27
4-30-79
2476 XTS

UCID-17984

Lawrence Livermore Laboratory

THREE-DIMENSIONAL THERMAL ANALYSIS OF A HIGH-LEVEL WASTE REPOSITORY

T. J. Altenbach

April 1979

This is an informal report intended primarily for internal or limited external distribution. The opinions and conclusions stated are those of the author and may or may not be those of the laboratory.

This work was supported by the U.S. Nuclear Regulatory Commission under Interagency Agreement DOE 40-550-75 with the U.S. Department of Energy.

MASTER

DISSEMINATION OF THIS REPORT IS UNLIMITED

FOREWORD

This report on the three-dimensional thermal analysis of a high-level waste repository was performed as part of the Nuclear Regulatory Commission Waste Management Program at Lawrence Livermore Laboratory under Task 3 in support of a Basic Order Agreement.

NOTICE

This notice was prepared in accordance with the provisions of the Freedom of Information Act, 5 U.S.C. 552, and the Privacy Act, 5 U.S.C. 552a, and is being made available to the public. It contains information that is not exempt from disclosure under the Act. It is being made available to the public in order to provide the public with the information requested by the public. It is being made available to the public in order to provide the public with the information requested by the public. It is being made available to the public in order to provide the public with the information requested by the public.

12

CONTENTS

Foreword	iii
Abstract	ix
Introduction	1
General Problem Specification	2
Unit Cell Model	4
Node Geometry	6
Individual Case Definition	11
CASE 1: Unventilated Base Case	11
CASE 2: Ventilated Base Case	11
CASE 3: Unventilated, Layered Geometry	12
CASE 4: Ventilated, Layered Geometry	13
CASE 5: Ventilated, Back-filled at 5 years	13
CASE 6: Ventilated, Back-filled at 25 years	13
Results and Conclusions	14
Acknowledgments	18
References	19
Appendix A: Plots Showing the Effect of Temperature as a Function of Time	21

LIST OF ILLUSTRATIONS

1.	Three-dimensional unit cell for TRUMP model of a geologic salt repository	5
2.	Side view of the unit cell showing the dimensions of the 14 sections	7
3.	Two-dimensional finite difference mesh used for sections 1 to 3 and 10 to 14	8
4.	Two-dimensional finite difference mesh used for sections 4 to 9	9
5.	Partial enlargement of the zoning shown in Fig. 4 for sections 4 to 9	10
A-1	Effect of temperature as a function of time for case 1 (nodes 601, 602, 607, 611, 615, 620, and 623)	23
A-2	Effect of temperature as a function of time for case 1 (node 1000)	24
A-3	Effect of temperature as a function of time for case 2 (nodes 601, 602, 607, 611, 615, 620, and 623)	25
A-4	Effect of temperature as a function of time for case 2 (node 1000)	26
A-5	Effect of temperature as a function of time for case 3 (nodes 601, 602, and 623)	27
A-6	Effect of temperature as a function of time for case 3 (node 1000)	28
A-7	Effect of temperature as a function of time for case 4 (nodes 601, 602, and 623)	29
A-8	Effect of temperature as a function of time for case 4 (node 1000)	30
A-9	Effect of temperature as a function of time for case 5 (nodes 601, 602, and 623)	31
A-10	Effect of temperature as a function of time for case 6 (nodes 601, 602, and 623)	32

LIST OF TABLES

1.	Power output of the high-level waste canister at various times after emplacement	2
2.	Properties of the salt used in TRUMP for the base case (cases 1 and 2) analyses	12
3.	Material properties input to TRUMP for cases 3 to 6	13
4.	Two-dimensional coordinates for the nodal points plotted in section 6	14
5.	Comparison of temperatures at different locations after 50 years	16
6.	Comparison of temperatures at different locations after 25 and 50 years	17

ABSTRACT

This report documents the three-dimensional thermal analysis of a high-level waste repository. The analysis used the TRUMP computer code to evaluate the thermal fields for six repository scenarios that studied the effects of room ventilation, room backfill, and repository thermal diffusivity. The results for selected nodes are presented as plots showing the effect of temperature as a function of time.

INTRODUCTION

This report documents a thermal analysis of a three-dimensional computer model of a high-level waste (HLW) repository in bedded salt. The TRUMP finite difference heat-transfer computer code¹ was used to evaluate six repository scenarios. The unit cell approach was used to model a single HLW canister that was buried in salt beneath a room in the repository. Thermal fields were generated for six cases for times up to 50 years after emplacement. The results for selected modes are presented as plots showing the effect of temperature as a function of time.

GENERAL PROBLEM SPECIFICATION

The problem is to generate three-dimensional thermal fields for a HLW repository from the time of emplacement up to 50 years later. The HLW canister is 8 feet long and 1 foot in diameter, and it is buried 10 feet below the room centerline. The initial power output of the canister (at the time of emplacement) is 3.5 kW. Table 1 shows how this power output decays up to 60 years after emplacement of the canister. The thermal properties of the high-level waste were assumed to be independent of temperature. The conductivity is 0.58 Btu/hr-ft-⁰F; the heat capacity is 0.22 Btu/lb-⁰F; the density is 200 lb/ft³. The waste is 10 years old at emplacement.

The room has a square cross section of 18 feet, with a salt pillar extending another 70 feet. The areal thermal loading on the repository is initially fixed at 100 kW/acre, thereby forcing the canister pitch along the room to be 17.325 feet.

TABLE 1. Power output of the high-level waste canister at various times after emplacement.

Time after emplacement, y	Thermal output, kW
0	3.50
5	2.86
10	2.49
20	1.93
40	1.19
60	0.74

Perfect thermal contact is assumed to exist between the waste canister and the salt. The initial temperature of the canister is 380°F.² The initial temperature of the repository varies with depth according to the natural geothermal gradient.³

UNIT CELL MODEL

The three-dimensional unit cell model is illustrated in Fig. 1. The cell consists of one-fourth of an HLW canister and the salt and room air associated with it. The cell is 44 by 8.6625 by 1000 feet overall. The front and left faces, which slice through the center of the canister, are adiabatic boundaries for the problem. The right face coincides with the pillar centerline, and the back face coincides with the midplane between canisters, making these faces also adiabatic boundaries. The top and bottom faces are isothermal boundaries. The adiabatic boundary conditions assume that the canister is in the center of the repository and surrounded by canisters of equal power output, which were emplaced simultaneously. The isothermal boundary conditions assume that these boundaries are sufficiently far away from the canister that they are unaffected by the heat generation.

FIG. 1. Three-dimensional unit cell for TRUMP model of a geologic salt repository.

NODE GEOMETRY

The unit cell is divided into 14 sections or planes (Fig. 2). Each section is then divided into a two-dimensional nodal structure. Sections 1, 2, 3, 10, 11, 12, 13, and 14 each contain six nodes as shown in Fig. 3. Each nodal point is located at the centroid, with the exception of the end node, which is located on the pillar centerline.

The nodal structure for sections 4, 5, 6, 7, 8, and 9 is illustrated in Fig. 4. (An enlarged view is shown in Fig. 5.) Each section contains 23 nodes, of which 20 are located at their centroids. The three exceptions are as follows: (1) node 1, which is located at the cell corner and represents the waste center temperature in sections 5 to 7; (2) node 2, which is a zero-volume node positioned at the canister-salt interface; and (3) node 23, which is located on the pillar centerline.

The tedious task of generating the finite difference geometry for input to TRUMP was somewhat alleviated through the use of the FED mesh generating code.⁴ Detailed examples in the use of FED for three-dimensional repository thermal analysis are documented by Lowry.⁵

FIG. 2. Side view of the unit cell showing the dimensions of the 14 sections.

FIG. 3. Two-dimensional finite difference mesh used for sections 1 to 3 and 10 to 14.

FIG. 4. Two-dimensional finite difference mesh used for sections 4 to 9.

FIG. 5. Partial enlargement of the zoning shown in Fig. 4 for sections 4 to 9.

INDIVIDUAL CASE DEFINITION

Six individual cases were specified for computer analysis. The first two are used as base cases and the last four as variations.

CASE 1: UNVENTILATED BASE CASE

Case 1 consists of the basic geometry described earlier. The repository media is salt with the properties listed in Table 2. Because no ventilation occurs in the room, heat transfer is by natural convection and radiation from the floor to the ceiling. The heat transfer coefficient for convection, h , is given by

$$h = 0.22 (T_f - T_c)^{1/3} ,$$

where T_f and T_c are the floor and ceiling temperatures, respectively.² Radiation from floor to ceiling is modeled with a view factor of 0.59 and an emissivity of 0.9.

CASE 2: VENTILATED BASE CASE

Case 2 differs from Case 1 in that ventilation occurs in the room. Forced convection transfers heat from the floor and ceiling to the bulk air. The equation for the heat transfer coefficient is

$$h = 0.102 (T - T_\infty)^{0.07} ,$$

where T and T_∞ are the surface and bulk air temperatures, respectively.² The bulk air was assumed to maintain a constant temperature of 79°F over the length of the unit cell. Radiation is modeled as in case 1.

TABLE 2. Properties of the salt used in TRUMP for the base case (cases 1 and 2) analyses.^a

Temperature, °F	Conductivity, Btu/hr-ft-°F	Specific heat, ^b Btu/lb-°F	Density, ^c lb/ft ³
32	3.09	0.204	135
122	2.61	--	--
212	2.23	0.217	--
302	1.94	--	--
392	1.70	0.222	--
482	1.53	--	--
572	1.39	--	--
662	1.29	--	--
752	1.18	0.230	--

^aSee reference 2.

^bInterpolation done between data points given.

^cAssumed constant with temperature.

CASE 3: UNVENTILATED, LAYERED GEOMETRY

Case 3 maintains the unventilated model of case 1, but the repository medium is modeled as a series of salt and shale layers. Shale layers occur in sections 1, 3, 12, and 14. The original salt remains in section 4 to 11, and salt with properties independent of temperature is used in sections 2 and 13. Table 3 lists the properties of the new materials, as specified by NRC.

TABLE 3. Material properties input to TRUMP for cases 3 to 6.

Material	Conductivity, Btu/hr-ft-°F	Specific heat, Btu/lb-°F	Density, lb/ft ³
Salt (sections 2 and 13 of cases 3 and 4)	2.1	0.21	135
Shale	1.8	0.16	125
Crushed salt (cases 5 and 6)	0.13	0.20	100

CASE 4: VENTILATED, LAYERED GEOMETRY

Case 4 combines the ventilation model of case 2 with the layered geometry of case 3. Table 3 lists the properties of the new materials.

CASE 5: VENTILATED, BACK-FILLED AT 5 YEARS

Case 5 follows case 2 for the first 5 years. After 5 years have passed, the room is back-filled with crushed salt. (The properties of the crushed salt are listed in Table 3.) The boundary between the back-fill and the room ceiling is modeled as a very thin radiation gap with a view factor of 1.0 and an emissivity of 0.9.

CASE 6: VENTILATED, BACK-FILLED AT 25 YEARS

Case 6 follows case 2 for 25 years. After 25 years have passed, the room is back-filled with crushed salt as in case 5 (Table 3).

RESULTS AND CONCLUSIONS

Results from the six cases are illustrated in Appendix A as plots of temperature versus time. Results from cases 1 and 2 include plots for nodes 601, 602, 607, 611, 615, 620, 623, and 1000. The first digit refers to the section number (section 6 is the canister midplane), and the second and third digits refer to the node position as shown in Fig. 4 and 5. Table 4 lists the coordinates of these nodes. Node 1000 represents the average floor temperature in the room.

TABLE 4. Two-dimensional coordinates for the nodal points plotted in section 6. The origin occurs at the canister center.

Node	X-coordinate, ft	Y-coordinate, ft
601	0.0	0.0
602	0.354	0.354
607	1.386	0.574
611	3.233	1.339
615	5.543	2.296
620	19.500	4.331
623	44.000	4.331

The plots included for cases 3 to 6 are for nodes 601, 602, 623, and 1000 (cases 3 and 4 only). These nodes represent the canister center, canister-salt interface, pillar centerline, and average floor temperature, respectively. Results are presented for 0 to 50 years after emplacement.

Enough time history plots are included in Appendix A for the base cases (1 and 2) that the interested reader can generate an approximate radial temperature profile from the canister center to the pillar centerline for any time during the modeled event. An examination of these time history plots

also reveals several other points of interest. In case 2, the nodes near the canister attain a broad maximum temperature within 50 years and begin to fall off due to the effects of ventilation. At the canister-salt interface, the temperature peaks at 564⁰F (296⁰C) about 20 years after emplacement.

Preliminary studies not presented here suggest that the shape of these time history curves is greatly influenced by the thermal model used for ventilation in the storage room. A different ventilation model will affect the maximum temperature, the time at which the maximum occurs, and the rate of change of the slope of the time history curve at the time of maximum temperature. It is recommended that these effects be studied by incorporating a more rigorous thermal model for ventilation, as is proposed by Davis.^{6,7} Such a model must include convection and radiation heat transfer from the floor, ceiling, and walls of the room.

In case 1, maximum temperatures are not reached during the problem duration. Since the room is not ventilated, heat may leave the unit cell only through its top and bottom surfaces. This heat flow is much less than the heat generation rate of the spent fuel, even at 50 years after emplacement.

The top and bottom isothermal boundary conditions were valid for the first 7 years after emplacement. At later times, these boundaries will attain higher temperatures than those artificially specified in the model. This effect causes a general underprediction of temperatures throughout the unit cell. This effect will be significant for problems extending longer than 50 years, and it is recommended that the unit cell be extended vertically to account for this.

Cases 3 and 4 study the effects of introducing several layers of shale into the repository. Due to the lower conductivity of shale as compared to salt, the salt temperatures across the canister midplane are slightly higher than in the comparable base cases (Table 5).

TABLE 5. Comparison of temperature at different locations after 50 years.

Case	Temperature, °F, at indicated location			
	Canister center	Canister-salt interface	Pillar centerline	Floor of room
1	1201	867	397	435
3	1256	922	432	473
2	866	531	207	167
4	876	542	215	171

Cases 5 and 6 study the effect of back-filling the room with crushed salt after ventilation times of 5 and 25 years, respectively. Some very interesting results were observed in these cases (Table 6). For the ventilation periods, the thermal fields are identical to case 2 results. However, after back-filling, the temperatures rise dramatically. In case 5, the canister and very near field salt temperatures equal those from case 1 after only 10 years, and significantly exceed those from case 1 after 50 years. The pillar centerline temperature remains slightly lower in case 5.

These results support analytical work by Davis⁷ in which the thermal conductance of salt or crushed salt in the room is shown to be much less than the effective conductance of still air, calculated by combining convection and radiation effects. From a thermal standpoint, it is much better to leave the storage room open, whether it is ventilated or not.

TABLE 6. Comparison of temperature at different locations after 25 and 50 years.

Case	Temperature, °F, at indicated location		
	Canister center	Canister-salt interface	Pillar centerline
25-year results			
1	1148	777	302
2	934	563	190
5	1164	793	298
6	934	563	190
50-year results			
1	1201	867	397
2	866	531	207
5	1226	892	396
6	1138	804	344

ACKNOWLEDGMENTS

The author would like to acknowledge the assistance provided by Dr. Billy W. Davis in the development of the TRUMP thermal model.

REFERENCES

1. A. L. Edwards, TRUMP: A Computer Program for Transient and Steady-State Temperature Distributions in Multidimensional Systems, Lawrence Livermore Laboratory, Livermore, CA, UCRL-14754, Rev. 3 (September 1, 1972).
2. C. M. Koplik, D. L. Pentz, and R. Talbot, Information Base for Waste Repository Design, Analytic Sciences Corporation, Reading, MA, Vol. 3, TR-1210-1 (August 1, 1978).
3. R. K. Kibbe and A. L. Boch, "Technical Support for GEIS: Radioactive Waste Isolation in Geologic Formations," Vol. 19, Thermal Analyses, U. S. Department of Energy, Report Y/OWI/TM-36/19 (April 1978).
4. D. A. Schauer, FED: A Computer Program to Generate Geometric Input for the Heat-Transfer Code TRUMP, Lawrence Livermore Laboratory, Livermore, CA, UCRL-50816, Rev. 1 (January 12, 1973).
5. W. Lowry, Using the FED Code to Generate Geometric Input for TRUMP Thermal Analyses of Spent Fuel Waste Repositories, Lawrence Livermore Laboratory (Waste Management Project) Livermore, CA, WM78-715 (August 15, 1978).
6. B. W. Davis, Limitations to the Use of Two-Dimensional Thermal Modeling of a Nuclear Waste Repository, Lawrence Livermore Laboratory, Livermore, CA, UCID-18101 (1979).
7. B. W. Davis, Thermal Modeling of a Nuclear Waste Repository Storage Room, Lawrence Livermore Laboratory, Livermore, CA, UCID-18103 (1979).

RM/n1

APPENDIX A
PLOTS SHOWING THE EFFECT OF
TEMPERATURE AS A FUNCTION OF TIME

FIG. A-1. Effect of temperature as a function of time for case 1 (nodes 601, 602, 607, 611, 615, 620, and 623).

FIG. A-2. Effect of temperature as a function of time for case 1 (node 1000).

FIG. A-3 Effect of temperature as a function of time for case 2 (nodes 601, 602, 607, 611, 615, 620, and 623).

FIG. A-4. Effect of temperature as a function of time for case 2 (node 1000).

FIG. A-5. Effect of temperature as a function of time for case 3 (node 601, 602, and 623).

FIG. A-6. Effect of temperature as a function of time for case 3 (node 1000).

FIG. A-7. Effect of temperature as a function of time for case 4 (nodes 601, 602, and 623).

FIG. A-8. Effect of temperature as a function of time for case 4 (node 1000).

FIG. A-9. Effect of temperature as a function of time for case 5 (nodes 601, 602, and 623).

FIG. A-10. Effect of temperature as a function of time for case 6 (nodes 601, 602, and 623).