

SANDIA REPORT

SAND88-1221 • UC-814

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Printed June 1990

Yucca Mountain Project

Thermal and Mechanical Codes First Benchmark Exercise Part I: Thermal Analysis

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Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789



HYDROLOGY DOCUMENT NUMBER 619

"Prepared by Yucca Mountain Project (YMP) participants as part of the Civilian Radioactive Waste Management Program (CRWM). The YMP is managed by the Yucca Mountain Project Office of the U.S. Department of Energy, Nevada Operations Office (DOE/NV). YMP work is sponsored by the Office of Geologic Repositories (OGR) of the DOE Office of Civilian Radioactive Waste Management (OCRWM)."

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SAND88-1221
Unlimited Release
Printed June 1990

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YUCCA MOUNTAIN PROJECT
THERMAL AND MECHANICAL CODES
FIRST BENCHMARK EXERCISE
PART I: THERMAL ANALYSIS

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ABSTRACT

Thermal and mechanical models for intact and jointed rock mass behavior are being developed, verified, and validated at Sandia National Laboratories for the Yucca Mountain Project. Benchmarking is an essential part of this effort and is the primary tool used to demonstrate verification of engineering software used to solve thermomechanical problems. This report presents the results of the first phase of the first thermomechanical benchmark exercise. In the first phase of this exercise, three finite element codes for nonlinear heat conduction and one coupled thermoelastic boundary element code were used to solve the thermal portion of the benchmark problem. The codes used by the participants in this study were DOT, COYOTE, SPECTROM-41, and HEFF. The problem solved by each code was a two-dimensional idealization of a series of drifts whose dimensions approximate those of the underground layout in the conceptual design of a prospective repository for high-level radioactive waste at Yucca Mountain. The initial results submitted by the participants showed that the finite element solutions agreed to within 1%, with the exception of one of the three solutions produced by COYOTE. This solution differed slightly from the others because of the different time-step size used in the pre-emplacment time regime of the problem. A revised solution was submitted that was nearly identical to the other solutions. The boundary element code HEFF was also used in this exercise because it calculates a solution to the thermal problem using an approximate analytical method and thus provides a means of comparing the finite element solutions with a solution obtained by an independent method. In addition, the comparison provides a means of determining the effect of the approximations made in HEFF on the thermal solution of a typical repository problem.

The Sandia National Laboratories Quality Assurance Program Plan (QAPP) [including Department 6310 QAPP specific to the Yucca Mountain Project (YMP)] was in effect during the course of this work. Criteria 1-7 and 15-18 of the QAPP applied for this work. Department Operating Procedures 2-4, 3-2, and 3-3 were specifically used to assure quality in the conduct of these analyses. The analysis definition was developed interactively through interactions with the participants. This report was reviewed by two technical peers, line management review, and was reviewed for policy concerns by the YMP Office. The work was assigned a QA level of II. More discussion of the specific QA requirements is in Section 4.1 of this report.

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1.0 INTRODUCTION

1.1 Background

Computer software that incorporates thermal and mechanical models for intact and jointed rock mass behavior is being developed, verified, and validated at Sandia National Laboratories (SNL) for the Yucca Mountain Project (YMP) administered by the Nevada Operations Office of the U.S. Department of Energy (DOE). Scientific and engineering software used in substantiating a license application for a radioactive waste repository must meet certain requirements intended to satisfy the Nuclear Regulatory Commission (NRC) of the quality of the software. These requirements are specified by the NRC (1983) and DOE (1985). In particular, two requirements--those of code verification and model validation--are addressed in this report. In this context, a distinction between codes and models needs to be made. A model is a mathematical representation of a physical process. A code is a numerical tool used to solve the equations associated with a model. Thus, code verification addresses the correctness of the implementation of the model equations and the numerical techniques used to solve those equations. Model validation, on the other hand, is the process of demonstrating that the models, as embodied in the software, are acceptable representations of the intended physical systems or processes being modeled.

Verification and validation of the modeling techniques and computer codes used in design and performance analyses must ultimately be shown by comparing code predictions with measured field data. Although essential to the validation process, field data are often limited in scope, and the experimental geometry and boundary conditions are too complex to be modeled accurately enough to provide a realistic test of the predictive capability of the code. Laboratory or small-scale experiments can also be used as part of the verification and validation process. However, critical phenomena can be overlooked or lost in the scaling and idealization of experiments. In addition, there is no guarantee that good agreement with experimental data from small-scale experiments will ensure the same degree of success on field experiments. Because of the limitations of various types of validation means (i.e., laboratory, benchscale, and field testing), a program that combines several approaches is most desirable and is the approach taken by the YMP.

One additional means of demonstrating verification and assessing the validity of engineering software is benchmarking, which is defined here as the comparison of the results obtained using one code with those obtained using other codes applied to identical problems. One advantage of benchmarking is that many more parameters are available for comparison than when comparing model results with field or laboratory data. With experimental measurements, only a few measurements of displacement or strain are available, and these measurements are subject to many uncertainties. In a benchmarking exercise, numerous mechanical and thermal parameters (stresses, strains, strain rates, displacements, joint motion, temperatures, etc.) can be compared over the entire analysis region. With the exact specification of geometry and material properties, many uncertainties in the comparison of results can be removed.

1.2 Objectives and Scope of the Benchmark Exercise

In the first thermomechanical benchmark exercise, a specific thermomechanical boundary value problem is solved. The problem is a generic extraction of a typical problem likely to be run by design analysts. However, the analyses performed as part of this exercise should not be considered to represent any type of "reference" analysis for repository design. The benchmark exercise, as specified by Problem Definition Memorandum (PDM) 71-032 (Appendix A of this report) includes three separate comparative analyses: a thermal analysis, a structural analysis using a linear elastic rock mass model, and a structural analysis using two different nonlinear continuum joint rock mass models. The two structural analyses will use, as inputs, the temperature histories resulting from the thermal analysis. Each of the three analyses will be performed by six different analysts using several different codes. The analysts and codes participating in this exercise are discussed in Section 3.

The codes and models used in this exercise were chosen so that several sets of comparisons could be made. For the thermal analysis, one comparison will be among the results of several thermal codes solving the same problem. This comparison will assist in documenting the verification of these codes. In addition, the results obtained by different analysts using the same code will be compared to document the variability in results that can be expected solely as the result of the analysts' preferences in meshing and running a problem. In the second part of the benchmark exercise, the results of the structural calculations using a linear elastic rock mass model will be compared. This comparison will assist in demonstrating verification of the structural codes for their intended use within the YMP and will provide baseline results for assessment of the results from the nonlinear analyses. The final analysis, a thermomechanical analysis using nonlinear continuum rock mass models, will allow for comparisons between results from two different models as well as results from different codes using the same model. Thus, further code verification will be achieved as well as some verification of the implementation of these new models. In addition, a direct comparison of the results of both models run with the same codes will provide a means of assessing the differences in the response predicted by the two models. The two continuum joint models to be used are the compliant joint model (CJM) (Chen, 1987) and the joint empirical model (JEM).^{*} These models are essentially different mathematical descriptions and implementations of the same physical process; that is, joint closure under normal stress and joint shear as a result of normal and shear stresses are explicitly addressed in both models.

The codes and models used in this benchmark exercise are only a subset of those that are being considered for use in repository design. Other codes, such as those based on discrete block motion rather than on continuum principles, have been developed and reported in the literature. This class of codes is also under consideration for use in the project and may be included in future benchmark exercises.

^{*}M. L. Blanford and S. W. Key, "The Joint Empirical Model--an Equivalent Continuum Model for Jointed Rock Masses," SAND87-7072, Sandia National Laboratories, Albuquerque, NM, draft.

This report documents the results obtained from the first part of the benchmark exercise, the thermal analysis. Separate reports will cover the second and third analyses, and a final summary report will present the conclusions and recommendations resulting from this benchmark exercise.

1.3 Report Outline

The remainder of this report will be limited, as much as possible, to discussions and analyses of the thermal portion of the benchmark problem. In Section 2, a general description of the benchmark problem will be presented. The thermal analysis portion of the problem will be discussed in some detail. The participant groups, analysts, and codes used for the thermal solution are presented in Section 3. An overview of the benchmarking process is given in Section 4, along with a discussion of the specific control procedures and requirements specified in the PDM to ensure that project quality assurance (QA) requirements have been met. Section 5 presents in graphical form the comparison of the results from all participants. These results are discussed in Section 6. Part of the benchmark process allows the participants to present a corrected or revised solution after comparing their initial results with the results of the other participants. Only one set of revised thermal results was submitted, and in Section 7, this set of results is presented and compared with other results. Section 8 presents the conclusions of the authors based on their analysis of the results.

2.0 PROBLEM FORMULATION

2.1 Problem Selection

The benchmark problem was designed to be a generic representation of a typical repository design analysis. For that reason, the drift dimensions, rock properties, and nominal in situ stresses were taken to be identical with those listed in the YMP Reference Information Base (RIB), Version 2.002 (draft). The rationale for using a geometry and material properties typical of those expected in the waste emplacement panels at Yucca Mountain was that the benchmark problem should be typical of the kind of problem that the codes being benchmarked would be required to solve as part of the license application design process. The principal investigators (PI) thought that it was highly desirable to provide evidence and documentation of code verification and validation efforts that were specific to the intended use of the particular codes involved.

The initial problem was formulated and issued to the participants on November 2, 1987, in the form of a draft PDM. The participants had several weeks to review the draft and prepare comments. On December 13, 1987, the PIs and participants met to review the comments. As a result of this review, several minor changes in the draft were made, and a final PDM was issued under a cover letter dated December 23, 1987 (Appendix A). The PDM completed management review and was sent to the participants on January 4, 1988.

2.2 Problem Definition

The problem is described in detail in PDM 71-032 (Appendix A). In the following paragraphs, a brief summary of the important features of the problem definition is presented.

2.2.1 General Description

The problem to be solved is a two-dimensional idealization of an infinite series of drifts with the approximate dimensions of the proposed design for vertical emplacement disposal of radioactive waste at Yucca Mountain (Figure 2-1). From symmetry, the analysis region could be reduced to a vertical strip extending from the centerline of the drift to the centerline of the adjacent pillar. Because none of the codes to be used by the participants (with the exception of HEFF) are coupled thermomechanical codes, the analyses were to be performed in three phases: thermal solution (using thermal codes only), thermomechanical solution using the linear elastic rock mass model (mechanical codes with input from the thermal solutions), and thermomechanical solution using jointed rock mass models (mechanical codes with input from the thermal solutions). After completion of each phase, a letter report and results from each participant were to be forwarded to the PIs for review and comparison of results. This report discusses the results of the first phase only.

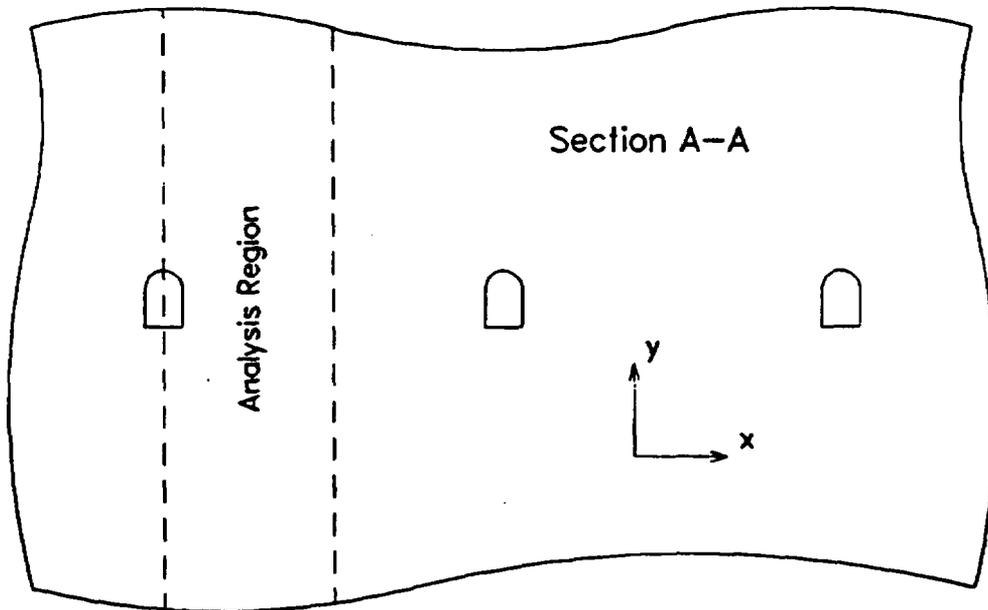
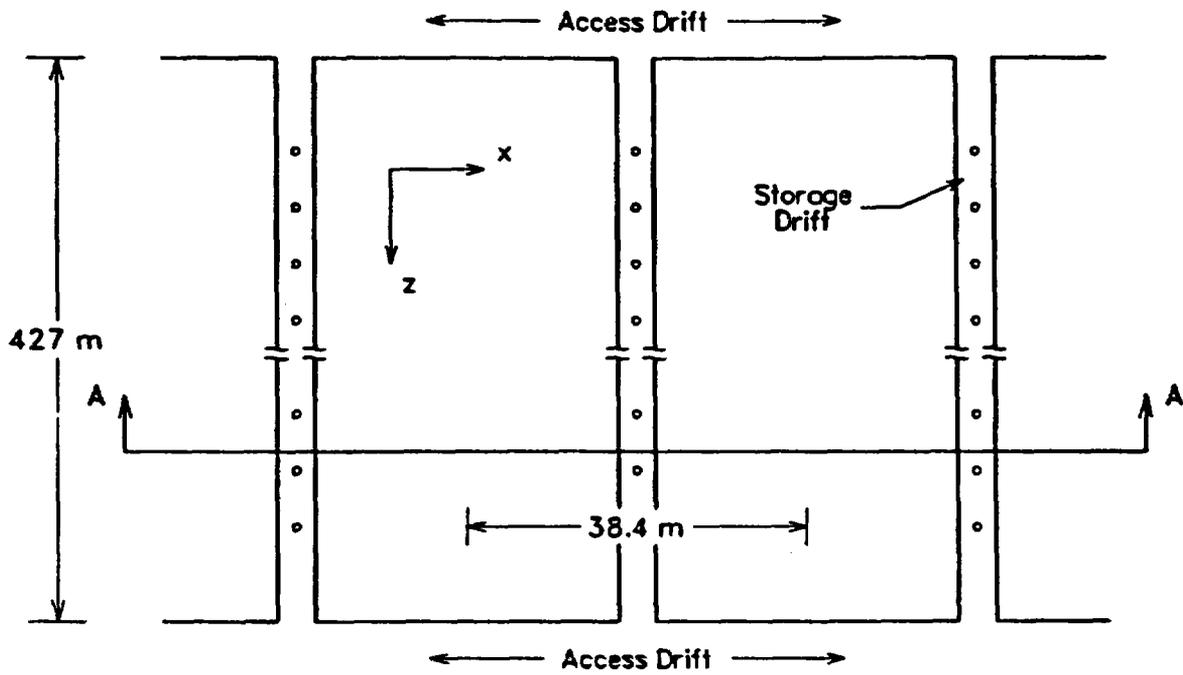


Figure 2-1. Sketch of Panel in the Vertical Emplacement Configuration and Analysis Region for Benchmark Problem

2.2.2 Thermal Analysis

The thermal analysis was conducted using three finite element codes: COYOTE, SPECTROM-41, and DOT, and one boundary element code: HEFF. The assumptions and model abstractions required to solve the thermal problem with HEFF differ somewhat from those used with the finite element codes. These differences will be noted where appropriate.

2.2.2.1 Geometry, Boundary Conditions, and Loads

The problem geometry is shown in Figure 2-2. The region analyzed is a strip bounded by the centerline of the drift on the left and by the centerline of the pillar on the right. The rock mass is assumed to be homogeneous throughout. The drift has a horizontal floor with a vertical side wall and an arched roof. The roof is formed by a circular sector with a radius of 2.74 m. The intersection of the floor with the side wall is rounded with a radius of 0.3 m. This was done to reduce the stress concentration at the corner of the drift. The floor of the drift is located 311 m below the surface, and the lower boundary of the modeled region extends 300 m below the drift floor.

A line of heat sources was simulated as being buried 3.05 m below the center of the drift floor. Because of the assumed plane symmetry, the heat source was modeled as a rectangular slab 0.74 m wide by 4.57 m long and of infinite extent in the out-of-plane (z-coordinate) direction. The initial power density of the heat sources was chosen so that the average heat load over an entire panel of such drifts would be approximately 80 kW/acre. This heat load is somewhat greater than the 57 kW/acre initial heat load expected for the conceptual design configuration, but the added load will cause larger stresses and more deformation in a greater region and thus test the structural codes and models more severely. The thermal output of the heat sources decays with time (Appendix A contains details).

Because the modeled region was assumed to be a vertical slice taken from an infinite array of emplacement drifts, the vertical boundaries through the centerline of the drift and the centerline of the pillar were to be modeled as adiabatic boundaries (Figure 2-2). The top surface of the model is assumed to be at the rock mass surface and was modeled as a constant temperature boundary. The lower surface of the model was placed sufficiently far away that the thermal disturbance should not reach it within the limits of the problem time. The lower surface was also modeled as a constant temperature boundary.

The finite element codes can model these boundary conditions precisely. However, HEFF differs from finite element codes in several significant ways. HEFF uses a closed form solution for a line heat source to determine the temperature distribution, and, as such, adiabatic boundaries cannot be specified directly.

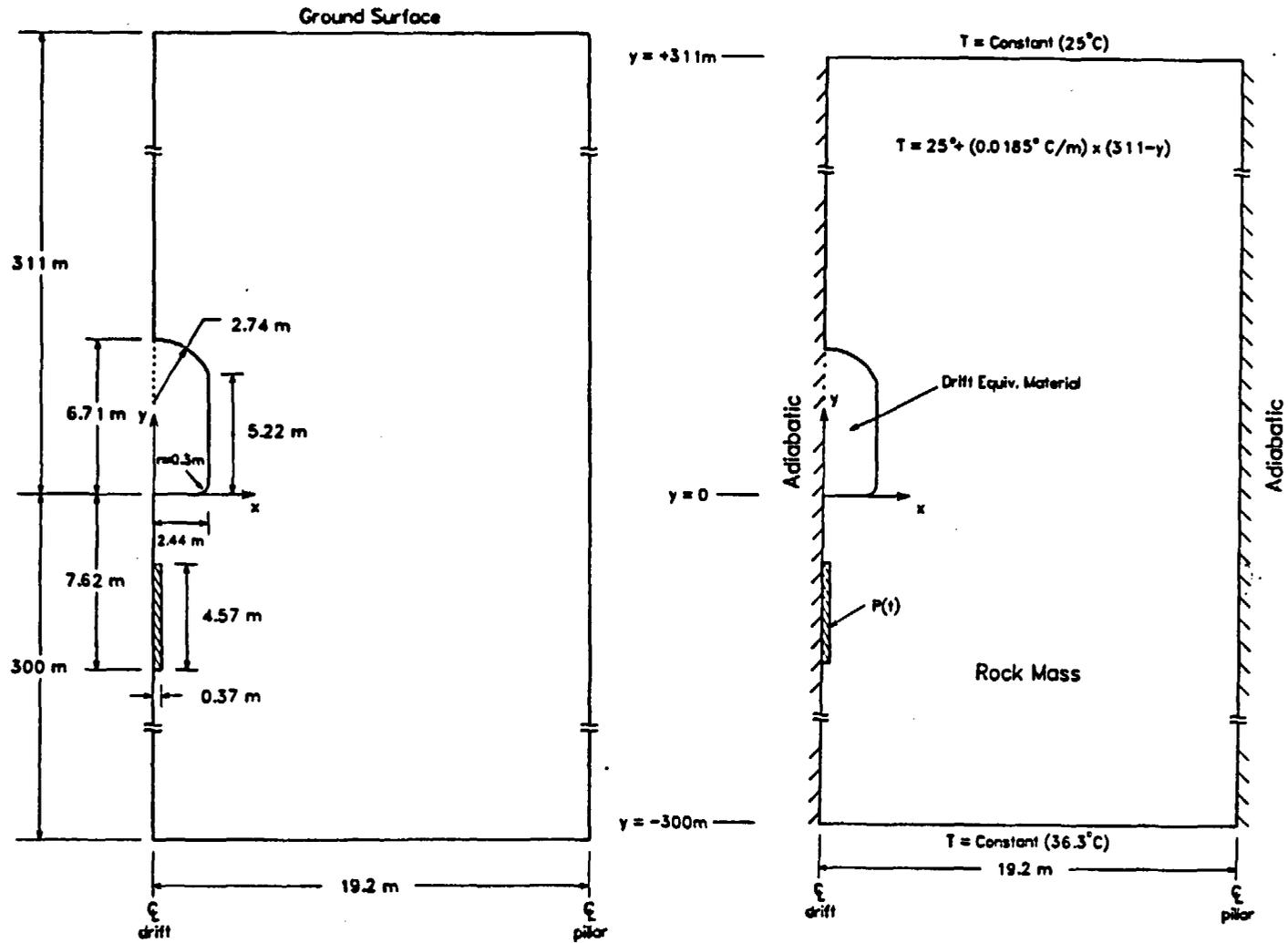


Figure 2-2. Analysis Region and Boundary Conditions

One mirror plane of symmetry, which is usually taken to be along the drift centerline, can be used. Thus, to simulate an infinite array of heated drifts, an array of 39 parallel drifts was used. It was assumed that this array was of sufficient extent that heat flow from the outermost drift would have little effect on the temperatures in the analysis region specified by the PDM. A plane of symmetry through the middle of the central drift was imposed, thereby requiring that the location of only 20 drifts be explicitly represented in the model. Figures 2-3 and 2-4 show the boundary element approximation of the problem.

The initial temperature at the upper surface of the analysis region was 25°C. A linear temperature gradient of 0.0185°C/m was assumed to run down from the top to the bottom of the modeled region. As a result, the lower boundary has a temperature of 36.3°C (Figure 2-2). Once the drift had been mined and the heat source had been emplaced, the material in the drift was considered to be an equivalent conductive material, where the conductivity of the equivalent material was assigned to account for the radiative, convective, and conductive heat transfer that would take place between the drift walls and the stagnant air in the drift.

The thermal output of the heated region was given in terms of a power density function (Appendix A). The rate of power density decay was chosen to correspond to the temporal decay of waste, 60% of which was produced by pressurized water reactor and 40% by boiling water reactors. The initial power density was 276 W/m² per metre of depth (z-direction).

The solution was to start at a problem time of 0 yr and to run through a problem time of 101 yr. The drift was mined instantaneously at a time of 0.5 yr. The heat source became active at a problem time of 1 yr.

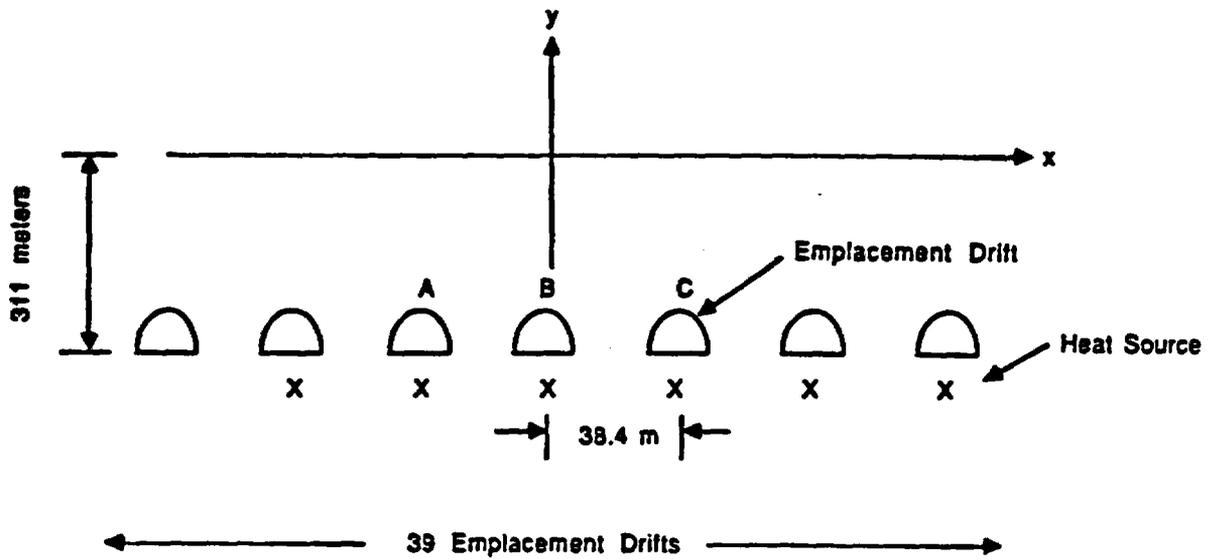


Figure 2-3. General Layout for HEFF Analysis

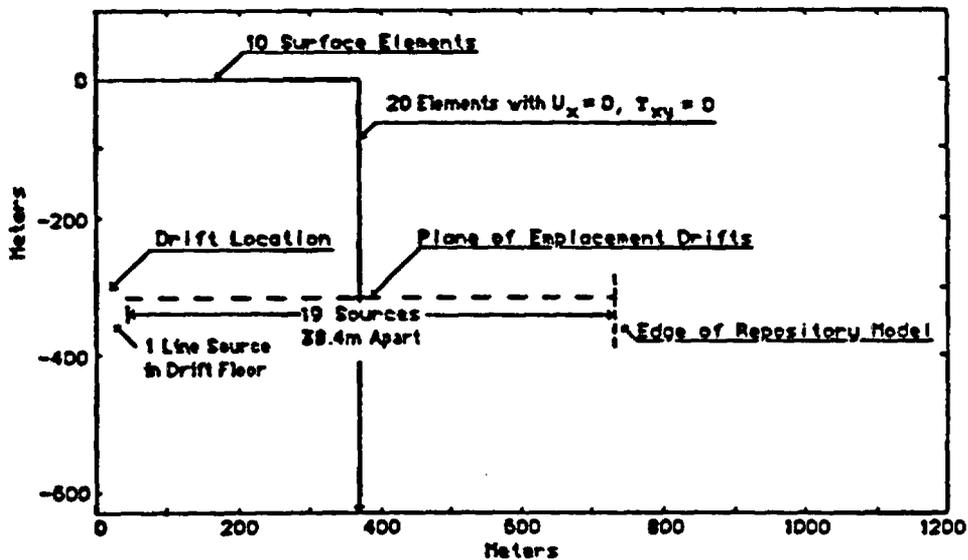


Figure 2-4. Layout of Heat Sources and Surface and Edge Elements for HEFF Analysis

2.2.2.2 Material Characterization

Both the thermal and mechanical properties were assumed to be uniform throughout the rock mass. The value of each property or material model parameter used in the solution was taken from the YMP RIB Version 2.002. It was assumed that the drift was located in the TSw2 thermal/mechanical unit. Specific values assigned to each parameter are given in Section 4 of Appendix A.

The drift was to be modeled as an unventilated, air-filled cavity. This was done without the necessity of calculating the radiative and convective heat transfer at the drift walls by assuming that the drift was filled with a conductive "drift equivalent material." The conductivity of the drift material was chosen to account for the combined effects of radiative, convective, and conductive heat transfer at the drift walls.

2.2.2.3 Output Specifications

Specific information concerning the calculations and the results was required to make a complete evaluation of the benchmark exercise and the codes and models used. In addition, each participant sent results in a specified format so that direct comparisons could be made easily. All results were transmitted by a letter report to the PIs, along with a computer-readable copy (magnetic tape or floppy disk) of the source code and required plot files.

Each participant was required to provide several pieces of information regarding his solution:

- problem run time (CPU seconds);
- computer used;
- convergence criteria and tolerance used for the solution; and
- mesh statistics:
 - figure showing the undeformed mesh,
 - the number of nodes,
 - the number and type of elements,
 - the number of degrees of freedom, and
 - the minimum and maximum node spacing.

Two sets of solution results were required. First, the temperature histories at Points A through G (Figure 2-5) were required. Second, the temperature as a function of distance along Lines 1, 2, and 3 (Figure 2-5) was required for Times 1, 6, 11, 26, 76, and 101 yr. Each solution produced 25 different plots for comparison.

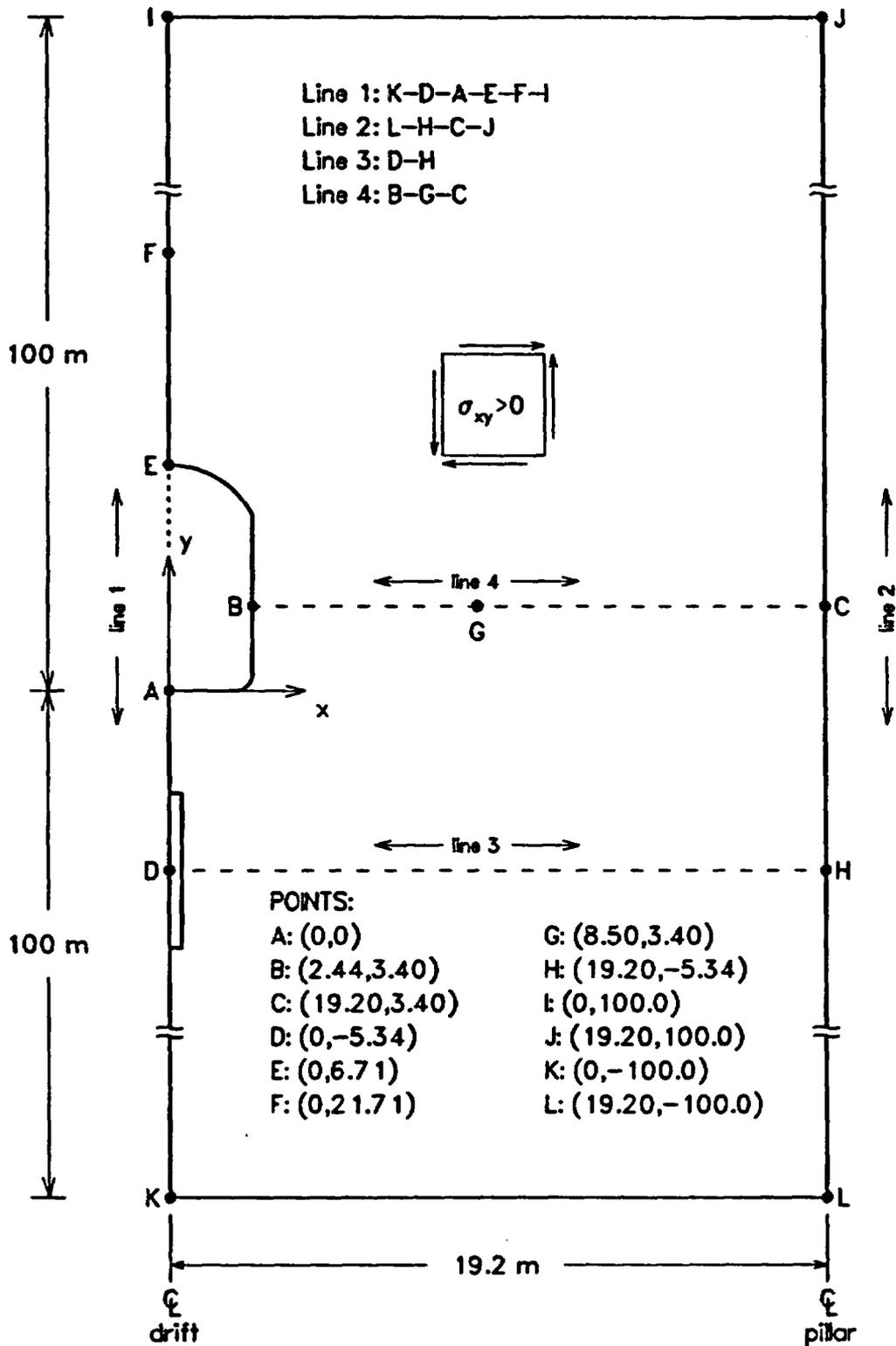


Figure 2-5. Points and Lines Where Data Are Reported

3.0 PARTICIPANTS

3.1 Participant Identification

The participant organizations, the analysts assigned, and the codes used are shown in Table 3-1. Three organizations are participating in the exercise: J. F. T. Agapito & Associates, Inc., located in Grand Junction, Colorado; SNL's Applied Mechanics Division (Division 1523); and RE/SPEC, Inc., located in Albuquerque, New Mexico. Because of the number of thermal and structural code combinations being used in the benchmark exercise, each participant organization assigned two analysts to the problem so that each analyst would be responsible for only one thermal and mechanical code combination.

TABLE 3-1

PARTICIPANT ORGANIZATIONS, ANALYSTS, AND CODES USED

<u>Participant Organization</u>	<u>Analyst</u>	<u>Thermal Code</u>	<u>Structural Code</u>	<u>Designation</u>
J. F. T. Agapito, Inc.	Asgian	DOT	JAC	DOT-J
	Goodrich	DOT ^a	VISCOT	DOT-V
	Goodrich	HEFF	HEFF	HEFF
SNL Division 1523	Holland	COYOTE	JAC	COYOTE-H
	Koteras	COYOTE	SANCHO	COYOTE-KM1 ^b
	Koteras	COYOTE	SANCHO	COYOTE-KM2 ^b
RE/SPEC, Inc.	Petney	SPECTROM-41	SANCHO	SPECTROM-41
	Labreche	SPECTROM-41 ^c	SPECTROM-31	(None)

- a. Two separate analyses were performed using different meshes that were compatible with the corresponding mechanical code.
- b. The second calculation used a more refined mesh for better resolution near the heat source.
- c. Only one thermal analysis was done (by S. Petney) using SPECTROM-41. The results will be used in the thermomechanical analysis using both SPECTROM-31 and SANCHO.

As shown in Table 3-1, some participants reported results from multiple runs of the same code using different meshes. In most cases, the reason that different meshes were used was that different mesh data were required for subsequent input to the structural codes that will be used in the next portions of the benchmarking exercise. The code designator given each analyst/code/mesh combination is used to identify the results from that run in the figures presented in the results section (Section 5).

3.2 Code Descriptions

In this section, a brief description of each code used in the thermal solution portion of the benchmark exercise is given.

3.2.1 COYOTE II

COYOTE II was developed at SNL by D. K. Gartling and is fully documented by Gartling (1987).* The code is intended for the analysis of heat conduction or other similar types of diffusion problems. The version used in this exercise (Version 02.00C) is limited to solving two-dimensional, plane, or axisymmetric problems. The code has both isotropic or orthotropic material models with properties that can vary with spatial location, time, or dependent variables. Volumetric source terms may be defined to vary in a general manner. The problems may be either steady-state or fully time-dependent.

Boundary conditions of all standard types (temperatures, heat fluxes, convective, and radiative) may be specified, subject to a few assumptions regarding radiation wave length and surface properties. All boundary conditions may be functions of spatial location or time.

COYOTE II is a self-contained code in the sense that it has its own mesh generator, data analysis package, and graphics routines. The element library includes isoparametric and subparametric quadrilaterals and triangles. Within each element, the temperature (and other variables) are approximated using either bilinear or biquadratic basis functions. For the solution of steady-state problems, a variant of the Picard iteration scheme is used. For solution of transient problems, implicit integration by either Euler (first order) or trapezoidal rule (second order) is used. Both integrators are used in a predictor/corrector mode with a fixed time step or a dynamic time step algorithm.

3.2.2 DOT

The Determination of Temperature (DOT) code was developed by Polivka and Wilson (1976). Supplemental documentation intended to meet NRC guidelines has been written by B. M. Thompson (1983) under contract to the Office of Nuclear Waste Isolation. The DOT code is a general purpose finite element heat transfer code. The code deals with linear and nonlinear transient or steady-state heat conduction in two-dimensional planar or axisymmetric geometries. Capabilities are provided for modeling anisotropic heterogeneous materials with temperature-dependent thermal properties and time-dependent temperature, heat flux, convection, and radiation boundary conditions. Time-dependent internal heat generation is

*Gartling, D. K., "COYOTE II--A Finite Element Computer Program for Nonlinear Heat Conduction Problems, Part II--User's Manual (2D)," SAND86-2725, Sandia National Laboratories, Albuquerque, NM, draft.

Gartling, D. K., "COYOTE II--A Finite Element Computer Program for Nonlinear Heat Conduction Problems, Part III--User's Manual (3D)," SAND86-2726, Sandia National Laboratories, Albuquerque, NM, draft.

Gartling, D. K., "COYOTE II--A Finite Element Computer Program for Nonlinear Heat Conduction Problems, Part IV--Example Analyses," SAND86-2727, Sandia National Laboratories, Albuquerque, NM, draft.

also available. Limitations of the code include the lack of a three-dimensional analysis capability, no radiative or convective internal heat transfer, and the need to maintain a constant time step in each program execution.

3.2.3 SPECTROM-41

SPECTROM-41 is a finite element heat transfer code developed specifically for the analysis of thermal problems related to the disposal of radioactive waste.* The principal component model used in the program is based on the Fourier law of conductance. Numerous options provide the capability of considering various boundary conditions, material stratification and anisotropy, and time-dependent heat generation.

3.2.4 HEFF

HEFF is a computer program based on an indirect formulation of the boundary element method for plane strain elastic analyses.** The initial conditions for such analyses are prescribed boundary tractions or displacements and self-equilibrated initial stress. Through use of a thermoelastic solution to the problem of a line heat source in an infinite elastic medium, thermal loading can be treated as additional initial displacements and initial stresses. This approach allows approximate solution of thermomechanical problems in which the heat transfer process is transient but in which the process of deformation is considered to be pseudostatic.

HEFF can be used on problems where it may be assumed that the medium is homogeneous, isotropic, and linearly elastic and that the material properties are independent of temperature. By virtue of its boundary element formulation, the code is well suited to solving problems involving long holes in an infinite medium. Semi-infinite problems can also be treated if the appropriate boundary conditions are defined at the free surface through the use of boundary elements and image heat sources.

HEFF was included in the benchmark exercise because it uses the boundary element method for the solution of linear elastic problems, which is considerably different from the finite element method used by the other codes. However, the boundary element method can only be used for linear elastic problems, and, in order to solve thermomechanical problems, the solution for the temperature field must be approximated by the analytical solution for a line heat source in an infinite medium. Because of the code's potential usefulness, the results from HEFF will be compared with the results from the other linear elastic solutions to assess the effect of the approximations used on the overall solution and to determine the limits of accuracy that can be expected.

*D. K. Svalstad, "Documentation of SPECTROM-41: A Finite Element Heat Analysis Program," SAND88-7122, Sandia National Laboratories, Albuquerque, NM, draft.

**J. F. T. Agapito and Associates, Inc., "HEFF--A User's Manual and Guide for the HEFF Code for Thermal-Mechanical Analysis Using the Boundary-Element Method," SAND87-7075, Contract Report for Sandia National Laboratories, Albuquerque, NM, draft.

4.0 CONTROL PROCEDURES

4.1 Quality Assurance Requirements

This benchmark exercise is being conducted under the procedures described in Department Operating Procedures for Analysis Control and Verification (DOP 2-4) and for Analysis Definition (DOP 3-3) prepared by SNL Department 6310. For the work done, the data transmission procedures followed are described in Section 4.3; no interface procedural controls were in place at the time the work was done. The analysis definition was accomplished through the issuance of a PDM, which completely described the problem to be solved and the reporting requirements (Appendix A). The PDM was first issued in draft form so that the participants could review the problem and submit comments. A meeting with the participants was then held to review and resolve all comments to the satisfaction of all participants so that a final PDM could be issued. Department operating procedures (DOP 2-4) also require that the conduct and results of the benchmark analyses be subjected to technical review. This requirement is being met by fully documenting each phase of the exercise in the form of a report subjected to technical and management review before release. In addition, it is intended that the results of this benchmark exercise be subjected to a peer review by a panel composed of technical experts not connected with the Project.

Department operating procedures also specify requirements for control and documentation of the software used in the analyses (DOP 3-2). These procedures did not come into force before the start of the benchmark analyses. However, before completion of the benchmark analyses, all requirements for software configuration management and certification will have been met. To ensure a complete record of the codes and procedures used in the benchmark exercise, the PDM required each participant to submit a computer-readable version of each code used, the input files for the code, and the required output files. The PIs also requested a copy of all documentation related to each code being used. The code versions used in this exercise were entered in the SNL software configuration management system as the initial version of the code to be used in the project. Any changes or alterations in the codes will be documented and controlled by the modification or discrepancy system (DOP 3-2). Once the codes and documentation had been entered in the SNL software QA system, memos of certification that certified the use of the code on this QA Level II activity were issued for each code used in the benchmark exercise.

4.2 Communications with Participants

All communications regarding the benchmark exercise were distributed through the PIs. Because each analyst who was assigned to use a specific code was expected to work the problem with no outside assistance, the PDM specifically required that the analysts not communicate among themselves. This requirement applied as well to analysts working for the same participant organization but using different codes. The requirement was invoked because of the desire to simulate conditions that occur during normal analyses; that is, the analyst was expected to follow the PDM exactly and contact only the PI for clarification, if necessary.

4.3 Transmission and Verification of Data

At the completion of each phase of the benchmark exercise, the participants were required to submit a letter report that included a description of how the analysis was conducted, any problems encountered, and output listings and plots of the results. In addition, four computer files of results (for the thermal analysis) were submitted on magnetic tape or floppy disk in ASCII format. These files were then read into SNL's VAX computer system and processed for comparison plots. Each set of computer results was plotted using the SNL system and was compared with the hard copy plots provided by each participant. This procedure allowed the PIs to verify that the data were transmitted and read correctly. No problems were encountered in transferring data to the PIs. Once the data had been verified, a series of plots was prepared that compared the results from all participants. These results are discussed in Section 5.

5.0 RESULTS

5.1 Mesh Statistics and Computer Usage

As part of the reported results, each participant was required to provide some general information regarding the mesh used, the type of computer used, and the computer processor time required to solve the problem. Table 5-1 lists the mesh statistics required by the PDM and discussed in Section 2.2.2.3 of this report. A mesh typical of those used for the finite element analyses is shown in Figure 5-1. The mesh shown in the figure is for the DOT-J computation. Meshes used by other analysts were quite similar, differing only in degree of coarseness or fineness near the drift. The computers and computation time (reported in CPU seconds) are listed in Table 5-2. The results are listed by the code designation given in Table 3-1. All of the codes listed in Tables 5-1 and 5-2 are finite-element-based thermal codes. The results from HEFF, which uses an approximate analytic solution for the thermal part of the problem, will be discussed separately.

TABLE 5-1
MESH STATISTICS

<u>Code</u>	<u>Number of Nodes*</u>	<u>Type of Element</u>	<u>Number of Elements</u>	<u>Spacing (m)</u>	
				<u>Minimum</u>	<u>Maximum</u>
SPECTROM-41	2,174	8-node quadrilateral	671	0.07	21.80
COYOTE-KM1	2,857	4-node quadrilateral	2,640	0.37	5.27
COYOTE-KM2	2,837	4-node quadrilateral	2,664	0.29	7.89
COYOTE-H	5,119	4-node quadrilateral	4,921	0.12	5.02
DOT-J	1,145	4-node quadrilateral	1,036	0.15	9.08
DOT-V	2,467	8-node quadrilateral	770	0.11	28.57

*Because the only variable is the temperature, the number of degrees of freedom is equal to the number of nodes.

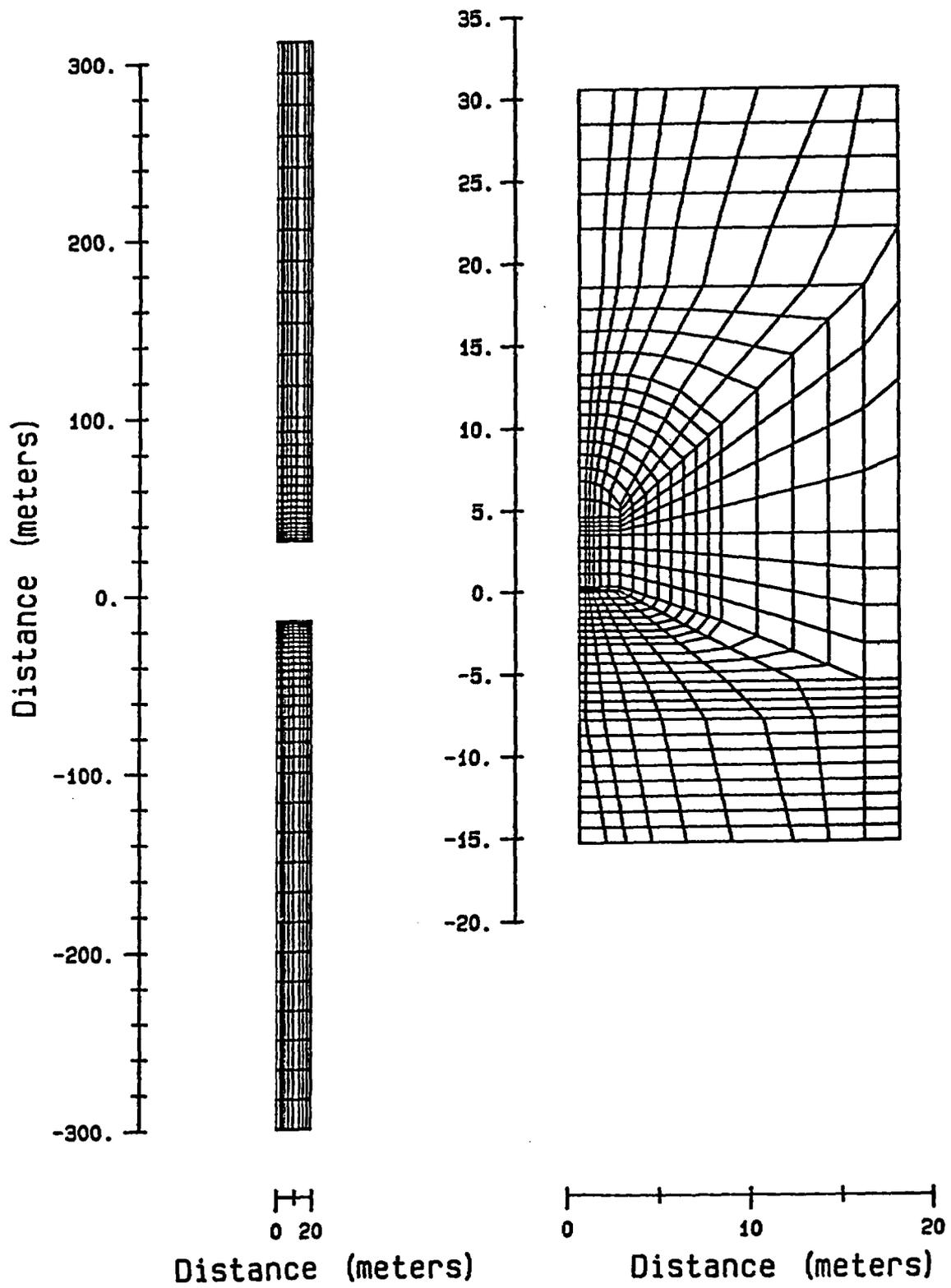


Figure 5-1. Finite Element Mesh Used in the DOT-J Calculation

TABLE 5-2
COMPUTER USAGE

<u>Code</u>	<u>Computer</u>	<u>CPU Time (sec)</u>
SPECTROM-41	VAX 11/750	33,827
COYOTE-KM1	CRAY XMP	1,456
COYOTE-KM2	CRAY XMP	1,491
COYOTE-H	CRAY XMP	869
COYOTE-H CORR*	CRAY XMP	631
DOT-J	IBM-PC/AT	17,640
DOT-V	IBM-PC/AT	15,120

*Corrected solution (Section 7).

Because the thermal model in HEFF is based on the solution for a line heat source in an infinite medium, the thermal analysis was performed as though the drifts were not present. The code generates a solution only for a given time. Thus, solutions for each time step require separate runs of the code. For the thermal problem, ten runs were made to get solutions at 1.0, 1.25, 1.5, 2.0, 4.0, 6.0, 11.0, 26.0, 76.0, and 101.0 yr. The code was run on an IBM-AT with a total run time of 4,020 CPU sec for 10 runs.

5.2 Temperature Histories at Selected Points

The temperature histories at Points A through G (Figure 2-5) from each code are compared in Figures 5-2 through 5-8. Five of the six finite element solutions (COYOTE-H is the exception) agree to within 1.0% or better at all points except Point D. During the early heating phase at Point D (Figure 5-5), the solutions vary by approximately 9% from the mean, which is probably caused by the different ways the heat source power history was put into the codes.

The COYOTE-H solution shows small deviations (1 to 2%) from the other finite element solutions, which are especially evident at Point A (Figure 5-4). It appears that this difference is caused by the premature activation of the heat source. The analyst was requested to investigate this anomaly and to rerun the problem, if necessary (Section 7).

The thermal solution from HEFF at Points A through G are within 15 to 18% of the finite element solutions at all points, and, in most places, better agreement is achieved. The difference is most noticeable at points closest to the drift because, in the approximate analytical solution incorporated in HEFF, the analysis region is assumed to have uniform and

constant properties. Thus, the presence of the drift is neglected in the thermal solution produced by HEFF. As a consequence, temperatures near the drift are higher than those predicted by the finite element solutions, which take into account the thermal properties of the unventilated drift air.

5.3 Temperature along Selected Paths at Six Times

The temperature distributions along Lines 1, 2, and 3 (Figure 2-5) at 6, 11, 26, 76, and 101 yr are shown in Figures 5-9 through 5-23. For Lines 1 and 2, the zero position is at $y = 0$ in Figure 2-5, and, for Line 3, the zero position is at Point D (Figure 2-5). Agreement among all the finite element solutions is quite good. The HEFF solution is in good agreement with the finite element results at 6 and 11 yr. With increasing time, HEFF tends to predict temperatures somewhat larger than those predicted by the other codes. At 101 yr, the maximum difference between HEFF and the other codes is approximately 20%. Part of this difference can be accounted for by the fact that HEFF does not take into account the changes in thermal properties of the rock mass that occur near the boiling point of water. In addition, the heat of vaporization of water is not taken into account, resulting in the deposition of more energy into the rock than is the case in the finite element solutions.

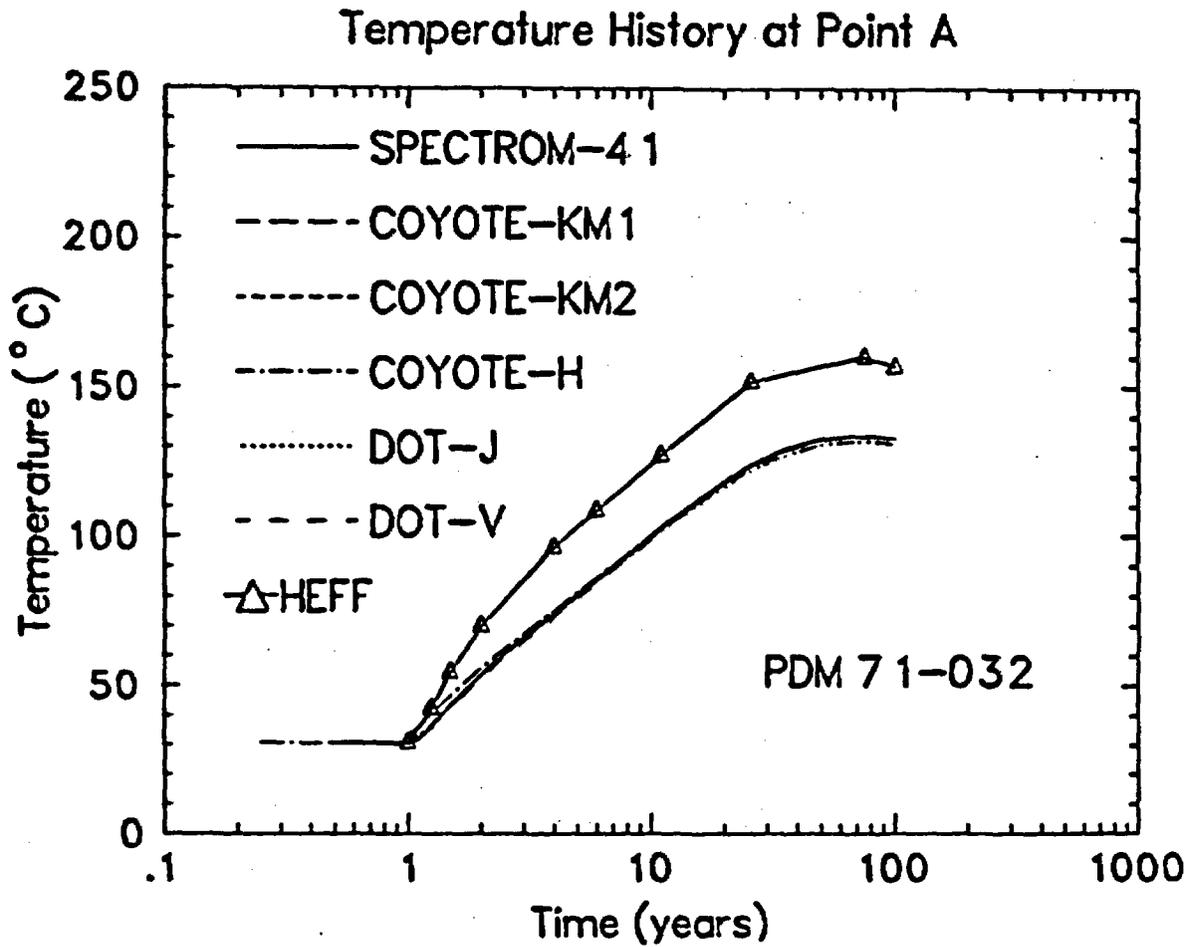


Figure 5-2. Comparison of Results for the Temperature History at Point A (Figure 2-5)

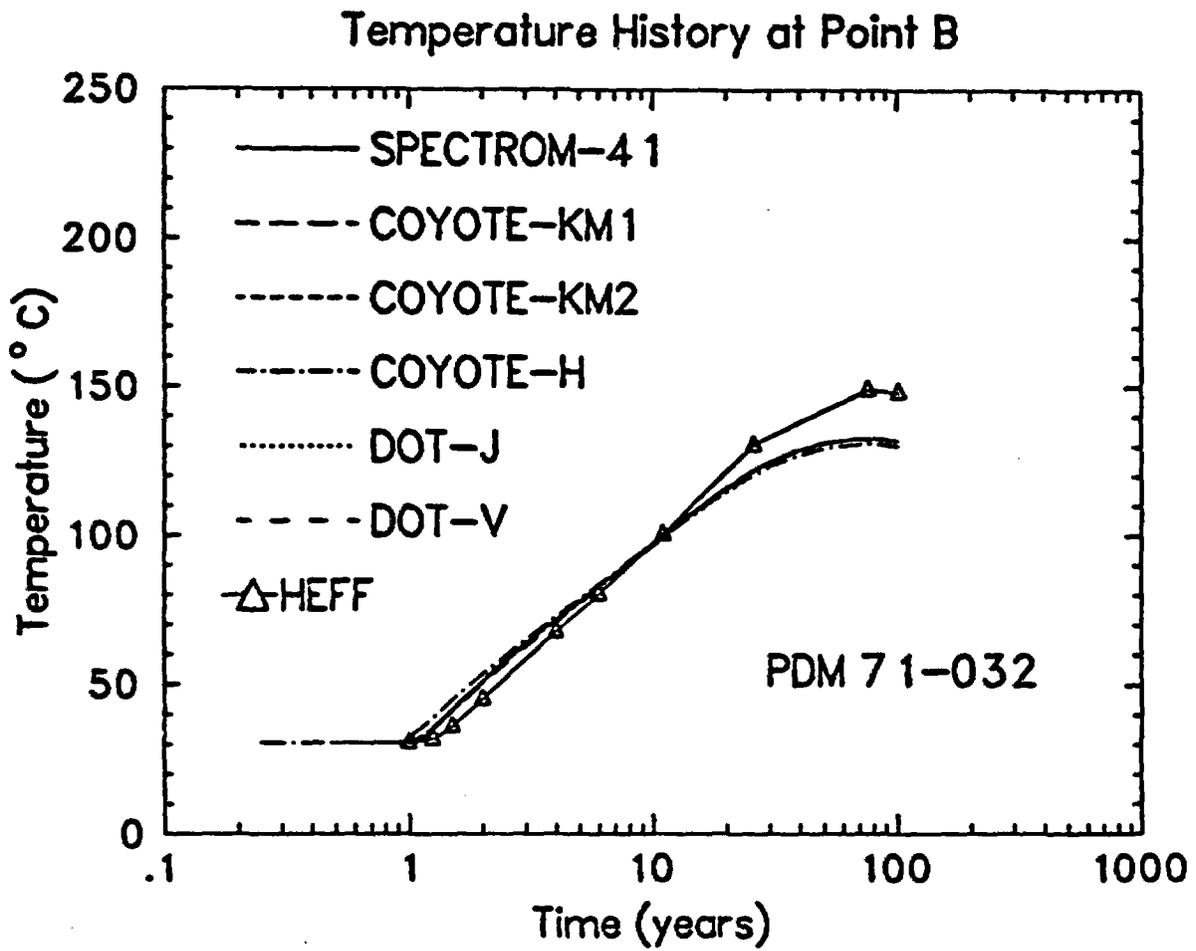


Figure 5-3. Comparison of Results for the Temperature History at Point B (Figure 2-5)

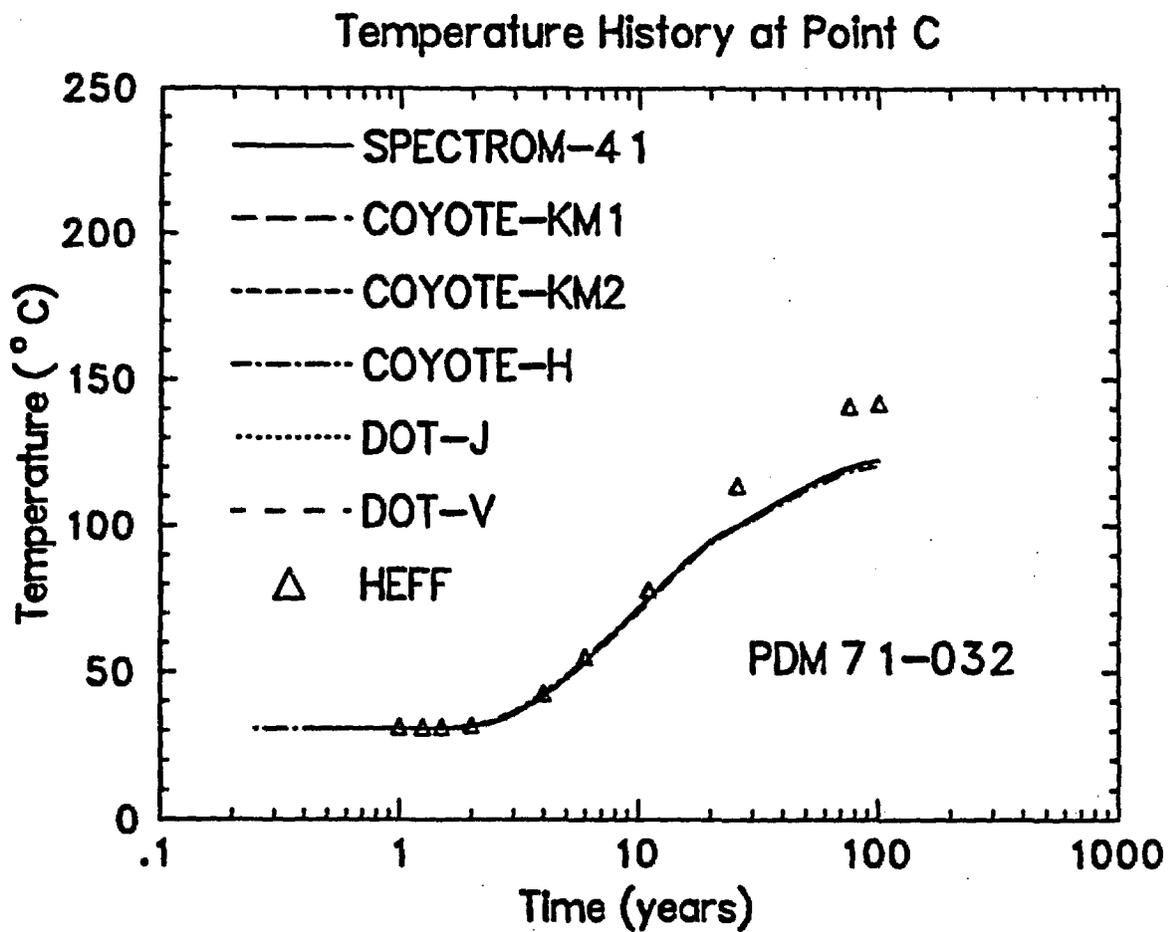


Figure 5-4. Comparison of Results for the Temperature History at Point C (Figure 2-5)

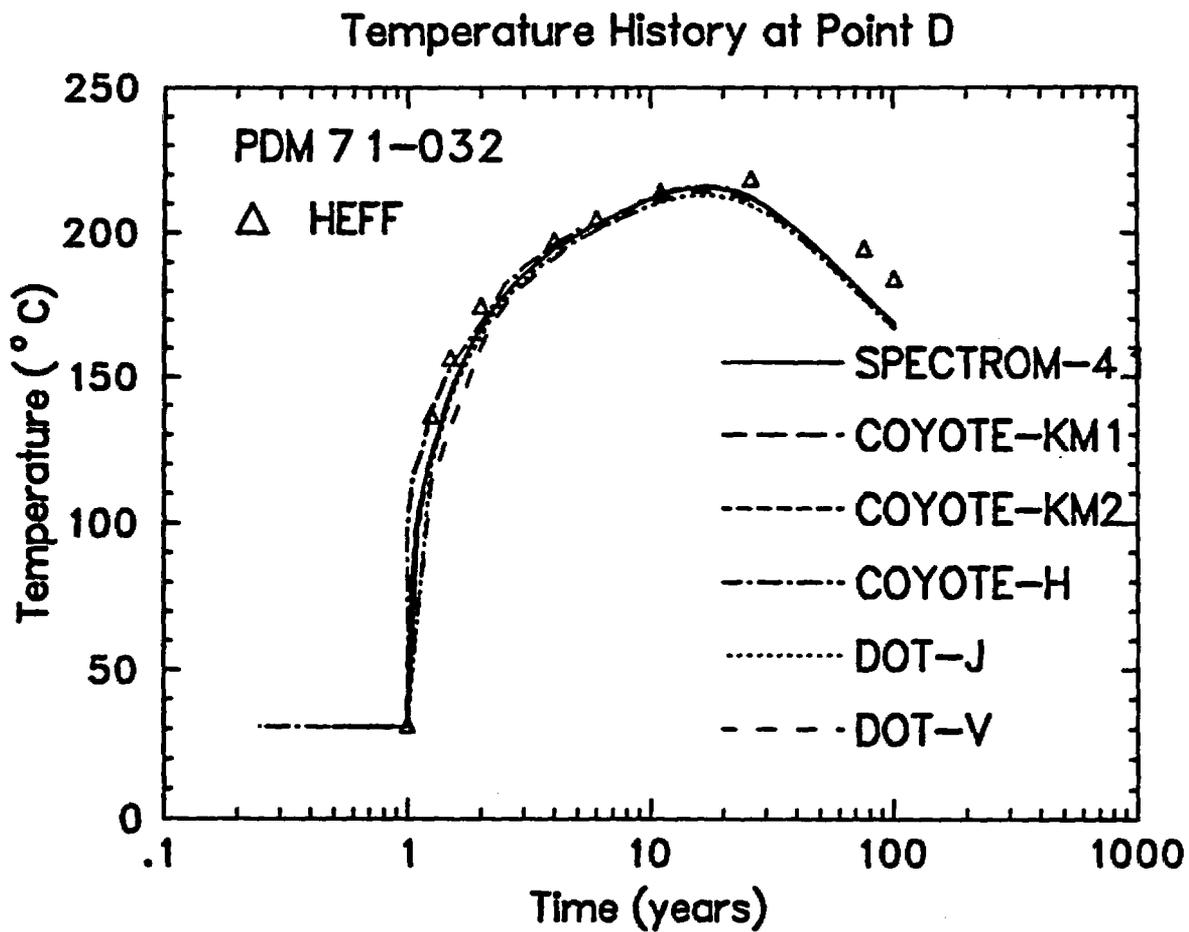


Figure 5-5. Comparison of Results for the Temperature History at Point D (Figure 2-5)

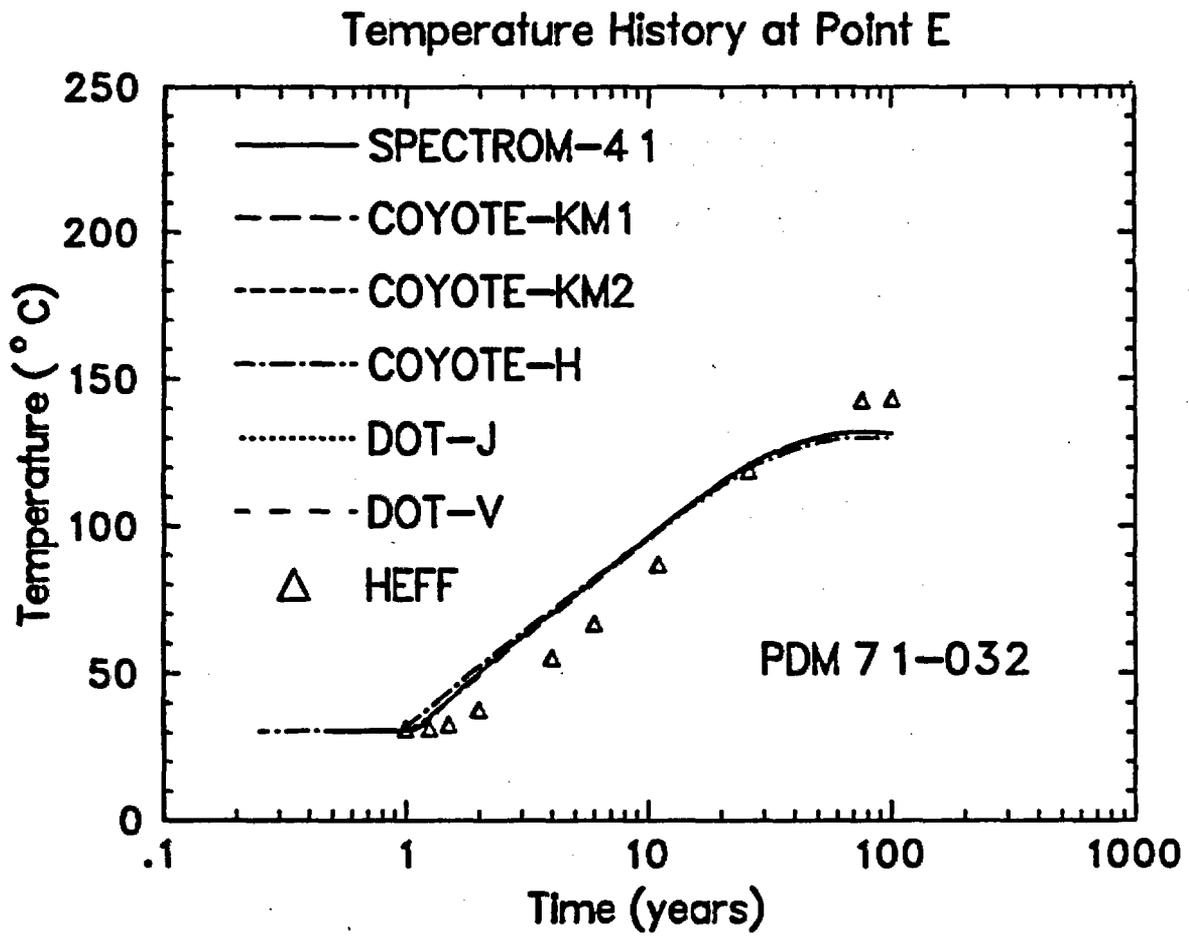


Figure 5-6. Comparison of Results for the Temperature History at Point E (Figure 2-5)

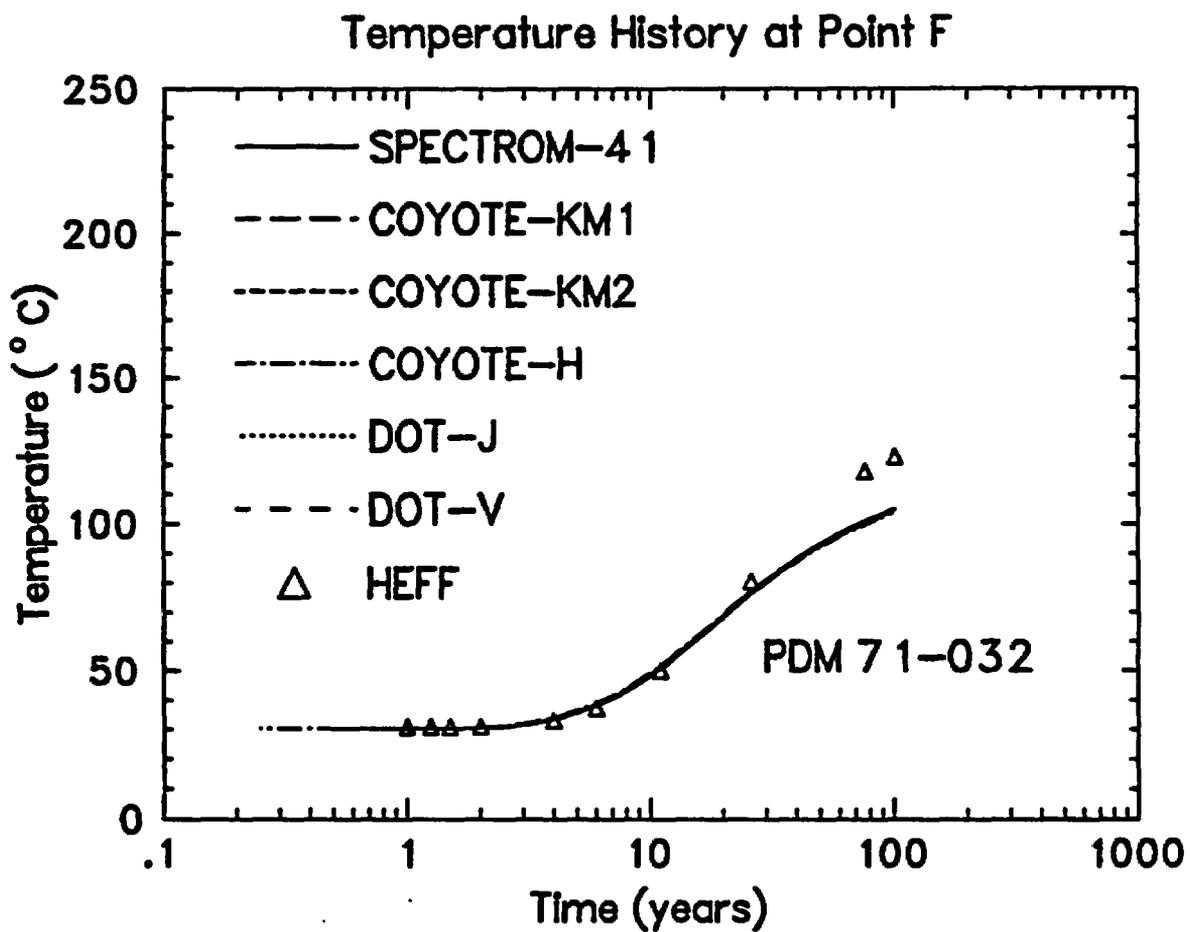


Figure 5-7. Comparison of Results for the Temperature History at Point F (Figure 2-5)

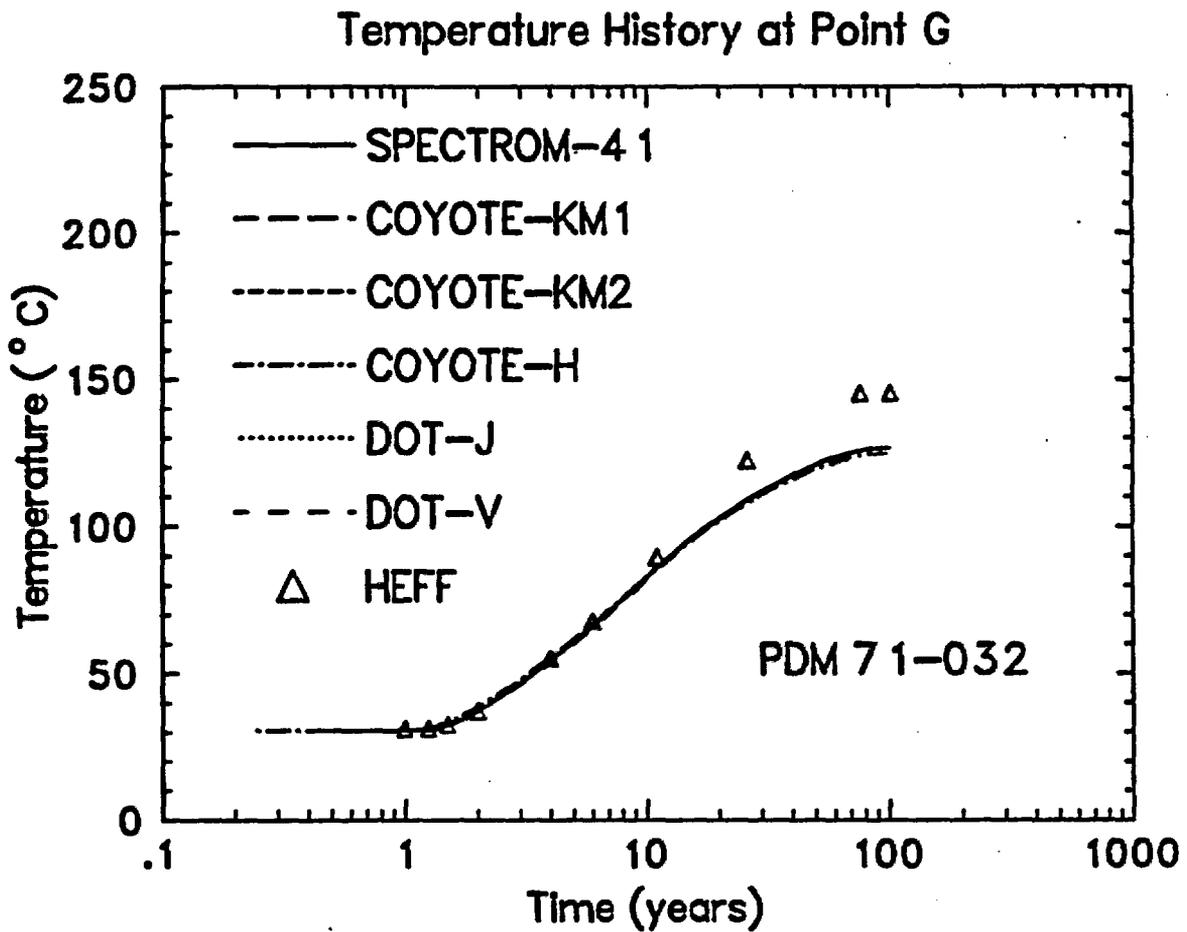


Figure 5-8. Comparison of Results for the Temperature History at Point G (Figure 2-5)

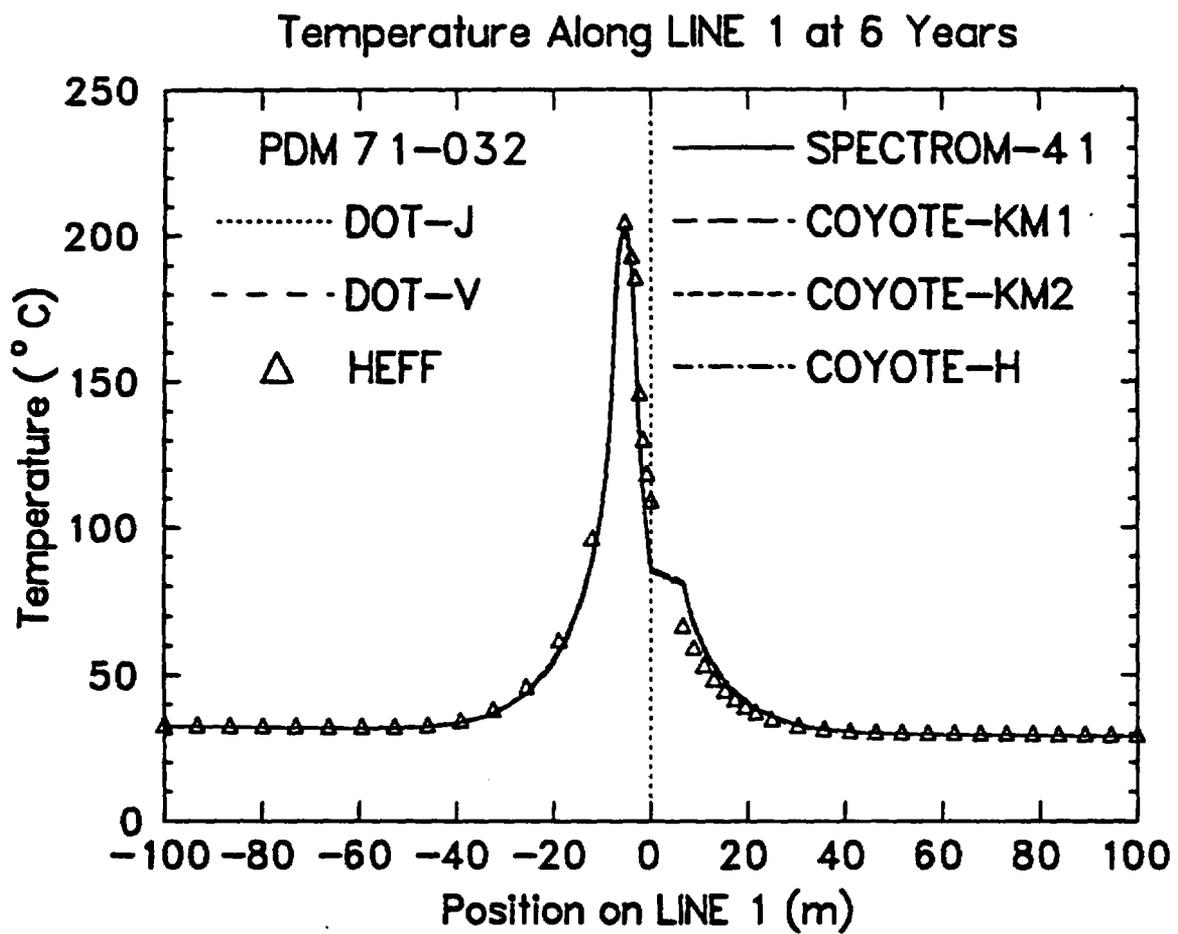


Figure 5-9. Comparison of Results for the Temperature along Line 1 (Figure 2-5) at 6 Yr

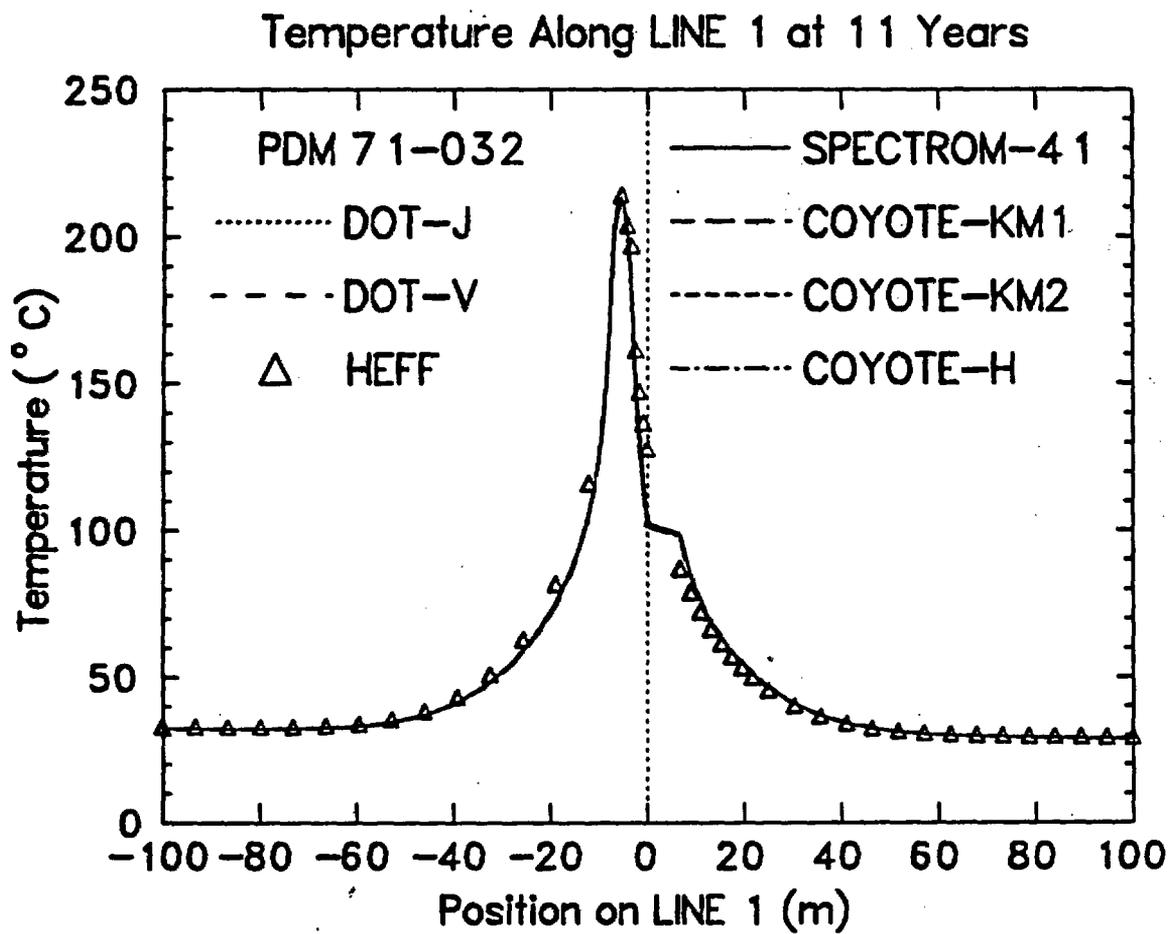


Figure 5-10. Comparison of Results for the Temperature along Line 1 (Figure 2-5) at 11 Yr

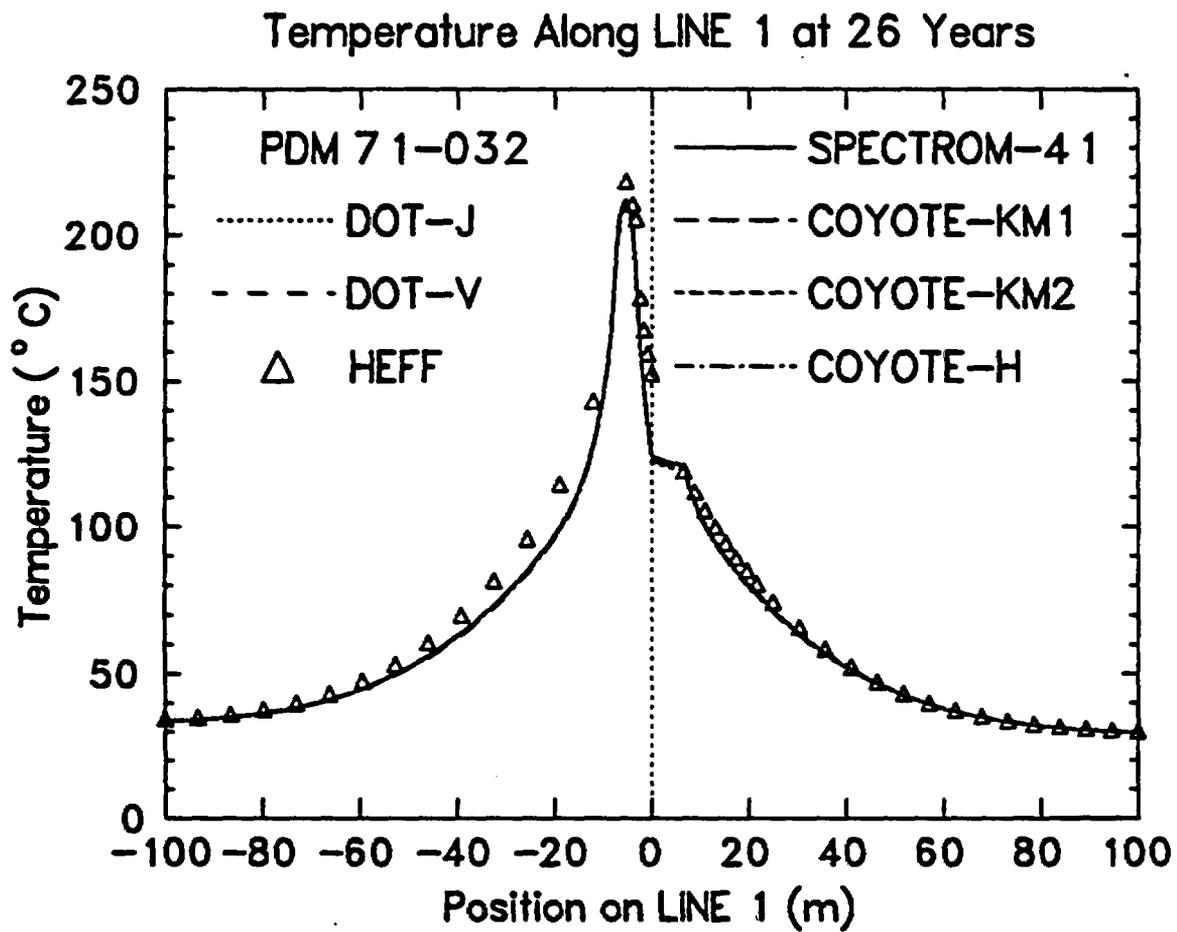


Figure 5-11. Comparison of Results for the Temperature along Line 1 (Figure 2-5) at 26 Yr

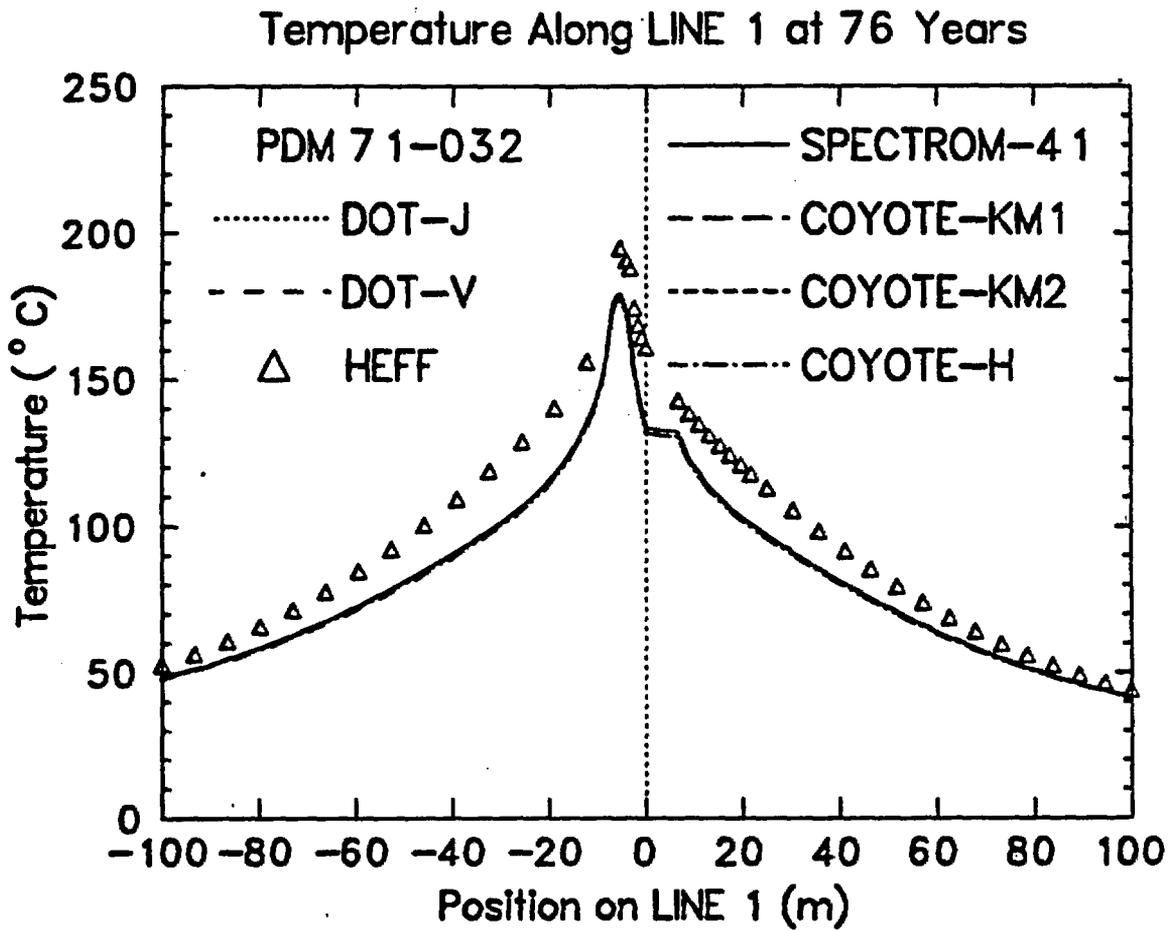


Figure 5-12. Comparison of Results for the Temperature along Line 1 (Figure 2-5) at 76 Yr

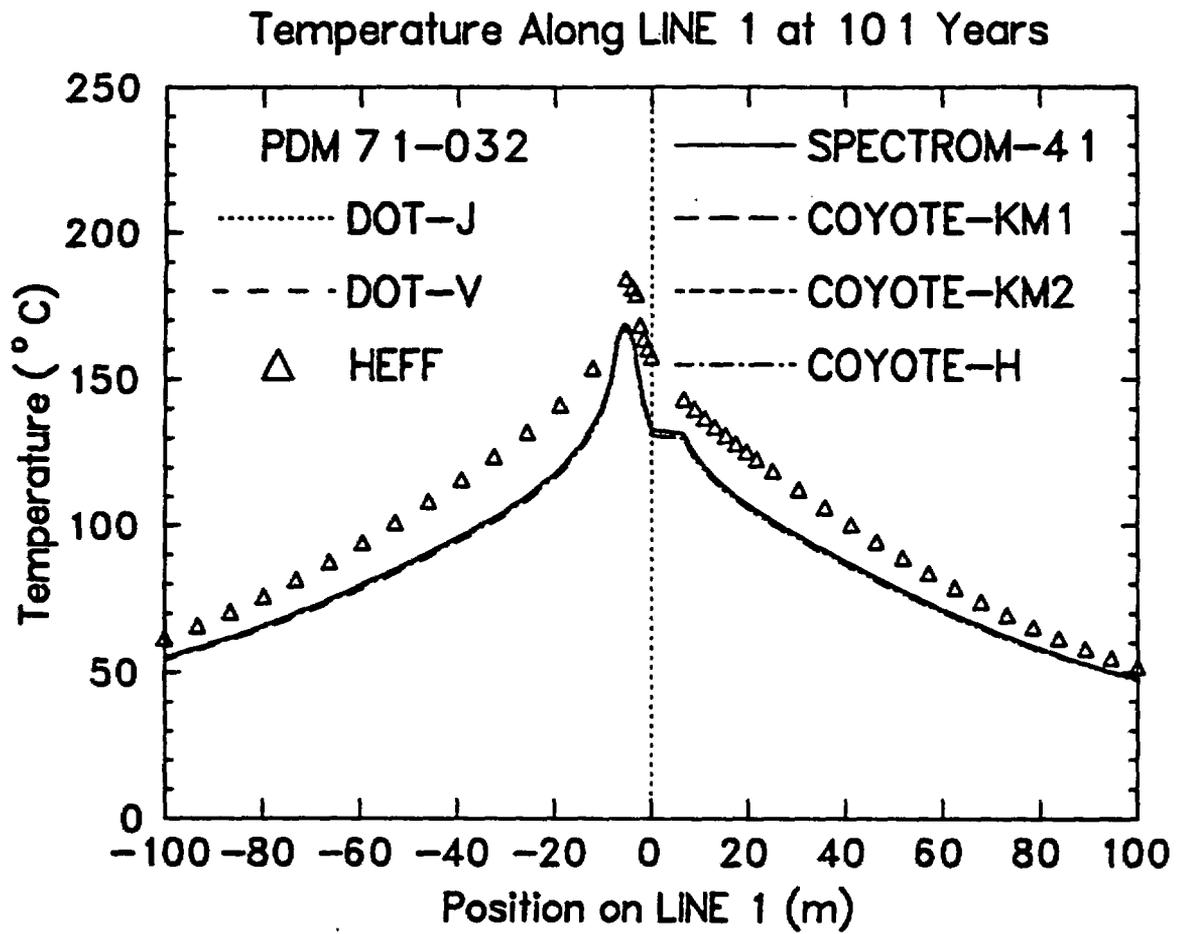


Figure 5-13. Comparison of Results for the Temperature along Line 1 (Figure 2-5) at 101 Yr

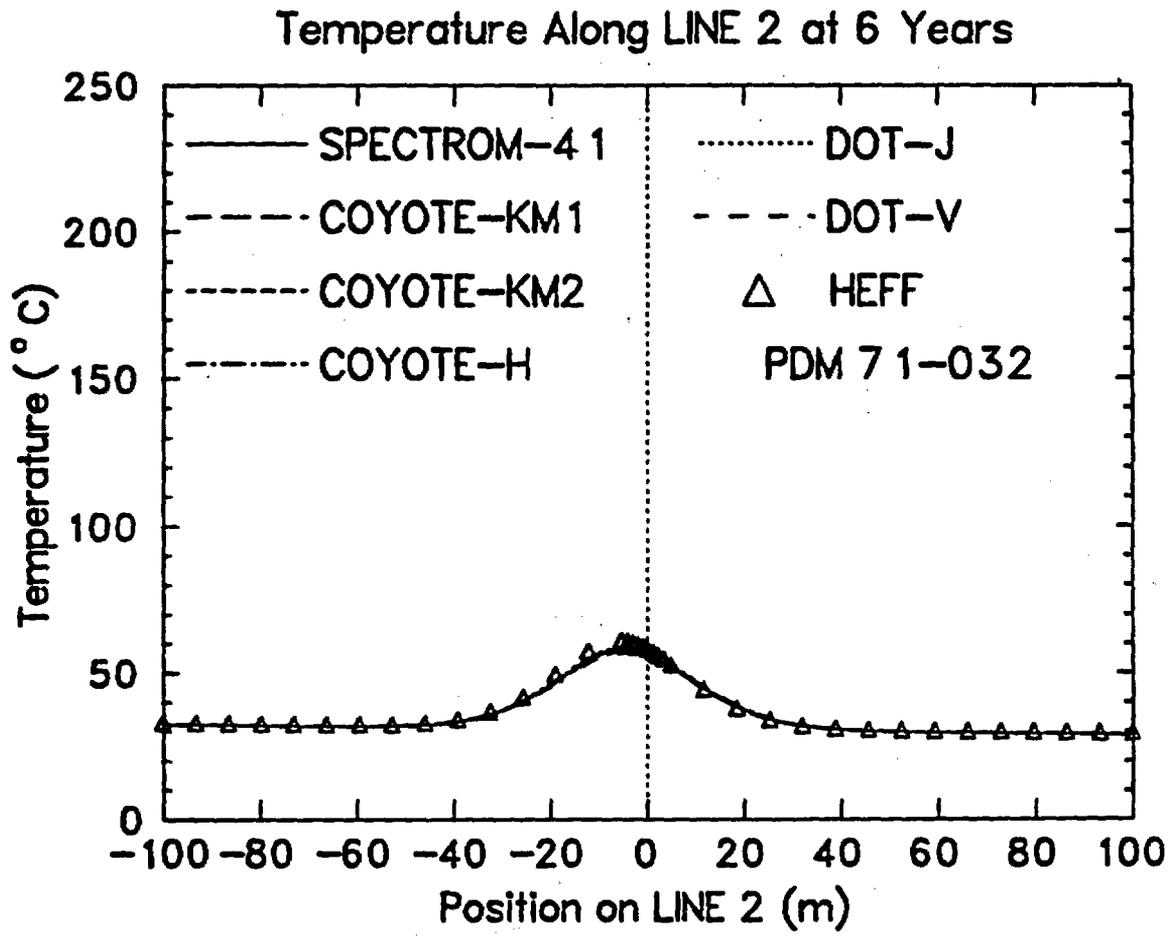


Figure 5-14. Comparison of Results for the Temperature along Line 2 (Figure 2-5) at 6 Yr

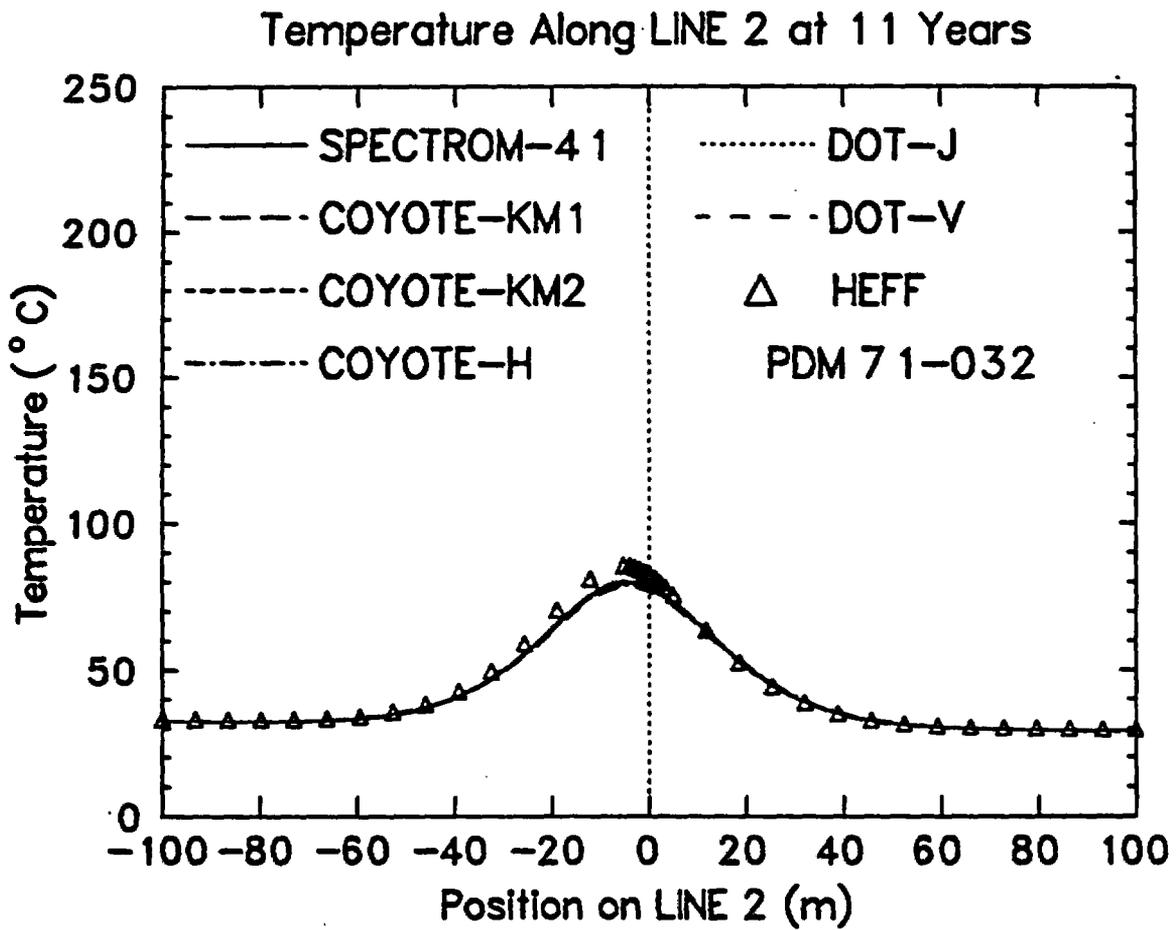


Figure 5-15. Comparison of Results for the Temperature along Line 2 (Figure 2-5) at 11 Yr

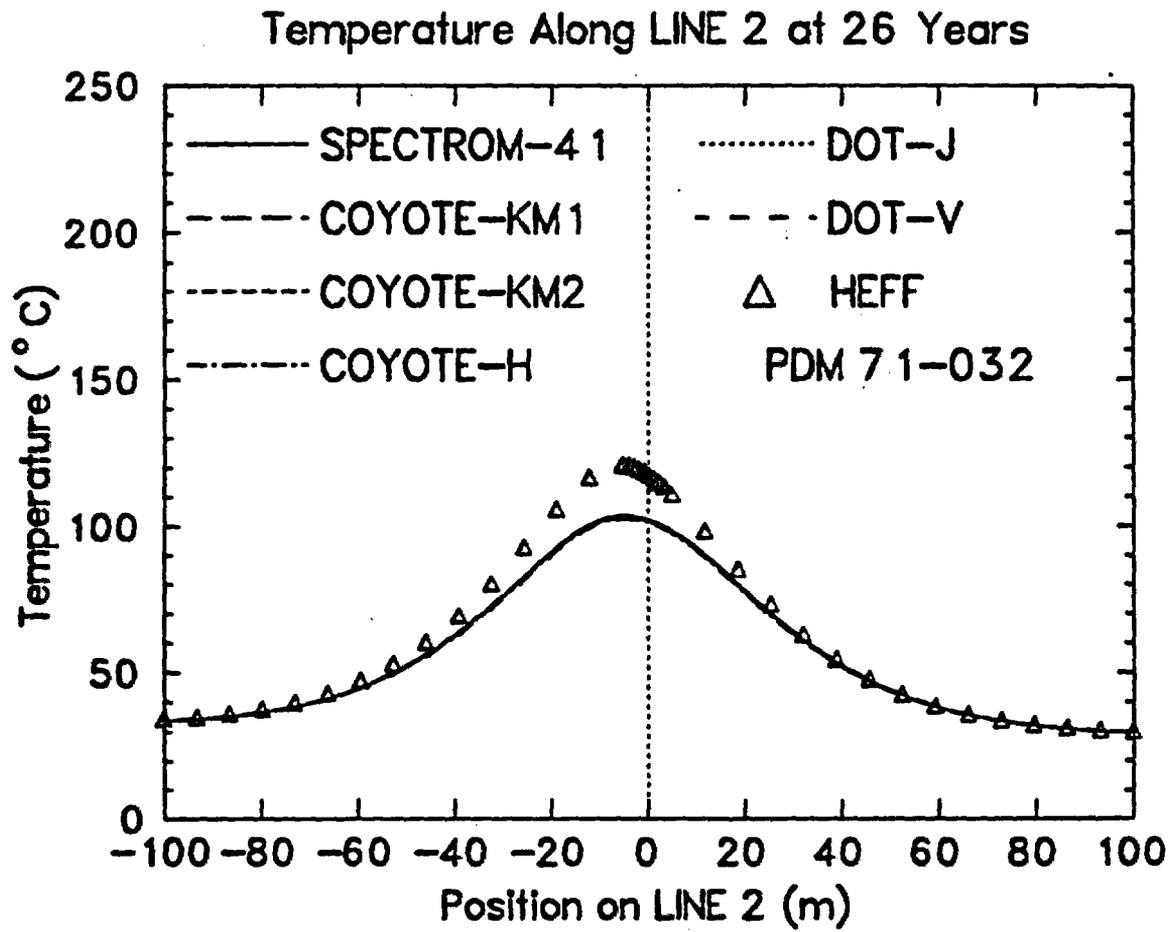


Figure 5-16. Comparison of Results for the Temperature along Line 2 (Figure 2-5) at 26 Yr

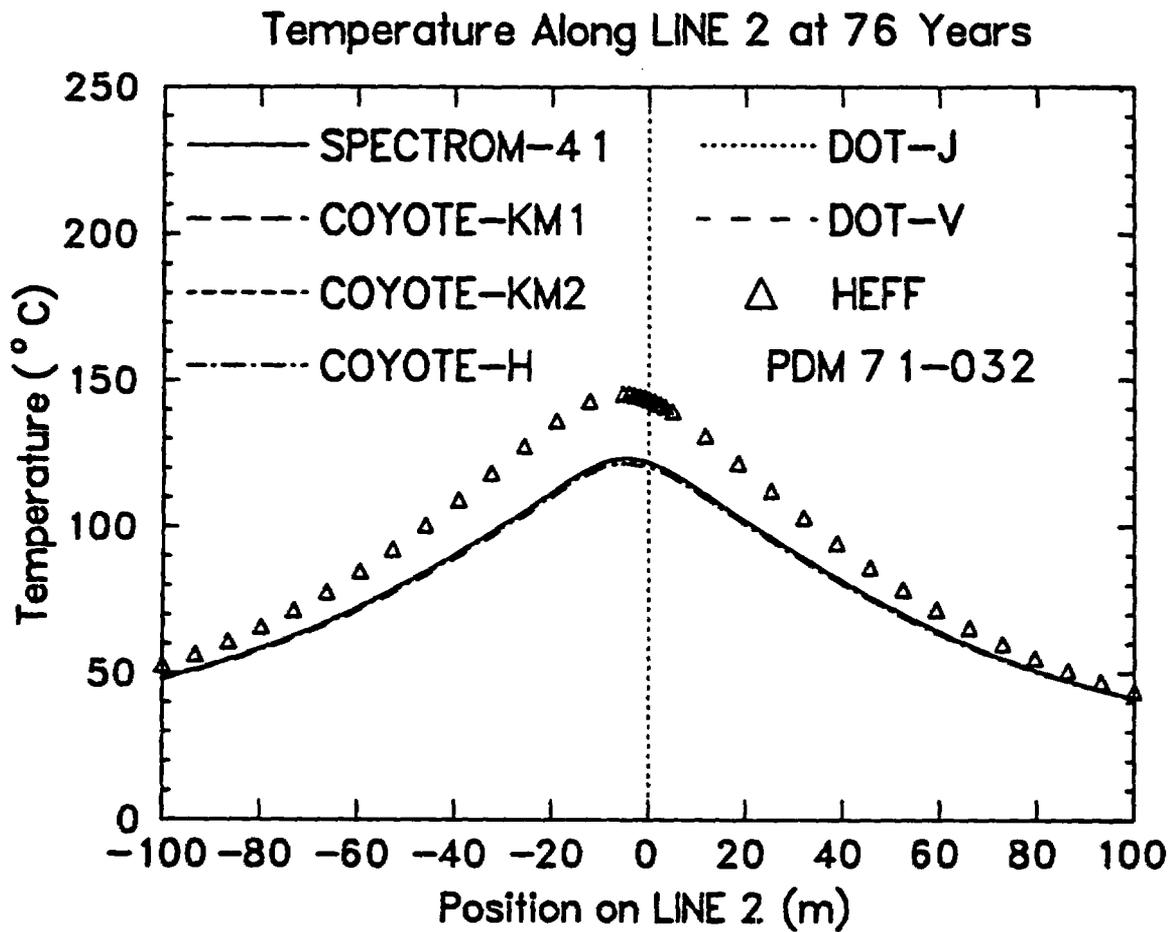


Figure 5-17. Comparison of Results for the Temperature along Line 2 (Figure 2-5) at 76 Yr

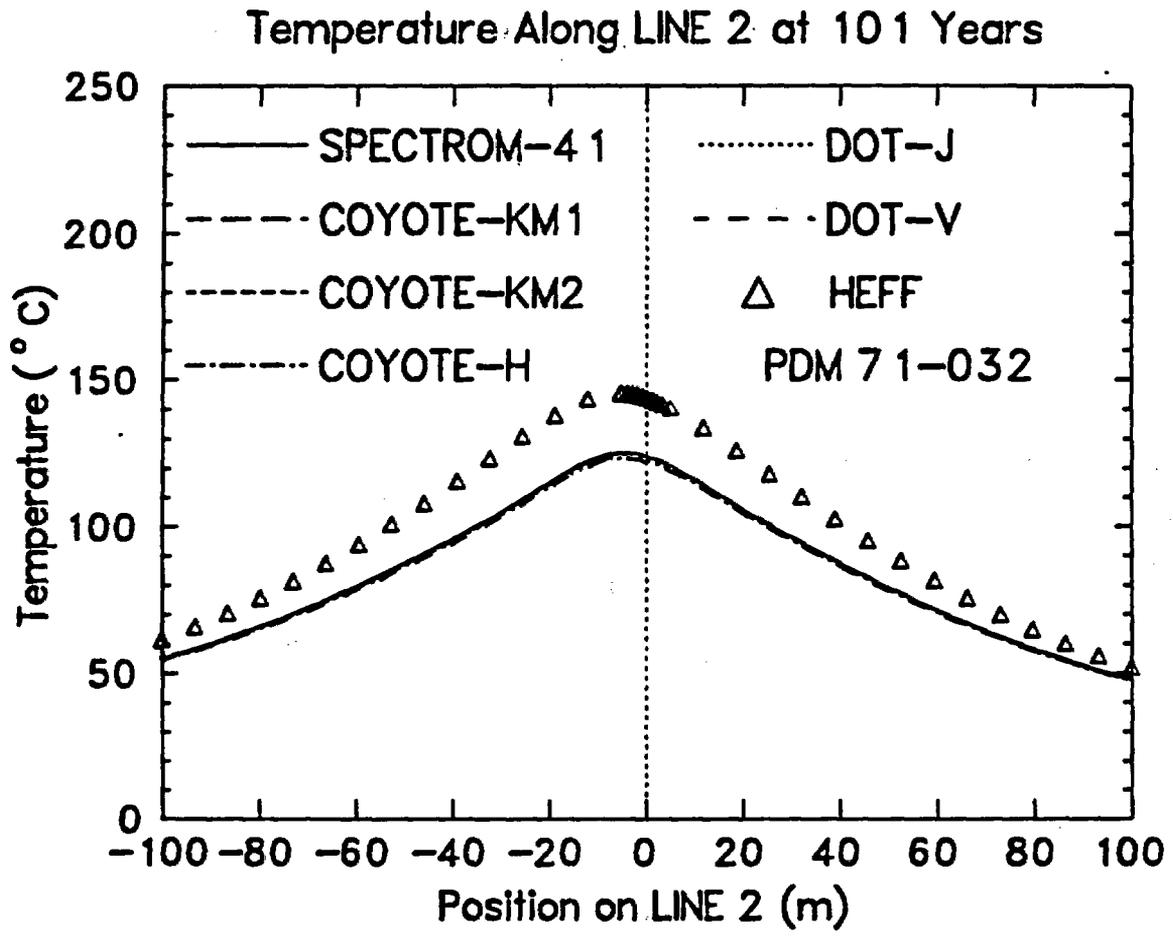


Figure 5-18. Comparison of Results for the Temperature along Line 2 (Figure 2-5) at 101 Yr

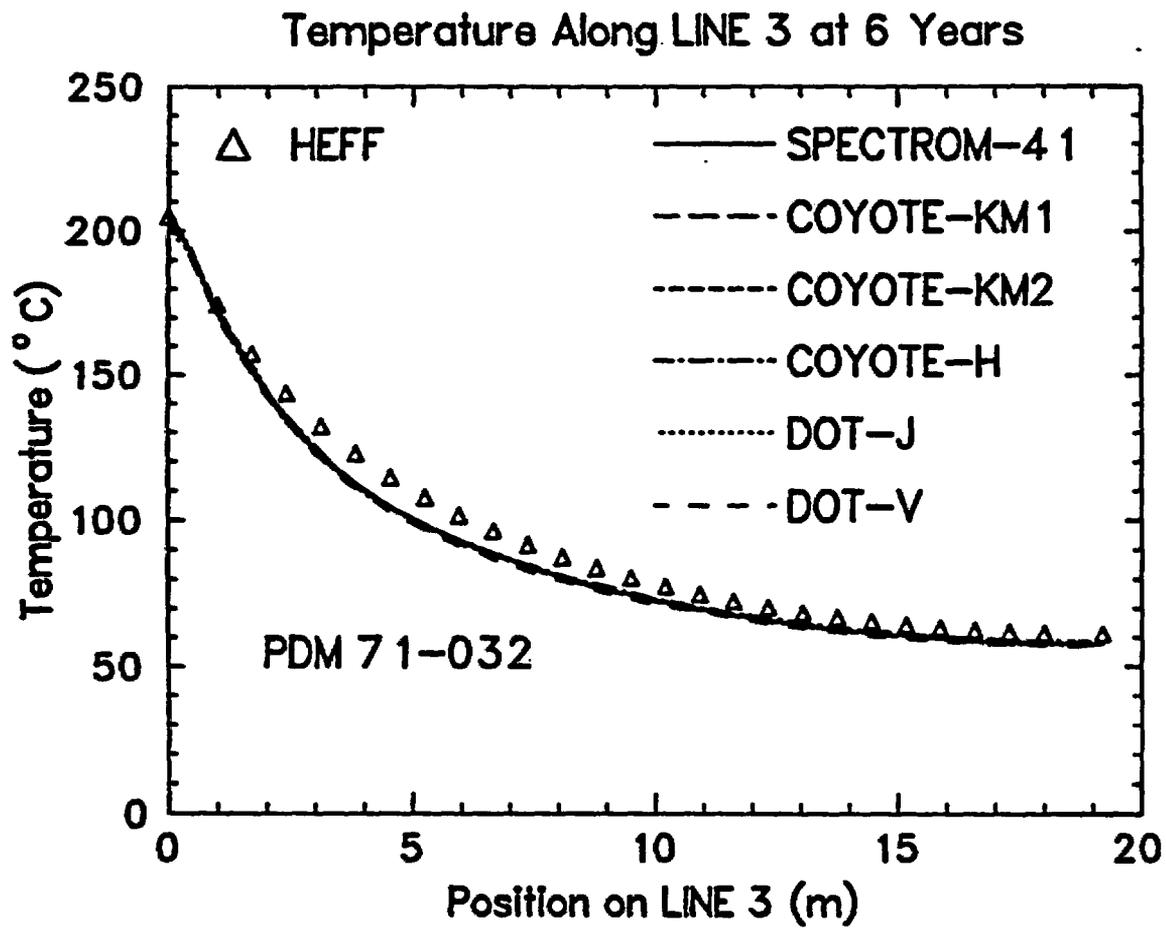


Figure 5-19. Comparison of Results for the Temperature along Line 3 (Figure 2-5) at 6 Yr

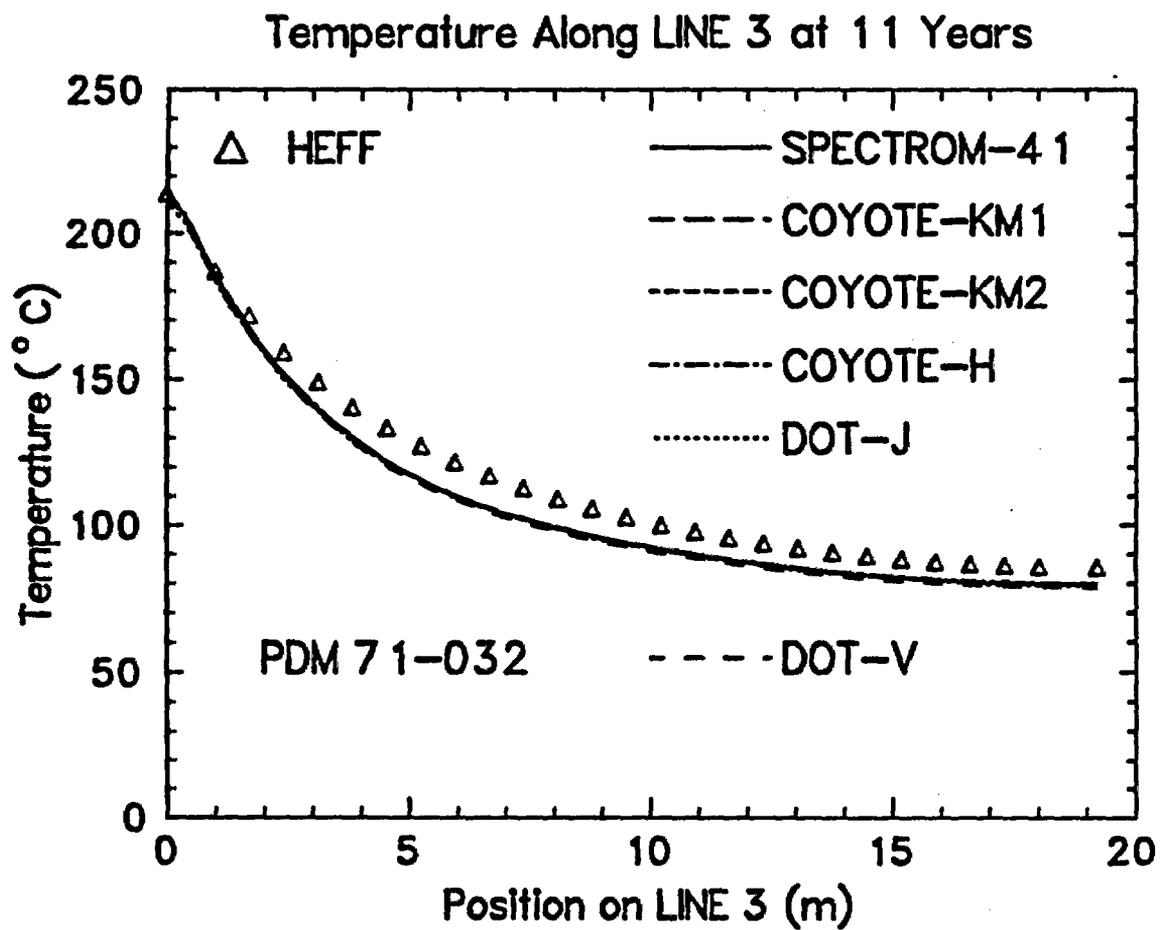


Figure 5-20. Comparison of Results for the Temperature along Line 3 (Figure 2-5) at 11 Yr

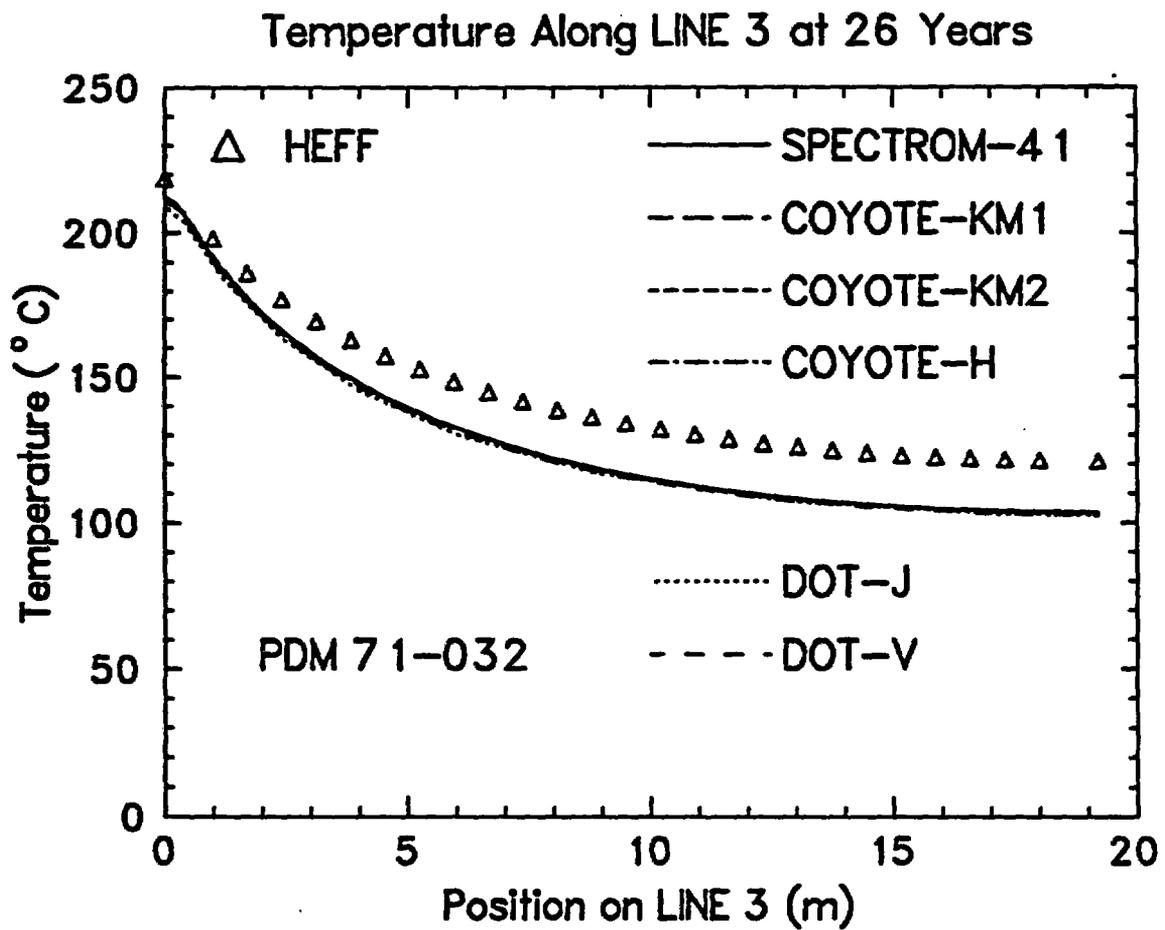


Figure 5-21. Comparison of Results for the Temperature along Line 3 (Figure 2-5) at 26 Yr

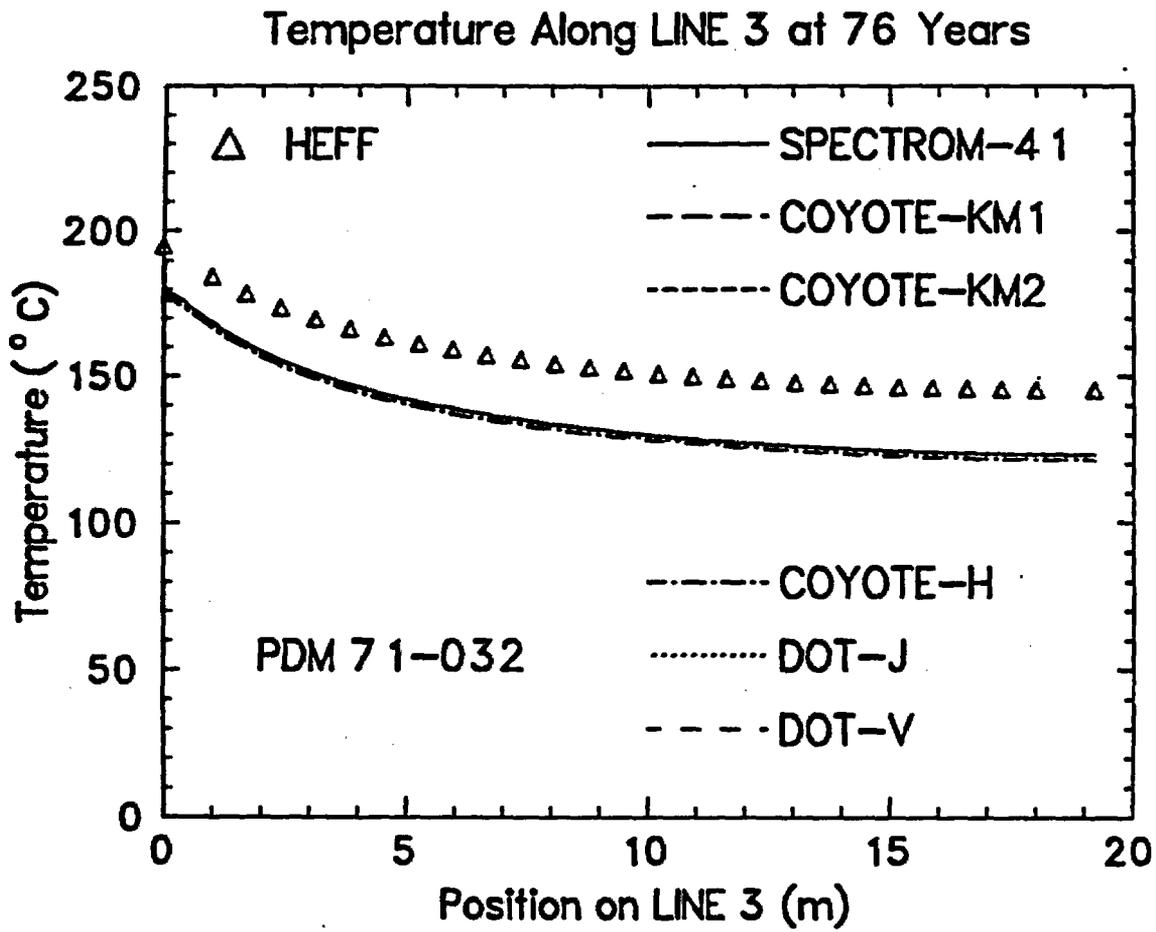


Figure 5-22. Comparison of Results for the Temperature along Line 3 (Figure 2-5) at 76 Yr

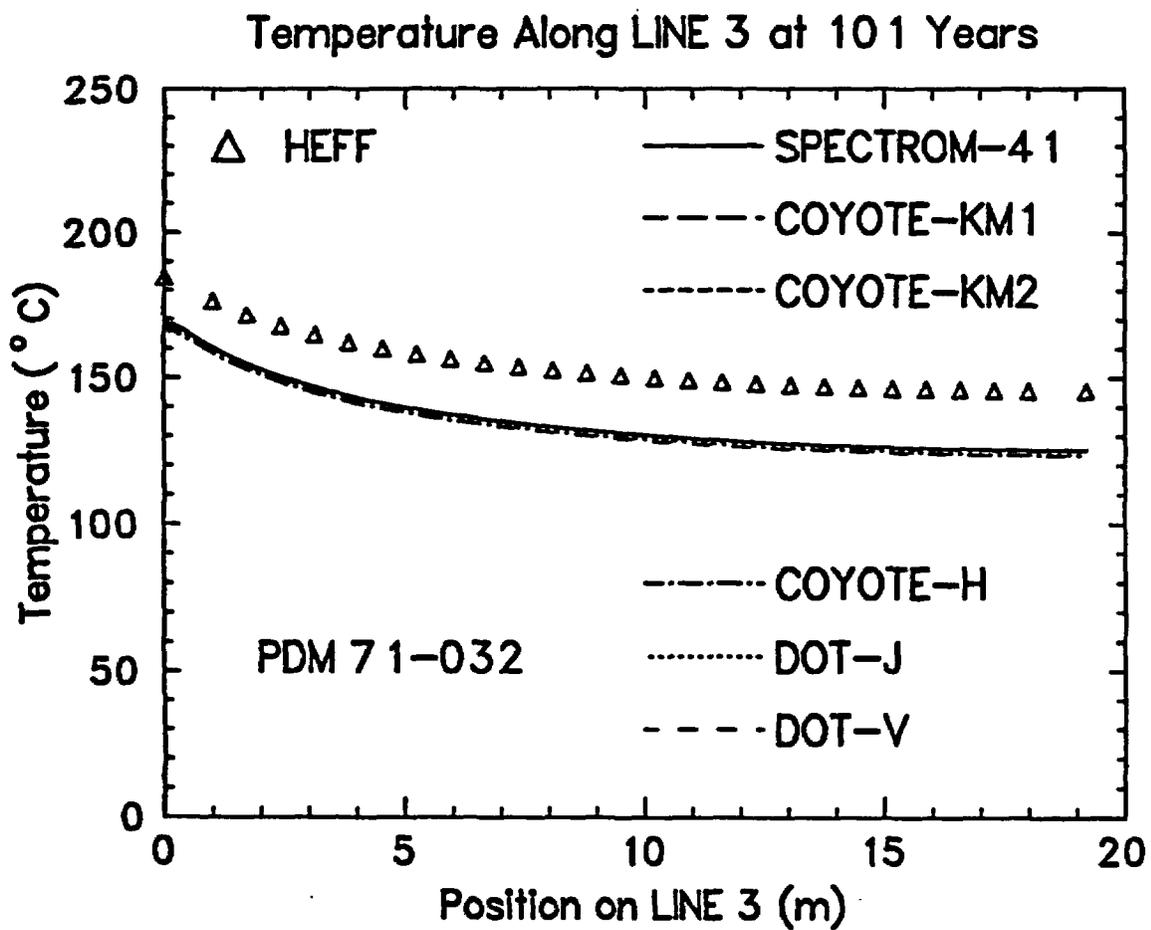


Figure 5-23. Comparison of Results for the Temperature along Line 3 (Figure 2-5) at 101 Yr

6.0 ASSESSMENT OF RESULTS

6.1 Comparison of Results from Finite Element Codes

The results from all runs of the the three finite element thermal codes are quite close (Section 5). The slight difference noted with the COYOTE-H solution was investigated by the analyst and found to be caused by the particular selection of time steps leading up to the time of emplacement of the heat source, which is discussed in more detail in Section 7. A comparison of the results from multiple runs by the different analysts who used COYOTE and DOT shows that the solutions are not very sensitive to variations in meshes (Table 5-1). For example, the results from the two runs in which DOT was used with different element types and mesh spacing are nearly identical. In addition, the comparison of results from different analysts using the same code shows that the solutions are not very sensitive to the analysts' choice of inputs used to control the solution process.

The computer usage (CPU time) given in Table 5-2 was requested and is presented here for completeness only. No conclusions can or should be drawn from this information.

6.2 Assessment of Boundary Element Code (HEFF) Results

One objective of the benchmark exercise is to assess the effect of the approximations made in obtaining a thermal solution in HEFF and to determine the limits of accuracy that can be expected in a thermoelastic analysis using the code. The comparison of the results of the HEFF thermal solution with those from the three finite element codes suggests that the difference between the HEFF solution and the others is primarily a result of the approximate nature of the solution and not a result of numerical errors or errors in the implementation of the solution method. Because the solution is derived from the analytic solution of a line heat source in an infinite, homogeneous, conducting medium, the solution does not account for the differences in conductance between the mined drift and the host rock. Also, it is not possible to have the thermal properties vary with temperature as was required in the PDM. Both of these approximations tend to cause an overestimation of the temperature, especially in regions near the drift. In addition, the boundary conditions on the vertical boundaries had to be approximated by extending the analysis region to include a large array of drifts. The effect of this approximation is not known. As shown in Figures 5-4 through 5-25, the deviation of the HEFF solution from those of the finite element codes is consistent with the trend expected from the nature of the approximations involved. In fact, good agreement is obtained for times less than 11 yr, with the deviation increasing with time. The HEFF solution differs from the others by 20% at most.

The primary use of the HEFF code by the Yucca Mountain Project has been for performing scoping analyses to investigate the behavior associated with different waste emplacement options, thermal loading densities, excavation shapes, and panel layouts of a potential repository for

high-level radioactive waste.* In these applications, both the heat sources and excavated volume are more diffuse relative to the analysis region (i.e., a far-field analysis) than is the case in this benchmark exercise. It could reasonably be expected that, for the intended applications of the HEFF code by the YMP, the accuracy of the results would be better than those obtained from the benchmark problem.

*J. F. T. Agapito and Associates, Inc., "HEFF--A User's Manual and Guide for the HEFF Code for Thermal-Mechanical Analysis Using the Boundary-Element Method," SAND87-7075, Contract Report for Sandia National Laboratories, Albuquerque, NM, draft.

7.0 REVISED ANALYSES

Once the initial thermal analyses had been completed and the results had been transmitted to the PIs for comparison, a memo showing the comparison plots was sent to the participants. Each analyst had the opportunity to check their results to be sure that the results had been properly interpreted. In addition, the analysts could revise their results, if necessary, and submit a second set of results. The COYOTE-H analysis was the only analysis that was revised and resubmitted.

The COYOTE-H analysis was repeated to determine the source of the small differences (1 to 2%) between the results of that analysis and the other analyses. It was determined that the discrepancies were caused by using too large a time step before the emplacement of the heat source at time 1.0 yr. In the original calculation, the times at which temperatures were calculated before emplacing the heat source at time 1.0 yr were 0.0, 0.25, 0.50, and 0.75 yr. The effect of this time step sequence was to activate the decaying heat source at a time earlier than 1 yr, thus causing the temperatures calculated at time 1.0 yr to be larger than those predicted by the other participants. The early activation was traced to the algorithm used in COYOTE II (Gartling, 1987b) to calculate transient temperatures and can be avoided if smaller time steps are used before activation of the heat source.

A second calculation was performed in which the only change from the original analysis was that the time steps up to time 1.0 yr were altered so that a step was included just before time 1.0 yr. The steps used in the second calculation were 0.0, 0.25, 0.50, 0.75, and 0.999 yr. The time step at 0.001 yr before activation of the heat source prevented the premature heating of the model.

The revised results submitted for the COYOTE-H (designated COYOTE-H CORR) analysis are compared with the original COYOTE-H results and the results from COYOTE-KM1 and COYOTE-KM2 in Figures 7-1 through 7-22. Very good agreement is achieved among the three COYOTE analyses, although the meshes used (Table 5-1) had quite different degrees of refinement.

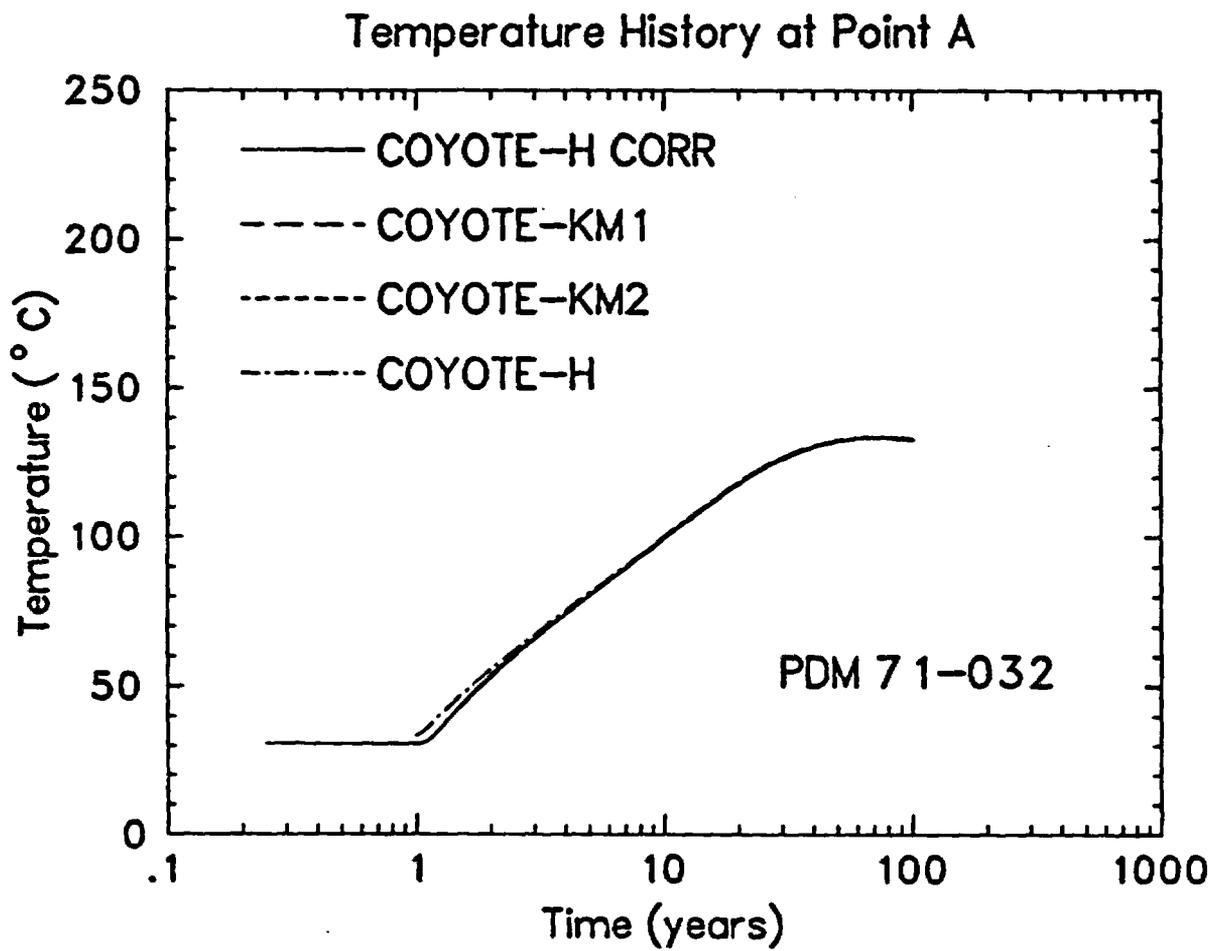


Figure 7-1. Comparison of the COYOTE-H CORR Solution with the Original COYOTE-H Solution and the COYOTE-KM1 and COYOTE-KM2 Solutions at Point A (Figure 2-5)

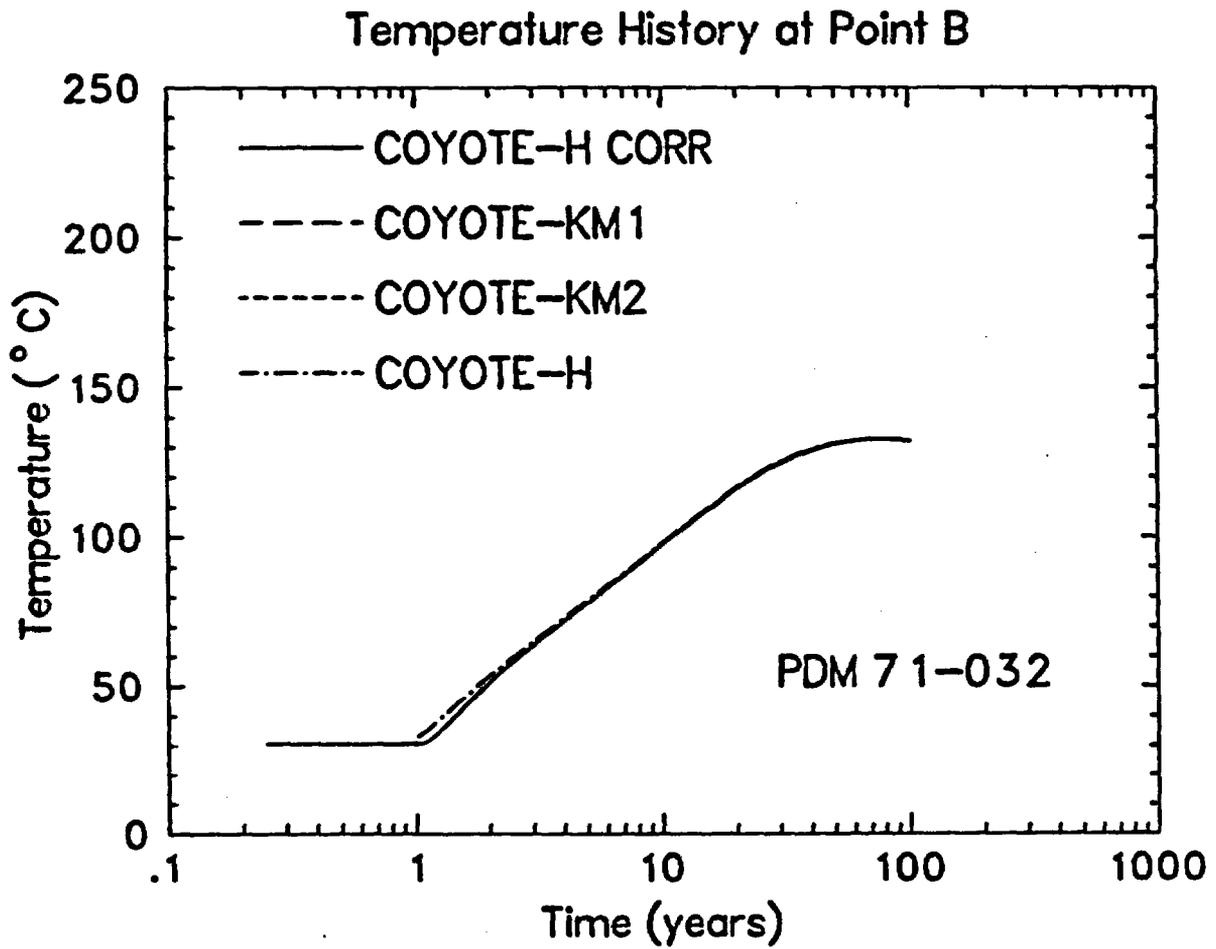


Figure 7-2. Comparison of the COYOTE-H CORR Solution with the Original COYOTE-H Solution and the COYOTE-KM1 and COYOTE-KM2 Solutions at Point B (Figure 2-5)

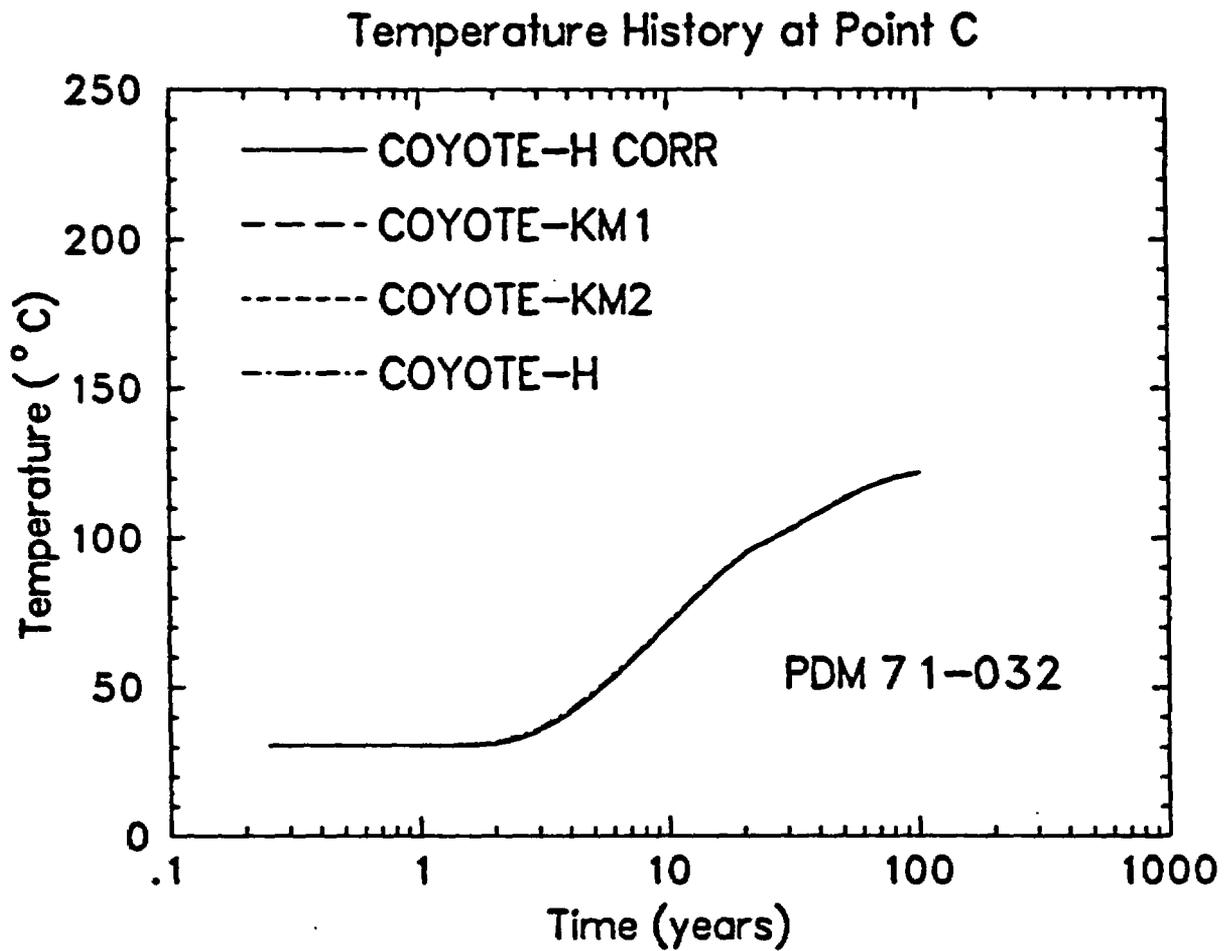


Figure 7-3. Comparison of the COYOTE-H CORR Solution with the Original COYOTE-H Solution and the COYOTE-KM1 and COYOTE-KM2 Solutions at Point C (Figure 2-5)

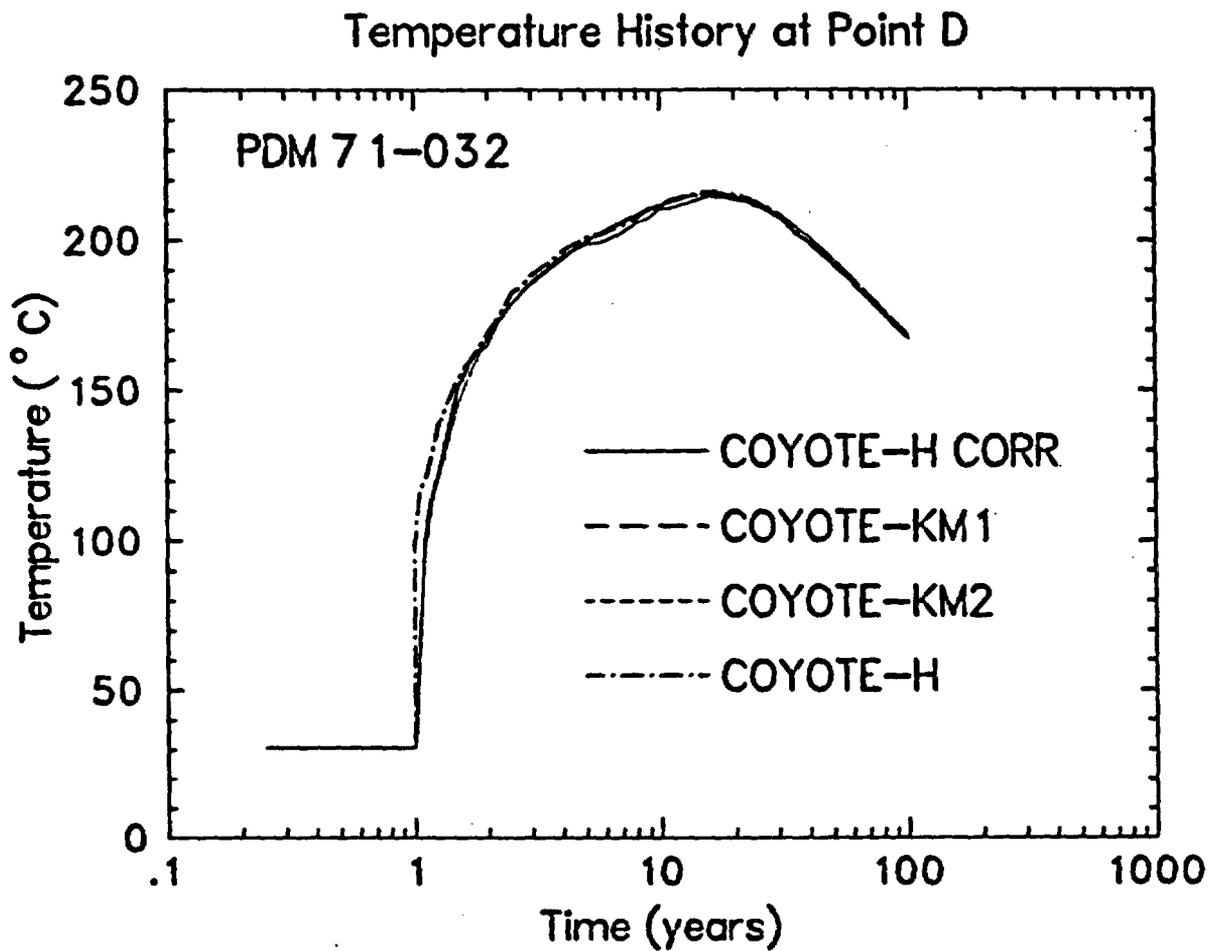


Figure 7-4. Comparison of the COYOTE-H CORR Solution with the Original COYOTE-H Solution and the COYOTE-KM1 and COYOTE-KM2 Solutions at Point D (Figure 2-5)

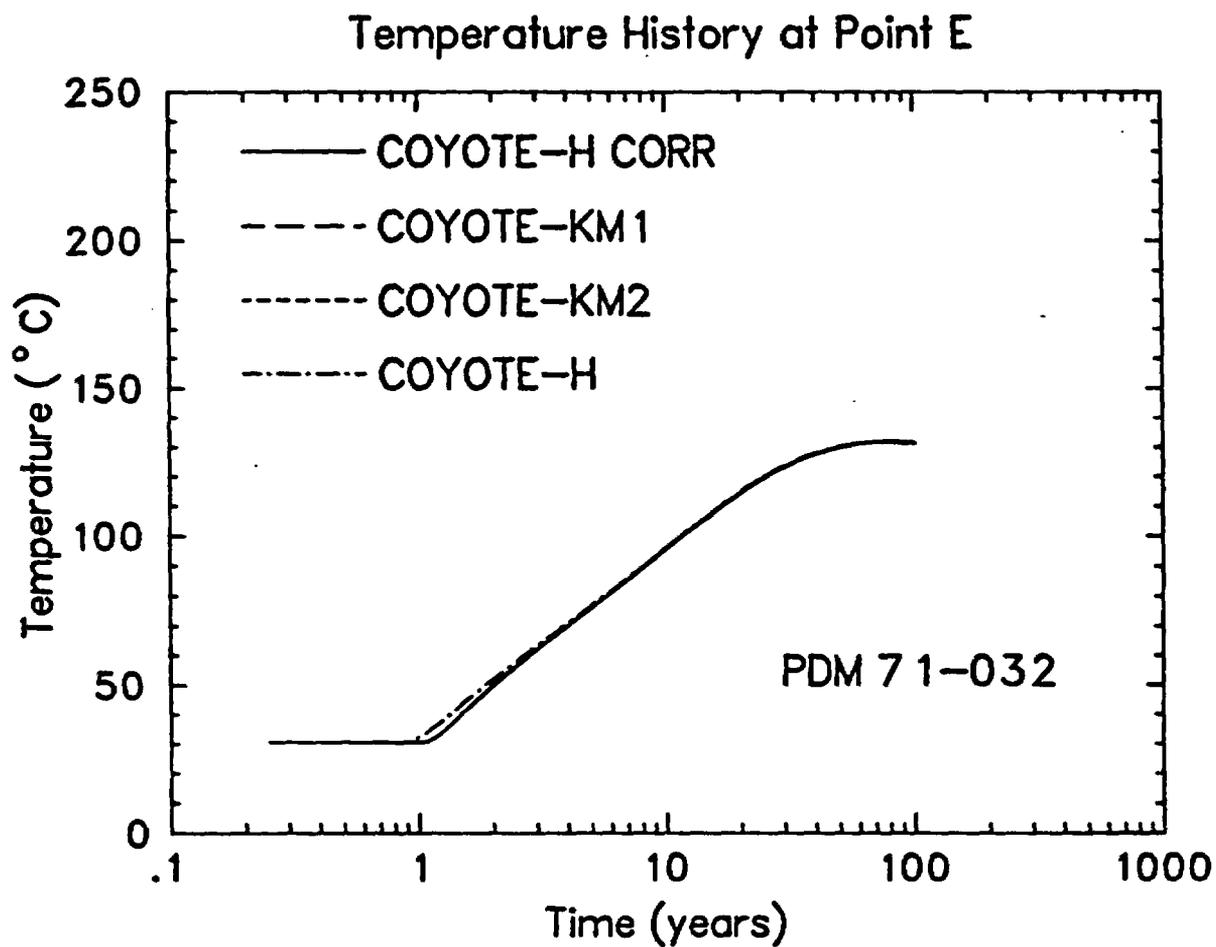


Figure 7-5. Comparison of the COYOTE-H CORR Solution with the Original COYOTE-H Solution and the COYOTE-KM1 and COYOTE-KM2 Solutions at Point E (Figure 2-5)

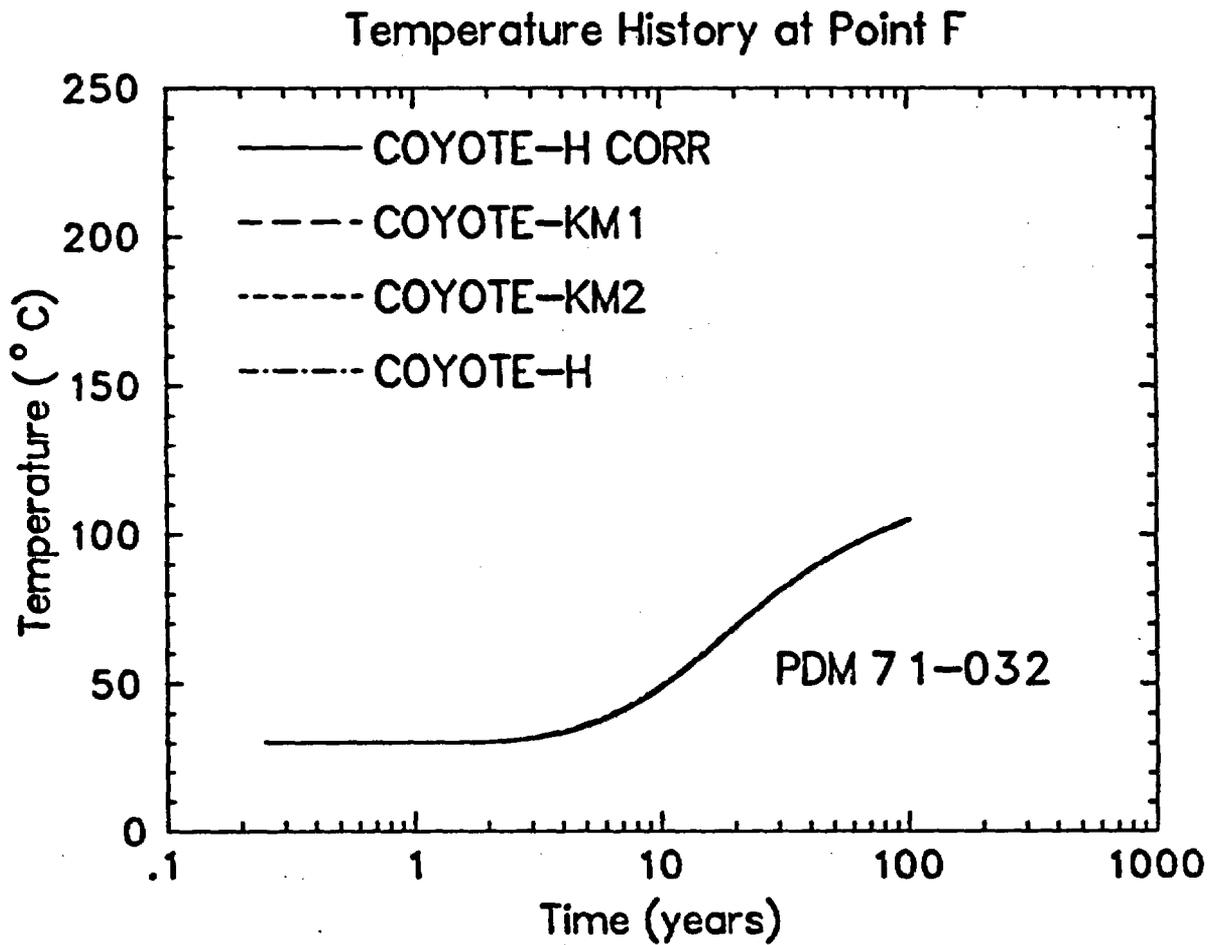


Figure 7-6. Comparison of the COYOTE-H CORR Solution with the Original COYOTE-H Solution and the COYOTE-KM1 and COYOTE-KM2 Solutions at Point F (Figure 2-5)

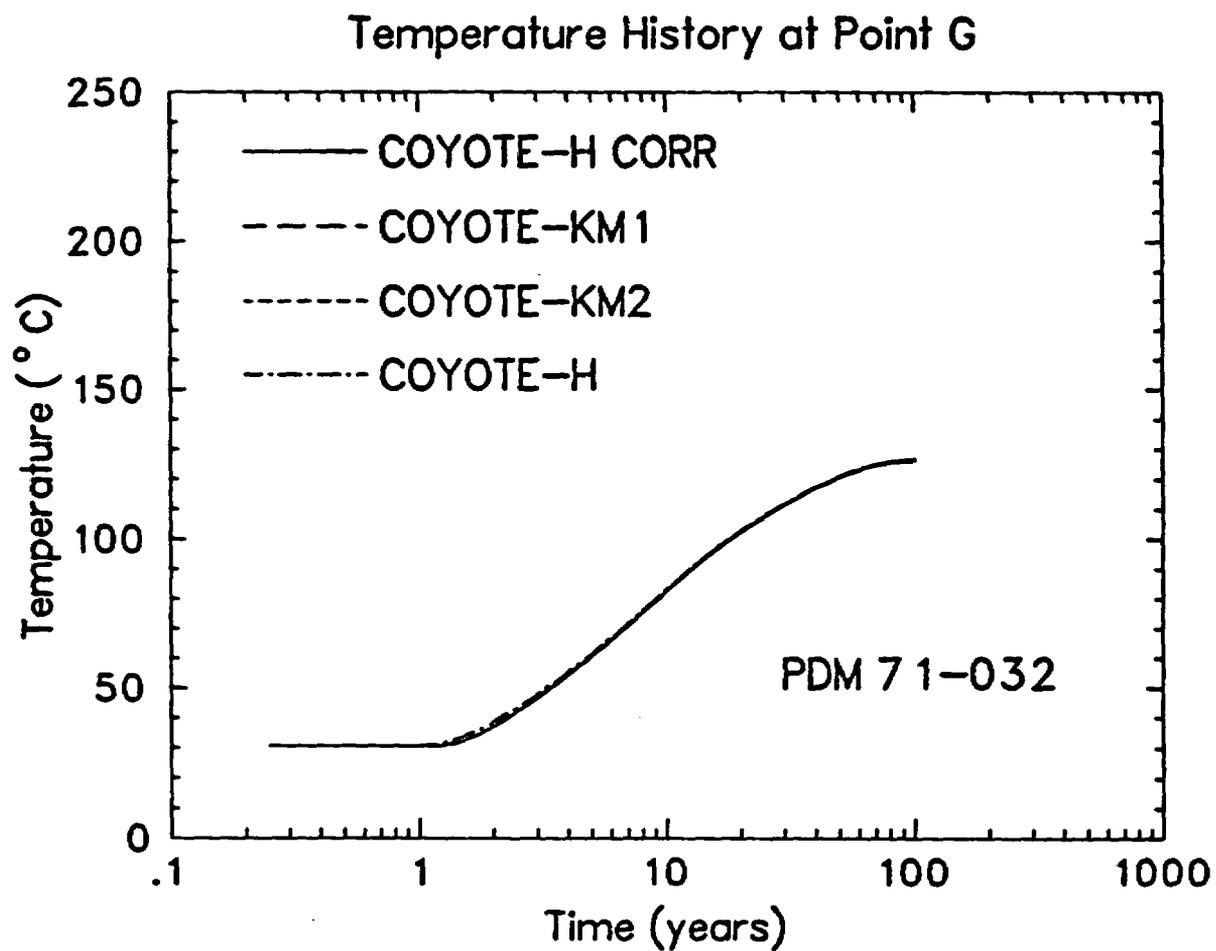


Figure 7-7. Comparison of the COYOTE-H CORR Solution with the Original COYOTE-H Solution and the COYOTE-KM1 and COYOTE-KM2 Solutions at Point G (Figure 2-5)

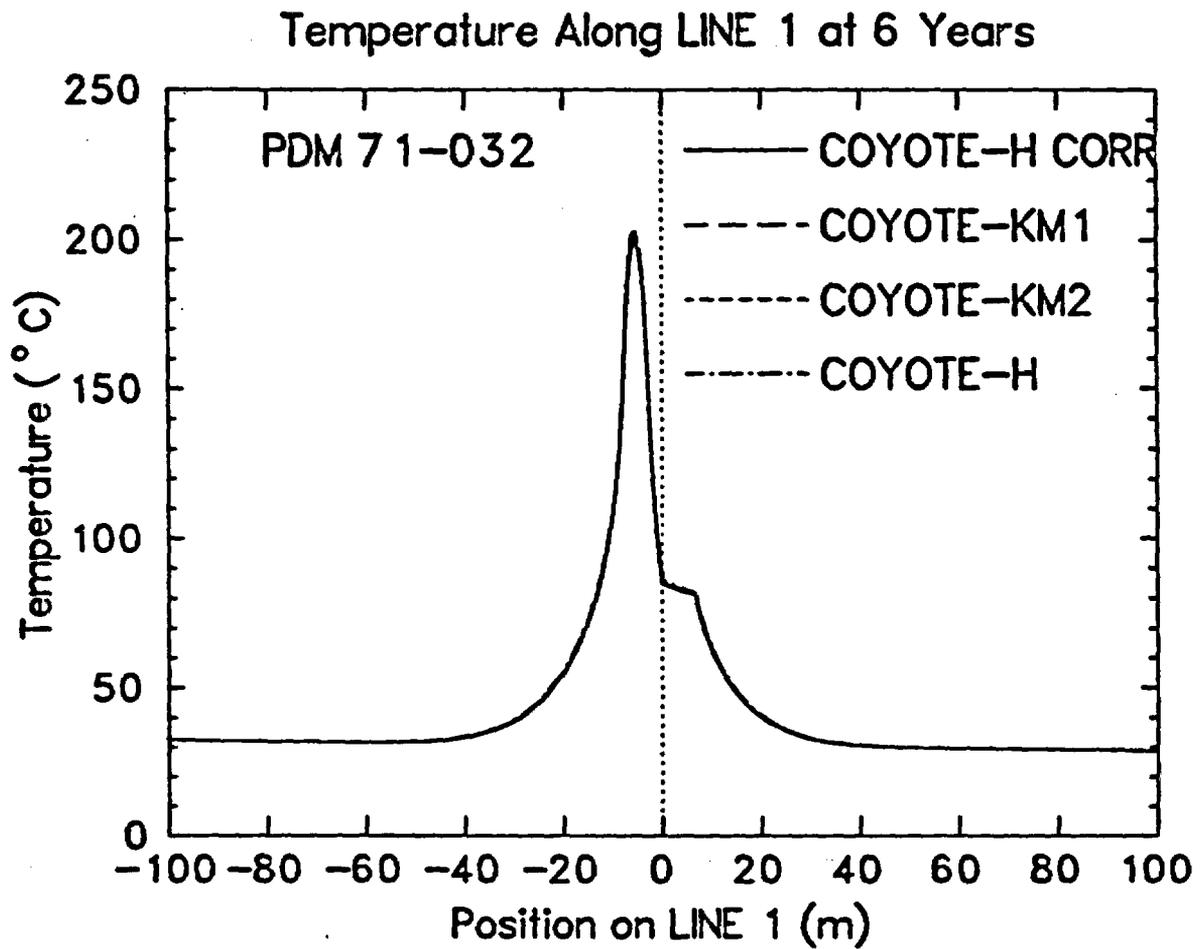


Figure 7-8. Comparison of the COYOTE-H CORR Solution with the Original COYOTE-H Solution and the COYOTE-KM1 and COYOTE-KM2 Solutions along Line 1 (Figure 2-5) at 6 Yr

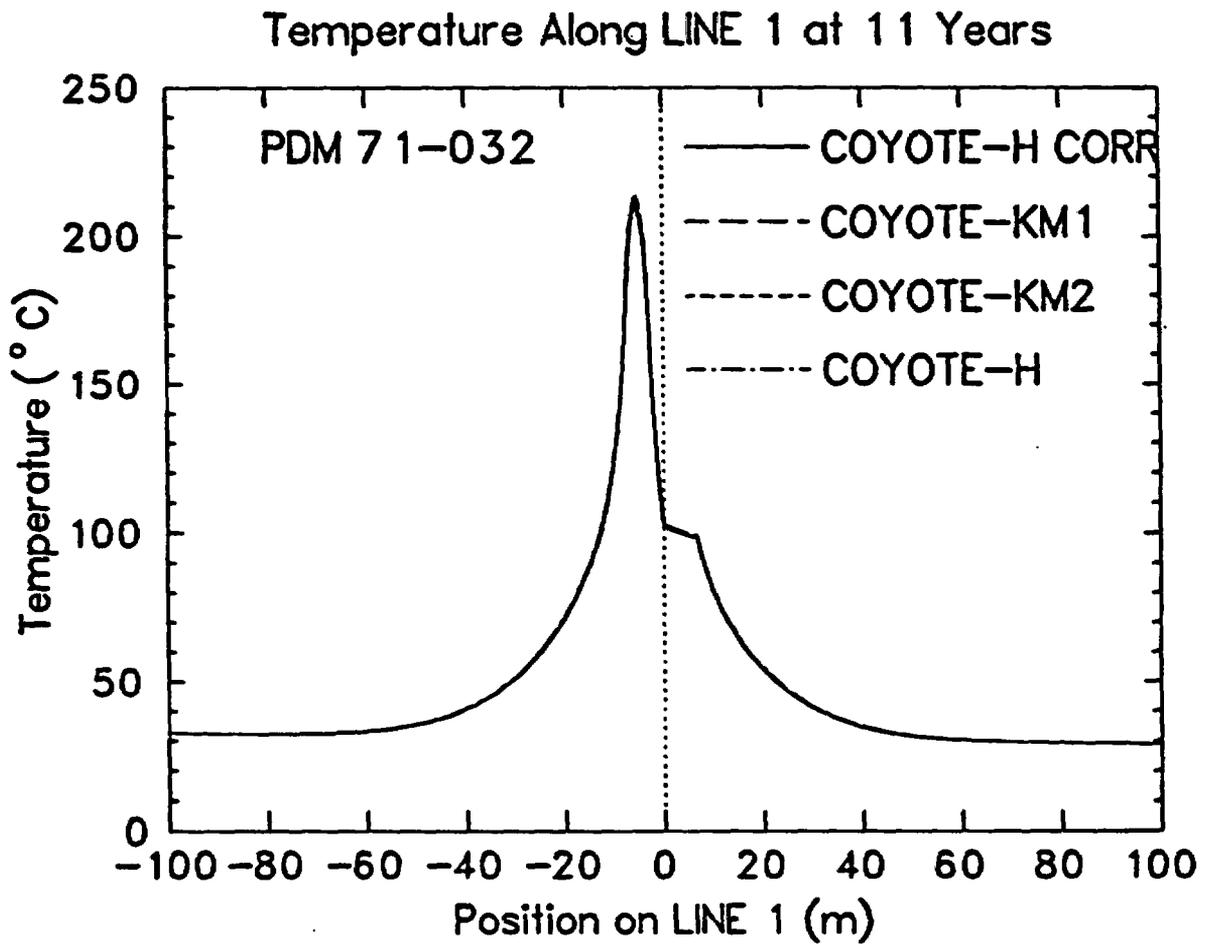


Figure 7-9. Comparison of the COYOTE-H CORR Solution with the Original COYOTE-H Solution and the COYOTE-KM1 and COYOTE-KM2 Solutions along Line 1 (Figure 2-5) at 11 Yr

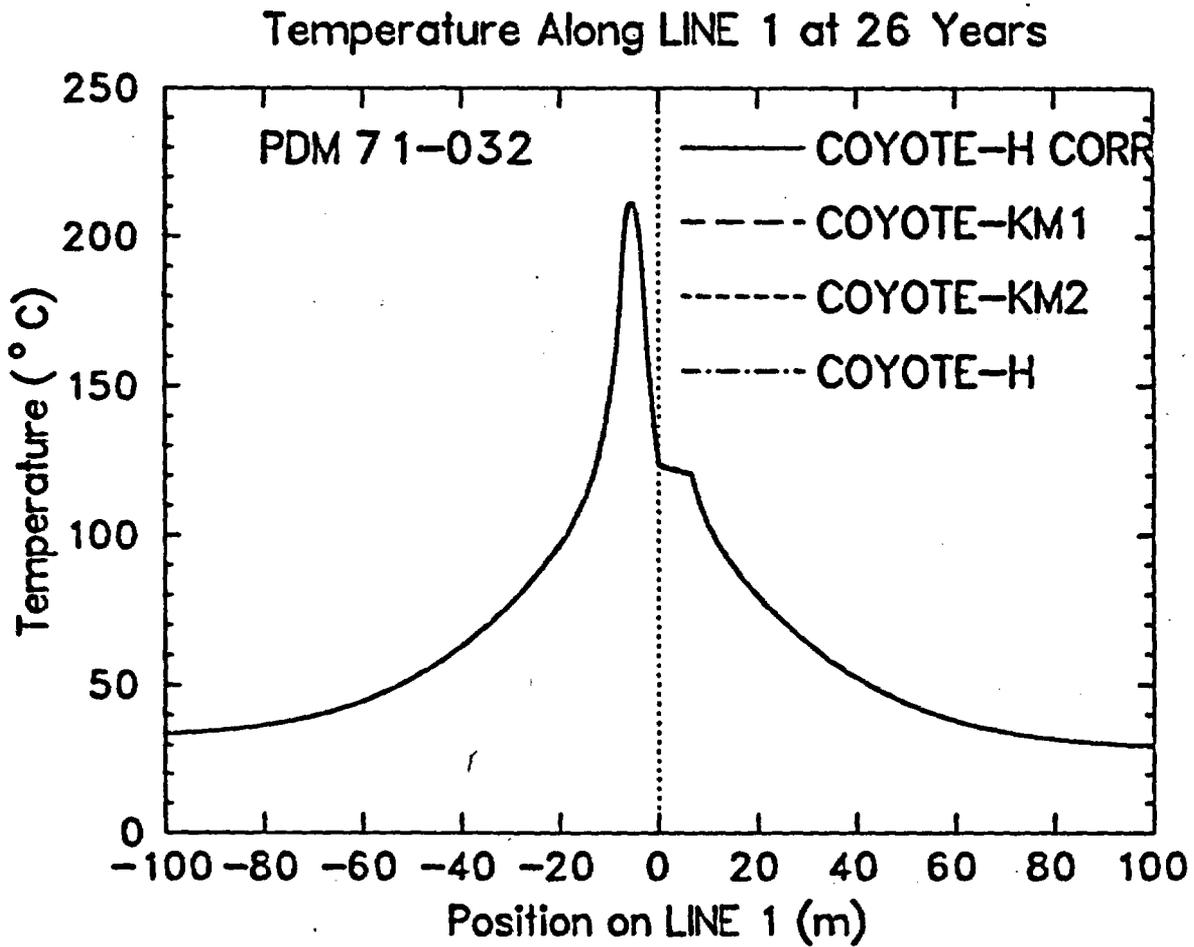


Figure 7-10. Comparison of the COYOTE-H CORR Solution with the Original COYOTE-H Solution and the COYOTE-KM1 and COYOTE-KM2 Solutions along Line 1 (Figure 2-5) at 26 Yr

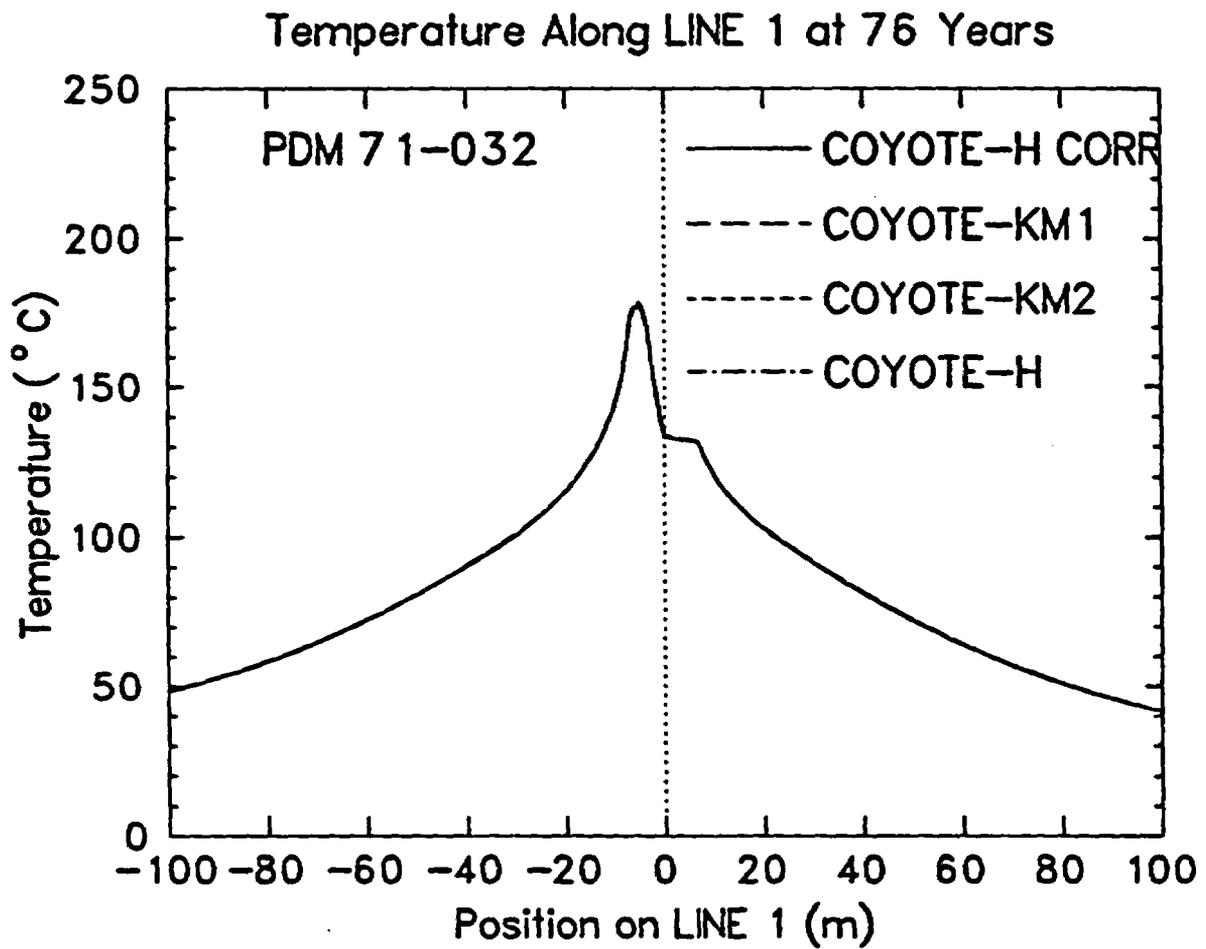


Figure 7-11. Comparison of the COYOTE-H CORR Solution with the Original COYOTE-H Solution and the COYOTE-KM1 and COYOTE-KM2 Solutions along Line 1 (Figure 2-5) at 76 Yr

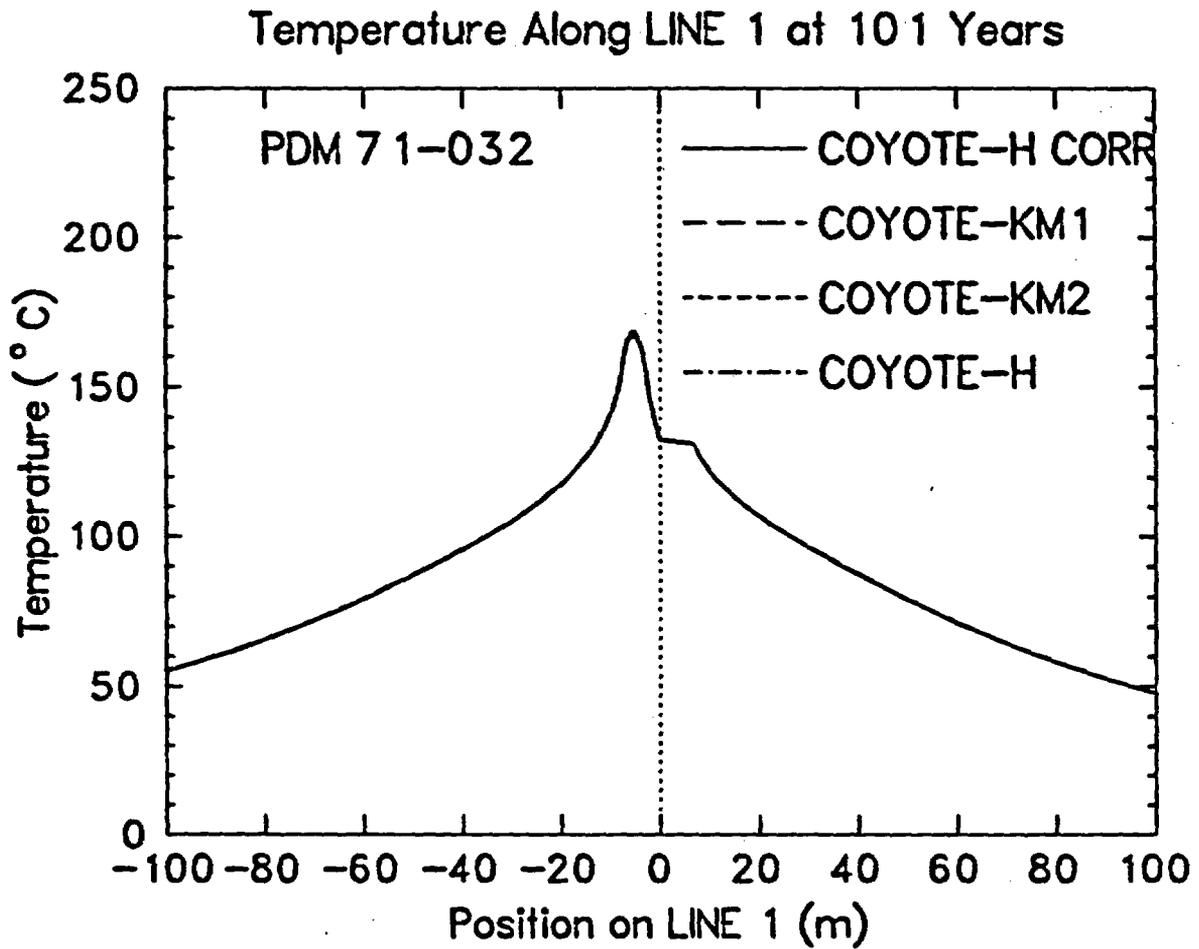


Figure 7-12. Comparison of the COYOTE-H CORR Solution with the Original COYOTE-H Solution and the COYOTE-KM1 and COYOTE-KM2 Solutions along Line 1 (Figure 2-5) at 101 Yr

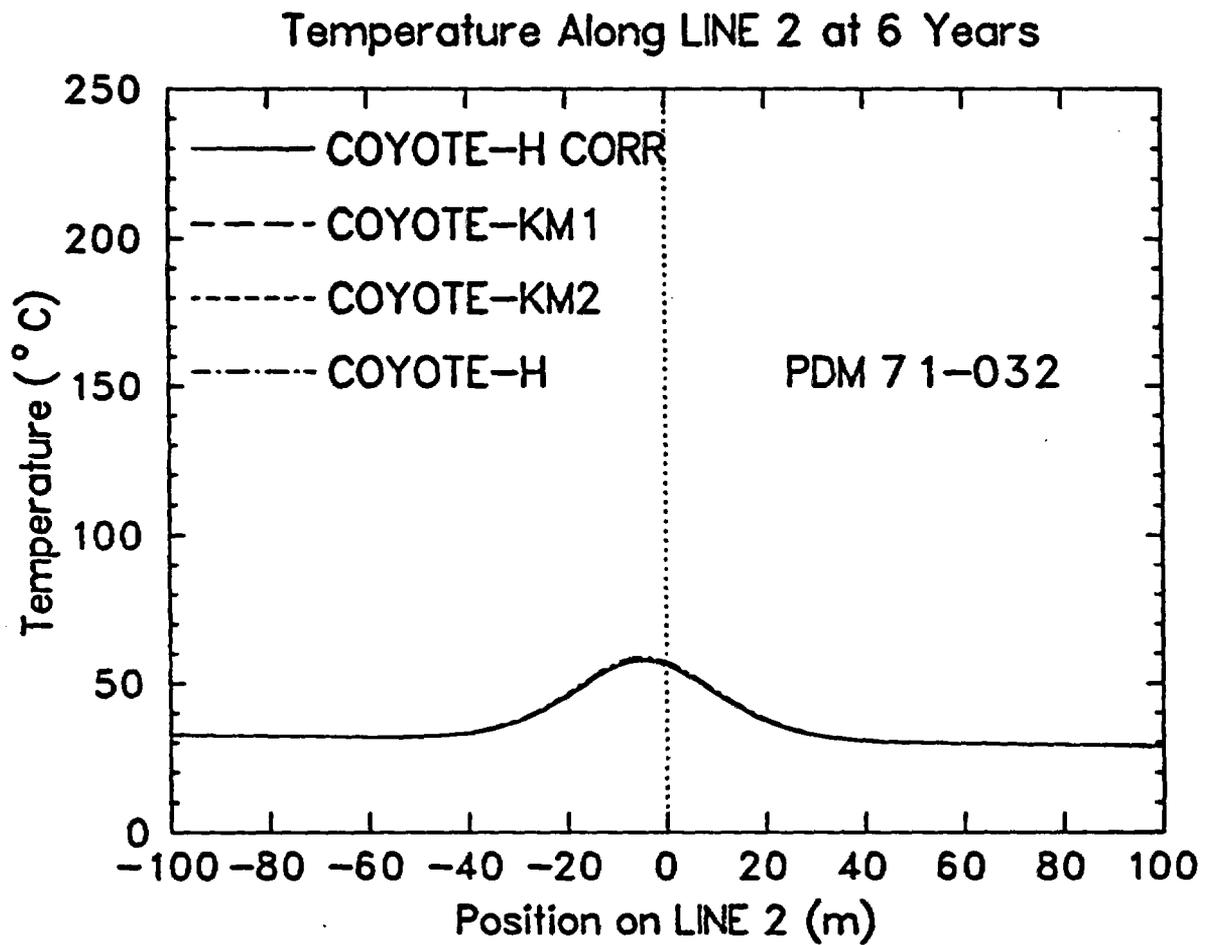


Figure 7-13. Comparison of the COYOTE-H CORR Solution with the Original COYOTE-H Solution and the COYOTE-KM1 and COYOTE-KM2 Solutions along Line 2 (Figure 2-5) at 6 Yr.

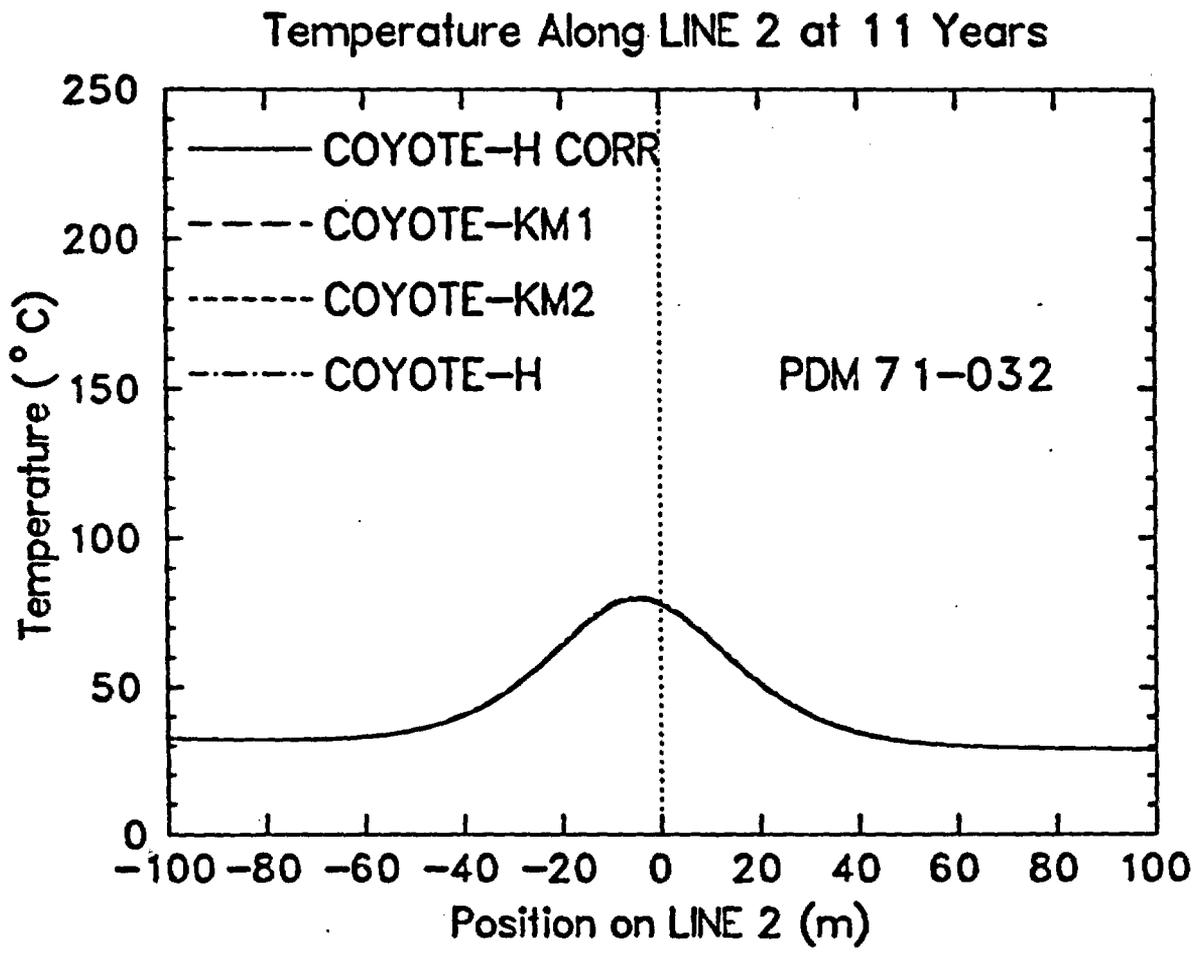


Figure 7-14. Comparison of the COYOTE-H CORR Solution with the Original COYOTE-H Solution and the COYOTE-KM1 and COYOTE-KM2 Solutions along Line 2 (Figure 2-5) at 11 Yr

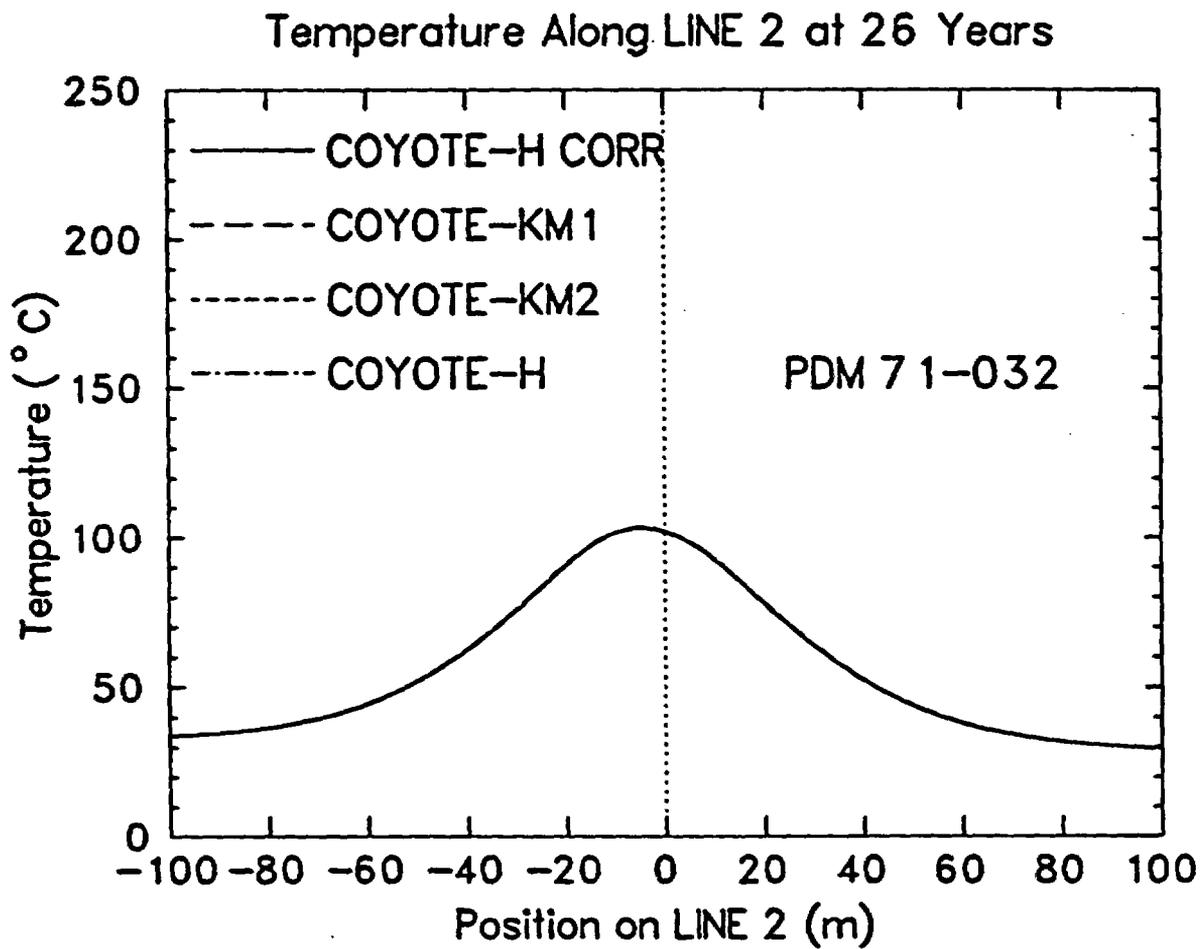


Figure 7-15. Comparison of the COYOTE-H CORR Solution with the Original COYOTE-H Solution and the COYOTE-KM1 and COYOTE-KM2 Solutions along Line 2 (Figure 2-5) at 26 Yr

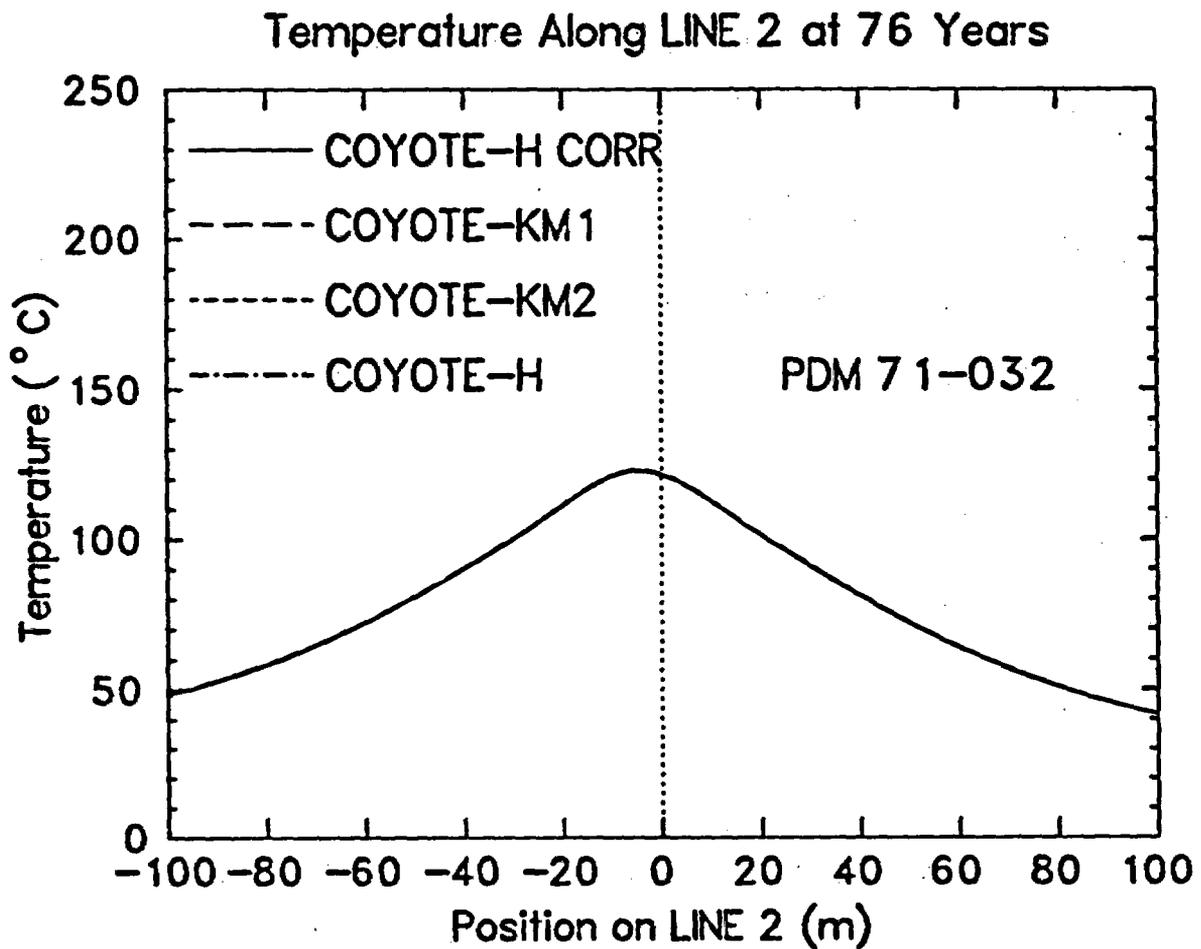


Figure 7-16. Comparison of the COYOTE-H CORR Solution with the Original COYOTE-H Solution and the COYOTE-KM1 and COYOTE-KM2 Solutions along Line 2 (Figure 2-5) at 76 Yr

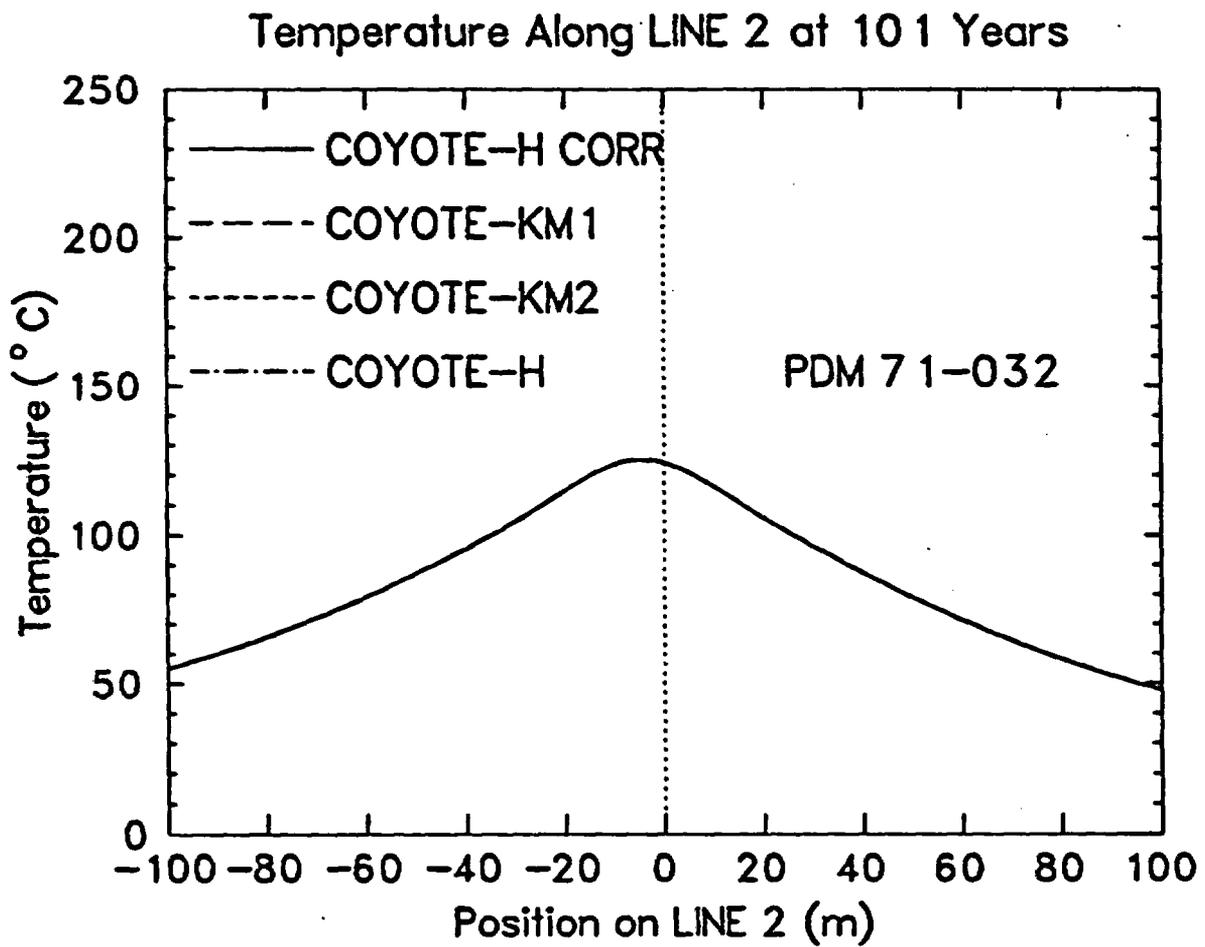


Figure 7-17. Comparison of the COYOTE-H CORR Solution with the Original COYOTE-H Solution and the COYOTE-KM1 and COYOTE-KM2 Solutions along Line 2 (Figure 2-5) at 101 Yr

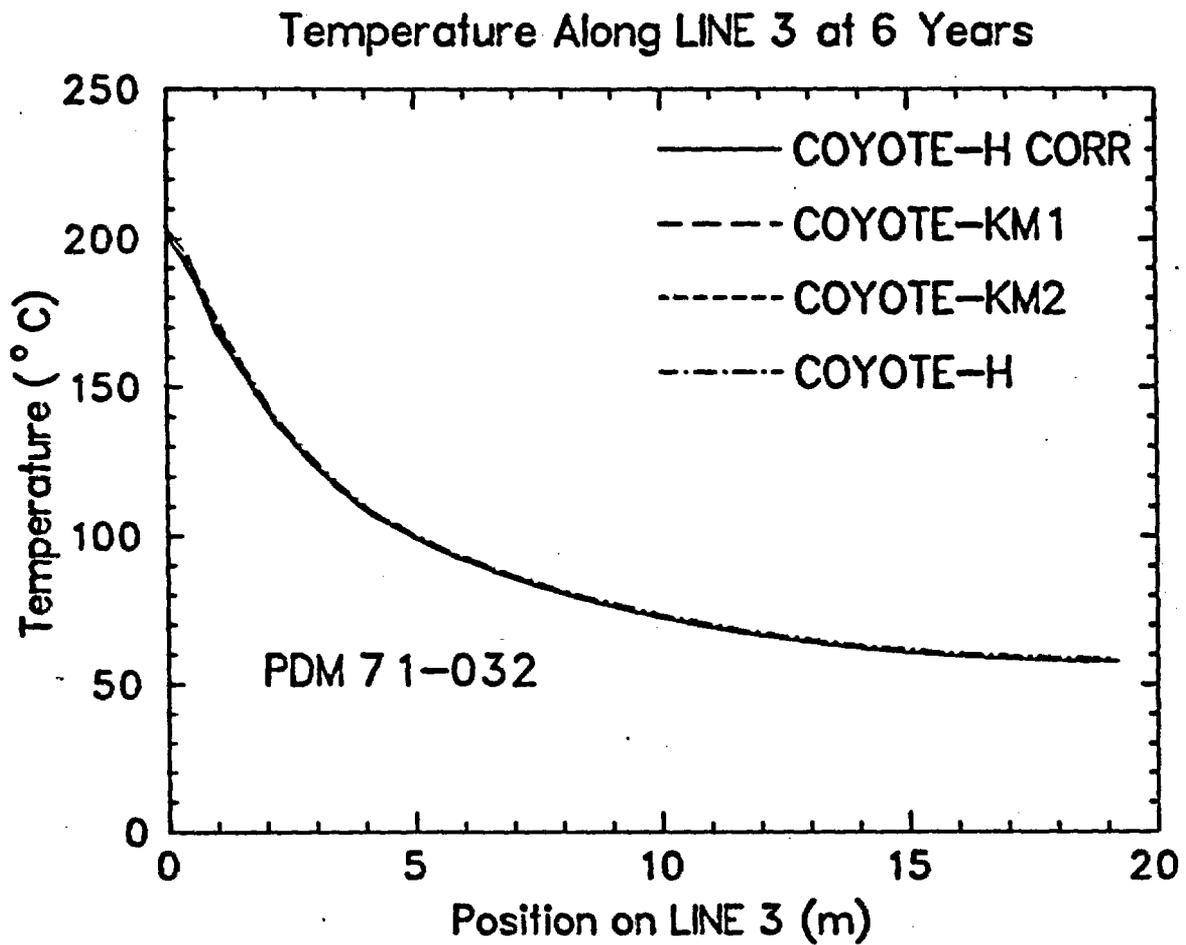


Figure 7-18. Comparison of the COYOTE-H CORR Solution with the Original COYOTE-H Solution and the COYOTE-KM1 and COYOTE-KM2 Solutions along Line 3 (Figure 2-5) at 6 Yr

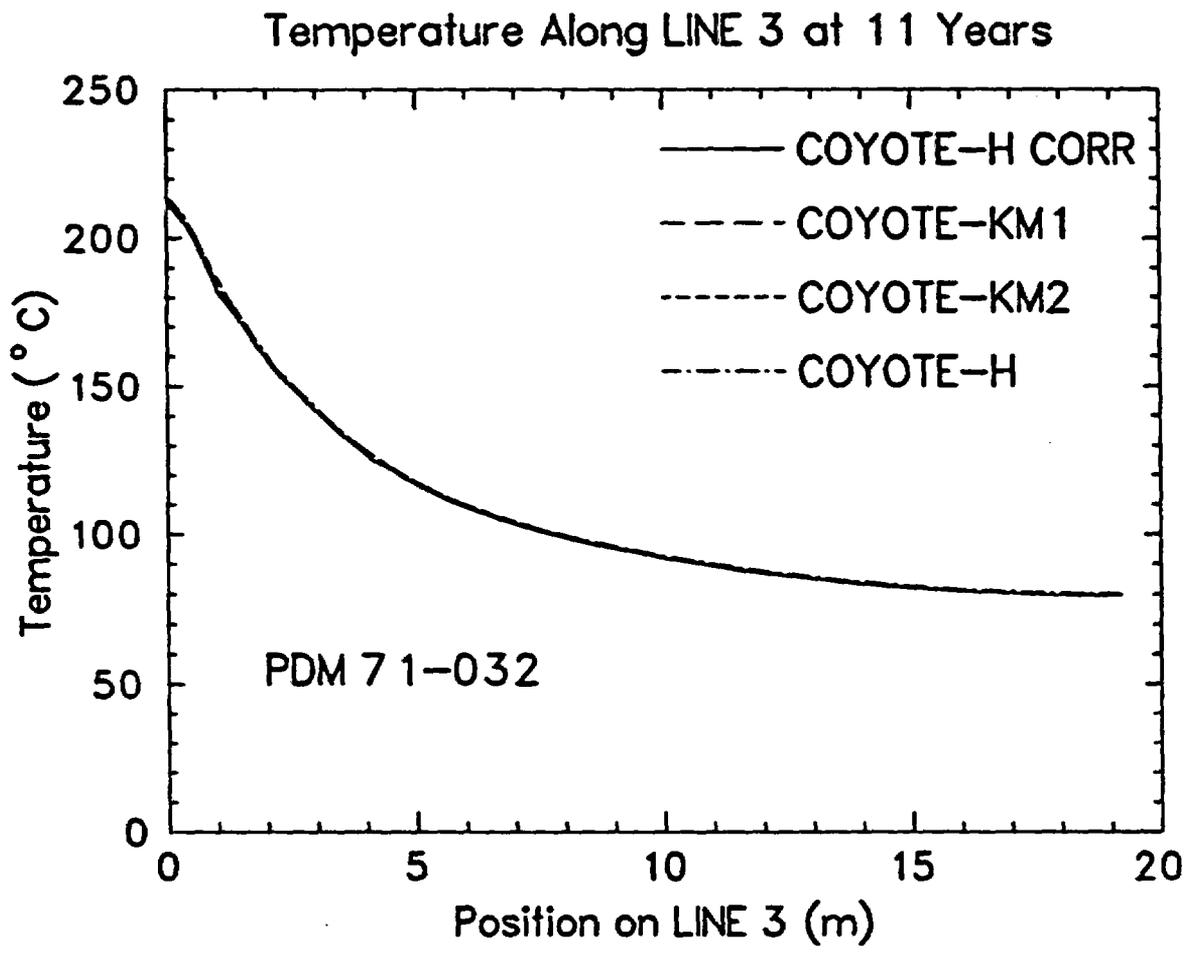


Figure 7-19. Comparison of the COYOTE-H CORR Solution with the Original COYOTE-H Solution and the COYOTE-KM1 and COYOTE-KM2 Solutions along Line 3 (Figure 2-5) at 11 Yr

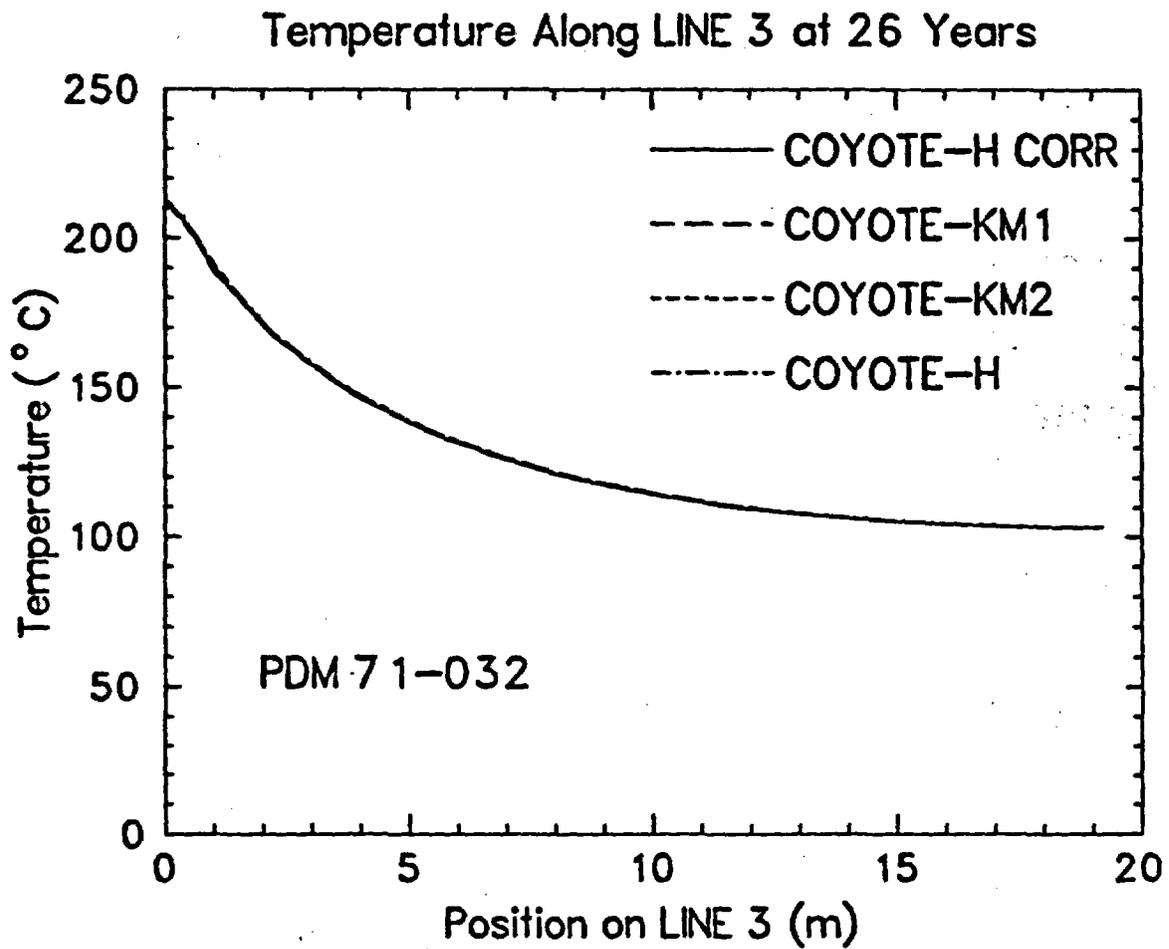


Figure 7-20. Comparison of the COYOTE-H CORR Solution with the Original COYOTE-H Solution and the COYOTE-KM1 and COYOTE-KM2 Solutions along Line 3 (Figure 2-5) at 26 Yr

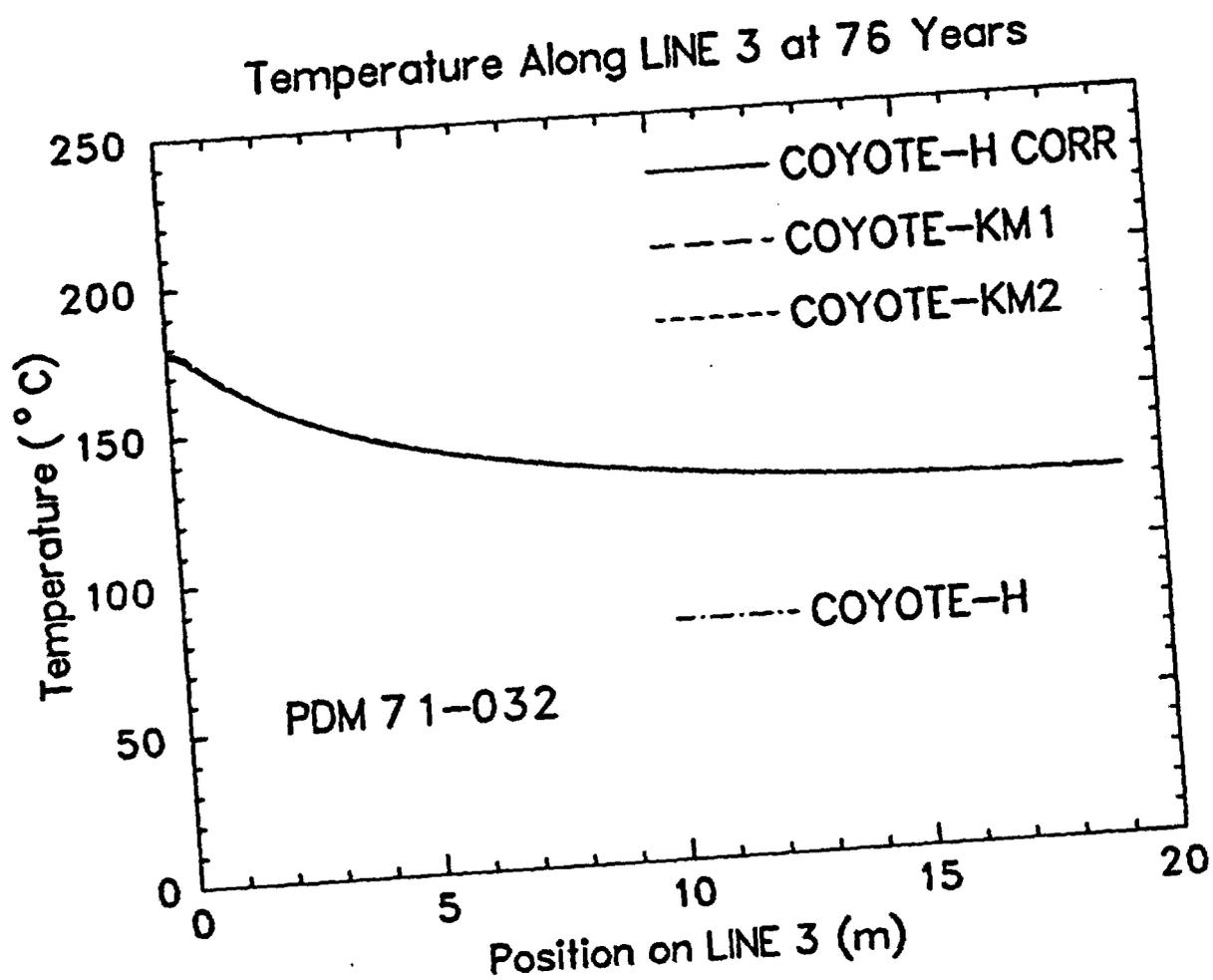


Figure 7-21. Comparison of the COYOTE-H CORR Solution with the Original COYOTE-H Solution and the COYOTE-KM1 and COYOTE-KM2 Solutions along Line 3 (Figure 2-5) at 76 Yr

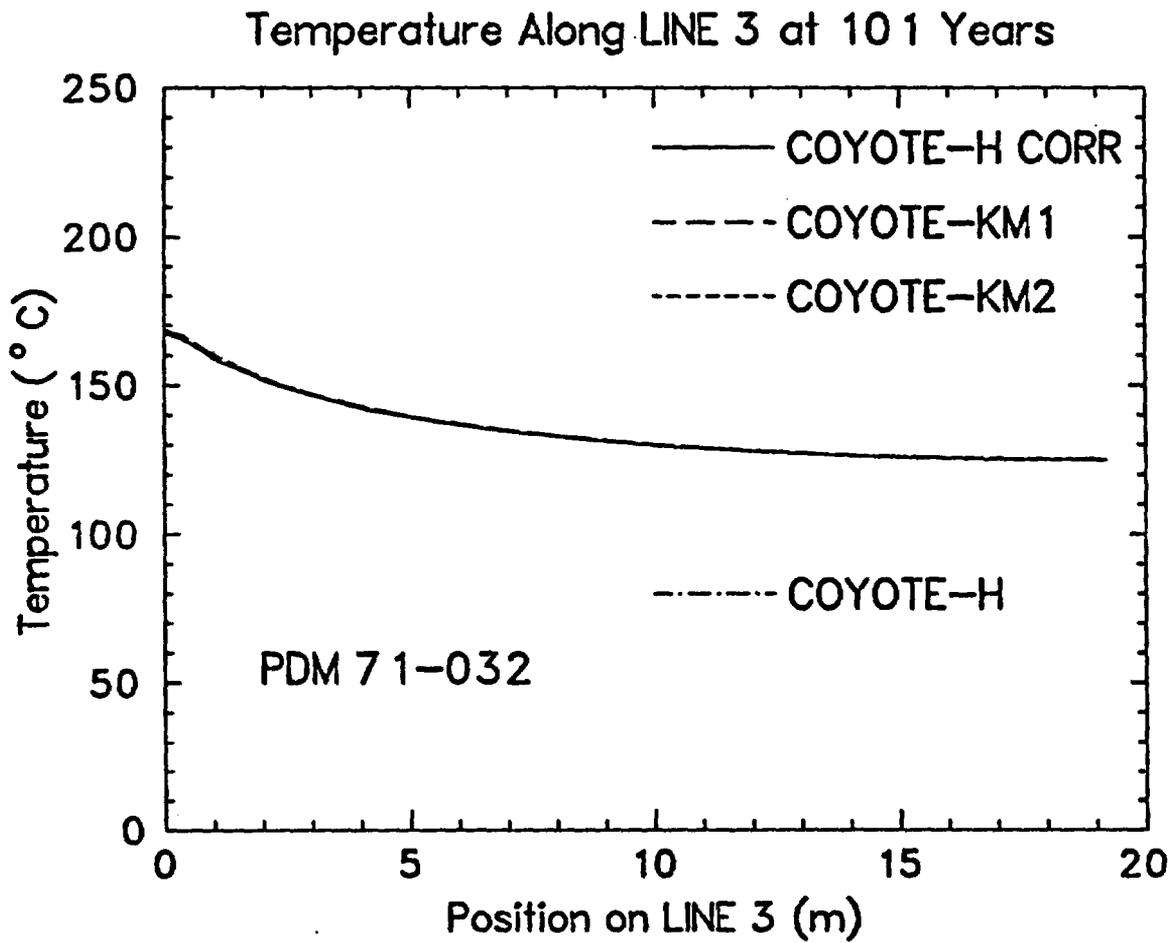


Figure 7-22. Comparison of the COYOTE-H CORR Solution with the Original COYOTE-H Solution and the COYOTE-KM1 and COYOTE-KM2 Solutions along Line 3 (Figure 2-5) at 101 Yr

8.0 CONCLUSIONS

The results in this report were presented as they were received from the participants and plotted in a form that the authors judged to be convenient for comparisons. It is left to the peer and technical reviewers and other interested readers to make their own assessments. It is, however, the intent of this report to document the results from the thermal analysis portion of the first benchmark exercise to an extent sufficient to support the verification of the codes involved.

Several observations can be made about the results from the thermal analysis portion of this benchmark exercise. First, the numerical methods used in the finite element codes to solve the nonlinear heat conduction problem with temperature-dependent material properties appear to be quite stable and insensitive to moderate variations in mesh and time-step size. The fact that separate sets of analysts can run the same problem using the same code and obtain virtually identical output is not a trivial result but an indication that the solution process is not very sensitive to the analysts' choice of inputs used to control the solution process. The second observation is that the benchmark exercise did reveal one potential problem with the COYOTE II code. Specifying the activation of a thermal source at a given time, t , causes the source to become active at time t instead of time $t+$. Thus, the effect of that source will enter the solution one time step before time t . If the time step before time t is small, the effect is not noticeable (as with the COYOTE-KM1 solution), but, if the step is large (as was the case with the COYOTE-H solution), an error may be introduced into the solution. Third, the HEFF code appears adequate for its intended use in scoping calculations. One reason for including the code in this benchmark exercise was to provide a data basis for estimating error bounds for a typical thermoelastic analysis using HEFF. Finally, codes using similar methods and models predicted virtually the same results. While this does not indicate that the model is the same as that necessary to model the YMP behavior (i.e., exploratory shaft evaluations are planned), it is sufficient to indicate that a variety of codes can be used for heat transfer simulations of repository behavior.

8.0 CONCLUSIONS

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9.0 REFERENCES

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APPENDIX A

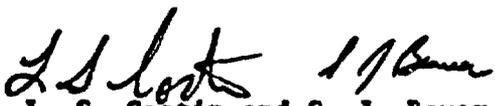
PROBLEM DEFINITION MEMO 71-032

Sandia National Laboratories

Albuquerque, New Mexico 87185

date: 23 December 1987

to: Distribution

from: 
L. S. Costin and S. J. Bauer, 6314

subject: Participation in the Preliminary Benchmark Exercise:
Thermomechanical Analysis Using a Jointed Rock Mass Model -
PDM 71-032

Department 6310 at Sandia National Laboratories (SNL) is engaged in the Nevada Nuclear Waste Storage Investigations (NNWSI) Project. An integral part of this project is the development, verification and validation of computer codes and the material models embodied in those codes. Benchmarking will assist in meeting both the verification and validation requirements of SOP-03-02 and NNWSI DOP 03-02 to provide the necessary and sufficient documentation for software quality assurance. Benchmarking is essentially a comparison of the results from two or more codes solving the same, well defined, boundary value problem. Preliminary benchmarking, such as the exercise to be discussed below, is also intended to assist in model development as a means of identifying potential problems with the software before validation is undertaken.

As a participant in the NNWSI Project, we request your support and participation in this preliminary benchmarking exercise. Attached is the Problem Definition Memo which describes the problem to be solved. Each participant is asked to review the problem definition, within the next two weeks. After careful review, please indicate in a Task Acceptance Memo (ATM) your acceptance (or rejection or conditional acceptance) of this task. In this ATM we request you to provide us with the following information:

- A. Name and signature of the analysts assigned to this task and the code/model with which they will be working.
- B. Name and signature of the person supervising the analyst, who confirms the qualifications of the analyst for this task.

The analysis of the proposed problem will be conducted in accordance with NNWSI DOP 2-4 and DOP 3-3 (Rev. A). Because this benchmarking exercise is a QA Level II activity, certain

documentation on each code/material-model used must be submitted before the conclusion of the analysis. This includes written documentation of the codes and material models used, a user's manual for each code used, a hard copy (preferably on microfiche) and a "computer readable" copy (preferable on magnetic tape) of the source version of each code/model used. Both hard copy (in the form of plots, etc.) and "computer readable" copies of the results in a specified format will also be required (see the PDM).

Because DOP 3-2 (draft) is not yet approved, work may begin on this exercise before the configuration management and document storage systems are fully implemented. Once these systems are in place, the PI's will insure that each code being used in this exercise is placed into the configuration management system and that all available documentation is collected.

Once the formal exercise begins, it is requested that the various analysis groups remain independent and not discuss the problem or results with other groups within their organization or other participant organizations. If questions arise, the PI's may be contacted for resolution or clarification. All necessary communication among analysis groups will be handled by the PI's

NNWSI Problem Definition Memo
Date: 23 December 1987

Analysis Title: Preliminary Benchmark Problem I: Thermomechanical Analysis
Using a Jointed Rock-Mass Model.

Work Breakdown Structure (WBS) No. 12461
PDM No. 71-032 Task/Subtask No. C.1 (QALA #102)
Task Title: Preliminary Benchmarking
QA Level II Case and Subcase No. 1561.750

1.0 Background

References [1] and [2] define the requirements to be met to satisfy the NRC of the quality of the scientific software used in substantiating a nuclear waste repository license application. For work conducted at SNLA, these requirements are reflected in DOP 3-2 [3]. One requirement of DOP 3-2 is that each computer code used must be verified as to the correctness of the implementation of the equations embodied in the code and the numerical techniques used to solve those equations. In general, the process of documenting this is referred to as code verification. In addition, the models used must be validated. This includes documented demonstrations that the models, as embodied in the software, are correct representations of the intended physical systems or processes.

Thermomechanical models for intact and jointed rock mass behavior are being developed, verified and validated under WBS 1.2.4.6.1. Because of the complex nature of the models being developed, comparison of computer code results to analytical solutions of selected boundary value problems is not always a practical means of verification. An alternative form of verification is documented benchmarking. In reality, benchmarking includes elements of both verification and validation and is considered very important for the complete documentation of finite element codes and models.

In the benchmarking exercise defined in this PDM, a specific thermomechanical boundary value problem will be solved. The problem is a generic extraction of a typical problem likely to be run by design analysts. The codes and models (Section 2.0) to be used for this problem were chosen so that several comparisons could be made. First, three different models, which we believe to simulate rock mass behavior, will be compared. These include a linear elastic model in which the elastic constants have been adjusted in an attempt to account for the influence of joints on the deformation. Two continuum joint models will also be used. These models, the Compliant Joint Model (CJM) [4,5] and the Joint Empirical Model (JEM) [6] are different mathematical descriptions and implementations of essentially the same physical processes; that is, joint closure under normal stress and joint shear as a result of normal and shear stresses are explicitly addressed in the model. Other models, such as those based on discrete block motion rather than continuum principles, have been developed and reported in the literature. This class of models is also under consideration for use in the project. However, one major purpose of this initial benchmark exercise is to develop part of the process of code/model

verification and not necessarily attempt to completely cover the range of possible methods that could be used in the design process.

A second comparison to be made is between codes using the same material model and the same thermal solution. Two different mechanical codes will be used with both the CJM and the JEM. In both cases, the codes to be compared employ somewhat different numerical solution techniques. In addition, all mechanical codes will be used to generate a solution using the linear elastic rock-mass model. The third comparison to be made is among the thermal solutions. Three different thermal codes will be used, thus, this exercise will serve to further document the verification of these codes. Finally, the results of different analyst groups solving the same problem with the same mechanical code will be compared to document the variability in results that can be expected solely due to analysts preferences in meshing and running a problem.

The computer code HEFF is included in the benchmark exercise because it employs the boundary element method for the solution of linear elastic problems which is considerably different from the finite element method used by the other codes. The boundary element method has the advantages that it is easy to use, very fast, and can be run on mini or personal computers. However, the boundary element method can only be used for linear elastic problems and in order to solve thermal-mechanical problems, the solution for the temperature field must be approximated by the analytical solution for a line heat source in an infinite media. Despite these restrictions and approximations, HEFF has proved to be a valuable tool in design analysis of underground openings. Because of its potential usefulness, the results from HEFF will be compared to the results from the other linear elastic solutions, in order to assess formally the effect of these approximations on the overall solution and to determine the limits of accuracy that can be expected.

The results of the analyses and comparisons of solutions directed by this PDM will be reviewed in accordance with DOP 2-4 (Section 5.0). The review will be conducted by an independent peer review panel approved by supervision. At a minimum, this will be a one-time review conducted at the completion of the exercise. However, intermediate or continuing reviews may be conducted at the discretion of the PI's with approval of management.

2.0 Participants

The participant groups and the code/model combinations they will use are listed in Table 2.1. Once the PDM is accepted, each participant group will assign one or more qualified analysts to perform the calculations. The analysts names and qualifications should be listed in the Task Acceptance Memo. The Principal Investigators for this exercise are:

Laurence S. Costin
SNL Division 6314
(505)846-0488

Stephen J. Bauer
SNL Division 6314
(505)846-9645

TABLE 2.1

Preliminary Benchmarking Exercise
Participant List

<u>Participant</u>	<u>Thermal Code</u>	<u>Mechanical Code</u>	<u>Material Model</u>
Sandia Labs.	COYOTE [12]	JAC [13]	Linear Elastic-Rock Mass and Compliant Joint [5]
	COYOTE [12]	SANCHO [16]	Linear Elastic-Rock Mass and Compliant Joint [5]
Re/Spec. Inc.	SPECTROM 41 [14]	SPECTROM 31 [15]	Linear Elastic-Rock Mass and Joint Emper. Model [6]
	SPECTROM 41 [14]	SANCHO [16]	Linear Elastic-Rock Mass and Joint Emper. Model [6]
J. F. T. Agapito	DOT [17]	JAC [13]	Linear Elastic-Rock Mass and Compliant Joint [5]
	DOT [17]	VISCOT [18]	Linear Elastic-Rock Mass
	HEFF [19,20]	HEFF [19,20]	Linear Elastic-Rock Mass

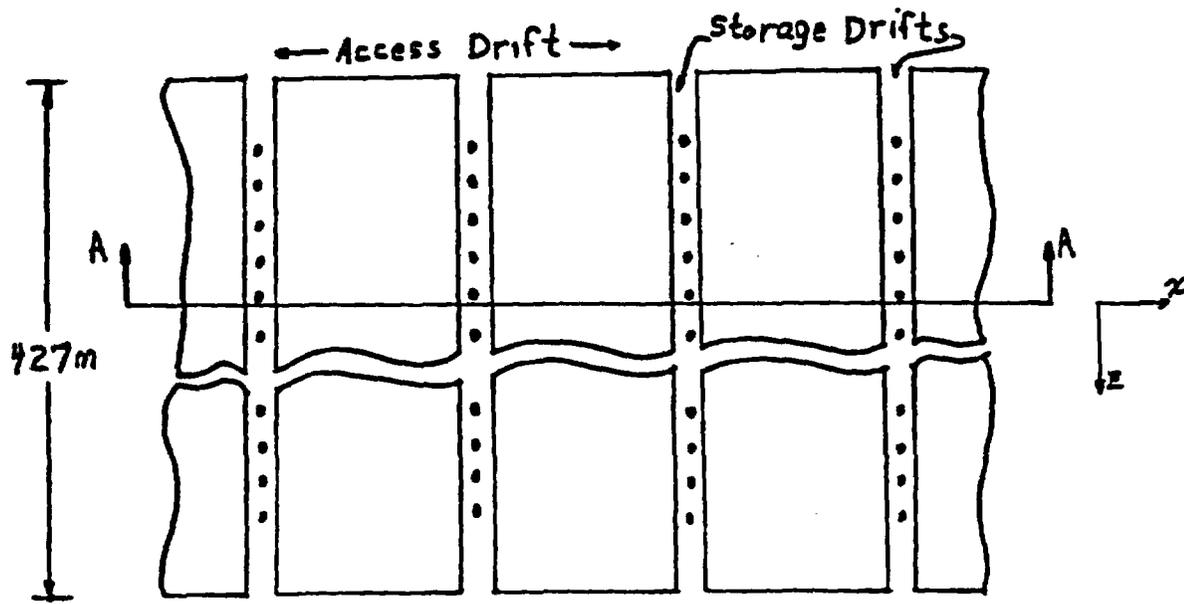
All correspondence or phone contact should be made through the PI's. Once the PDM is accepted by all parties and the analyses begin, the analysts should not discuss the problem or the results with any of the other groups. In this context, a group is one or more analysts using a specific code/model combination to solve the problem. Several different groups may be working within one participant organization and they should make every effort to remain independent and not discuss or share information or results. Any questions or need for clarification should be addressed to the PI's. In cases where two different groups will use the same thermal code solution as input to two different mechanical code/model analyses, only one thermal solution is required which may be shared with both groups.

3.0 Problem Definition

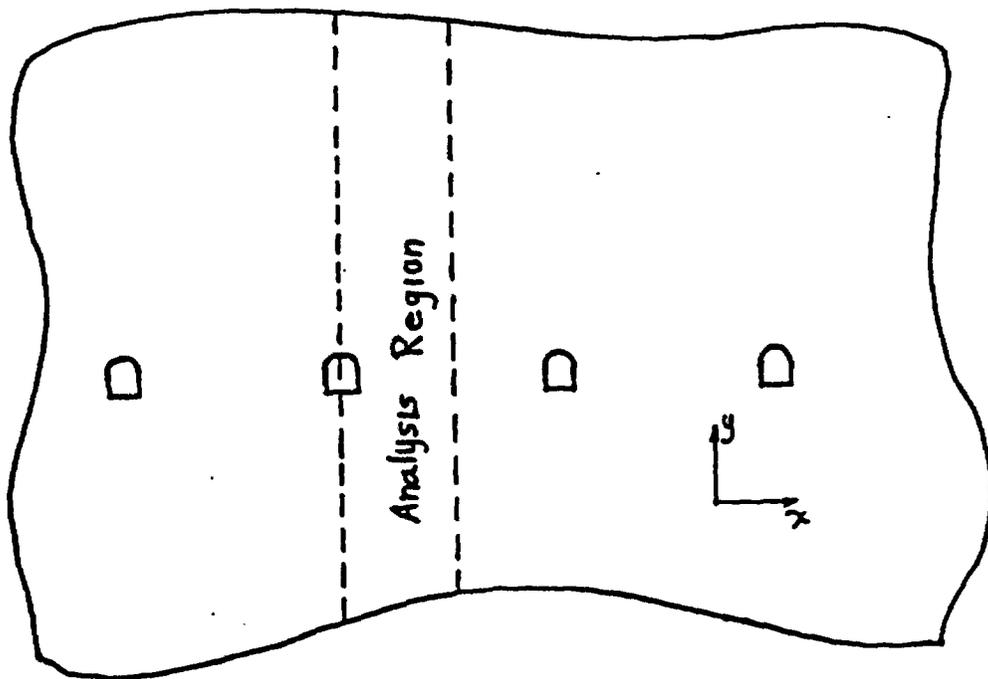
The problem to be solved is a two-dimensional idealization of a series of drifts with the approximate dimensions of the proposed design for vertical emplacement storage of nuclear waste at Yucca Mountain (Figure 3.1). Because of symmetry, only a vertical strip from the centerline of the room to the centerline of the adjacent pillar will be analyzed. Plane strain conditions are assumed to exist and the analyzed region is assumed to be part of an infinite array of such rooms. Since none of the codes to be used by the participants (with the exception of HEFF) are coupled thermomechanical codes, the analyses will be performed in three stages. First, the thermal analyses will be run and the solutions compared (see Section 6.0 for schedule). Next, each mechanical code will be used with the linear elastic rock-mass model to solve the mechanical problem. This will provide the opportunity to compare the results of all codes using the same material model. In addition, a comparison of results from this second stage will help assure that input parameters such as boundary conditions are being implemented correctly before trying to solve the mechanical problem using a non-linear jointed-rock model. Finally, the mechanical analyses will be performed using the appropriate jointed-rock material model (see Table 2.1). After completion of each stage of the analysis, a letter report and results will be forwarded to the PI's for review and comparison of results. A meeting with the participants will then be held to discuss the results and give each participant an opportunity to correct any errors before proceeding on to the next stage.

The region involved in the thermal analysis will be greater in vertical extent than the region to be included in the mechanical analysis. This will simplify the prescribed boundary conditions for thermal problem and prevent reflections from the region boundaries from interfering with the solution in the near drift region to be analyzed with the mechanical code. This difference in geometry between the thermal and mechanical problem may require the use of a translation program which translates and interpolates the temperature field from the thermal mesh to the mechanical mesh.

In the following subsections the thermal and mechanical problems are described in detail.



38.4m
 (a) Repository Panel (Plan View)



(b) Elevation A-A

FIGURE 3.1: General Layout Showing Analysis Region.

3.1 Geometry

The problem geometry is shown in Figure 3.2. The region to be analyzed is a strip that is bounded by the centerline of the drift on the left and by the centerline of the pillar on the right. The vertical extent of the analysis region will be different for the thermal and mechanical portions of the problem and will be discussed in the following subsections. The rock mass is assumed to be uniform and homogeneous throughout. The drift has a horizontal floor with a vertical side wall and an arched roof. The roof is formed by a circular sector with a radius of 2.74 m. The intersection of the floor with the side wall should be rounded with a radius of 0.3 m. This is done to reduce the stress concentration at the corner of the drift. A heat source is buried below the center of the drift as shown in Figure 3.2. The rock mass in the analysis region is assumed to be homogeneous to the extent that mechanical and thermal properties do not vary with location. The rock mass has two sets of joints which are orthogonal to each other with one set oriented horizontally and the other vertically. The heat source is assumed to have the same thermal and mechanical properties as the host rock.

3.1.1 Thermal Problem

The geometry of the region to be analyzed using the designated thermal analysis code is shown in Figure 3.3. The floor of the drift is located 311 m below the surface. For common reference, the intersection of the drift centerline with the floor should be chosen as the coordinate axes origin (Figure 3.3). The lower boundary of the modeled region extends 300 m below the drift floor.

A line of heat sources is buried 3.05 m below the center of the drift floor. Because of the assumed plane symmetry, the heat source is to be modeled as a rectangular slab 0.74 m wide by 4.57 m long and of infinite extent in the out-of-plane (z-coordinate) direction. Note that because only one-half of the drift is modeled, the heat source in the modeled region is only 0.37 m wide. The initial power density of the heat sources was chosen so that the average heat load over an entire panel of such drifts would be approximately 80 kw/acre (see Appendix A). This is somewhat greater than the 57 kw/acre initial heat load expected for the current design configuration, but the added load will cause larger stresses and more deformation in a greater region and, thus, test the numerical solution schemes in the codes more severely. The thermal output of the heat sources decays with time as described in Section 3.3.

The solution should begin at a problem time of zero years and run through a problem time of 101 years. The heat source becomes active at a problem time of one year (see section 3.4 for problem time event sequence). The drift will be modeled as an unventilated, air filled cavity. This can be done without the necessity of calculating the radiative and convective heat transfer at the drift walls by assuming that the drift is filled with a conductive "drift equivalent material". The specified conductivity of the drift material (see Section 4.0) was chosen to account for the combined effects of radiative, convective and conductive heat transfer at the drift walls [7-9].

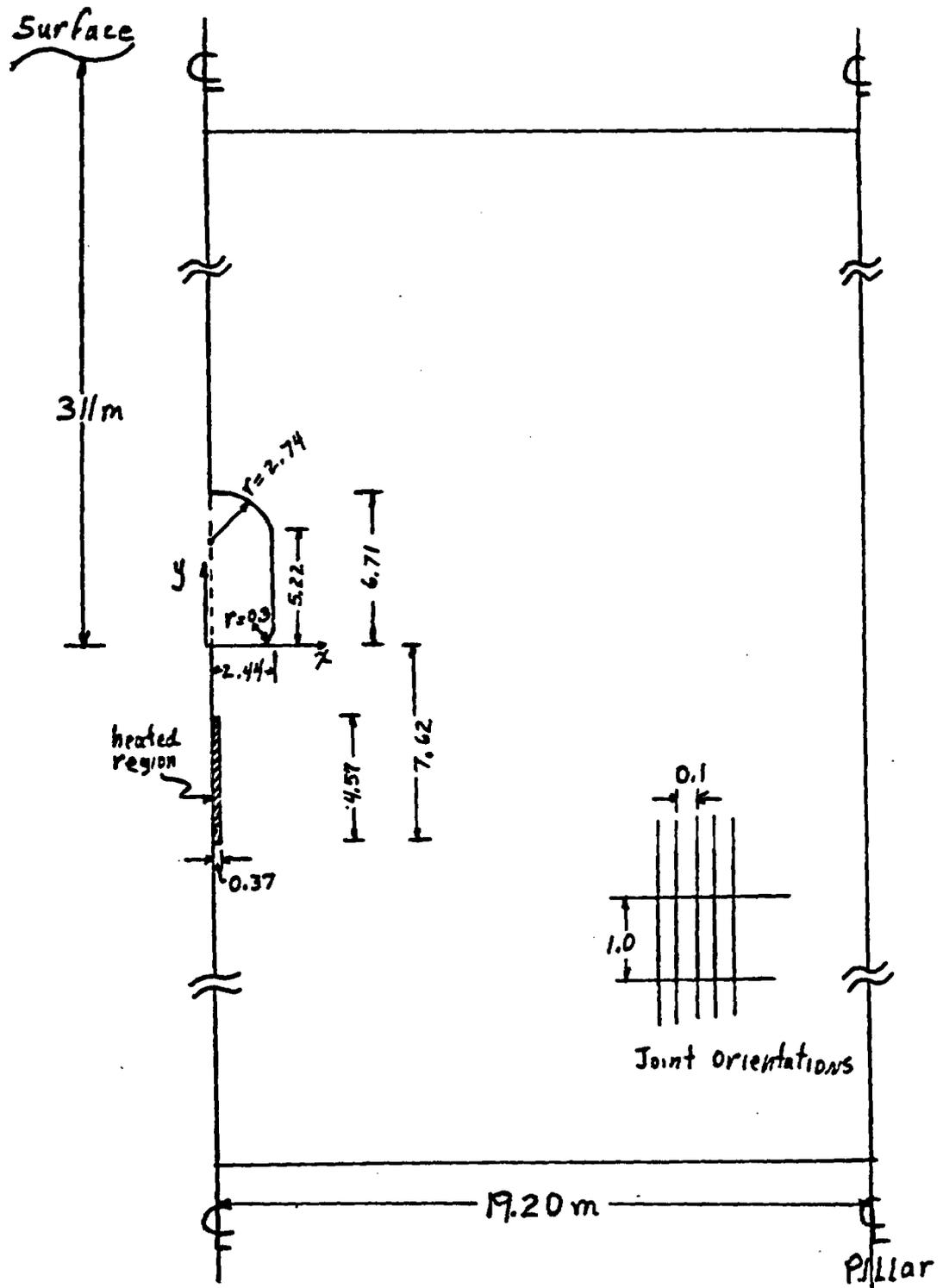


FIGURE 3.2: Problem Geometry.

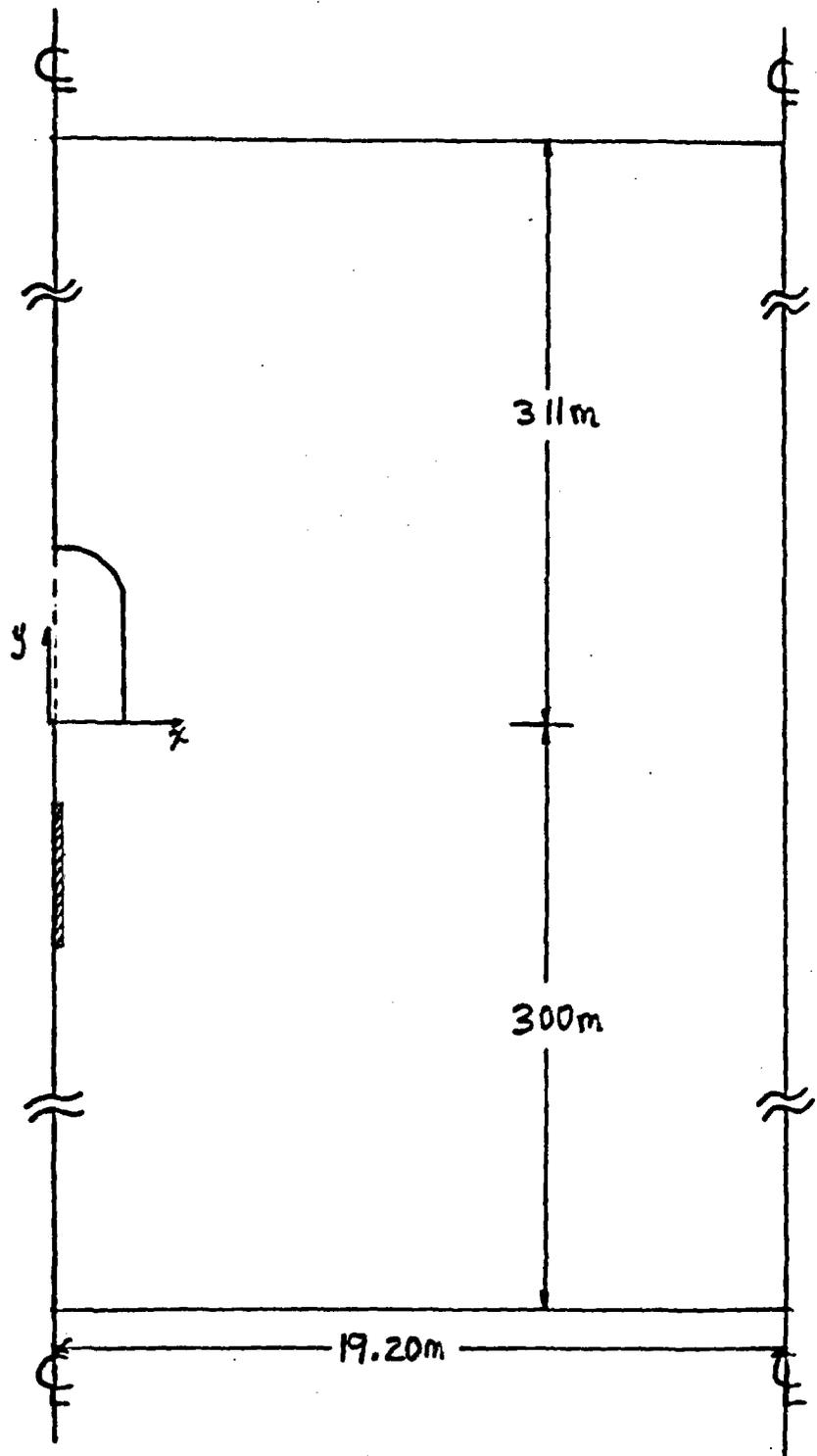


FIGURE 3.3: Analysis Region for Thermal Solution.

3.1.2 Mechanical Problem

The geometry for the corresponding mechanical analysis is shown in Figure 3.4. The only difference from the thermal problem is that the vertical extent of the modeled region is reduced to 100 m above and below the floor of the drift. As with the thermal problem, the coordinate axes origin is at the intersection of the floor with vertical drift centerline. For the mechanical analysis, the drift is assumed to be empty, i.e. the material in the drift after mining has occurred has no stiffness or strength. The material comprising the heat source is assumed to have mechanical properties identical to the rock mass, i.e. the heat source is not modeled as a separate material.

The rock mass is assumed to be uniform and homogeneous with two sets of joints oriented orthogonal to each other and striking in the out-of-plane (z-coordinate) direction. The first set dips vertically and the second set is horizontal. The distance between joints in each joint set is assumed to be uniform, although the two sets have different spacings (see Section 4.0). The spacing of each joint set was chosen to correspond to the approximate spacing of vertical and horizontal joints at Yucca Mountain (RIB Version 2.002 Section 1.3.2.4.2).

3.1.3 Special Requirements

For simplicity and uniformity in reporting the results of this exercise it is important that each participant use the same set of measurement units and the same coordinate system. The reference coordinate system will be a cartesian system with the origin at the intersection of the drift centerline and the drift floor (point A in Figure 3.5). The positive x-axis extends to the right to the pillar centerline, the positive y-axis extends vertically to the surface and the positive z-axis is directed out of the plane of the paper. In reporting results, displacements in a positive coordinate direction should be reported as positive displacements. Tensile stresses should be reported as positive and compressive stresses as negative. Positive shear stresses are as shown in Figure 3.5.

Standard SI units as defined by ASTM E 380-76 [10] should be used throughout. Specifically, stresses and pressures are in MPa, distances and displacements are in metres or millimetres and temperatures are in degrees Celsius. Because of the nature of the problem and the decay of the thermal source, the problem should be run in time units of years (see Section 3.4).

In order to compare the results from different analyses of this problem, each participant will be asked to provide the values of several output parameters (stress, displacement, temperatures etc.) as functions of time at certain key locations within the problem region (see Section 5.0). Figure 3.5 shows the location of these points. In addition, each analyst will be asked to provide the values of several output parameters at certain times as functions of distance along several prescribed lines. Four such lines are designated in Figure 3.5. Line 1 is a vertical line, $x=0$, through points K-D-A-E-F-I in the figure. Line 2 is a line along the centerline of the pillar ($x=19.20$ m) through points L-H-C-J. Line 3 is a horizontal line,

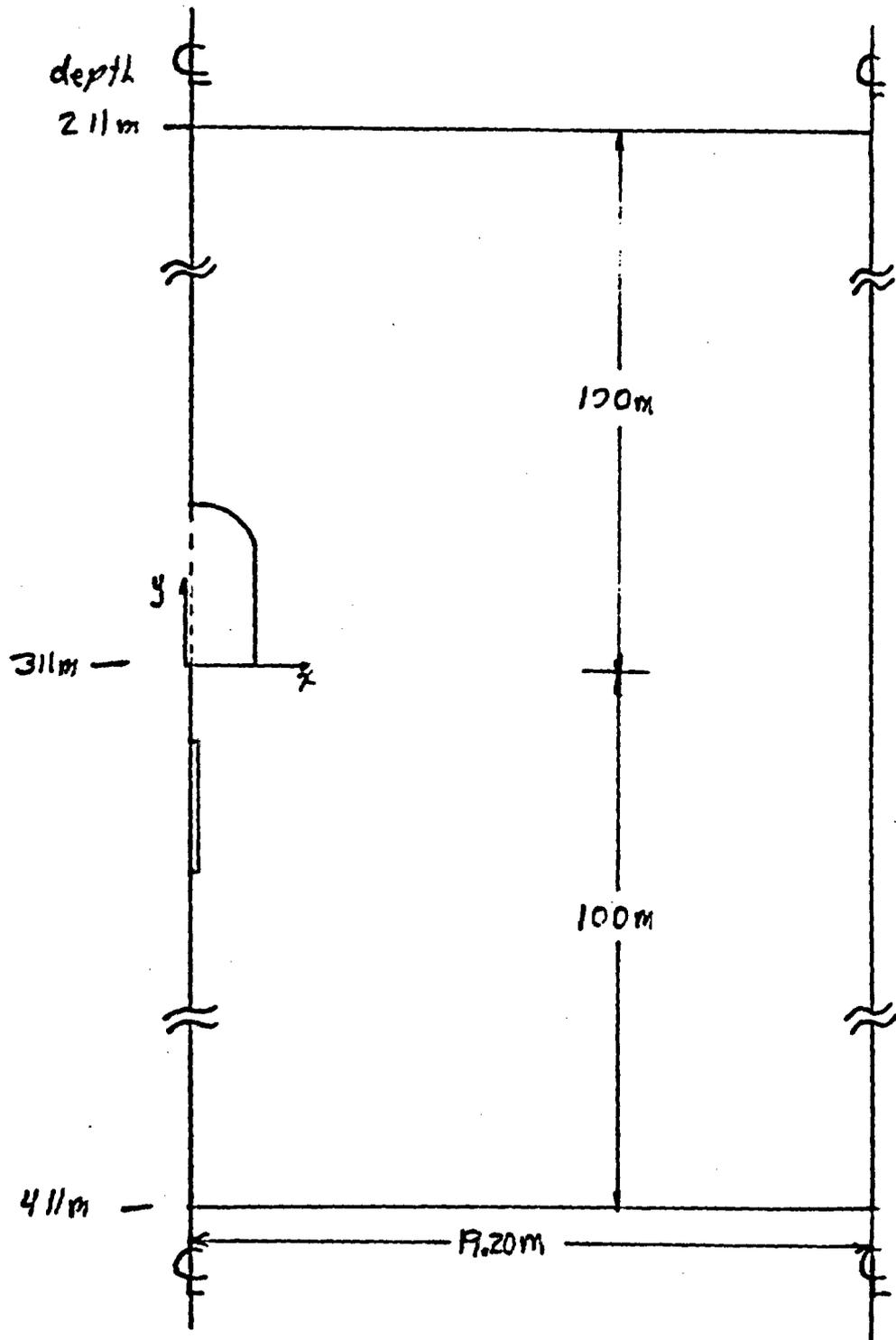


FIGURE 3.4: Analysis Region for Mechanical Solution.

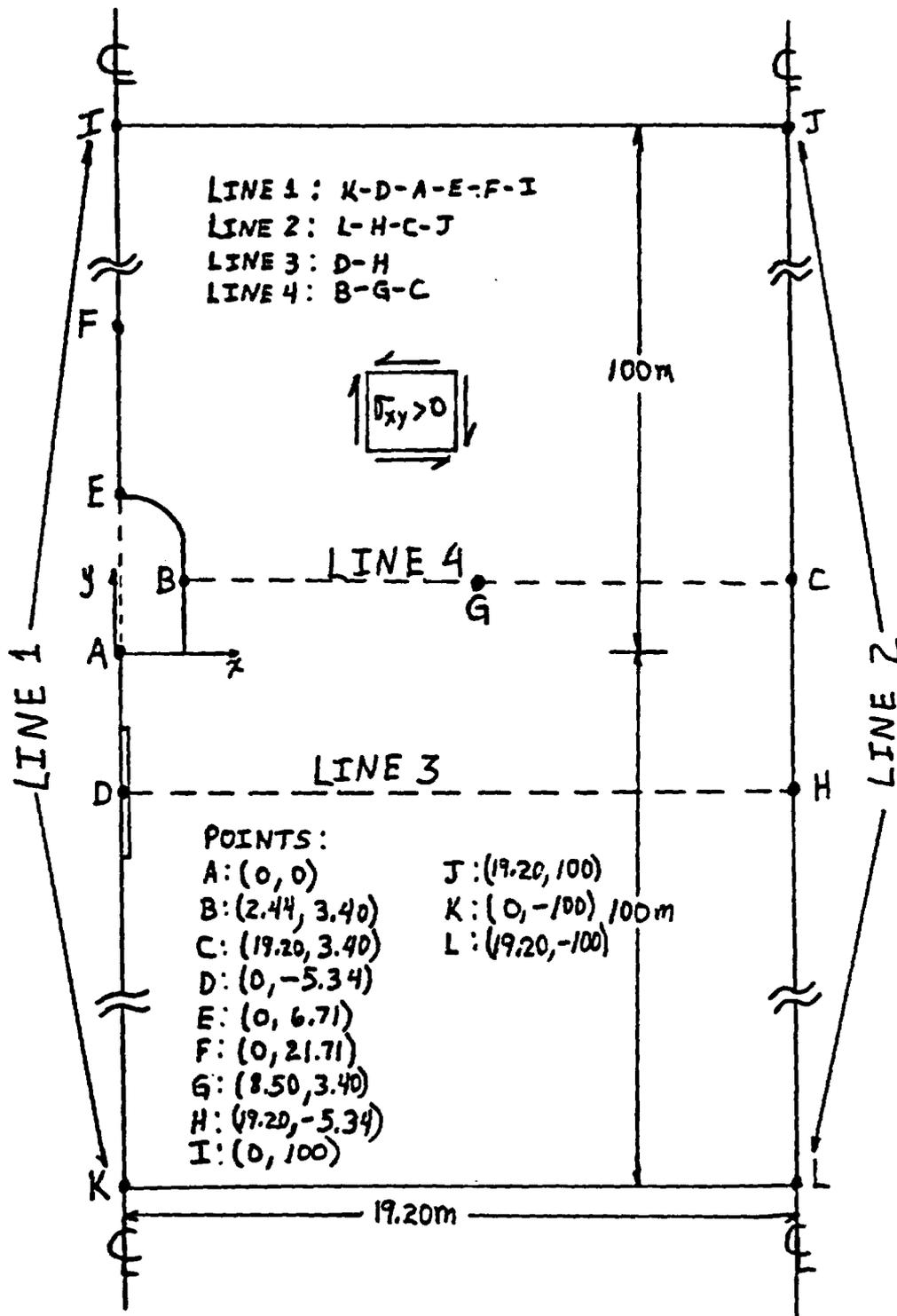


FIGURE 3.5: Points and Lines Where Data Will Be Required.

y=-5.34 m, which runs from the center of the heater (point D) to the center of the pillar (point H). Finally, Line 4 is a horizontal line (y=2.44 m) running from the midpoint of the drift wall (point B) to the center of the pillar (point C). The locations of these points and lines should be taken into account when generating the finite element meshes for both the thermal and mechanical solutions so that sufficient spatial resolution is obtained.

3.2 Boundary and Initial Conditions

3.2.1 Thermal Problem

Because the modeled region is assumed to be a vertical slice taken from an infinite array of emplacement drifts, the vertical boundaries through the centerline of the drift and the centerline of the pillar should be modeled as adiabatic boundaries (Figure 3.6). The top surface of the model is assumed to be at the rock mass surface, and should be modeled as a constant temperature boundary. The lower surface of the model is sufficiently far away that the thermal disturbance should not reach it within the limits of the problem time. The lower surface should also be modeled as a constant temperature boundary.

The initial temperature at the upper surface of the analysis region is 25°C. A temperature gradient of 0.0185°C/m runs down to the bottom of the modeled region. The magnitude of the gradient was chosen to be the average gradient in the analysis region (RIB Version 2.002 Section 1.3.1.7). Thus, the temperature at any depth is given by

$$T = 25.0 + (0.0185)(\text{depth in metres}).$$

This results in the lower boundary being maintained at a temperature of 36.3°C (Figure 3.6). Once the drift is mined and the heat source emplaced (see Section 3.4 for event times), the material in the drift should be considered as an equivalent conductive material with the conductivity specified in Section 4.0. This "equivalent drift material" is an approximation to an unventilated drift, where the thermal conductivity of the equivalent material takes into account the radiative, convective and conductive heat transfer that would take place between the drift walls and the stagnant air [7-9]. The time history of the power density in the heated region is given in Section 3.3. The material in the heated region is assumed to have the same thermal properties as the surrounding rock mass.

3.2.2 Mechanical Problem

Because of symmetry, the two vertical boundaries should be constrained from displacement in the x-direction (roller boundaries, as shown in Figure 3.7). The bottom boundary should also be a roller boundary, constrained from vertical displacement. A uniform normal pressure should be applied to the upper surface of the modeled region. This pressure is the result of the overburden of rock above the modeled region. The upper boundary is 211 m

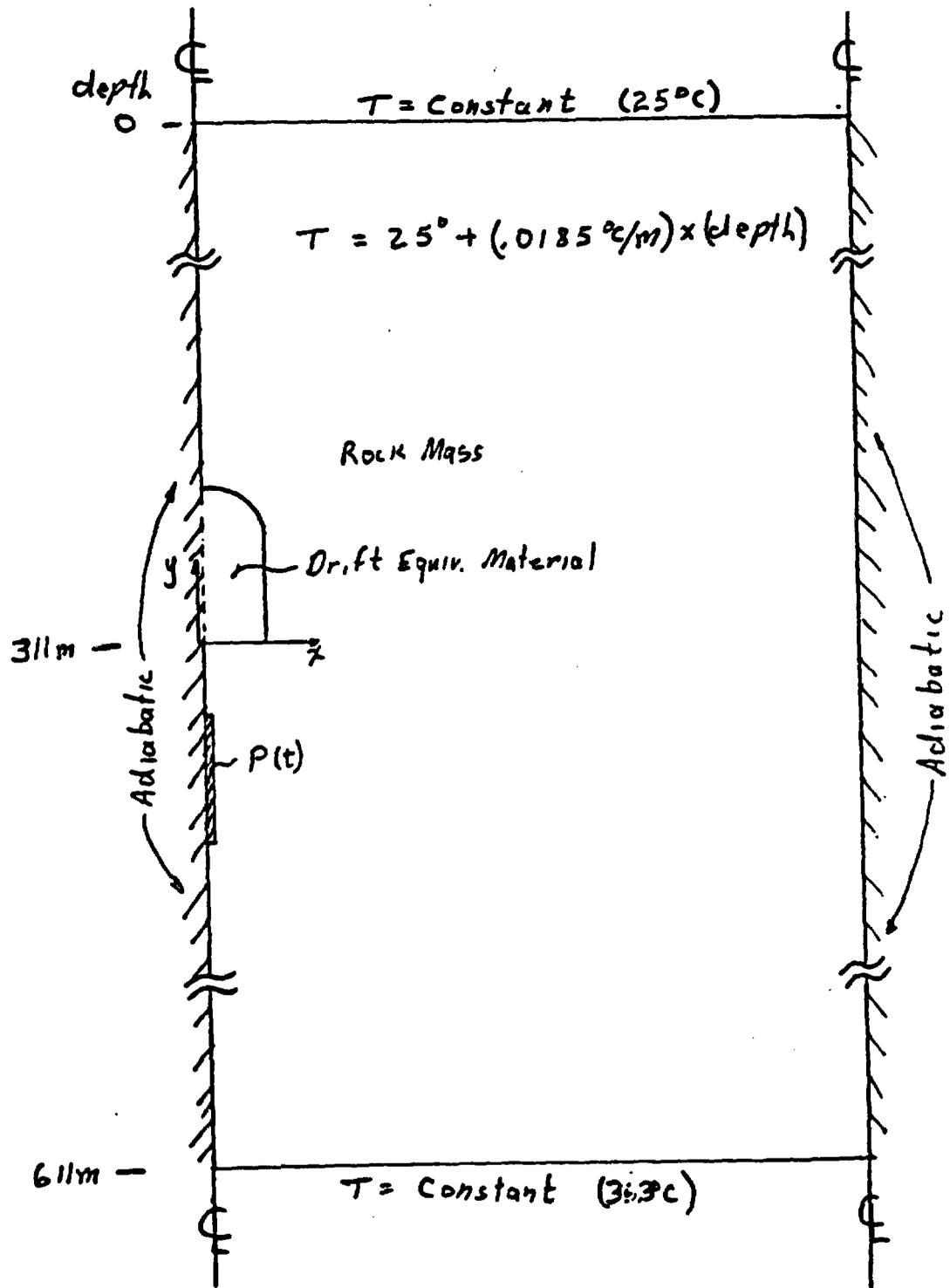


FIGURE 3.6: Boundary Conditions for Thermal Problem.

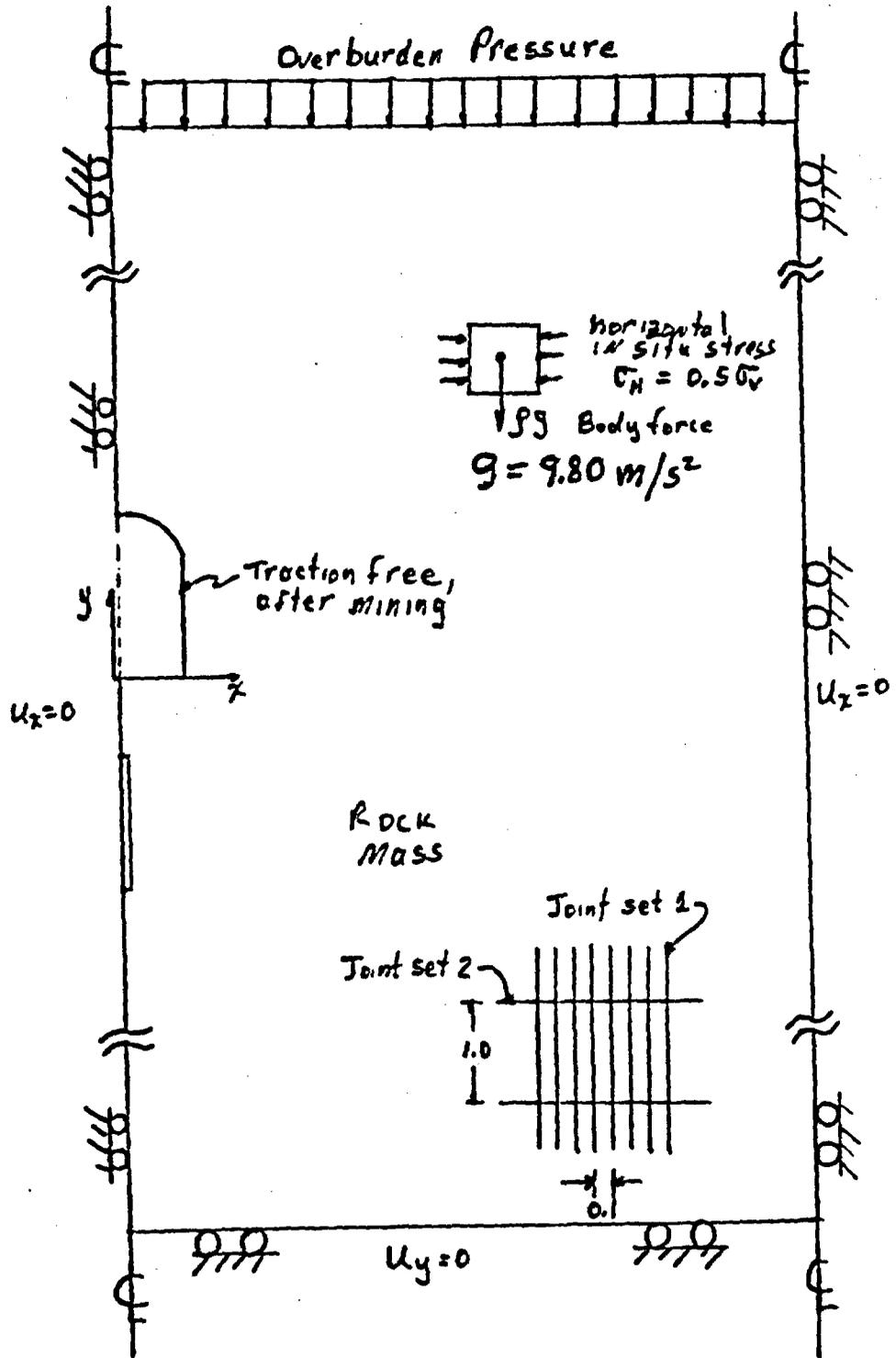


FIGURE 3.7: Boundary Conditions for Mechanical Problem.

below the surface. Using the thickness and densities of the overlying strata as provided by the NNWSI Reference Information Base (RIB Version 2.002) the overburden pressure to be applied is calculated to be 4.72 MPa (see Appendix B). In addition to the overburden, a gravitational body force is applied to the rock mass (Figure 3.7). An initial horizontal in situ stress should be applied so that, at each point in the region, the ratio of initial horizontal in situ stress to initial vertical in situ stress is 0.5. These stresses are applied during problem initialization at time zero and the displacements after stress initialization must be zero at time zero. Once the drift is mined, the drift walls are assumed to be traction free.

3.3 Thermal Loading

The thermal output of the heated region is given in terms of a power density function. The power density as a function of time is given by

$$P(t) = P_0 \left[\sum_{i=1}^4 a_i e^{-b_i t} \right]$$

where P_0 is the initial power density, and t is the time, in years, from emplacement. The decay constants a_i and b_i are chosen to correspond to the temporal decay of 60% PWR/ 40% BWR waste (RIB Version 2.002 Section 3.1.1.1) and are given in Table 3.1.

Table 3.1: Decay Constants

i	a_i	b_i (yrs ⁻¹)
1	0.15602	0.00135
2	0.59787	0.01914
3	0.15227	0.05188
4	0.09384	0.43768

The initial power density is 276 w/m² per metre depth (z-direction). The total power per metre depth into the plane is found by multiplying the power density by the area of heated region (see Appendix A).

3.4 Problem Time

The problem is to be run from zero to 101 yrs. At time zero, the in situ stresses (overburden, gravitational body force and horizontal stress) are applied to the model region where no drift cavity is yet present. This will

establish the initial in situ equilibrium stress state (at zero displacement) before drift mining. At time 0.5, the drift is instantaneously mined. This can be done by applying an element death option, if available. At time 1.0 the heated region becomes active, simulating instantaneous emplacement of the waste. The calculation should continue to time 101.0.

In order to impose some uniformity on the solution process and to insure that solutions are obtained at certain critical times, solutions with full data and plot files should be obtained at the following times, as a minimum:

At time zero, the initial stress state should be recorded and checked.

At time 0.5 the post-mining solution should be recorded.

From time 1.0 to time 3.0, solutions every 0.25 yrs
(i.e. 1.0, 1.25, 1.50, ... , 2.75, 3.0).

From time 3.0 to time 5.0, solutions every 0.5 yrs.

From time 5.0 to time 31.0, solutions every 1.0 yrs.

From time 31.0 to time 101.0, solutions every 5.0 yrs.

Solutions may be obtained at more frequent intervals, with or without storage of results, at the discretion of the analyst.

4.0 Material Properties

Thermal and mechanical properties are assumed to be uniform throughout the rock mass. The value of each property cited is taken from the NNWSI RIB Version 2.002, assuming the drift is located in the TSw2 Thermal/Mechanical Unit, unless otherwise noted.

Thermal Properties: Thermal properties are given for specific ranges of temperatures. For temperature ranges designated as "Transition Regions" a linear interpolation between the value at the lower end of the range and the value at the upper end should be used to obtain the values within the transition region.

Rock Mass (TSw2 Unit):

Thermal Conductivity ($T < 100^{\circ}\text{C}$) - 2.29 w/mK (see NOTE 1)

($T > 125^{\circ}\text{C}$) - 1.88 w/mK (see NOTE 1)

($T = 100 - 125^{\circ}\text{C}$ Transition) Linear Interp.

Thermal Capacity ($T < 100^{\circ}\text{C}$) - 2.16 J/cm³K

($T > 125^{\circ}\text{C}$) - 2.17 J/cm³K

($100 < T < 125^{\circ}\text{C}$) - 9.26 J/cm³K (see NOTE 2)

Coefficient of Thermal Expansion ($T < 200^{\circ}\text{C}$) - $8.8 \times 10^{-6} \text{ K}^{-1}$

($T > 200^{\circ}\text{C}$) - $24.0 \times 10^{-6} \text{ K}^{-1}$

Bulk Density = 2.32 g/cm^3 (in the analysis region)

Drift Equivalent Material: (see NOTE 3)

Thermal Conductivity = 50.0 w/mK (all temperatures)

Thermal Capacity = $1.0 \times 10^{-3} \text{ J/cm}^3\text{K}$ (all temperatures)

Density = $1.0 \times 10^{-3} \text{ g/cm}^3$

Mechanical Properties: Listed by material model.

Rock Mass Model:

Bulk Density = 2.32 g/cm^3
Young's Modulus = 15.2 GPa
Poisson's Ratio = 0.22

Compliant Joint Model:

Density = 2.32 g/cm^3
Young's Modulus = 30.4 GPa
Poisson's Ratio = 0.24
Joint Cohesion = 0.1 MPa
Joint Friction Coefficient = 0.54
Unstressed Aperture = 0.030 mm
Half Closure Stress = 2.0 MPa
Shear Stiffness (G_s) = $1.0 \times 10^6 \text{ MPa/m}$
Shear Hardening (G_{sp}) = $1.0 \times 10^4 \text{ MPa/m}$ (see NOTE 4)
Spacing Between Joints (see NOTE 5)
 Vertical Joints = 0.1 m
 Horizontal Joints = 1.0 m

Joint Empirical Model:

Use appropriate values given for the Compliant Joint Model for intact rock properties and to calculate equivalent joint closure parameters. In addition use:

$JRC_o = 9.0$ (degrees)
 $JCS_o = 171.0 \text{ MPa}$
Base (Residual) Friction Angle = 28.4 (degrees)
Scaling Parameter = 1.0 (see NOTE 6)
Joint dilation should be neglected (set to zero)

NOTES:

1. Value given is from the SCP. Value given in the RIB Version 2.002 is in error
2. Calculated using Attachment 1 to Appendix O of the SCP-CDR, assuming an in situ saturation to completely dry transition in the 100 to 125°C range and a pore volume fraction of 0.12 with 67% saturation (see Appendix C, for details).
3. Values based on results in reference [9].
4. Slope of the shear stress-joint displacement curve after slip begins (equivalent to the plastic tangent modulus in elastic-plastic model).
5. From Appendix O of the SCP-CDR.
6. Required by the JEM model implementation [6]. Joint parameters for both sets of joints (other than spacing) are assumed to be derived from the same set of laboratory data.

5.0 Reporting Requirements

Specific information concerning the calculations and the results are required in order to make a complete evaluation of the benchmark exercise and the codes/models used. In addition, the results provided by each participant needs to be presented in a specified format so that direct comparisons can be made easily. The results should be transmitted via letter report. Separate reports are required for each phase of the analysis: thermal, elastic rock-mass, and jointed rock-mass. Each participant group is also given the option of submitting a final report at the end of the exercise which should contain their comments on the exercise as well as corrections or additions to their solutions that they wish to submit for inclusion in the record (see report schedule, Section 6.0). Each letter report should contain a description of the calculations and the results presented in the standard formats described below. In addition, a computer readable copy (tape) of the source code with the material model along with the requested plot results is required. The tape files should be recorded at 1600 bpi in a format (word size, etc.) readable by a VAX 11/780 or VAX 8600. If requested, the PI's will provide you with the tapes. If a tape drive is not available, floppy disks may be used, but the PI's should be informed in advance to insure that compatible formats are used.

A specific ASCII file format is specified below for each set of results. All results will be plotted and compared using the GRAPH [11] plot package at SNLA. Each plot file should have a beginning header which describes what data is contained in the file. Each column of data should also be labeled. In GRAPH file format this is done by using a "!" at the beginning of a line to indicate a comment line. GRAPH employs a free field reader for columns of data, so entries need only be separated by a space or a comma.

5.1 General Requirements

Several general pieces of information should be reported for each solution (both thermal and mechanical). These include:

1. Problem run time (CPU seconds)
2. Computer used.
3. Convergence criteria and tolerance used for solution.
4. Mesh Statistics:
 - a. Figure showing the undeformed mesh.
 - b. The number of nodes.
 - c. The number and type of elements.
 - d. The number of degrees of freedom.
 - e. The minimum and maximum node spacing.

5.2 Thermal Solution

5.2.1 Temperature Time Histories

Referring to Figure 3.5, the temperature time history at points A, B, C, D, E, F, and G should be plotted. In the hard copy plots presented in the report, the results at each point should be plotted separately with Time as the abscissa (log scale from 0.1 to 1000. yrs) and Temperature as the ordinate (linear scale from 0. to 250°C). The GRAPH plot file should have the following format:

```
! TEMPERATURE VS TIME FOR POINTS A THROUGH G PER PDM 71-032, BENCHMARK
! PROBLEM.
!
! ANALYST:                CODES USED:
!
! TIME    TEMP A    TEMP B    TEMP C    TEMP D    TEMP E    TEMP F    TEMP G
! (YRS)   (C)       (C)       (C)       (C)       (C)       (C)       (C)
! 0.0     31.        31.      etc.....
!
!
! 101.    300.     200.     etc.....
[EOF]
```

5.2.2 Temperature Profiles

Referring to the Lines defined in Section 3.1.3 and shown in Figure 3.5, the temperature as a function of distance along Lines 1, 2, and 3 should be plotted for times 1, 6, 11, 26, 76, and 101 yrs. One hardcopy plot should be made for each Line with distinct curves for each requested time. The abscissa should run from -100. to +100. m (drift floor is the middle of the line) for Lines 1 and 2 and from 0. to 20. m for Line 3. The ordinates

should be scaled 0. to 250. °C. GRAPH plot files should be recorded with the following format:

```
! TEMPERATURE PROFILE ALONG LINE (N=1,2,OR 3), PDM 71-032, BENCHMARK
!
! ANALYST:                CODES USED:
!
! POSITION ON              TEMP      TEMP      TEMP      TEMP      TEMP      TEMP
! LINE N                  @1yrs   @6yrs   @11yrs  @26yrs  @76yrs  @101yrs
! (m)                     (C)     (C)     (C)     (C)     (C)     (C)
! -100.                   31.    40.    ... etc.
!
!
! 100.                   31.    45.    ... etc.
[EOF]
```

5.3 Mechanical Solution

5.3.1 Displacement Histories

Plots of the vertical and horizontal displacement at the drift as functions of time from 0. to 101 yrs are required. The vertical (y-coordinate direction) and horizontal (x-coordinate direction) displacements of Point B (Figure 3.5) are required. The vertical (y-coordinate direction) displacements of Points A and E are also required. Displacements should be considered positive if they are directed along the positive x or y coordinate axes. The displacements should be plotted in units of mm, with time plotted on a logarithm scale using decades 0.1 to 1000. yrs. The format for the plot file is as follows:

```
! HORIZONTAL AND VERTICAL DRIFT CLOSURE, PDM 71-032, BENCHMARK
!
! ANALYST:                CODES USED:
!
! TIME                    VERT. DISP.    HORIZ. DISP.    VERT. DISP.    VERT. DISP.
! (YRS)                  POINT B        POINT B         POINT A        POINT E
!                         (mm)          (mm)           (mm)          (mm)
! 0.0                    0.0           0.0            0.0           0.0
!
!
! 101.                   -1.5          3.0            1.5           -2.0
[EOF]
```

5.3.2 Displacement Profiles

The vertical displacement profile along Line 1 (Section 3.1.3, Figure 3.5) and the horizontal displacement profile along Line 3 are required at times 0.5, 1, 6, 11, 26, 76, and 101 yrs. The abscissa for the Line 1 plot should

November 13, 1987: Comments from participants and peer reviewers due.

November 13, 1987: Review meeting to resolve comments and finalize PDM.

December 7, 1987: Revised PDM issued.

December 16, 1987: Final comments on PDM due.

December 23, 1987: Final PDM issued.

January 11, 1988: Task Acceptance Memos from participants due.
Authorizations to Proceed issued.

February 22, 1988: Letter report of the results and computer readable data from the thermal solution due. Plots of the results will be made by the PI's and forwarded to the participants for verification. Any errors in data transmission will be corrected.

March 21, 1988: Review meeting for the thermal solution. Comparison of results will be discussed. Participants will have an opportunity to correct any errors they perceive in their solution before beginning the mechanical analysis. Any changes made and final thermal results that will be used as input to the mechanical solution will be documented in a letter report.

April 18, 1988: Letter report of the results and computer readable data from the mechanical analysis using the Elastic Rock-Mass model due. Plots of the results will be made by the PI's and forwarded to the participants for verification. Any errors in data transmission will be corrected.

May 9, 1988: Review meeting for the Elastic Rock-Mass solution. Comparison of results will be discussed. Participants will have an opportunity to correct any errors they perceive in their solution before beginning the mechanical analysis. Any changes made and final thermal results that will be used as input to the mechanical solution will be documented in a letter report.

June 20, 1988: Letter reports of the results and computer readable data from the mechanical analyses using non-linear joint models due. Plots will be made of each data set and forwarded to the respective participants so that they can check to insure that their data has been read and plotted correctly. Any errors in data sets will be corrected before comparisons among the various solutions are made.

August 8, 1988: Meeting with participants and the Peer Review Panel to discuss the results of all calculations. After this meeting the participants will have the opportunity to correct any errors they perceive in their solution.

September 5, 1988: Final letter report due. This report will detail any revision to the initial results and include any comments the participants wish to make concerning the exercise.

October 17, 1988: Peer Review Panel report due. The panel will document its review of the results and make recommendations and judgements as to the success or failure of the benchmark exercise.

February 20, 1989: A SAND report covering the benchmark problem and results along with the review panel's recommendations is submitted for approval.

7.0 References

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APPENDIX A: Calculation of Heater Power Density.

P_d - Drift centerline power
 P_o - Heater volumetric power density
 APD - Areal Power Density
 DS - Drift Spacing
 PW - Panel Width
 HDL - Heated Drift Length
 SO - Standoff Distance
 BPW - Barrier Pillar Width
 ADW - Access Drift Width

From RIB Version 2.002 Sections 2.2.2.8 and 2.2.2.9

DS - 126 ft.
 PW - 1400 ft.
 SO - 85.0 + 92.5 = 177.5 ft.
 BPW - 63 ft.
 ADW - 21 ft.

HDL = PW - SO - BPW - ADW = 1138.5 ft.

$$P_d = \frac{\text{APD} \times \text{DS} \times \text{PW}}{\text{HDL}}$$

Assuming APD = 80 kW/acre

$$\begin{aligned}
 P_d &= \frac{(80 \text{ kW/acre})(126 \text{ ft})(1400 \text{ ft})}{(4.356 \times 10^4 \text{ ft}^2/\text{acre})(1138.5 \text{ ft})} \\
 &= 284.5 \text{ W/ft} \times 3.28 \text{ ft/m} = 933.34 \text{ W/m}
 \end{aligned}$$

$$P_o = \frac{P_d}{(\text{heated area})}$$

$$\begin{aligned}
 &= \frac{933.34 \text{ W/m}}{(0.74 \text{ m})(4.57 \text{ m})} \\
 &= 276 \text{ W/m}^2
 \end{aligned}$$

APPENDIX B: Calculation of Overburden

The overburden pressure exerted by a layer of thickness T is given by

$$\text{PRESSURE} = (\text{DENSITY})(g)(T)$$

where $g = 9.8 \text{ m/s}^2$

For densities taken from the RIB Version 2.002 Section 1.3.1.2 and thicknesses from Section 1.3.1.1.3 (drill hole G-4)

UNIT	DENSITY (g/cm^3)	THICKNESS (m)	PRESSURE (MPa)
UO	-----	9.14	0.5 (assumed)
TCw	2.31	26.80	0.61
PTn	1.58	38.10	0.59
TSw1	2.25	130.10	2.87
TSw2	2.32	6.86	0.15
		<hr/>	<hr/>
		211.0	4.72
		(top of model)	

APPENDIX C: Calculation of Transitional Thermal Capacity

C_T - Transitional Thermal Capacity - Heat Capacity of rock-water system during vaporization of the water.

C_A - Heat Capacity of dry rock.

C_B - Heat Capacity of rock at nominal saturation.

H - Heat of vaporization (2217.52 J/cm³)

Xw - volume fraction of water.

dT - Temperature change over which vaporization occurs

From Appendix O of the SCP-CDR

$$C_T = \frac{C_A + C_B}{2} + \frac{H (Xw)}{dT}$$

From the RIB Version 2.002 Section 1.3.1.3.1-5

$$C_A = 2.17 \text{ J/cm}^3\text{K}$$

$$C_B = 2.16 \text{ J/cm}^3\text{K}$$

From RIB Version 2.002 Section 1.3.1.2.1-4

porosity of TSw2 = 12%

saturation = 67% (from comparison of saturated versus dry densities)

Xw = 0.08

assuming dT = 25°C

$$C_T = 9.26 \text{ J/cm}^3\text{K}$$

APPENDIX B

COMPARISON OF REPORT DATA WITH THOSE IN THE RIB AND SEPDB

All material property and design configuration data used in the benchmark calculations reported in this document were taken from the YMP Reference Information Base (RIB), Version 2.002. Specific values of the data used are given in Appendix A, Section 4. This report contains no data taken from or that should be included in the Site Engineering Properties Data Base (SEPDB).

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NNA.900515.0142

