NISTIR 5528

Finite Element Analysis of Advanced Technology Laboratories (ATL) Isolation Slab Conditioning System -

An Interim Progress Report

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Stephen J. Treado**

U.S. DEPARTMENT OF COMMERCE
Technology Administration
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*Computing and Applied Mathematics Laboratory
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U.S. DEPARTMENT OF COMMERCE
Ronald H. Brown, Secretary

TECHNOLOGY ADMINISTRATION
Mary L. Good, Under Secretary for Technology

NATIONAL INSTITUTE OF STANDARDS
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Arati Prabhakar, Director

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An Interim Progress Report[1] *on*
Finite Element Analysis of ATL[2] Isolation Slab Conditioning System

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Abstract:

Using a finite-element analysis package named ANSYS (v. 5.0a), we model a precision temperature-control slab conditioning system in order to solve a steady state and transient heat transfer problem for a new NIST facility known as the Advanced Technology Laboratories (ATL). The problem arises because the concrete floor slabs of some of the ATL laboratories are exposed to warm room air above and cold earth below, and a supplementary heating source consisting of embedded electric cables and heated water pipes (hydronic system) is proposed to alleviate the difficulty of achieving precision temperature control due to a constant heat loss to the ground. For this interim report, two sets of computer codes, one for the steady state and the other for the transient phenomenon, were developed for a two-dimensional slab/insulation/ soil configuration, and applied to three steady-state and six transient loading cases. Preliminary results of this study are: (a) The time constant for the slab conditioning system is estimated to be between 10 to 20 hours. (b) The temperature distribution along the top surface of the slab is not uniform, with a significant discrepancy between the center and the edge of the slab in the order of 0.06°C. (c) The proposed hydronic heating system is found to be beneficial to temperature stabilization and slab isolation. Additional questions to be answered in the final report include (d) the effect of the heating cable system, (e) the influence of the long time constant to the performance of the laboratory temperature control system, and (f) the "goodness" of the 2-D approximate model solution to the actual 3-D physical configuration.

Keywords: Convective heat transfer; finite element analysis; heat transfer; mathematical analysis; partial differential equations; Poisson's equation; slab conditioning system; temperature control system; thermal conduction.

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[1] For official distribution only. To obtain a working copy, contact either author by letter, phone, or email.

[2] Advanced Technology Laboratories, a new NIST facility being designed to be built at its Gaithersburg site.

A typical color plot generated in an interim report entitled

Finite Element Analysis of ATL Isolation Slab Conditioning System

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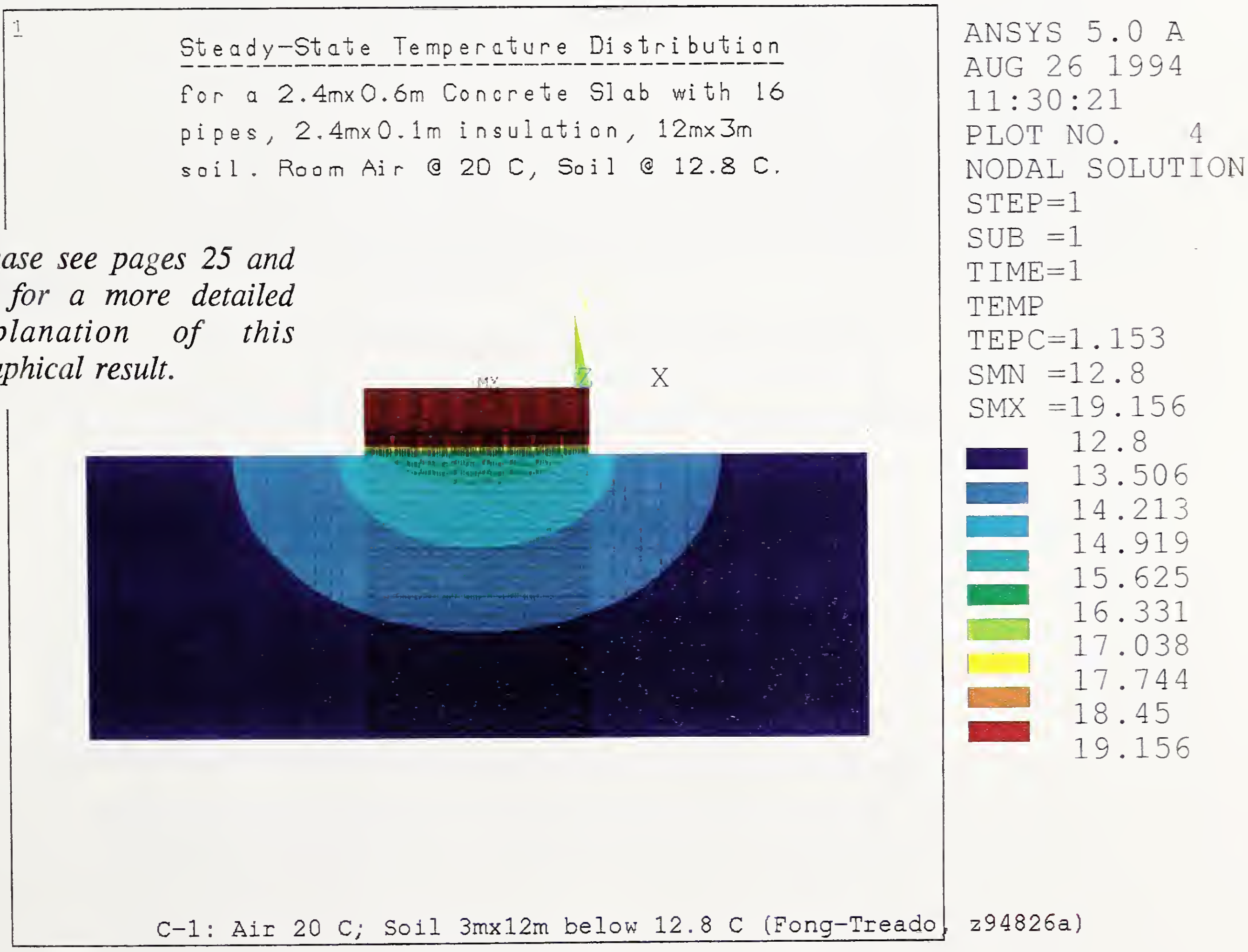

Steady-State Temperature Distribution
for a 2.4mx0.6m Concrete Slab with 16 pipes, 2.4mx0.1m insulation, 12mx3m soil. Room Air @ 20 C, Soil @ 12.8 C.

Please see pages 25 and 28 for a more detailed explanation of this graphical result.

C-1: Air 20 C; Soil 3mx12m below 12.8 C (Fong-Treado, z94826a)

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Note to Readers: This is an interim progress report of a consulting task undertaken by the NIST Computing and Applied Mathematics Laboratory (CAML) as part of its mission in support of the technical staff of NIST and other government agencies (to be referred to hereinafter as "Client"). No part of this report may be reproduced or quoted for public dissemination without prior written authorization from the authors or the Director of CAML at NIST. Ref.: 94901-tb.con

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Executive Summary

This is an interim progress report of a consulting project undertaken by Fong of NIST Computing and Applied Mathematics Laboratory (CAML) in response to a request by Dr. Stephen Treado of NIST Building and Fire Research Laboratory (BFRL).

The project was initiated after two phone calls in March 1994. The first call came on March 7, 1994 when Fong was contacted by Ms. Bea Sennewald of Henningson, Durham & Richardson (HDR), Inc., Alexandria, VA. Two days later, Dr. Treado called and requested assistance on the same problem.

HDR is an architectural firm that has been retained by NIST to design a Temperature Control Test Module to be constructed in Building 226 of NIST's Gaithersburg site as a research and testing project in support of the design and construction of a new laboratory known as the Advanced Technology Laboratories (ATL).

In the March 7 call, Ms. Sennewald of HDR wanted to know if Fong could use a finite-element analysis technique to verify a handbook value HDR used to determine the "time constant" of an isolation slab conditioning system under transient thermal loadings. HDR has designed the slab system as part of a scheme to control the temperature of a specific laboratory module to +/- 0.01° C, and NIST needs a confirmation of the time constant to ensure that the slab conditioning system will indeed function as designed.

In the second call, Fong was informed by Treado that he has been appointed the NIST Lead Person responsible for the Temperature Control Test Module. Treado requested and Fong agreed as part of CAML's mission to collaborate with NIST staff, that a modeling and analysis project for the ATL Isolation Slab Conditioning System be initiated. Four specific tasks of the project were defined and their goals are:

Task 1 To develop an appropriate mathematical model and a collection of computational codes as a design and analysis tool for understanding and predicting the transient behavior of the slab conditioning system under a variety of geometric configurations, material parameters, discretization schemes, and loading histories.

Task 2 To illustrate the capabilities of the tool by applying it to a selected choice of modeling assumptions, system geometries, material coefficients, mesh designs, and loading conditions. The results of this task should include:

(2.1) An estimate of the time constant of a model for the slab system.

Task 2 (Cont'd)	(2.2)	An evaluation of the uniformity of temperature distribution along the top surface of the concrete slab, and
	(2.3)	An assessment of the design decision to install a hydronic heating system as a supplement to the electric resistance heating cables embedded in the concrete slab to overcome the heat losses to the earth.
	(2.4)	To document results of Tasks 1 and 2 in the form of an interim report.
Task 3		To solicit discussion and comments on the interim report from HDR and other interested parties in order to formulate more specific questions of interest to NIST. This is an open-ended task and may result in refining the mathematical model and generating additional computational results to suit the needs of NIST.
Task 4		To introduce a state-of-the-art error-monitoring technique developed by Fong and his colleagues to assess the "correctness" of a selected set of the solutions based on a finite-element analysis technique. Results of both Tasks 3 and 4 should be documented in a Final Report.

Using a finite-element analysis package named ANSYS (v. 5.0a), we choose to begin with a two-dimensional model for the solution of the steady-state heat equation (Poisson Equation) and the time-dependent differential equations for heat conduction with initial and boundary conditions such that the effect of convection and internal heat generation are also included.

To model a 4.775m-wide by 0.6m-deep slab with 30 pipes spaced at 0.15m center-to-center and located 0.485m below the top surface of the slab, we used a symmetry command to generate from a 1-pipe (0.15m-wide) configuration to a 2-pipe, 4-pipe, 8-pipe, 16-pipe (2.4m-wide), and 32-pipe (4.8m-wide) slab geometries. With ANSYS codes generated for both the 16-pipe and 32-pipe models, we obtain the following preliminary results:

(2.1) Using physical constants and material parameters from design handbooks, we estimated the time constant for a 16-pipe (2.4m-wide) slab-insulation-3.0m wide soil model to be between 10 to 20 hours.

(2.2) Using a soil width larger than the slab to simulate multi-dimensional heat losses, we estimated that, for the steady-state case of a 16- or 32-pipe slab with no heating in the pipes, the difference of the temperatures at the top surface between the center and the edge of the slab ranges from 0.014° C (16-pipe model) to 0.063°C (32-pipe model).

(2.3) We also did a parametric study to show that a hydronic heating system when embedded in the concrete slab reduces significanly the effect of the soil below in slab heat loss and temperature stabilization.

The documentation of two ANSYS codes, one for steady-state and the other for transient, and the presentation of the above three results in this interim report completes subtask (2.4). A final report will be prepared when we complete both Tasks 3 and 4 as described earlier.

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Note: All of the above figures were reproduced from drawings submitted to NIST on March 18, 1994 by Henningson, Durham & Richardson, the architect for the ATL project.

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List of Symbols

Symbol	*Meaning of Symbol*	*Where first mentioned*
c	specific heat.	Sect. 2, p. 15.
h_d	surface convection coefficient for downward air flow.	Sect. 3.2, p. 18.
h_u	surface convection coefficient for upward air flow.	Sect. 3.2, p. 18.
K	thermal conductivity.	Sect. 2, p. 15.
q	heat flow rate.	Sect. 2, p. 15.
t	time.	Sect. 2, p. 15.
T	temperature variable as a function of x, y, z, and t .	Sect. 2, p. 15.
T_1	temperature at center of top surface of concrete slab.	Sect. 3.2, p. 18.
T_2	temperature of air in room immediately above top surface of concrete slab.	Sect. 3.2, p. 18.
TEM1	$= T_2$.	Sect. 4, p. 21.
TEM2	temperature at inner surface of polyethylene pipe embedded in slab.	Sect. 4, p. 21.
TEM3	temperature at bottom of soil located at several meters below insulation.	Sect. 4, p. 21.
x_o	half-thickness of an infinite slab.	Sect. 6.4, p. 39.
x, y, z	Cartesian coordinates.	Sect. 2, p. 15.

List of Symbols (Cont'd)

Symbol	Meaning of Symbol	Where first mentioned
α^2	thermal diffusivity.	Sect. 2, p. 15.
ΔT	temperature difference between room air and top surface of concrete slab ($= \lvert T_2 - T_1 \rvert$).	Sect. 3.2, p. 18.
∇	gradient operator.	Sect. 2, p. 15.
ρ	density.	Sect. 2, p. 15.
τ	time constant.	Sect. 6.4, p. 39.

An Interim Progress Report on

Finite Element Analysis of ATL Isolation Slab Conditioning System

Jeffrey T. Fong[1], P.E., and Stephen J. Treado[2]

1. Project Description and Scope of Work

The National Institute of Standards and Technology (NIST) is currently engaged in the planning of a new facility known as the Advanced Technology Laboratories (ATL). Henningson, Durham & Richardson (HDR), Inc., an Alexandria, Va.-based architectural firm, has been retained to furnish the necessary architectural and engineering services to NIST on the ATL facility.

During the planning stage of the project, NIST and HDR conducted a special study of high accuracy temperature control concepts. The study concluded that a Temperature Control Test Module be built and various control concepts be tested to ensure that the required accuracies be achieved in the ATL.

According to two documents [1, 2][3] and 23 drawings [3][4] submitted by HDR to NIST on March 18, 1994, a typical laboratory module in the ATL will be 7m x 3.5m x 3.5m high, and the temperature control systems shall be tested in one such module to be built in the environmental chambers in Building 226 of the NIST Gaithersburg site. The chambers are operated by the NIST Building and Fire Research Laboratories and Stephen J. Treado is the Lead Person responsible for the Temperature Control Test Module.

As stated on the first page of the HDR Design Basis report [1], which documents the design decisions and concepts of the Test Module, "the mission of the ATL requires the ultimate in environment conditions such as precise temperature and humidity control, air cleanliness, clean electrical power, and absence of vibration. Among the many rigorous environmental control requirements, the most challenging task of the project is to control the temperature in some of the laboratories to +/- 0.01° C accuracy."

Broadly speaking, two categories of technical problems have been identified. The first category relates to the control and air distribution system that is supposed to respond to any heat gain or loss after the temperature of the module has been stabilized to a set level.

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[1] Physicist, Applied and Computational Mathematics Division, Computing and Applied Mathematics Laboratory (CAML), NIST. Dr. Fong is the Consultant and Principal Investigator of this analysis project.

[2] Mechanical Engineer and Project Leader, Building Environment Division, Building & Fire Research Laboratory, NIST. Dr. Treado is the "Client" and a Co-Investigator of this analysis project.

[3] The number in square brackets refers to a reference listed at the end of the report.

[4] Nine of the 23 drawings have been used in this report (Figs. 1-12) as part of the basis for this investigation.

The second category of problems resulted from a design decision, where some of the laboratories with high accuracy temperature control requirements will have concrete slabs directly exposed to the room environment. Since the slabs are installed on earth with year-round temperatures of 10-13° C, their surface temperature will be less than the room temperature (20° C) owing to the presence of a temperature gradient to assure heat transfer. A difference of the order of 0.1 or 1.0° C due to a constant heat loss through the slab with or without insulation between the slab and the earth is not acceptable. HDR has designed a so-called Isolation Slab Conditioning System consisting of electric resistance heating cables and embedded pipes with heated water (hydronic heating) "to eliminate or minimize the slab effect [1, p.9][5]." Some of the questions of the second category, as discussed in documents[6] furnished by Treado, are:

(a) What is the time constant of the slab conditioning system? The answer to this question bears directly on the first category of problems, namely, the performance of the control and air distribution system.

(b) How uniform is the temperature distribution on top of the slab where the edges are exposed to more heat loss due to the surrounding earth than the middle of slab?

(c) Is the electric cable or the hydronic heating system necessary for the ATL?

To answer the above and any other related questions of the second category, a mathematical modeling and analysis project within NIST was initiated with Fong and Treado as co-investigators. Four specific tasks of the analysis project are defined:

<u>Task 1</u> To develop an appropriate mathematical model and a collection of computational codes as a <u>design and analysis tool</u> for understanding and predicting the transient behavior of the slab conditioning system under a variety of geometric configurations, material parameters, discretization schemes, and loading histories.

<u>Task 2</u> To illustrate the <u>capabilities</u> of the tool by applying it to a selected choice of modeling assumptions, system geometries, material coefficients, mesh designs, and loading conditions.

<u>Task 3</u> To solicit discussion and comments on the interim report from HDR and other interested parties in order to formulate more specific questions of interest to NIST. This is an open-ended task and may result in refining the mathematical model and generating <u>additional computational results</u> to suit the needs of NIST.

<u>Task 4</u> To introduce a state-of-the-art error-monitoring technique developed by Fong and his colleagues to assess the "correctness" of a selected set of the solutions based on a finite-element analysis technique.

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[5] Portions of the two HDR documents [1, 2] that relate to the slab conditioning system have been excerpted and reproduced in full in Appendix F of this report.

[6] See Appendix A for a list of such documents.

VICINITY MAP

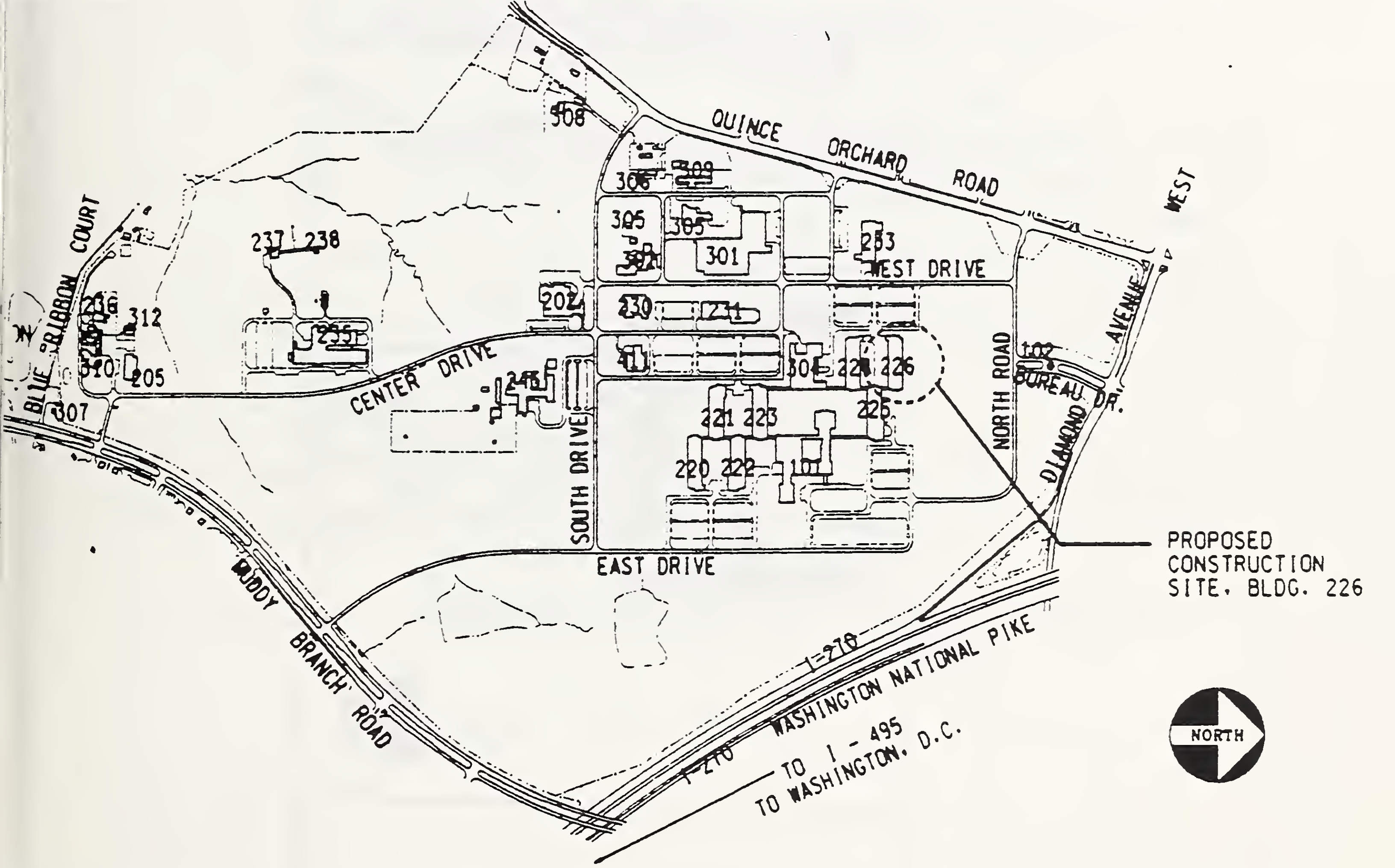


Fig. 1 Vicinity Map of NIST-ATL-Temperature Control Test Module

ROOM LIST

ROOM NO.	ROOM NAME
E-A134	OBSERVATION ROOM
E-A140	ENVIRONMENTAL ENGINEERING LAB
101	CONTROL ROOM
102	VESTIBULE
103	LABORATORY MODULE
104	PLENUM AREA

NOTES:

① ISOLATION SLAB CONDITIONING PIPES SHALL BE SPACED AT 150mm ON CENTER AND CENTERED BETWEEN THE ENDS OF THE SLAB.

② TOTAL SLAB CONDITIONING SYSTEM WATER FLOW (SEE SCHEDULED P-12 CAPACITY) SHALL BE DIVIDED EQUALLY BETWEEN THE PIPES THRU THE SLAB.

③ KEEP PIPING AS CLOSE AS POSSIBLE TO UNDERSIDE OF ATTIC FLOOR SLAB IN STRUCTURAL TEST ROOM.

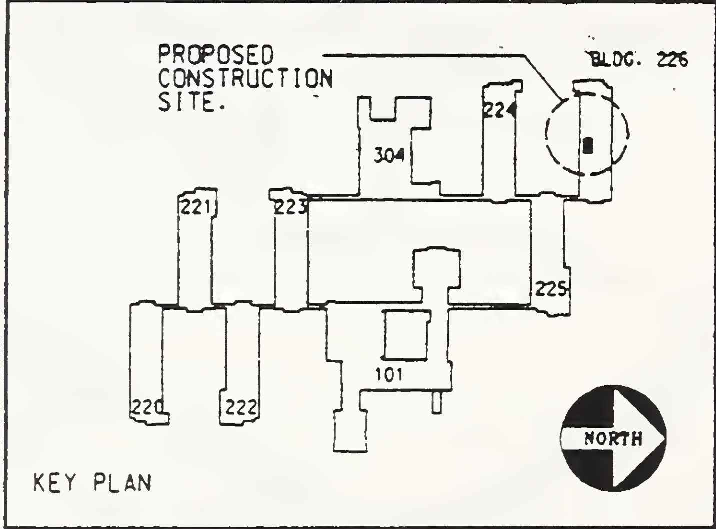


Fig. 2 Key Plan & Notes on Isolation Slab Conditioning System

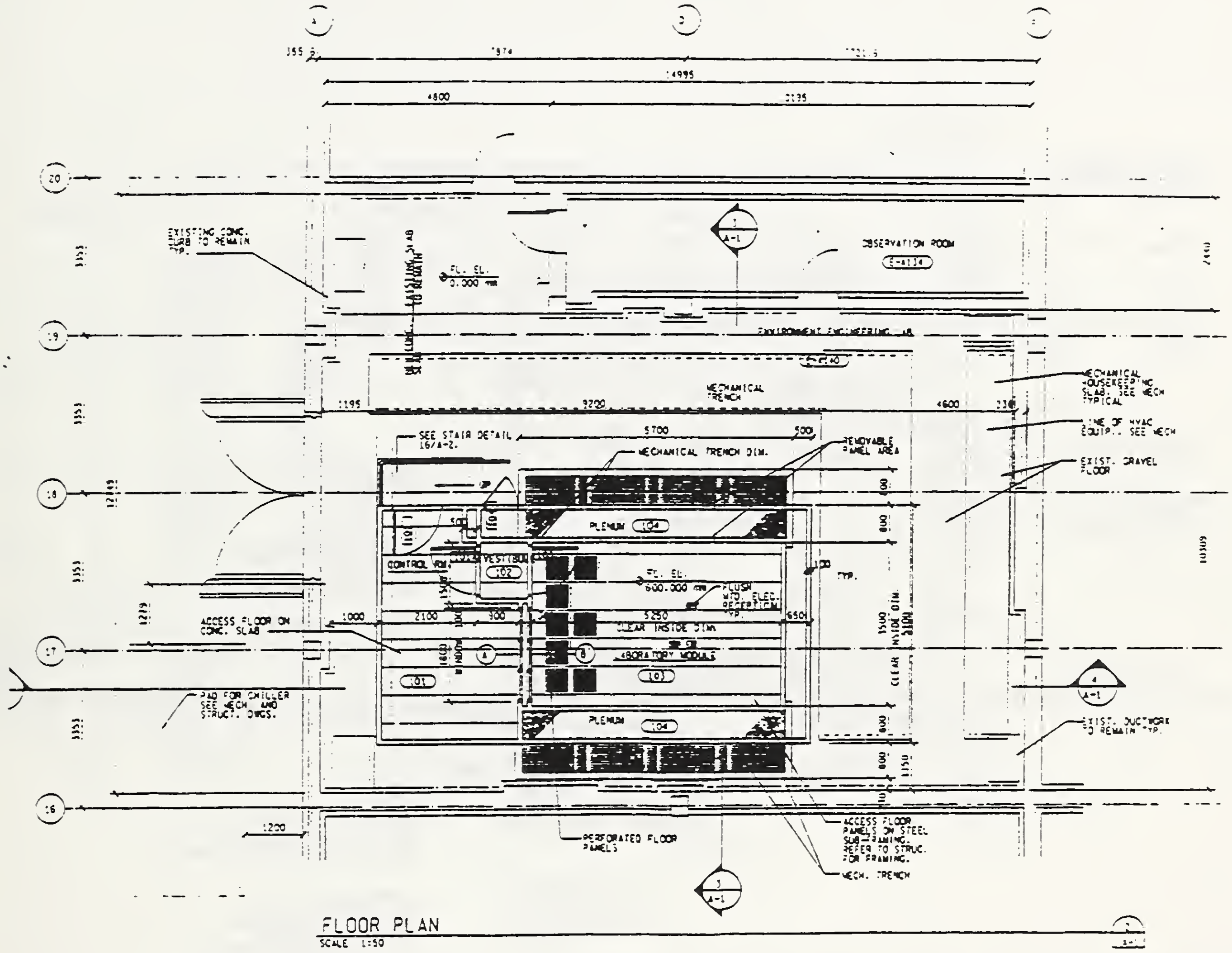


Fig. 3 Access Floor (El. 600.00 mm) Plan

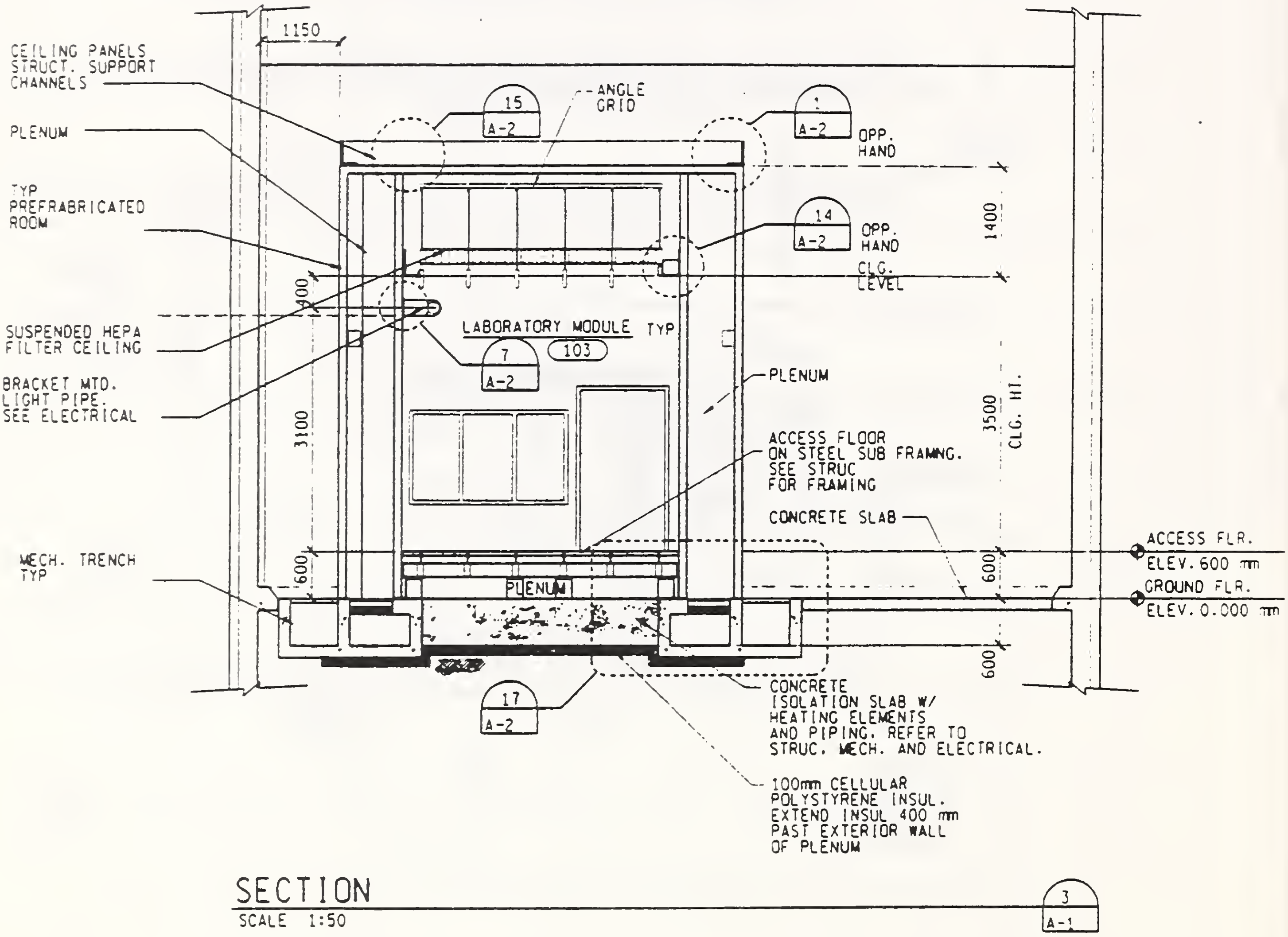


Fig. 4 Transverse Section (Label 3)

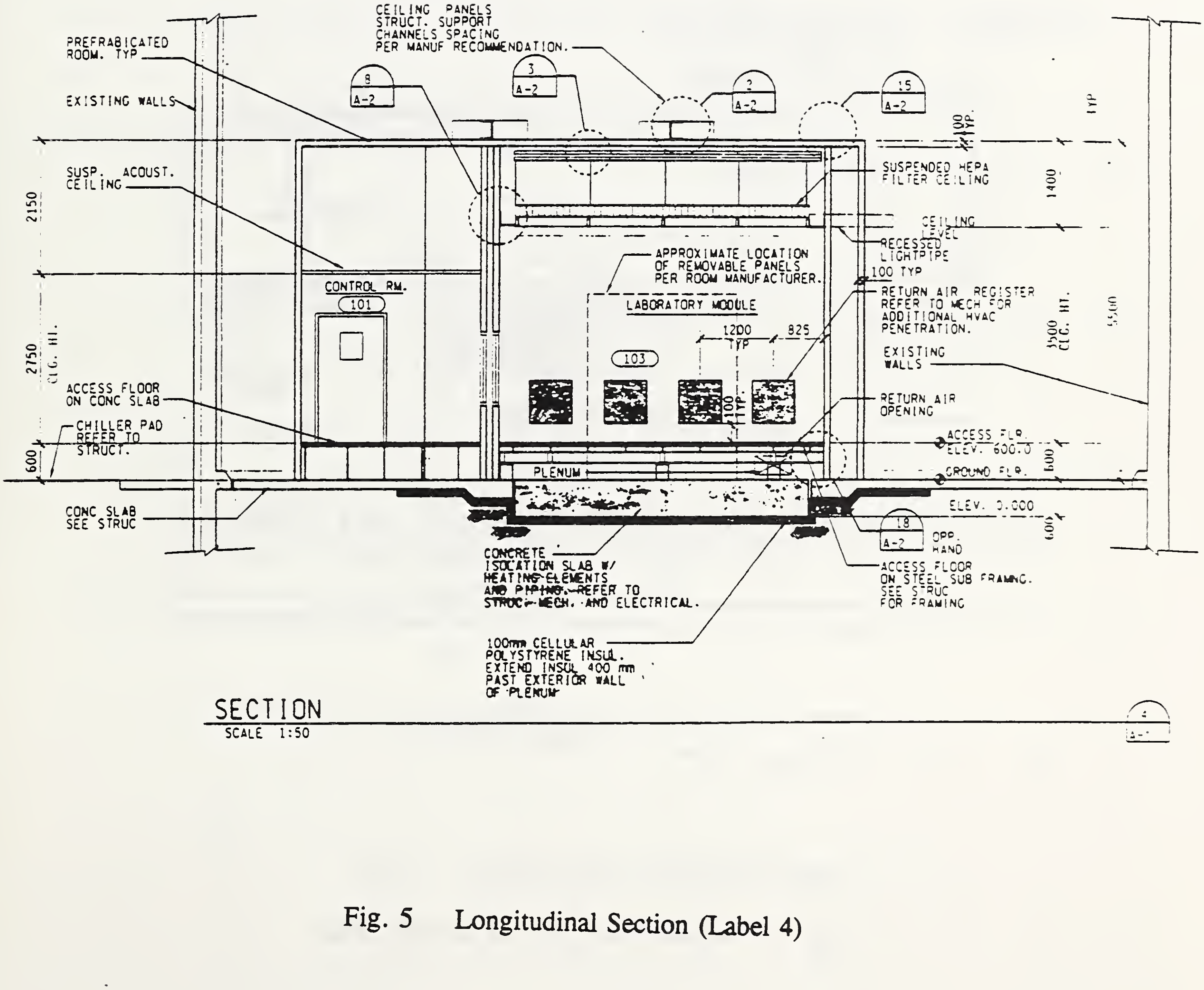


Fig. 5 Longitudinal Section (Label 4)

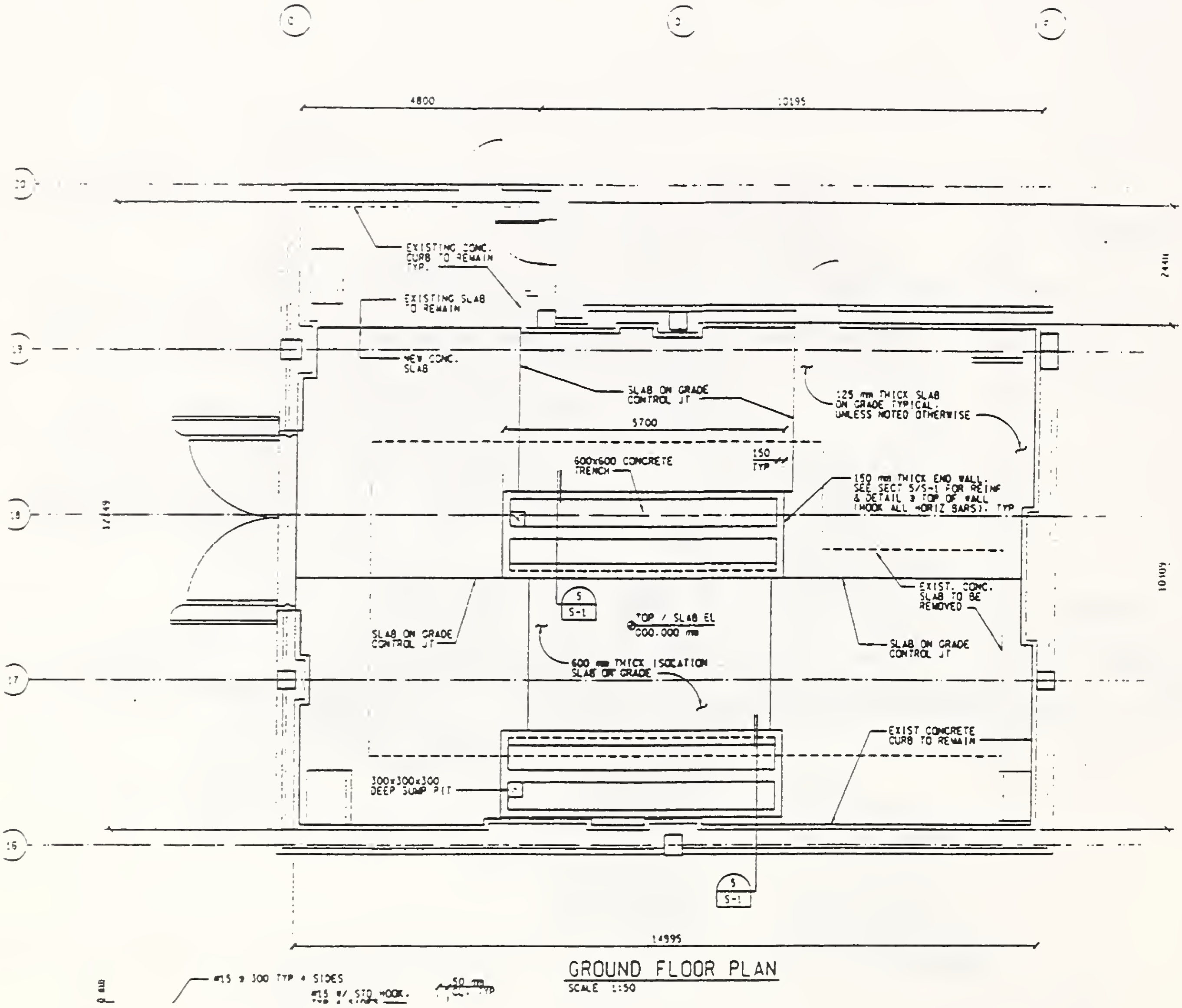


Fig. 6 Ground Floor (El. 000.00 mm) Plan

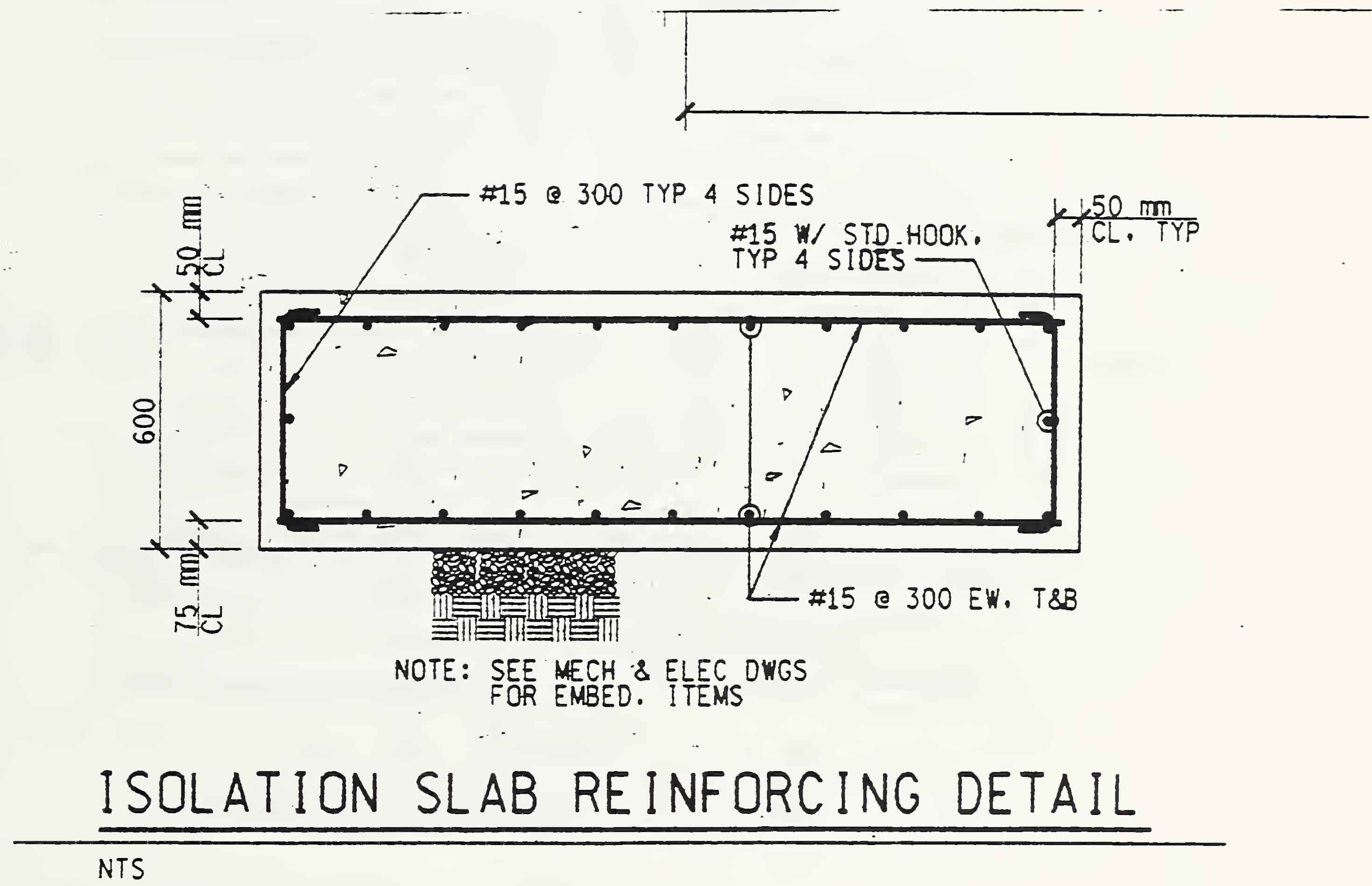
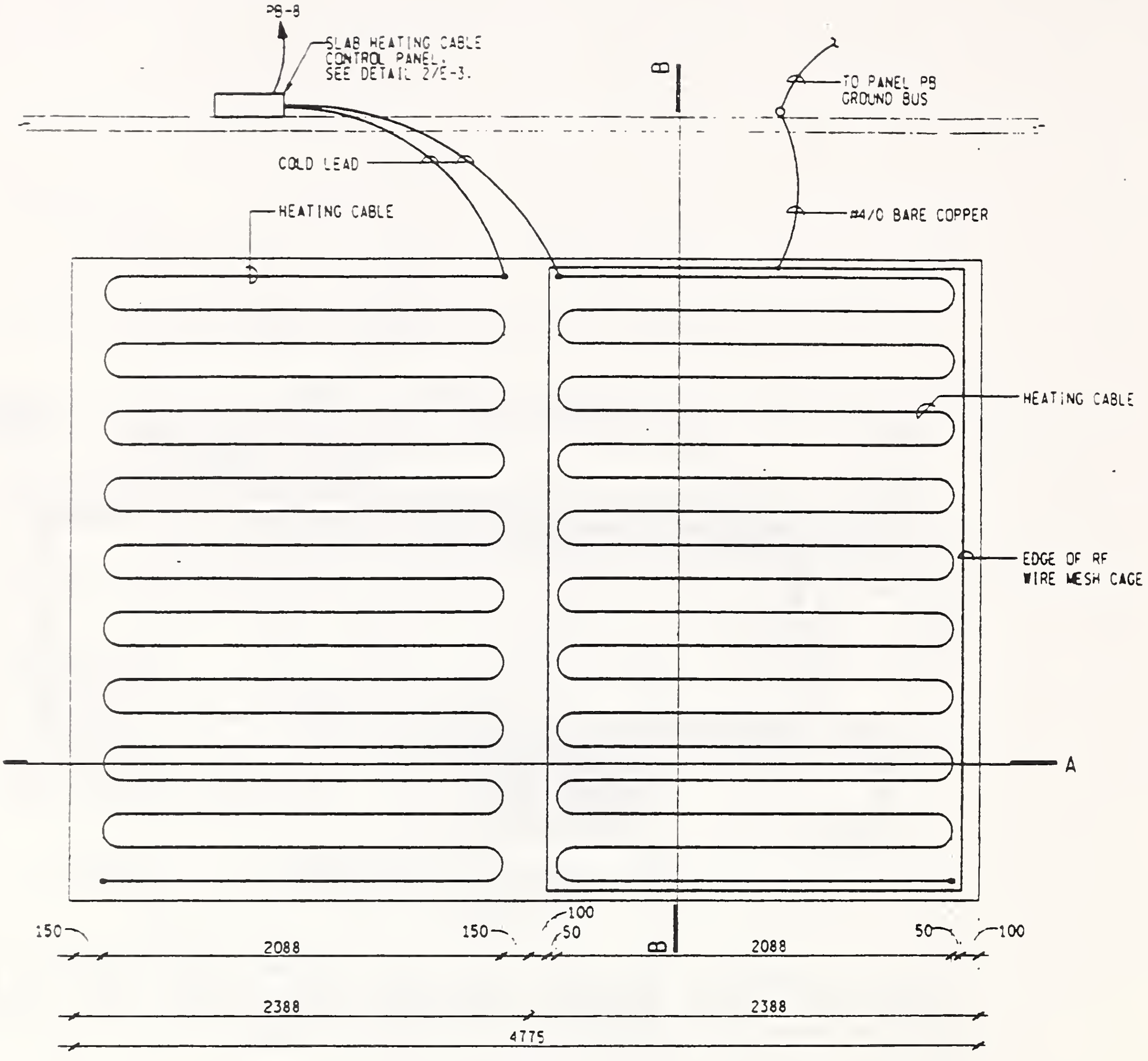
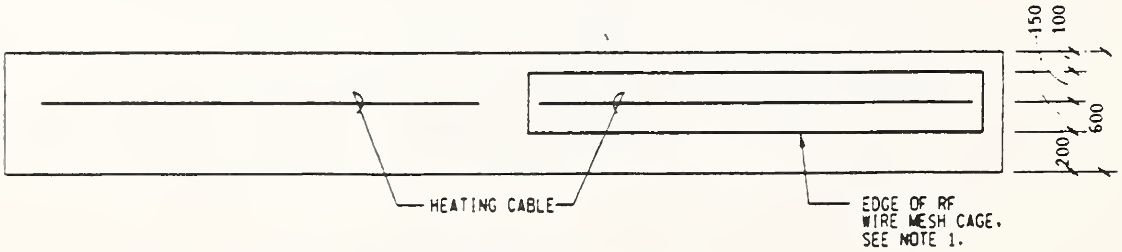


Fig. 7 Isolation Slab Reinforcing Detail

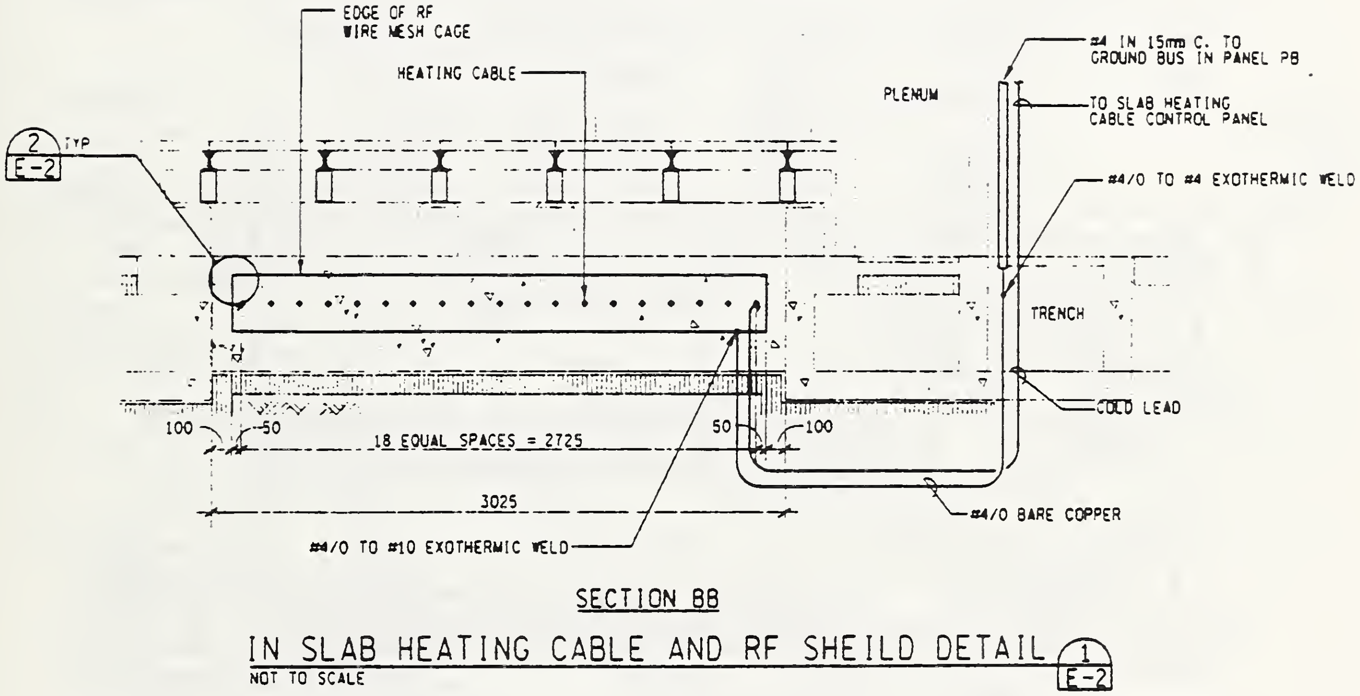


PLAN



SECTION AA

Fig. 8 Plan & Section AA for In Slab Heating Detail



NOTES:

1. RF WIRE MESH CAGE SHALL BE CADWELD PREFABRICATED WIRE MESH OR EQUAL WITH #10 SOLID COPPER CONDUCTORS 50mm X 50mm SPACING.

Fig. 9 Section BB for In Slab Heating Cable & RF Shield Detail

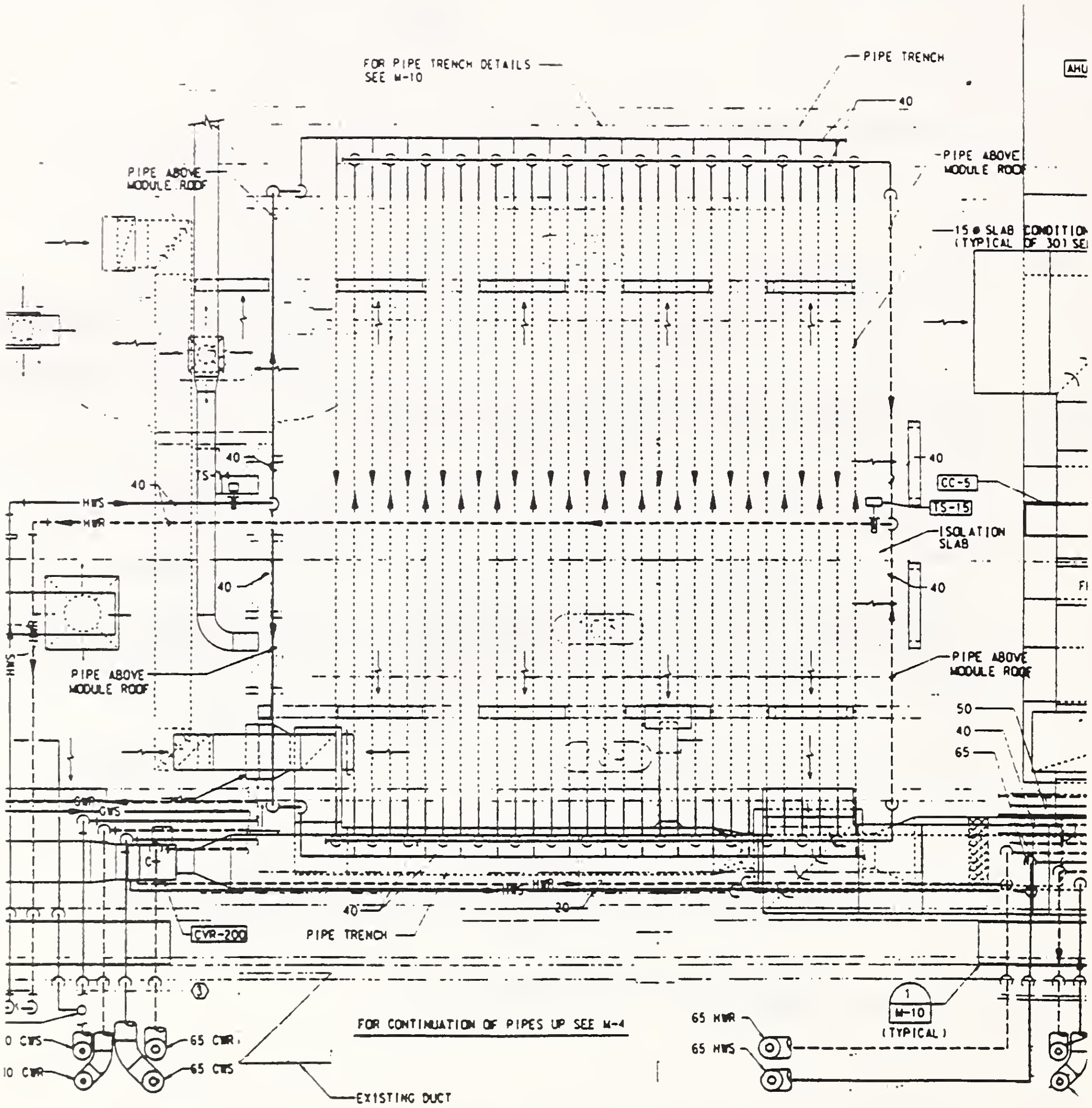


Fig. 10 Piping Layout Plan for Isolation Slab Conditioning System

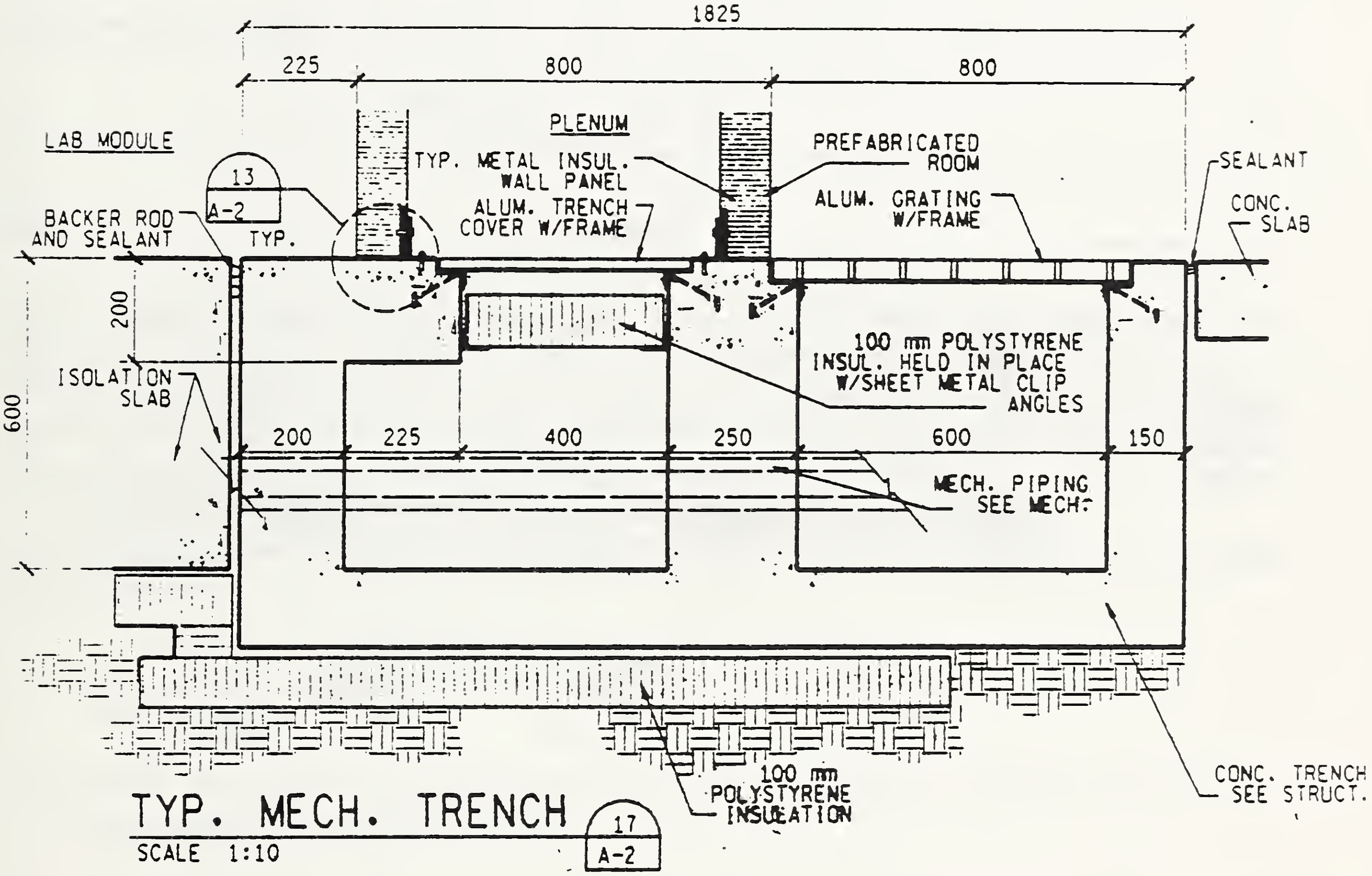


Fig. 11 Joint Detail between Isolation Slab and Mechanical Trench

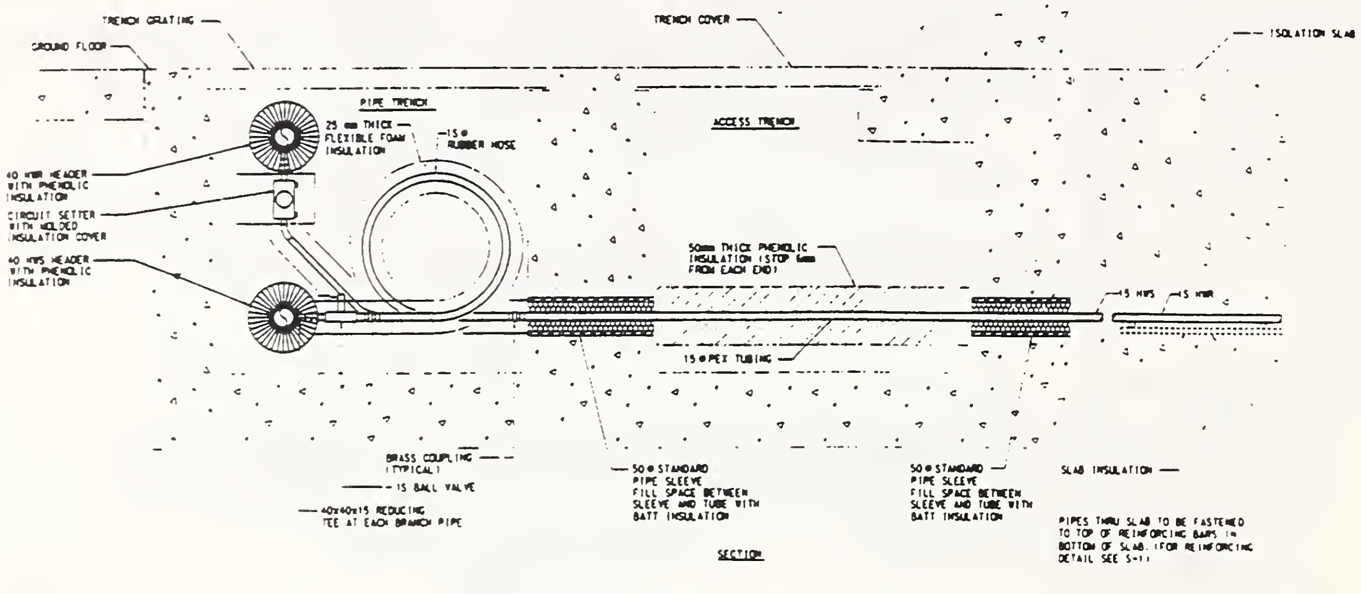


Fig. 12 Piping Detail for Isolation Slab next to Mechanical Trench

2. Governing Equations and Loading Conditions

To develop a mathematical model for the time-dependent phenomenon of heat transfer in solids, we need to prescribe the appropriate governing equations, the initial condition and the boundary conditions for a given geometric configuration.

As shown in references [4, 5, 6], the mathematical theory of heat conduction yields the following partial differential equation for $T(x, y, z, t)$, the time-varying distribution of temperature T in a three-dimensional Cartesian coordinate system (x, y, z):

$$\nabla \cdot (K \nabla T) = (K / \alpha^2) \frac{\partial T}{\partial t} - q , \tag{1}$$

where we have written

$$\nabla = (\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}) , \tag{2}$$

and

$$\alpha^2 = K / \rho c , \tag{3}$$

with t being the time, K the conductivity, ρ the density, and c the specific heat of the solid. The quantities K, ρ and c could all be functions of x, y, and z. The quantity α^2 is known as the thermal diffusivity of the material. In equation (1), the quantity q represents a heat generation term (in W/m^3) which could be due to the presence of an internal heat source or an applied heat flow at the boundary due to convection or radiation.

For steady-state cases, equation (1) yields the following when the temperature T is no longer a function of t:

$$\nabla \cdot (K \nabla T) = - q . \tag{4}$$

For constant K, equation (4) becomes either the well-known Poisson Equation for non-zero q, or the Laplace Equation for zero q.

For our first-stage investigation, we shall ignore the presence of the heating cable by assuming that q vanishes at interior points, and becomes non-zero at the horizontal surface of the top of the concrete slab where it obeys a handbook formula for natural convection [7, 8][7] with downward heat flow from room air to the slab. For the transient analysis using equation (1), we shall use the steady-state solution based on equation (4) as the initial condition and a selected set of loading histories as the time-varying boundary conditions. Examples of such loading histories to be used in our calculations are given in Fig. 13.

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[7] For a more detailed explanation of the handbook formula for natural convection, see Section 3.

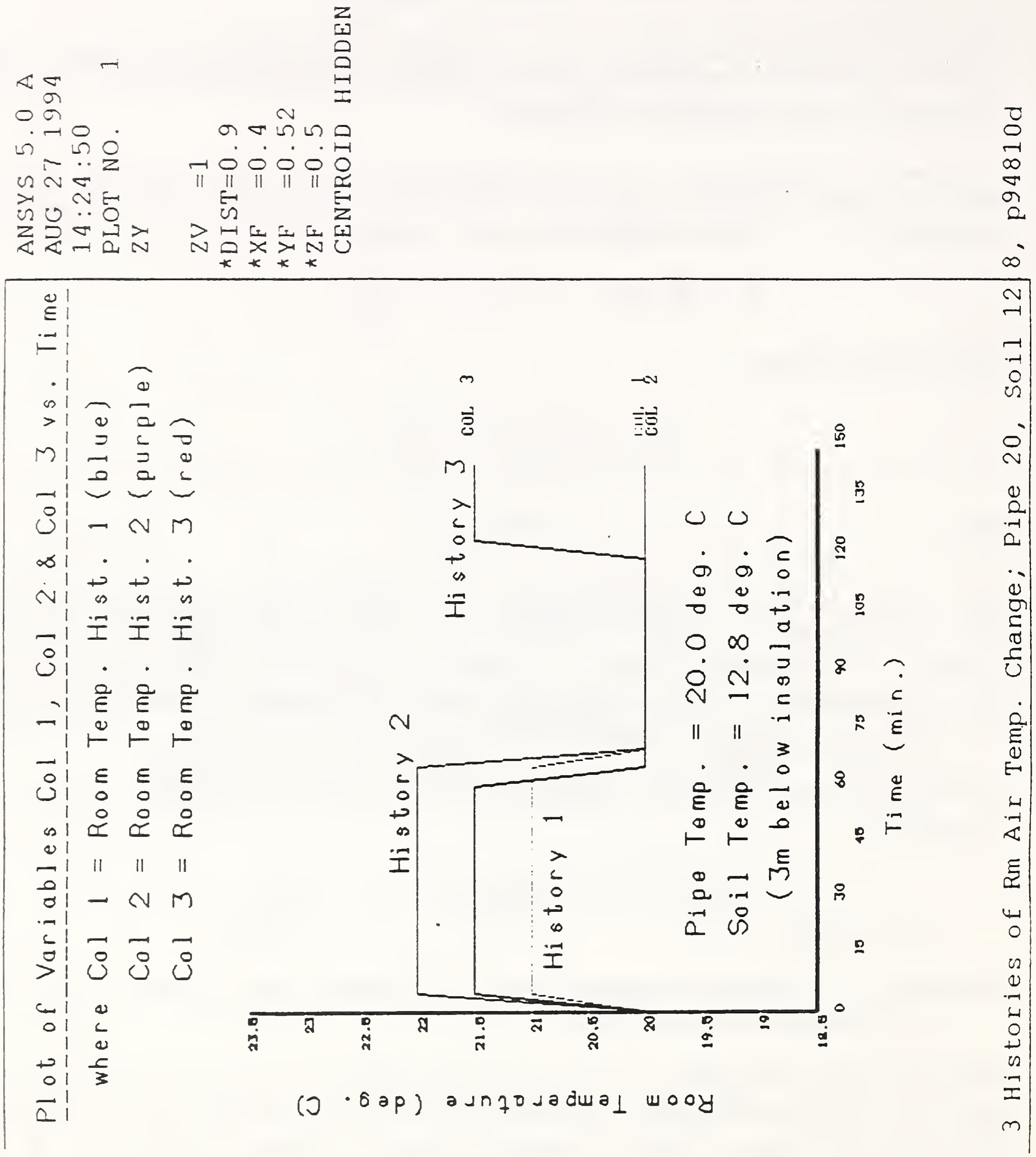


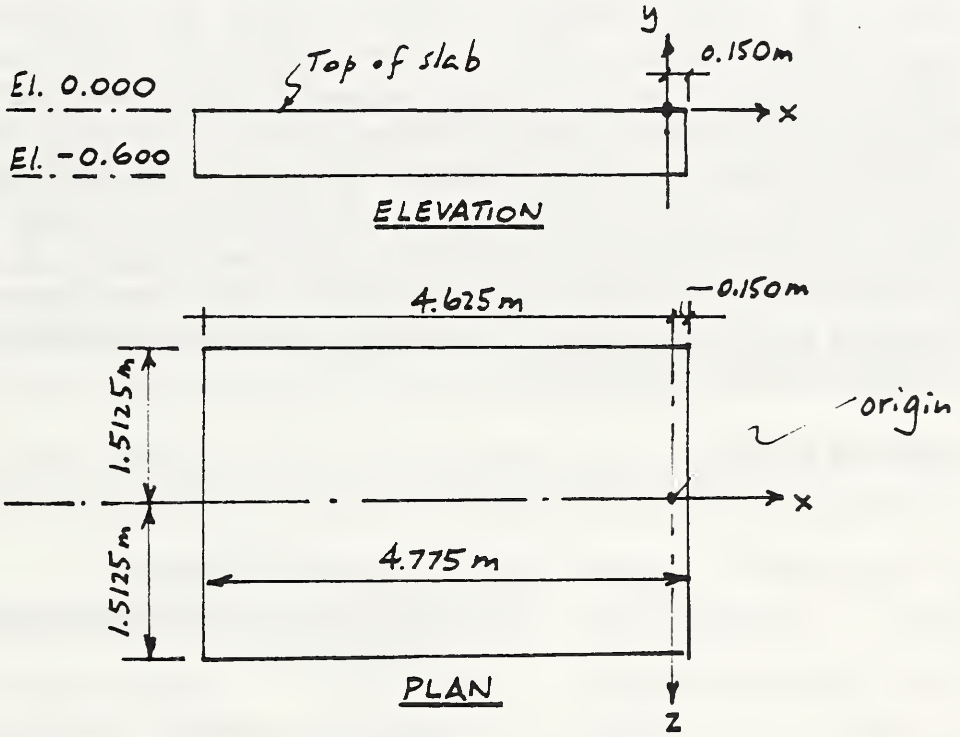
Fig. 13 Typical Loading Histories for Transient Analysis

3. Geometric Parameters and Physical Constants

In modeling the isolation slab conditioning system, we need to identify six specific components to complete the formulation of a well-posed initial- and boundary-value problem in classical theory of linear partial differential equations. The six components are:

3.1 The Isolation Slab

As shown in Figs. 6, 8, 9 and 10, the isolation slab will be made of concrete of 4.775m by 3.025m by 0.600m deep. HDR, the architect, has specified that the top of the slab be at El. 0.000. The bottom of the slab is therefore at El. -0.600. For reasons that will become clear in a moment, a Cartesian coordinate system will be used with x-axis parallel to the length (4.775m), y-axis parallel to the depth (0.600m), and z-axis parallel to the width (3.025m) of the slab. The origin of the coordinate system shall be located at 0.150m away from the left edge of the length as shown in the diagram below:



Using handbooks [8, 9] and interpolation techniques based on the authors' experience and judgment, the physical constants to be used in this study for concrete are as follows:

Symbol	Name of Constant	Value in SI Unit	(Non-SI, optional)	Reference
K	Thermal Conductivity	1.818 W/m*K	(1.05 Btu/h*ft*F)	[9, p.4-84].
ρ	Density	2275 kg/m^3	(142 lb/cu.ft.)	[9, p.4-84].
c	Specific Heat	653 J/kg*K		[8, p.36.3], [9, p.4-61].

3.2 The Room Air/Slab Interface

The top surface of the slab is in direct contact with the air in the lab module immediately above the slab. In this study, we shall assume that there is heat transfer between the room air and the slab through natural convection as well as conduction. For this study, we adopt the following equation [8, pp. 3.1-3.3] for a convective transfer of heat between a constant room air temperature T_2 and the slab surface temperature T_1 :

$$q = h_d (T_2 - T_1), \text{ if } T_2 \geq T_1 ; \qquad (5)$$

$$q = h_u (T_1 - T_2), \text{ if } T_2 < T_1 ; \qquad (6)$$

where q is the heat flow rate and h_u , h_d the surface convection coefficients.

The values of the surface convection coefficients could only be estimated due to lack of knowledge regarding the actual airflow conditions at the top of the floor slab. Some reasonable assumptions were made based upon design handbook relations, and then the sensitivity of the solution results to the assumed surface convection values was examined. The primary reference was the 1993 ASHRAE Handbook of Fundamentals [8]. In that handbook, Section 3.12 lists relations for natural convection from large horizontal plates with heat flowing upward, and recommends a value of about one half of that for downward heat flow. It is likely that the slab surface in the ATL test module will be exposed to some forced convection due to the air handling system for the room, thus the appropriate convection coefficient will be greater than that for natural (free) convection alone.

From ASHRAE 3.12 [8]:

$h_u = 1.52 (\Delta T)^{0.33}$ where: ΔT = temperature difference,
h_u = convection coefficient for heat flow up $W/m^2\,K$; and

$h_d = 0.5\,h_u$ where: h_d = convection coefficient for heat flow down $W/m^2\,K$.

For $\Delta T = 1.0$ C, this leads to $h_u = 1.52$ and $h_d = 0.76$, for still air. Following these relations, the surface convection coefficient would vary with temperature, airflow and direction of heat flow. In the initial simulations, as well as when the test module is in the cooling mode, the air temperature will be greater than surface temperature, so the direction of heat flow will be down (into the slab). As a compromise, a surface convection coefficient value of 2.0 $W/m^2\,K$ was selected to account for downward heat flow with mixed free and forced convection. This value was varied to determine the sensitivity of the results and conclusions to the convection coeffeicient.

3.3 The Embedded Heating Cable in the Slab

Based on Figs. 8, 9, and the HDR Basis of Design document [1, p.245][8], two sections of copper cables, of 42.4m length each, using material type 19E2 (nominal resistance 0.41 ohms/m), are located within the concrete slab at El. -0.250 in a pattern shown in Fig. 8. The total design load for the heating cable is 63 watts.

To model this heat source, we assume that the effect of the cable heating is uniformly distributed along a plane of 4.775m x 3.025m (=14.4444 sq.m.) such that the heat source $q = 63.0/14.4444 = 4.362\ \text{W/m}^2$. In a two-dimensional model for the slab system, the heat source would be assigned a value of 4.362 W/m.

3.4 The Embedded Pipes in the Slab

Based on Fig. 10 and the HDR Basis of Design document [1, p.36 & p.38][9], 30 tubes of 13mm polyethylene tubing (0.016m nominal outside diameter, and 0.012m inside) are spaced at 0.150m center-to-center parallel to the short length (3.025m) of the slab. As shown in Fig. 7 and a client document, Appendix D, the pipes are to be fastened to the top of the reinforcing bars in the bottom of the slab. Since the net clearance between the reinforcing bars and the bottom of the slab is 0.075m, the bottom of the reinforcing bars is therefore at El. -0.525. Let us assume that the center line of the pipes be at El. -0.485, the bottom of the pipes at El. -0.493, and the thickness of two layers of reinforcing bars no more than (0.525 - 0.493) or 0.032m.

Again, using handbook reference [10] and interpolation techniques based on experience and judgment, the physical constants to be used in this study for polyethylene pipes are:

Symbol	Name of Constant	Value in SI Unit	(Non-SI, optional)	Reference
K	Thermal Conductivity	0.404 W/m*K	(0.000965 cal/s*cm*C)	[10, p.8].
ρ	Density	953 kg/m^3	(0.953 sp. gr.)	[10, p.7].
c	Specific Heat	550 J/kg*K		[10, p.8].

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[8] The design calculation submitted by HDR is reproduced in this report on page F-8, Appendix F.

[9] The design calculation submitted by HDR is reproduced in this report on p.F-5 and p.F-7, Appendix F.

3.5 The Insulation Beneath the Slab

Based on Figs. 4 and 5, there is a 0.1m-thick sheet of polystyrene insulation beneath the slab. The physical constants to be used in this study for polystyrene insulation are:

Symbol	Name of Constant	Value in SI Unit	(Non-SI, optional)	Reference
K	Thermal Conductivity	0.0502 W/m*K	(0.029 Btu/h*ft*F)	[9, p.4-85][10].
ρ	Density	42.5 kg/m^3		[8, p.22.6].
c	Specific Heat	1220 J/kg*K		[8, p.22.6].

3.6 The Soil Beneath & Surrounding the Insulation

One of the most difficult and important issues in this study is the prescription of the temperature boundary condition in the ground beneath the slab. In HDR's design calculation [1, p.37][11], the ground temperature is assumed to be uniform at 12.8° C. The difficulty lies in assigning the proper location for the constant earth temperature, since the presence of the heated slab will cause the ground temperature to increase over time. For this study, we shall consider a variety of soil depths, namely, 3m, 6m, and 10m below the insulation, where a constant temperature boundary condition at 12.8° C will be imposed. Furthermore, since heat loss to the ground is three-dimensional, we shall consider two scenarios for the extent of the soil below in absorbing the heat from above:

Scenario "A" Heat loss is one-dimensional downward. The width of soil equals that of the insulation in a two-dimensional model.

Scenario "B" Heat loss is two-dimensional. The width of soil equals that of the insulation and an additional 4.8m on each side of the insulation.

Again, using handbooks [8, 9] and interpolation techniques, the physical constants to be used in this study for the ground (earth with moisture) are:

Symbol	Name of Constant	Value in SI Unit	(Non-SI, optional)	Reference
K	Thermal Conductivity	1.073 W/m*K	(0.62 Btu/h*ft*F)	[9, p.4-84].
ρ	Density	1730 kg/m^3	(108 lb/cu.ft.)	[9, p.4-84].
c	Specific Heat	920 J/kg*K		[8, p.36.3].

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[10] The conductivity value given in Ref. [9, p.4-85] is for "insulating boards, insulite, celotax, etc. (density 192-300 kg/m^3)," and is considerably higher than that recommended in the ASHRAE handbook [8, p.22.6] for "expanded polystyrene extruded (density 29-56 kg/m^3)." Since the insulation is sandwiched between the concrete slab and the earth, chances are there will be some stresses and deformation such that in time there will be less resistance to heat transfer. Conservatively speaking, we choose the higher conductivity value as recommended by Ref. [9].

[11] The design calculation submitted by HDR is reproduced in this report on page F-6, Appendix F.

4. Assumptions and Finite Element Modeling

With the heat conduction equations (1) and (4) given in Section 2, the geometric parameters and physical constants defined in Section 3, the surface convection equations (5) and (6) described in Section 3.2, and two scenarios for the loss of heat from room air to the ground as stated in Section (3.6), we now complete the formulation of a mathematical model by introducing the following additional assumptions:

Dimensionality	As a start, a two-dimensional model will be formulated.
Model Slab Width	Since the embedded pipes run parallel to the short length of the slab (3.025m) and are spaced at 0.150m center to center, we shall choose two model slab widths to approximate the long length of the slab (4.775m), namely, a 16-pipe (2.40m) and a 32-pipe configuration (4.8m). The two configurations are chosen because we first build our model with a one-pipe geometry and then repeatedly use symmetry to build a bigger model from a 2-pipe to a 2^n-pipe model.
Model Soil Width	For heat loss scenario "A", the soil width is the same as the slab width. For scenario "B", the soil width is 12.0m for a 16-pipe, and 14.4m for a 24-pipe slab model.
Temperature Boundary Conditions	There will be three temperature boundary conditions, among which one is allowed to vary with time during the first stage of this study: Room Air (TEM1): TEM1(t) is prescribed. Pipe Inner Surface (TEM2): TEM2 is either constant or unspecified. Soil Bottom Surface (TEM3): TEM3 = 12.8° C.
Heat Flow Boundary Conditions	For heat loss scenario "A", there will be zero heat flow along either side of the slab/insulation/soil system. For heat loss scenario "B", we shall also impose a zero heat loss condition on the top surface of the soil at the same elevation as the bottom of the insulation.

Even though the above assumptions allow us to address a simplified problem, the geometrical complexity associated with 16 or 32 pipes and a varying soil depth/width forbids us to seek a closed-form solution. However, the problem is ideal for the use of an approximate method known as the "Finite Element Method (FEM)."

The basic concept of FEM is not new. As succinctly stated by Kardestuncer [11], FEM is "finding an approximate solution to a boundary- and initial-value problem by assuming that the domain is divided into well-defined subdomains (elements) and that the unknown function of the state variable is defined approximately within each element." There are, of course, many other approximate methods such as the Rayleigh-Ritz method, the finite difference method, etc., but the primary difference between FEM and most other methods is that in FEM, approximation is accomplished through the use of the so-called admissible functions defined over element domains with simple geometry where the choice of admissible functions are not tied to the boundary conditions. There is a price to pay for this freedom and one can only implement FEM through

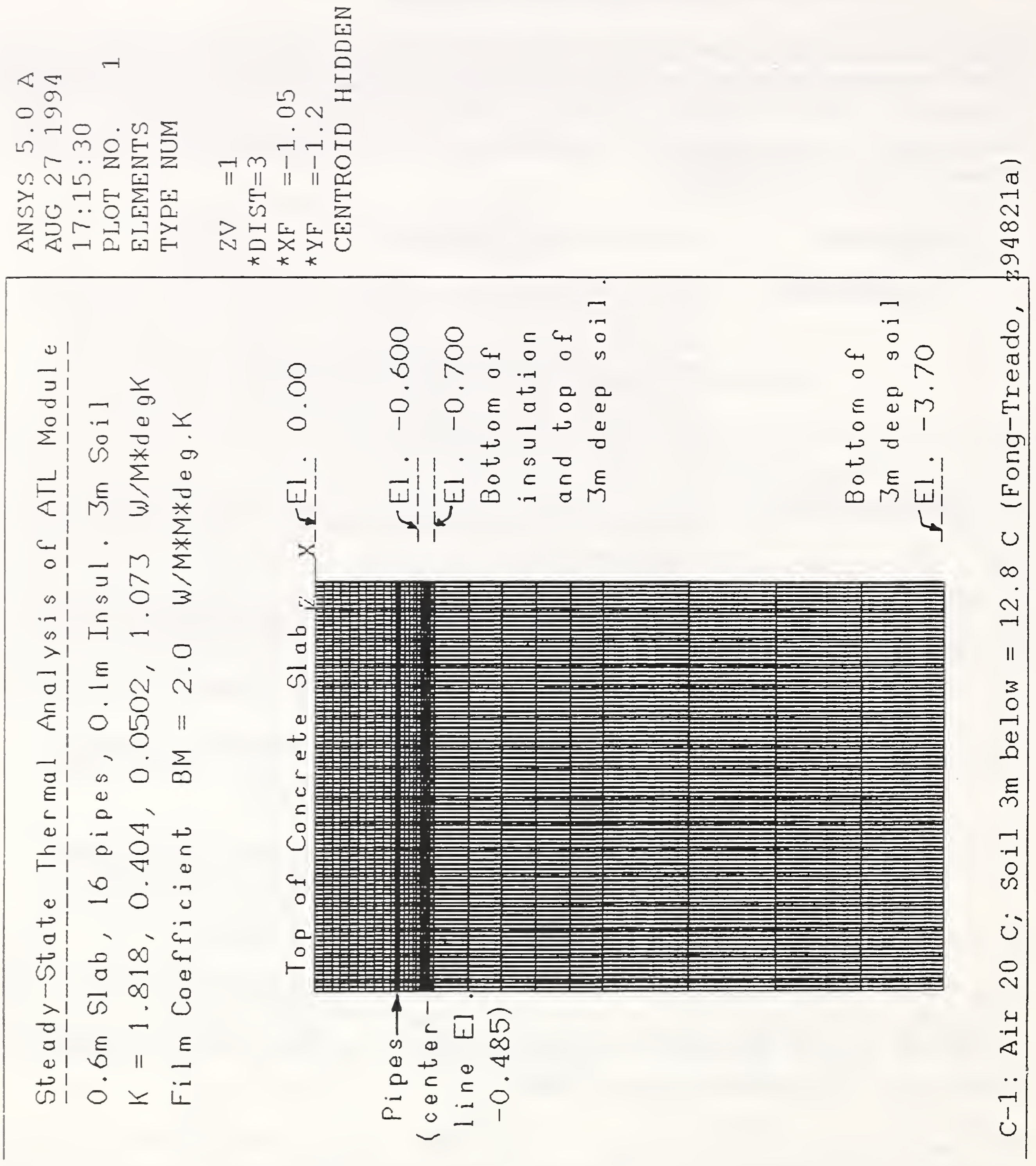

Fig. 14 A Typical Mesh Design for a 16-pipe Slab Conditioning System

the use of high-speed computer with large core memory and disk space. In fact, seven of the 12 steps outlined by Kardestuncer [11] and listed below for applying FEM to any well-posed problem are ideally suited for a computer-based approach:

Step	User-Driven	Computer-Driven
1	Definition of the Problem and its Domain.	
2	Discretization of the Domain.	
3	Identification of State Variable(s).	
4	Formulation of the Problem with Governing Equations.	
5		Establishing Coordinate Systems.
6		Constructing Approximate Functions for the Elements.
7		Obtain Element Matrices and Equations.
8		Coordinate Transformations.
9		Assembly of Element Equations.
10		Introduction of Boundary Conditions.
11		Solution of the Final Set of Simultaneous Equations.
12	Interpretation of the Results.	

The first use of FEM in solving heat transfer problems was due to Fried [12, 13]. Since then, there has been an explosion of research and application as reviewed by Zienkiewicz and Wood [14]. The method has also been applied to a more advanced problem involving fluid-solid modeling with conduction and convection [15].

For this study, we choose to work with a general-purpose finite element analysis software package named ANSYS [16] because of a special feature that is not yet available in any other packages. All FEM packages, except ANSYS, offer a black-box type of software where a user provides a series of commands and input data to obtain output. ANSYS provides a user to enter the system with his/her own Fortran code to enhance the solution process including the estimation of errors and the alteration of solution algorithm to handle nonlinear phenomena. This feature is particularly valuable because of a user's concern on the rates of convergence [17] and the accuracy of the resulting approximate solution [18, 19, 20].

To solve the model problem using ANSYS, version 5.0A, we have developed two classes of codes[12], one for handling steady state and the other for transient loading cases as defined in the next Section. Using either of the two codes, a typical mesh design and an enlarged view around a pipe can be obtained as shown in Figs. 14 and 15.

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[12] See Appendices G and H for typical listing of codes developed for steady state and transient cases, respectively.

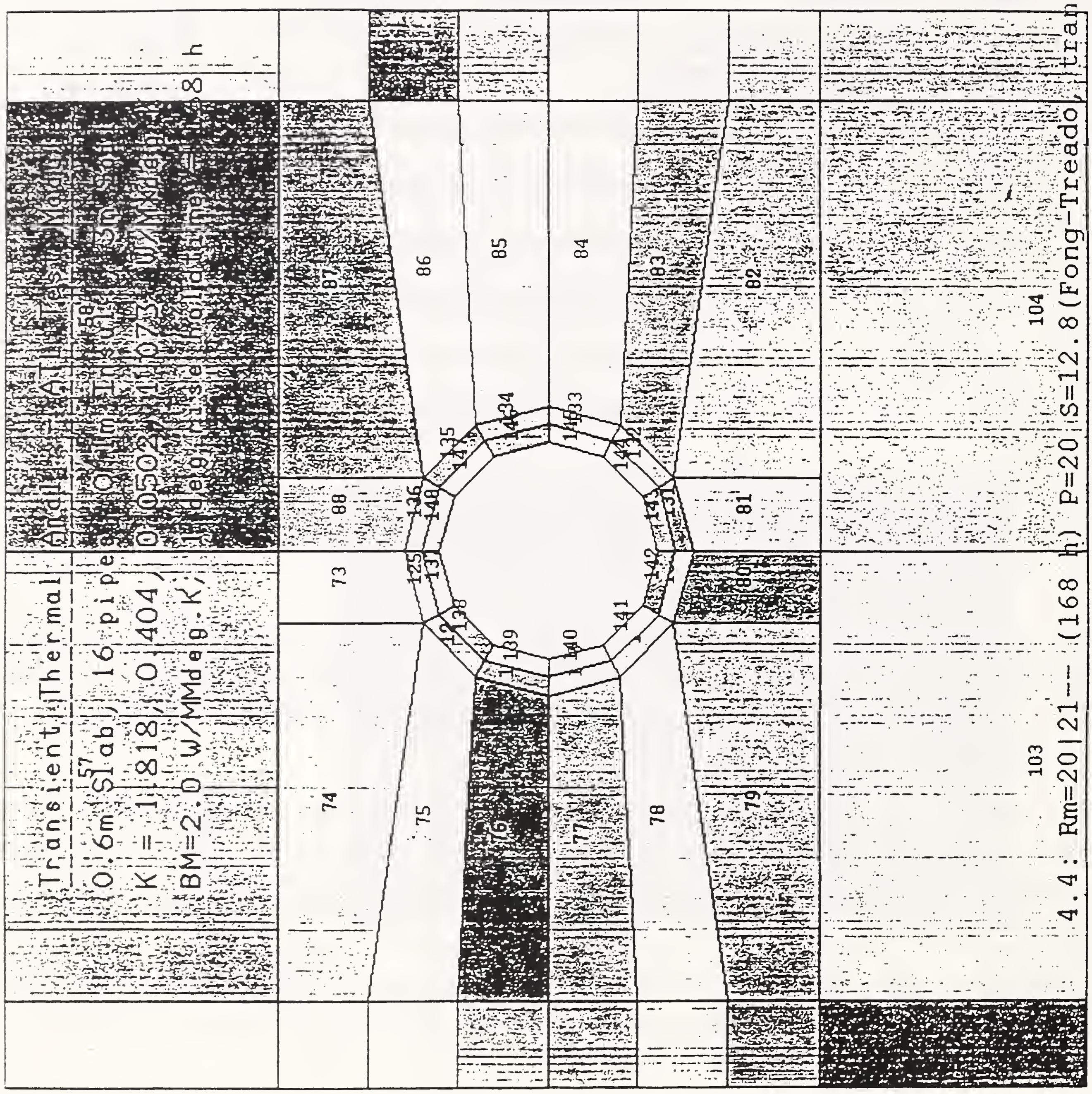

Fig. 15 An Enlarged View of the Mesh Design Around a Typical Pipe

5. Computational Codes and Numerical Solutions

To answer the specific questions outlined in Section 1, we propose to apply the FEM codes we developed for the model problem to the following three steady state and six transient loading cases (see Section 6 for a discussion of the preliminary results):

Steady-State	16-pipe Model (2.4m-slab)	32-pipe Model (4.8m-slab)
Loading Case 1 TEM1 = 20.0° C TEM2, unspecified TEM3 = 12.8° C	Subcase 1-a (heat loss "A") (Soil 2.4m by 3.0m deep. See Figs. 16 and 20.)	Subcase 1-f (heat loss "A") (Soil 4.8m by 3.0m deep. See Fig. 17 for solution.)
	Subcase 1-b (heat loss "A") (Soil 2.4m by 6.0m deep. See Fig. 20 for solution.)	
	Subcase 1-c (heat loss "A") (Soil 2.4m by 10.0m deep. See Fig. 20 for solution.)	
	Subcase 1-d (heat loss "B") (Soil 12.0m by 3.0m deep. See Figs. 18 and 20.)	Subcase 1-e (heat loss "B") (Soil 14.4m by 3.0m deep. See Figs. 19 and 20.)
Loading Case 2 TEM1 = 20.0° C TEM2 = 20.0° C TEM3 = 12.8° C	Subcase 2-a (heat loss "A") (Soil 2.4m by 3.0m deep. See Fig. 22 for boundary condition plot and Fig. 23 for solution plot.)	
Loading Case 3 TEM1 = 21.0° C TEM2 = 20.0° C TEM3 = 12.8° C	Subcase 3-a (heat loss "A") (Soil 2.4m by 3.0m deep. See Fig. 22 for boundary condition plot and Fig. 23 for solution plot.)	

Transient

TEM1 = TEM1(t)
TEM2 = 20.0° C
TEM3 = 12.8° C

TEM1 Loading History 1 (Ramp or Step Rise of 1° to 21.0° C; Holdtime = 60 min. See Figs. 24 and 25 for solution.)

TEM1 Loading History 2 (Ramp or Step Rise of 2° to 22.0° C; Holdtime = 60 min. See Figs. 24 and 25 for solution.)

TEM1 Loading History 3 (Ramp or Step Rise of 1.5° to 21.5° C; Holdtime = 55 min. See Figs. 24 and 25 for solution.)

TEM1 Loading History 4 (1° step rise to 21.0° C; Holdtime = 20 hours.)
TEM1 Loading History 5 (1° step rise to 21.0° C; Holdtime = 120 hrs.)
TEM1 Loading History 6 (1° step rise to 21.0° C; Holdtime = 168 hours. See Figs. 26 and 27 for solution and its exponential fit[13].)

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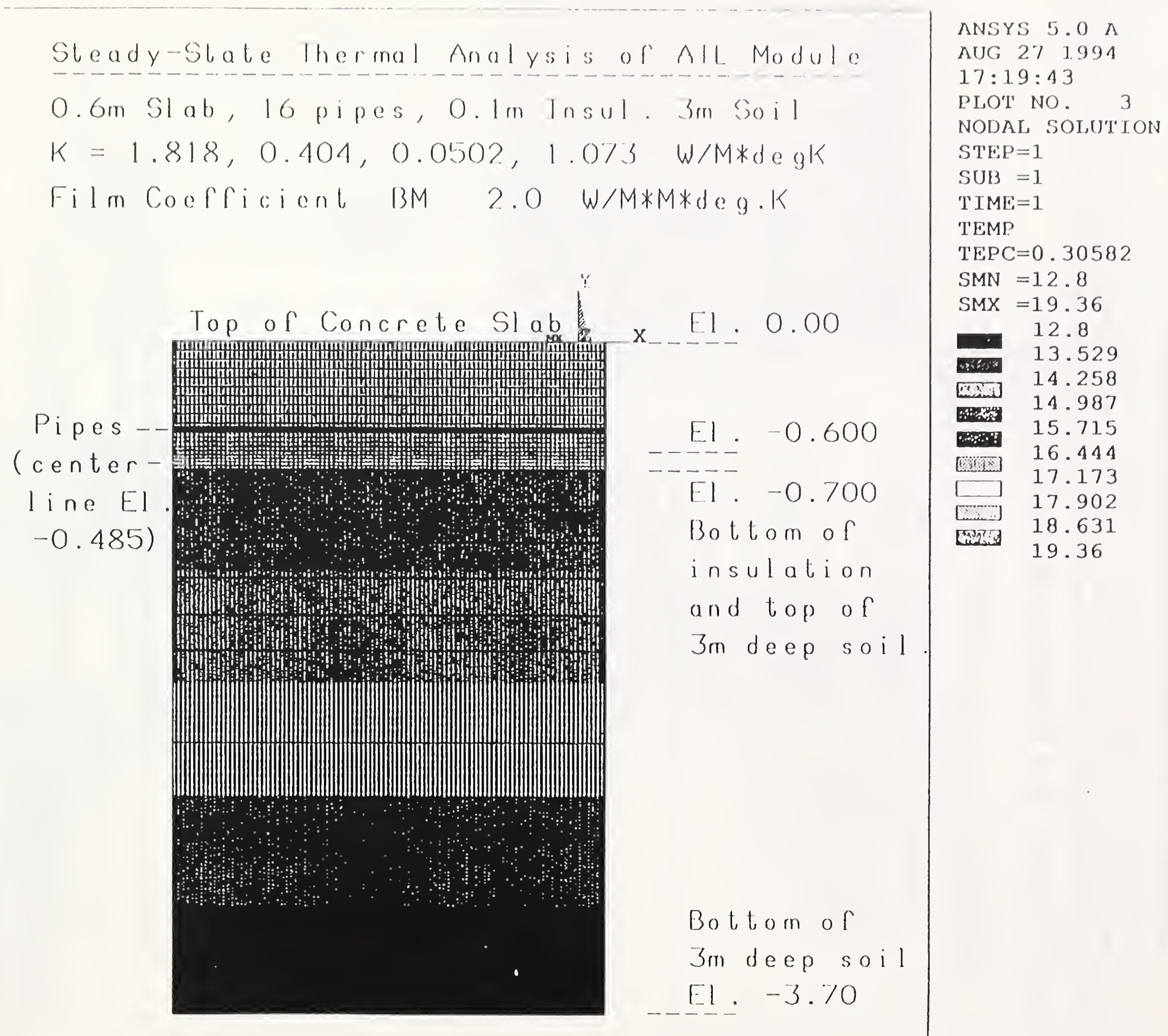
[13] An exponential fit [21] of the solution is obtained using an NIST-developed package named DATAPLOT [22].



C-1: Air 20 C; Soil 3m below = 12.8 C (Fong-Treado, z94821a)

Fig. 16 Temperature Distribution in 16-pipe Slab + Insulation + Soil (2.4mx3m) for Loading Case 1 (Steady-State, No heat in pipes or cable, Room Air Temperature at 20° C, and Soil Bottom Temperature at 12.8° C)

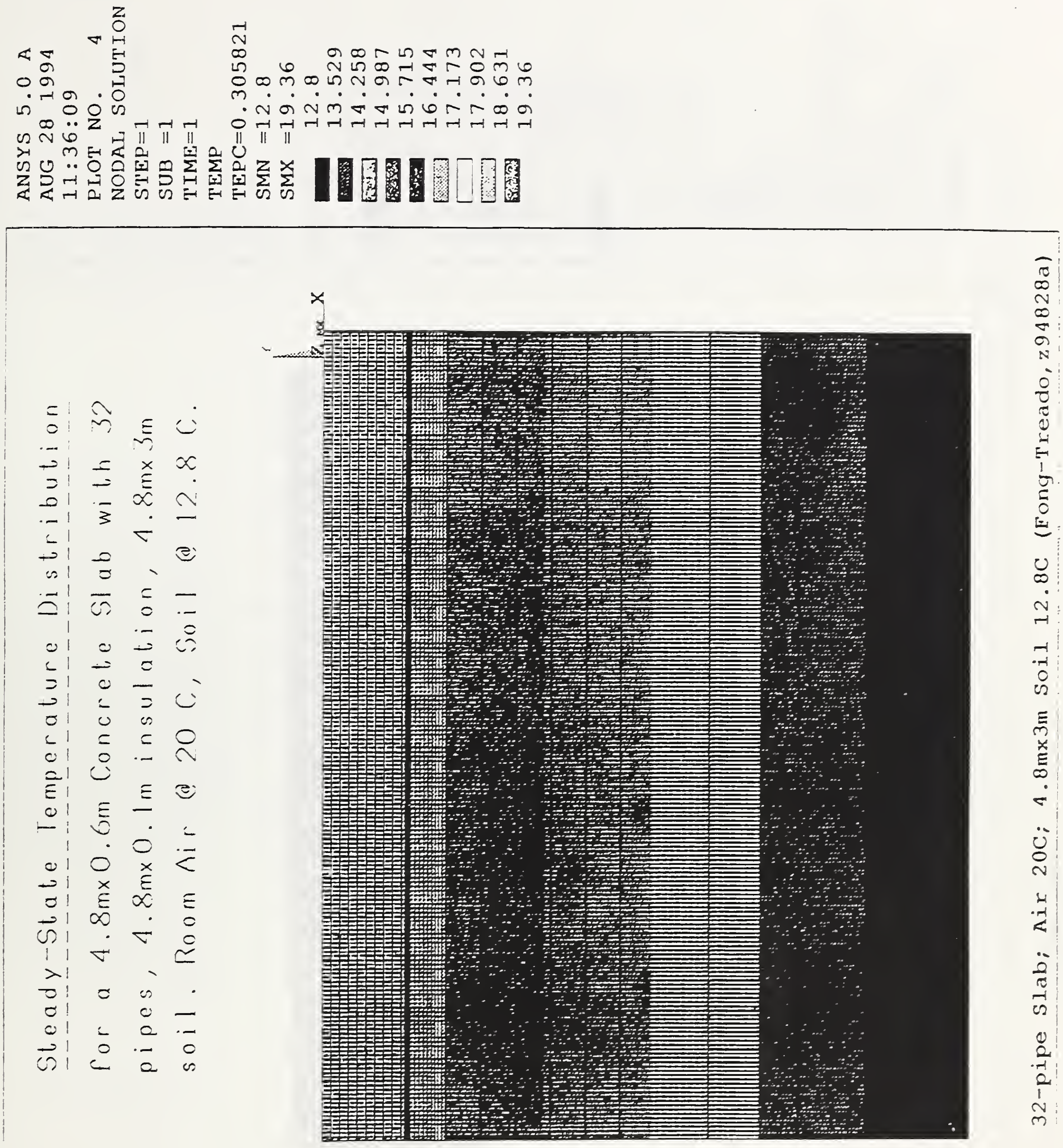


Fig. 17 Temperature Distribution in 32-pipe Slab + Insulation + Soil (4.8mx3m) for Loading Case 1 (Steady-State, Room Air 20°, Soil Bottom 12.8°)

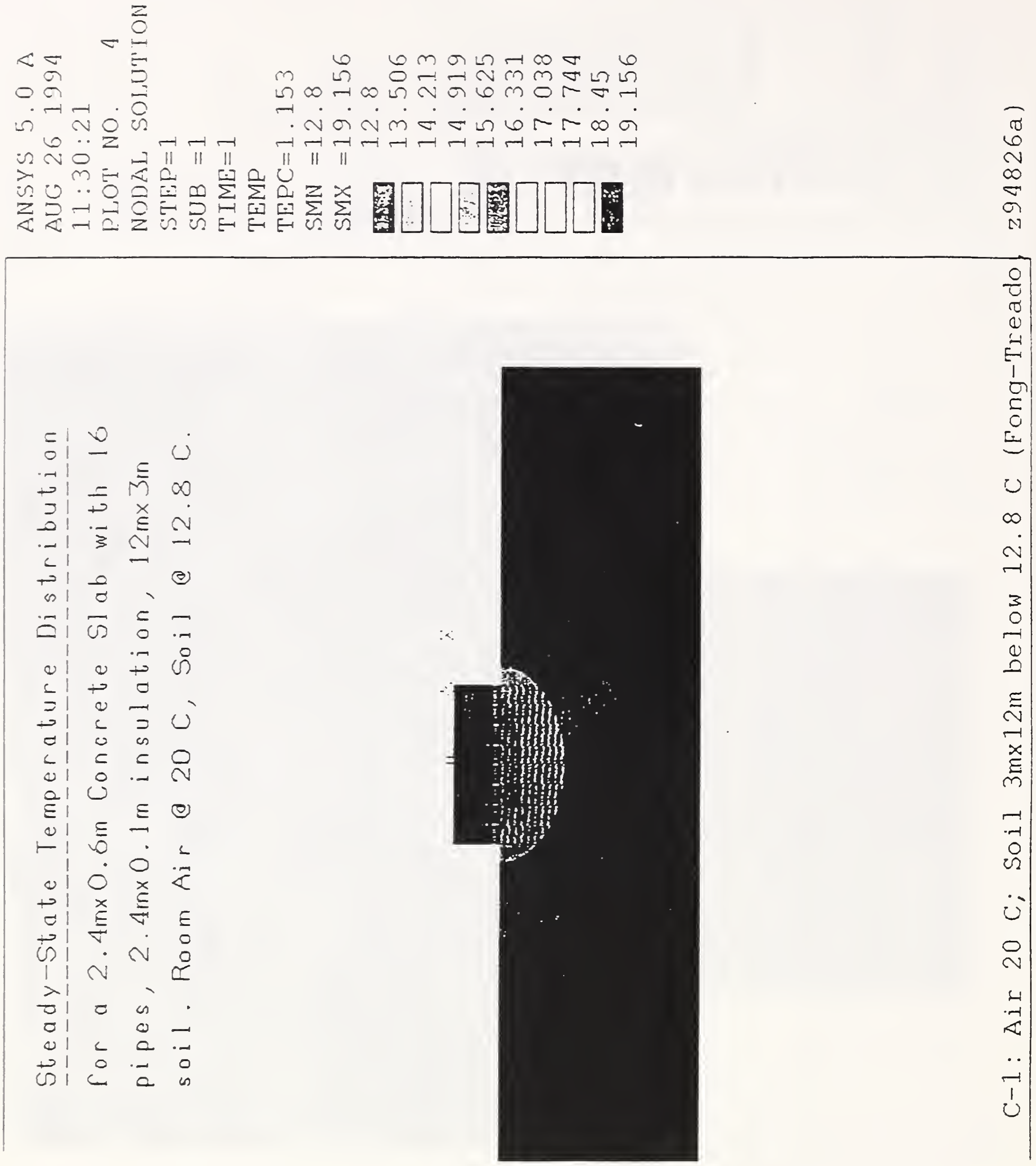


Fig. 18 Temperature Distribution in 16-pipe Slab + Insulation + Soil (12mx3m) for Loading Case 1 (Steady-State, Room Air 20°, Soil Bottom 12.8°)

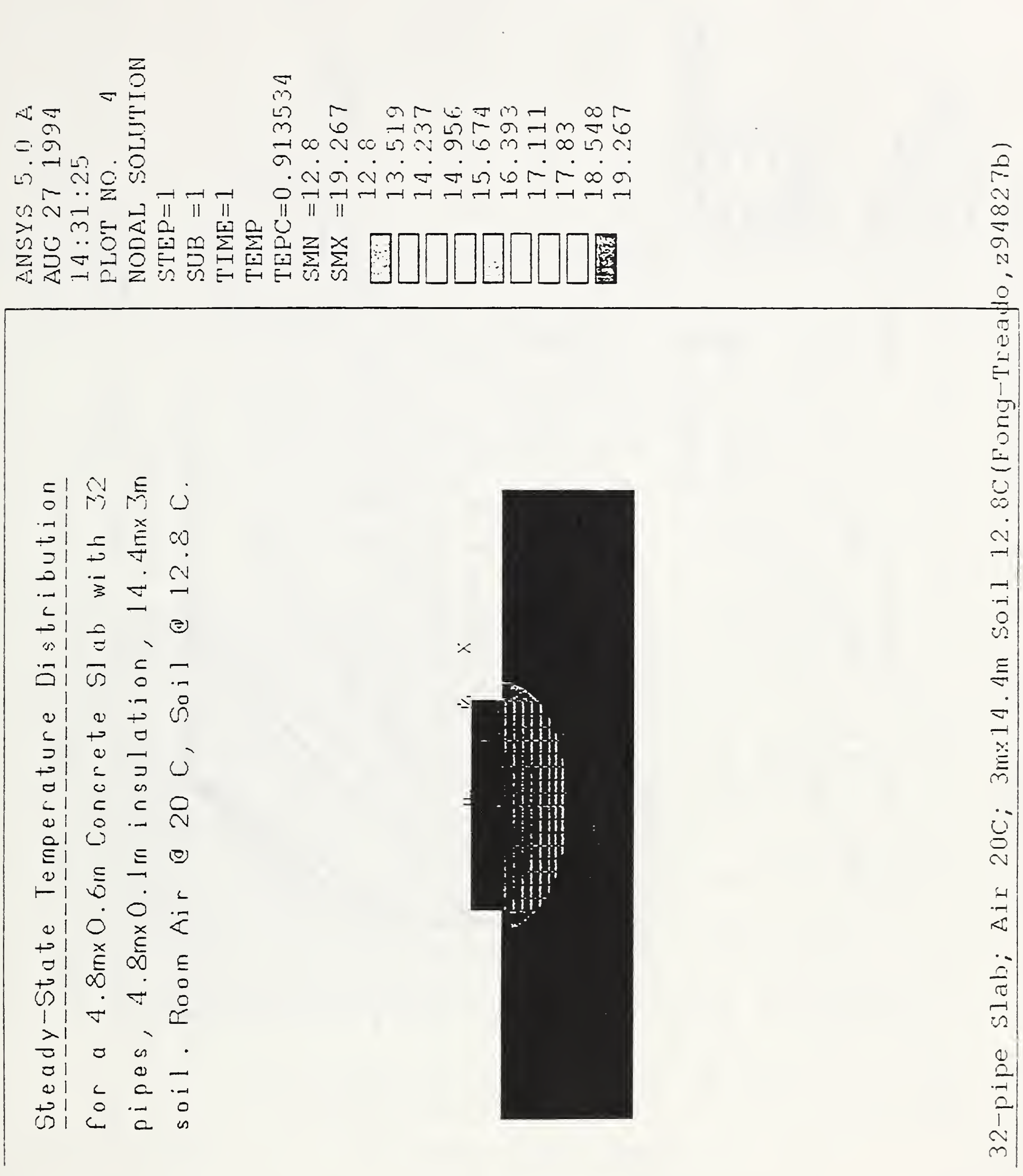


Fig. 19 Temperature Distribution in 32-pipe Slab + Insulation + Soil (14.4mx3m) for Loading Case 1 (Steady-State, Room Air 20°, Soil Bottom 12.8°)

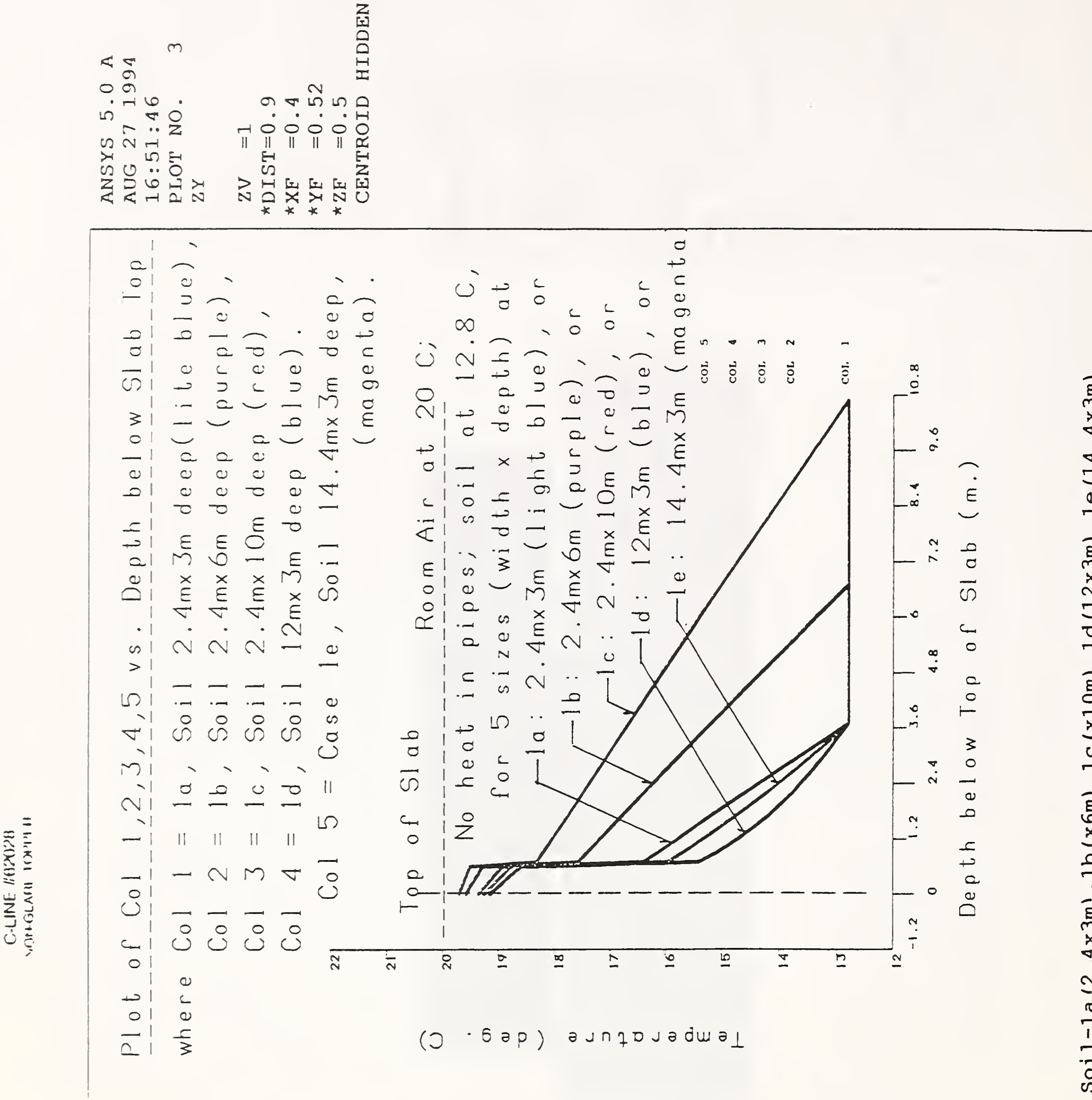
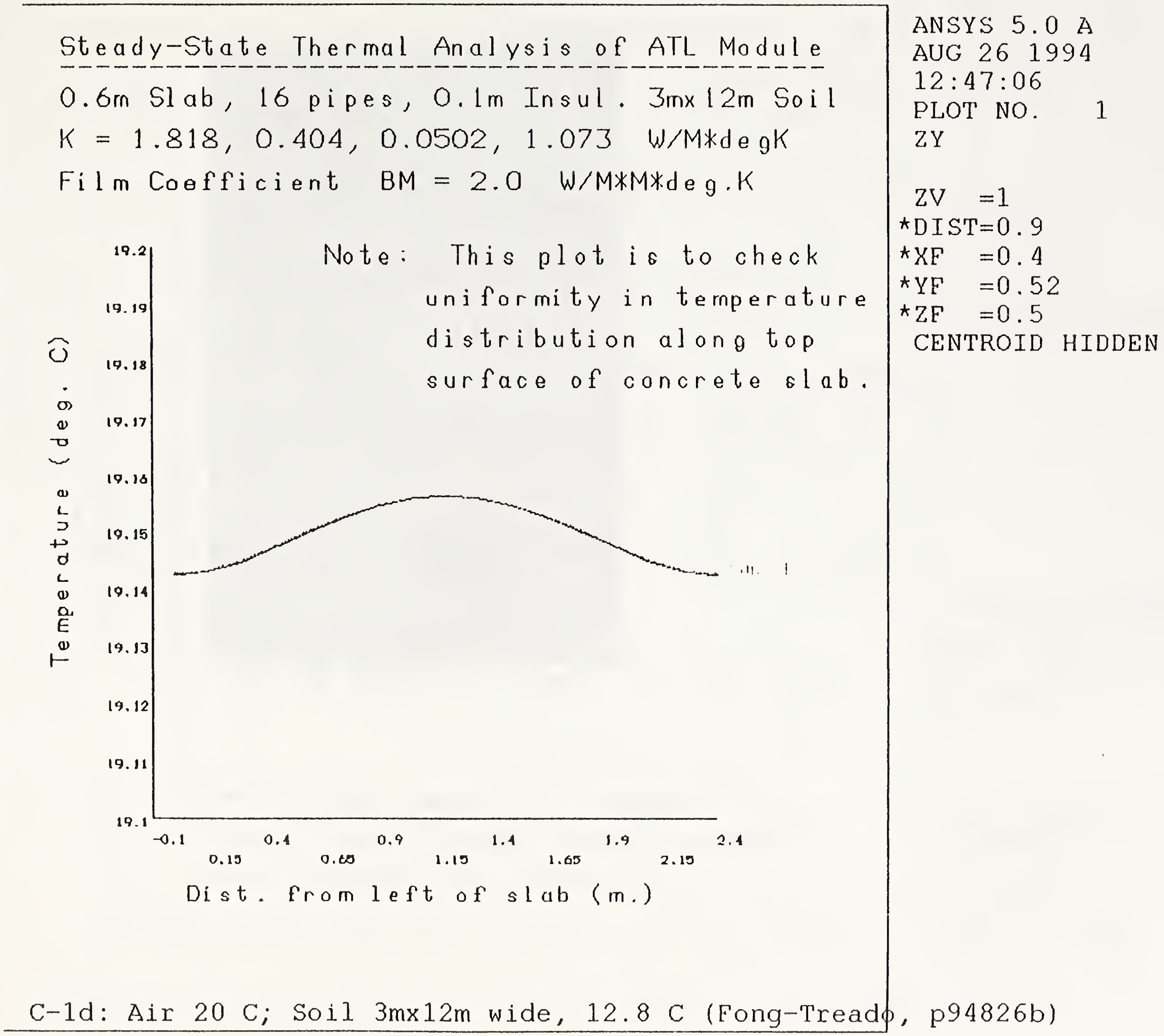


Fig. 20 Temperature Profiles (Case 1, Steady-State, Room at 20° C) thru Centerline of Slab, Insulation & Soil (no heat in pipes, soil bottom at 12.8° C) with soil width x depth = 2.4mx3m (Case 1a), 2.4mx6m (Case 1b), 2.4mx10m (Case 1c), 12mx3m (Case 1d), & 14.4mx3m (Case 1e)



Steady-State Thermal Analysis of ATL Module

0.6m Slab, 16 pipes, 0.1m Insul. 3mx12m Soil
K = 1.818, 0.404, 0.0502, 1.073 W/M*degK
Film Coefficient BM = 2.0 W/M*M*deg.K

Note: This plot is to check uniformity in temperature distribution along top surface of concrete slab.

```
ANSYS 5.0 A
AUG 26 1994
12:47:06
PLOT NO.    1
ZY

 ZV   =1
*DIST=0.9
*XF   =0.4
*YF   =0.52
*ZF   =0.5
CENTROID HIDDEN
```

C-1d: Air 20 C; Soil 3mx12m wide, 12.8 C (Fong-Treado, p94826b)

Fig. 21 Temperature Profile at El. 0.00 (Top of 16-pipe Slab) for Case 1d

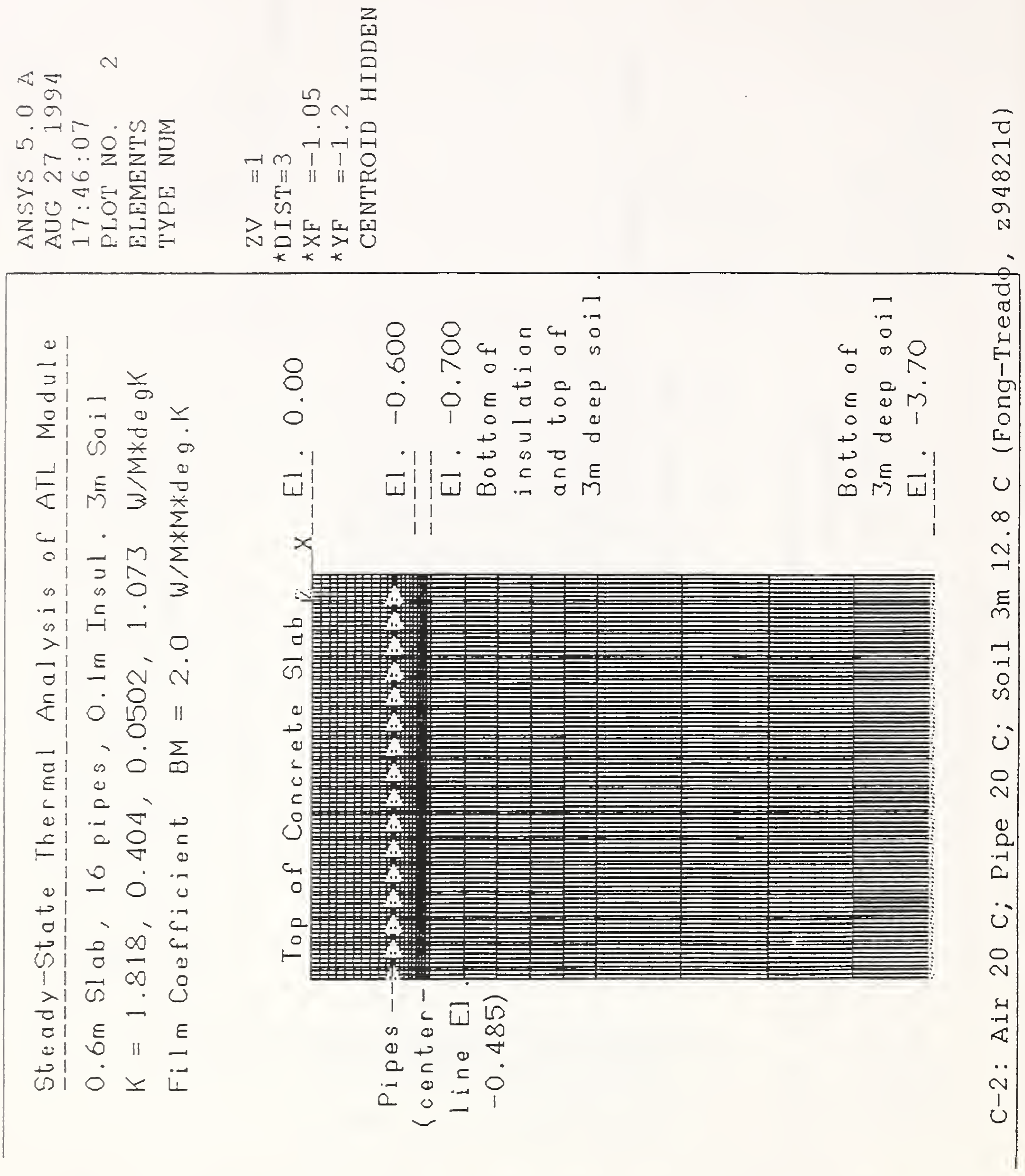


Fig. 22 Boundary Conditions for Case 2 (Room at 20°) or Case 3 (Room at 21°) for 16-pipe concrete slab + insulaiton + soil (2.4mx3m) with pipe heated to 20° C, an soil bottom held at 12.8° C

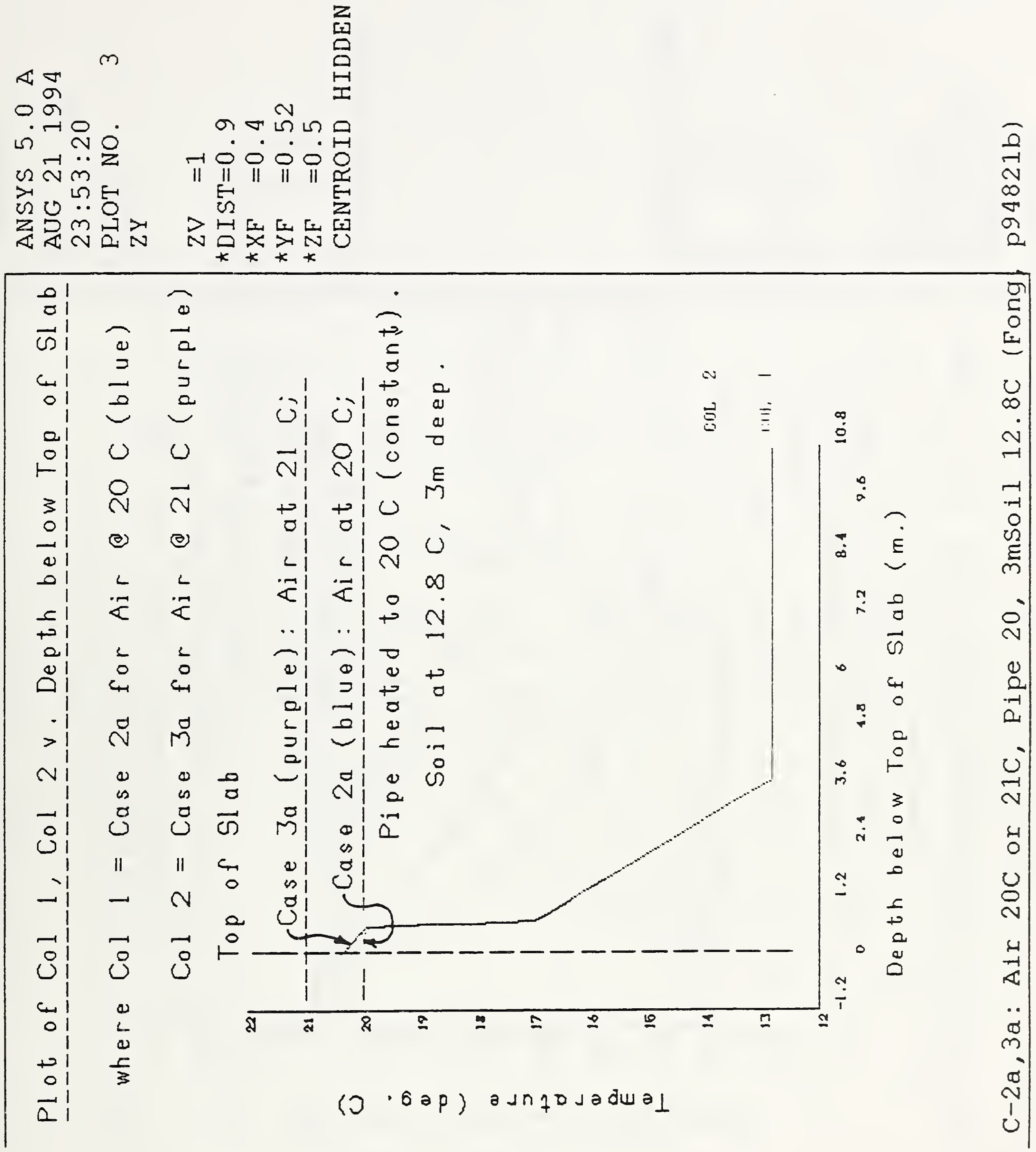


Fig. 23 Temperature Profiles through 16-pipe Slab + Insulation + Soil (2.4mx3m) for Loading Cases 2 and 3 (Steady-State, Pipe at 20°, Soil at 12.8°, Room Air at 20° or 21° C.

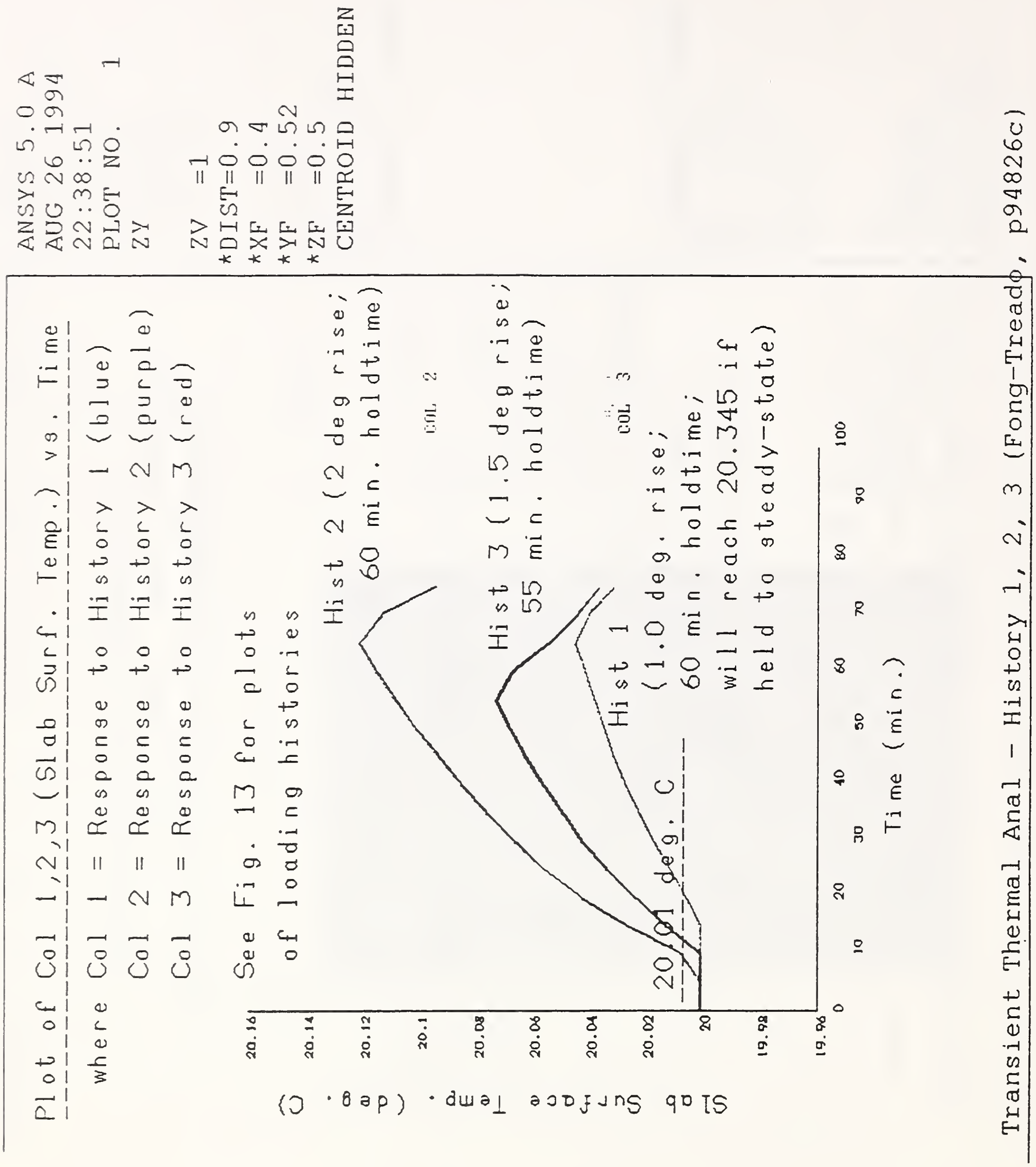


Fig. 24 Temperature History Plots at Top of 16-pipe Slab for Transient Loading Histories 1, 2, & 3 with Ramp Function for Changes

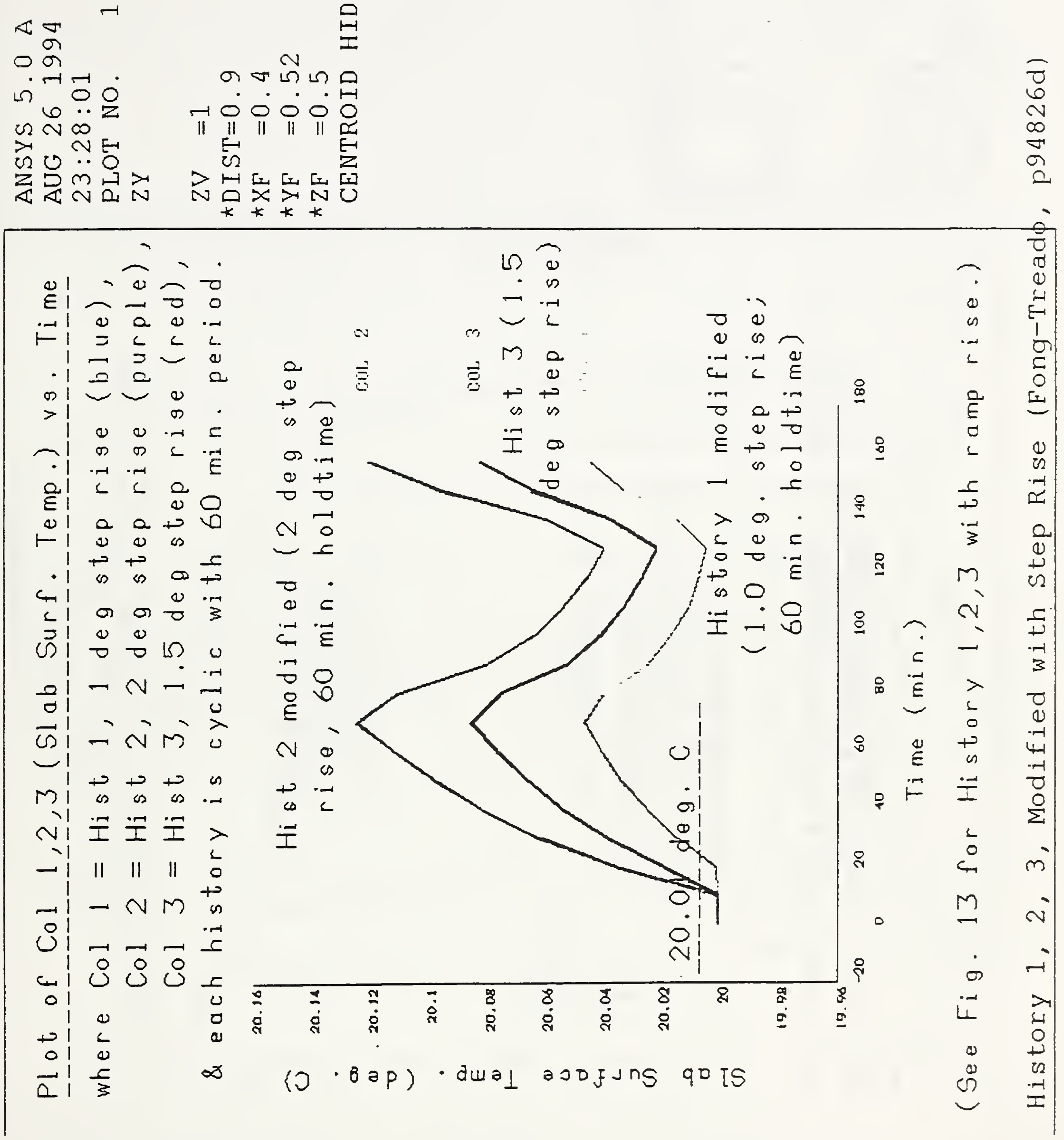


Fig. 25 Temperature History Plots at Top of 16-pipe Slab for Cyclic Loading Histories 1, 2, & 3 with Step Function for Changes

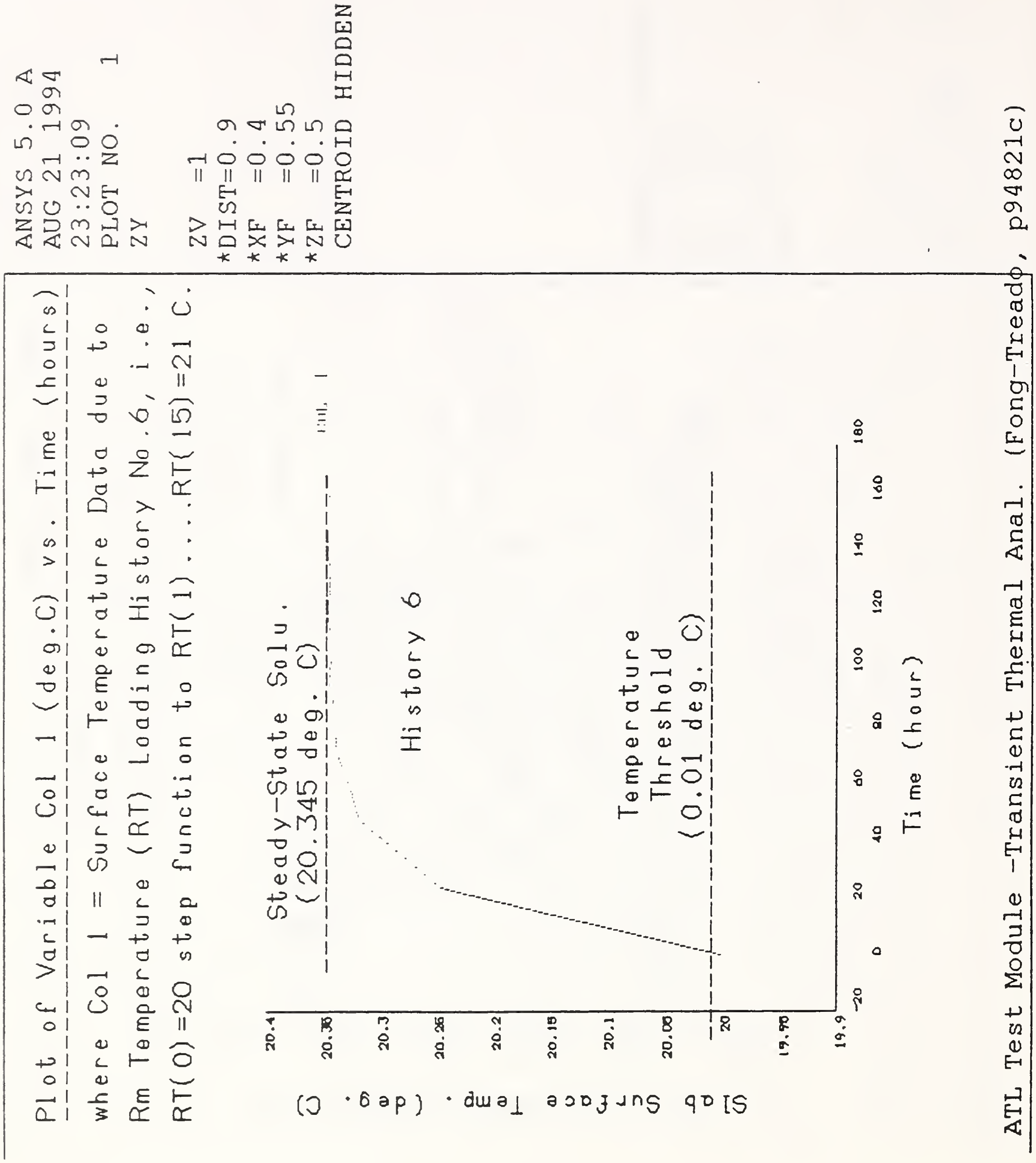
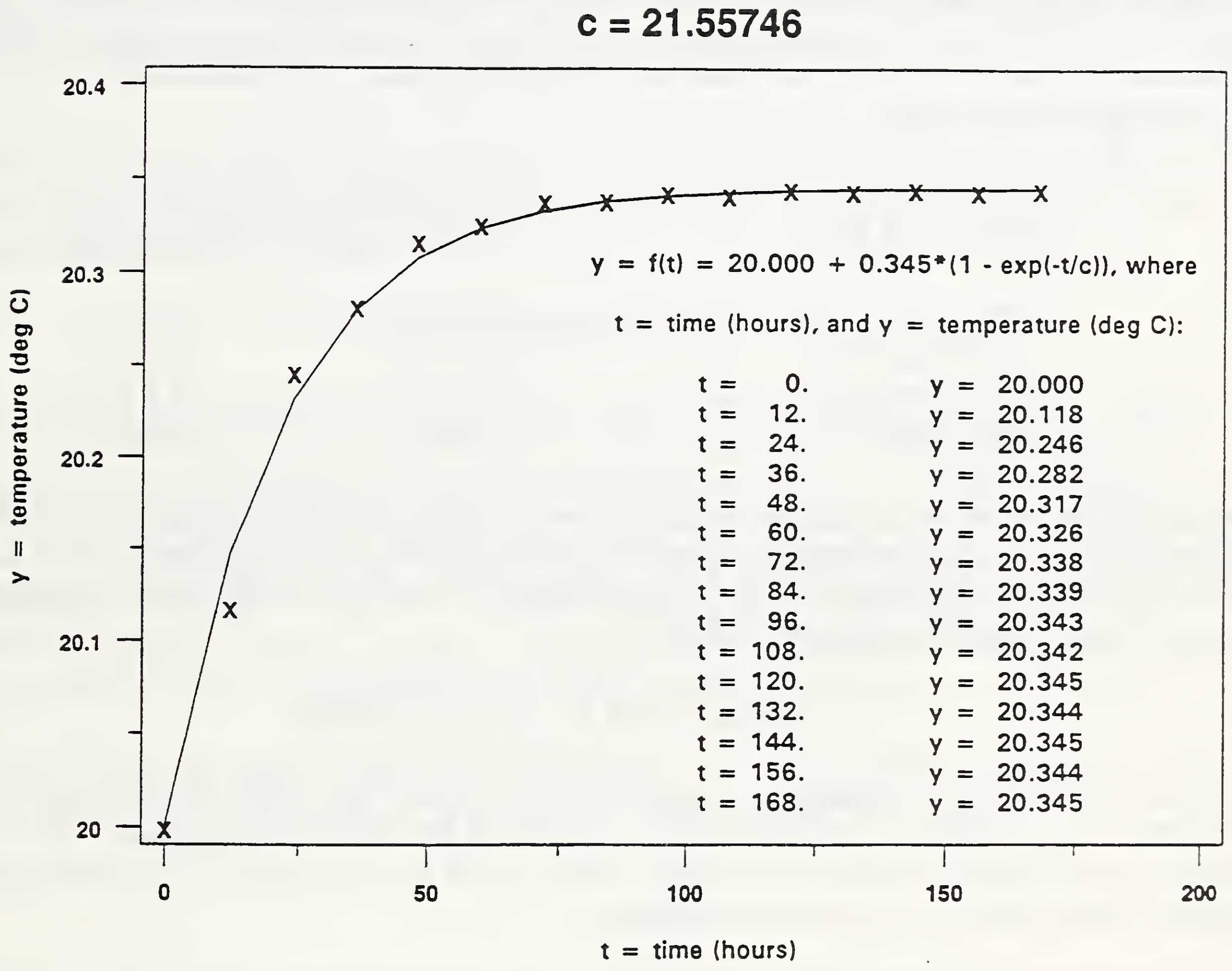


Fig. 26 Temperature History Plot at Top of 16-pipe Slab for Step <u>Loading History No. 6</u> with 168 hours of holdtime



y = f(t) = 20.000 + 0.345*(1 - exp(-t/c)), where

t = time (hours), and y = temperature (deg C):

t	y
t = 0.	y = 20.000
t = 12.	y = 20.118
t = 24.	y = 20.246
t = 36.	y = 20.282
t = 48.	y = 20.317
t = 60.	y = 20.326
t = 72.	y = 20.338
t = 84.	y = 20.339
t = 96.	y = 20.343
t = 108.	y = 20.342
t = 120.	y = 20.345
t = 132.	y = 20.344
t = 144.	y = 20.345
t = 156.	y = 20.344
t = 168.	y = 20.345

Fig. 27 Exponential Fit of Temperature Response Curve for 16-pipe Slab Conditioning System for 1-degree Step Loading History No. 6

6. Discussion of Preliminary Results

The development of two classes of FEM codes and their application to three cases of steady state and six histories of transient loadings made it possible for us to answer the three specific questions posed in Section 1. A discussion of the significance of our results follows.

6.1 ASHRAE Formula vs. FEM Numerical Results

In order to verify some of our FEM solutions, it is possible to use the so-called series resistance method to compute the slab surface temperature for four soil depths (0.0m, 3.0m, 6.0m, 10.0m) under the one-dimensional heat loss scenario "A". The calculation follows standard ASHRAE procedure [8, Ch. 3.1, eq. 2]. As shown in the following table, the formula checks very well the computed FEM results:

Depth of Soil	*2.4m-wide Slab Surface Temperature*	
(Constant 12.8° C)	*(ASHRAE Formula)*	*(FEM Results)*
0.0m	*18.72° C*	*18.73° C*
3.0m (Case 1-a)	*19.35° C*	*19.36° C*
6.0m (Case 1-b)	*19.56° C*	*19.57° C*
10.0m (Case 1-c)	*19.69° C*	*19.70° C*

The analysis also showed that the depth of the assumed constant soil temperature had a noticeable effect on the computed slab surface temperature for an unconditioned slab, i.e., the pipe inner surface temperature TEM2 is unspecified, but in all cases slab surface temperature was well below the air temperature (20.0° C).

6.2 Effect of Model Slab and Soil Widths

Because of symmetry considerations, we model the actual slab width (4.775m) with two configurations, one with 16 embedded pipes (2.4m) and the other with 32 pipes (4.8m). The following table shows the effect of the slab width as well as that of the soil by examining the computer results under two heat loss scenarios:

Heat Loss	*Top Surface Temperature at Slab/Insulation/Soil Center Line*	
Scenario	*2.4m-wide Slab*	*4.8m-wide Slab*
"A"	*19.36° C (Case 1-a, Fig. 16).*	*19.36° C (Case 1-f, Fig. 17).*
"B"	*19.16° C (Case 1-d, Fig. 18).*	*19.27° C (Case 1-e, Fig. 19).*

A graphical plot of the results of Subcases 1-a thru 1-e is given in Fig. 20. Under heat loss scenario "B", we can also check the uniformity of temperature distribution at the top surface of the concrete slab by computing the temperature difference between the edge and the center of the slab. The difference is 0.014° C and 0.063° C for a 2.4m- and 4.8m-wide slab, respectively. The surface temperature profile for the 2.4m-slab/12.0m-wide soil model is given in Fig. 21.

6.3 Effect of Hydronic Heating

To answer one of the three questions posed in Section 1 regarding the necessity of installing electric cable and/or hydronic heating systems to minimize heat loss to the ground, we introduce steady state Loading Cases 2 and 3 for a 2.4m-slab model as shown in Section 5, where the pipe inner surface temperature TEM2 is specified at 20° C, the soil 3m below at 12.8° C, and the room air at 20.0° C (Case 2) or 21.0° C (Case 3). A typical plot of the boundary conditions is given in Fig. 22. The temperature profiles through the slab/insulation/soil center line for the two cases are given in Fig. 23, where we observe that except for the difference in surface temperature in the concrete slab due to the difference in the room air temperature, the insulation and soil temperature for the two cases are practically identical.

A comparison of the results in Fig. 23 (with hydronic heating) with those in Fig. 20 (without hydronic heating) shows that the installation of hydronic heating contributes significantly to the stabilization of temperature at the insulation level and the removal of the uncertainties of the ground temperature distribution.

6.4 Estimate of Slab/Insulation/Soil Time Constant

Assuming a 2.4m-wide slab/insulation/soil system where the depths of the slab, insulation, and soil are 0.6m, 0.1m, and 3.0m, respectively, and considering steady-state loading cases 2-a and 3-a, and transient loading histories 4, 5 and 6 where we specify the room air temperature TEM1 = 21° C, pipe inner surface temperature TEM2 = 20° C, and soil bottom temperature TEM3 = 12.8° C, we showed in Fig. 26 that it takes a long time (of the order of 100 hours) to bring the surface temperature from one steady-state value (20.0° C) to another (20.345° C). Using a NIST-developed statistical analysis package named DATAPLOT [22], we obtained an exponential fit of the data with the time constant equal to 21.6 hours (see Fig. 27).

Alternatively, one may estimate the time constant τ of an infinitely-wide slab of thickness $2\,x_o$ and thermal diffusivity α^2, by using the following formula [6, p.38]:

$$\tau = \frac{4\,x_o^2}{\pi^2\,\alpha^2}. \qquad (7)^{14}$$

Using Eq. (3), the physical constants K, ρ and c of concrete given in Section 3.1, and the value of $x_o = 0.3$m, we calculate from Eq. (7) that the time constant for a 0.6m-thick slab without insulation and soil equals 8.3 hours. Since the formula does not apply to a composite slab, we can only combine our earlier computer result and formula (7) to estimate that the time constant for a 2.4m-wide slab/insulation/soil system to be somewhere between 10 to 20 hours.

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[14] A comparison of this formula with the one used by HDR in computing their estimate [1, p.35, or our Appendix F, p. F-4] shows that the two formulas are essentially the same except that in our formula, we interpret x_o to be the half-thickness of the slab whereas in HDR's case, they interpret L the full thickness. Other discrepancies include a major difference in specifying the conductivity of concrete (1.818 W/m*K, our value, vs. 1.04, HDR's) and its specific heat (653 J/kg*K, ours, vs. 1050, HDR's). The consequence is that our estimate of 8.3 hours is considerably lower than that of HDR (= 105 hours).

6.5 Completion of Tasks 1 and 2

With the previous four discussion items, we now conclude that we have completed the assignments of Tasks 1 and 2 as stated in Section 1. The answers to the three questions originally posed are:

Question	*Answer*
Time Constant	Using physical constants and material parameters from design handbooks, we estimated the time constant for a 16-pipe (2.4m-wide) slab-insulation-3.0m deep soil model to be between 10 to 20 hours.
Uniformity in Surface Temperature Distribution	Using a soil width larger than the slab to simulate multi-dimensional heat losses, we estimated that, for the steady-state case of a 16- or 32-pipe slab with no heating in the pipes, the difference of the temperatures at the top surface between the center and the edge of the slab ranges from 0.014° C (16-pipe model) to 0.063°C (32-pipe model).
Need for Hydronic or Cable Heating System in Slab Conditioning	We also did a parametric study to show that a hydronic heating system when embedded in the concrete slab reduces significanly the effect of the soil below in slab heat loss and temperature stabilization.

6.6 Future Work under Tasks 3 and 4

As stated in Section 1 under Task 3, we plan to solicit discussion and comments on this report from HDR and other interested parties in order to formulate more specific questions of interest to NIST. Among the future questions already being asked are:

Question 3.1	What is the effect of the heating cable?
Question 3.2	What is the effect of the long time constant of the slab on the performance of the temperature control system?
Question 3.3	In what way should the hydronic heating system be controlled to reduce the long time constant of the slab system?

Under Task 4, we plan to introduce a state-of-the-art solution monitoring and error estimation technique developed by Fong and others [18, 19, 20] to assess the "correctness" of the principal results of this investigation. A final report will be prepared to document the results of the remaining tasks of this study.

7. Additional Results (to appear in Final Report)

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Final Report.)

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Final Report.)

8. Concluding Remarks (to appear in Final Report)

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Final Report.)

9. Acknowledgment

In the course of this investigation, we have benefited from many of our NIST colleagues and others for their technical assistance and/or discussion that contributed to the completion of this report. In particular, we would like to thank the following individuals for their valuable assistance:

Affiliation	*Name (Last, First)*	*Subject Area of Assistance*
Illinois Institute of Technology Chicago, IL 60616	*Bernstein, Barry*	*Intelligent Agent for FEM Solution Monitoring & Mesh Refinement [20].*
NIST Div. 351	*Conley, Christopher G.*	*Discussion of Results.*
	Snouffer, Todd W.	*Discussion of Results.*
Div. 863	*Burch, Douglas M.*	*Film Coefficient.*
	Walton, George N.	*Discussion of Results.*
Div. 871	*Fong, Elizabeth N.*	*Intelligent Agent [20].*
Div. 881	*Boggs, Paul T.*	*Discussion of Results.*
	Boisvert, Ronald F.	*Discussion of Results.*
Div. 882	*Eberhardt, Keith R.*	*Exponential Fit [22].*
	Filliben, James J.	*Exponential Fit [22].*
Div. 883	*Antonishek, Michael*	*SUN System Support.*
	Barnett, P. Darcy	*SUN System Support.*
	Crosson, Robert J.	*SUN System Support.*
	Heckert, N. Alan	*SUN System Support.*
	Raybolt, Robert C.	*SUN System Support.*
	Strawbridge, Debra	*SUN System Support.*
	Strawbridge, Michael L.	*SUN System Support.*
	Tang, Hai C.	*ANSYS System Support.*
Div. 886	*Helfer, Linda E.*	*PC System Support.*
Swanson Analysis Systems, Inc. Houston, PA 15342	*Dietrich, David E.*	*ANSYS System Support and FEM Modeling.*

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[2] Anon., NIST Temperature Control and Vibration Isolation Research Project - Building 226, Project Manual, March 18, 1994. Alexandria, VA: Henningson, Durham & Richardson, Inc. (1994).

[3] Anon., NIST Temperature Control and Vibration Isolation Research Project - Building 226, Nine of 23 Drawings (Nos. 226-171, 226-172, 226-173, 226-174, 226-176, 226-178, 226-181, 226-188 and 226-192), March 18, 1994. Alexandria, VA: Henningson, Durham & Richardson, Inc. (1994).

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Appendix A

List of Documents furnished by Client

Appendix A - List of Documents furnished by Client

Item	Date	Description	Remark
1	Jan. 25, 1994	Memo to: S. Kramer, Assoc. Dir., NIST Through: R.H.F. Jackson, 820 D.S. Blomquist, 822 From: D.G. Eitzen, 822.01, NIST A. Donmez, 822.05, NIST C. Evans, 821.02, NIST Subject: Technical Design of ATL	Copy attached (AppendixB).
2	Mar. 7, 1994	Minutes of Jan. 27, 1994 Meeting to Review ATL Procurement Options and Their Schedule Implications From: Peter R. Roy, Proj. Mgr., NIST [Including corrections by Bernie Randolph of HDR dated 2/23/94].	Information non-germaine to this analysis task.
3	Mar. 7, 1994	Minutes of Feb. 2, 1994 Meeting to Brief Management on the Progress of the Vibration and Temperature Res. Construction Projects; etc. From: Peter R. Roy, Proj. Mgr., NIST [Including corrections by Norman C. Pardue, Jr. of HDR dated 2/25/94].	Copy attached (Appendix C).
4	Mar. 18, 1994	NIST Temperature Control and Vibration Isolation Research Project - Bldg. 226, Project Manual. Furnished by Henningson, Durham & Richardson, Inc., Alexandria VA.	Selected pages attached in Appendix F.
5	Mar. 18, 1994	NIST Temperature Control and Vibration Isolation Research Project - Bldg. 226, Basis of Design. Furnished by Henningson, Durham & Richardson, Inc., Alexandria VA.	Selected pages attached in Appendices E & F.
6	Mar. 18, 1994	23 Drawings for NIST Temperature Control and Vibration Isolation Research Project. Furnished by Henningson, Durham & Richardson, Inc., Alexandria VA.	9 drawings of the 23 used to form the basis for Figs. 1-12.
7	Apr. 4, 1994	Fax to: Jeffrey Fong, Div. 881, NIST From: Stephen J. Treado, Div. 863, NIST Subject: Geometric & Physical Constants	Copy attached (Appendix D).

Appendix B

Jan. 25, 1994 Memo to S. Kramer

by D. G. Eitzen, et al, on

<u>Technical Design of ATL</u>

NIST
UNITED STATES DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
Gaithersburg, Maryland 20899-0001

January 25, 1994

MEMORANDUM FOR S. Kramer, Associate Director, NIST

Through: R.H.F. Jackson, Deputy Director, MEL

D.S. Blomquist, Chief, 822

From: D.G. Eitzen, 822.01
A. Donmez, 822.05
C. Evans, 821.02

Subject: Technical Design of ATL

We have attended several of the design review meetings for the planned Advanced Technology Laboratory (ATL), the most recent on December 21, and are concerned about the lack of basic engineering science being used by the design team. This concern encompasses the lack of both analytical tools and the use made of the past experimental base. The design team has visited a large number of sites, but seems intent on an experiment to rediscover or design new systems with performance that has already been demonstrated. For example, the enclosure for LODTM at Livermore exceeds the ATL design requirement and approches .001° as measured by MEL staff and does so with an elegant, simple design. The thermal control for the ATL experimental module presented on December 21st was far more complex, and there is no assurance that it will work any better.

The failure to apply well known analysis tools is as pervasive. These are but two examples:

1) There has been extensive discussion about controlling the slab temperature. From the response to our questions at the meeting it seemed that the designers did not fully understand the concept of a thermal time constant, nor how to calculate one. If the thermal time constants are long, an active slab temperature control is irrelevant. A relatively simple analytical model would show, very rapidly, if this issue is worth further effort. 2) Given the use of buried heater water pipes, two questions remained unanswered: The required pipe spacing to achieve a uniform temperature at the surface of the slab and pipe sizing to minimize vibration due to turbulent flow. Pipe spacing for uniformity and sizing to keep flow laminar are straight forward exercises in heat transfer and fluid flow.

The use of additional science base would, with certainty, reduce the scope and cost of the experimental ATL module since it effects issues large and small in the design of the ATL. The skills to apply the available tools exists at NIST or are readily available from known consultants.

cc: Chris Conley

Sam -

The problems raised by Blomquist are not unique to his group. Other concerns have been raised by some of the smart people in MEL about some of the technical approaches. E.g., Brian Scace is concerned about the approach used in the vibration isolation experiment in 220. I am concerned that we are pressing rapidly ahead with an approach that will produce an answer that is fraught with errors. Can we talk about closer interaction perhaps or other possible remedies? The last thing we want is a flawed building.

Ric Jackson

Appendix C

Mar. 7, 1994 Version of Minutes of Feb. 2, 1994 Meeting by P. R. Roy on <u>Progress of the Vibration and Temperature Research Construction Projects</u>

MINUTES OF MEETING

DATE: February 2, 1994 (Revised 3/7/94)

LOCATION: CIFP Conference Room, Bldg. 301

PURPOSE:
1. Brief Management on the Progress of the Two (Vibration and Temperature) Research Construction Projects;
2. Make decisions necessary to confirm the direction taken or adjust it.
3. Make new decisions necessary to keep projects moving forward.

ATTENDEES: Per attached sign-in list

DISTRIBUTION: Attendees, File 0050, Paul Greenhalgh

Items of Discussion:

1. In accordance with the agenda, Norm Pardue was requested to explain the history of Barry Controls' interface with the planning, design, and construction of this project.

2. Norm stated that Barry was recommended by Acentech. Acentech and HDR were attempting to incorporate the "best available" off-the-shelf air spring into this design. During the initial stages of the design, HDR and Acentech sought the advice of Barry Controls' engineers, especially pertaining to the type and number of springs for this application.

3. Norm Pardue explained that the Barry "servi-level" system performs within the prescribed criteria down to 1.5 Hz at the maximum rated load of 100 lbs. per square foot. The system specified also to perform within the prescribed criteria down to 1.75 Hz at 50% of the total load. The system is specified to perform down to 2 Hz at 25% of the total load. The system is specified to perform within the criteria down to 2.5 Hz horizontally with 10% damping.

4. Norm explained that the HDR specification incorporates vertical damping control, which costs approximately $400 per spring.

5. Norm explained that the spring system is height-sensing and self-leveling. This type of spring has been used~~recommended~~ by the coordinate measuring machine manufacturers (See attached N. Pardue note re. this item).

6. Norm pointed out that Barry manufactured springs were used by both Delta and Zeiss in Europe. Norm pointed out, however, that these springs were different from the springs that will be used in the Vibration Research Project because the Zeiss and Delta springs were custom made.

7. Norm stated that the specification requires Barry to supply, install, and operationally test the spring system and that Hal Amick will participate in this process.

8. Guy Chamberlin stated that it might be best, because of the research nature of the project, to consider a different philosophy from that adopted by HDR. Guy commented that the project, as currently configured, seems to be designed to verify decisions made rather than to try different things. Guy has been informed that the cost of the springs is minor within the context of the overall program and that the cost of the springs, therefore, should not be a factor governing the overall design.

9. Guy stated that HDR should consider the possibility of incorporating several types of springs into the design, if appropriate. HDR should plan on testing out different things. Guy was concerned that the project is relying on a singular system, which may not reflect the full range of applications that will come up in the ATL.

10. Clayton Teague stated that NIST has used Barry Springs before, but that NIST has had some problems, especially with the leveling system. Clayton feels that the leveling system has some shortcomings that would need to be dealt with in this project. Clayton will provide information to the project team on the problems NIST has had with the Barry springs.

11. Clayton Teague stated that he would feel more comfortable if there was some form of written guarantee from Barry Controls regarding the fact that their system must meet a set of pre-established performance perameters.

12. Norm Pardue stated, on the subject of predicted performance, that originally Hal Amick thought that the project could "beat" the "A-1" criterion with another ~~non-~~Barry brand less sophisticated spring, but that Hal Amick's research shows that Barry can do even better than the established criteria (See attached N. Pardue note re. this item).

13. Guy Chamberlin suggested that this project should be trying for the "best there is" for all relevant NIST applications. Clayton Teague agrees that it makes sense for NIST to pursue the best type of spring for this particular application, in his view.

14. Norm Pardue stated that it is the intent of the project design to perform at a very high level, but that a reasonable set of criteria had to be set in advance such that the design team would have something to "shoot for" in the development of the design. Peter Roy agreed that saying "best there is" is fine, but that minimum threshold criteria for performance is needed.

15. Clayton Teague stated that as long as flexibility is inherently built into the design, it is acceptable to have set criteria.

16. ~~Norm Pardue of HDR will check into the characteristics of the Barry system provided to the Zeiss laboratories and report on the options they had~~(See attached N. Pardue note re. this item).

17. Clayton Teague noted that 1.5 to 2 Hz is acceptable to him for resonant frequency. Clayton stated, however, that there are some impacts at the higher frequencies that he is concerned about, and that he believes that the project team should explore more alternatives to the currently selected springs in order that the performance of the entire assembly is maximized (See attached N. Pardue note re. this item).

18. Guy Chamberlin requested HDR to try to find better springs for specific uses after the current design is tested out. Peter Roy stated that he will ensure that the CRSS agreement with Barry is as flexible as it can be such that CRSS may be able to more readily buy additional springs or options and attachments to the current springs, if appropriate.

19. Clayton Teague and Brian Scace will provide through Chris Conley information regarding where they believe enhancements may be required or are possible for the Barry springs (See attached N. Pardue note re. this item).

20. Clayton Teague pointed out that the slab itself is also variable. Clayton pointed out that it would be beneficial to have a system of anchors distributed over the top of the slab. The design could incorporate drilled holes in the top of the slab with threaded connections at two feet on center in both directions. This would give NIST flexibility to attach lead weights or some other form of dampening system.

21. Brian Scace inquired whether the ATL design itself continues to be open pertaining to the type of spring employed. Norm Pardue replied that yes, the ATL design is still open, and that this project does not restrict the selection of springs.

22. Brian Scace indicated that he is concerned regarding the ability of this system to laterally damp movement of the experiment on the slab itself and that it would be desirable from his standpoint to incorporate lateral damping in this research project.

23. Norm Pardue stated that many configurations of suspended A-1 criterion slabs are still possible for the ATL design. There is just a short amount of design time for the development of this prototype. For example, girders and purlins can be changed for the walk-on floor configuration in order to retain some of the flexibility desired by Brian Scace.

24. Brian Scace stated that, in general, he would prefer to see a larger bearing surface for the springs supporting the slab. This would give him more flexibility in terms of the type of spring he employs because the Barry springs have a much smaller footprint than some of the other springs by other manufacturers.

25. Norm Pardue pointed out that his design does not incorporate any "dampcrete" admixture because he does not have any good engineering data on this material. Norm Pardue stated that HDR is not in favor of incorporating dampcrete, despite the purported dampening characteristics it is supposed to impart to the concrete mass, according to some sources.

26. Norm Pardue stated, on the subject of the various design attributes and the flexibility of this research project, that the ATL Project design will have adequate information from this test project as needed to design all aspects of the ATL "A-1" criterion vibration isolation spaces, including any relevant options.

27. Guy Chamberlin stated that HDR should identify the departments that require "A-1" isolation and HDR should meet with these people to establish the possible options in terms of performance characteristics of the various springs.

28. Sam Kramer stated that the specifications need to be very clear regarding the performance and the nature of the springs. In particular, Sam wants to ensure that the HDR specification contains a very good testing procedure to establish whether the springs are performing either satisfactorily or unsatisfactorily, for various criteria.

29. ~~Norm Pardue stated that there are various kinds of testing required by this specification, including advance testing in the plant~~ (See attached N. Pardue note re. this item).

30. Clayton Teague agrees regarding the need for very specific testing requirements and that the testing should allow for varying loads.

31. It was decided that CRSS may go ahead and procure the springs on behalf of NIST using the HDR specifications. ~~This decision means that CRSS will procure the entirety of both research projects.~~(See attached N. Pardue note re. this item)

32. On the subject of item 4 in the agenda, Ted Zsirai was requested to explain why this project has not stayed with the original plan to test the "best available" commercial temperature control devices.

33. Ted Zsirai explained the history of this issue. First HDR attempted to determine whether the equipment for tight temperature control was available. Initial indications were that there were no devices on the market available capable of controlling to +/-0.01 degrees C.

34. Ted explained that later the manufacturers indicated that they could use commercially available controllers and other devices to control to 0.01 degrees C, but that no currently available transmitter was capable of operating at the resolution needed to attain the control we are seeking on this project. The resolution needed is 0.001 degrees C, whereas current transmitters have a resolution of 0.1 degrees C. The matter of the speed of transmitter responsiveness was also in question.

35. Guy Chamberlin recalled that the original plan was to utilize the "best available" commercial transmitter, in order to "benchmark" baseline result for comparison to later results. This would establish the point at which the project had started and would give us a clear indication of the improvements attained through refinement of the system.

36. It was decided that the Temperature Research Project would utilize the "best available" commercial transmitter that is currently on the market as well as a new transmitter operating at the resolution and speed needed to attain +/-0.01 degrees C. Guy Chamberlin directed that both of these be identified in the initial specification procuring such work.

37. Guy Chamberlin requested HDR to configure the specification such that the Temperature Control Systems contractor would be encouraged to propose enhancements to the system.

38. Pertaining to item 5 in the agenda, on the subject of the steps for the testing program and associated responsibility, Guy Chamberlin wants to establish a structure that will deal with all potential outcomes. For

example, in the event that the Temperature Control system does not work as planned, Guy does not want to have any diffusion of accountability because of involvement of NIST scientific personnel.

39. Guy recalled that the Temperature Control work plan stated that Steve Treado would be the "lead" in the development of the testing and evaluation plan. Guy wants to be sure that Steve does not take responsibility for the outcome of this program and that such responsibility will stay with HDR.

40. Ted Zsirai explained that once the system is installed, HDR will develop the testing program in coordination with the Temperature Control systems contractor. When the contractor implements his own testing program and states that the results indicate that he has achieved the specified performance, he will then demobilize his forces, provided he has also corrected any deficiencies and/or incomplete work..

41. After contractor demobilization, it is HDR's plan that Steve Treado would develop a totally independent measuring system overlaid on the contractor's system such that the project team can compare the Temperature Control system contractor's information to Steve Treado's data and require the contractor to make any adjustments and corrections well within the warranty period.

42. Guy Chamberlin stated that all of the variables pertaining to the system have to be tested. Guy wants the overall scheduling, management and implementation responsibilities to be clear. Peter Roy explained that the overall coordination of responsibilities will be CRSS'. HDR is responsible for development of all technical information necessary to construct the project and to evaluate and test its performance. Steve Treado will provide an independent "third party" testing service without taking out any further responsibility beyond the furnishing of such testing and providing the results.

43. Ted Zsirai stated that it would be best that Steve Treado should develop the testing basis, but that HDR would provide the necessary support and documentation to deliver the information within the project schedule.

44. Chris Conley will verify the written task order to HDR pertaining to their responsibilities in this respect.

45. Steve Treado stated that it is acceptable to him for NIST to take responsibility for the testing itself. Steve clarified, however, that if there are any problems discovered or coordination required, he will rely on the

CIFP team consisting of HDR and others to follow up with the contractors, as necessary.

46. Guy Chamberlin inquired as to whether the testing regime has been worked out, i.e., where will the temperature be measured?

47. Ted Zsirai stated that the location of the control thermistors is flexible and that his specification allows for different thermistors in different locations in the chamber to be the primary control over the entire temperature control system. The controlling measurement can be an average over several thermistors or can be a single thermistor at a particular location.

48. Guy Chamberlin requested HDR to configure their specifications such that the responsibility for variations in the performance of the system can be readily traced to their source (i.e. <u>one</u> contracting entity).

49. Guy pointed out that the experiments that will take place within the temperature control chamber will need advance coordination. Guy stated that CRSS, HDR, Steve Treado, and the person setting up the experiments should develop the specifics of the respective testing programs for each temperature control systems contractor well in advance and feed this information into the schedule.

50. Regarding item 6 in the agenda, Chris Conley explained that the project team originally expected to procure the TCS contract through NIST Acquisition in order to benefit from the type of record-keeping that the NIST Acquisition approach to RFP contractor selection would create for the history and basis of the awards to the two contractors in this instance.

51. Peter Roy explained that the division between the construction of the chamber itself and the temperature control system contractors is set up such that the temperature control system contractors will provide the "active" temperature control devices to the construction contractor for incorporation within his work. The construction contractor will furnish the "passive" elements of the TCS system (those that have no potential for impact on temperature control). The temperature control system contractor will be responsible for the furnishing of items such as reheat coils and various other devices which have a bearing on the accuracy of the temperature control.

52. It was decided that CRSS would contract directly with the temperature control systems contractor instead of the project using the NIST acquisition RFP process. This approach is taken because this project is a research project and different from the usual project procurement.

53. Guy Chamberlin stated that he wants to personally review the entire Temperature Research Project package before it is bid.

54. Regarding item 7 in the agenda, it was confirmed that both TCS contractors will test their systems with each of the three experiments consisting of a diamond turning machine mock-up, a balance and an interferometer (total of six tests). Guy Chamberlin pointed out, however, that this approach is only to be implemented if time allows.

55. Dave Talley explained the system that CRSS has put in place (and continues to develop) pertaining to the qualifications of the construction contractors. The essence of the system consists of sending out a questionnaire. The team then evaluates the qualifications of the interested proponents and ultimately, the team settles on three bidders from whom we will take proposals. This approach applies to both the construction contract and the TCS contract.

56. Guy Chamberlin would prefer that the project team only invite bidders who have experience in temperature control chambers. Peter Roy confirmed that if an adequate number of such contractors are available on the market and they have the appropriate qualifications, this will be implemented as requested.

57. Regarding item 9 in the agenda, Bernie Randolph stated that the Vibration Research Project, based on 95% CD documents, is estimated by HDR at $135,000. Some of the cost components of the project have gone up and others have gone down. The portions that have gone up include the walk-on slab and the demolition.

58. Bernie Randolph stated that the Temperature Research Project has a higher estimated cost than had previously been identified because the system is now moving more air and the "A"-rated slab has been added, including the slab heating system. The controls, however, as an estimated cost element, are expected to be simpler and therefore have been estimated at a lower cost than originally anticipated. HDR, therefore, expects that the Temperature Control System cost will be approximately the same as that originally as that estimated by HDR.

59. Sam Kramer requested the project team to ensure that the "Government Estimates" are not disclosed to any third parties.

60. Bernie Randolph stated that the Temperature Research Project cost estimate will be produced Wednesday, February 9.

61. Sam Kramer wants the team to show in the schedule the actual steps of notifying the personnel within the buildings who may be affected by the research projects. A general notice is in order, including occupants of adjacent buildings. Sam suggested that e-mail be used, including notification of Sam Kramer and Guy Chamberlin. There should be posters put up at all entrances to the buildings concerned, giving notice of the projects underway.

62. It was agreed that a procedure for pumping of the concrete needs to be clearly set out in the specification, since it is evident that the contractor must pump large volumes of concrete to the location of the Vibration Research Project in the basement of Building 220.

63. It was decided that the Temperature Research Project documents must clearly define a laydown area for the contractors outside of the building.

64. Allam Alami reviewed the attached schedules explaining the various steps in the processes. The logic of the schedule pertaining to the placement of the springs will be changed.

65. Chris Conley stated that various NIST personnel have been involved in the review and development of the two research projects, including people from Plant, Safety, and the Fire Chief.

Should there be any errors and/or omissions in the above, please advise the undersigned immediately.

Peter R. Roy, Project Manager

February 25, 1994

HDR

Peter Roy
~~Vice President~~
CRSS
CIFP Suite-Room B168
Building 301
Gaithersburg, Maryland 20899

DISTRIB
0050
PR:

Re: Minutes of Meeting, February ~~7~~ 2, 1994

Dear Peter:

I wish to correct or clarify comments that you recorded as made by me. I will refer to the item numbers in your minutes.

5. I did not indicate that "this type of spring has been recommended by the coordinate measuring machine manufacturers." I indicated that Barry Springs are used by coordinate measuring machine manufacturers.

12. Hal Amick never indicated to me or recommended "another non-Barry less sophisticated spring." Hal Amick did, in his initial recommendation, recommend a less sophisticated Barry spring and control which HDR encouraged him to upgrade.

16. I do not recall it being discussed that I would "check into the characteristics of the Barry System provided to the Zeiss Laboratories and report on the options they had." This is currently not being done.

17. I do not recall Clayton Teague raising concerns over how the selected springs effect the higher frequencies. In my discussion with Dr. Teague, he was satisfied that at the higher frequencies, the Barry springs would deliver results considerably below the A1 criteria level.

we should ask C.T what he wants

19. I do not recall that Clayton Teague and Brian Scace would be providing enhancement information to Chris Conley.

29. I do not recall stating "that there are various kinds of testing required by this specification, including advancing testing in the plant." I do not know what quality control methods or testing are used by Barry Controls in their plant. HDR's specification does not require any testing by Barry Controls except that required for Barry to render the "work complete and in proper operating

Henningson, Durham & Richardson, Inc.
103 Oronoco Street
Alexandria, Virginia
22314-2096
Telephone
703 683-3400
Architecture
Engineering
Planning

condition." The actual field testing will be performed by Acentech under a separate work order. The scope of HDR's work at this time does not include testing. A testing procedure will be developed by HDR/Acentech in conjunction with NIST once we negotiate a contract and receive a notice to proceed.

31. It is not clear to me what the last sentence is referring to: "this decision means that CRSS will procure the entirety of both research projects." If it is decided that CRSS may go ahead and procure the springs on behalf of NIST, it does not follow that "CRSS will procure the entirety of both research projects."

The clarifications offered above constitute my understanding of the issues cited in your minutes.

Very truly yours,

HENNINGSON, DURHAM & RICHARDSON, INC.

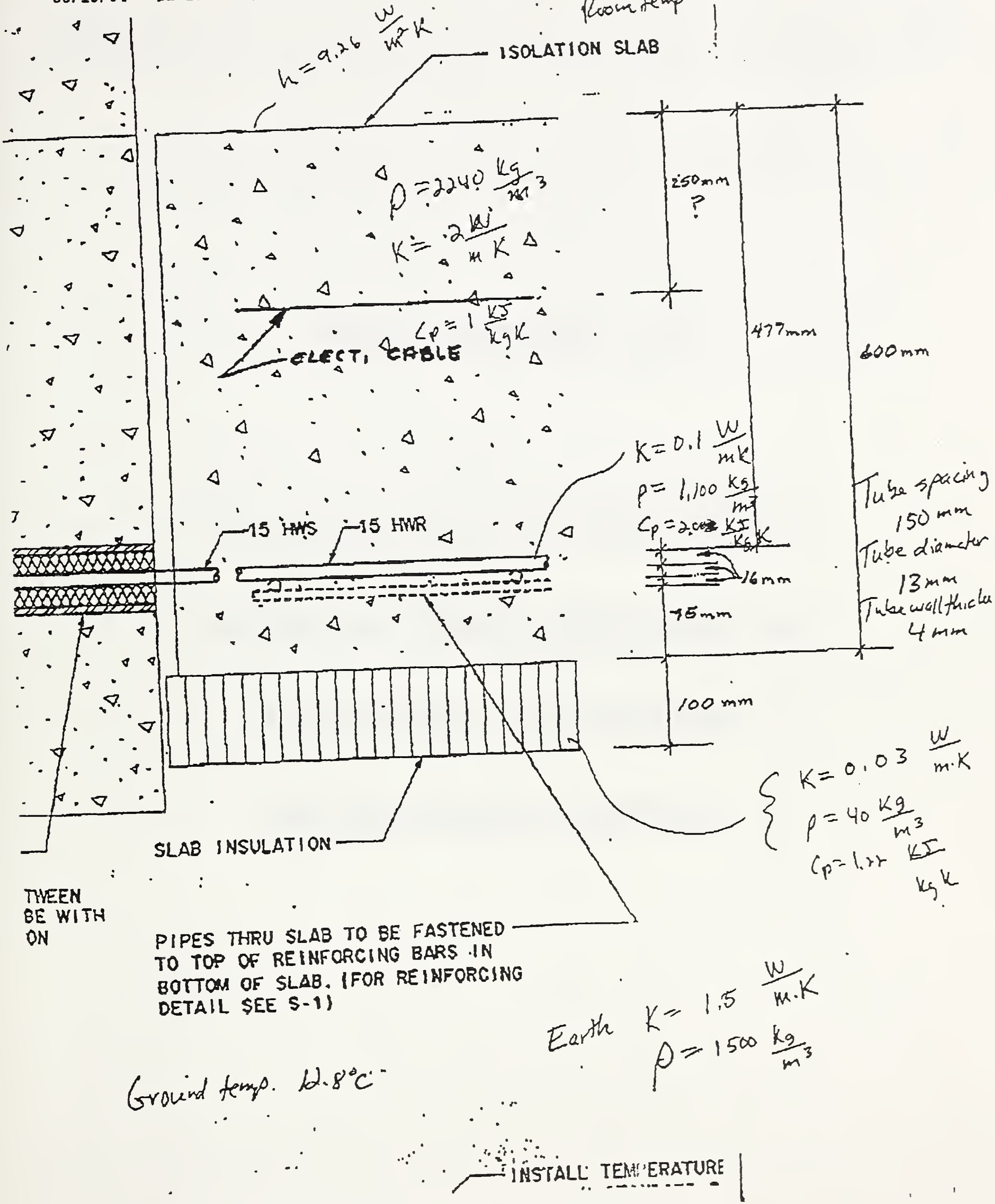
Norman C. Pardue, Jr., P.E., S.E.
Vice President

cc: Bernie Randolph

f:\docs\nist\corr\L2^2-25.wp

Appendix D

Apr. 4, 1994 Memo (via Fax) to J. Fong from S. Treado on <u>Geometric and Physical Constants for the Isolation Slab</u>


Room temp 20°C
h = 9.26 W/m²K
ISOLATION SLAB
ρ = 2240 kg/m³
K = .2 W/mK
Cp = 1 KJ/kgK
ELECT. CABLE
250mm
?
477mm
600mm
K = 0.1 W/mK
ρ = 1,100 kg/m³
Cp = 2.0 KJ/kgK
16mm
75mm
Tube spacing 150 mm
Tube diameter 13mm
Tube wall thickness 4mm
15 HWS
15 HWR
100 mm
K = 0.03 W/m·K
ρ = 40 kg/m³
Cp = 1.22 KJ/kgK
SLAB INSULATION
TWEEN
BE WITH
ON
PIPES THRU SLAB TO BE FASTENED TO TOP OF REINFORCING BARS IN BOTTOM OF SLAB. (FOR REINFORCING DETAIL SEE S-1)
Earth K = 1.5 W/m.K
ρ = 1500 kg/m³
Ground temp. 12.8°C
INSTALL TEMPERATURE

Appendix E

Excerpts from 3/18/94 HDR Document (Basis of Design) on Temperature Control and Air Distribution Systems

MECHANICAL ENGINEERING

A. High Accuracy Temperature Control Issues

The design and operation of a laboratory for +/-0.01 degC accuracy is highly complex. It requires highly sophisticated temperature control and air distribution systems, a thorough understanding of the user's requirements, and the user's understanding of the systems' limitations.

Table 1

Maximum Allowed Heat Gain in the Temperature Control Test Module

Accuracy ± 0.01 °C

Air Flow L/s	Air Changes	Watts
5000	280	123
4500	252	111
4000	224	98
3500	196	86
3000	168	74
2500	140	62
2000	112	49
1500	84	37
1000	56	25
500	28	12
400	22	10
300	17	7
200	11	5
100	6	2

Because of the low specific heat and conductivity of the air, only minimum heat gain to the room can be tolerated. Table 1 indicates the heat in watts which will increase the air temperature by 0.02 degC at various air changes.

As indicated above, at low air flow rates of 6 air changes per hour, only 2.5 watts heat gain can be added to the room without increasing the theoretical leaving air temperature more than 0.02 degC. If the air changes per hour is increased to 280, the maximum acceptable heat gain will increase to 123 watts. In perspective, the sensible heat gain from a human body is about 200 watts depending on the person's activity level.

While increasing the air flow through a room will reduce its sensitivity to temperature fluctuations, the vibration created by the high rate of air flow is a major concern. Since each room has its specific characteristics regarding heat gain, temperature stability, and sensitivity to vibration, the flexibility of the HVAC system operation is essential.

Another major issue of controlling to such high accuracies is the limited availability of temperature sensors, controllers, and particularly system manufacturers and installers with the capability of +/-0.01 degC accurate temperature controls. Although many industrial manufacturers have controllers with accuracies of +/-0.1 degC, only a few expressed interest in further developing their products to accept the challenge at NIST.

One of the most important issues is the understanding of the operation of the controls and the system limitations at various air flows and activities in the lab.

B. Description of the test laboratory module and the basic design concept.

The typical laboratory module in the ATL will be 7 m x 3.5 m x 3.5 m high. The NIST/HDR design team decided that the temperature control systems shall be tested in one lab module. Consequently, NIST identified one of the environmental chambers in Building 226 as a site for the test. The chamber is operated by the Building and Fire Research Group.

The first concept of the test module included a full size space surrounded by a cavity wall. It was planned to be built on a 100 mm concrete slab. The floor of the space was designed such that 1 m space below the floor allowed air flow underneath. The entire structure consisted of 100 mm insulated metal panels including the inner and outer walls, roof, and floor.

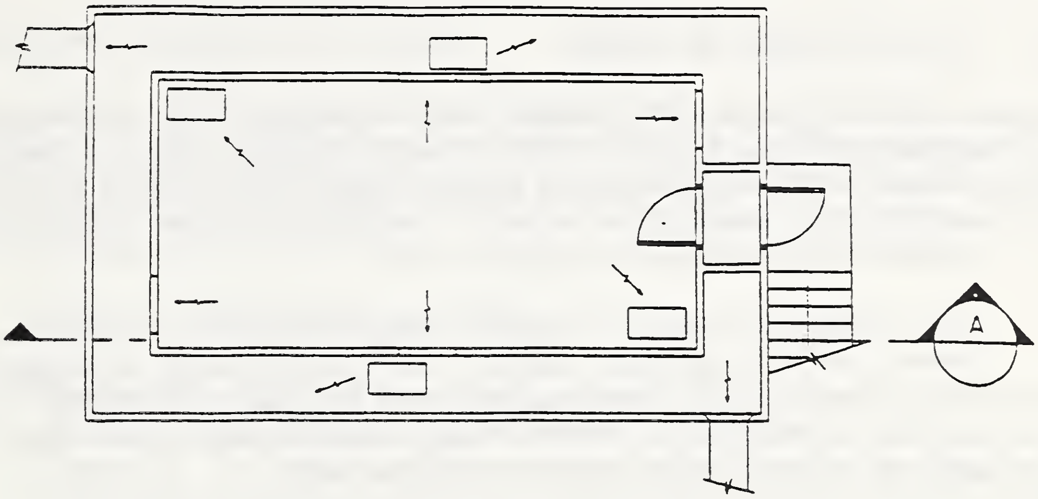
It was decided jointly with NIST scientists that the air flow will be vertical from top to bottom. Consequently, the air distribution will be through 150 mm deep, high efficiency, HEPA, filter ceiling. In order to provide even air flow and the least possible velocity, the entire ceiling will be made up of filters. Lights will be tear drop types mounted below the ceiling.

While even air distribution can be accomplished by perforated ceiling panels, HEPA filters offer additional advantages: They provide the required air cleanliness in the space, and improve the room acoustical characteristics.

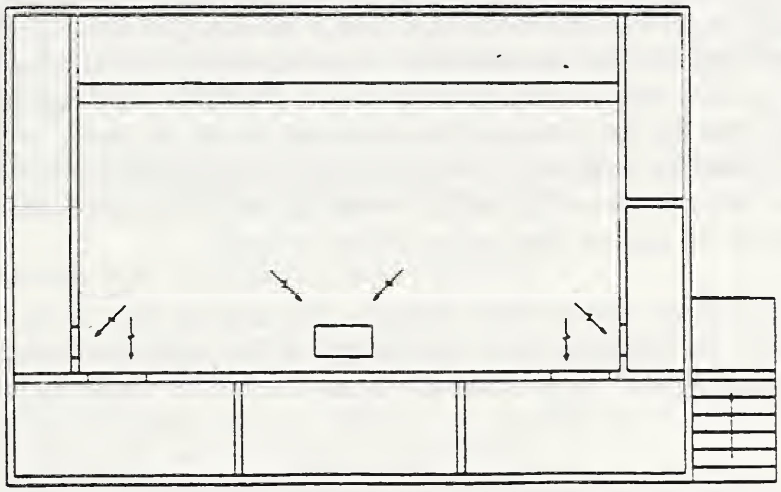
The plenum above the ceiling will be pressurized. Several supply air ducts with low discharge velocity (1.5 m/s) will assure even air distribution. The velocity pressure of this air stream will be 1.4 Pa, while the pressure loss created through the air filters will be significantly higher, 42 Pa at full flow. One of the objectives of the test project is to verify the uniformity of the air distribution through the filters from the pressurized plenum. While there are some suggestions from filter manufacturers that additional baffles may be required, it is the opinion of the design team at this point that the low discharge velocity to the plenum, combined with the pressure loss through the filters, will assure even air distribution and even air flow through the room. Should this not be the case, additional perforated panels or discharge boots with dampers can be installed above the filters.

The air will return from the room through low wall return registers and a limited number of perforated floor tiles. The decision to use low wall registers was made jointly with the users. The use of a fully perforated floor was not preferred because of their concern about vibrations generated by the weaker floor structure. The air through the wall registers will flow back through the wall cavity. Assuming that the return air will be within +/-0.01 degC of the room temperature, as it envelopes the room, it will thermally shield the lab from the outside. The return air through the floor will thermally insulate the floor from the slab below.

Figure 1 indicates the original module concept.



PROTOTYPE LAB MODULE - PLAN
NOT TO SCALE



SECTION A
NOT TO SCALE

FIGURE 1

C. Air Flow Through the Module

At the early stages of the design, several discussions were held with the NIST scientists about the required air flow through the module. High air flow rate assures uniform temperature in the room, and also, higher heat gain can be tolerated without sacrificing the temperature control. The higher air flow, however, introduces vibration which may not be acceptable.

After evaluating various air velocities through the room, it was the joint decision between the NIST and HDR team that 3000 L/s or about 125 air changes per hour, with 0.12 m/s velocity through the full room area, will be acceptable. However, it was also decided that the air flow through the room should be variable. This will allow to reduce the vibration due to air movement.

As the result of the domestic lab tour and further discussions with the design team, various changes were made which affected the air flow rate of the room and consequently the whole design. After visiting the Oakridge National Laboratory at Oakridge, Tennessee and observing their new lab with a diamond turning machine (DTM), the team was convinced that higher air changes than the previously agreed should be used for the test module. Approximately 300 air changes will allow a DTM to operate with minimum temperature gradient. Also, the team came to the conclusion that the limitations of the room can better be tested with air flows which are higher than the original. Another change which dramatically altered the original design was the addition of a control room, air lock, and removable panels to allow equipment to be moved into the controlled space.

The current design reflects these changes. The total air flow to the room is increased to 5000 L/s. At the same time, the volume of the controlled space was reduced to 75 % of the original. This allows the outer size of the whole module to remain the same.

In order to provide the lowest possible velocity through the room, about 75 % of the total ceiling area will be filters. Through the filters, the velocity of the air will be 0.27 m/s. The maximum air change rate in the module will be 280 per hour. The 300 air changes per hour air flow and the full size module test can not be achieved due to the space limitations in the environmental chamber.

D. Description of the Mechanical Systems

The mechanical systems of the module consist of a make up air unit with an outside air temperature and humidity simulating section, the main recirculating air handling unit, exhaust fan, air distribution system, heat exchangers and associated piping system, slab conditioning systems (hydronic and electric), low temperature chiller, and the temperature control system.

- Make Up Air Handling Unit (AHU-1)

  The function of the make up air unit is to provide the necessary ventilation air, room pressurization, humidity control, and make up air for smoke evacuation. For the test module, it is also designed to allow the simulation of the various outside air conditions, hot and humid summer weather and the cold winter temperatures.

  While in the ATL one make up air unit will serve several recirculating units, for the test module, the smallest commercially available air handling unit provides more air than necessary. Consequently, the remainder of the air is used for the control room conditioning and partially discharged to the environmental chamber.

  AHU-1 is specified as 50 mm double wall factory packaged unit representing the most cost effective choice of air handlers.

- Recirculating Air Handling Unit (AHU-2)

  The heart of the room temperature control system is the recirculating unit. It supplies 5000 L/s air at maximum capacity. The components of the unit are high efficiency filters, cooling coil, supply fan with variable speed drive, electric reheat coil, and sound attenuators.

  The specifications of AHU-2 call for 100 mm double wall, factory built, high quality unit. The different construction of the two air handling units, make up air and recirculating units, will allow NIST to make direct comparison between the two types of units and decide the quality level for the ATL.

- Exhaust Air

The third major component of the air system is the exhaust fan. The exhaust fan will allow the removal of the make up air and provides for the capability to directly exhaust heat from electronic equipment racks. It also assures proper pressurization of the room without excessive pressures on the doors, and it will be used for smoke exhaust.

- Air Distribution

The main objective of the air distribution system design is to minimize noise and vibration in the ducts by maintaining low velocities and to allow even air flow through coils and air flow measuring devices. Also, in order to measure accurately the temperatures downstream of heating and cooling coils, the best possible air mixing has to be achieved at the sensor locations by using multiple air blenders.

The air from AHU-2 is supplied to the plenum above the filters through four duct branches. The use of multiple branches provides for a quieter system, it allows multiple discharge ducts to the plenum to minimize vibration, it allows of testing different coil arrangements. It also permits the use of variable air flow to the room while maintaining the required velocities through the electric resistance coil. This is accomplished by closing individual branch dampers sequentially as the air flow is reduced.

In order to prevent any unconditioned air escaping to the room, multiple damper and scavenging ducts are used.

The three identical branches represent the typical design envisioned for the ATL. The fourth branch includes additional components for various testing. The hot water reheat coil will be tested to learn the accuracy of the controls achievable with water coils. The cooling coil will allow the team to verify if additional accuracy can be achieved by locating the cooling coil closer to the controlled environment and the final reheat coil.

- Piping Systems

  The test module will be served by existing utilities, steam and chilled water. The connections will be made in the attic mechanical equipment room where adequate capacity is available. The required heat exchangers and pumps are also located there. The indirect connection to utilities, particularly to the site chilled water system, is necessary to provide stable temperature and flow of chilled water to the cooling coil in AHU-2.

- Slab Conditioning System

  Some of the laboratories with high accuracy temperature control requirements will have concrete slabs directly exposed to the room environment. Since the slabs are installed on earth with year around temperatures of 10 - 13 degC, their surface temperature will be less than the room temperature. The difference can be more than 1 degC without or as low as 0.16 degC with insulation. Depending on the final usage of the high accuracy labs, even small amount of deviation from the set room temperature may be unacceptable.

  In order to eliminate or minimize the slab effect, it was decided jointly by the NIST/HDR team to install a slab conditioning/heating system. The simplest way to accomplish slab heating is with electric heating cables. (In the laboratories in Europe, they also used electric cables with a fixed heating capacity setting.) The other option is the use of hydronic heating. Discussing these options with the NIST scientists, they had concerns about both approaches. With the electric heating the problem is EMI/RFI, with hydronic system the concern is vibration.

  It is not certain that slab conditioning will be necessary for the ATL. However, in order to evaluate the system performance, construction techniques, the effect of the slab conditioning on the room temperature control, EMI/RFI, and potential vibration, it was the joint decision of the NIST/HDR team that both electric and hydronic slab conditioning systems should be installed.

E. Control Systems

The objective in designing the automatic control system has been to utilize standard, commercially available products as much as possible to establish a baseline for achievable accuracy. Many components of necessity will be industrial grade, of an accuracy and performance level not normally utilized in HVAC applications. However, only certain sensor and transmitter components will require custom design or modification from standard products.

AHU-1 provides makeup air to the module to meet outside air ventilation requirements. This unit consists of three sections.

The first section functions to simulate outside air conditions and is applicable only to the test module. Discharge air temperature can be controlled as low as -17 degC and as high as 43 degC and steam can be injected as necessary to increase humidity.

The second section, which will be necessary in the ATL, preheats and precools the outside air to maintain a constant 12.7 degC. For simplicity of design, a hot water preheat coil will be used for the test module. For the ATL, options of hot water, steam, and glycol coils will be evaluated. The industrial type supply fan in this section will be controlled by a variable frequency drive. Fan speed will be controlled to maintain constant supply air static pressure, thereby minimizing interaction of downstream systems. At this point, in the final ATL design, distribution will be made to several modules. For the test module, it serves only the module and the control room.

The third section includes a low temperature cooling coil, humidifier, and reheat coil. The space humidity will be maintained by controlling the cooling coil in sequence with the humidifier. The reheat coil will then be controlled to heat makeup air to the same temperature as module return air to minimize disruption when they are mixed. The design calls for +/-1% RH accuracy for humidity and +/-0.1 degC for temperature control.

AHU-2 provides the basic air movement through the module. The cooling coil CC-5 will be controlled to maintain discharge air temperature 1.0 degC below the desired room temperature setpoint, to an accuracy of +/-0.1 degC.

The room temperature is controlled by reheating the supply air from AHU-1 by low watt density electric reheat coils with SCR controllers just prior to its entering the ceiling plenum. A high accuracy control loop on each reheat coil has a temperature sensor just prior to discharge into the ceiling plenum. The control loop maintains a stable discharge air temperature which is reset as necessary to maintain room temperature setpoint.

In order to minimize any heat gain or loss in the air prior to its entering the module, heating coils and temperature sensors are placed as close as possible to the space, and the connecting ductwork has a high level of insulation.

Humidity level in the module is controlled by varying the humidity content of the makeup air in response to a humidity sensor in the return air. It is raised by the injection of steam into the makeup air just prior to its being mixed with the return air at the inlet to AHU-2. It is reduced by cooling the makeup air at CC-4 to as low as 2 degC, allowing space humidity to be maintained at 40% RH.

- Additional Reheat and Cooling Coil Control Modes

  To evaluate other reheat and cooling coil arrangements, three other alternatives will be tested. One reheat branch is equipped with a hydronic reheat coil HC-6. It will be tested to determine if an acceptable degree of accuracy can be obtained.

  Supply duct branch A is equipped with cooling coil CC-6. It will be evaluated for use in the ACL in applications where AHU-2 is remote from the supplied module, and excessive heat gain is experienced in the connecting duct. It will be controlled like CC-5, maintaining a discharge temperature 1.0 degC below the desired discharge temperature.

  The main supply duct is equipped with electric reheat coil HC-4, controlled in the same manner as the electric coils on the individual duct branches. It will be tested to determine if an acceptable degree of accuracy can be obtained in the room without the use of separate coils and controls in each duct branch. Additionally, tests will be run to determine how low air flow can be reduced on this single coil.

As stated earlier, it is necessary to test the module under widely varying air flow conditions. The module is designed to allow the air flow rate to be varied from 280 down to 40 air changes per hour. A variable frequency drive will be used on the supply fan in AHU-2. As fan air flow is manually reduced, automatic dampers in the four supply duct branches close off one at a time, preventing reheat coil air velocity from falling below acceptable limits.

To test the harmonics and EMI produced by variable frequency drives, two different types will be tested. SF-1 will be equipped with a pulse width modulated drive and SF-2 will use a six step drive. The pulse width modulated drive is less expensive and simpler in design but inherently produces more harmonics and EMI. The tests will determine if the pulse width modulated type will be acceptable in the ATL or if the six step drive must be used. We may also learn that, because of stringent criteria in certain parts of the ATL, no variable frequency drive is acceptable.

Appendix F

Excerpts from 3/18/94 HDR Documents

(Basis of Design & Project Manual) on

Slab Conditioning System

- Piping Systems

  The test module will be served by existing utilities, steam and chilled water. The connections will be made in the attic mechanical equipment room where adequate capacity is available. The required heat exchangers and pumps are also located there. The indirect connection to utilities, particularly to the site chilled water system, is necessary to provide stable temperature and flow of chilled water to the cooling coil in AHU-2.

- Slab Conditioning System

  Some of the laboratories with high accuracy temperature control requirements will have concrete slabs directly exposed to the room environment. Since the slabs are installed on earth with year around temperatures of 10 - 13 degC, their surface temperature will be less than the room temperature. The difference can be more than 1 degC without or as low as 0.16 degC with insulation. Depending on the final usage of the high accuracy labs, even small amount of deviation from the set room temperature may be unacceptable.

  In order to eliminate or minimize the slab effect, it was decided jointly by the NIST/HDR team to install a slab conditioning/heating system. The simplest way to accomplish slab heating is with electric heating cables. (In the laboratories in Europe, they also used electric cables with a fixed heating capacity setting.) The other option is the use of hydronic heating. Discussing these options with the NIST scientists, they had concerns about both approaches. With the electric heating the problem is EMI/RFI, with hydronic system the concern is vibration.

  It is not certain that slab conditioning will be necessary for the ATL. However, in order to evaluate the system performance, construction techniques, the effect of the slab conditioning on the room temperature control, EMI/RFI, and potential vibration, it was the joint decision of the NIST/HDR team that both electric and hydronic slab conditioning systems should be installed.

G. Slab Heating Cable

Electric resistance heating cable will be provided in the isolation slab to overcome the heat losses to the earth and to stabilize the temperature of the slab. It is provided, in addition to the hydronic heating system, to determine its heating effectiveness and to determine the RFI/EMI effects. This information will be compared with the hydronic system for preparing a recommendation for the ATL.

Although there is no known hard data on heating cable RF field strength, it is recommended that two conductor cable be used and to maintain a tight spacing to reduce RF effects. Although a certain amount of attenuation or RF energy, on the order of -10 to -15 dB, can be expected from the concrete itself, half of the slab will be provided with a grounded cage around the heating cable to further reduce the field strength. The cage will be constructed of welded copper mesh with wires spaces 50 mm on center. Measurements can be taken with either side of the slab energized to determine the additional attenuation due to the cage.

Because the heating requirement for this application is significantly less than its traditional snow melting applications, the use of standard cables at 120 volts would require excessively long cables compromising bending radiuses and increasing cost and complexity of the installation. Therefore, the cables will be operated at a reduced voltage. The design is based on 24 volt operation. The cables will be controlled by varying the voltage through a variable voltage transformer to reach a steady state condition where the heating cables are energized continuously providing enough heat to equal the heat losses to the soil.

H. Communication

One telephone outlets will be located at the desk in the control area and one outlet within the module near the door. Each outlet will be provided with an empty conduit stub-out to the corridor ceiling space.

A surface mounted raceway will be provided for routing of experimental control circuits (mechanical control circuits will be provided in conduit separately). The raceway will be mounted on three walls of the module 1200 mm AFF. It will be connected to a pullbox at the control room desk with a 32 mm empty conduit. A 32 mm empty conduit will be provided from the pull box to the corridor ceiling space.

Job No [illegible] No

Computation

HDR

Project N I S T - T C M

Computed Z S / R A 1

Date 2/94

Subject I S O L A T I O N S L A B

Checked

Date

Task T H E R M A L T I M E C O N S T A N T C A L C U L A T I O N

Sheet

Of

```
          CALCULATION OF SLAB THERMAL TIME CONSTANT          10-Feb-94
          AT VARIOUS SLAB THICKNESS

T=0.5*d*c*L^2/k


T         TIME CONSTANT           HR                      HR

L         SLAB THICKNESS       0.6 m DESIGN COND       0.91 m  ORIGINAL ASSUMPTION

d         DENSITY             2080 kg/m3              2080 kg/m3

c         SPECIFIC HEAT       1050 Ws/kg*k            1050 Ws/kg*k

k         CONDUCTIVITY        1.04 W/m*K             1.038 W/m*K

T                              105 HRS                 244 HRS
```

Job No. 57575-001-06
No.

Computation

HDR

Project NIST-TCM
Computed ZSIRAI
Date 2/94
Subject ISOLATION SLAB CONDITIONING SYSTEM
Checked
Date
Task REYNOLDS NUMBER CALCULATION
Sheet
Of

```
CALCULATION OF REYNOLDS NUMBER                           10-Feb-94
FOR SLAB HEATING SYSTEM



Re=VD/v

Re            REYNOLDS NUMBER

Re>10000      TURBULENT
Re<2000       LAMINAR

V             VELOCITY                     m/s
D             DIAMETER             0.0158  m
v             VISCOSITY     1.003320E-06   m2/s

          V            Re
        m/s


      0.061           960
      0.122          1920
      0.183          2880
      0.244          3840
      0.305          4800 RECOMMENDED VELOCITY
      0.366          5759
      0.427          6719
      0.488          7679
      0.549          8639
```

Job No 07575-001-06 No

Computation

HDR

Project NIST-TCM | Computed SANDROCK | Date 1/94

Subject ISOLATION SLAB CONDITIONING SYSTEM | Checked | Date

Task SLAB SIZE & HEAT LOSS, HEATER SELECTION | Sheet | Of

ISOLATION SLAB SIZE:

Lab Module :	5250 mm	× 3500 mm (inside clear)
Wall to Slab	−237.5	−237.5
	−237.5	−237.5
	4775	3025

Slab Size = 4775 mm long × 3025 mm wide × 600 mm deep

HEAT LOSS SURFACES:

Slab Bottom : 4.775 m × 3.025 m = 14.44 m²

Long Sides : 4.775 m × 0.6 m (2) = 5.73 m²

Short Sides : 3.025 m × 0.6 m (2) = 3.63 m²

23.8 m²

Assumptions:

Slab is uniform at 20 °C.
Ground is uniform at 12.8 °C.
Insulation Resistance = $34.7 \frac{K\,m}{W}$
(expanded polystyrene)

100 mm insulation $R = 34.7 \frac{K\,m}{W} \times 0.1\,m = 3.47 \frac{K\,m^2}{W}$

Heat Loss $h = U A \Delta t$

$\Delta t_{°C} = \Delta t_K$

$$= 0.288 \frac{W}{K\,m^2} \times 23.8\,m^2 \times (20\,°C - 12.8\,°C)$$

$$= 49.35\ W$$

USE $h = 50\ W$

Indeeco Immersion Cartridge Heater
(smallest brass type unit)
S 751 N011
100 W at 120 V, 1 Ph

Job No. 07575-001-06 No

Computation

HDR

Project NIST - TCM		Computed SANDROCK	Date 1/94
Subject ISOLATION SLAB CONDITIONING SYSTEM		Checked	Date
Task HYDRONIC TUBE & WATER FLOW CALCULATION		Sheet	Of

TUBES REQUIRED: (at 150 mm center-to-center spacing)

$$\frac{4775\,mm}{150\,mm} = 31.83$$

Use even number of tubes for ease of water flow balancing and to allow adequate concrete cover on the end pipes while avoiding conflict with rebar.

Use 30 tubes at 150 mm = 4500 mm

$$4775 - 4500 = 275\,mm \div 2 = 137.5\,mm$$ space on each end

WATER FLOW:

13 mm Wirsbo-hePEX tubing contains 0.114 L/m.
using recommended velocity of 0.305 m/s;

Total Water flow = 0.114 L/m per tube × 0.305 m/s × 30 tubes

$$= 1.043\ L/s$$

Water Temperature Difference:

$$\Delta t = \frac{h}{4.2\ Q} = \frac{0.05\ kW}{(4.2)(1.043\ L/s)}$$

$$\Delta t = 0.0114\ °C$$

No

Computation

HDR

Project TEMP CONTROL MODULE
Subject
Task SLAB HEATING CALCS

Computed DWD
Checked DRE
Sheet 1

Date 1/12/94
Date 3-3-94
Of 1

1. DESIGN LOAD - 63 WATTS
   ∴ 31.5 WATTS PER SECTION

2. VOLTAGE - 24 V (FOR SUCH A SMALL LOAD, 120 V WOULD REQUIRE HIGHER RESISTIVE CABLE PER FOOT THAN IS AVAILABLE AND/OR VERY LONG LENGHTS)

3. MINIMUM TOTAL RESISTANCE $\frac{E^2}{P} = \frac{24^2}{31.5} = 18.3\ \Omega$

4. CABLE LENGTH 42.4 m

5. MAXIMUM CABLE RESISTANCE PER METER $\frac{\Omega}{m} = \frac{18.3\ \Omega}{42.4\ m} = 0.43\ \Omega/m$

6. USE CABLE 19E2 $\Omega/m = 0.41$

7. ACTUAL CABLE RESISTANCE $0.41\ \Omega/m \times 42.4\ m = 17.4\ \Omega$

8. ACTUAL POWER $= \frac{E^2}{R} = \frac{24^2}{17.4} = 33.1\ w > 31.5\ w$ ∴ OK

9. ACTUAL CURRENT $= \frac{E}{R} = \frac{24}{17.4} = 1.34\ A$

IF OPERATED AT 120 V:

ACTUAL POWER $= \frac{E^2}{R} = \frac{120^2}{17.4} = 828\ W \times 2$ CABLES $= 1656\ W$

$1658/42.4\ m = 39.1\ W/m = 11.9\ W/FT < 25$ ∴

ACTUAL CURRENT $= \frac{E}{R} = \frac{120}{17.4} = 6.9\ A \times 2$ CABLES $= 13.8\ A$

∴ 1800 VA, 15 A
VARIABLE VOLTAGE
TRANSFORMER

SECTION 16855

ELECTRIC HEATING CABLES

PART 1 - GENERAL

1.01 DESCRIPTION

A. Related sections:
    1. General requirements: Division 1.
    2. General electrical requirements: Section 16010.

1.02 SUBMITTALS (See Division 1)

A. Shop drawings:
    1. Cables and mats:
        a. Complete cable layout for each area.
        b. Calculations.
        c. Materials list, indicating brand names, types and catalog numbers.

B. Product data.

C. Samples: Not required for COTR review.

D. Project information:
    1. Test reports.

E. Contract closeout information:
    1. Operating and maintenance data.

1.03 JOB CONDITIONS

A. Coordinate layout and installation of system with concrete work; provide Drawings to Contractor for coordination purposes.

PART 2 - PRODUCTS

2.01 MATERIALS -

A. Acceptable manufacturers:
    1. Electric slab heating system:
        a. Base:
            (1) Pyrotenax.
            (2) Nelson.
            (3) Easy-Heat.

B. Electric slab heating system:
  1. Provide minimum of 3.4 watts per square meter of heating.
  2. See Drawings for location and layout of heating cables and auxiliary equipment.

C. Variable voltage transformer:
  1. 120 volt single phase input.
  2. 0-120 volt single phase continuously adjustable output with full AC wave form.
  3. 15 ampere output.
  4. STACO type 1510 or equal.

D. Heating cables: Type MI twin-conductor, providing 33 watts of heating each at 24 volt, single phase operation, Pyrotenax type D/19E2/*/33/24/*/14/Y or equal. Verify length of hot and cold cables with calculations and field conditions.
  1. Include 3 m or longer mineral-insulated cold leads.
  2. Threaded glands: UL approved, with insulated pigtail leads 300 mm long.

PART 3 - EXECUTION

3.01 INSTALLATION

A. Install in accord with manufacturer's instructions and recommendations.

B. Provide technical direction during installation by snow-melting equipment manufacturer.

C. Plan installation so that concrete finish course and first course will be monolithic.

D. Do not splice or shorten heating cables.

E. Do not install heating cables and cold leads across expansion joints.

F. Do not walk on heating cable during installation.

G. Do not energize cable when air temperature is above 40 degF except for a few seconds for testing.

H. Provide separate grounding conductor.

I. Make joints watertight.

Appendix G

Listing of Computer Code for Steady-State Analysis

```
/BATCH
   ! ----------------------------------------------------------------------
   !
   !   Date:   Aug. 21, 1994         Time:   02:15 p.m.
   !
   !   By:   Dr. Jeffrey T. Fong, P.E., Physicist
   !
   !   Applied & Computational Mathematics Division
   !   Computing & Applied Mathematics Laboratory
   !   National Institute of Standards & Technology
   !   Mail Code A238/101, Gaithersburg MD 20899
   !
   !   Tel. (301) 975-2720   Fax:  (301) 975-2128
   !
   !   and   Dr. Stephen J. Treado, Building Environment Div.
   !        BFRL, NIST-Gaithersburg   (301) 975-6444
   !
   ! ----------------------------------------------------------------------
   !
   !   *****  A Mathematical Modeling & Analysis Project  *****
   !
   ! ----------------------------------------------------------------------
   !
   !   Project Title:   NIST-ATL-Temperature Control Test Module -
   !
   !                  Steady State Solution of Temperature Distribution
   !                  in Slab/Pipe/Insulation/Soil Combination (2-dim Model)
   !
   ! ----------------------------------------------------------------------
   !
   !   Filename:  /tmp_mnt/home/fs3c/fong/94821-ca.se3/stdstate
   !
   ! ---------------------------------------------------------------------
   !
   !   What's New:   Case 3:  Air Temp = 21 deg C.  Pipe = 20 C, Soil Temp 3m below = 12.8 C.
   !
! -------------------------------------------------------------------------
   !
/SHOW,file33,stdstate
/FILNAM,stdstate
/TITLE,        C-3: Air 21 C; Pipe 20 C; Soil 3m 12.8 C(Fong-Treado, stdstate)
   !                                                     !Last character
/UNITS,SI
   ! ------------------------------------------------------------------------
/PREP7
   !
ET,1,PLANE55            *ELEMENT TYPE 1 (Concrete) IS STIF55
   !
ET,2,PLANE55            *ELEMENT TYPE 2 (Polyethylene Pipe) IS STIF55
   !
ET,3,PLANE55            *ELEMENT TYPE 3 (Cellular Polystyrene Insulation) IS STIFF55
   !
ET,4,PLANE55            *ELEMENT TYPE 4 (Earth with 42% water) IS STIFF55
   !
KD1=1.818          *KD1 = CONDUCTIVITY OF CONCRETE IN SI UNITS (W/M*DEG.K)
```

```
   !
KD2=0.404            *KD2 = CONDUCTIVITY OF POLYETHYLENE PIPE
   !
KD3=0.0502            *KD3 = CONDUCTIVITY OF POLYSTYRENE INSULATION
   !
KD4=1.073            *KD4 = CONDUCTIVITY OF EARTH WITH 42% WATER
   !
   !
MP,KXX,1,KD1
MP,KYY,1,KD1
   !
MP,KXX,2,KD2
MP,KYY,2,KD2
   !
MP,KXX,3,KD3
MP,KYY,3,KD3
   !
MP,KXX,4,KD4
MP,KYY,4,KD4
   !
BM=2.0             *BM = Film Coefficient for concrete/air interface (W/M*M*DEG.K)
   !
TEM1=21.000           *TEM1 = Temp. in air beyond isolation slab.
   !
TEM2=20.000           *TEM2 = Temp. of water circulating at pipe inner surface.
   !
TEM3=12.800           *TEM3 = Temp. at ground several meters below insulation.
   !
   ! ------------------------------------------------------------------------
CSYS,0         *CSYS,0 = CARTESIAN
   !
HX1=0.150
   !
HY1=0.450
HY2=0.020
HY3=0.030
HY4=0.100
   !
HY5=0.100
   !
HY6=1.000
HY7=2.000
HY8=3.000
HY9=4.000
   !
DX1=0.025
DX2=0.050
   !
DY1=0.005
DY2=0.020
DY3=0.025
DY4=0.050
DY5=0.200
DY6=0.500
DY7=1.000
```

```
DY8=2.000
   !
DR1=0.001
DR2=0.002
   !
RD=0.006              ! RD = inner radius of pipe.
TH=0.002
TH1=0.50*TH
RD1=RD+TH1              ! RD1 = mid-surface of pipe.
RD2=RD+TH              ! RD2 = outer radius of pipe.
   !
NX=12
   !
NY1=9
NY2=1
NY3=6
NY4=4
   !
NY5=4
   !
NY6=4
NY7=4
NY8=3
NY9=2
   !
   !
N,1001,0,0                  *NODE 1001 = ORIGIN.
N,1007,HX1,0
   !
FILL,1001,1007,5,1002,1,1,1,1
   !
   !        LAYER 10 (El. 0.000) GENERATED WITH NODE NUMBER 1001 THRU 1007.
   !
NGEN,10,100,1001,1007,1,0,-DY4,0,1
   !
   !        LAYERS 10 THRU 19 (El. -0.450) GENERATED WITH NODE NUMBERS
   !          1001 THRU 1007, 1101 THRU 1107, ... 1901 THRU 1907.
   !
/USER,1
/VIEW,1,0,0,1           ! WINDOW 1, XV=0, YV=0, ZV=1, THIS IS THE X-Y PLANE
   !
/DIST,1,0.33
/FOCUS,1,0.075,-0.3,0
   !
! /TSPEC,0,,2
/TLABEL,-0.9,0.9,       Steady-State Thermal Analysis of ATL Module
/TLABEL,-0.9,0.86,      ------------------------------------------
!         This is a test1 test2 test3 test4 test5 test6 test7
/TLABEL,-0.9,0.8,       0.6m Slab, 16 pipes, 0.1m Insul. 3m Soil
/TLABEL,-0.9,0.72,        K = 1.818, 0.404, 0.0502, 1.073  W/M*degK
/TLABEL,-0.9,0.64,        Film Coefficient  BM = 2.0  W/M*M*deg.K
!
NPLOT                             ! ----------------------- PLOT NO. 1
!
   !
```

```
NGEN,2,100,1901,1907,1,0,-DY2,0,1
   !
   !         LAYERS 19 THRU 20 (El. -0.470) GENERATED WITH NODE NUMBERS
   !           1901 THRU 1907, 2001 THRU 2007.
   !
NGEN,7,100,2001,2007,1,0,-DY1,0,1
   !
   !         LAYERS 20 THRU 26 (El. -0.500)  GENERATED WITH NODE NUMBERS
   !           2001 THRU 2007, 2101 THRU 2107, ..., 2601 THRU 2607.
   !
   !         CENTER OF PIPE IS LOCATED AT LAYER 23.
   !
   !           NODES 2003, 2004, 2005, 2103, 2104, 2105, ETC.
   !           DOWN TO 2603, 2604, 2605 FORM A BLOCK TO BE
   !           REPLACED BY A BLOCK WITH A PIPE IN IT.
   !
NDELE,2104,2204,100
NDELE,2404,2504,100
   !
/DIST,1,0.1
/FOCUS,1,0.075,-0.485,0
/PNUM,NODE,1
NPLOT                          ! ---------------------- PLOT NO. 2
/PNUM,NODE,0
   !
/DIST,1,0.33
/FOCUS,1,0.075,-0.3,0
NPLOT                          ! ---------------------- PLOT NO. 3
   !
NGEN,5,100,2601,2607,1,0,-DY3,0,1
   !
   !         LAYERS 26 THRU 30 (El. -0.60) GENERATED WITH NODE NUMBERS
   !           2601 THRU 2607, 2701 THRU 2707, ..., 3001 THRU 3007.
   !
   !         ----- END OF CONCRETE SLAB -----
   !
NPLOT                          ! ---------------------- PLOT NO. 4
   !
   !
NGEN,6,100,3001,3007,1,0,-DY2,0,1
   !
   !         LAYERS 30 THRU 35 (El. -0.70) GENERATED WITH NODE NUMBERS
   !           3001 THRU 3007, 3101 THRU 3107, ..., 3501 THRU 3507.
   !
   !         ----- END OF INSULATION -----
   !
   !
/AUTO
NPLOT                          ! ---------------------- PLOT NO. 5
   !
NGEN,6,100,3501,3507,1,0,-DY5,0,1
   !
   !         LAYERS 35 THRU 40 (El. -1.70) GENERATED WITH NODE NUMBERS
   !           3501 THRU 3507, 3601 THRU 3607, ..., 4001 THRU 4007.
   !
```

```
NPLOT                              ! --------------------  PLOT NO. 6
   !
NGEN,5,100,4001,4007,1,0,-DY6,0,1
   !
   !        LAYERS 40 THRU 44 (El. -3.70) GENERATED WITH NODE NUMBERS
   !          4001 THRU 4007, 4101 THRU 4107, ..., 4401 THRU 4407.
   !
NPLOT                              ! --------------------  PLOT NO. 7
   !
! NGEN,4,100,4401,4407,1,0,-DY7,0,1
   !
   !        LAYERS 44 THRU 47 (El. -6.70) GENERATED WITH NODE NUMBERS
   !          4401 THRU 4407, 4501 THRU 4507, ..., 4701 THRU 4707.
   !
! NPLOT                              ! --------------------  PLOT
   !
! NGEN,3,100,4701,4707,1,0,-DY8,0,1
   !
   !        LAYERS 47 THRU 49 (El. -10.70) GENERATED WITH NODE NUMBERS
   !          4701 THRU 4707, 4801 THRU 4807, AND 4901 THRU 4907.
   !
   !        ----- END OF SOIL -----
   !
! NPLOT                              ! -------------------- Plot
   !
N,2010,0.071,-0.470,0
N,2015,0.079,-0.470,0
N,2610,0.071,-0.500,0
N,2615,0.079,-0.500,0
   !
/USER,1
/DIST,1,0.1
/FOCUS,1,0.075,-0.485,0
   !
NPLOT                              ! --------------------  PLOT NO. 8
   !
CS,11,1,2304,2305,2004,1
   !
CSYS,11
   !
N,2315,RD2,0,0
N,2215,RD2,30,0
N,2115,RD2,60,0
N,2104,RD2,90,0
   !
N,2110,RD2,120,0
N,2210,RD2,150,0
N,2310,RD2,180,0
N,2410,RD2,210,0
N,2510,RD2,240,0
N,2504,RD2,270,0
   !
N,2515,RD2,300,0
N,2415,RD2,330,0
   !
```

```
N,2314,RD1,0,0
N,2214,RD1,30,0
N,2114,RD1,60,0
N,2109,RD1,90,0
   !
N,2111,RD1,120,0
N,2211,RD1,150,0
N,2311,RD1,180,0
N,2411,RD1,210,0
N,2511,RD1,240,0
N,2509,RD1,270,0
   !
N,2514,RD1,300,0
N,2414,RD1,330,0
   !
N,2313,RD,0,0
N,2213,RD,30,0
N,2113,RD,60,0
N,2204,RD,90,0
   !
N,2112,RD,120,0
N,2212,RD,150,0
N,2312,RD,180,0
N,2412,RD,210,0
N,2512,RD,240,0
N,2404,RD,270,0
   !
N,2513,RD,300,0
N,2413,RD,330,0
   !
NPLOT                        ! ----------------- PLOT NO. 9
!
! -----------------------------------------------------------------------------
!
TYPE,1                 ! ELEMENT DEFINITION FOR TYPE 1 (CONCRETE SLAB)
MAT,1
!
E,1001,1101,1102,1002        ! ELEMENT NO. 1 DEFINED NEAR ORIGIN.
!
EGEN,6,1,ALL                 ! ELEMENT NOS. 1 THROUGH 6 CREATED
                     !   BETWEEN LEVEL 10 AND 11.
!
EGEN,10,100,1,6,1            ! ELEMENTS 1-6, 7-12, ETC. THRU 55-60 CREATED
                     !   BETWEEN LEVEL 10 (L10) AND 20 (L20).
!
! ------- DEFINITION OF ELEMENTS AROUND PIPE BEGINS
!
E,2001,2101,2102,2002        ! ELEMENT 61 DEFINED.
E,2002,2102,2103,2003        ! ELEMENT 62 DEFINED.
!
EGEN,6,100,61,62,1           ! ELEMENTS 61-62, 63-64, 65-66, 67-68,
                     !   69-70, 71-72 CREATED BETWEEN L20 AND L26.
!
!
E,2010,2110,2104,2004        ! ELEMENT 73 DEFINED.
```

```
E,2003,2103,2110,2010        ! ELEMENT 74 DEFINED.
!
EGEN,6,100,74              ! ELEMENT 74,75,76,77,78,79 CREATED AROUND PIPE.
!
E,2510,2610,2604,2504        ! ELEMENT 80 CREATED BELOW PIPE.
!
!
E,2504,2604,2615,2515        ! ELEMENT 81 CREATED BELOW PIPE.
!
E,2515,2615,2605,2505        ! ELEMENT 82 DEFINED.
!
EGEN,6,-100,82             ! ELEMENT 82,83,84,85,86,87 CREATED AROUND PIPE.
!
E,2004,2104,2115,2015        ! ELEMENT 88 CREATED.
!
!
E,2005,2105,2106,2006        ! ELEMENT NO. 89 DEFINED.
E,2006,2106,2107,2007        ! ELEMENT NO. 90 DEFINED.
!
EGEN,6,100,89,90,1          ! ELEMENTS 89-90, 91-92, ETC. 99-100
                    !    created between L20 AND L26.
!
! -------- DEFINITION OF ELEMENTS AROUND PIPE ENDS
!
! -------- ADDITIONAL ELEMENTS OF CONCRETE SLAB
!
E,2601,2701,2702,2602        ! ELEMENT 101 DEFINED.
!
EGEN,6,1,101               ! ELEMENTS 101-106 DEFINED BETWEEN L26 & L27.
!
EGEN,4,100,101,106,1         ! ELEMENTS 101-106, 107-112, 113-118, 119-124
                    !    CREATED BETWEEN L26 AND L30.
!
/USER,1
/DIST,1,0.33
/FOCUS,1,0.075,-0.3,0
/PNUM,ELEM,1
!
EPLOT                                  ! --- PLOT NO. 10 (SLAB ONLY)
!
! --------- END OF ELEMENT DEFINITION FOR TYPE 1, material 1.
!
!
TYPE,2                    ! ELEMENT TYPE 2 (POLYETHYLENE PIPE)
MAT,2
!
E,2110,2111,2109,2104        ! ELEMENT NO. 125 DEFINED.
E,2210,2211,2111,2110        ! ELEMENT NO. 126 DEFINED.
EGEN,4,100,126              ! ELEMENTS 126,127,128,129 CREATED.
E,2511,2510,2504,2509        ! ELEMENT 130 CREATED.
!
E,2509,2504,2515,2514        ! ELEMENT 131 DEFINED.
E,2514,2515,2415,2414        ! ELEMENT 132 DEFINED.
EGEN,4,-100,132             ! ELEMENTS 132,133,134,135 GENERATED.
E,2104,2109,2114,2115        ! ELEMENT 136 CREATED.
```

```
!
E,2111,2112,2204,2109        ! ELEMENT 137 DEFINED.
E,2211,2212,2112,2111        ! ELEMENT 138 DEFINED.
EGEN,4,100,138             ! ELEMENT 138,139,140,141 CREATED.
E,2512,2511,2509,2404        ! ELEMENT 142 CREATED.
!
E,2404,2509,2514,2513        ! ELEMENT 143 DEFINED.
E,2513,2514,2414,2413        ! ELEMENT 144 DEFINED.
EGEN,4,-100,144            ! ELEMENT 144,145,146,147 CREATED.
E,2109,2204,2113,2114        ! ELEMENT 148 DEFINED.
!
/DIST,1,0.1
/FOCUS,1,0.075,-0.485,0
!
EPLOT                                ! --- PLOT NO. 11 (SLAB + PIPE)
!
/DIST,1,0.03
EPLOT                                ! --- PLOT NO. 12 (PIPE ENLARGED)
!
/DIST,1,0.015
EPLOT                                ! --- PLOT NO. 13 (PIPE ENLARGED)
!
/PNUM,TYPE,1
/DIST,1,0.10
/FOCUS,1,0.075,-0.485,0
!
EPLOT                                ! --- PLOT NO. 14 (SLAB + PIPE)
!
! --------- END OF ELEMENT DEFINITION FOR TYPE 2, material 2 (polyethylene pipe).
!
TYPE,3                  ! ELEMENT DEFINTION FOR TYPE 3 (POLYSTYRENE INSULATION)
MAT,3
!
E,3001,3101,3102,3002        ! ELEMENT NO. 149 DEFINED
!
EGEN,6,1,149               ! ELEMENTS 149 THRU 154 CREATED.
!
EGEN,5,100,149,154,1         ! ELEMENTS 149-154, 155-160, 161-166, 167-172,
                    !    AND 173-178 CREATED BETWEEN L30 AND L35.
!
/PNUM,ELEM,0
/PNUM,TYPE,0
/DIST,1,0.5
/FOCUS,1,0.075,-0.4,0
!
EPLOT                                ! --- PLOT NO. 15 (SLAB+PIPE+INS)
!
! ---------- END OF ELEMENT DEFINTION FOR TYPE 3, material 3 (insulation).
!
TYPE,4
MAT,4
!
E,3501,3601,3602,3502        ! ELEMENT 179 DEFINED.
!
EGEN,6,1,179               ! ELEMENTS 179 THROUGH 184 CREATED.
```

```
!
EGEN,5,100,179,184,1
!                ! ELEMENTS 179-184 BETWEEN L35 AND L36
                 !      185-190 between L36 and L37
                 !      191-196 between L37 and L38
                 !      197-202 between L38 and L39
                 !      203-208 between L39 and L40
!
/DIST,1,0.935
/FOCUS,1,0.075,-0.85,0
!
EPLOT                                ! --- PLOT NO. 16 (SLAB+PIPE+INS+SOIL-1)
!
! -----------------------------------------------------------------------------------
!
!                      208 ELEMENTS IF SOIL DEPTH IS 1.0 METER
!
! -----------------------------------------------------------------------------------
!
EGEN,5,100,203,208,1
                 ! ELEMENTS 203-208 BETWEEN L39 AND L40
                 !      209-214 BETWEEN L40 AND L41
                 !      215-220 between L41 and L42.
                 !      221-226 between L42 and L43.
                 !      227-232 between L43 and L44.
!
/DIST,1,2.3
/FOCUS,1,0.075,-2,0
!
EPLOT                                ! --- PLOT NO. 17 (SLAB+PIPE+INS+SOIL-3)
!
! ------------------------------------------------------------------------------------
!
!                      232 ELEMENTS IF SOIL DEPTH IS 3.0 METERS
!
! ------------------------------------------------------------------------------------
!
! EGEN,4,100,227,232,1
                 ! ELEMENTS 227-232 BETWEEN L43 AND L44.
                 !      233-238 BETWEEN L44 AND L45
                 !      239-244 BETWEEN L45 AND L46
                 !      245-250 BETWEEN L46 AND L47
!
! /DIST,1,4.5
!  /FOCUS,1,0.075,-3.5,0
!
! EPLOT                               ! --- PLOT
!
! -------------------------------------------------------------------------------------
!
!                      250 elements if soil depth is 6.0 meters.
!
! -------------------------------------------------------------------------------------
!
! EGEN,3,100,245,250,1
```

```
                    ! ELEMENTS 245-250 BETWEEN L46 AND L47.
                    !       251-256 BETWEEN L47 AND L48
                    !       257-262 BETWEEN L48 AND L49.
!
! /DIST,1,6.5
! /FOCUS,1,0.075,-5.35,0
!
! EPLOT                                 ! --- PLOT
!
! ----------------------------------------------------------------------------------------------
!
!                     262 elements if soil depth is 10.0 meters
!
! ----------------------------------------------------------------------------------------------
   !
   !
! ----------------------------------------------------------------------------
   !
CSYS,0
   !
NSYM,X,10000,ALL
/AUTO
NPLOT                              ! ----------------- PLOT No.  18
   !
CS,12,0,11007,1001,2304
CSYS,12
NSYM,X,20000,ALL
NPLOT                            !--------------------- PLOT NO. 19
   !
CS,13,0,21007,1001,2304
CSYS,13
NSYM,X,40000,ALL
NPLOT                            ! -------------------- PLOT NO. 20
   !
CS,14,0,41007,1001,2304
CSYS,14
NSYM,X,80000,ALL
NPLOT                            ! --------------------- PLOT NO. 21
   !
/USER,1
/DIST,1,1.7
/FOCUS,1,-1.05,-1.2,0
NPLOT                            !---------------------- PLOT NO. 22
!
! ------------------------------------------------------------------------------
!
!   Nodes for strip 0 have numbers from 1001 to 4407.  Elements number from 1 thru 232.
!
!   Nodes for strip 1 have numbers from 11001 to 14407.
!
!   etc.
!
!   Nodes for strip 15 have numbers from 151001 to 154407
!
! ------------------------------------------------------------------------------
```

```
!
CSYS,0
!
ESYM,,10000,1,232,1                  ! strip 1, elements 233 thru 464.
!
/AUTO
EPLOT                            ! ----------------------- PLOT NO. 23
!
CSYS,12
ESYM,,20000,1,464,1                  ! strips 2 & 3, elements 465 thru 928.
!
EPLOT                            ! ---------------------- PLOT NO. 24
!
CSYS,13
ESYM,,40000,1,928,1                  ! strips 4, 5, 6, 7; elements 929 thru 1856.
!
CSYS,14
ESYM,,80000,1,1856,1                  ! strips 8 thru 15; elements 1857 thru 3712.
!
/USER,1
/DIST,1,3
/FOCUS,1,-1.05,-1.2
!
EPLOT                            ! ----------------------PLOT NO. 25
!
!
/PNUM,TYPE,-1
EPLOT                             ! ------------------- PLOT NO. 26
!
OUTRES,ALL,ALL
OUTPR,ALL,ALL
               ! ------------------------------
               !  Loading condition begins
               ! ------------------------------
               !
               !  1. Convective surface at y = 0, i.e.,
               !      Node 1001 thru 1007
               !
               !  2. Air temp. above y = 0 equals TEM1.
               !
               !
               !  3. Surface temp. at inner surface of pipe = TEM2.
               !
               !  4. Surface temp. at bottom of soil = TEM3.
               !
! ----------------------------------------------------------------------
NSEL,S,NODE,,1001,1007
NSEL,A,NODE,,11001,11007
NSEL,A,NODE,,21001,21007
NSEL,A,NODE,,31001,31007
NSEL,A,NODE,,41001,41007
NSEL,A,NODE,,51001,51007
NSEL,A,NODE,,61001,61007
NSEL,A,NODE,,71001,71007
NSEL,A,NODE,,81001,81007
```

```
NSEL,A,NODE,,91001,91007
NSEL,A,NODE,,101001,101007
NSEL,A,NODE,,111001,111007
NSEL,A,NODE,,121001,121007
NSEL,A,NODE,,131001,131007
NSEL,A,NODE,,141001,141007
NSEL,A,NODE,,151001,151007
!
                    ! ---------------------------------------------
                    ! SELECT ALL NODES FROM 1001 TO 151007 AT Y = 0
SF,ALL,CONV,BM,TEM1      ! CONVECTIVE FACE with temp = TEM1 in air beyond.
ALLSEL,ALL               ! RESELECT ALL TO RETURN TO ORIGINAL STATE.
                    ! ---------------------------------------------
!
!
! ---------------------------------------------------- End of b.c. at top of slab
!
!
!
D,2112,TEMP,TEM2,,2512,100
!
D,2113,TEMP,TEM2,,2513,100
!
                         ! ------------------------------
                         !
D,2204,TEMP,TEM2,,2404,200       ! TEMPERATURE B.C. AT NODES 2112, 2212, 2312, 2412, 2512;
                         !
                         !    2113, 2213, 2313, 2413, 2513;
                         !
                         !    2204, 2404; all at inner surface of pipe
                         !
                         ! ------------------------------
!
D,12112,TEMP,TEM2,,12512,100
D,12113,TEMP,TEM2,,12512,100
D,12204,TEMP,TEM2,,12404,200
!
D,22112,TEMP,TEM2,,22512,100
D,22113,TEMP,TEM2,,22512,100
D,22204,TEMP,TEM2,,22404,200
!
D,32112,TEMP,TEM2,,32512,100
D,32113,TEMP,TEM2,,32512,100
D,32204,TEMP,TEM2,,32404,200
!
D,42112,TEMP,TEM2,,42512,100
D,42113,TEMP,TEM2,,42513,100
D,42204,TEMP,TEM2,,42404,200
!
D,52112,TEMP,TEM2,,52512,100
D,52113,TEMP,TEM2,,52512,100
D,52204,TEMP,TEM2,,52404,200
!
D,62112,TEMP,TEM2,,62512,100
D,62113,TEMP,TEM2,,62512,100
```

```
D,62204,TEMP,TEM2,,62404,200
!
D,72112,TEMP,TEM2,,72512,100
D,72113,TEMP,TEM2,,72512,100
D,72204,TEMP,TEM2,,72404,200
!
D,82112,TEMP,TEM2,,82512,100
D,82113,TEMP,TEM2,,82513,100
D,82204,TEMP,TEM2,,82404,200
!
D,92112,TEMP,TEM2,,92512,100
D,92113,TEMP,TEM2,,92512,100
D,92204,TEMP,TEM2,,92404,200
!
D,102112,TEMP,TEM2,,102512,100
D,102113,TEMP,TEM2,,102512,100
D,102204,TEMP,TEM2,,102404,200
!
D,112112,TEMP,TEM2,,112512,100
D,112113,TEMP,TEM2,,112512,100
D,112204,TEMP,TEM2,,112404,200
!
D,122112,TEMP,TEM2,,122512,100
D,122113,TEMP,TEM2,,122513,100
D,122204,TEMP,TEM2,,122404,200
!
D,132112,TEMP,TEM2,,132512,100
D,132113,TEMP,TEM2,,132512,100
D,132204,TEMP,TEM2,,132404,200
!
D,142112,TEMP,TEM2,,142512,100
D,142113,TEMP,TEM2,,142512,100
D,142204,TEMP,TEM2,,142404,200
!
D,152112,TEMP,TEM2,,152512,100
D,152113,TEMP,TEM2,,152512,100
D,152204,TEMP,TEM2,,152404,200
!
! ---------------------------------- End of b.c. for piping
!
!
D,4401,TEMP,TEM3,,4407,1
D,14401,TEMP,TEM3,,14407,1
D,24401,TEMP,TEM3,,24407,1
D,34401,TEMP,TEM3,,34407,1
D,44401,TEMP,TEM3,,44407,1
D,54401,TEMP,TEM3,,54407,1
D,64401,TEMP,TEM3,,64407,1
D,74401,TEMP,TEM3,,74407,1
D,84401,TEMP,TEM3,,84407,1
D,94401,TEMP,TEM3,,94407,1
D,104401,TEMP,TEM3,,104407,1
D,114401,TEMP,TEM3,,114407,1
D,124401,TEMP,TEM3,,124407,1
D,134401,TEMP,TEM3,,134407,1
```

```
D,144401,TEMP,TEM3,,144407,1
D,154401,TEMP,TEM3,,154407,1
                        ! ------------------------------
                        !
                        ! SOIL TEMP B.C. AT NODES 4401 THRU 4407 (TEMPERATURE = TEM3)
                        !
                        ! ------------------------------
                   ! ------------------------------------------------
F,81007,HEAT,0,,84407,100  ! Heat flow = 0 at x = -2.25 (nodes 81007 to 84407 step 100).
                   ! ------------------------------------------------
!
                   ! ------------------------------------------------
F,1007,HEAT,0,,4407,100  ! Heat flow = 0 at x = 0.150 (nodes 1007 to 4407 step 100)
                   ! ------------------------------------------------
!
                   ! -------------------------------
                   ! Display Mesh Geometry with Boundary Conditions
                   ! -------------------------------
/PBC,ALL,,1
ALLSEL,ALL
/PNUM,NODE,-1
/PNUM,ELEM,-1
!
EPLOT                 ! ---------------------------------PLOT NO. 27
!
/DIST,1,1.0
/FOCUS,1,-1.05,-0.48,0
EPLOT                 ! ---------------------------------PLOT NO. 28
!
/DIST,1,0.5
EPLOT                 ! ---------------------------------PLOT NO. 29
!
/PNUM,ELEM,-1
/DIST,1,1.0
/FOCUS,1,-0.225,-3.0,0
EPLOT                 ! ---------------------------------PLOT NO. 30
ALLSEL,ALL
   !
!
CSYS,0
!
NUMMRG,NODE
!
LSWRITE
!
FINISH                ! END OF PREP7
!
! --------------------------------------------------------------------------------
   !
   !   9.  Solution Phase begins
   !
   ! ----------------------------------------------------------------------------
/SOLU                 ! CALLS ON SOLUTION PHASE OF ANSYS
SOLVE
   ! ----------------------------------------------------------------------------
```

```
    !
    !                               Solution phase ends !!!
    !
    ! -----------------------------------------------------------------------
FINISH              ! END OF SOLUTION PHASE
!
    ! ------------------------------------------------------------------------
    !
    !   10.  Postprocessing Phase
    !
    ! -------------------------------------------------------------------------
/POST1              ! CALLS ON POST1 PHASE OF ANSYS
                ! ---------------------------------------------
/USER,1
/DIST,1,3
/FOCUS,1,-1.05,-1.2
PLNSOL,TEMP          ! ------- Temperature Distribution Plot No. 31
                ! ---------------------------------------------
!
/USER,1
/DIST,1,0.015
/FOCUS,1,0.075,-0.480,0
PLNSOL,TEMP                    ! ----- PLOT NO. 32
!
/DIST,1,0.33
/FOCUS,1,-0.15,-0.3
PLNSOL,TEMP                    ! ----- PLOT NO. 33
!
/DIST,1,0.8
/FOCUS,1,-0.15,-0.2,0
PLNSOL,TEMP                    ! ------ PLOT NO. 34
!
/FOCUS,1,-0.15,-1.0,0
PLNSOL,TEMP                    ! ------ PLOT NO. 35
!
/FOCUS,1,-0.15,-2.0,0
PLNSOL,TEMP                    ! ------- PLOT NO. 36
!
/DIST,1,0.3
/FOCUS,1,-0.15,-3.0,0
PLNSOL,TEMP                    ! ------ PLOT NO. 37
!
/DIST,1,0.5
/FOCUS,1,-0.15,-3.4,0
PLNSOL,TEMP                    ! ------ PLOT NO. 38
!
! ---------------------------------------------------------------------
NEND=40             ! NEND = No. of Points on x-axis for y(x) plot
NEN1=NEND-5
NPL=1               ! NPL = No. of plots using Col 1, Col 2, Col 3, etc.
!
*DIM,VY1,,NEND
!
*DIM,VN1,,NEND
*DIM,VX1,,NEND
```

```
!
VN1(1)=1001
*DO,I,2,NEN1
VN1(I)=VN1(I-1)+100
*ENDDO
!
! ---------------------------------- VX1
*DO,I,1,NEN1
*GET,VX1(I),NODE,VN1(I),LOC,Y
VX1(I)=-VX1(I)
*ENDDO
!
! ---------------------------------- VY1
!
*DO,I,1,NEN1
*GET,VY1(I),NODE,VN1(I),TEMP
*ENDDO
!
NEN2=NEN1+1
*DO,I,NEN2,NEND
VY1(I)=TEM3
VX1(I)=10.6
*ENDDO
!
/OUTPUT,z94821e,101
*DO,I,1,NEND
*STATUS,VY1(I)
*ENDDO
/OUTPUT
!
! -----------------------------------------------------
!   Plot VY1(I) vs. VX1(I)
! ----------------------------------------------------
!
*DIM,zy,table,NEND,NPL
*DIM,zx,table,NEND,1
!
*DO,I,1,NPL
zy(0,I)=I
*ENDDO
!
*DO,I,1,NEND
zy(I,0)=I
zy(I,1)=VY1(I)
*ENDDO
!
zx(0,1)=0
!
*DO,J,1,NEND
zx(J,0)=J
zx(J,1)=VX1(J)
*ENDDO
!
/XRANGE,-1.2,10.8
/AXLAB,X,Depth below Top of Slab (m.)
```

```
        ! maximum label = 30 charac. l
/YRANGE,12.0,22.0
/AXLAB,Y,Temperature (deg. C)
!
! /TLABEL,-0.9,0.9,      Plot of Variables Col 1, Col 2 & Col 3 vs. Time
! /TLABEL,-0.9,0.86,      --------------------------------------------
! /TLABEL,-0.9,0.8,       where Col 1 = Rm Temp +1 deg, 65 min.(blue)
! /TLABEL,-0.9,0.72,            Col 2 = Rm Temp +2 deg, 65 min.(purple)
! /TLABEL,-0.9,0.64,            Col 3 = Rm Temp +1.5deg, 60 min.(red)
!
! /TLABEL,-0.36,-0.27,  Temperature
! /TLABEL,-0.36,-0.35,   Threshold
! /TLABEL,-0.36,-0.43, (0.01 deg. C)
! /TLABEL,-0.46,-0.47, ______________________
!
! /TLABEL,0.5,-0.5, temperature control threshold
! /TLABEL,-0.5,-0.5, __________
! /TLABEL,-0.4,-0.6, __________
! /TLABEL,-0.3,-0.7, __________
!
/USER,1
/DIST,1,0.9
/FOCUS,1,0.40,0.52,0.5
*VPLOT,zx(1,1),zy(1,1)      ! ---------------- PLOT NO. 39 (reduced size)
    ! --------------------------------------------------------------------------
    !
    !                                   Postprocessing phase ends lll
    !
    ! --------------------------------------------------------------------------
FINISH              ! END OF POST1 PHASE
/EXIT
```

Appendix H

Listing of Computer Code for Transient Analysis

```
/BATCH
   ! ------------------------------------------------------------------------
   !
   !   Date:  Aug. 21, 1994          Time:  5:00 p.m.
   !
   !   By:  Dr. Jeffrey T. Fong, P.E., Physicist
   !
   !   Applied & Computational Mathematics Division
   !   Computing & Applied Mathematics Laboratory
   !   National Institute of Standards & Technology
   !   Mail Code A238/101, Gaithersburg MD 20899
   !
   !   Tel. (301) 975-2720   Fax:  (301) 975-2128
   !
   !   and   Dr. Stephen J. Treado, Building Environment Div.
   !        BFRL, NIST-Gaithersburg   (301) 975-6444
   !
   ! ------------------------------------------------------------------------
   !
   !   *****  A Mathematical Modeling & Analysis Project  *****
   !
   ! ------------------------------------------------------------------------
   !
   !          Project Title:  Transient Thermal Analyses of NIST-ATL-
   !                          Temp. Control Test Module using Finite Element Method
   !
   ! ------------------------------------------------------------------------
   !
   !   Filename:  /fs3c/fong/94821-ca.se4/transien
   !
   ! ----------------------------------------------------------------------
   !
   ! 94-08-12-05:00 pm  Apply loading history No. 6 consisting of a rise from 20 to 21 (step function)
   !                    at step 1, and a contant temp. of 21 thereafter for 14 more steps each
   !                    lasting 12 hours, i.e., TDL = 43200 sec.  Number of substeps per step = 1.
   !
   !                    Purpose: To check steady-state solution (surface temperature = 20.345)
   !                    and to estimate time constant for a one-degree rise in room temperature.
   !
   ! ---------------------------------------------------------------------------------------------------
   !
/SHOW,file33,transien
/FILNAM,transien
/TITLE,      4.4: Rm=20|21-- (168 h) P=20 S=12.8(Fong-Treado, transien)
   !
/UNITS,SI
   !
/PREP7                 *Preprocessing Begins (Nodes & Elements generated)
   !
ET,1,PLANE55              *ELEMENT TYPE 1 (Concrete) IS STIF55
ET,2,PLANE55              *ELEMENT TYPE 2 (Polyethylene Pipe) IS STIF55
ET,3,PLANE55              *ELEMENT TYPE 3 (Cellular Polystyrene Insulation) IS STIFF55
ET,4,PLANE55              *ELEMENT TYPE 4 (Earth with 42% water) IS STIFF55
   !
KD1=1.818             *KD1 = CONDUCTIVITY OF CONCRETE IN SI UNIT (W/M*deg.K)
```

```
DS1=2275              *DS1 = DENSITY OF CONCRETE IN SI UNIT (KG/CU.M.)
SHT1=653              *SHT1= SPECIFIC HEAT OF CONCRETE IN SI UNIT (J/KG*deg.K)
   !
KD2=0.404             *KD2 = CONDUCTIVITY OF POLYETHYLENE PIPE
DS2=953
SHT2=550
   !
KD3=0.0502             *KD3 = CONDUCTIVITY OF POLYSTYRENE INSULATION
DS3=42.5
SHT3=1220
   !
KD4=1.073             *KD4 = CONDUCTIVITY OF EARTH WITH 42% WATER
DS4=1730
SHT4=920
   !
   !
MP,KXX,1,KD1
MP,KYY,1,KD1
MP,DENS,1,DS1
MP,C,1,SHT1
   !
MP,KXX,2,KD2
MP,KYY,2,KD2
MP,DENS,2,DS2
MP,C,2,SHT2
   !
MP,KXX,3,KD3
MP,KYY,3,KD3
MP,DENS,3,DS3
MP,C,3,SHT3
   !
MP,KXX,4,KD4
MP,KYY,4,KD4
MP,DENS,4,DS4
MP,C,4,SHT4
   !
BM=2.0               *BM = Film Coefficient for concrete/air interface (W/M*M*DEG.K)
   !
TEM1=20.000            *TEM1 = Temp. in air beyond isolation slab at beginning of load cycle.
   !
TEM2=20.000            *TEM2 = Temp. at inner surface of all polyethylene pipes.
   !
TEM3=12.800            *TEM3 = Temp. at ground several meters below insulation.
   !
      ! -----------------------------------------------------------
      !
      !
      !    Parameters for Transient Loadings  (Variable prefixed with V is a vector)
      !
      !
   ! ----------------------------------------------------------------------
   !
*DIM,VTIM,,100              ! VTIM = Time vector as a function of load step number.
*DIM,VTEM,,100              ! VTEM = Bulk Air Temperature as a function of load step.
!
```

```
!
VTIM(1)=1.0
TDL=43200.0              ! TDL = Time step size
!
NLST=15                      ! NLST = No. of Last time step
!
*DO,I,2,NLST                 ! ------------------------------- First do loop
!
VTIM(I)=VTIM(I-1)+TDL
!
*ENDDO                       ! ------------------------ End of First do loop
!
!
VTEM(1)=TEM1
ADL=1.0                      ! ADL = Bulk Air Temperature Change (deg. C)
!
VTEM(2)=VTEM(1)+ADL
!
*DO,I,3,NLST       ! -------------------------------- Second do loop
!
VTEM(I)=VTEM(I-1)
!
*ENDDO                       ! ------------------------- End of Second do loop
!
   ! ----------------------------------------------------------------------
   !
   !   Preprocessing-1  (Node Definition)
   !
   ! ----------------------------------------------------------------------
   !
CSYS,0          *CSYS,0 = CARTESIAN
   !
HX1=0.150
   !
HY1=0.450
HY2=0.020
HY3=0.030
HY4=0.100
   !
HY5=0.100
   !
HY6=1.000
HY7=2.000
HY8=3.000
HY9=4.000
   !
DX1=0.025
DX2=0.050
   !
DY1=0.005
DY2=0.020
DY3=0.025
DY4=0.050
DY5=0.200
DY6=0.500
```

```
DY7=1.000
DY8=2.000
   !
DR1=0.001
DR2=0.002
   !
RD=0.006             ! RD = inner radius of pipe.
TH=0.002
TH1=0.50*TH
RD1=RD+TH1              ! RD1 = mid-surface of pipe.
RD2=RD+TH              ! RD2 = outer radius of pipe.
   !
NX=12
   !
NY1=9
NY2=1
NY3=6
NY4=4
   !
NY5=4
   !
NY6=4
NY7=4
NY8=3
NY9=2
   !
N,1001,0,0                 *NODE 1001 = ORIGIN.
N,1007,HX1,0
   !
FILL,1001,1007,5,1002,1,1,1,1
   !
   !       LAYER 10 GENERATED WITH NODE NUMBER 1001 THRU 1007.
   !
NGEN,10,100,1001,1007,1,0,-DY4,0,1
   !
   !       LAYERS 10 THRU 19 GENERATED WITH NODE NUMBERS
   !         1001 THRU 1007, 1101 THRU 1107, ... 1901 THRU 1907.
   !
/USER,1
/VIEW,1,0,0,1           ! WINDOW 1, XV=0, YV=0, ZV=1, THIS IS THE X-Y PLANE
   !
/DIST,1,0.33
/FOCUS,1,0.075,-0.3,0
   !
/TLABEL,-0.9,0.9,       Transient Thermal Anal. - ATL Test Module
/TLABEL,-0.9,0.86,      ----------------------------------------
/TLABEL,-0.9,0.8,       0.6m Slab, 16 pipes, 0.1m Insul., 3m Soil
/TLABEL,-0.9,0.72,        K = 1.818, 0.404, 0.0502, 1.073  W/M*deg.K
/TLABEL,-0.9,0.64,        BM=2.0 W/MMdeg.K; 1 deg rise holdtime = 168 h
!
NPLOT                            ! ----------------------- PLOT NO. 1
   !
NGEN,2,100,1901,1907,1,0,-DY2,0,1
   !       LAYERS 19 THRU 20 GENERATED WITH NODE NUMBERS
   !         1901 THRU 1907, 2001 THRU 2007.
```

```
   !
NGEN,7,100,2001,2007,1,0,-DY1,0,1
   !        LAYERS 20 THRU 26 GENERATED WITH NODE NUMBERS
   !          2001 THRU 2007, 2101 THRU 2107, ..., 2601 THRU 2607.
   !
   !        CENTER OF PIPE IS LOCATED AT LAYER 23.
   !
   !          NODES 2003, 2004, 2005, 2103, 2104, 2105, ETC.
   !          DOWN TO 2603, 2604, 2605 FORM A BLOCK TO BE
   !          REPLACED BY A BLOCK WITH A PIPE IN IT.
   !
NDELE,2104,2204,100
NDELE,2404,2504,100
   !
/DIST,1,0.1
/FOCUS,1,0.075,-0.485,0
/PNUM,NODE,1
NPLOT                          ! ---------------------- PLOT NO. 2
/PNUM,NODE,0
   !
/DIST,1,0.33
/FOCUS,1,0.075,-0.3,0
NPLOT                          ! ---------------------- PLOT NO. 3
   !
NGEN,5,100,2601,2607,1,0,-DY3,0,1
   !        LAYERS 26 THRU 30 GENERATED WITH NODE NUMBERS
   !          2601 THRU 2607, 2701 THRU 2707, ..., 3001 THRU 3007.
   !
   !        ----- END OF CONCRETE SLAB -----
   !
NPLOT                          ! ---------------------- PLOT NO. 4
   !
   !
NGEN,6,100,3001,3007,1,0,-DY2,0,1
   !
   !        LAYERS 30 THRU 35 GENERATED WITH NODE NUMBERS
   !          3001 THRU 3007, 3101 THRU 3107, ..., 3501 THRU 3507.
   !
   !        ----- END OF INSULATION -----
   !
/AUTO
NPLOT                          ! ---------------------- PLOT NO. 5
   !
NGEN,6,100,3501,3507,1,0,-DY5,0,1
   !
   !        LAYERS 35 THRU 40 GENERATED WITH NODE NUMBERS
   !          3501 THRU 3507, 3601 THRU 3607, ..., 4001 THRU 4007.
   !
NPLOT                          ! --------------------- PLOT NO. 6
   !
NGEN,5,100,4001,4007,1,0,-DY6,0,1
   !
   !        LAYERS 40 THRU 44 GENERATED WITH NODE NUMBERS
   !          4001 THRU 4007, 4101 THRU 4107, ..., 4401 THRU 4407.
   !
```

```
NPLOT                          ! -------------------- PLOT NO. 7
   !
! NGEN,4,100,4401,4407,1,0,-DY7,0,1
   !
   !        LAYERS 44 THRU 47 GENERATED WITH NODE NUMBERS
   !          4401 THRU 4407, 4501 THRU 4507, ..., 4701 THRU 4707.
   !
! NPLOT                          ! -------------------- PLOT
   !
! NGEN,3,100,4701,4707,1,0,-DY8,0,1
   !
   !        LAYERS 47 THRU 49 GENERATED WITH NODE NUMBERS
   !          4701 THRU 4707, 4801 THRU 4807, AND 4901 THRU 4907.
   !
   !        ----- END OF SOIL -----
   !
! NPLOT                          ! -------------------- PLOT
   !
N,2010,0.071,-0.470,0
N,2015,0.079,-0.470,0
N,2610,0.071,-0.500,0
N,2615,0.079,-0.500,0
   !
/USER,1
/DIST,1,0.1
/FOCUS,1,0.075,-0.485,0
   !
NPLOT                          ! -------------------- PLOT NO. 8
   !
CS,11,1,2304,2305,2004,1
   !
CSYS,11
   !
N,2315,RD2,0,0
N,2215,RD2,30,0
N,2115,RD2,60,0
N,2104,RD2,90,0
   !
N,2110,RD2,120,0
N,2210,RD2,150,0
N,2310,RD2,180,0
N,2410,RD2,210,0
N,2510,RD2,240,0
N,2504,RD2,270,0
   !
N,2515,RD2,300,0
N,2415,RD2,330,0
   !
N,2314,RD1,0,0
N,2214,RD1,30,0
N,2114,RD1,60,0
N,2109,RD1,90,0
   !
N,2111,RD1,120,0
N,2211,RD1,150,0
```

```
N,2311,RD1,180,0
N,2411,RD1,210,0
N,2511,RD1,240,0
N,2509,RD1,270,0
   !
N,2514,RD1,300,0
N,2414,RD1,330,0
   !
N,2313,RD,0,0
N,2213,RD,30,0
N,2113,RD,60,0
N,2204,RD,90,0
   !
N,2112,RD,120,0
N,2212,RD,150,0
N,2312,RD,180,0
N,2412,RD,210,0
N,2512,RD,240,0
N,2404,RD,270,0
   !
N,2513,RD,300,0
N,2413,RD,330,0
   !
NPLOT                          ! PLOT NO. 9
!
! ----------------------------------------------------------------------------------------
!
!   Preprocessing-2   Element Definition
!
! ----------------------------------------------------------------------------------------
!
TYPE,1                 ! ELEMENT DEFINITION FOR TYPE 1 (CONCRETE SLAB)
MAT,1
!
E,1001,1101,1102,1002        ! ELEMENT NO. 1 DEFINED NEAR ORIGIN.
!
EGEN,6,1,ALL               ! ELEMENT NOS. 1 THROUGH 6 CREATED
                  !   BETWEEN LEVEL 10 AND 11.
!
EGEN,10,100,1,6,1            ! ELEMENTS 1-6, 7-12, ETC. THRU 55-60 CREATED
                  !   BETWEEN LEVEL 10 (L10) AND 20 (L20).
!
! ------- DEFINITION OF ELEMENTS AROUND PIPE BEGINS
!
E,2001,2101,2102,2002        ! ELEMENT 61 DEFINED.
E,2002,2102,2103,2003        ! ELEMENT 62 DEFINED.
!
EGEN,6,100,61,62,1           ! ELEMENTS 61-62, 63-64, 65-66, 67-68,
                  !   69-70, 71-72 CREATED BETWEEN L20 AND L26.
!
!
E,2010,2110,2104,2004        ! ELEMENT 73 DEFINED.
E,2003,2103,2110,2010        ! ELEMENT 74 DEFINED.
!
EGEN,6,100,74              ! ELEMENT 74,75,76,77,78,79 CREATED AROUND PIPE.
```

```
!
E,2510,2610,2604,2504          ! ELEMENT 80 CREATED BELOW PIPE.
!
!
E,2504,2604,2615,2515          ! ELEMENT 81 CREATED BELOW PIPE.
!
E,2515,2615,2605,2505          ! ELEMENT 82 DEFINED.
!
EGEN,6,-100,82               ! ELEMENT 82,83,84,85,86,87 CREATED AROUND PIPE.
!
E,2004,2104,2115,2015          ! ELEMENT 88 CREATED.
!
!
E,2005,2105,2106,2006          ! ELEMENT NO. 89 DEFINED.
E,2006,2106,2107,2007          ! ELEMENT NO. 90 DEFINED.
!
EGEN,6,100,89,90,1            ! ELEMENTS 89-90, 91-92, ETC. 99-100
                    !    created between L20 AND L26.
!
! -------- DEFINITION OF ELEMENTS AROUND PIPE ENDS
!
! -------- ADDITIONAL ELEMENTS OF CONCRETE SLAB
!
E,2601,2701,2702,2602          ! ELEMENT 101 DEFINED.
!
EGEN,6,1,101                  ! ELEMENTS 101-106 DEFINED BETWEEN L26 & L27.
!
EGEN,4,100,101,106,1           ! ELEMENTS 101-106, 107-112, 113-118, 119-124
                    !    CREATED BETWEEN L26 AND L30.
!
/USER,1
/DIST,1,0.33
/FOCUS,1,0.075,-0.3,0
/PNUM,ELEM,1
!
EPLOT                                    ! --- PLOT NO. 10 (SLAB ONLY)
!
! --------- END OF ELEMENT DEFINITION FOR TYPE 1.
!
TYPE,2                      ! ELEMENT TYPE 2 (POLYETHYLENE PIPE)
MAT,2
!
E,2110,2111,2109,2104          ! ELEMENT NO. 125 DEFINED.
E,2210,2211,2111,2110          ! ELEMENT NO. 126 DEFINED.
EGEN,4,100,126               ! ELEMENTS 126,127,128,129 CREATED.
E,2511,2510,2504,2509          ! ELEMENT 130 CREATED.
!
E,2509,2504,2515,2514          ! ELEMENT 131 DEFINED.
E,2514,2515,2415,2414          ! ELEMENT 132 DEFINED.
EGEN,4,-100,132              ! ELEMENTS 132,133,134,135 GENERATED.
E,2104,2109,2114,2115          ! ELEMENT 136 CREATED.
!
!
E,2111,2112,2204,2109          ! ELEMENT 137 DEFINED.
E,2211,2212,2112,2111          ! ELEMENT 138 DEFINED.
```

```
EGEN,4,100,138              ! ELEMENT 138,139,140,141 CREATED.
E,2512,2511,2509,2404        ! ELEMENT 142 CREATED.
!
E,2404,2509,2514,2513        ! ELEMENT 143 DEFINED.
E,2513,2514,2414,2413        ! ELEMENT 144 DEFINED.
EGEN,4,-100,144             ! ELEMENT 144,145,146,147 CREATED.
E,2109,2204,2113,2114        ! ELEMENT 148 DEFINED.
!
/DIST,1,0.1
/FOCUS,1,0.075,-0.485,0
!
EPLOT                                ! --- PLOT NO. 11 (SLAB + PIPE)
!
/DIST,1,0.03
EPLOT                                ! --- PLOT NO. 12 (PIPE ENLARGED)
!
/DIST,1,0.015
EPLOT                                ! --- PLOT NO. 13 (PIPE ENLARGED)
!
/PNUM,TYPE,1
/DIST,1,0.10
/FOCUS,1,0.075,-0.485,0
!
EPLOT                                ! --- PLOT NO. 14 (SLAB + PIPE)
!
! --------- END OF ELEMENT DEFINITION FOR TYPE 2.
!
TYPE,3                   ! ELEMENT DEFINTION FOR TYPE 3 (POLYSTYRENE INSULATION)
MAT,3
!
E,3001,3101,3102,3002        ! ELEMENT NO. 149 DEFINED
!
EGEN,6,1,149                ! ELEMENTS 149 THRU 154 CREATED.
!
EGEN,5,100,149,154,1         ! ELEMENTS 149-154, 155-160, 161-166, 167-172,
                     !    AND 173-178 CREATED BETWEEN L30 AND L35.
!
/PNUM,ELEM,0
/PNUM,TYPE,0
/DIST,1,0.5
/FOCUS,1,0.075,-0.4,0
!
EPLOT                                ! --- PLOT NO. 15 (SLAB+PIPE+INS)
!
! ---------- END OF ELEMENT DEFINTION FOR TYPE 3 (INSULATION).
!
TYPE,4
MAT,4
!
E,3501,3601,3602,3502        ! ELEMENT 179 DEFINED.
!
EGEN,6,1,179                ! ELEMENTS 179 THROUGH 184 CREATED.
!
EGEN,5,100,179,184,1
!                     ! ELEMENTS 179-184 BETWEEN L35 AND L36
```

```
                        !       185-190 between L36 and L37
                        !       191-196 between L37 and L38
                        !       197-202 between L38 and L39
                        !       203-208 between L39 and L40
!
/DIST,1,0.935
/FOCUS,1,0.075,-0.85,0
!
EPLOT                                     ! --- PLOT NO. 16 (SLAB+PIPE+INS+SOIL-1)
!
! -----------------------------------------------------------------------------------------------
!
!                            208 ELEMENTS IF SOIL DEPTH IS 1.0 METER
!
! -----------------------------------------------------------------------------------------------
!
EGEN,5,100,203,208,1
                        ! ELEMENTS 203-208 BETWEEN L39 AND L40
                        !       209-214 BETWEEN L40 AND L41
                        !       215-220 between L41 and L42.
                        !       221-226 between L42 and L43.
                        !       227-232 between L43 and L44.
!
/DIST,1,2.3
/FOCUS,1,0.075,-2,0
EPLOT                                     ! --- PLOT NO. 17 (SLAB+PIPE+INS+SOIL-3)
! -----------------------------------------------------------------------------------------------
!                            232 ELEMENTS IF SOIL DEPTH IS 3.0 METERS
! -----------------------------------------------------------------------------------------------
! EGEN,4,100,227,232,1
                        ! ELEMENTS 227-232 BETWEEN L43 AND L44.
                        !       233-238 BETWEEN L44 AND L45
                        !       239-244 BETWEEN L45 AND L46
                        !       245-250 BETWEEN L46 AND L47
!
! /DIST,1,4.5
!  /FOCUS,1,0.075,-3.5,0
! EPLOT                                     ! --- PLOT
! -----------------------------------------------------------------------------------------------
!                            250 elements if soil depth is 6.0 meters.
! -----------------------------------------------------------------------------------------------
!
! EGEN,3,100,245,250,1
                        ! ELEMENTS 245-250 BETWEEN L46 AND L47.
                        !       251-256 BETWEEN L47 AND L48
                        !       257-262 BETWEEN L48 AND L49.
!
! /DIST,1,6.5
! /FOCUS,1,0.075,-5.35,0
!
! EPLOT                                     ! --- PLOT
!
! -----------------------------------------------------------------------------------------------
!
!                            262 elements if soil depth is 10.0 meters
```

```
!
! ------------------------------------------------------------------------------------------------------------
   !
! ---------------------------------------------------------------------------
!
!   Preprocessing-3 (Additional Nodes & Elements via Symmetry Commands)
!
! ---------------------------------------------------------------------------
   !
   ! Change back to rectangular coordinates in order to use symmetry to add nodes
CSYS,0
   !
NSYM,X,10000,ALL
/auto
NPLOT                          ! ---------------------PLOT No.  18
   !
CS,12,0,11007,1001,2304
CSYS,12
NSYM,X,20000,ALL
NPLOT                          !-------------------- PLOT NO. 19
   !
CS,13,0,21007,1001,2304
CSYS,13
NSYM,X,40000,ALL
NPLOT                          ! ------------------- PLOT NO. 20
   !
CS,14,0,41007,1001,2304
CSYS,14
NSYM,X,80000,ALL
NPLOT                          ! -------------------- PLOT NO. 21
   !
/USER,1
/DIST,1,1.7
/FOCUS,1,-1.05,-1.2,0
NPLOT                          !--------------------- PLOT NO. 22
!
! ---------------------------------------------------------------------------------
!
!   Nodes for strip 0 have numbers from 1001 to 4407.  Elements number from 1 thru 232.
!   Nodes for strip 1 have numbers from 11001 to 14407.
!        etc.
!   Nodes for strip 15 have numbers from 151001 to 154407
!
! ---------------------------------------------------------------------------------
!
CSYS,0
!
ESYM,,10000,1,232,1                 ! strip 1, elements 233 thru 464.
!
/AUTO
EPLOT                          ! ----------------------- PLOT NO. 23
!
CSYS,12
ESYM,,20000,1,464,1                 ! strips 2 & 3, elements 465 thru 928.
EPLOT                          ! ---------------------- PLOT NO. 24
```

```
!
CSYS,13
ESYM,,40000,1,928,1                  ! strips 4, 5, 6, 7; elements 929 thru 1856.
!
CSYS,14
ESYM,,80000,1,1856,1                  ! strips 8 thru 15; elements 1857 thru 3712.
!
CSYS,0
!
/USER,1
/DIST,1,3
/FOCUS,1,-1.05,-1.2
EPLOT                        ! ----------------------PLOT NO. 25
!
NUMMRG,NODE
SAVE
FINISH          ! End of PREP7
!
   ! --------------------------------------------------------------------------
   !
   !   Solution Phase and Postprocessing
   !
   ! --------------------------------------------------------------------------
             !
/SOLU         ! CALLS ON SOLUTION PHASE OF ANSYS
             !
ANTYPE,TRANS
TRNOPT,FULL
!
OUTRES,ALL,ALL
OUTPR,ALL,ALL
!
! ---------- Use Steady-State Solution as Initial Conditions ----------------------------------------
TIMINT,OFF
!
TIME,VTIM(1)                   ! Time at end of load step 1.  Choose small value
!                                to simulate initial conditions
!
D,2112,TEMP,TEM2,,2512,100
!
D,2113,TEMP,TEM2,,2513,100
!
                    ! ------------------------------
                    !
D,2204,TEMP,TEM2,,2404,200      ! TEMPERATURE B.C. AT NODES 2112, 2212, 2312, 2412, 2512;
                    !
                    !    2113, 2213, 2313, 2413, 2513;
                    !
                    !    2204, 2404; all at inner surface of pipe
                    !
                    ! ------------------------------
!
D,12112,TEMP,TEM2,,12512,100
D,12113,TEMP,TEM2,,12512,100
D,12204,TEMP,TEM2,,12404,200
```

```
!
D,22112,TEMP,TEM2,,22512,100
D,22113,TEMP,TEM2,,22512,100
D,22204,TEMP,TEM2,,22404,200
!
D,32112,TEMP,TEM2,,32512,100
D,32113,TEMP,TEM2,,32512,100
D,32204,TEMP,TEM2,,32404,200
!
D,42112,TEMP,TEM2,,42512,100
D,42113,TEMP,TEM2,,42513,100
D,42204,TEMP,TEM2,,42404,200
!
D,52112,TEMP,TEM2,,52512,100
D,52113,TEMP,TEM2,,52512,100
D,52204,TEMP,TEM2,,52404,200
!
D,62112,TEMP,TEM2,,62512,100
D,62113,TEMP,TEM2,,62512,100
D,62204,TEMP,TEM2,,62404,200
!
D,72112,TEMP,TEM2,,72512,100
D,72113,TEMP,TEM2,,72512,100
D,72204,TEMP,TEM2,,72404,200
!
D,82112,TEMP,TEM2,,82512,100
D,82113,TEMP,TEM2,,82513,100
D,82204,TEMP,TEM2,,82404,200
!
D,92112,TEMP,TEM2,,92512,100
D,92113,TEMP,TEM2,,92512,100
D,92204,TEMP,TEM2,,92404,200
!
D,102112,TEMP,TEM2,,102512,100
D,102113,TEMP,TEM2,,102512,100
D,102204,TEMP,TEM2,,102404,200
!
D,112112,TEMP,TEM2,,112512,100
D,112113,TEMP,TEM2,,112512,100
D,112204,TEMP,TEM2,,112404,200
!
D,122112,TEMP,TEM2,,122512,100
D,122113,TEMP,TEM2,,122513,100
D,122204,TEMP,TEM2,,122404,200
!
D,132112,TEMP,TEM2,,132512,100
D,132113,TEMP,TEM2,,132512,100
D,132204,TEMP,TEM2,,132404,200
!
D,142112,TEMP,TEM2,,142512,100
D,142113,TEMP,TEM2,,142512,100
D,142204,TEMP,TEM2,,142404,200
!
D,152112,TEMP,TEM2,,152512,100
D,152113,TEMP,TEM2,,152512,100
```

```
D,152204,TEMP,TEM2,,152404,200
!
! ---------------------------------- end of b.c. for piping (temperature = TEM2)
!
!
!
NSEL,S,NODE,,4401,4407,1
NSEL,A,NODE,,14401,14407,1
NSEL,A,NODE,,24401,24407,1
NSEL,A,NODE,,34401,34407,1
NSEL,A,NODE,,44401,44407,1
NSEL,A,NODE,,54401,54407,1
NSEL,A,NODE,,64401,64407,1
NSEL,A,NODE,,74401,74407,1
NSEL,A,NODE,,84401,84407,1
NSEL,A,NODE,,94401,94407,1
NSEL,A,NODE,,104401,104407,1
NSEL,A,NODE,,114401,114407,1
NSEL,A,NODE,,124401,124407,1
NSEL,A,NODE,,134401,134407,1
NSEL,A,NODE,,144401,144407,1
NSEL,A,NODE,,154401,154407,1
!
D,ALL,TEMP,TEM3
ALLSEL,ALL,NODE
                          ! --------------------------------
                          !
                          ! SOIL TEMP B.C. AT NODES 4401 THRU 4407 (TEMPERATURE = TEM3)
                          !
                          ! --------------------------------
                    ! ----------------------------------------------------
F,81007,HEAT,0,,84407,100  ! Heat flow = 0 at x = -2.25 (nodes 81001 to 84401 step 100).
                    ! ----------------------------------------------------
!
                    ! ----------------------------------------------------
F,1007,HEAT,0,,4407,100  ! Heat flow = 0 at x = 0.150 (nodes 1007 to 4407 step 100)
                    ! ----------------------------------------------------
!
NSEL,S,NODE,,1001,1007
NSEL,A,NODE,,11001,11007
NSEL,A,NODE,,21001,21007
NSEL,A,NODE,,31001,31007
NSEL,A,NODE,,41001,41007
NSEL,A,NODE,,51001,51007
NSEL,A,NODE,,61001,61007
NSEL,A,NODE,,71001,71007
NSEL,A,NODE,,81001,81007
NSEL,A,NODE,,91001,91007
NSEL,A,NODE,,101001,101007
NSEL,A,NODE,,111001,111007
NSEL,A,NODE,,121001,121007
NSEL,A,NODE,,131001,131007
NSEL,A,NODE,,141001,141007
NSEL,A,NODE,,151001,151007
!
```

```
               ! ---------------------------------------------
               ! SELECT ALL NODES FROM 1001 TO 151007 AT Y = 0
SF,ALL,CONV,BM,VTEM(1)  ! CONVECTIVE FACE with temp = VTEM(1)  in air beyond.
ALLSEL,ALL,NODE         ! RESELECT ALL TO RETURN TO ORIGINAL STATE.
               ! ---------------------------------------------
                       !
/PBC,TEMP,,1
/PBC,HEAT,,1
!
EPLOT                         ! PLOT NO. 26
!
ESEL,S,ELEM,,1,3712,1
/PNUM,ELEM,-1
EPLOT                         ! PLOT NO. 27 (LOADING CONDITIONS)
ALLSEL,ALL,ELEM
!
LSWRITE
   !
   ! --------------------------Transient Loadings --------------------------
   !
! ------------------------------ Time steps No. 2 to NLST -------------------
!
*DO,I,2,NLST                                   ! ---------- 4th do loop begins
!
TIMINT,ON
DELTIM,TDL,,,OFF
NSUBST,1,,,ON      ! NSUBST,NSBSTP,NSBMX,NSBMN,Carry
                   !  where NSBSTP = No. of substeps for this step
            !
            ! Carry  ON = Use final time step from previous load step as the starting time step
            !        OFF = Use NSBSTP to define time step at start of each load step
      !
KBC,1           ! KBC,0 = ramp function from step I-1 to step I
            ! KBC,1 = step function from first substep of step I to values of step I
!
TIME,VTIM(I)
!
NSEL,S,NODE,,1001,1007
NSEL,A,NODE,,11001,11007
NSEL,A,NODE,,21001,21007
NSEL,A,NODE,,31001,31007
NSEL,A,NODE,,41001,41007
NSEL,A,NODE,,51001,51007
NSEL,A,NODE,,61001,61007
NSEL,A,NODE,,71001,71007
NSEL,A,NODE,,81001,81007
NSEL,A,NODE,,91001,91007
NSEL,A,NODE,,101001,101007
NSEL,A,NODE,,111001,111007
NSEL,A,NODE,,121001,121007
NSEL,A,NODE,,131001,131007
NSEL,A,NODE,,141001,141007
NSEL,A,NODE,,151001,151007
!
SFDELE,ALL,CONV
```

```
!
                ! ---------------------------------------------
                ! SELECT ALL NODES FROM 1001 TO 151007 AT Y = 0
SF,ALL,CONV,BM,VTEM(I)   ! CONVECTIVE FACE with temp = VTEM(I) in air beyond.
ALLSEL,ALL,NODE          ! RESELECT ALL TO RETURN TO ORIGINAL STATE.
                ! ---------------------------------------------
                      !
LSWRITE
!
*ENDDO                                  ! ------------- 4th do loop ends
!
! ------------------------- End of load step specification ---------------------
!
SAVE
LSSOLVE,1,NLST,1
!
FINISH
!
!
  ! ----------------------------------------------------------------------
  !
  !     Postprocessing Phase begins
  !
  ! ----------------------------------------------------------------------
!
                ! ---------------------------------------------
/POST1             ! CALLS ON POST1 PHASE OF ANSYS
                ! ---------------------------------------------
!
! ---------------------------------------------------------------------
/USER,1
/DIST,1,3
/FOCUS,1,-1.05,-1.2
!
*DO,I,1,NLST                            ! --------------- 5th do loop begins
!
SET,I
!
PLNSOL,TEMP          ! Temperature Distribution PLOT NO. 27+I
!
PRNSOL,TEMP
  !
*ENDDO
!
FINISH             ! END OF POST1 PHASE
/EXIT
  ! ----------------------------------------------------------------------
```