checked for each Case by study of the respective temperature distribution plots for the full geometrical extent of the model. An example of such plots is shown in Figure 1.1.

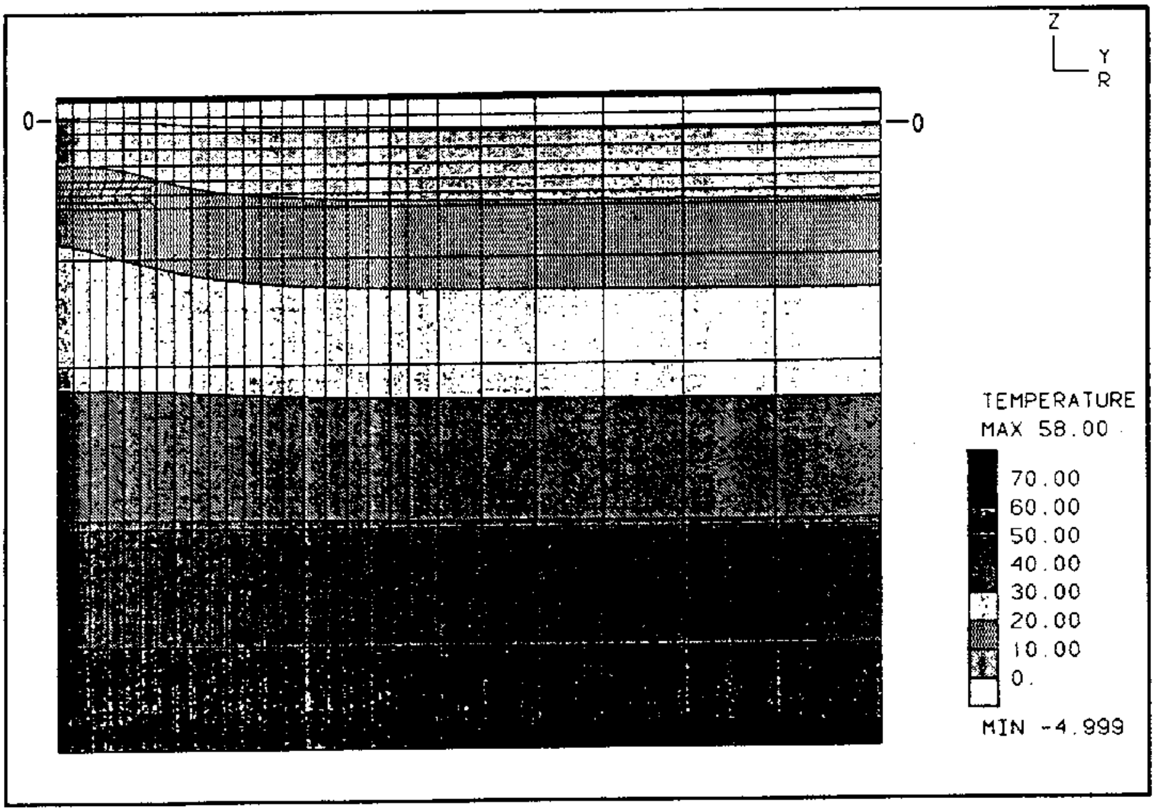


Figure 1.1 Verification of geometrical model size. Temperature distribution plot for Case B at time 10 000 years.

2. PERMAFROST DEVELOPMENT AS FUNCTION OF TIME

Computer test calculations were carried out with a simple truss model, which modelled the earth's crust with a vertical cylinder with a circular cross-section of 1 m^2 area. The truss model extended from the ground surface 4 000 m downwards, thus as far down as the proper computer model described in the preceding text. The material was assumed to be bedrock with geothermal properties according to Table 3.1 in the main text.

The calculations were, in addition, based on the following assumptions:

- boundary temperature at level -4 000 m equal to +58° C,
- air temperature constantly equal to +6° C before simulation starts,
- instantaneous decrease of the air temperature to -5° C at simulation start; the air temperature was thereafter kept constant.

The calculations were carried out with a time step of about 10 years during the initial 200 years and thereafter with a time step of about 100 years for a total simulation period of 200 000 years.

The results were treated to show temperature profiles from the ground surface and downwards for the times 0, 10 000, 20 000 and 140 000 years from start, respectively. These profiles are shown in Figure 2.1.

An analytical solution exists for the case with cooling of an infinitely thick wall after an instantaneous decrease of the surrounding temperature to a value which is thereafter kept constant, see Ref. (11). With this method, the temperature distribution in the ground was manually calculated for the specific time after which the temperature would decrease at level -4 000 m. This time was calculated to be 20 294 years. The analytically calculated temperature values are indicated with crosses in Figure 2.1. As can be seen from this Figure, the values from the computer calculations for the time 20 000 years and the manual calculations are the same.

This comparison shows that the temperature distribution in the ground, and thereby also permafrost development as function of time, can be calculated properly with the program Solvia. It also verifies that the selected geometrical model extension in the vertical direction was sufficient for the considered simulation period of 10 000 years.

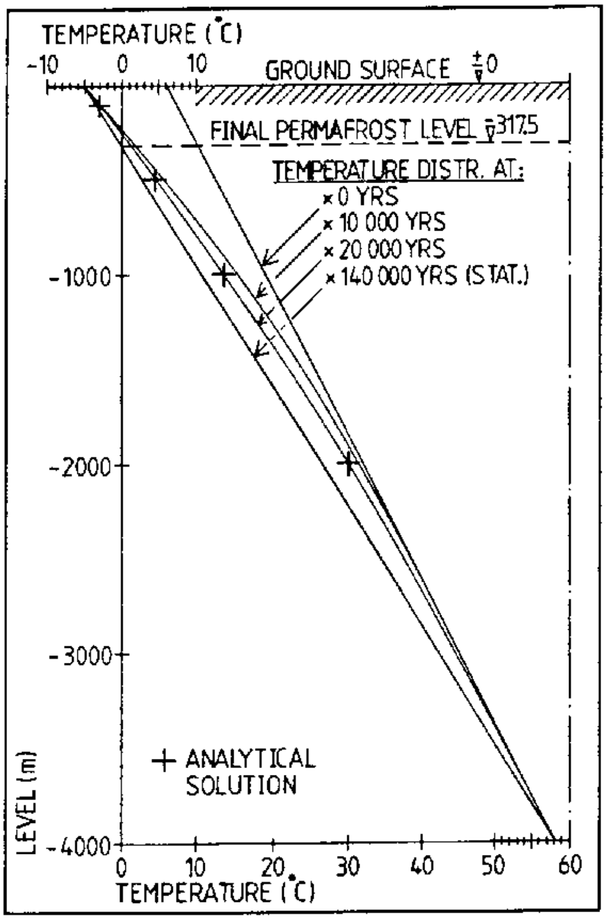


Figure 2.1 Temperature profiles for test run. Values from analytical calculations shown with crosses. Conditions according to Appendix 6, section 2.

From the computer calculation results was elaborated a graph of the permafrost level as function of time, Figure 2.2. The graph shows that, with the given conditions, the stationary permafrost level of - 317.5 m is reached after some 140 000 years. The permafrost level after 10 000 years is approx. 220 m, cf. also the level given by Figure 1.1.

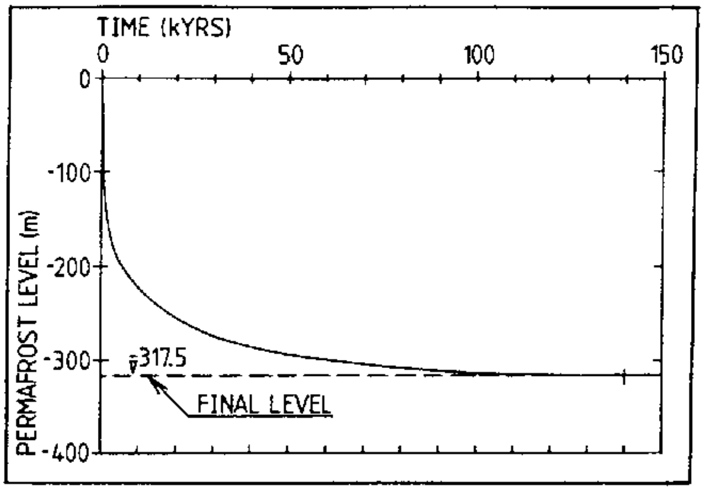


Figure 2.2 Permafrost level vs time for test run. Conditions according to Appendix 6, section 2.

3. LAKE FREEZING TIME

Computer test calculations were carried out with the same truss model as has been described in section 2. The material was assumed to be lake water down to level - 15.0 m and from there and downwards bedrock. The finite element mesh was relatively coarse with a node spacing of 3.0 m in the lake and much more in the bedrock. The proper model described in section 4 in the main text had a FE-mesh with considerably less spacing under the lake and should, therefore, give more reliable results.

The geothermal properties of the water and the bedrock were set in accordance with Table 3.1 in the main text.

The calculations were, in addition, based on the following assumptions:

- boundary temperature at level -4 000 m equal to +58° C,
- air temperature constantly equal to +6° C before simulation start,
- decrease of the air temperature to -3° C during 5 000 years after simulation start and thereafter constant air temperature.

The calculations were carried out with a time step of about 10 years during the initial 200 years and thereafter with a time step of about 100 years for a total simulation period of 10 000 years.

The temperature histories for the nodes in the test model lake are exhibited in Figure 2.3.

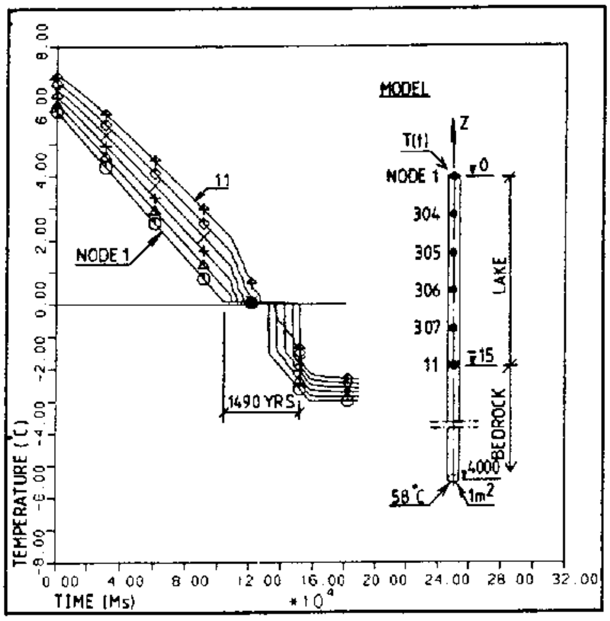


Figure 2.3 Temperature histories for the nodes in the test model lake.

The calculations showed that, cf. Figure 2.3:

- it will take nearly 1 500 years to freeze the lake completely,
- as soon as the latent heat has been transported away, the ice temperature will very soon be adapted to the surrounding temperature,
- node 11 on the lake bottom represents average weighted thermal properties for the lake and the bedrock; the latter dominates.

In order to check the computer calculations, a model, suitable for iterative manual calculations, was elaborated. A vertical water column of 15 m height and with a cross-sectional area of 1 m^2 was divided into horizontal slices of equal small height. Each respective uppermost unfrozen slice was considered per time step. It was assumed that:

- during the next time step, heat will be transferred corresponding to the sum of the heat flow from below and the latent heat in the studied slice,
- heat will be transferred by conduction alone,
- the time required for the heat to be transferred is determined by the temperature difference between the slice in question and the air at the ice upper surface.

The manual calculations showed that, with the assumptions given, it will take about 900 years to freeze the lake completely.

This time is less than was calculated with the computer test model. However, the finite element mesh of the test model was rather coarse and not too fit for precise calculation of the lake freezing time history. With less distance between the model nodes the heat would be more effectively transferred in the model, since the heat transfer rate then would be determined by the thermal conductivity for ice alone instead of the conductivities for both ice and water.

The comparison nevertheless shows that the order of magnitude of the time calculated with the computer model is right.

It should be noted that in nature, the freezing of a lake will be determined by conduction, convection, evaporation as well as radiation mechanisms. Thus, both calculations outlined suffer from simplifications.

List of SKB reports

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Stefan Sehlstedt, Tomas Stark
SGAB, Luleå
January 1991

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Description of geophysical data in SKB database GEOTAB Version 2
Stefan Sehlstedt
SGAB, Luleå
January 1991

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2. Spent fuel degradation
R S Forsyth
Studsvik Nuclear
January 1991

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Plutonium solubilities
I Puigdomènech[1], J Bruno[2]
[1]Enviromental Services, Studsvik Nuclear, Nyköping, Sweden
[2]MBT Tecnologia Ambiental, CENT, Cerdanyola, Spain
February 1991

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SGAB, Luleå
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Description of background data in the SKB database GEOTAB
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Margareta Gerlach (ed.)
Mark Radon Miljö MRM Konsult AB, Luleå
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Kaj Ahlbom[1], Sven Tirén[2]
[1]Conterra AB
[2]Sveriges Geologiska AB
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SGAB, Uppsala
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Eva Hakami[1], Anders Ekstav[2], Ulf Qvarfort[2]
[1]Vattenfall HydroPower AB
[2]Golder Geosystem AB
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Akke Bengtsson[1], Bertil Grundfelt[1], Anders Markström[1], Anders Rasmuson[2]
[1]KEMAKTA Konsult AB
[2]Chalmers Institute of Technology
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[1]Starprog AB
[2]SKB AB
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Akke Bengtsson[1], Anders Boghammar[1], Bertil Grundfelt[1], Anders Rasmuson[2]
[1]KEMAKTA Consultants Co
[2]Chalmers Institute of Technology

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Starprog AB
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[1]Conterra AB
[2]Teollisuuden Voima Oy (TVO)
[3]Svensk Kärnbränslehantering AB (SKB)
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[1]MBT Tecnologia Ambiental, CENT, Cerdanyola, Spain
[2]KTH, Dpt. of Inorganic Chemistry, Stockholm, Sweden
[3]VTT, Tech. Res. Center of Finland, Espoo, Finland
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Håkan Sandstedt[1], Curt Wichmann[1], Roland Pusch[2], Lennart Börgesson[2], Bengt Lönnerberg[3]
[1]Tyréns
[2]Clay Technology AB
[3]ABB Atom
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Leonardo Romero, Luis Moreno , Ivars Neretnieks
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October 1991

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Roland Pusch[1], Ivars Neretnieks[2], Patrik Sellin[3]
[1] Clay Technology AB. Lund
[2] The Royal institue of Techonology Department of
Chemical Engineering, Stockholm
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TR 91-50
Concentrations of particulate matter and humic substances in deep groundwaters and estimated effects on the adsorption and transport of radionuclides
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TR 91-51
Gideå study site. Scope of activities and main results
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TR 91-52
Fjällveden study site. Scope of activities and main results
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