TEMPERATURE DISTRIBUTIONS AND EFFECTS OF HEAT APPLIED TO PLANT STEMS

Thesis for the Degree of Ph. D.
MICHIGAN STATE UNIVERSITY
CARL HENRY THOMAS
1969

This is to certify that the

thesis entitled

TEMPERATURE DISTRIBUTIONS AND EFFECTS OF
HEAT APPLIED TO PLANT STEMS

presented by

Carl H. Thomas

has been accepted towards fulfillment
of the requirements for

Ph.D. degree in Agr. Eng.

F.W. Bakker-Arkema
Major professor

Date August 19, 1969

O-169

ABSTRACT

TEMPERATURE DISTRIBUTIONS AND EFFECTS
OF HEAT APPLIED TO PLANT STEMS

by

Carl H. Thomas

The objectives of this investigation were the determination of the response of a plant stem exposed to a high temperature environment and the development of an expression for the prediction of the temperature distribution in the stem. The findings will be useful for improving recommendations involving the use of flame and electric heating for such processes as the control of weeds in crops, the burning of leaves from sugar cane and foliage from potatoes, the defoliating of cotton plants, and the rapid drying of biological materials.

Expressions for predicting the temperature distribution in plant stems exposed to a suddenly changing temperature environment were developed and solved numerically by finite-differences using a digital computer. the analysis accounted for the change in the physical properties due to a change in the temperature and moisture content.

It was found that the cell tissue of corn stems is killed by approximately 60 degree-seconds of heat exposure above 130°F. Therefore, a high temperature heat for a short time does not necessarily result in tissue damage at a critical depth.

A parametric study showed that the diameter of the stem is the most important factor to be considered when applying heat to that part

of a plant. This offers the possibility of selectivity for killing weeds of small diameter without causing critical damage to the crops with stems of larger diameter.

The stem of a living plant has a very complex structure with properties that are difficult to describe for use in engineering analyses. The properties change with changes in their environment and are not reversible. Wide variations in densities and moisture contents were measured among positions on the corn stems.

Approved F. W. Bakker-Arkema 9-2-69
Major Professor

Approved Carl W. Hall
Department Chairman

TEMPERATURE DISTRIBUTIONS AND EFFECTS OF HEAT APPLIED TO PLANT STEMS

By

Carl Henry Thomas

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Agricultural Engineering

1969

661359
4-3-10

To:

My Wife,

Chris

and children,

Jill

Steve

Dan

Mike

ACKNOWLEDGMENTS

The author wishes to extend his most sincere appreciation to Dr. F. W. Bakker-Arkema for his untiring guidance and advice throughout the author's graduate program at Michigan State University and to Dr. B A. Stout for his many helpful suggestions for getting this study under way.

To Dr. J. V. Beck, Mechanical Engineering Department, and Dr. S. K. Ries, Horticulture Department, appreciation is extended for assisting with guidance of this study and for serving on the graduate committee.

The author also wishes to thank Dr. C. W. Hall, Chairman of the Agricultural Engineering Department, for his assistance in so many ways.

Also, the author thanks Louisiana State University and the National Science Foundation for allowed leave and financial assistance to complete the graduate program.

Finally, appreciation is extended to Gloria Allain, Sue George, and Lynra Gieger for typing the first copies of the manuscript and to Pamela Lombard for the final typing.

****

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

FIGURE PAGE

NOMENCLATURE

α	=	thermal diffusivity (Ft^2/Hr).
c_p	=	specific heat (BTU/Lb °F).
D	=	mass diffusivity (Ft^2/Hr).
h_C	=	overall heat transfer coefficient, $\theta > \theta_1$ (BTU/Hr Ft^2 °F).
h_H	=	overall heat transfer coefficient, $0 < \theta \le \theta_1$ (BTU/Hr Ft^2 °F).
k	=	thermal conductivity (BTU/Hr Ft °F).
m	=	number of time step.
n	=	number of node.
N	=	node at surface.
q''_c	=	rate of heat lost during cooling, $\theta > \theta_1$ (BTU/Hr Ft^2).
q''_h	=	rate of heat gained during heating, $0 < \theta \le \theta_1$ (BTU/Hr Ft^2).
r	=	radius of cylinder (Ft).
r_c	=	critical radius at point of property changes, (Ft).
r_s	=	outside radius of cylinder (Ft).
R	=	dimensionless radius (r/r_s).
ρ	=	density (Lb/Ft^3).
t	=	temperature (°F).
t_i	=	initial temperature (°F).
t_s	=	surface temperature (°F).
t_{fl}	=	fluid temperature (°F).
T	=	dimensionless temperature (t/t_s).
T_s	=	dimensionless surface temperature (t_s/t_s).
T_{fl}	=	dimensionless fluid temperature (t_{fl}/t_s).
θ	=	time (Hr).
θ_1	=	total time for heating (Hr).

τ = dimensionless time $(\alpha\theta/r_s^2)$.

τ_1 = dimensionless time for heating $(\alpha\theta_1/r_s^2)$.

Note:

subscript 1 implies $r < r_c$.

subscript 2 implies $r \geq r_c$.

I. INTRODUCTION

Flame has been used effectively for the control of weeds in crops for the past decade. The principle use has been in row crops with plants tall enough to allow passage of the flame underneath the foliage. The plant stem is exposed to the intense heat for a short period of time during each flame application. In cotton, corn and soybeans the flame applications supplement the uses of chemical and mechanical cultivation for the control of weeds.

The normal flaming operation utilizes two or more burners for each row directing the flames toward the base of the crop plant and allowing the flames to pass over the seedbed surface. The flamer normally travels at speeds between 3 and 6 miles per hour. At 3 miles per hour with two conventional burners, 7.5 inches wide, the flame contacts the main stem of a plant a maximum of 0.28 second. Due to the short exposure of the plant stem to the flame, the high temperature can be tolerated by the stem. Watson (1961) measured the flame temperature to be approximately 2000 degrees Fahrenheit in the zone where the flame contacts the plant stems. This high temperature prevails at the base of the plant and near the soil surface on both sides of the seedbed.

The tolerance of a plant to the flame is affected by the surface structure of the plant stem as well as internal characteristics. The characteristics of the surface of the stem may be influenced by the stage of plant maturity. For example, a young fast-growing cotton plant has a smooth waxy stem, while a mature cotton plant has a rough and corky stem. The stem of a corn plant is smooth for all stages of maturity. See Figures 1, 2 and 3.

The stems of corn plants are high in moisture (55 pounds per cubic foot) near the ground and low in total moisture (25 pounds per cubic foot) near the top of the plant. The stem density is approximately 63 pounds per cubic foot near the ground and may reduce to approximately 30 pounds per cubic foot near the top of the corn plant.

The use of flame for weed control in crops offers several distinct advantages over chemical and mechanical methods. Flame leaves no harmful residue in the soil and does not contaminate the crop, while chemicals may cause crop contamination and leave harmful residues in the soil. The hazards of handling flame are not as great as they are for handling chemicals.

The disadvantages of using flame include the need for precise placement and timing of the application and the low efficiency for controlling weeds. The efficiency may be improved as a result of increased knowledge of the effects of applied heat on plant tissue. Data on physical and thermal properties are essential to an analysis of the influence of applied heat on plants. There is not much information presently available relative to these properties. The physical properties such as surface roughness, moisture content and bending strength of the stem influence the timing and techniques of operations such as mechanical cultivations, chemical applications and flaming for weed control. Thermal properties such as specific heat and thermal conductivity influence the heat tolerance as well as the movement of heat into the stem. With information on these factors, more precise timing and techniques of applications of flame could be developed.

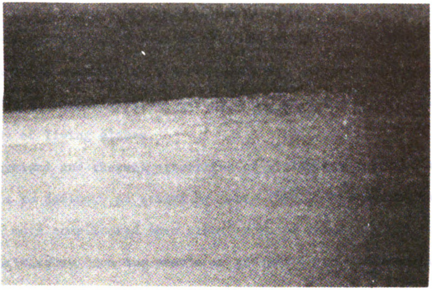


Figure 1: Surface of corn plant (one inch diameter).

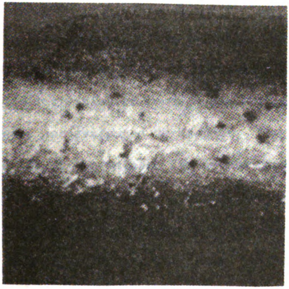


Figure 2: Surface of cotton stem (one-half inch diameter, two months old).

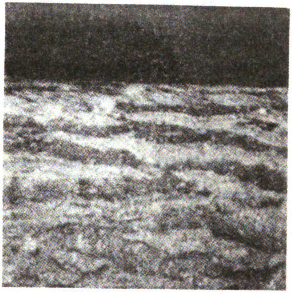


Figure 3: Surface of cotton stem (one-fourth inch diameter, three weeks old).

II. LITERATURE REVIEW

Very few investigations in the heat transfer literature have been concerned with living plants. However, the techniques developed for studying other biological products may have some application to the study of living plants.

Physical and thermal properties of biological products are very difficult to define. As stated by Lentz (1964):"Biological materials are much more complicated than other types of materials and they may vary considerably from one sample to another in both composition and structure." Many of the properties will change with changes in time, temperature and surroundings. These changes may not be consistent and they are probably not reproducible or reversible.

Many references are available in the literature dealing with the measurement of the thermal properties of biological products (foods). Woodams et al. (1968) accumulated a list of literature values of thermal conductivities of foods. The methods used for measuring these values were not evaluated by Woodams. However, Reidy (1968) made an exhaustive study of the methods for determining thermal conductivity and thermal diffusivity of foods. Reidy's accumulation of values for thermal properties of foods gathered from the literature is probably the most complete list of these data available. His most prevalent comment regarding methods used by researchers to determine thermal properties was that the procedures used and the existing conditions were generally not adequately described. This lack of information reduces the confidence with which others can use the data.

A few of the investigations from the literature are included in the following review as they may relate to this investigation. As most of the thermal properties reported are for foods, the values are not readily applicable to the plant stem model used.

THERMAL CONDUCTIVITY, SPECIFIC HEAT AND THERMAL DIFFUSIVITY

Gurney et al. (1923) recognized that "the temperature-time relations in the interior of solid bodies which are either being heated or cooled may be empirically determined by inserted thermometers, thermocouples or other temperature measuring apparatus, or may be calculated from the assumed conditions in conjunction with the physical constants of the materials, the surrounding contours, shapes and media." Thermal physical data are not sufficient and technical conditions can rarely be controlled to coincide with the theoretical prototypes. "Where empirical observations and theoretical calculations may be made concurrently, new physical constants may be determined which will be found to be more reliable in predicting other time-temperature relations under different, though similar conditions." The curves of Gurney were obtained by converting some of the more common formulas for heat diffusion into expressions containing pure ratios or nondimensional variables only, thereby enormously reducing the necessary basic calculations as well as extending their field of applicability.

Kethley et al. (1950) determined the average thermal conductivities of some fruits and vegetables over the range of 0° to 80° F by immersing solid objects of food and canned foods suddenly into a cold constant-temperature medium. The temperature history of the food pieces and canned foods made possible the calculation of the thermal diffusivities using the graphical method of Gurney. For the specific heat of a fruit or vegetable, these investigators used an average apparent specific heat which was defined as "the quotient obtained by dividing by 80 the total BTU's required to raise the temperature of one pound of the substance from 0° to 80° F." For the temperature interval of 32° to 80° F Kethley found that the average thermal conductivities of strawberries, Irish potato flesh, English peas and peach flesh ranged from 0.61 to 0.78 BTU/Hr Ft °F.

Eucken (1940) applied a formula, derived by Maxwell (1904) and published in (1954) by Dover Publications, Inc., that expressed the thermal conductivity of a material as a function of the relative volumes and the conductivities of the different particles of which the material is composed.

Lentz (1961) applied the Maxwell-Eucken equation to 6%, 12% and 20% gelatin gel solutions and obtained a theoretical thermal conductivity. The theoretical and experimental values are in good agreement (-2.4% to 0.4% difference) for the 6% and 12% gel solutions but not for the 20% gel solution (4.3% to 14.1% difference). Lentz used a guarded hot plate apparatus to determine the experimental thermal conductivity of the concentrations of gelatin gels from -25° to 5° C. Using this method for determining the thermal conductivity of ice, Lentz obtained results with the guarded hot plate that are about 1% lower than the most reliable values available. In experiments with heat flow both parallel and perpendicular to the grain of meat, Lentz also determined the thermal conductivities of several kinds of meat for -25° C to 10° C. The thermal conductivities of all the meats are about equal and about 10% below the established values for water. For temperatures below -10° C, thermal conductivity curves for meats are a linear function of temperature with the thermal conductivity increasing as the temperature decreases. Lentz did not find a direct correlation between the thermal conductivity and the moisture content or fat content of the product. Heat conduction was found to be 15% to 30% higher along the fibers than across the fibers.

A simple method for calculating the thermal diffusivity, α, involves the use of the equation $\alpha \frac{\partial^2 t}{\partial x^2} = \frac{\partial t}{\partial \theta}$. This equation is put in finite-difference form using temperatures, t, at three positions, x, in a one-dimensional body at two times, θ. The thermal diffusivity, α, is then calculated from the finite-difference equation. The thermal diffusivity is found as a function of time and temperature. Beck (1963), however, developed a calculational method which is superior to the above method with respect to errors in the thermal diffusivity caused by differences between measured temperatures and those calculated by the finite-difference equations. The calculated temperatures are determined using a finite-difference approximation of the heat conduction equation. An iteration procedure is used to find the thermal diffusivity, beginning with an initially estimated value. After the thermal diffusivity is found for one time interval, it can be found for succeeding time intervals and expressed as a function of temperatures (provided the changes in temperature with respect to position and the time intervals are not too large). The accuracy of the thermal diffusivity value depends, therefore, on the number of measured and calculational positions as well as upon the accuracy of the measurements.

Matthews (1966) determined the thermal diffusivity of potatoes from temperature measurements with a transient heat source using a numerical method of finite-difference approximations. The temperature change was measured within a finite thickness of potato resulting from an applied heat at one face. The finite-difference approximations used by Matthews were based on the procedure developed by Beck (1963).

Parker et al. (1967) made measurements of the density, specific heat, and thermal diffusivity of cherry flesh between 80° F and 40° F from which they calculated the thermal conductivity. They arrived at the following empirical equation by multiple correlation analysis:

$$K_{fl} = -0.275 - 0.0009SS + 0.280\rho_{fl} + 0.327c_{fl}$$

Where: K_{fl} = estimated thermal conductivity (BTU/Hr Ft °F)

SS = soluble solids content of the flesh (%)

ρ_{fl} = density of the flesh (gm/cc)

c_{fl} = specific heat of the flesh (BTU/Lb °F)

Beck (1964) developed a technique for the simultaneous determination of specific heat and thermal conductivity of solids from transient temperature measurements. The properties are found by making the calculated temperatures match the measured temperatures through a nonlinear least-squares analysis. Finite-difference approximation to the heat conduction equation is used to calculate the temperatures. The thermal conductivity is determined using steady-state conditions while specific heat and thermal diffusivity require transient conditions. The heat flux and temperatures alone can be used to determine thermal diffusivity. With the use of a digital computer, these properties can be readily calculated by this method with less than 0.1% error as a result of approximations in the numerical procedure. Errors in the properties considerably greater than this are usually found due to errors in the temperature and flux measurements.

Kopelman (1966) suggested the relation:

$$c_p = M.C.\ (1.0) - (1.0 - M.C.)\ P$$

Where: c_p = specific heat of a substance (BTU/Lb m)

M.C. = moisture content (w.b.) expressed as a decimal.

P = Factor relating the contribution of the solids to the specific heat.

This relation is of the general form:

$$c_p = \sum_{j=1}^{n} C_j\ P_j$$

Where: n = Number of components of the material considered.

P_j = Factor relating the contribution of each component to the specific heat.

For potatoes and carrots, which contain components quite similar to those of corn stems, Kopelman's equation agrees with the most reliable values of specific heats obtained by others and compiled by Reidy (1968) with less than 1% error.

Many other literature sources are available on the determination of specific heats of foods; however, most of these report specific heats for temperatures below 80° F, except for some meats. These results have little or no application to this investigation with the stems of plants.

HEAT TRANSFER EQUATIONS

Numerous papers have been written on the solution of heat transfer equations for various solids of different shapes. Some of the theories were developed many years ago.

A great number of solutions of the heat conduction equation for many different initial and boundary conditions and changing thermal properties have been collected by Carslaw et al.(1965). To solve the temperature-time history analytically at a large number of locations is, however, a very tedious operation because of the infinite series, Bessel functions and other complicated terms in the solution.

Kreith (1964) pointed out that the graphical method of analysis known as the "Schmidt plot" can be applied to long solid or hollow cylinders. The accuracy of this method depends on the number of approximations used in the solution. The Schmidt method is flexible and yields practical solutions to problems which have such complicated boundary conditions that they cannot be handled conveniently by analytical methods. In the past, the graphical method for solving unsteady heat conduction problems was widely used in industry as it gave a continuous record of the changing temperature distribution and its details could be delegated to relatively untrained personnel. However, for precise computations, especially when variations of physical properties are important, numerical methods are preferred.

Because of striking engineering advances involving complex shapes of bodies, Dusinberre (1961) explained that it might be best to use numerical methods to predict temperature distributions. Even though the details of such calculations are often simple enough, the size of the job might be appalling. This handicap has largely been eliminated by the rapid development and widespread availability of digital and analog computers.

EVAPORATIVE COOLING FROM MASS TRANSFER

Luikov (1964) stated that the effect of mass transfer with evaporation of liquid from capillary-porous bodies mainly results in the change of heat and mass transfer mechanisms due to deepening of the evaporation surface into the interior of the body. When the surface of evaporation deepens, the heat transfer coefficient is higher than that with evaporation on the surface. At drying with deepening of the surface of evaporation, the heat transfer coefficient will be higher than that of a dry body.

Luikov (1964) further discussed experiments by Mironov (1962) who showed that with porous cooling the heat-transfer Nusselt number is larger than Nusselt numbers for pure heat transfer. Also, Nusselt numbers with porous cooling are larger than those with drying. This difference increases with Reynolds number. Mass transfer Nusselt numbers with porous cooling are smaller than those with drying. This difference decreases with increase of Reynolds number. "With porous cooling, evaporation occurs at a body surface or in a layer close to it. With drying of a moist body, evaporation 'can' take place at a certain depth even at constant rate of drying. Increase in air velocity is known to move the evaporation zone into the interior of the body." The amount of heat spent for evaporation is relative to the amount of moisture evaporated. Heat required for this evaporation is transferred to the evaporation zone not only through a boundary layer at the surface, but also through a very thin layer of the body. Heat and mass are transferred through this layer of the body by conduction and diffusion. External heat and mass transfer depends on heat and mass transfer inside the body.

TECHNIQUE FOR TESTING PLANT CELLS FOR EVIDENCE OF LIFE

Attempts have been made to develop a quick and simple technique for detecting evidences of life in a plant cell. The use of a microscope for this purpose requires the skill of a rarely found individual. Moore (1960) has discussed a technique using tetrazolium (2, 3, 5 - triphenyl tetrazolium chloride) which gives a normal red color when hydrogen from respiration processes of each living cell combines with the absorbed solution. Peculiar purplish red colors are produced by chemical reactions other than that between hydrogen and tetrazolium.

DISCUSSION OF THE LITERATURE CITED

The unrestricted use of values for thermal properties of biological materials as compiled in the literature is questionable. The method by which the properties were measured apparently plays an important part in the magnitude of the values reported. The materials and the conditions under which the data were obtained are often poorly described. This limits the field of the applicability of the data.

For this author's study, no data on thermal and physical properties of plant stems were found. It was apparent that these properties must be measured or assumed. From the study of the literature, it appeared that the methods of measuring the thermal diffusivity used by Matthews (1966) and the specific heat used by Kopelman (1966) were quite reliable. By measuring the density of the corn stems used as models, the thermal conductivity could then be calculated by the relation:

$$\alpha = \frac{k}{\rho c_p}$$

where: α = thermal diffusivity (1/Ft^2)

k = thermal conductivity (BTU/Hr Ft F)

ρ = density (Lbm/Ft^3)

c_p = specific heat (BTU/Lbm)

The evaluations of the literature regarding methods of measuring thermal properties as made by authors such as Matthews (1966), Parker, et al. (1966), Kopelman (1966) and Reidy (1968) were very helpful.

The numerical approximation to the solution of the heat conduction equation as described by Dusinberre (1961) appeared to be the best available means of approaching this problem. Exact analytical solutions as compiled by Carslaw _et al._ (1965) were not applicable to this problem, as a description of the temperature distribution at the immediate end of a very short heating period was needed to express the temperature distribution at various times during cooling.

A search of the literature revealed very little information on methods of determining whether or not cell tissue of plant stems was killed with applied heat Also, no information was found relative to the temperature and time of exposure required to kill cell tissue of plant stems. The method described by Moore (1960) using tetrazolium (2, 3, 5 - diphenyl tetrazolium chloride) appeared to have some possible application to this problem although the technique was developed for determining the viability of seeds.

III. STATEMENT OF THE PROBLEM

The purposes of this investigation were to determine the responses of a plant stem to high temperature heat exposures and to develop expressions indicating the temperature history of the exposed stem.

The objectives were the following:

1) To determine the temperature and time required to kill the cells of a plant stem by applied heat.
2) To measure the temperature history and depth at which cells in a plant stem are killed by a short exposure to heat.
3) To demonstrate by numerical approximations the temperature history for a plant stem as affected by the following variables:
    a) Temperature of the heat source
    b) Time of exposure to heat
    c) Diameter of the plant stem
    d) Density of the plant stem
    e) Thermal properties of the plant stem

IV. EQUIPMENT

The following apparatus and instruments were used:

1) Potentiometers -

   a) Servo Riter II, Manufactured by Texas Instrument Company, 2 pens, single chart, continuous recording, accuracy ± 0.25% of full scale.

   b) Model G, Manufactured by Leeds and Northrup Company, 2 pens, single chart, continuous recording, accuracy ± 0.3% of full scale.

   c) Visicorder, Model 906C, Manufactured by Honneywell, Inc., 12 channel, single chart, continuous recording, accuracy ±0.3% of full scale.

   d) Precision Potentiometer, Model 8686, Manufactured by Leeds and Northrup Company, accuracy ± 0.03% reading, + 3 micro-volts without a reference junction, for calibrating recording potentiometers.

2. Thermocouples -

   a) Copper-constantan, 0.012 inch diameter (30 gauge) wire, in 1/6 inch diameter stainless steel probe, for internal temperatures when using flame as the heat source.

   b) Iron-constantan, 0.012 inch diameter (30 gauge) wire, for surface temperature of silicone rubber model using flame as the heat source.

   c) Chromel-alumel, 0.003 inch diameter wire, closed junction in a 0.02 inch diameter stainless steel probe, used for surface and internal temperatures of the samples when using the electric furnace as a heat source.

3) Heat Exposure Apparatus -

   a) Flame burner equipment, illustrated later.

   b) Electric furnace, Type FH305, Manufactured by Hoskins Mfg. Company, 20 volts, 50 amperes.

   c) Hot water bath with stirrer and heaters.

4) Sample Holders -

   a) Holder for stem segments when using flame as a heat source, illustrated later.

   b) Holder for stem segments when using the electronic oven as a heat source, illustrated later.

5) Hand Microtomes -

   a) 3/8 inch diameter tube

   b) 1/2 inch diameter tube

   c) 3/4 inch diameter tube

6) Thermal Diffusivity Apparatus -

   This apparatus was designed and built by Matthews (1966) and modified to handle corn stem sections.

7) Miscellaneous equipment used for measuring the density, specific heat and moisture content of the corn segments -

   a) Torsion balance, Manufactured by Torbal, 0.1 gram graduation.

   b) Electric ovens, For determining the moisture content of corn stem segments.

c) Hand refractometer, Type 25B, Manufactured by American Optical Company.

d) Constant temperature reference junction box, Type 106, Manufactured by Thermo-Electric Company.

e) Graduated cylinders to measure water displacement.

8) Electric timer - Manufactured by Cramer, 0.01 second graduation.

9) Computational Services -

CDC 3600 and IBM 7040 Digital Computers

10) Corn stalks -

a) MSU 100 variety - near stage of maturity, starch kernels.

b) Aristogold Sweet - at milk stage, developed kernels.

11) 2, 3, 5 - triphenyl tetrazolium chloride

V. PROCEDURES

Stem segments from living corn stalks were selected as the plant model because of the possible homogeneity of the physical properties and the close relationship of the corn plant to the existing problem. Corn and cotton are two of the main crops on which flame is used for weeding. On comparing the cross sections of stems of corn and cotton plants as shown in Figures 4 and 5, the corn stem was selected as the model for this study.

Corn plants were selected from the field and stem segments were selected from the plants on the basis of size, shape and location on the stalks.

1) The stem segment was trimmed with a cork borer to fit the selected hand microtome. The trimmed segment was placed in the microtome tube and thin sections, approximately 0.035 inch thick, were cut with a razor blade. Although thinner sections could have been cut by this method, they were more difficult to handle and did not improve the results.

   The thin sections were exposed to heat using a stirred water bath at the selected temperature. To establish the desired ranges of temperatures and times of exposure, initial studies included the following treatments:

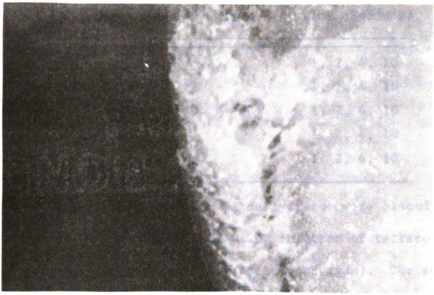


Figure 4: Cross-section of one inch diameter corn stem.

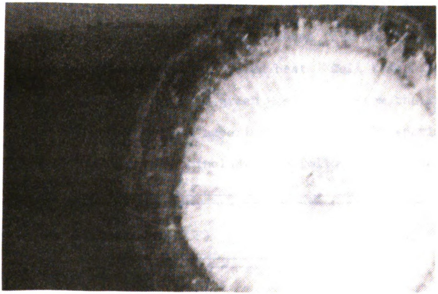


Figure 5: Cross-section of one-half inch diameter cotton stem.

Water Bath Temperature (°F)	Exposure Time (Seconds)
120	1, 2, 4, 10
140	1, 2, 4, 10
160	1, 2, 4, 10
180	1, 2, 4, 10
210	1, 2, 4, 10

The exposed sections of cell tissue were placed in small vials containing a 0.25% solution of tetrazolium (2, 3, 5 - triphenyl tetrazolium chloride). The solution was prepared by adding one gram of the tetrazolium powder to one pint of distilled water.

Staining was normally apparent within four hours after being treated and stored at approximately 85° F. The distinct pink coloring was evidence that the cell tissue was not killed by the applied heat. Cell tissue that remained white or pale green was dead. From the results of the above initial experiment, additional experiments were planned, which included the following treatments:

Water Bath Temperature (°F)	Exposure Time (Seconds)
120	4, 6, 8, 10
160	1, 2, 3, 4
180	1, 2, 3, 4
210	½, 1, 1½, 2

Additionally, the above indicated treatments were repeated to include samples of plant tissue from four locations on the stems of corn plants. These locations were the first, third, fifth and seventh internodes above the surface of the seedbed on which the plants were grown.

Heat exposed sections were compared with tissue sections that were not exposed to heat. Photographs of the results were taken and used in the discussions.

2) To simulate the exposure of plant stems to high temperature heat as in flaming for weed control, an electric furnace as illustrated in Figure 6 was used. The temperature inside the furnace was regulated with a rheostat. Temperatures up to 2200° F could be obtained with this equipment.

Stem segments were obtained from corn plants at selected internode locations on the plant. The internodes were numbered, beginning at the ground level. Selected stem segments were trimmed at the node on each end and carefully weighed. The volume was measured by displacement of water in a graduated cylinder. A thermocouple, 0.02 inch diameter probe, was inserted from the end of the stem segment and the prepared sample was placed in the holder, which is also illustrated in Figure 6. The sample was exposed to heat inside the furnace

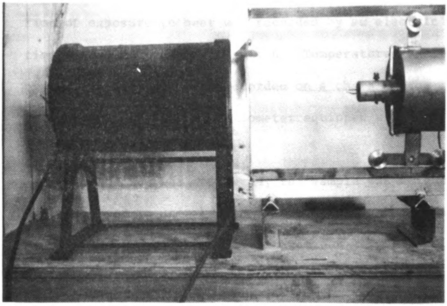


Figure 6: Electric furnace and sample holder used to expose plant samples to heat.

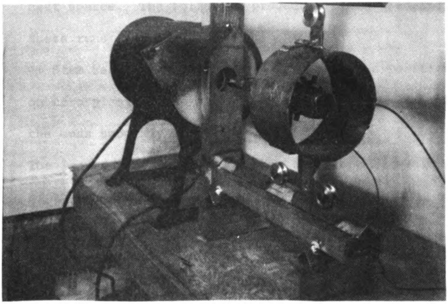


Figure 7: Equipment used to inject plant samples into electric furnace.

with the aid of the apparatus illustrated in Figure 7. Time of exposure to heat was recorded by an electric timer actuated by a micro-switch. Temperatures sensed by the thermocouple were recorded on a chart by the Visicorder recording potentiometer equipped with an amplifier.

After the run was completed, the sample was weighed and sectioned to determine moisture losses and the depth of the thermocouple. Microtome sections were placed in vials containing tetrazolium solution and studied as indicated in procedure 1). Photographs of these results were made for use in discussions that follow later.

Experimental runs were made also using flame as the heat source. The following procedures were used for these runs:

Stem segments were obtained from selected positions on corn plants. The segments were prepared by trimming the ends smoothly to give a sample seven inches long. The leaves were removed and the weight and dimensions of the sample obtained before the run.

Thermocouples were inserted from the end at approximately 1/16 inch and 1/4 inch depths from the surface of the sample. The prepared samples were held in the specimen holder shown in Figure 8.

The heat exposure apparatus consisted of four Stoneville type agricultural burners mounted on a turntable

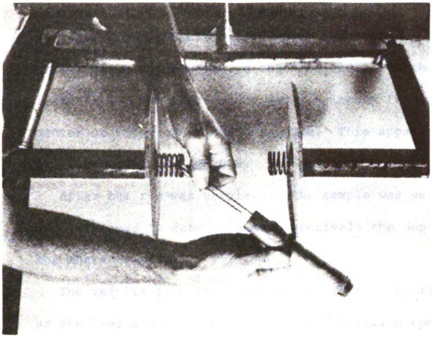


Figure 8: Thermocouple probes being inserted into the corn stem segment.

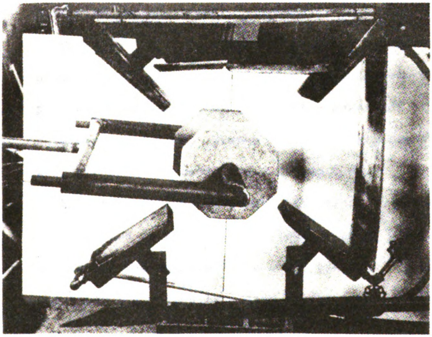


Figure 9: The corn stem segment was exposed to flames from four Stoneville type burners.

equipped with a liquified petroleum gas system. The burner frame was mounted so that the center of the frame passed the stem sample at 51.5 inches from the center of rotation of the turntable. This apparatus is illustrated in Figure 9.

After the run was completed, the sample was weighed and sectioned to determine more precisely the depths of the thermocouples.

The results from the experimental runs using flame as the heat source were used in the discussion comparing experimental and theoretical temperature histories.

3) A numerical solution of the conduction heat transfer equation was developed to demonstrate temperature histories for an infinitely long cylinder.

The solution was written and computer programs were prepared. The contributing effect of each selected parameter was studied by varying the magnitude of one parameter at a time. Graphs of the temperature histories were prepared and used in the discussions.

The study of the parameters affecting the temperature distribution in an infinitely long cylinder with uniform heating of the surface for a short period of time included the following values (standard values are underlined):

a) h_H (BTU/Hr/ Ft^2 F) = 2., 4., 10., 20., <u>40.</u>, 100.

b) h_C (BTU/Hr Ft^2 F) = 1., <u>2.</u>, 5., 10., 20.

c) k_1 (BTU/Hr Ft F) = .1, <u>.2</u>, .3, .6, 1.0.

d) k_2 (BTU/Hr Ft F) = .1, .2, <u>.3</u>, .6, 1.0.

e) c_{p_1} (BTU/Lb F) = .87, <u>.91</u>, 1.00.

f) c_{p_2} (BTU/Lb F) = <u>.87</u>, .91, 1.00.

g) ρ_1 (Lb/Ft^3) = 30., <u>40.</u>, 60., 65.

h) ρ_2 (Lb/Ft^3) = 30., 40., <u>60.</u>, 65.

i) r_s (Ft) = .01, .02, .03, <u>.04</u>, .05, .06, .08, .16, .32, .64.

j) r_c (Ft) = <u>.035</u>, r_s - 0.005

k) t_{f1} (F) = 500., 1000., 1500., <u>1641.</u>, 2000. (Heating).

l) t_{f1} (F) = <u>77.</u> (Cooling).

m) $\Delta\theta$ (Hr) = <u>.00004</u>.

n) Δr (Ft) = <u>.002</u>.

o) N = <u>20</u>, r_s/0.002 (Integer).

The values of the standard parameters were selected to approximate those for a corn stem specimen as follows:

a) h_H = <u>40.0</u> BTU/Hr Ft^2 F -- approximated experimentally with the aid of a silicone rubber model.

b) h_C = <u>2.0</u> BTU/Hr Ft^2 F -- approximated for free connection from a horizontal cylinder, Kreith (1958).

c) k_1 = <u>0.2</u> BTU/Hr Ft F -- measured

d) k_2 = <u>0.3</u> BTU/Hr Ft F -- measured

e) c_{p_1} = <u>0.91</u> BTU/Lb F -- measured

f) c_{p_2} = $\underline{0.87}$ BTU/Lb F -- measured

g) ρ_1 = $\underline{40.0}$ Lb/Ft^3 -- measured

h) ρ_2 = $\underline{60.0}$ Lb/Ft^3 -- measured

i) r_s = $\underline{0.040}$ Ft -- measured diameter of the lower stem segments of a corn stalk.

j) r_c = $\underline{0.035}$ Ft -- assumed point of change of properties in a corn stem.

k) t_{f1} = $\underline{1641.0}$ F -- Patin (1967), $0 < \theta \leq \theta$.

l) t_{f1} = $\underline{77.0}$ F -- normal atmospheric temperature, $\theta > \theta$.

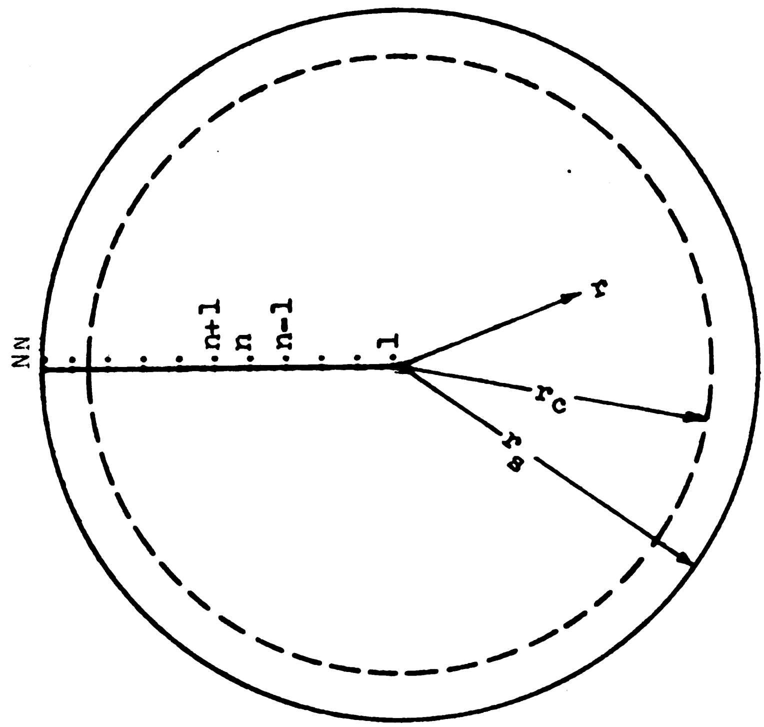
m) $\Delta\theta$ = $\underline{0.00004}$ Hr -- assumed time increment small enough to allow several time steps during the heating period.

n) Δr = $\underline{0.002}$ Ft -- $\underline{r_s}/\underline{N}$.

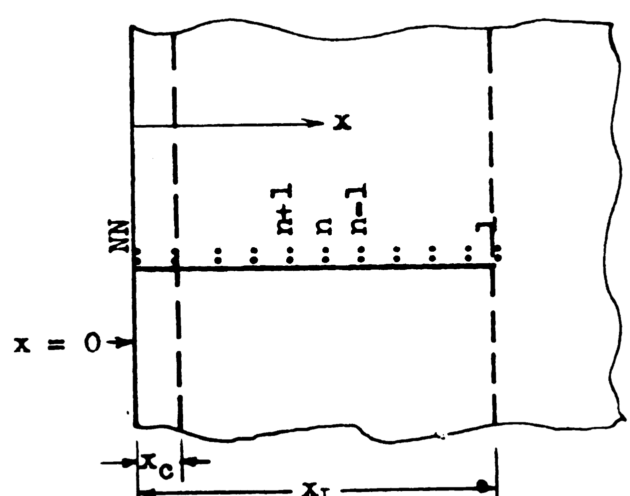
o) N = $\underline{20}$ -- convenient number of depth increments as illustrated in Figure 10. The nodal system used for the cylinder as well as a semi-infinite wall are shown. A solution of the heat equations for a semi-infinite wall was obtained and a sample output from the prepared computer program is shown in the Appendix (B and C).

Figure 10

NOMENCLATURE OF NODAL POINTS USED FOR FINITE-DIFFERENCE APPROXIMATIONS OF THE TEMPERATURE DISTRIBUTIONS



CYLINDER



SEMI-INFINITE WALL

VI. NUMERICAL SOLUTION OF THE MATHEMATICAL MODEL

The rapidly changing boundary conditions of the mathematical model make this problem difficult to handle analytically. Exact analytical solutions of the governing heat transfer equations require accurate descriptions of the initial conditions for all phases of heating and cooling. As heat is applied rapidly to the surface of the model for a very short period of time (less than 0.5 second) and then the model is allowed to cool at ambient conditions, the temperature of the surface and points below the surface is changing rapidly.

Therefore, the intital condition for the cooling phase is not well defined. The numerical treatment of the heat conduction equation using finite-difference approximations by the Crank-Nicholson (1947) method, however, gives reliable indications of the temperature distribution at any time. This application of finite-difference approximations demonstrates a uniqueness not normally seen in the use of heat transfer equations.

The mathematical formulation of this problem involves rates of change of the dependent variable, temperature, with respect to two independent variables, radius and time.

The computational development of the numerical method involves a large amount of arithmetic; therefore, whenever possible, terms are arranged for one solution to suffice for a variety of different problems.

Several simplifying assumptions are made to facilitate the solution to the problem. The assumptions include the following:

1) The material is homogeneous in radial segments.
2) Non-homogeneity may exist among radial segments.
3) The specimen is cylindrical in shape.
4) The specimen is infinitely long.
5) Heat is applied evenly around the circumference and over the length of the specimen.
6) Physical and thermal properties are constant for each radial segment of the specimen.
7) The diameter is constant over the entire length of the specimen.
8) No mass transfer is assumed to occur.

Considering the above listed assumptions, the basic differential conduction heat transfer equation reduces to:

$$\frac{\partial}{\partial r}\left(kr\,\frac{\partial t}{\partial r}\right) = \rho c_p r\,\frac{\partial t}{\partial \theta} \tag{6-1}$$

Since k is assumed to be constant for each radial segment, equation (6-1) may be written in the form:

$$kr\,\frac{\partial^2 t}{\partial r^2} + k\,\frac{\partial t}{\partial r} = \rho c_p r\,\frac{\partial t}{\partial \theta} \tag{6-2}$$

Or:

$$\frac{\partial^2 t}{\partial r^2} + \frac{1}{r}\,\frac{\partial t}{\partial r} = \frac{1}{\alpha}\,\frac{\partial t}{\partial \theta} \tag{6-3}$$

Equation (6-3) can be put in the dimensionless form:

$$\frac{\partial^2 T}{\partial R^2} + \frac{1}{R}\frac{\partial T}{\partial R} = \frac{\partial T}{\partial \tau} \tag{6-4}$$

Where:

$$R = \frac{r}{r_s} \; ; \; T = \frac{t}{t_s} \; ; \; \tau = \frac{\alpha\theta}{r_s^{\,2}}$$

The initial and boundary conditions are assumed to be:

$$T(R,0) = Ti \; ; \; \tau = 0, \text{ for all } R \tag{6-5}$$

$$\frac{\partial T(0,\tau)}{\partial R} = 0 \; ; \text{ for all } \tau \tag{6-6}$$

$$\dot{q}''_H = - k \frac{\partial T}{\partial R}\Big|_{r = 1}$$

$$= h_H (T_s - T_{fl}) \; ; \text{ for } 0 < \tau \leq \tau_1 \tag{6-7}$$

$$\dot{q}''_c = - k \frac{\partial T}{\partial R}\Big|_{r = 1}$$

$$= h_c (T_s - T_{fl}) \; ; \text{ for } \tau > \tau_1 \tag{6-8}$$

Now, consider the finite-difference approximation to equation (6-4) using the Taylor series expansion:

$$T_{(n+1,m)} = T_{(n,m)} + \Delta R \frac{\partial T}{\partial R}\Big|_{(n,m)} + \tfrac{1}{2}(\Delta R)^2 \frac{\partial^2 T}{\partial R^2}\Big|_{(n,m)} + \frac{1}{6}(\Delta R)^3 \frac{\partial^3 T}{\partial R^3}\Big|_{(n,m)} + \ldots. \tag{6-9}$$

$$T_{(n-1,m)} = T_{(n,m)} - \Delta R \frac{\partial T}{\partial R}\Big|_{(n,m)} + \frac{1}{2}(\Delta R)^2 \frac{\partial^2 T}{\partial R^2}\Big|_{(n,m)} - \frac{1}{6}(\Delta R)^3 \frac{\partial^3 T}{\partial R^3}\Big|_{(n,m)} + \ldots. \tag{6-10}$$

Adding equations (6-9) and (6-10), neglecting fourth and higher order terms and solving for $\frac{\partial^2 T}{\partial R^2}\Big|_{(n,m)}$ gives:

$$\frac{\partial^2 T}{\partial R^2}\Big|_{(n,m)} = \frac{T_{(n-1,m)} + T_{(n+1,m)} - 2T_{(n,m)}}{(\Delta R)^2} \tag{6-11}$$

Which is of order $(\Delta R)^2$.

With small $\Delta\tau$, the approximation,

$$T_{(n,m+\frac{1}{2})} = \frac{T_{(n,m)} + T_{(n,m+1)}}{2} \tag{6-12}$$

can be used in equation (6-11),

$$\left.\frac{\partial^2 T}{\partial R^2}\right|_{(n,m+\frac{1}{2})} = \frac{1}{2\ (\Delta R)^2}\left[T_{(n-1,m)} + T_{(n-1,m+1)} - 2T_{(n,m)} - 2T_{(n,m+1)} + T_{(n+1,m)} + T_{(n+1,m+1)}\right] \tag{6-13}$$

By subtracting equation (6-10 from (6-9) four times τ_m and τ_{m+1}, one can obtain

$$\left.\frac{\partial T}{\partial R}\right|_{(m+\frac{1}{2})} = \frac{1}{4\Delta R}\left[T_{(n+1,m)} + T_{(n+1,m+1)} - T_{(n-1,m)} - T_{(n-1,m+1)}\right] \tag{6-14}$$

With an error of order $(\Delta R)^2$.

It can be shown also that,

$$\left.\frac{\partial T}{\partial \tau}\right|_{(m+\frac{1}{2})} = \frac{T_{(n,m+1)} - T_{(n,m)}}{\Delta\tau} \tag{6-15}$$

With error of order $(\Delta\tau)^2$.

With the substitution of equations (6-13), (6-14) and (6-15) and rearranging terms, the approximation of the solution to equation (6-4) becomes,

$$\left(\frac{1}{2(\Delta R)^2} + \frac{1}{4R\Delta R}\right) T_{(n+1,m+1)} - \left(\frac{1}{(\Delta R)^2} + \frac{1}{\Delta\tau}\right) T_{(n,m+1)} + \left(\frac{1}{2(\Delta R)^2} - \frac{1}{4R\Delta R}\right) T_{(n-1,m+1)} = -\left(\frac{1}{2(\Delta R)^2} + \frac{1}{4R\Delta R}\right) T_{(n+1,m)} + \left(\frac{1}{(\Delta R)^2} - \frac{1}{\Delta\tau}\right) T_{(n,m)} - \left(\frac{1}{2(\Delta R)^2} - \frac{1}{4R\Delta R}\right) T_{(n-1,m)} \tag{6-16}$$

For the case of k and ρc_p varying with temperature, one can derive similar to equation (6-16) for the temperature distribution in a cylinder,

$$[(kr)_{(n+\frac{1}{2})} + \frac{k_{n+\frac{1}{2}}\,\Delta r}{2}]\; t_{(n+1,m+1)} - [(kr)_{(n+\frac{1}{2})} + (kr)_{(n-\frac{1}{2})}$$
$$+ 2(\rho c_p r)_{(n)}\, \frac{(\Delta r)^2}{\Delta\theta}]\; t_{(n,m+1)} + [(kr)_{(n+\frac{1}{2})} - \frac{k_{n-\frac{1}{2}}\Delta r}{2}] t_{(n-1,m+1)}$$
$$= - [(kr)_{(n+\frac{1}{2})} + \frac{k_{n+\frac{1}{2}}\,\Delta r}{2}]\; t_{(n+1,m)} + [(kr)_{(n+\frac{1}{2})} + (kr)_{(n-\frac{1}{2})}$$
$$-2(\rho c_p r)_{(n)}\, \frac{(\Delta r)^2}{\Delta\theta}] t_{(n,m)} - [(kr)_{(n-\frac{1}{2})} - \frac{k_{n-\frac{1}{2}}\Delta r}{2}] t_{(n-1,m)} \qquad (6\text{-}17)$$

Equation (6-17) permits temperature variable properties. For small $\Delta\tau$'s, k and ρc_p can be evaluated at τ_m.

Equation (6-17) is stable and valid for any values of $\Delta\theta$ and Δr.

For the <u>temperature at the center of the cylindrical model</u>, R = 0, n = 0 and $\frac{\partial T}{\partial R} = 0$, Carslaw and Jaeger (1965) expressed the result as

$$\left[\frac{\partial^2 T}{\partial R^2} + \frac{1}{R}\frac{\partial T}{\partial R}\right]_{R=0} = \frac{4}{(\Delta R)^2}\,(T_i - T_o) \qquad (6\text{-}18)$$

When evaluated at time, $(m + \frac{1}{2})$.

$$\left[\frac{\partial^2 T}{\partial R^2} + \frac{1}{R}\frac{\partial T}{\partial R}\right]_{R=0} = \frac{2}{(\Delta R)^2}\,[T_{(1,m+1)} + T_{(1,m)} - T_{(0,m+1)}$$
$$-T_{(0,m)}] \qquad (6\text{-}19)$$

correspondingly,

$$\frac{\partial T}{\partial \tau}\Big|_{R=0} = \frac{T_{(0,m+1)} - T_{(0,m)}}{\Delta\tau} \qquad (6\text{-}20)$$

Substituting equations (6-18) and (6-19) into (6-4),

$$\frac{2}{(\Delta R)^2}\,[T_{(1,m+1)} + T_{(1,m)} - T_{(0,m+1)} - T_{(0,m)}]$$
$$= \frac{1}{\Delta\tau}\,[T_{(0,m+1)} - T_{(0,m)}] \qquad (6\text{-}21)$$

and rearranging terms, gives

$$- (1 + \frac{(\Delta R)^2}{2\Delta\tau})\; T_{(0,m+1)} + T_{(1,m+1)} = (1 - \frac{(\Delta R)^2}{2\Delta\tau}\;)\; T_{(0,m)}$$
$$- T_{(1,m)} \qquad (6\text{-}22)$$

Putting equation (6-22) in dimensional terms and multiplying by $k_{(\frac{1}{2})}$ results in

$$- (k_{(\frac{1}{2})} + \frac{\rho c_p (\Delta r)^2}{2\Delta\theta}) \, t_{(0,m+1)} + k_{(\frac{1}{2})} \, t_{(1,m+1)}$$

$$= (k_{(\frac{1}{2})} - \frac{\rho c_p (\Delta r)^2}{2(\Delta\theta)}) \, t_{(0,m)} + k_{(\frac{1}{2})} \, t_{(1,m)} \qquad (6\text{-}23)$$

Equation (6-23) is valid for determining the <u>temperature at the center of the cylinder</u>.

At the surface $n = N$, $r = r_s$, with the conditions (6-7) and (6-8) and the approximations,

$$\left.\frac{\partial t}{\partial r}\right|_{(N,m)} = \frac{h}{k} [t_{f1} - t_{(N,m)}]$$

$$= \frac{t_{(N,m+1)} - t_{(n,m)}}{\Delta r} \qquad (6\text{-}24)$$

$$\left.\frac{\partial t}{\partial \theta}\right|_{(m+\frac{1}{2})} = \frac{t_{(N,m+1)} - t_{(N,m)}}{\Delta\theta} \qquad (6\text{-}25)$$

$$\left.\frac{\partial^2 t}{\partial r^2}\right|_{(N,m+\frac{1}{2})} = \frac{1}{2(\Delta r)^2} [t_{(N-1,m)} + t_{(N-1,m+1)}$$

$$-2t_{(N,m)} - 2t_{(N,m+1)} + t_{(N+1,m)} + t_{(N+1,m+1)}] \qquad (6\text{-}26)$$

From equation (6-26),

$$t_{(N+1,m)} = \frac{h\Delta r}{k} [t_{f1} - t_{(N,m)}] + t_{(N,m)} \qquad (6\text{-}27)$$

Or,

$$t_{(N+1,m+1)} = \frac{h\Delta r}{k} [t_{f1} - t_{(N,m+1)}] + t_{(N,m+1)} \qquad (6\text{-}28)$$

Therefore,

$$\frac{\partial^2 t}{\partial r^2}\Big|_{(N,m+\frac{1}{2})} = \frac{1}{2(\Delta r)^2}\Big[t_{(N-1,m)} + t_{(N-1,m+1)} - 2t_{(N,m)}$$

$$-2t_{(N,m+1)} + \frac{h\Delta r}{k}(t_{f1} - t_{(N,m)}) + t_{(N,m)} + \frac{h\Delta r}{k}$$

$$(t_{f1} - t_{(N,m+1)}) + t_{(N,m+1)}\Big] \qquad (6\text{-}29)$$

$$\frac{\partial t}{\partial r}\Big|_{(N,m+\frac{1}{2})} = \frac{h}{2k}\left[2t_{f1} - t_{(N,m)} - t_{(N,m+1)}\right] \qquad (6\text{-}30)$$

Substituting equations (6-25),(6-29), and (6-30) into the dimensionalized form of the differential equation (6-4) gives,

$$\frac{1}{2(\Delta r)^2}\Big[t_{(N-1,m)} + t_{(N-1,m+1)} -2t_{(N,m)} -2t_{(N,m+1)}$$

$$+ \frac{h\Delta r}{k}(2t_{f1} - t_{(N,m)} -t_{(N,m+1)}) + t_{(N,m)} + t_{(N,m+1)}$$

$$+ \frac{h}{2kr}(2t_{f1} - t_{(N,m)} -t_{(N,m+1)})\Big] = \frac{\rho c_p}{k\Delta\theta}(t_{(N,m+1)} -t_{(N,m)} \qquad (6\text{-}31)$$

Multiplying by 2 $(k_{N-\frac{1}{2}})$ $(\Delta r)^2$ and rearranging terms, gives,

$$(k)_{(N-\frac{1}{2})}\, t_{(N-1,m+1)} - \Big[(k)_{N-\frac{1}{2}} + (1 + \frac{\Delta r}{r_s})\, h\Delta r + 2\rho c_p \frac{(\Delta r)^2}{\Delta\theta}\Big]$$

$$t_{(N,m+1)} = -\,(k)_{n-\frac{1}{2}}\, t_{(N-1,m)} + \Big[(k)_{N-\frac{1}{2}} + (1 + \frac{\Delta r}{r_s})\, h\Delta r$$

$$-\, 2\rho c_p \frac{(\Delta r)^2}{\Delta\theta}\Big]\, t_{(N,m)} - 2h\Delta r\,(1 + \frac{\Delta r}{r_s})\, t_{f1} \qquad (6\text{-}32)$$

for calculating the temperature at the surface of the cylinder.

VII. DISCUSSION OF RESULTS

DISCUSSION OF COMPARISONS BETWEEN EXPERIMENTAL AND CALCULATED TEMPERATURE DISTRIBUTIONS

In the attempt to obtain a reasonable estimate of the overall heat transfer coefficient for the surface of a cylinder of silastic silicone, several values of the coefficient for heating were used. The value giving the closest prediction of the temperatures actually measured was selected as the standard overall heat transfer coefficient for heating. In a similar manner, the coefficient for cooling was chosen. These results are illustrated in Figure 11 for the surface temperatures measured and predicted with two times of exposure using flame for the heat source as was illustrated in Figures 8 and 9. There was a time response lag in the recording potentiometer used. As the response of the recorder was one second for full scale response, the actual peak temperature of the surface was never reached with the recorder. This response lag was not important when measuring the temperature at a depth of 0.004 foot in the cylinder; therefore, a relatively good prediction resulted as can be seen in Figure 12.

Temperature measurements at a depth of 0.008 foot in corn stems were consistently higher than the predicted temperatures as illustrated in Figure 13. Since the surface temperature of the corn stalk specimen was not measured, there was no indication that the predicted surface temperature was correct. The assumed source temperature can be too low. The accuracy of these predictions can be greatly improved

Figure 11

TEMPERATURE AT THE SURFACE OF SILICONE RUBBER SPECIMEN (CYLINDER)

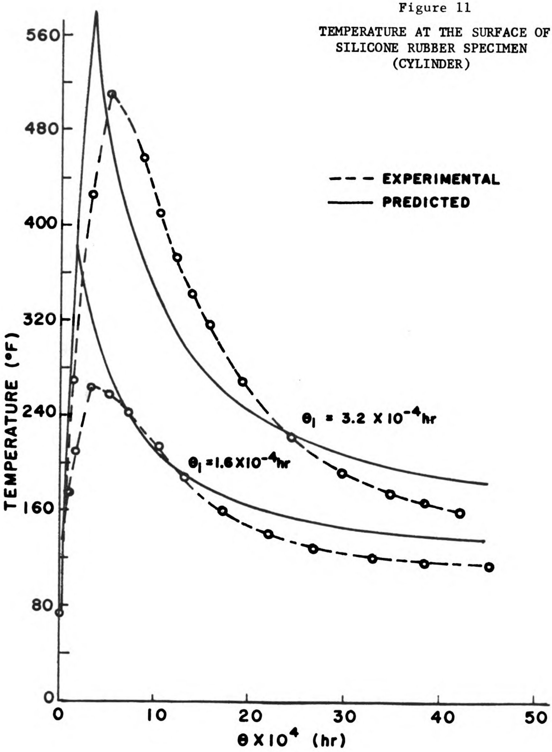


Figure 12

TEMPERATURE AT A DEPTH OF 0.004 FT.
IN SILICONE RUBBER SPECIMEN
(CYLINDER)

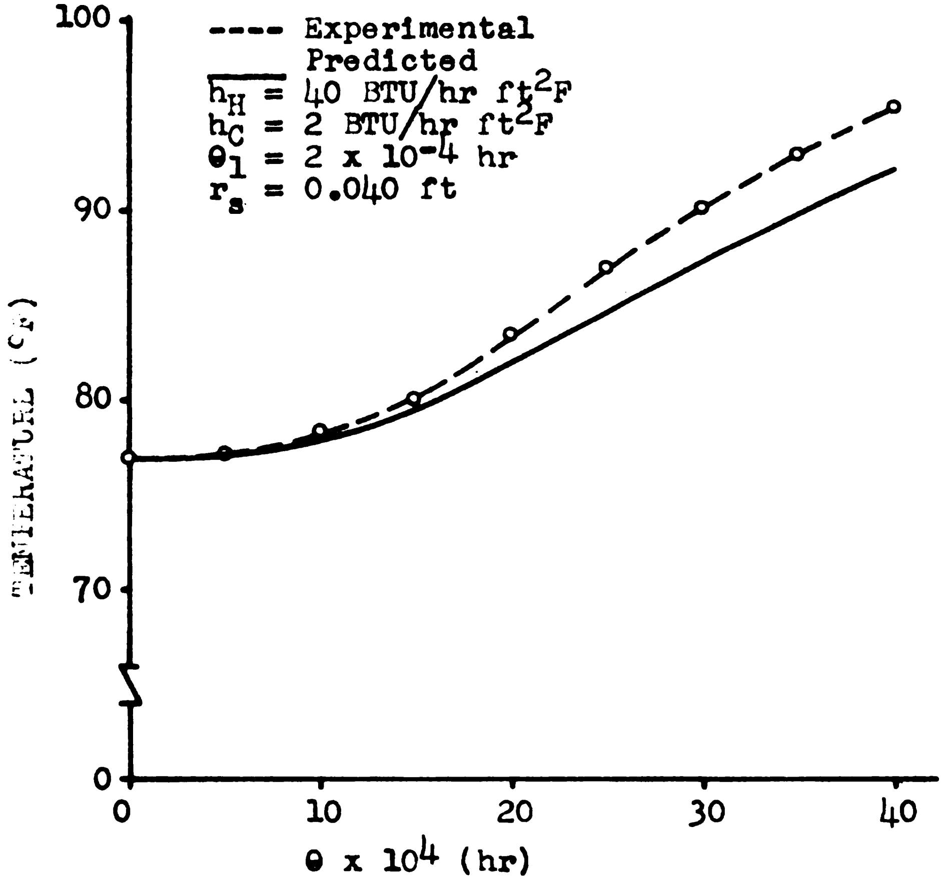
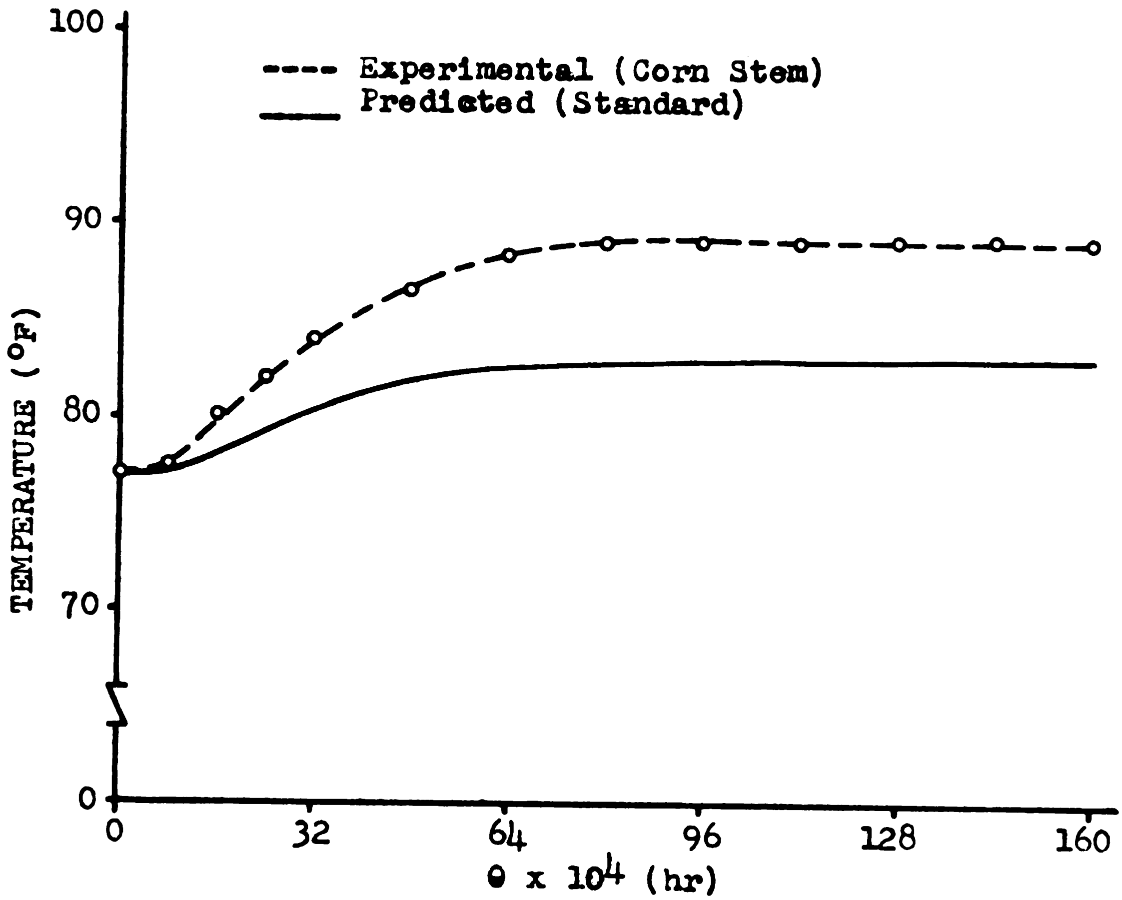


Figure 13

TEMPERATURE AT 0.008 FT. FOR EXPERIMENTAL
PREDICTED



when more complete and accurate descriptions are available for the properties of the bodies considered.

DISCUSSION OF RESULTS FROM EXPERIMENTS WITH HEAT EXPOSURE OF CORN STEM SEGMENTS

Initial studies were made to establish the general ranges of temperatures and times of exposure required to kill the cell tissue from corn stems. The observations from these initial studies using the water bath as the source of applied heat indicated the following results of whether or not cell tissue was killed:

Temperature (°F)	Time of Exposure (Seconds) 1	2	3	4
120	No	No	No	No
140	No	No	No	Yes
160	No	Yes	Yes	Yes
180	Yes	Yes	Yes	Yes
210	Yes	Yes	Yes	Yes

It was obvious that there was a temperature *vs* time of exposure relationship existing. Therefore, further studies were planned with narrower ranges of times of exposure. The same general temperatures were used as in the initial studies except that the 120° F temperature was eliminated.

A complete list of treatments, data and observations for each run was accumulated and shown in Table 1. The visual observations are illustrated in Figure 14. Although it was difficult to arrive

Table 1

TEMPERATURE *vs* TIME OF EXPOSURE OF STEM TISSUES OF CORN PLANTS

Treatment No.	Temperature of Water Bath (°F)	Time of Sample Exposure (Seconds)	Internode of Stem Above Ground	Density of Sample (lbs/ft^3)	Moisture Content (% D.B.)	Observations for Stem Tissue (0=Not Dead, X=Dead)
1	140	4	1	64.90	517	0
2	140	6	1			0
3	140	8	1	63.13	590	X
4	140	10	1			X
5	140	4	3	31.87	377	0
6	140	6	3			X
7	140	8	3	53.12	641	X
8	140	10	3			X
9	140	4	5	20.62	272	0
10	140	6	5			0
11	140	8	5	56.25	652	X
12	140	10	5			X
13	140	4	7	20.00	248	0
14	140	6	7			0
15	140	8	7	60.62	772	0
16	140	10	7			0
17	160	1	1	64.90	452	0
18	160	2	1			0
19	160	3	1	55.62	667	X
20	160	4	1			X
21	160	1	3	41.82	474	X
22	160	2	3			X
23	160	3	3	42.50	598	X
24	160	4	3			X
25	160	1	5	30.00	427	X
26	160	2	5			X
27	160	3	5	36.87	470	X
28	160	4	5			X

Table 1
(Continued)

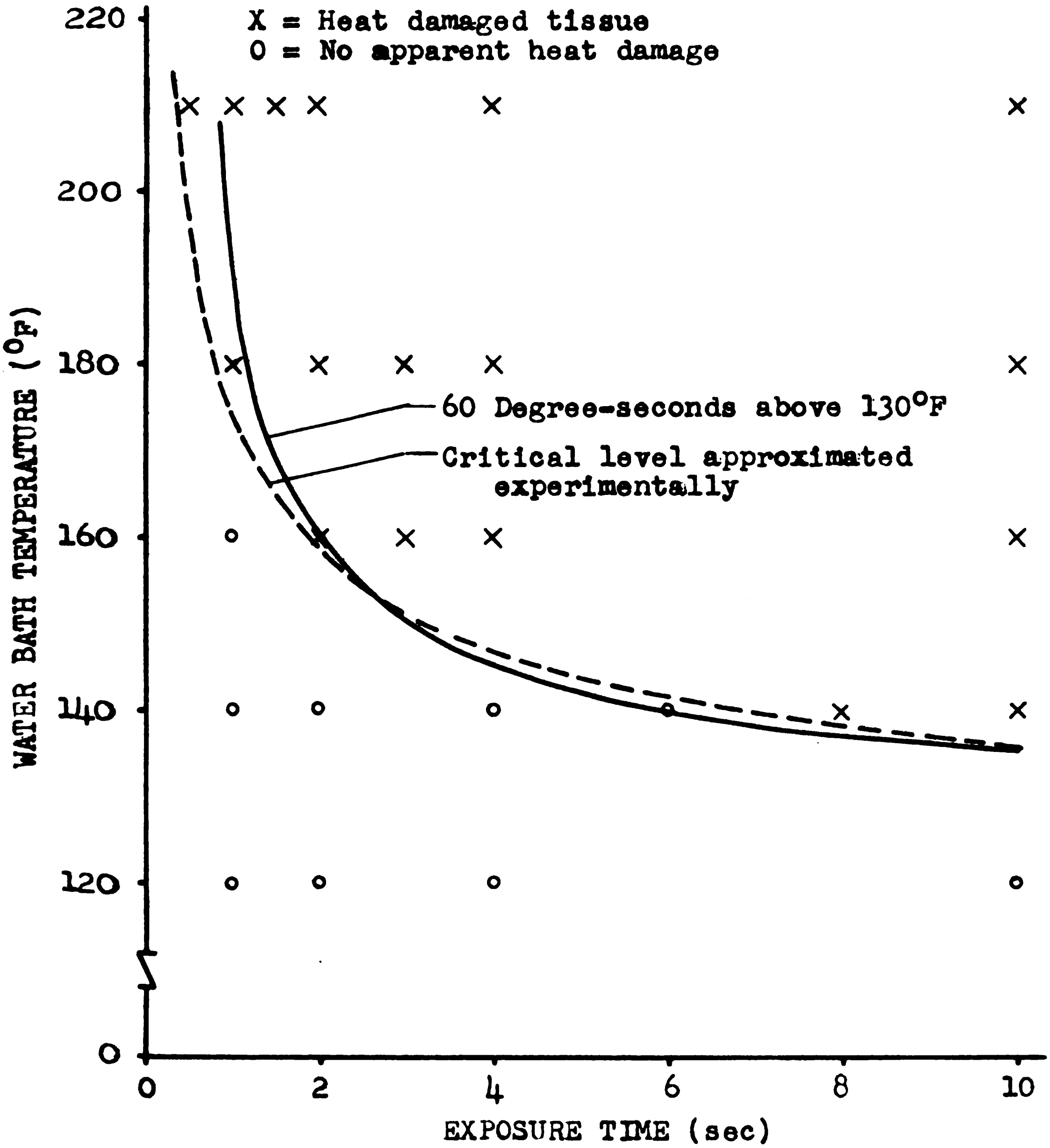
Treatment No.	Temperature of Water Bath (°F)	Time of Sample Exposure (Seconds)	Internode of Stem Above Ground	Density of Sample (lbs/ft^3)	Moisture Content (% D.B.)	Observations for Stem Tissue (0=Not Dead, X=Dead)
29	160	1	7	27.50	363	0
30	160	2	7			X
31	160	3	7	51.25	650	X
32	160	4	7			X
33	180	1	1	60.00	567	X
34	180	2	1			X
35	180	3	1	53.75	536	X
36	180	4	1			X
37	180	1	3	32.50	523	X
38	180	2	3			X
39	180	3	3	48.12	578	X
40	180	4	3			X
41	180	1	5	23.75	374	X
42	180	2	5			X
43	180	3	5	40.62	580	X
44	180	4	5			X
45	180	1	7	20.62	308	X
46	180	2	7			X
47	180	3	7	46.25	593	X
48	180	4	7			X
49	210	½	1			0
50	210	1	1			X
51	210	1½	1			X
52	210	2	1			X
53	210	½	3			0
54	210	1	3			X
55	210	1½	3			X
56	210	2	3			X

Table 1
(Continued)

Treatment No.	Temperature of Water Bath (°F)	Time of Sample Exposure (Seconds)	Internode of Stem Above Ground	Density of Sample (lbs/ft^3)	Moisture Content (% D.B.)	Observations for Stem Tissue (O=Not Dead, X=Dead)
57	210	½	5			X
58	210	1	5			X
59	210	1½	5			X
60	210	2	5			X
61	210	½	7			X
62	210	1	7			X
63	210	1½	7			X
64	210	2	7			X

Figure 14

EFFECTS OF TEMPERATURE vs TIME OF EXPOSURE ON CELL TISSUE OF CORN STEMS



at specific levels of heat exposure at which the plant tissue was killed, the results indicated that the lower portions of the stems of the corn plants were more heat tolerant than the upper portions. The moisture content per unit volume of stem tissue was higher for the lower portion of the plant; therefore, the total heat capacity was higher. Also, moisture was more readily available at the surface which probably resulted in evaporative cooling.

In Figure 14, a broken line was drawn connecting points immediately below the lowest points of cell kill for each exposure time. This dotted line represents the approximate critical level for exposure of corn stem segments to heat. The line very closely approximates a level of 60 degree-seconds of exposure above a base line of 130° F.

The critical level for heat exposure is an important factor for most plants and plant products. This factor would be important in developing flame weeding recommendations, crop processing techniques including curing and drying, and other recommendations related to heat exposure.

Measurement of the surface temperatures obtained when segments of corn stems were exposed to heat was attempted with a small thermocouple (.02 inch o.d.). These temperatures were not consistent with any particular characteristic of the stem segments. Considerable difficulty was encountered with the placement of the thermocouple on the surfaces of the samples. An exposure time of two seconds with the electric furnace was used for these studies. Relatively uniform heating over the surface of the samples was obtained with this system. As this heat source was primarily radiation, the time of two seconds was used to reach a surface temperature comparable to that reported earlier and illustrated in Figure 11.

A chromel-alumel thermocouple probe, 0.02 inch diameter, was imbedded in a knife slit on the surface of the sample. It was attempted to place the level of the thermocouple as near the level of the surface of the sample as possible. Large errors would have been introduced with the thermocouple attached to the outside of the surface of the sample. This would produce a fin effect resulting in indications of the temperature of the heat source rather than the sample.

Attempts to use temperature indicating lacquers were unsuccessful, as it was very difficult to interpret the zone of actual temperature indication. Surface radiometers could not be used with flame as a heat source because radiation of the flaming particles introduce large radiation errors. They could not be used with the electric furnace because the resolution was not small enough to sense only the surface of the sample and the furnace completely enclosed the sample as it was heating.

A thermocouple was used, therefore, for this portion of the study.

The surface temperatures recorded are tabulated in Table 2 and plotted in the graphs that follow. Figure 15 shows the results obtained for the relationship between the internode of the stems of the corn plants and the surface temperature obtained when exposed to 2000° F for two seconds with the electric furnace. Correlation was poor between the surface temperature and the stem internode above the surface of the ground. Likewise, the correlations were poor between the surface temperature and stem diameter and between the surface temperature and the density of the stem samples as shown in Figures 16 and 17. The maximum

Table 2

SURFACE TEMPERATURES OBTAINED WITH STEM SEGMENTS OF CORN PLANTS EXPOSED TO 2000° F FOR TWO SECONDS

Treatment No.	Internode	Stem Diameter (In)	Stem Density (lb/ft^3)	Maximum Surface Temperature (°F)
1	1	0.50	57.0	315
2	1	1.00	58.2	315
3	1	1.00	64.5	322
4	1	1.10	58.2	233
5	1	0.84	63.6	520
6	1	0.68	62.5	288
7	1	0.64	62.6	554
8	1	0.72	57.3	274
9	1	0.75	63.0	254
10	3	0.44	50.6	431
11	3	0.85	38.4	541
12	3	1.00	31.8	409
13	3	0.75	37.2	346
14	3	0.60	47.1	470
15	3	0.58	47.2	299
16	3	0.60	28.9	306
17	3	0.68	41.2	256
18	5	0.40	50.0	415
19	5	0.79	31.1	294
20	5	0.90	21.2	330
21	5	0.65	26.6	234
22	5	0.52	31.6	375
23	5	0.50	38.6	253
24	5	0.55	22.9	284
25	5	0.55	24.3	494
26	7	0.28	48.9	348
27	7	0.71	40.2	294
28	7	0.57	28.8	425
29	7	0.70	20.8	447
30	7	0.55	28.0	312
31	7	0.50	28.5	307
32	7	0.40	48.3	257
33	7	0.50	23.5	287

Figure 15

THE SURFACE TEMPERATURE OBTAINED ON SEGMENTS OF CORN STEMS EXPOSED TO 2000° F FOR TWO SECONDS AS AFFECTED BY THE HEIGHT ON THE STALK AT WHICH THE SAMPLE IS TAKEN

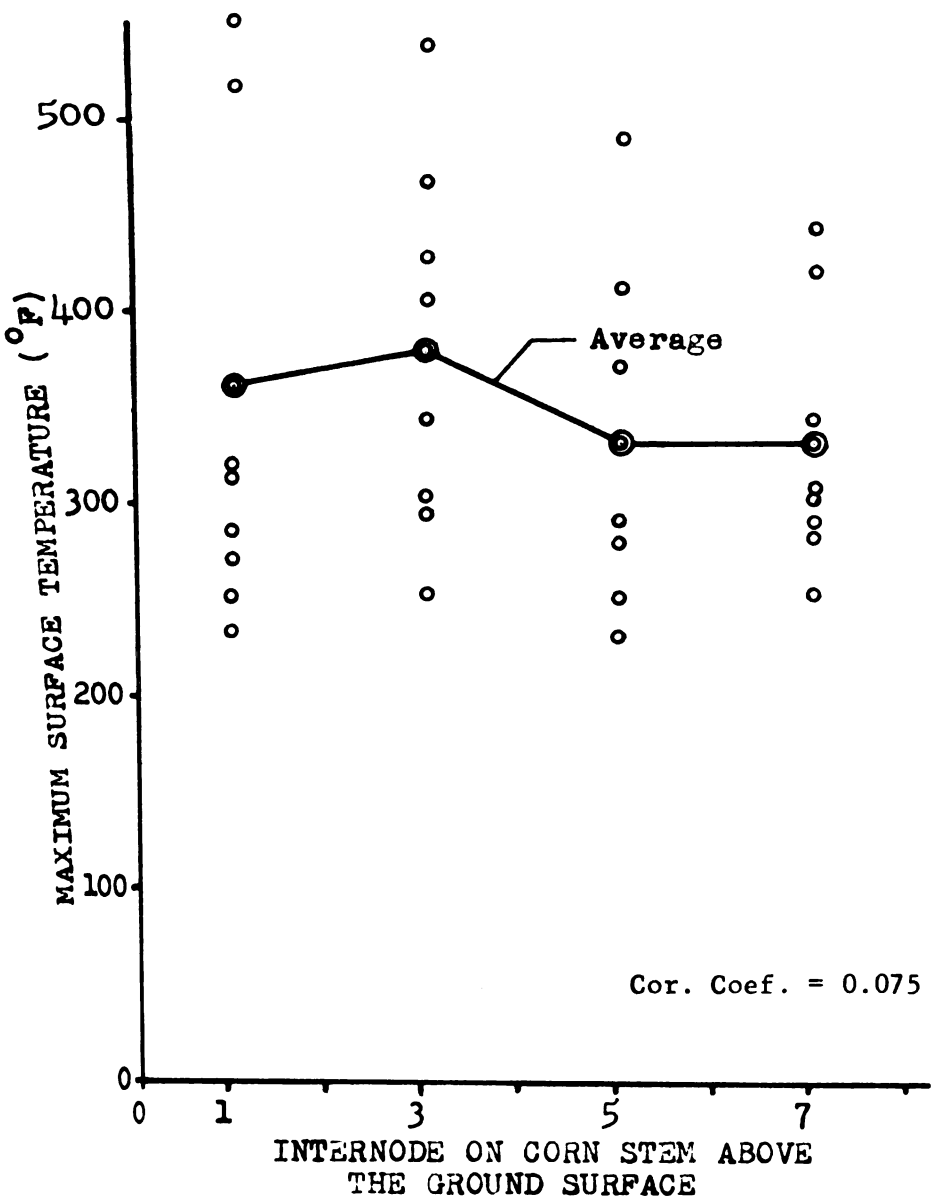


Figure 16

THE SURFACE TEMPERATURE OBTAINED ON SEGMENTS OF CORN STEMS EXPOSED TO 2000° F FOR TWO SECONDS AS AFFECTED BY THE DIAMETER OF THE STEM

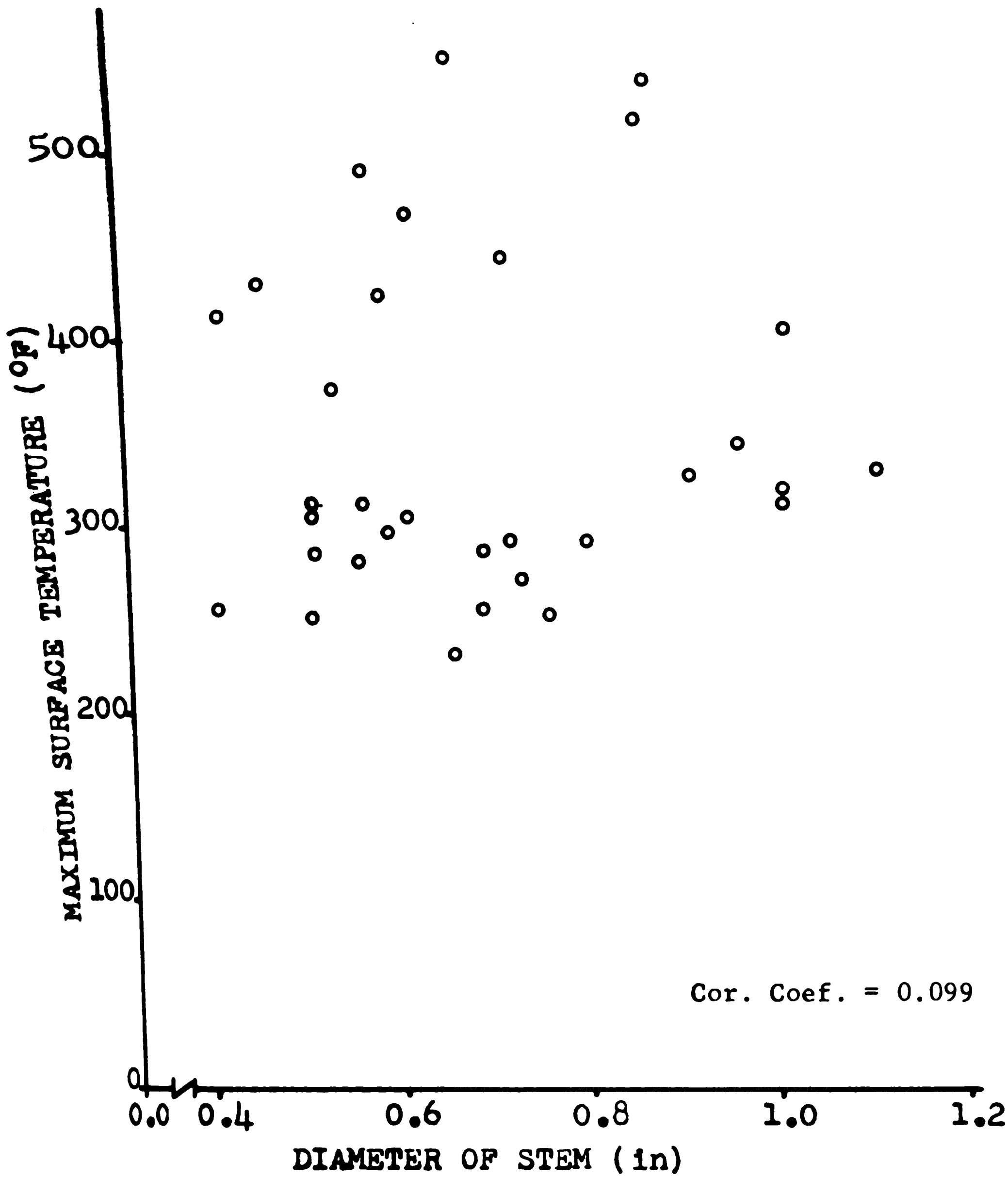
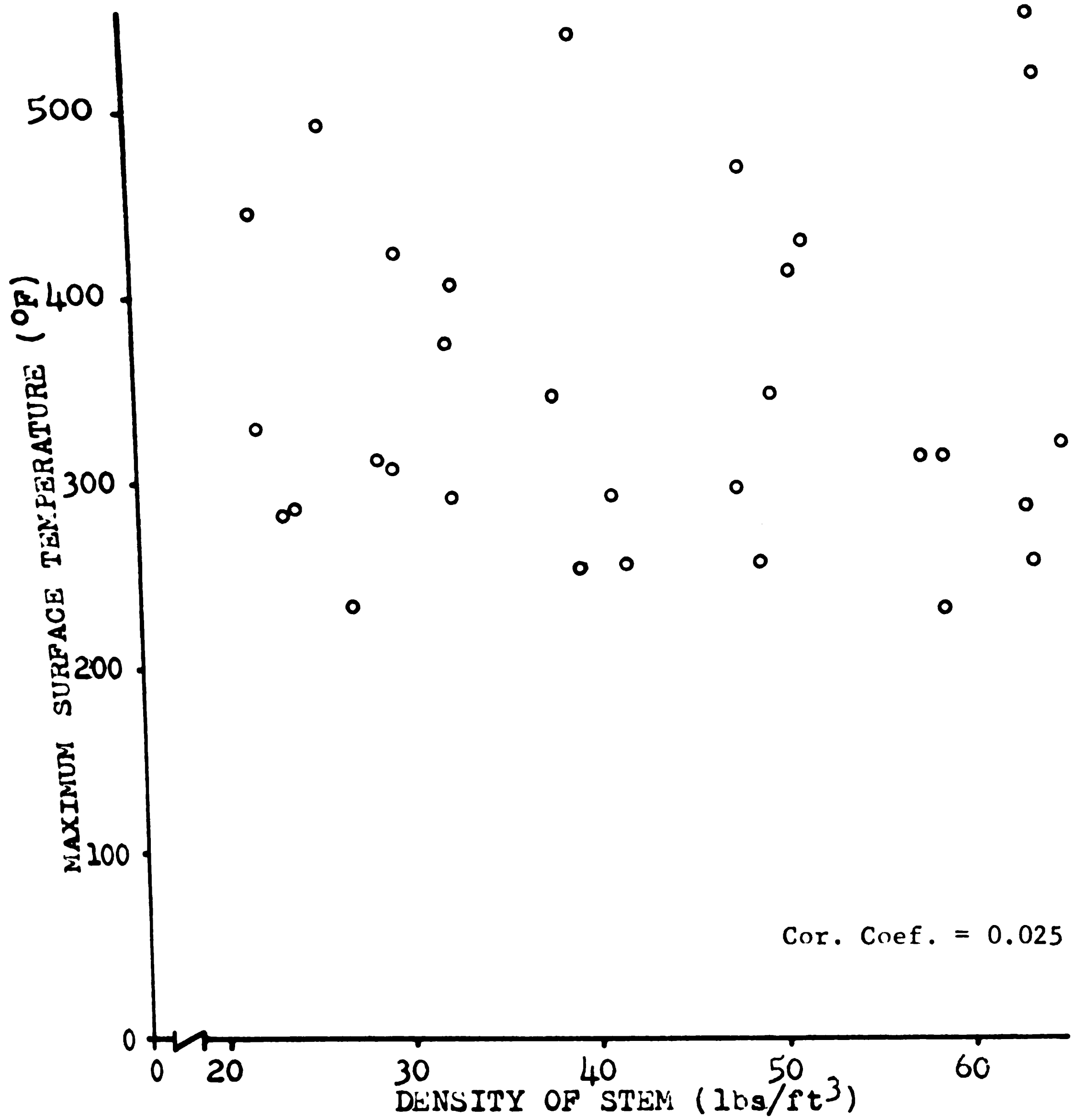


Figure 17

THE SURFACE TEMPERATURE OBTAINED ON SEGMENTS OF CORN STEMS EXPOSED TO 2000° F FOR TWO SECONDS AS AFFECTED BY THE DENSITY OF THE STEM



surface temperature recorded when exposing a corn stem segment to 2000° F for two seconds was 554° F and the minimum was 233° F.

The inconsistency of data obtained in these experiments can be related in part to the non-uniformity of the characteristics of the corn stem segments and partly to the faulty location of the thermocouple. For example, attempts were made to measure the densities and moisture contents of segments of the stems. Though all of the plants were approximately the same age, it was found that the densities for all nodes ranged from 20.0 to 72.5 pounds per cubic foot. The overall variation of moisture contents on a dry basis for all internodes was 248 to 772 percent; however, the greatest variations for an internode was for the seventh internode, for which the moisture content varied from 248 to 772 percent. On a wet basis, however, the overall variation in moisture contents was from 71.3 to 88.5 percent. The relationship between density and the internode of the corn stem above the ground is shown in Figure 18. Obviously, the density of the stem does not vary linearly from the ground to the top of the corn plant.

The relationship between moisture content and the internode of the corn stem above the ground is shown in Figure 19. It is difficult to describe accurately the physical characteristics of the stem of a corn plant. These characteristics are important, however, when attempting to relate reactions of prediction models with reactions of the plant. Therefore, predictions of temperature distributions within the stem of a plant cannot be very reliable unless more accurate measurements of the physical characteristics are made.

Figure 18

THE RELATIONSHIP BETWEEN THE DENSITY OF A
CORN STEM AND THE HEIGHT ON THE
STALK AT WHICH THE SAMPLE
IS TAKEN

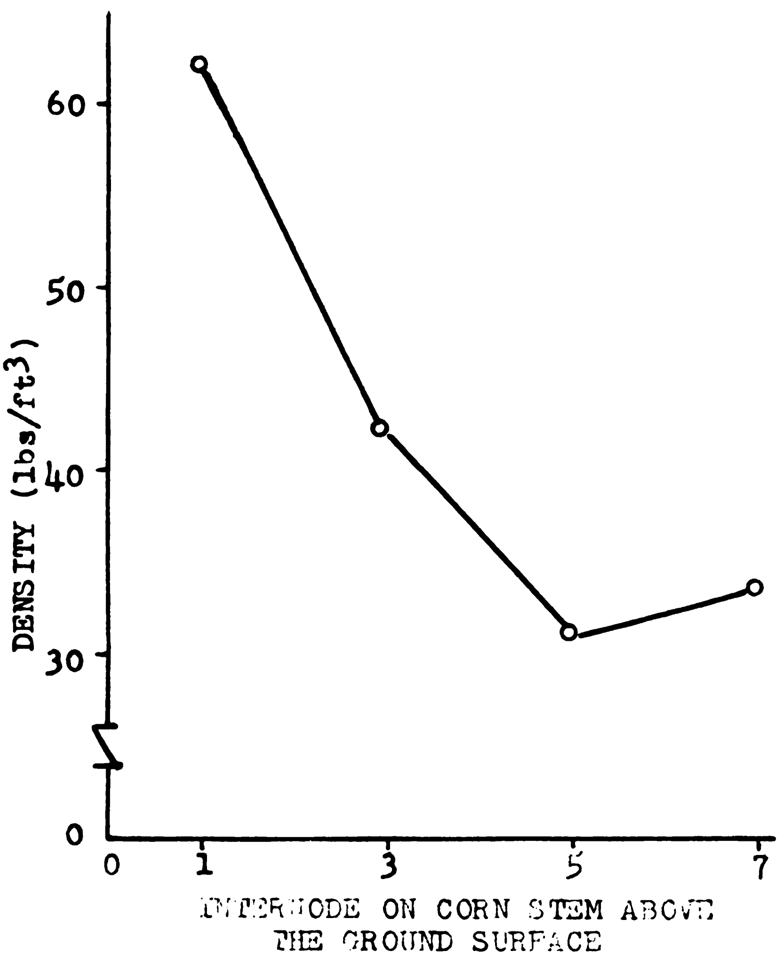
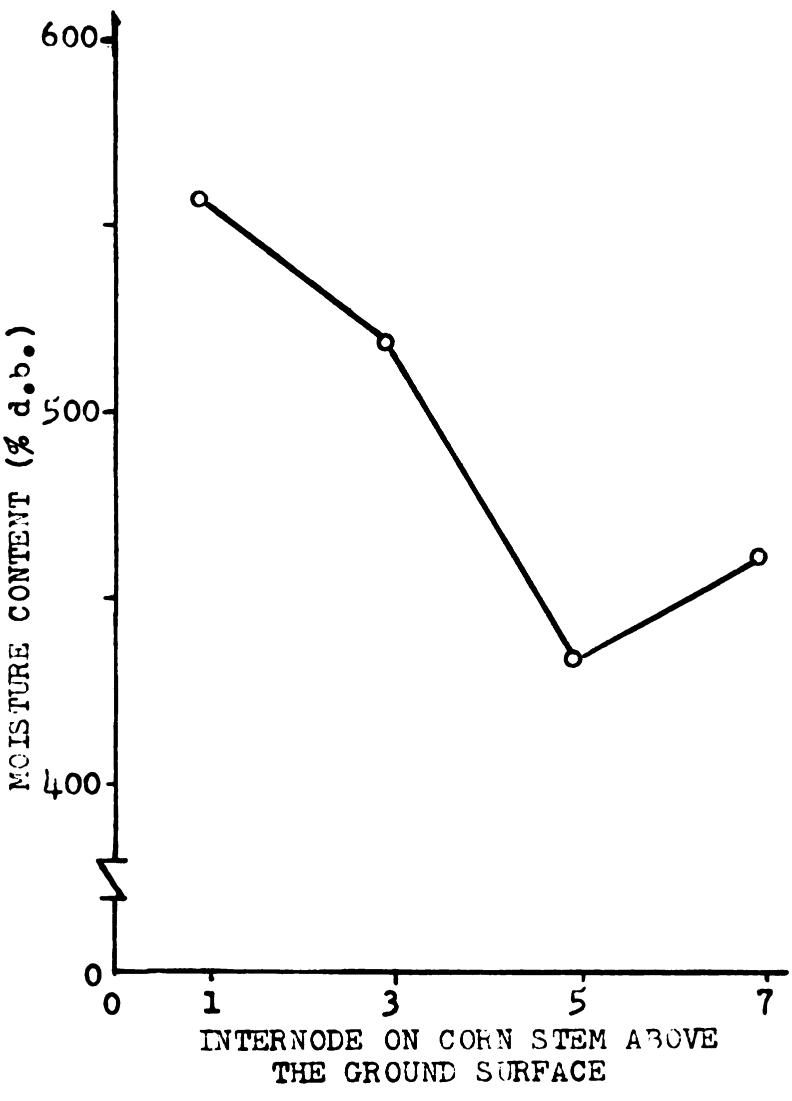


Figure 19

THE RELATIONSHIP BETWEEN THE MOISTURE CONTENT OF A CORN STEM AND THE HEIGHT ON THE STALK AT WHICH THE SAMPLE IS TAKEN



The loss of moisture from the sample during heating was always less than 0.5 percent (w.b.); however, the total loss for the heating and cooling cycle was approximately 1.0 percent. Although the moisture loss was relatively small, all occurred from a very thin layer at the surface of the sample and from the ends. As the heat was applied to the surface for a short period of time, the evaporative cooling effect of the moisture could be significant.

DISCUSSION OF PARAMETRIC EFFECTS

The influence of any one parameter on the temperature distribution in a body cannot be entirely separated from the remaining parameters. It was difficult, if not impossible, to allow changes in one parameter in real cases without causing a change in one or more of the other parameters. For each parameter study, the temperature distributions obtained were compared with the temperatures obtained with the assumed standard sample illustrated in Figure 20.

A discussion follows for each parameter and its influence on the temperature and, in some cases, its influence on one or more of the other parameters.

1) h_H (BTU/Hr Ft^2 F) -- overall heat transfer coefficient for the surface during heating.

The temperature at the surface of the model is directly proportional at any given time to the magnitude of the surface coefficient for heat transfer as shown in Figure 21. This effect is further explained under a following section discussing the influences of the diameter of the body. Additionally, the influence of the surface coefficient is

Figure 20

TEMPERATURE DISTRIBUTION HISTORY FOR THE STANDARD SAMPLE USED IN THIS STUDY

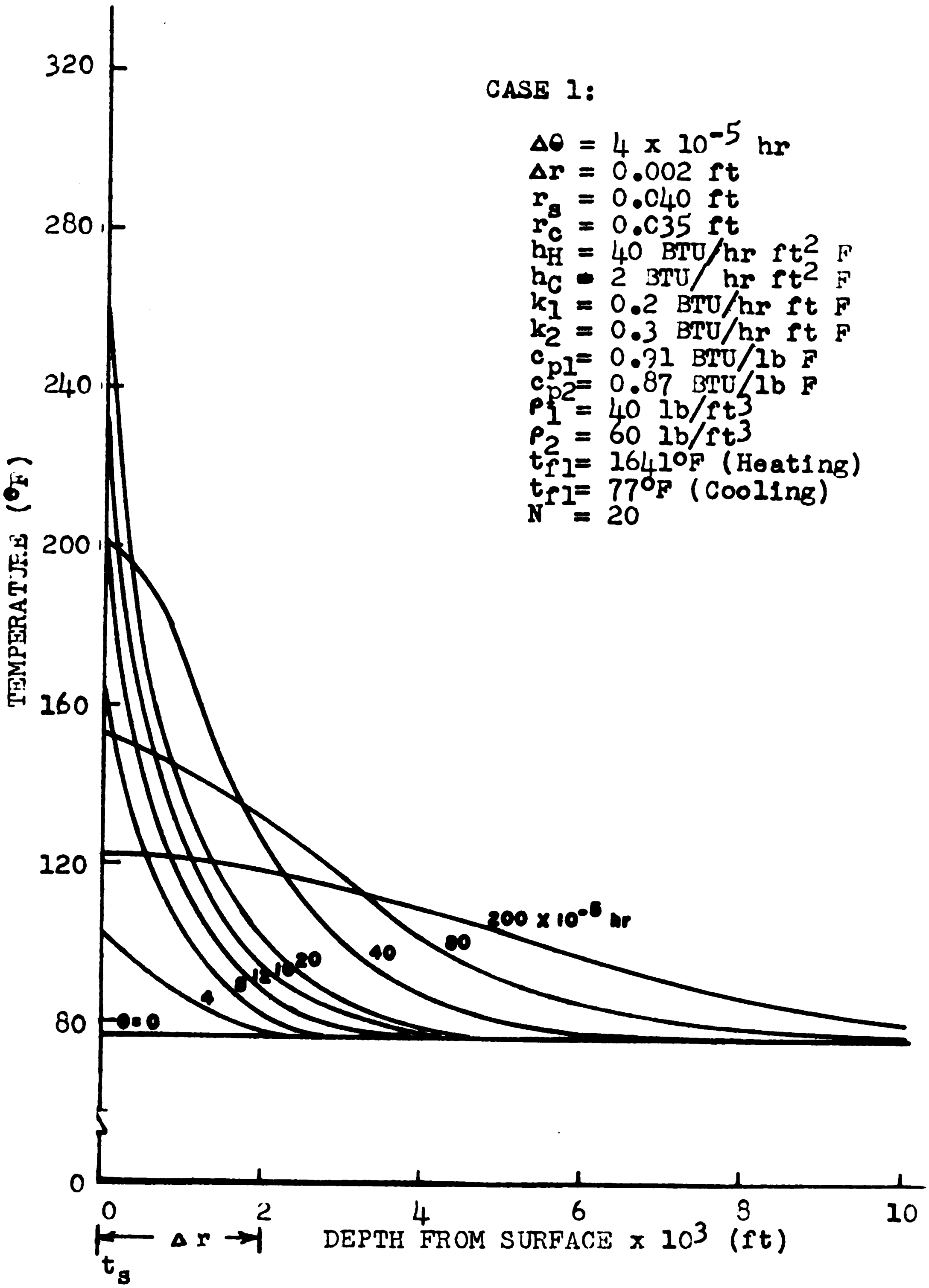
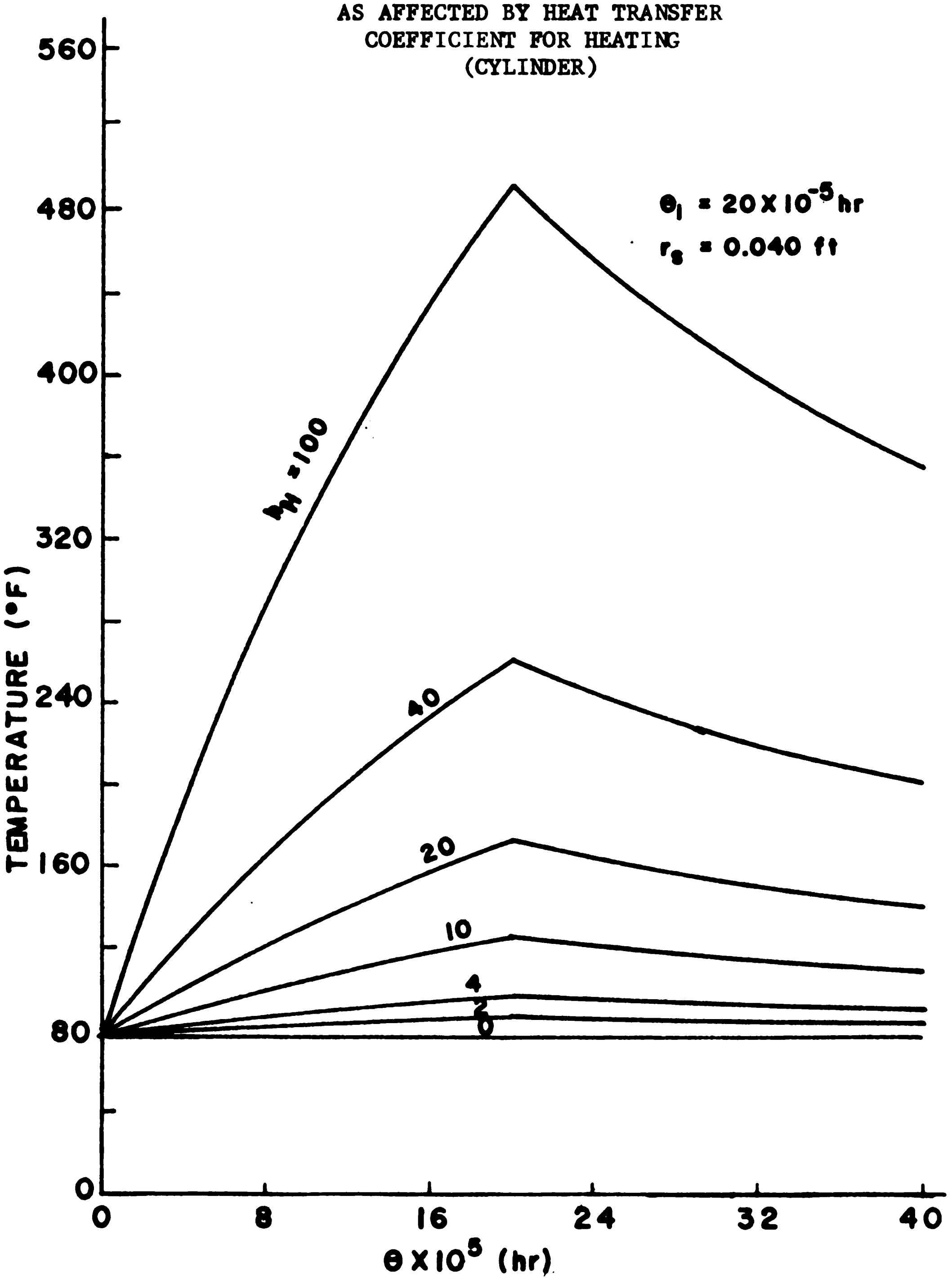


Figure 21

TEMPERATURE AT THE SURFACE
AS AFFECTED BY HEAT TRANSFER
COEFFICIENT FOR HEATING
(CYLINDER)



directly related to the temperature of the surrounding fluid (heat source).

The heat transfer coefficient included portions of radiation, convection and conduction heat transfer as an open flame was used as the source. The extremely rapid change from heating to cooling made it very difficult to accurately describe the surface temperatures.

2) h_C (BTU/Hr Ft^2 F) -- overall heat transfer coefficient for the surface during cooling.

As the temperature of the surrounding fluid was considered to be relatively low during cooling, a change in the value of the heat transfer coefficient for the surface had very little effect on the surface temperature of the model. This can be seen in Figure 22. The surface heat transfer coefficient for the cooling period included primarily free convective heat transfer into atmospheric air.

3) k (BTU/Hr Ft F) -- thermal conductivity of the model.

The thermal conductivity factor of the model was not assumed to be a function of temperature and was assumed to be constant in radial segments of a cylindrical body. A step change, therefore, was assumed to occur at a critical radius of 0.035 ft.

As illustrated in Figure 23, the thermal conductivity in the radial segment nearest the surface of the model played a very important part in the temperature distribution. The higher thermal conductivity factors resulted in lower temperatures at the surface. During heating, the heat was conducted away from the surface more rapidly by high thermal conductivity and the heat was made more readily available for dissipation from the surface during cooling.

Figure 22

TEMPERATURE AT THE SURFACE
AS AFFECTED BY HEAT TRANSFER
COEFFICIENT FOR COOLING
(CYLINDER)

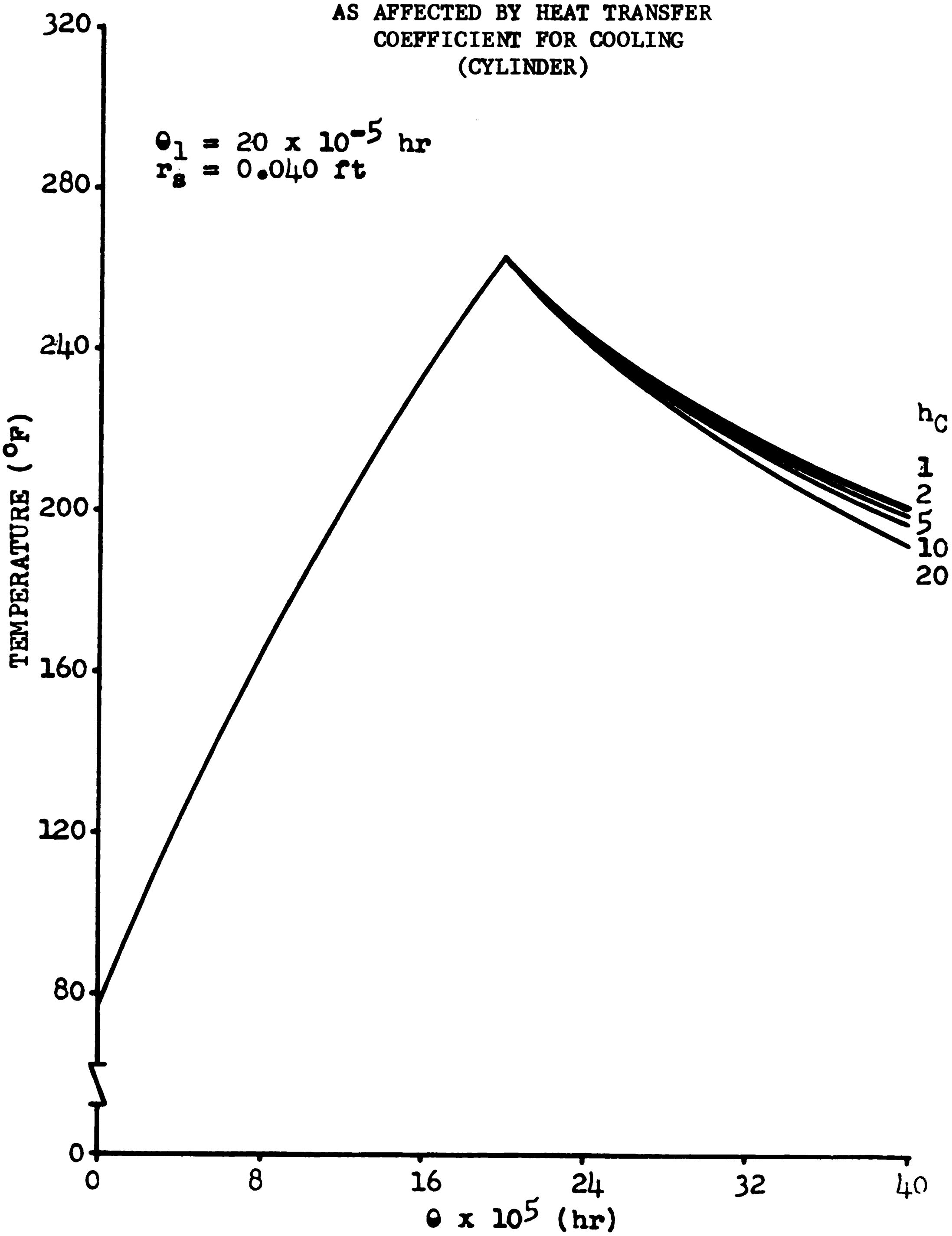
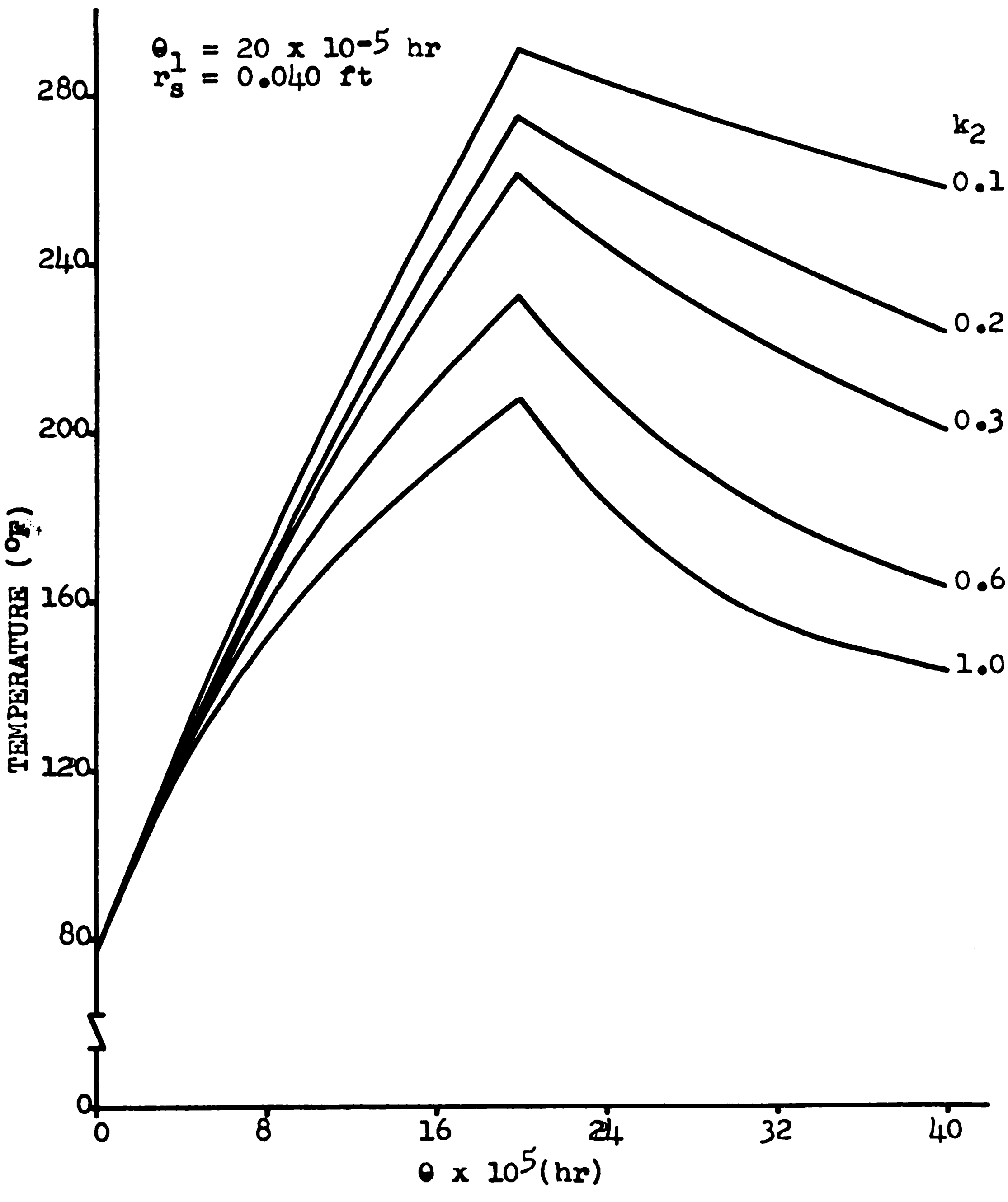


Figure 23

SURFACE TEMPERATURE AS AFFECTED BY THERMAL CONDUCTIVITY FOR $r > r_c$ (CYLINDER)



The thermal conductivity of the radial segment smaller than r_c had no effect on the surface temperature for the heating time considered.

At a position of 0.004 ft from the surface of the cylinder, higher thermal conductivity values in the segment greater than r_c resulted in more rapid temperature changes. The effect was not as pronounced for changes in thermal conductivity for the segment less than r_c. These effects are illustrated in Figures 24 and 25.

4) c_p (BTU/Lb F) -- specific heat of the model.

The specific heat was assumed to be constant and uniform in radial segments of the cylindrical body. One stepwise change in specific heat was assumed to occur at the critical radius, r_c.

The changes considered in the specific heat had no appreciable effect on the temperature distribution of the body. A very slight effect was found for changes in the specific heat at $r > r_c$. This effect as shown in Figure 26 for the surface of the model was inversely related to the magnitude of the specific heat.

As shown in Figure 27, the effects of changes in specific heat at a depth of 0.004 ft were very slight for $r > r_c$ and there were no effects from changes at $r \leq r_c$.

5) ρ (Lb/Ft^3) -- density of model.

The density was assumed to be constant and uniform in radial segments in the cylindrical model. One stepwise change in density was assumed at the critical radius, r_c.

Figure 24

TEMPERATURE AT A DEPTH OF 0.004 FT AS
AFFECTED BY THE THERMAL CONDUCTIVITY AT $r < r_c$
(CYLINDER)

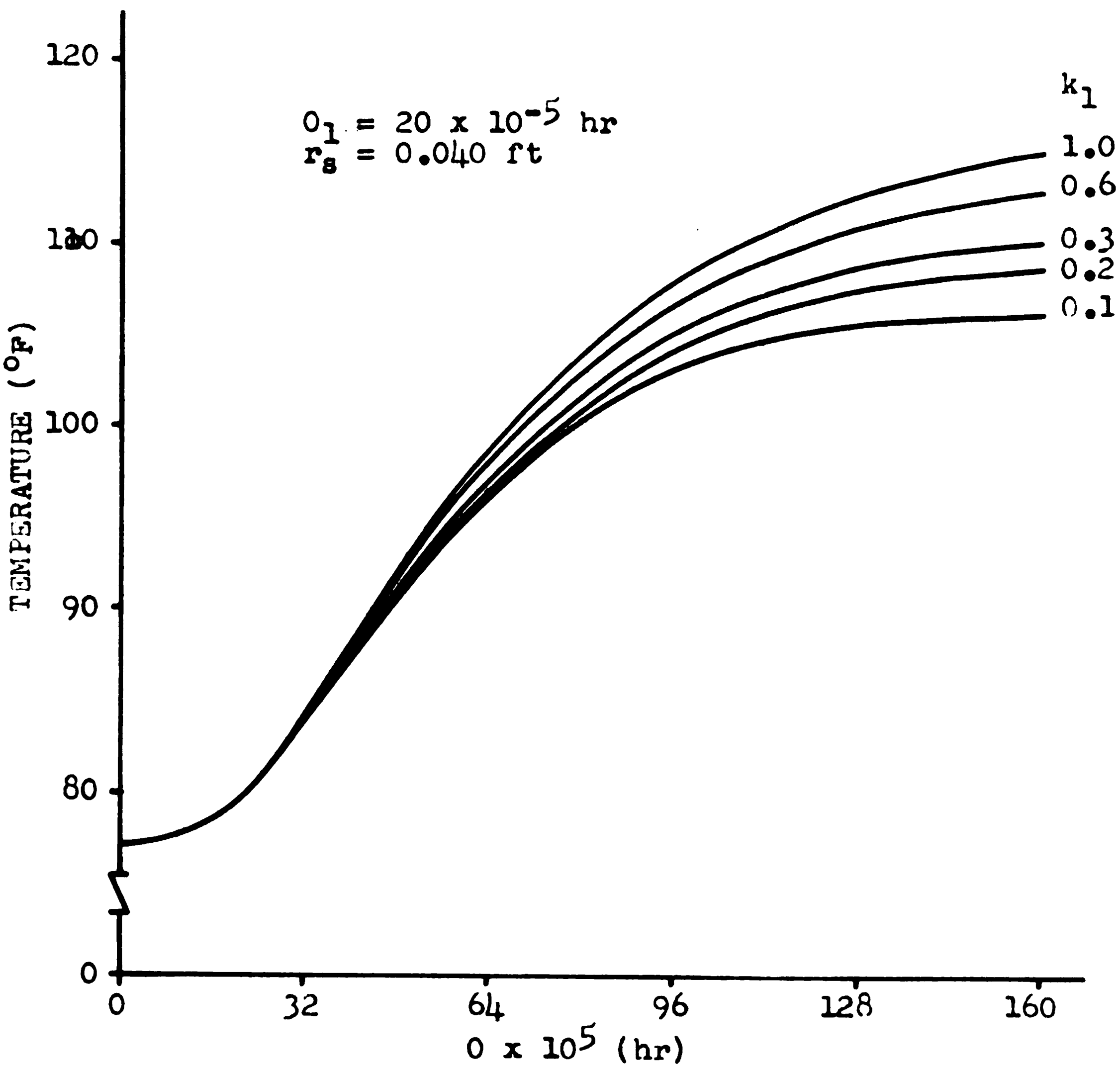


Figure 25

TEMPERATURE AT A DEPTH OF 0.004 FT
AS AFFECTED BY THE THERMAL CONDUCTIVITY AT $r > r_c$
(CYLINDER)

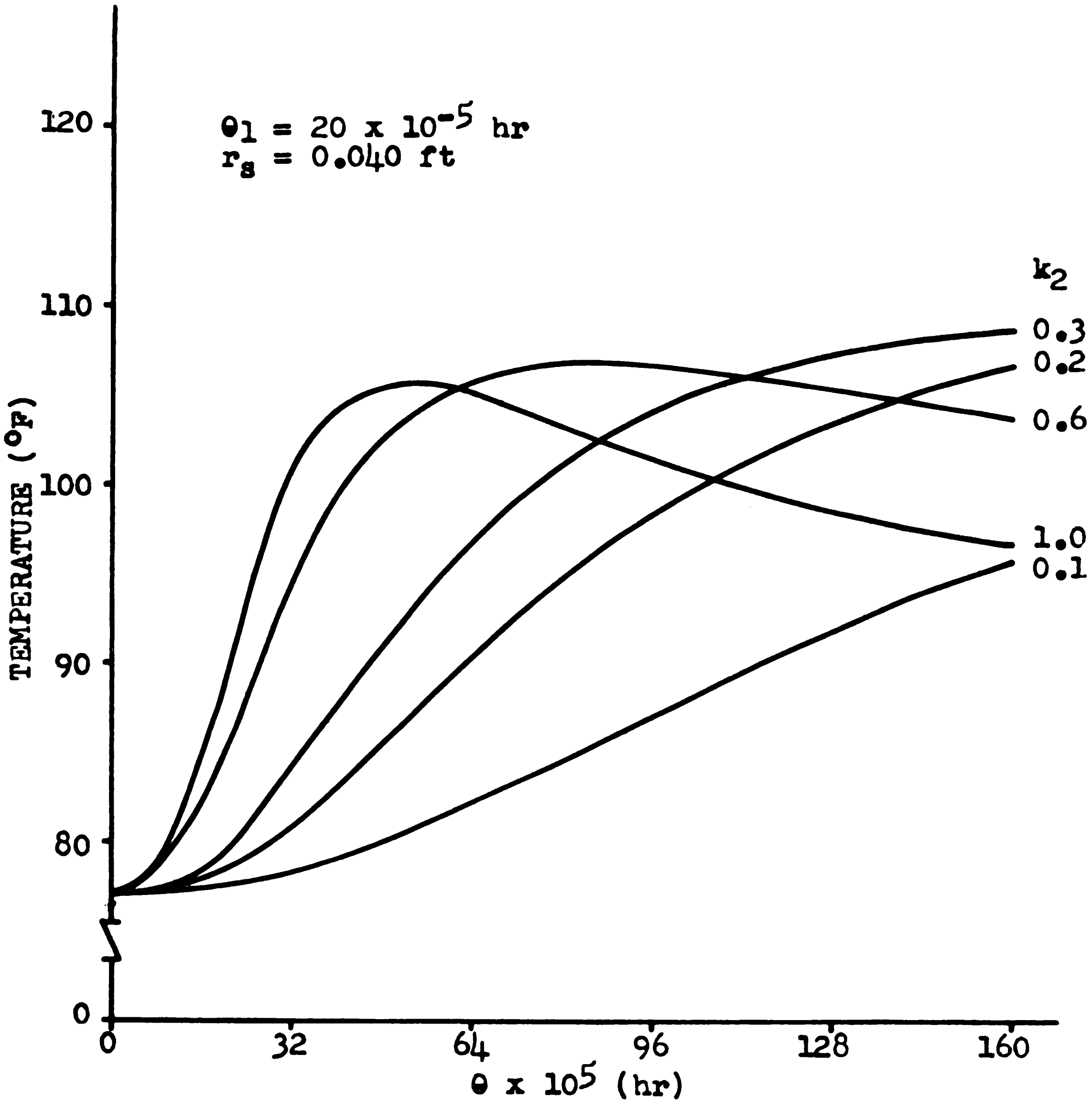


Figure 26

SURFACE TEMPERATURE AS AFFECTED
BY SPECIFIC HEAT FOR $r > r_c$
(CYLINDER)

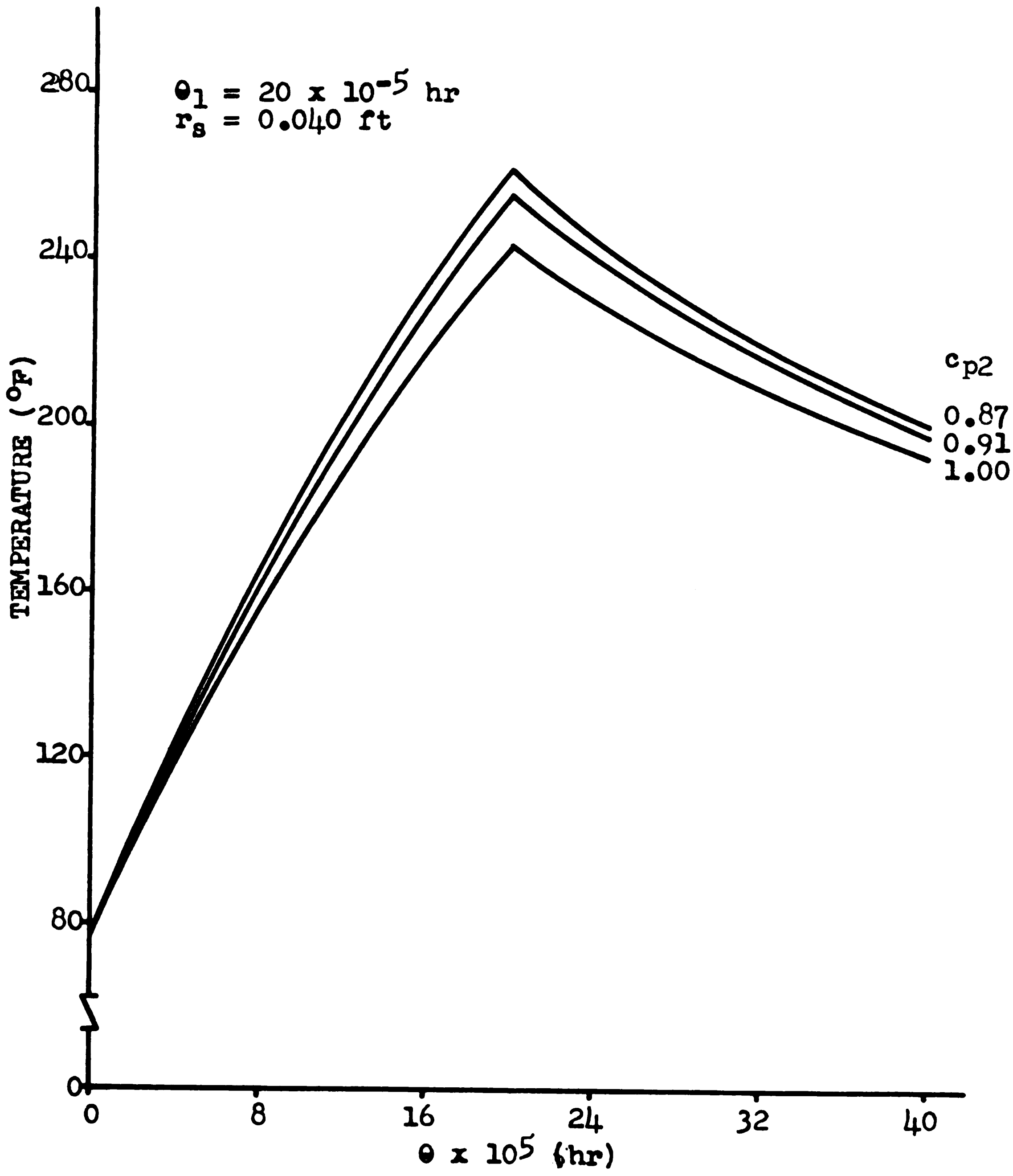
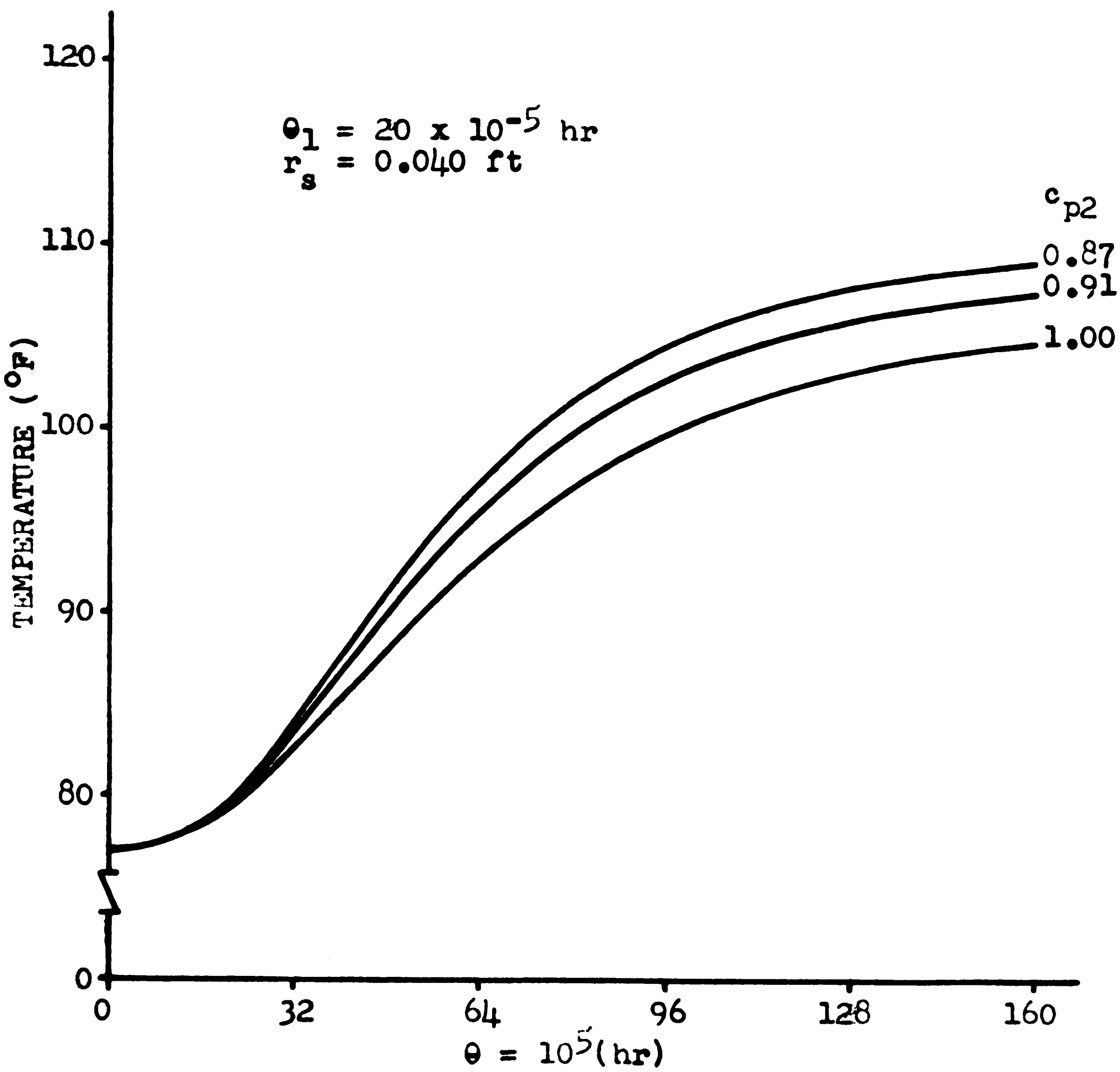


Figure 27

TEMPERATURE AT A DEPTH OF 0.004 FT AS AFFECTED BY SPECIFIC HEAT FOR $r > r_c$ (CYLINDER)



For the segment less than r_c, a change in the density had no noticeable effect on the temperature distribution.

A change in density for the segment greater than r_c, however, had a very pronounced effect on the surface temperature, which resulted in an important effect at a depth of 0.004 ft from the surface. See Figure 28 for the effects at the surface and Figure 29 for the resulting effects at a depth of 0.004 ft. A 50% increase in the density resulted in approximately a 20% lower peak temperature at the surface. If sudden drying occurs in the surface layer resulting in a decreased density, a rapid increase in surface temperature can result. Under this circumstance, however, the thermal conductivity factor probably decreases at a rate comparable to the rate of decrease in density.

6) r_s (Ft) -- radius of the model.

The radius of the model had a greater potential effect on the temperature at the critical point, r_c, than any of the other parameters included in this study with the exception of the temperature of the surrounding fluid (heat source). Although this effect appeared relatively insignificant on the surface as indicated in Figure 30, the internal effect was extremely pronounced as shown in Figure 31. The temperature at the 0.004 ft depth in Figure 31 rose to 125° F in a period of 0.0016 hour (5.76 seconds) for the 0.01 foot radius and eventually peaked at 130° F in 0.004 hour (14.4 seconds). A peak temperature of 108.9° F at a similar depth in the cylinder of 0.02 ft radius was reached in a much shorter period, 0.002 hour. As the radius was increased, the time required to reach the peak temperature

Figure 28

SURFACE TEMPERATURE AS AFFECTED
BY DENSITY FOR $r > r_c$
(CYLINDER)

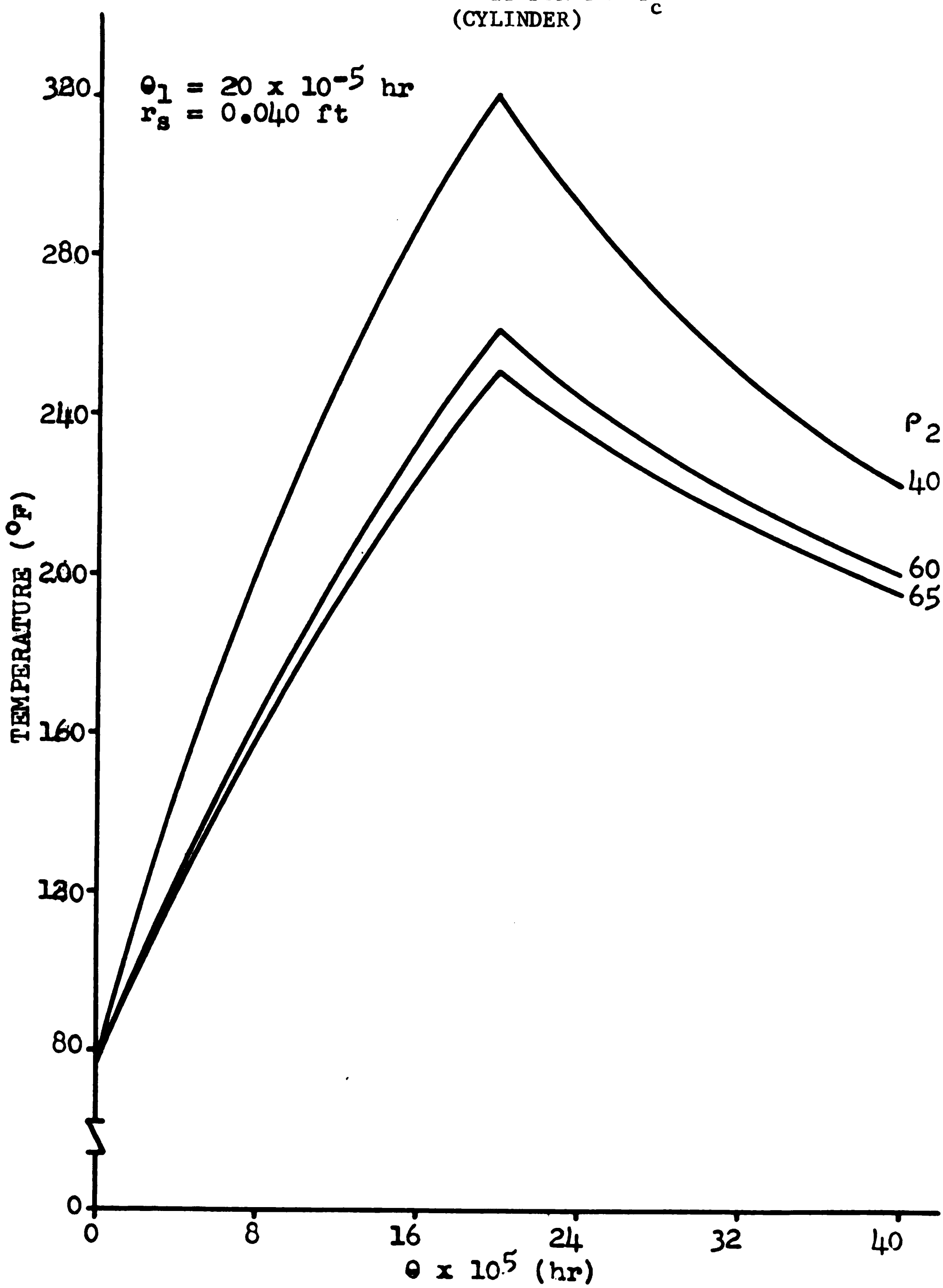


Figure 29

TEMPERATURE AT A DEPTH OF
0.004 FT AS AFFECTED BY
DENSITY AT $r > r_c$
(CYLINDER)

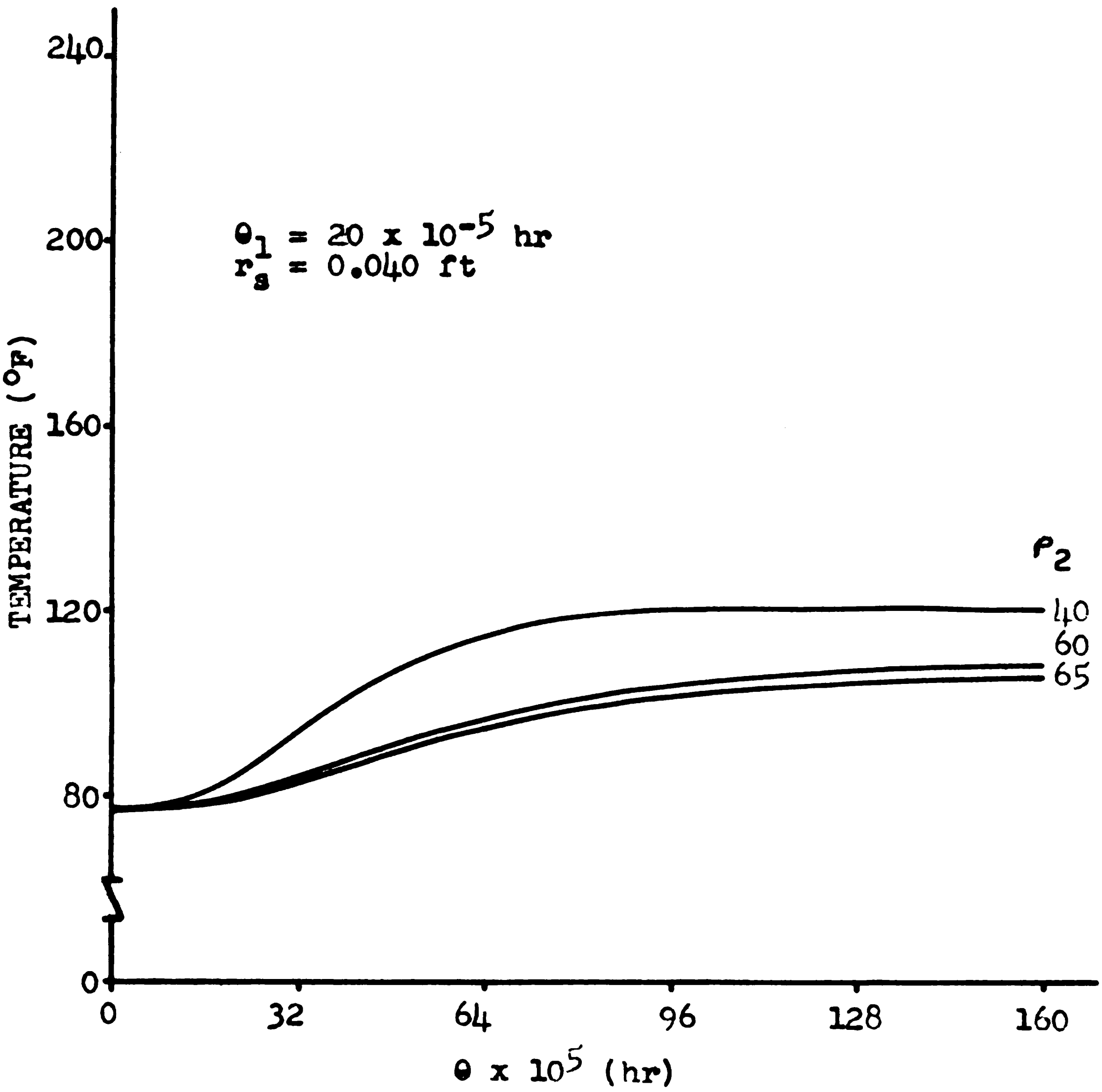


Figure 30

SURFACE TEMPERATURE OF CYLINDER AS AFFECTED BY DIAMETER

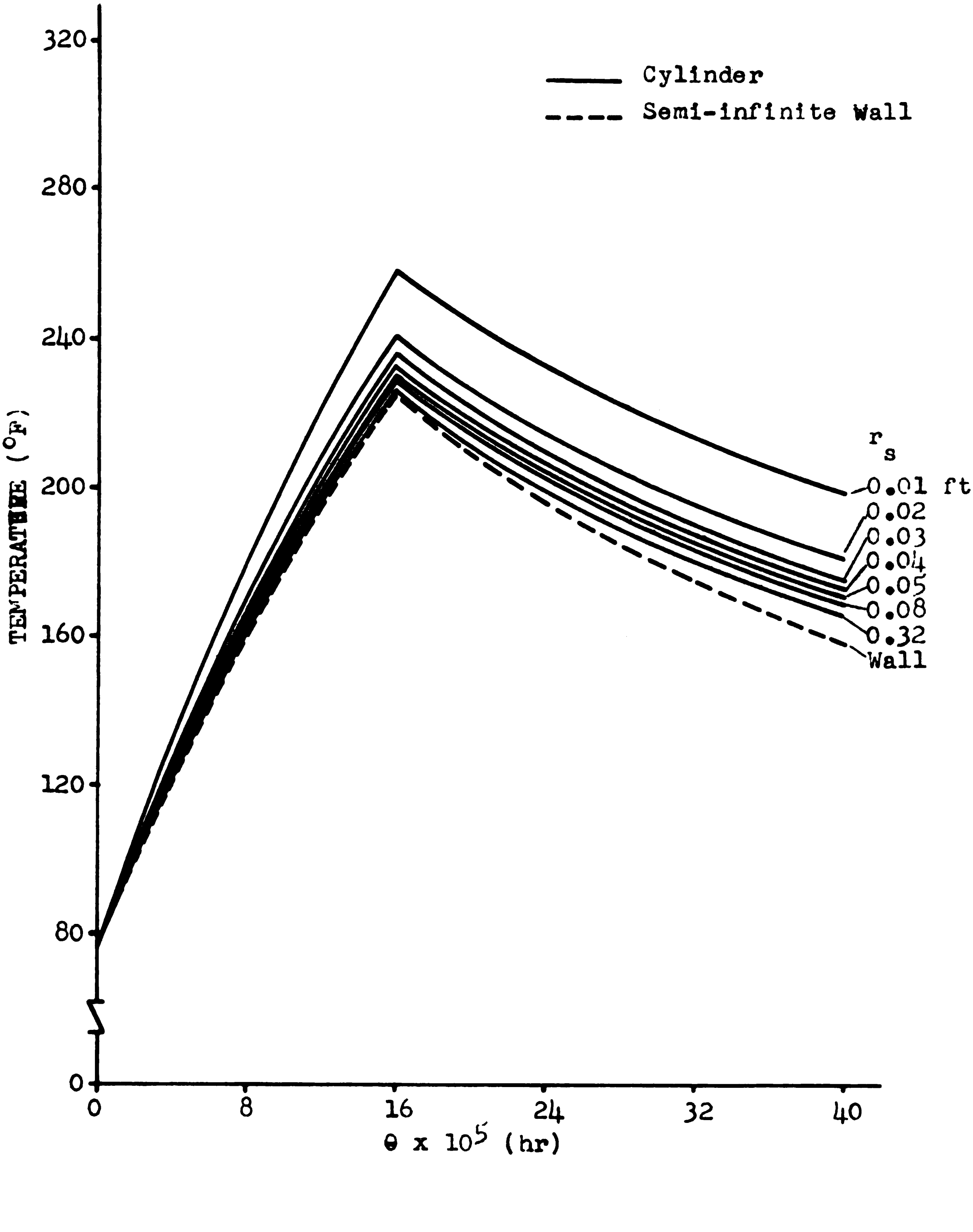
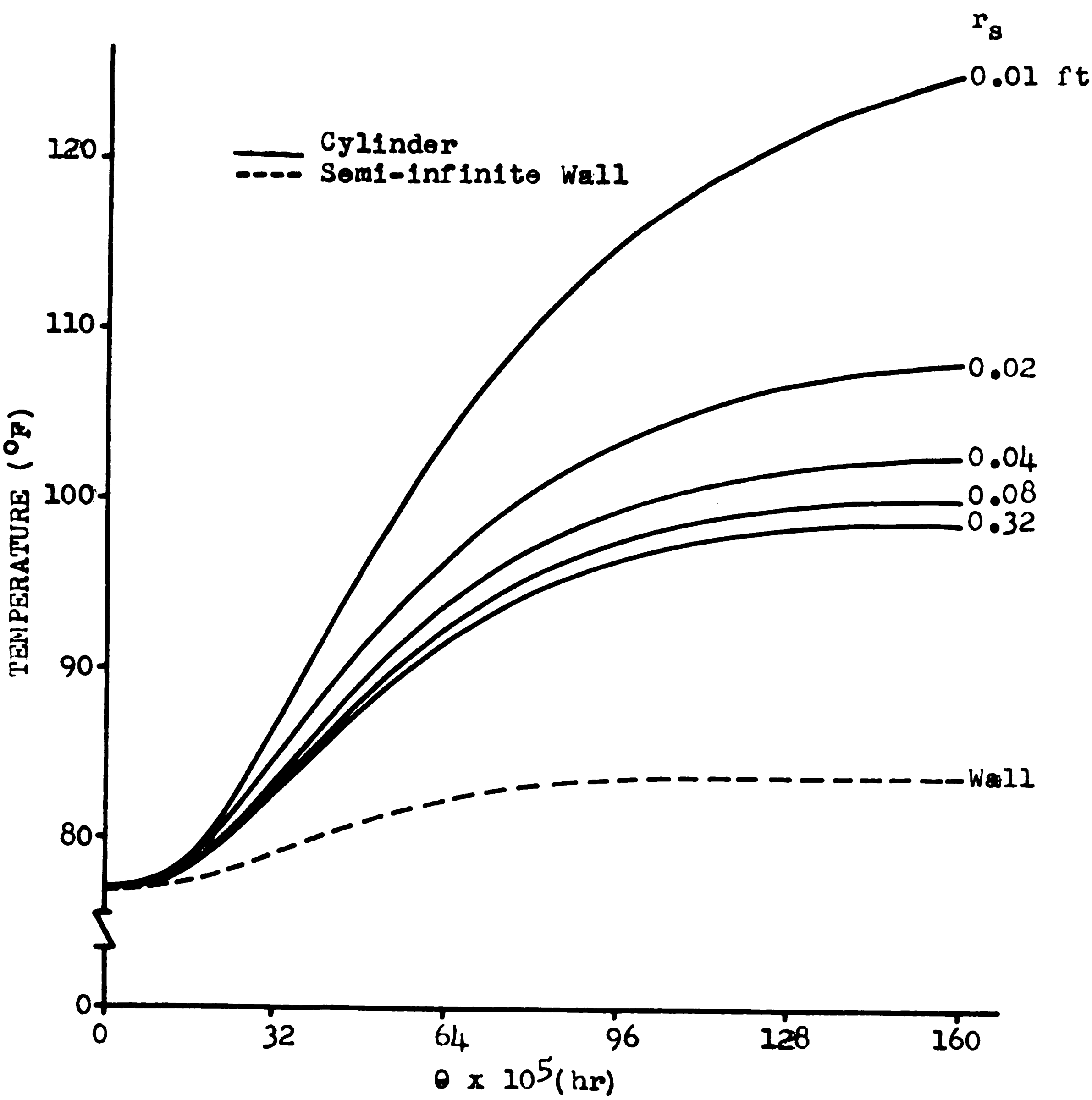


Figure 31

TEMPERATURE AT A DEPTH OF 0.002 FT
AS AFFECTED BY CYLINDER DIAMETER



continued to decrease.

The effects resulting from changes in the size of the cylinder can be caused by several factors. The surface area per unit volume per unit of length increases as the cylinder diameter decreases, thereby allowing more heat per unit of volume. A point at a given depth in a small cylinder is close to a greater surface area than at a similar depth in a large cylinder. Therefore, the temperature of a point at the considered depth in a small cylinder is influenced more readily by a rise in the surface temperature than at a comparable depth in a large cylinder.

7) t_{fl} (°F) -- temperature of fluid surrounding the model.

The surface temperature obtained was directly proportional to the temperature of the flame used as a heat source as illustrated in Figure 32.

The temperature at some fixed point in the flame was normally not constant; however, for this study, the flame temperature at the point considered was assumed to be constant. A heat source with a temperature varying from atmospheric up to 2500° F for an average temperature of 1641° F during the heating period gave a surface temperature of the model quite different from that obtained with a constant heat source at a temperature of 1641° F. See Figure 33, which indicates a higher surface temperature for the constant temperature source.

Only one fluid temperature, 77° F, was used for the cooling period.

Figure 32

SURFACE TEMPERATURE AS AFFECTED
BY SURROUNDING FLUID TEMPERATURE
(CYLINDER)

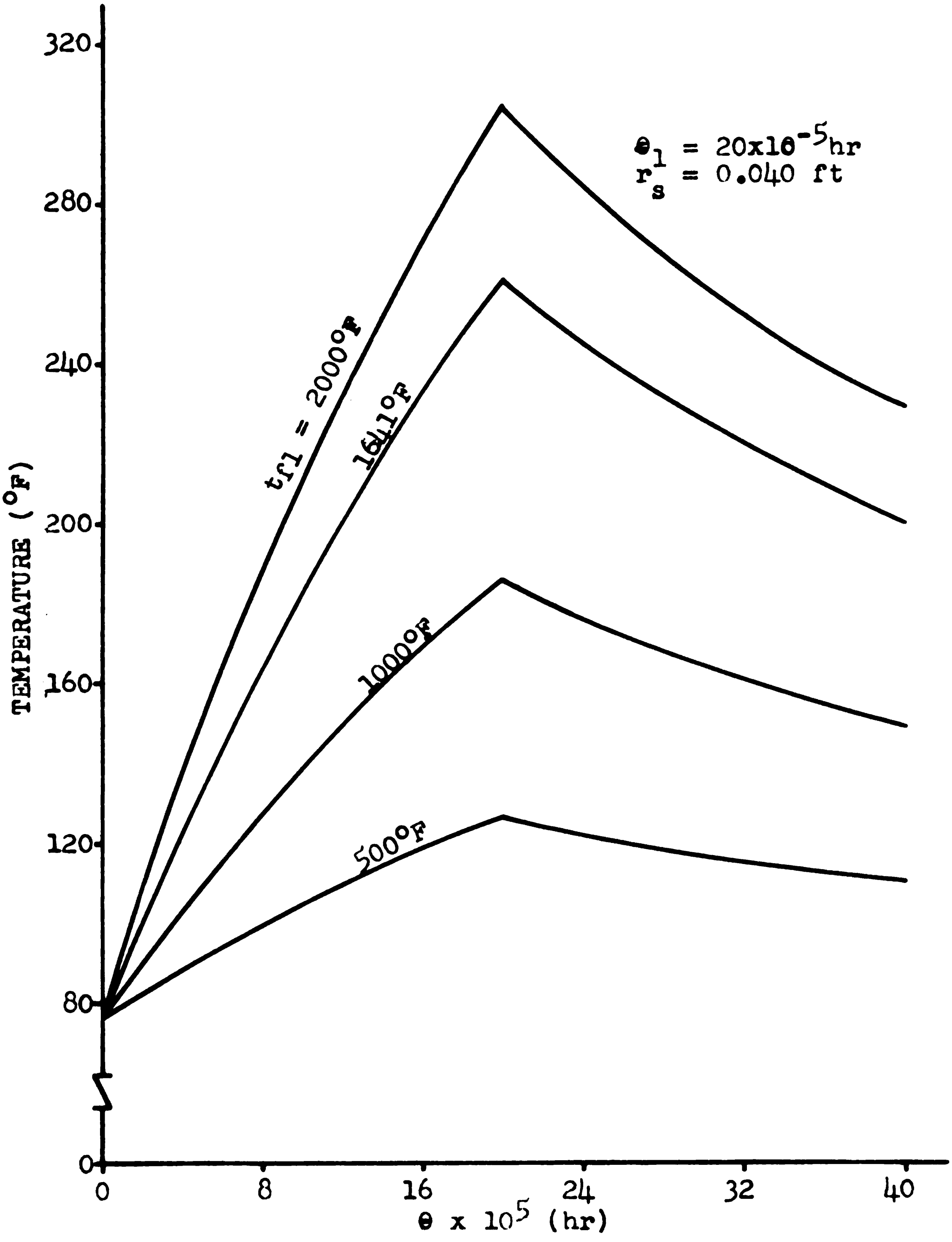
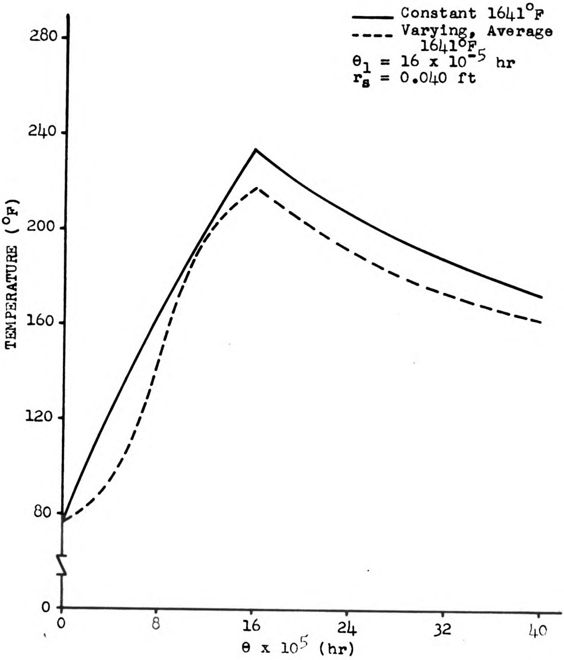


Figure 33

SURFACE TEMPERATURE WITH
CONSTANT vs VARYING HEAT SOURCE
(CYLINDER)



DISCUSSION OF ERRORS

The accuracy of the predicted temperatures by the numerical analysis procedures used is almost entirely dependent upon the accuracy of measuring or assuming the values of the contributing parameters. These parameters for biological materials vary widely due to non-homogeneity of the samples. The errors of measurement of some of the characteristics of the stems of corn plants include the following estimates:

1) Density - ± 1% - by water displacement and weighing
2) Specific heat - ± 2% by Kopelman (1966).
3) Thermal diffusivity - ± 10% - Matthews (1966).
4) Thermal conductivity - ± 12% - ($\alpha\rho c_p$)
5) Diameter - ± 1% by measurement.
6) Moisture content - ± 1% (w.b.) by oven.

To evaluate the relative effects of each of the above indicated errors, each parameter must be considered for its relative contribution to the temperature distribution. For example, the error of measuring the thermal conductivity is obviously greater than that for measuring the diameter of the sample. However, the effects of changes in the diameter are greater than a comparable percentage change in the thermal conductivity.

Kardas (1964) evaluated errors obtained when using finite-difference solutions to the heat flow equation. His analysis was for a slab with errors indicated at the surfaces and center of the slab. The procedure involves the use of two figures reported by Kardas and factors such as Biot No. (ha/k), Fourier No. ($\alpha\tau/a^2$) and r ($n^2 \Delta\theta$) in the expression,

$$\varepsilon\, n^2 = \tfrac{1}{4}\,(1 \pm 6r) \cdot E$$

where: ε = discretization error

E = error parameter from graph

a = ½ distance, r_s for cylinder

n = number of increments

These errors are less than ±2%. Likewise, Freed et al. (1961) reported that errors resulting from using finite-difference methods are less than ±2%.

Combining all of the above indicated sources of errors in the numerically approximated solution, the predicted temperatures will have an estimated error up to ±12%.

An additional source of error could be the evaporative cooling effect of the moisture losses from the surface of the plant stem. Measurements in this study indicated that approximately one-half gram of the total weight of each 100 gram sample was lost during the heating period. If all of this moisture was lost from the surface of the stem, not including the ends, the heat energy required to evaporate the moisture can be significant.

SUMMARY

The use of finite-difference techniques for describing the temperature distribution in an agricultural specimen was demonstrated. The accuracy of the calculated temperatures depended on the accuracy with which the properties of the specimen were described. The application of an earlier developed technique for measuring the thermal diffusivity of the specimen was demonstrated. This technique was found to be readily usable with some slight modification of the thermal diffusivity apparatus.

Of the parameters discussed in relation to their effects on the temperature distribution of the selected model, the diameter of the cylinder is most critical. The diameter of the plant stem is a reliable criterion for recommending intensity and time of exposure to flame for weed control in crops. The moisture content of a plant stem probably has considerable influence on the internal temperatures resulting from flaming. Although the moisture losses from the samples during heating was small (less than 1% by weight) as found in this study, significant evaporative cooling probably resulted.

A uniform temperature of the flame had a greater effect on the temperature of the body than an asymptotically increasing and decreasing temperature. For more weed kill, therefore, exposure to a constant energy source for a given period of time would be more effective than a higher energy for a shorter period of time.

SUGGESTIONS FOR FURTHER WORK

In order that processes involving the application of heat to biological materials can be better understood and recommendations be made for improving these processes, there is a real need to continue to measure and accumulate data on the physical properties of these materials. It is necessary to determine these properties as they are related to temperature and mositure content. Evaluation of the effects of moisture losses from the surface of a biological material as related to the surface temperature is an important area of study.

Techniques and equipment for measuring the surface temperatures and moisture losses from the surfaces of biological materials are needed. It is difficult to attach sensing devices such as thermocouples or thermistors to maintain intimate contact with the surface of a biological material without altering the characteristics of the surface.

The suggested procedures for predicting temperatures and determining heat damage should be tested on some fruits and vegetables, such as apples, pears, squash, potatoes and sugar beets to obtain optimum rates of applying heat if used for curing and storing them.

The effects of coupled heat and mass transfer (moisture diffusion and evaporation) were not shown. More information relative to the coupling phenomena was needed to show these effects. The heat equations and the diffusion equations could be developed though the coupling equations were not available. The heat equations would show the temperature history when the body is considered as a semi-infinitely thick wall. The resulting temperatures would be lower than those obtained for an infinitely long cylinder with similar heat exposure. Sample outputs for the temperature distributions obtained for a semi-infinite wall as well as for a long cylinder are shown in Appendix C.

Using prediction equations with properties of the body to be considered and data on the heat tolerance of the plant tissue as demonstrated, the relative damage to a plant with applied heat can be predicted.

These prediction techniques may be applicable to other processes such as curing and storing sweet potatoes, burning the leaves from sugar cane and foliage from potatoes, rapid drying of biological materials, and applying heat for defoliating cotton when physical properties of the plants and plant products are known.

APPENDIX A

List of computer symbols used:

CP1	--	c_{p_1} (BTU/Lb F) -- Specific heat ($r < r_c$).
CP2	--	c_{p_2} (BTU/Lb F) -- Specific heat ($r \geq r_c$).
DR	--	Δr (Ft) -- Radius increment.
DX	--	X (Ft) -- Depth increment.
DT	--	$\Delta\theta$ (Hr) -- Time increment.
HH	--	h_H (BTU/Hr Ft^2 F) -- Overall heat transfer coefficient ($0 < \theta \leq \theta_1$).
HC	--	h_C (BTU/Hr Ft^2 F) -- Overall heat transfer coefficient ($\theta > \theta_1$)
N	--	Number of internodes (distance increments).
NN	--	N + 1 -- Total number of nodes.
PKK1	--	k_1 (BTU/Hr Ft F) -- Thermal conductivity ($r < r_c$).
PKK2	--	k_2 (BTU/Hr Ft F) -- Thermal conductivity ($r \geq r_c$).
R	--	r (Ft) -- Radius
RC	--	r_c (Ft) -- Radius at which properties change.
RO	--	r_s (Ft) -- Outside radius.
RHO1	--	ρ_1 (Lb/Ft^3) -- Density ($r < r_c$).
RHO2	--	ρ_2 (Lb/Ft^3) -- Density ($r \geq r_c$).
T	--	t (°F) -- Temperature.
TAH	--	t_{f1}(°F) -- Temperature of surrounding fluid ($\theta \leq \theta_1$).
TAC	--	t_{f1}(°F) -- Temperature of surrounding fluid ($\theta > \theta_1$).
TT	--	θ (Hr) -- Accumulated time.
TI	--	t_i (°F) -- Initial temperature ($\theta = 0$)

X -- X (Ft) -- Depth in wall.

XC -- X_c (Ft) -- Depth at which properties change.

XL -- X_L (Ft) -- Total depth considered.

YYY -- θ (Hr) -- Total time of run.

Other computer symbols were used for calculational purposes only and were defined in comment statments in the computer programs included under Appendix B.

APPENDIX B

Sample Computer Programs used:

1) PROGRAM TEMPCYL -- to calculate the temperature distribution in a long cylinder.

2) PROGRAM TEMPWAL -- to calculate the temperature distribution in a semi-infinite wall.

```
C       PROGRAM TEMPCYL
C       FIND TEMPERATURE DISTRIBUTION IN AN INFINITE CYLINDER AF
C       TER A SHORT EXPOSURE TO FLAME UNIFORMLY OVER ITS SURFACE.
        DIMENSION A(300),B(300),C(300),D(300),T(300),R(300),
       1RK(300),CC(300),DD(300),X(300),U(300)
        COMMON A,B,C,D,T,CC,DD,TT,DT,TA,DR,RO,RHO1,RHO2,PCC1,
       1PCC2,PKK1,PKK2,CP1,CP2,H,HH,HC,RC,N,TAH,TAC,TH,DTH
C       RC=OUTSIDE RADIUS, RHO1=DENSITY AT R.LT.RC,RHO2=DENSITY
C       AT R.GT.RC, CP1=SPECIFIC HEAT AT R.LT.RC, CP2=SPECIFIC
C       HEAT AT R.GT.RC, PKK1=THERMAL CONDUCTIVITY AT R.LT.RC,
C       PKK2=THERMAL CONDUCTIVITY AT R.GT.RC,T(NN) IS THE TEMPER-
C       ATURE AT THE SURFACE.
C       T(1) IS THE TEMPERATURE AT THE CENTER.
    100 FORMAT(1X,F8.5,1X,10F8.3)
    103 READ 104,CASE,DT,YYY,RHO1,RHO2,RO,CP1,CP2,PKK1,PKK2,TH,
       1TI,N
    104 FORMAT(    F4.0,F8.5,F6.3,2F7.2,5F6.3, F7.5,F7.2,I4)
        IF(CASE.EQ.0.0)GO TO 1000
        NN=N+1
        READ 105, DTH,TNNC,TAH,TAC,HH,HC,RC
    105 FORMAT(1X,F7.5,3F7.2,2F7.2,F6.3)
        YYY=0.0060
        RC=RO-0.005
        PRINT 205
    205 FORMAT(1H1//)
        PRINT 106
    106 FORMAT(15X,42HCASE    DT         YYY    RHO1  RHO2  CP1   CP2,
       13X,11HPKK1  PKK2  /)
        PRINT 107,CASE,DT,YYY,RHO1,RHO2,CP1,CP2,PKK1,PKK2
    107 FORMAT(15X,F4.0,F8.5,F7.4,2F6.2,4F6.3//)
        PRINT 108
    108 FORMAT(19X,41H  RO     RC      HH      HC      TAH     TAC   ,
       11X,9HTI      N  /)
        PRINT 109,RO,RC,HH,HC,TAH,TAC,TI,N
    109 FORMAT(19X,2F6.3,2F7.2,3F7.1,I4//)
C       TT IS TIME,T(K) IS TEMP AT NODE K, PKKK=K, PCCC=RHO*CP
        J=0
        TT=0.0
        AN=N
        DR=RO/AN
        DO 200 KM=1,NN
    200 T(KM)=TI
C       BEGINNING OF PROGRAM CALCULATIONS.
    211 CALL COEFS
    212 CALL TRIDI
        TT=TT+DT
        DO 40 II=1,NN
        L=NN-II+1
     40 U(II)=T(L)
        IF(N.GE.20)GO TO 45
        IF(N.EQ.15)GO TO 44
        IF(N.EQ.10)GO TO 43
        PRINT 410,TT,(U(K),K=1,NN)
    410 FORMAT(10X,F8.5,6F8.3/)
```

```
      GO TO 450
   43 PRINT 110,TT,(U(K),K=1,7)
      PRINT 451,(U(K),K=8,NN)
  451 FORMAT(18X,4F8.3/)
      GO TO 450
   44 PRINT 110,TT,(U(K),K=1,7)
      PRINT 111,(U(K),K=8,14)
      GO TO 450
   45 PRINT 110,TT,(U(K),K=1,7)
  110 FORMAT(10X,F8.5,7F8.3)
      PRINT 111, (U(K),K=8,14)
  111 FORMAT(18X,7F8.3)
      PRINT 112, (U(K),K=15,21)
  112 FORMAT(18X,7F8.3/)
  450 J=J+1
      IF(J.EQ.11)GO TO 801
      IF(J.EQ.25)GO TO 801
      IF(J.EQ.39)GO TO 801
      IF(J.EQ.53)GO TO 801
      IF(J.EQ.67)GO TO 801
      GO TO 901
  801 PRINT 802
  802 FORMAT(1H1)
  901 IF(TT-YYY) 211,211,103
C     YYY IS MAX TIME FOR CALCULATIONS.
 1000 CONTINUE
      STOP
      END
```

```
      SUBROUTINE COETS
C     THIS PROGRAM GENERATES THE COEFFICIENTS.
      DIMENSION A(300),B(300),C(300),D(300),T(300),R(300),
     1RK(300),CC(300),DD(300),X(300),U(300)
      COMMON A,B,C,D,T,CC,DD,TT,DT,TA,DR,RO,RHO1,RHO2,PCC1,
     1PCC2,PKK1,PKK2,CP1,CP2,H,HH,HC,RC,N,TAH,TAC,TH,DTH
      AN=N
      NN=N+1
  500 DRR=DR*DR
      IF(TT.GT.0.0035)DT=0.00004
      IF(TT.GT.0.0024)DT=0.0004
      DDT=DRR/DT
      PCC1=RHO1*CP1
      PCC2=RHO2*CP2
      PDDT1=PCC1*DDT/2.0
      PDDT2=PCC2*DDT/2.0
  222 A(1)=0.0
      R(1)=0.0
      B(1)=-(PKK1+PDDT1)
      C(1)= PKK1
      D(1)= (PKK1-PDDT1)*T(1)-PKK1*T(2)
      IF(TT.GT.0.0015)GO TO 49
      TA=TAH
      H=HH
      GO TO 225
   49 TA=TAC
      H=HC
  225 RDA=RO-DR
      RDB=RO+DR
      RDAA=2.0*RO+DR
      PKRA=PKK2*RDA
      PKRB=PKK2*RDB
      A(NN)=PKK2*RDA
      B(NN)=-(A(NN)+H*DR*RDB+2.0*RO*PDDT2)
      C(NN)=0.0
      D(NN)=-A(NN)*T(N)+(A(NN)+H*DR*RDB-2.0*RO*PDDT2)*T(NN)-
     1 2.0*H*DR*RDB*TA
      DO 2 K=2,N
      KL=K+1
      KJ=K-1
      PKJ=K-1
      PKL=K+1
      PK=K
      PN=N
      R(K)=DR*PKJ
      IF(R(K).GE.RC) GO TO 3
      PKKK=PKK1
      PDDT=PDDT1
      GO TO 4
    3 PKKK=PKK2
      PDDT=PDDT2
    4 RK(K)=PKKK*(R(K)-0.5*DR)
      KK=KL
C     RK(KK) IN SUBROUTINE COETS EQUALS CONDUCTIVITY*RADIUS AT
```

```
C       POSITION ONE-HALF NODE BEYOND (+) NODE K. RK(K) IS AT
C       ONE-HALF NODE LESS (-) THAN NODE K.
        RK(KK)=RKKK*(R(K)+0.5*DR)
        A(K)=RK(K)-RKKK*DR/2.0
        B(K)=-(RK(K)+RK(KK)+4.0*PDDT*(R(K)+DR/2.0))
        C(K)=RK(KK)+RKKK*DR/2.0
        D(K)=-C(K)*T(KK)+(RK(K)+RK(KK)-4.0*PDDT*(R(K)+DR/2.0))*
     1 T(K)-A(K)*T(KJ)
      2 CONTINUE
        RETURN
        END
```

```
      SUBROUTINE TRIDI
      DIMENSION A(300),B(300),C(300),D(300),T(300),R(300),
     1RK(300),CC(300),DD(300),X(300),U(300)
      COMMON A,B,C,D,T,CC,DD,TT,DT,IA,DR,RO,RHO1,RHO2,PCC1,
     1PCC2,PKK1,PKK2,CP1,CP2,H,HH,HC,RC,N,TAH,TAC,TH,DTH
C     THIS SUBROUTINE SOLVES A TRIDIAGONAL SET OF EQUATIONS.
C     CC IS C*, DD IS D*
      NN=N+1
      CC(1)=C(1)/B(1)
      DD(1)=D(1)/B(1)
      DO 1 K=2,NN
      KJ=K-1
      KL=K+1
      CC(K)=C(K)/(B(K)-A(K)*CC(KJ))
    1 DD(K)=(D(K)-A(K)*DD(KJ))/(B(K)-A(K)*CC(KJ))
      T(NN)=DD(NN)
      DO 2 KK=2,NN
      KKK=NN-KK+1
      KKKK=KKK+1
    2 T(KKK)=DD(KKK)-CC(KKK)*T(KKKK)
      RETURN
      END
```

```
      C      PROGRAM TEMPWAL
      C      FIND TEMPERATURE DISTRIBUTION IN AN INFINITE CYLINDER AF
      C      TER A SHORT EXPOSURE TO FLAME UNIFORMLY OVER ITS SURFACE.
  1          DIMENSION A(300),B(300),C(300),D(300),T(300),X(300),
            1XK(300),CC(300),CD(300),Y(300)
  2          COMMON A,B,C,D,T,CC,CD,TT,DT,TA,DX,XL,RHO1,RHO2,PCC1,
            1PCC2,PKK1,PKK2,CP1,CP2,H,HH,HC,XC,N,TAH,TAC,TH,DTH,X
      C      RC=OUTSIDE RADIUS, RHO1=DENSITY AT R.LT.RC,RHO2=DENSITY
      C      AT R.GT.RC, CP1=SPECIFIC HEAT AT R.LT.RC, CP2=SPECIFIC
      C      HEAT AT R.GT.RC, PKK1=THERMAL CONDUCTIVITY AT R.LT.RC,
      C      PKK2=THERMAL CONDUCTIVITY AT R.GT.RC,T(NN) IS THE TEMPER-
      C      ATURE AT THE SURFACE.
      C      T(1) IS THE TEMPERATURE AT THE CENTER.
  3     100  FORMAT(1X,F8.5,1X,10F8.3)
  4     103  READ 104,CASE,DT,YYY,RHO1,RHO2,XL,CP1,CP2,PKK1,PKK2,TH,
            1TI,N
  6     104  FORMAT(    F4.0,F8.5,F6.3,2F7.2,5F6.3, F7.5,F7.2,I4)
  7          IF(CASE.EQ.0.0)GO TO 1000
 12          NN=N+1
 13          READ 105, DTH,TNNC,TAH,TAC,HH,HC,XC
 14     105  FORMAT(1X,F7.5,3F7.2,2F7.2,F6.3)
 15          YYY=0.006
 16          PRINT 205
 17     205  FORMAT(1H1//)
 20          PRINT 106
 21     106  FORMAT(15X,42HCASE    DT        YYY    RHO1   RHO2   CP1    CP2,
            13X,11HPKK1   PKK2   /)
 22          PRINT 107,CASE,DT,YYY,RHO1,RHO2,CP1,CP2,PKK1,PKK2
 23     107  FORMAT(15X,F4.0,F8.5,F7.4,2F6.2,4F6.3//)
 24          PRINT 108
 25     108  FORMAT(19X,41H   XL      XC       HH       HC       TAH      TAC   ,
            11X,9HTI      N   /)
 26          PRINT 109,XL,XC,HH,HC,TAH,TAC,TI,N
 27     109  FORMAT(19X,2F6.3,2F7.2,3F7.1,I4//)
      C      TT IS TIME,T(K) IS TEMP AT NODE K, PKKK=K, PCCC=RHO*CP
 30          J=0
 31          TT=0.0
 32          AN=N
 33          DX=XL/AN
 34          DO 200 KM=1,NN
 35     200  T(KM)=TI
      C      BEGINNING OF PROGRAM CALCULATIONS.
 37     211  CALL COETS
 40     212  CALL TRIDI
 41          TT=TT+DT
 42          IF(N.GE.20)GO TO 45
 45          IF(N.EQ.15)GO TO 44
 50          IF(N.EQ.10)GO TO 43
 53          PRINT 410,TT,(T(K),K=1,NN)
 60     410  FORMAT(10X,F8.5,6F8.3/)
 61          GO TO 450
 62      43  PRINT 110,TT,(T(K),K=1,7)
 67          PRINT 451,(T(K),K=8,NN)
 74     451  FORMAT(18X,4F8.3/)
```

```
      GO TO 450
   44 PRINT 110,TT,(T(K),K=1,7)
      PRINT 111,(T(K),K=8,14)
      GO TO 450
   45 PRINT 110,TT,(T(K),K=1,7)
  110 FORMAT(10X,F8.5,7F8.3)
      PRINT 111, (T(K),K=8,14)
  111 FORMAT(18X,7F8.3)
      PRINT 112, (T(K),K=15,21)
  112 FORMAT(18X,7F8.3/)
  450 J=J+1
      IF(J.EQ.11)GO TO 801
      IF(J.EQ.25)GO TO 801
      IF(J.EQ.39)GO TO 801
      IF(J.EQ.53)GO TO 801
      IF(J.EQ.67)GO TO 801
      GO TO 901
  801 PRINT 802
  802 FORMAT(1H1)
  901 IF(TT-YYY) 211,211,103
C     YYY IS MAX TIME FOR CALCULATIONS.
 1000 CONTINUE
      STOP
      END
```

```
      SUBROUTINE COEFS
C     THIS PROGRAM GENERATES THE COEFFICIENTS.
      DIMENSION A(300),B(300),C(300),D(300),T(300),X(300),
     1XK(300),CC(300),CD(300),Y(300)
      COMMON A,B,C,D,T,CC,CD,TT,DT,TA,DX,XL,RHO1,RHO2,PCC1,
     1PCC2,PKK1,PKK2,CP1,CP2,H,HH,HC,XC,N,TAH,TAC,TH,DTH,X
      AN=N
      NN=N+1
      DXX=DX*DX
      IF(TT.GT.0.00035)DT=0.00004
      IF(TT.GT.0.0024)DT=0.0004
      DDT=DXX/DT
      PCC1=RHO1*CP1
      PCC2=RHO2*CP2
      PDDT1=PCC1*DDT
      PDDT2=PCC2*DDT
      IF(TT.GT.0.00015)GO TO 49
      TA=TAH
      H=HH
      GO TO 222
   49 TA=TAC
      H=HC
  222 A(1)=0.0
      X(1)=0.0
      B(1)=-(1.0+PDDT2/PKK2)
      C(1)=1.0
      D(1)=(1.0-PDDT2/PKK2)*T(1)-T(2)-2.0*H*DX*(TA-T(1))/PKK2
      XD=2.0*PDDT1/PKK1
      A(NN)=1.0
      B(NN)=-(1.0+XD)
      C(NN)=0.0
      D(NN)=-T(N)+(1.0-XD)*T(NN)
      DO 2 K=2,N
      KL=K+1
      KJ=K-1
      PKJ=K-1
      PKL=K+1
      PK=K
      PN=N
      X(K)=DX*PKJ
      IF(X(K).LT.XC) GO TO 3
      PKKK=PKK1
      PDDT=PDDT1
      GO TO 4
    3 PKKK=PKK2
      PDDT=PDDT2
    4 XK(K)=PKKK*(X(K)-0.5*DX)
      KK=KL
      XK(KK)=PKKK*(X(K)+0.5*DX)
C     POSITION ONE-HALF NODE BEYOND (+) NODE K. RK(K) IS AT
C     ONE-HALF NODE LESS (-) THAN NODE K.
      XDP=2.0*PDD1*X(K)
      A(K)=XK(K)
      B(K)=-(XK(K)+XK(KK)+XDP)
```

```
      C(K)=XK(KK)
      D(K)=-XK(K)*T(KJ)+(XK(K)+XK(KK)-XDP)*T(K)-XK(KK)*T(KL)
    2 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE TRIDI
      DIMENSION A(300),B(300),C(300),D(300),T(300),X(300),
     1XK(300),CC(300),DD(300),Y(300)
      COMMON A,B,C,D,T,CC,DD,TT,DT,TA,DX,XL,RHC1,RHC2,PCC1,
     1PCC2,PKK1,PKK2,CP1,CP2,H,HH,HC,XC,N,TAH,TAC,TH,DTH,X
C     THIS SUBROUTINE SOLVES A TRIDIAGONAL SET OF EQUATIONS.
C     CC IS C*, DD IS D*
      NN=N+1
      CC(1)=C(1)/B(1)
      DD(1)=D(1)/B(1)
      DO 1 K=2,NN
      KJ=K-1
      KL=K+1
      CC(K)=C(K)/(B(K)-A(K)*CC(KJ))
    1 DD(K)=(D(K)-A(K)*DD(KJ))/(B(K)-A(K)*CC(KJ))
      T(NN)=DD(NN)
      DO 2 KK=2,NN
      KKK=NN-KK+1
      KKKK=KKK+1
    2 T(KKK)=DD(KKK)-CC(KKK)*T(KKKK)
      RETURN
      END
```

APPENDIX C

Samples of computer outputs:

1) Case 1 as a cylinder.

2) Case 1 as a semi-infinite wall.

Explanation of output:

Column 1	2	3	4	5	6	7	8
(TT)	T(1)	T(2)	T(3)	T(4)	T(5)	T(6)	T(7)
	T(8)	...	----	----	----	...	T(14)
	T(15)	...	----	----	----	...	T(21)
(TT+DT)	T(1)	----	----	----	----	----	
	----	----	----	----	----	----	
	----	----	----	----	----	----	T(21)

CASE	CT	YYY	RHO1	RHO2	CP1	CP2	PKK1	PKK2
1.	0.00004	0.0060	40.00	60.00	0.910	0.870	0.200	0.300

RC	RC	HF	HC	TAH	TAC	TI	N
0.040	0.035	40.00	2.00	1641.0	77.0	77.0	20

0.00004	124.079	78.315	77.037	77.001	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00008	165.195	81.957	77.208	77.007	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00012	201.344	87.384	77.616	77.029	77.001	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00016	233.342	94.165	78.323	77.078	77.004	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00020	219.045	100.764	79.333	77.169	77.010	77.001	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00024	206.861	105.981	80.572	77.311	77.022	77.001	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00028	196.438	110.079	81.949	77.509	77.042	77.003	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00032	187.486	113.273	83.395	77.765	77.072	77.006	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00036	179.766	115.736	84.860	78.074	77.115	77.010	77.001
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00040	173.082	117.609	86.308	78.433	77.171	77.017	77.001
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00044	167.268	119.006	87.713	78.834	77.243	77.026	77.002
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000

0.00048	162.190	120.020	89.057	79.273	77.330	77.039	77.004
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00052	157.733	120.726	90.330	79.742	77.434	77.056	77.006
	77.001	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00056	153.805	121.185	91.525	80.235	77.554	77.077	77.009
	77.001	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00060	150.326	121.447	92.638	80.746	77.689	77.104	77.013
	77.001	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00064	147.232	121.551	93.670	81.269	77.841	77.135	77.018
	77.002	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00068	144.467	121.530	94.621	81.801	78.007	77.172	77.025
	77.003	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00072	141.985	121.411	95.494	82.335	78.186	77.215	77.033
	77.004	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00076	139.747	121.215	96.292	82.869	78.379	77.264	77.043
	77.006	77.001	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00080	137.721	120.959	97.020	83.400	78.583	77.320	77.055
	77.008	77.001	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00084	135.878	120.658	97.682	83.924	78.797	77.381	77.069
	77.011	77.001	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00088	134.196	120.321	98.282	84.439	79.021	77.449	77.085
	77.014	77.002	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00092	132.655	119.959	98.824	84.943	79.253	77.523	77.103
	77.018	77.003	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00096	131.237	119.579	99.313	85.435	79.492	77.604	77.124
	77.022	77.003	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00100	129.927	119.186	99.752	85.914	79.737	77.690	77.148
	77.027	77.004	77.001	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000

0.00104	128.715	118.785	100.147	86.378	79.986	77.782	77.174
	77.034	77.006	77.001	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00108	127.588	118.380	100.500	86.828	80.240	77.880	77.203
	77.041	77.007	77.001	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00112	126.537	117.975	100.815	87.262	80.496	77.982	77.235
	77.049	77.009	77.001	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00116	125.555	117.570	101.096	87.680	80.754	78.090	77.270
	77.058	77.011	77.002	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00120	124.634	117.169	101.345	88.082	81.014	78.203	77.307
	77.068	77.013	77.002	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00124	123.768	116.772	101.564	88.469	81.273	78.320	77.348
	77.080	77.016	77.003	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00128	122.953	116.381	101.758	88.840	81.533	78.441	77.391
	77.093	77.019	77.004	77.001	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00132	122.183	115.996	101.927	89.195	81.792	78.566	77.438
	77.107	77.023	77.004	77.001	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00136	121.454	115.618	102.075	89.535	82.049	78.695	77.487
	77.122	77.027	77.005	77.001	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00140	120.763	115.247	102.202	89.860	82.304	78.827	77.539
	77.139	77.032	77.007	77.001	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00144	120.107	114.884	102.312	90.171	82.557	78.961	77.594
	77.157	77.037	77.008	77.001	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00148	119.483	114.529	102.405	90.468	82.807	79.099	77.652
	77.177	77.043	77.009	77.002	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00152	118.887	114.182	102.483	90.751	83.053	79.238	77.712
	77.198	77.049	77.011	77.002	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00156	118.319	113.842	102.547	91.021	83.297	79.380	77.774
	77.221	77.056	77.013	77.003	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000

0.00160	117.776	113.511	102.599	91.278	83.537	79.523	77.840
	77.245	77.064	77.015	77.003	77.001	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00164	117.256	113.187	102.640	91.523	83.772	79.668	77.907
	77.271	77.072	77.017	77.004	77.001	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00168	116.757	112.871	102.671	91.756	84.004	79.814	77.977
	77.298	77.081	77.020	77.004	77.001	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00172	116.278	112.563	102.692	91.978	84.231	79.961	78.049
	77.327	77.091	77.023	77.005	77.001	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00176	115.818	112.262	102.705	92.189	84.454	80.108	78.123
	77.358	77.102	77.026	77.006	77.001	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00180	115.376	111.968	102.710	92.390	84.673	80.257	78.199
	77.389	77.113	77.030	77.007	77.001	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00184	114.950	111.681	102.708	92.580	84.887	80.405	78.277
	77.423	77.125	77.034	77.008	77.002	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00188	114.540	111.401	102.700	92.762	85.096	80.554	78.357
	77.458	77.138	77.038	77.009	77.002	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00192	114.144	111.128	102.686	92.934	85.301	80.702	78.438
	77.494	77.152	77.042	77.011	77.002	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00196	113.761	110.861	102.667	93.097	85.501	80.851	78.521
	77.532	77.167	77.047	77.012	77.003	77.001	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00200	113.391	110.600	102.643	93.252	85.696	80.998	78.606
	77.571	77.182	77.053	77.014	77.003	77.001	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00204	113.034	110.346	102.614	93.400	85.887	81.146	78.691
	77.612	77.199	77.058	77.016	77.004	77.001	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00208	112.688	110.097	102.582	93.539	86.073	81.293	78.778
	77.654	77.216	77.065	77.018	77.004	77.001	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00212	112.353	109.854	102.546	93.672	86.255	81.439	78.866
	77.697	77.234	77.071	77.020	77.005	77.001	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000

0.00216	112.028	109.616	102.508	93.797	86.432	81.584	78.955
	77.742	77.253	77.078	77.022	77.006	77.001	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00220	111.713	109.384	102.466	93.916	86.604	81.728	79.045
	77.788	77.273	77.086	77.025	77.007	77.002	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00224	111.407	109.157	102.421	94.029	86.773	81.870	79.136
	77.835	77.294	77.094	77.028	77.007	77.002	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00228	111.111	108.934	102.375	94.136	86.936	82.012	79.228
	77.883	77.315	77.103	77.031	77.008	77.002	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00232	110.822	108.717	102.326	94.237	87.096	82.153	79.320
	77.933	77.338	77.112	77.034	77.009	77.002	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00236	110.542	108.504	102.275	94.333	87.251	82.292	79.413
	77.983	77.362	77.121	77.037	77.011	77.003	77.001
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00240	110.269	108.296	102.222	94.423	87.402	82.429	79.507
	78.035	77.386	77.131	77.041	77.012	77.003	77.001
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00244	110.004	108.092	102.168	94.509	87.549	82.566	79.600
	78.087	77.411	77.142	77.045	77.013	77.003	77.001
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00284	107.675	106.260	101.579	95.151	88.822	83.839	80.543
	78.658	77.707	77.277	77.100	77.034	77.011	77.003
	77.001	77.000	77.000	77.000	77.000	77.000	77.000
0.00324	105.831	104.746	100.944	95.486	89.777	84.942	81.466
	79.287	78.074	77.466	77.188	77.071	77.025	77.008
	77.003	77.001	77.000	77.000	77.000	77.000	77.000
0.00364	104.323	103.472	100.318	95.628	90.489	85.879	82.335
	79.941	78.496	77.706	77.311	77.129	77.050	77.019
	77.007	77.002	77.001	77.000	77.000	77.000	77.000
0.00404	103.058	102.380	99.720	95.649	91.017	86.664	83.131
	80.593	78.953	77.990	77.470	77.210	77.089	77.036
	77.014	77.005	77.002	77.001	77.000	77.000	77.000
0.00444	101.979	101.432	99.159	95.592	91.406	87.320	83.850
	81.225	79.431	78.309	77.663	77.317	77.144	77.063
	77.026	77.011	77.004	77.002	77.001	77.000	77.000
0.00484	101.044	100.600	98.636	95.485	91.689	87.865	84.492
	81.827	79.914	78.654	77.886	77.450	77.217	77.101
	77.045	77.019	77.008	77.003	77.001	77.001	77.000

C.00524	100.224	99.862	98.149	95.347	91.893	88.318	85.062
	82.392	80.394	79.016	78.134	77.606	77.309	77.151
	77.071	77.033	77.015	77.007	77.003	77.001	77.001
C.00564	99.497	99.202	97.697	95.188	92.036	88.695	85.566
	82.917	80.862	79.388	78.402	77.784	77.420	77.216
	77.107	77.052	77.025	77.012	77.006	77.003	77.002
C.00604	98.848	98.607	97.276	95.018	92.131	89.008	86.012
	83.403	81.314	79.762	78.685	77.982	77.548	77.295
	77.154	77.078	77.039	77.019	77.010	77.006	77.004

CASE	CT	YYY	RHC1	RHC2	CP1	CP2	PKK1	PKK2
1.	0.00004	0.0060	40.00	60.00	0.910	0.870	0.200	0.300

XL	XC	HH	HC	TAH	TAC	TI	N
0.040	0.005	40.00	2.00	1641.0	77.0	77.0	20

0.00004	122.367	77.617	77.013	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00008	161.614	79.319	77.071	77.002	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00012	195.686	81.841	77.210	77.008	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00016	225.375	84.970	77.449	77.021	77.001	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00020	210.062	87.978	77.789	77.046	77.002	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00024	196.725	90.301	78.202	77.085	77.005	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00028	185.080	92.067	78.657	77.138	77.010	77.001	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00032	174.885	93.382	79.130	77.207	77.017	77.001	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00036	165.935	94.332	79.602	77.289	77.026	77.002	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00040	158.059	94.989	80.062	77.384	77.039	77.003	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00044	151.109	95.409	80.501	77.489	77.055	77.005	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000

0.00048	144.960	95.641	80.912	77.603	77.075	77.008	77.001
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00052	139.505	95.722	81.294	77.724	77.098	77.011	77.001
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00056	134.653	95.684	81.643	77.849	77.124	77.015	77.002
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00060	130.327	95.552	81.959	77.977	77.154	77.020	77.002
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00064	126.459	95.348	82.243	78.107	77.167	77.026	77.003
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00068	122.991	95.088	82.495	78.237	77.222	77.033	77.004
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00072	119.875	94.787	82.718	78.367	77.261	77.041	77.006
	77.001	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00076	117.068	94.454	82.911	78.494	77.301	77.051	77.007
	77.001	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00080	114.533	94.100	83.079	78.618	77.344	77.061	77.009
	77.001	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00084	112.237	93.731	83.222	78.739	77.389	77.072	77.012
	77.002	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00088	110.154	93.354	83.342	78.855	77.435	77.085	77.014
	77.002	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00092	108.259	92.973	83.441	78.967	77.482	77.098	77.017
	77.003	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00096	106.532	92.591	83.521	79.074	77.530	77.113	77.021
	77.003	77.000	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00100	104.953	92.211	83.585	79.176	77.579	77.128	77.024
	77.004	77.001	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000

0.00104	103.507	91.837	83.633	79.273	77.628	77.145	77.029
	77.005	77.001	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00108	102.180	91.468	83.666	79.365	77.677	77.162	77.033
	77.006	77.001	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00112	100.960	91.108	83.688	79.451	77.726	77.180	77.038
	77.007	77.001	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00116	99.835	90.756	83.698	79.532	77.775	77.199	77.044
	77.008	77.001	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00120	98.796	90.413	83.698	79.607	77.824	77.218	77.050
	77.010	77.002	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00124	97.835	90.080	83.690	79.678	77.872	77.238	77.056
	77.012	77.002	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00128	96.945	89.757	83.673	79.743	77.919	77.259	77.063
	77.013	77.002	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00132	96.118	89.444	83.650	79.804	77.966	77.280	77.070
	77.015	77.003	77.000	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00136	95.348	89.141	83.620	79.860	78.011	77.301	77.077
	77.017	77.003	77.001	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00140	94.631	88.849	83.586	79.911	78.056	77.323	77.085
	77.020	77.004	77.001	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00144	93.961	88.566	83.546	79.958	78.099	77.345	77.094
	77.022	77.005	77.001	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00148	93.336	88.293	83.503	80.001	78.141	77.367	77.102
	77.025	77.005	77.001	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00152	92.750	88.030	83.457	80.041	78.182	77.390	77.111
	77.028	77.006	77.001	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00156	92.200	87.776	83.407	80.076	78.222	77.412	77.120
	77.031	77.007	77.001	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000

0.00160	91.684	87.531	83.355	80.108	78.260	77.434	77.130
	77.034	77.008	77.002	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00164	91.198	87.294	83.301	80.137	78.297	77.457	77.140
	77.038	77.009	77.002	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00168	90.741	87.066	83.245	80.162	78.333	77.479	77.150
	77.041	77.010	77.002	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00172	90.310	86.847	83.187	80.185	78.368	77.501	77.160
	77.045	77.011	77.003	77.000	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00176	89.902	86.634	83.129	80.204	78.401	77.523	77.170
	77.049	77.013	77.003	77.001	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00180	89.517	86.430	83.069	80.221	78.433	77.545	77.181
	77.053	77.014	77.003	77.001	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00184	89.153	86.232	83.009	80.236	78.463	77.567	77.192
	77.057	77.015	77.004	77.001	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00188	88.807	86.042	82.949	80.248	78.492	77.589	77.203
	77.062	77.017	77.004	77.001	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00192	88.480	85.858	82.888	80.258	78.520	77.610	77.214
	77.066	77.018	77.005	77.001	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00196	88.168	85.680	82.827	80.266	78.547	77.631	77.225
	77.071	77.020	77.005	77.001	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00200	87.873	85.509	82.766	80.272	78.572	77.651	77.236
	77.076	77.022	77.006	77.001	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00204	87.591	85.343	82.705	80.277	78.596	77.672	77.248
	77.081	77.024	77.006	77.001	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00208	87.322	85.183	82.645	80.279	78.619	77.692	77.259
	77.086	77.026	77.007	77.002	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00212	87.067	85.028	82.584	80.280	78.641	77.711	77.271
	77.092	77.028	77.008	77.002	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000

0.00216	86.822	84.879	82.524	80.280	78.662	77.739	77.282
	77.097	77.030	77.008	77.002	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00220	86.589	84.734	82.465	80.279	78.682	77.749	77.294
	77.103	77.032	77.009	77.002	77.000	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00224	86.366	84.594	82.406	80.276	78.700	77.768	77.305
	77.108	77.035	77.010	77.003	77.001	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00228	86.152	84.458	82.347	80.272	78.718	77.786	77.317
	77.114	77.037	77.011	77.003	77.001	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00232	85.948	84.327	82.290	80.267	78.735	77.803	77.328
	77.120	77.039	77.012	77.003	77.001	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00236	85.752	84.200	82.232	80.261	78.750	77.820	77.340
	77.126	77.042	77.013	77.003	77.001	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00240	85.564	84.077	82.176	80.254	78.765	77.837	77.351
	77.132	77.045	77.014	77.004	77.001	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00244	85.383	83.958	82.120	80.246	78.779	77.853	77.363
	77.138	77.047	77.015	77.004	77.001	77.000	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00284	83.887	82.934	81.603	80.136	78.876	77.994	77.471
	77.201	77.078	77.028	77.009	77.003	77.001	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00324	82.843	82.163	81.159	79.990	78.913	78.096	77.566
	77.266	77.114	77.045	77.016	77.006	77.002	77.000
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00364	82.071	81.564	80.783	79.834	78.911	78.165	77.646
	77.328	77.153	77.066	77.026	77.010	77.003	77.001
	77.000	77.000	77.000	77.000	77.000	77.000	77.000
0.00404	81.478	81.087	80.463	79.680	78.885	78.209	77.710
	77.384	77.192	77.089	77.038	77.015	77.006	77.002
	77.001	77.000	77.000	77.000	77.000	77.000	77.000
0.00444	81.008	80.699	80.190	79.534	78.844	78.233	77.761
	77.434	77.230	77.113	77.052	77.023	77.009	77.003
	77.001	77.000	77.000	77.000	77.000	77.000	77.000
0.00484	80.626	80.378	79.955	79.398	78.795	78.244	77.799
	77.477	77.266	77.138	77.068	77.031	77.013	77.005
	77.002	77.001	77.000	77.000	77.000	77.000	77.000

0.00524	80.311	80.107	79.751	79.272	78.743	78.243	77.827
	77.514	77.299	77.163	77.084	77.041	77.019	77.008
	77.003	77.001	77.000	77.000	77.000	77.000	77.000
0.00564	80.045	79.876	79.572	79.157	78.688	78.235	77.846
	77.544	77.329	77.187	77.100	77.051	77.025	77.011
	77.005	77.002	77.001	77.000	77.000	77.000	77.000
0.00604	79.819	79.677	79.414	79.051	78.634	78.222	77.859
	77.569	77.355	77.210	77.117	77.062	77.031	77.015
	77.007	77.003	77.001	77.000	77.000	77.000	77.000

APPENDIX D

Graphs of temperature distributions for individual cases.

1) Standard -- Case 1.

2) Effects of density -- Cases 2, 3, 4, and 5.

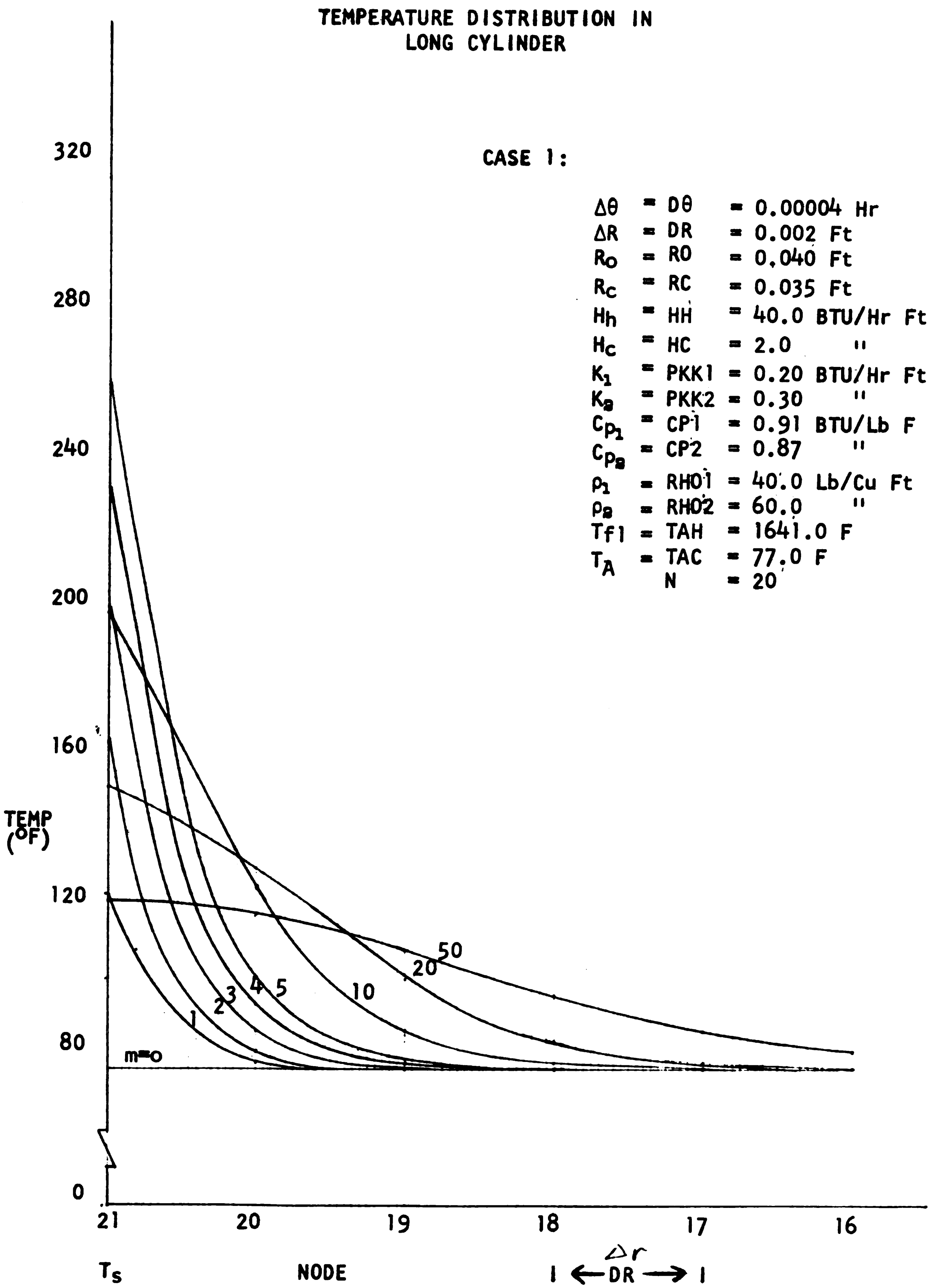
3) Effects of diameter -- Cases 6, 7, 8, 9, and 10.

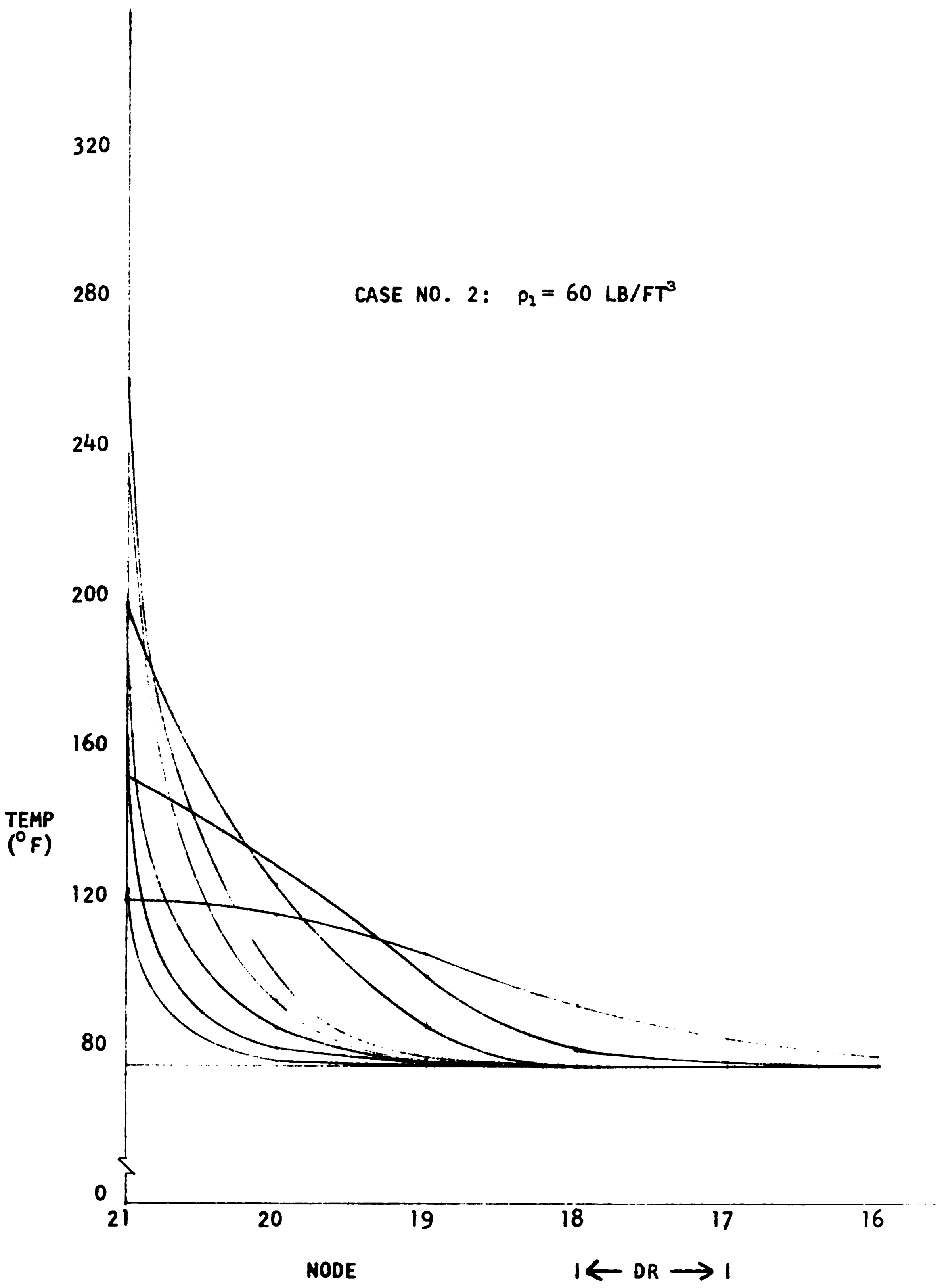
4) Effects of thermal conductivity -- Cases 11, 12, 13, 14, 15, 16, 17, and 18.

5) Effects of specific heat -- Cases 19, 20, 21, and 22.

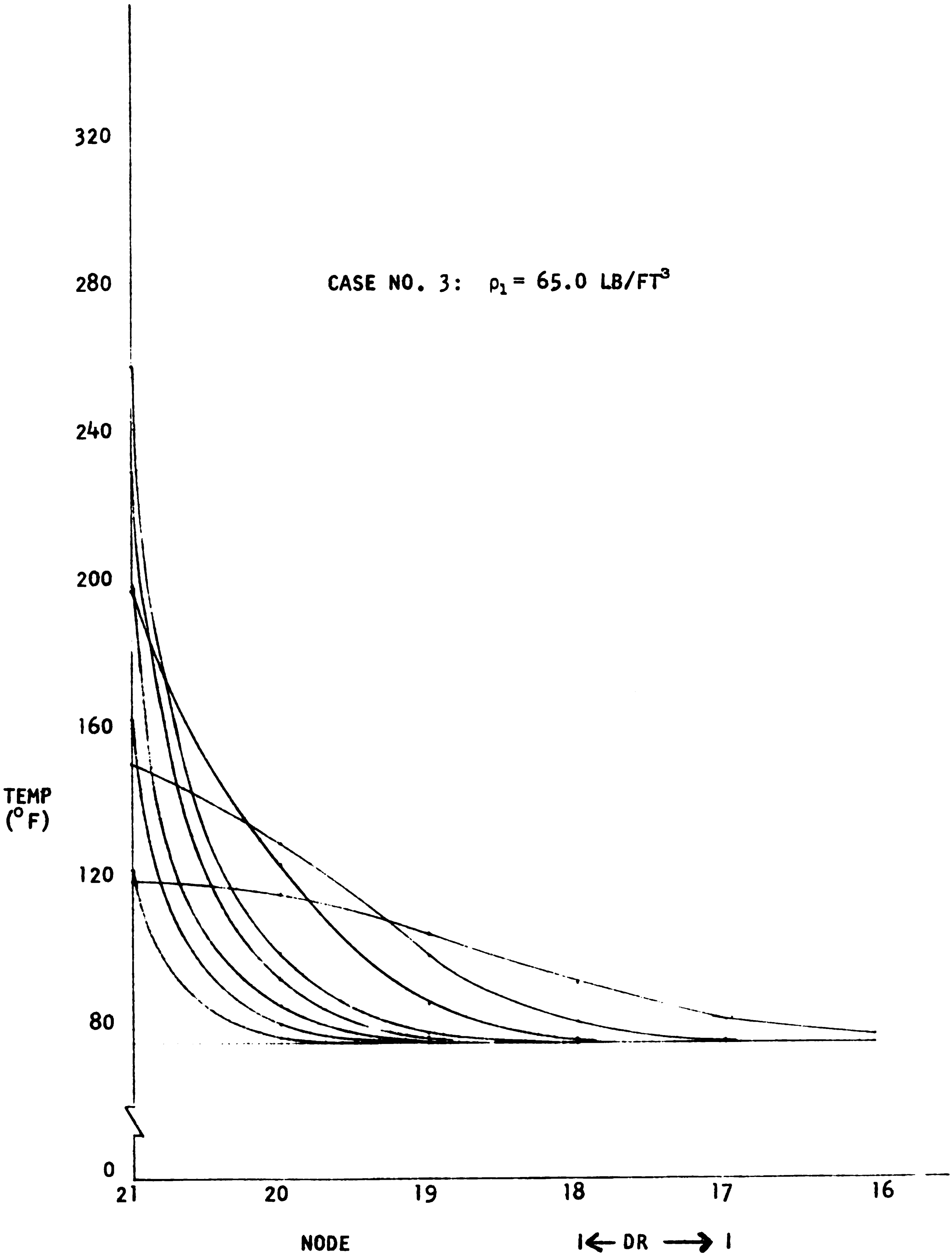
6) Effects of heat transfer coefficient -- Cases 23, 24, 28, and 29.

7. Effects of temperature of the heat source -- Cases 32, 33, and 34.

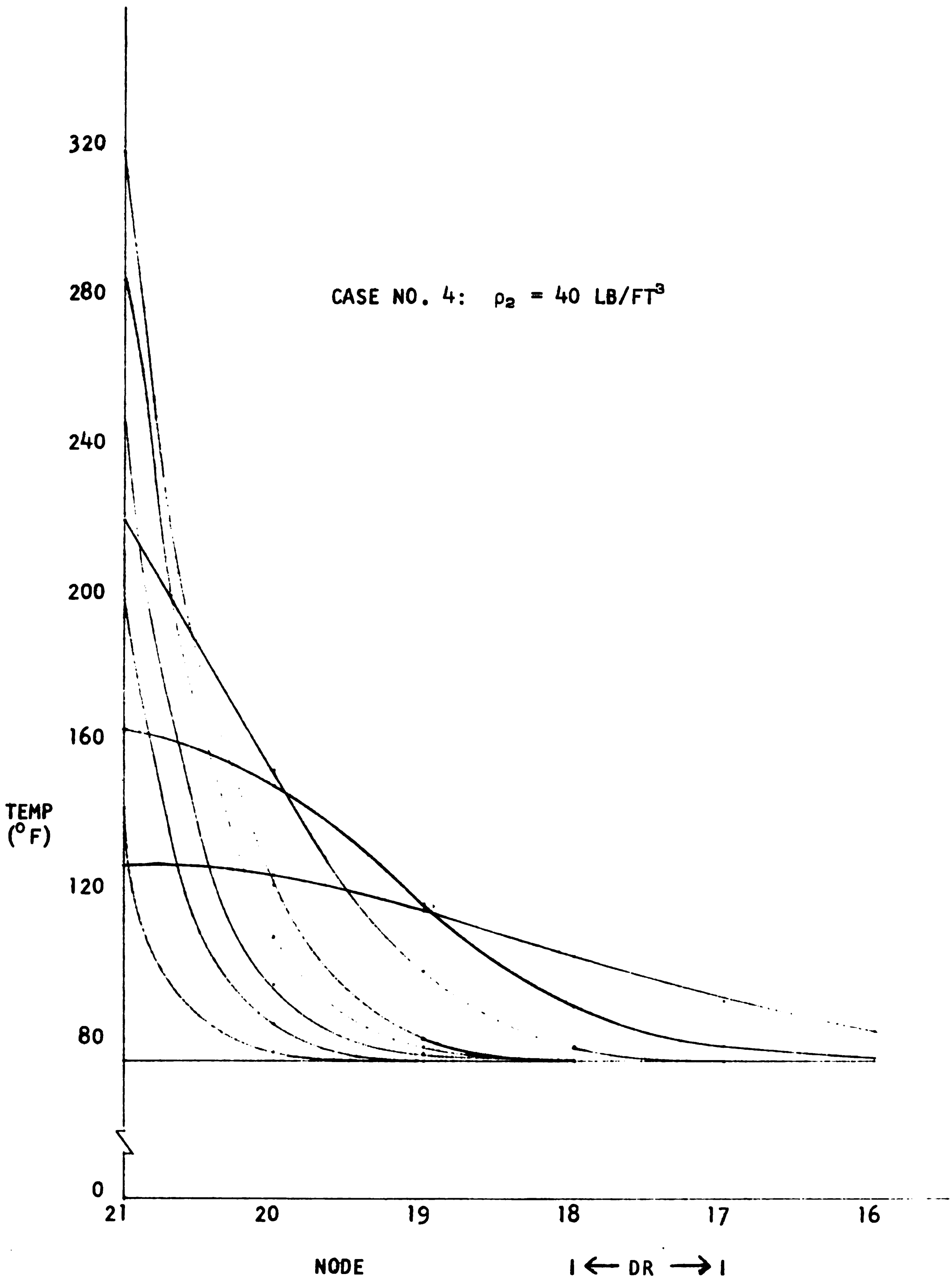

TEMPERATURE DISTRIBUTION IN
LONG CYLINDER
CASE 1:
Δθ = Dθ = 0.00004 Hr
ΔR = DR = 0.002 Ft
Ro = RO = 0.040 Ft
Rc = RC = 0.035 Ft
Hh = HH = 40.0 BTU/Hr Ft2F
Hc = HC = 2.0 "
K1 = PKK1 = 0.20 BTU/Hr Ft F
K2 = PKK2 = 0.30 "
Cp1 = CP1 = 0.91 BTU/Lb F
Cp2 = CP2 = 0.87 "
ρ1 = RHO1 = 40.0 Lb/Cu Ft
ρ2 = RHO2 = 60.0 "
Tf1 = TAH = 1641.0 F
TA = TAC = 77.0 F
N = 20
TEMP
(°F)
320
280
240
200
160
120
80
0
m=o
1
2
3
4
5
10
20
50
21
20
19
18
17
16
Ts
NODE
Δr
DR



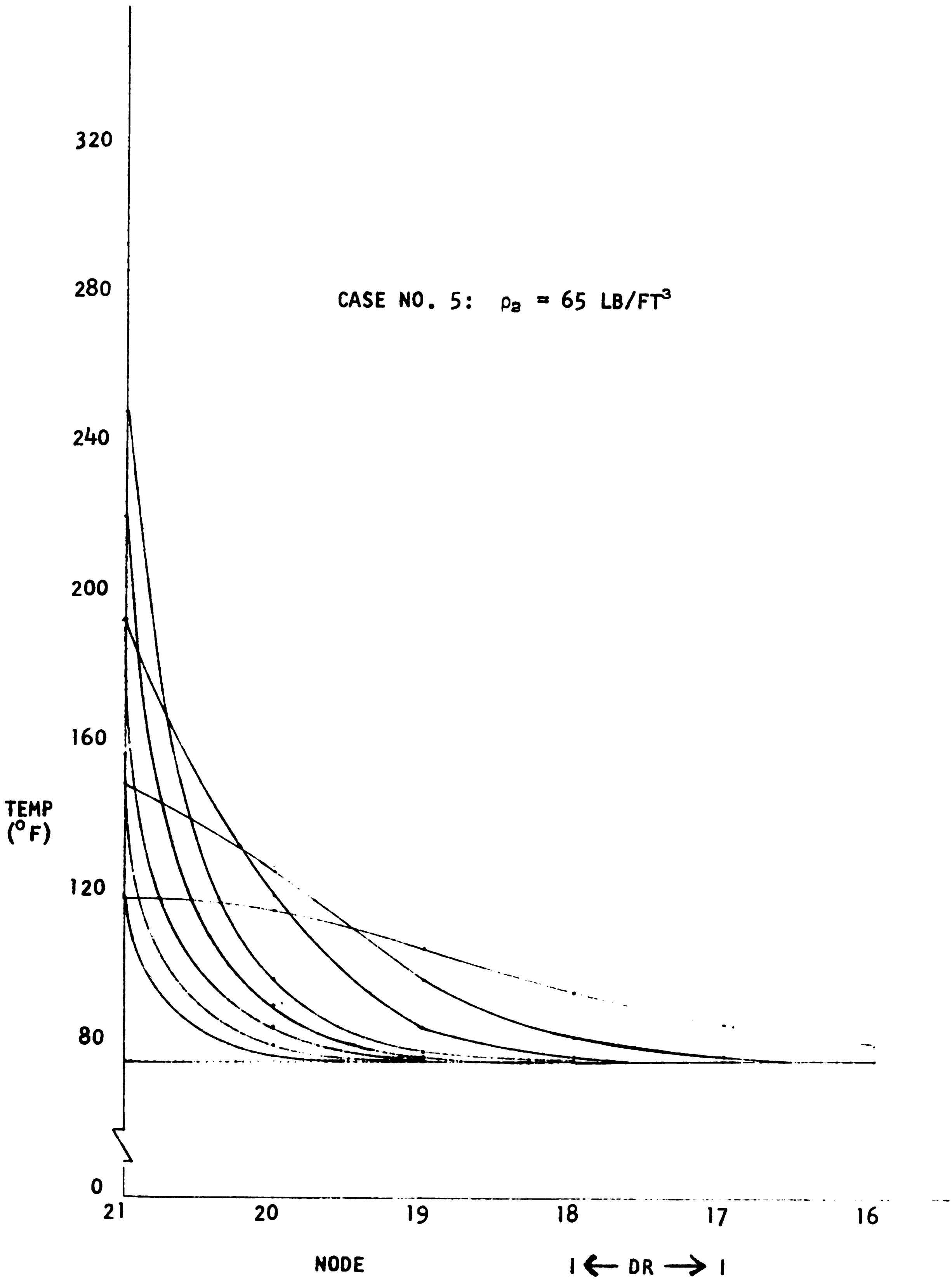
CASE NO. 2: $\rho_1 = 60$ LB/FT^3
320
280
240
200
160
TEMP
(°F)
120
80
0
21
20
19
18
17
16
NODE
I← DR → I

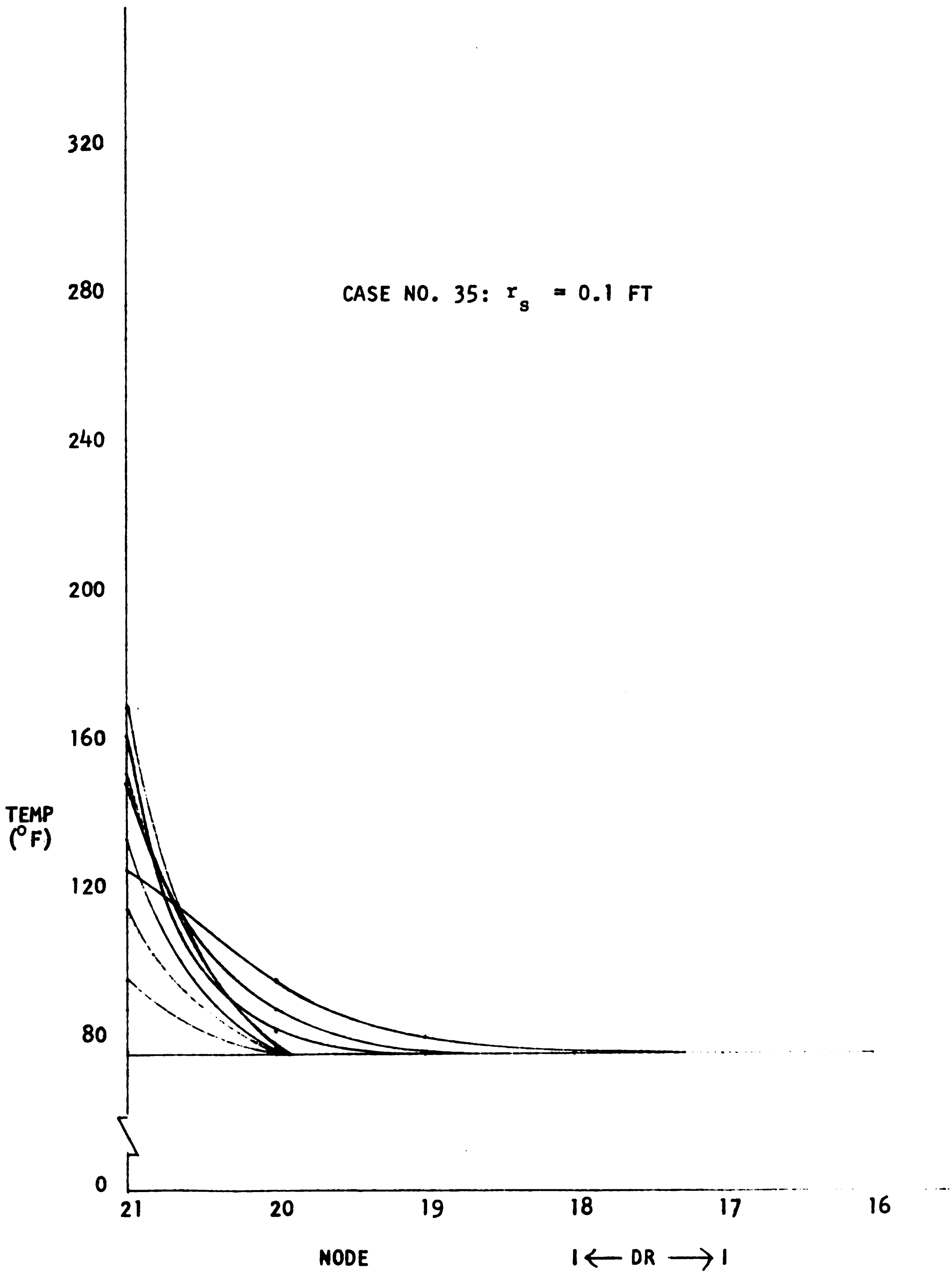


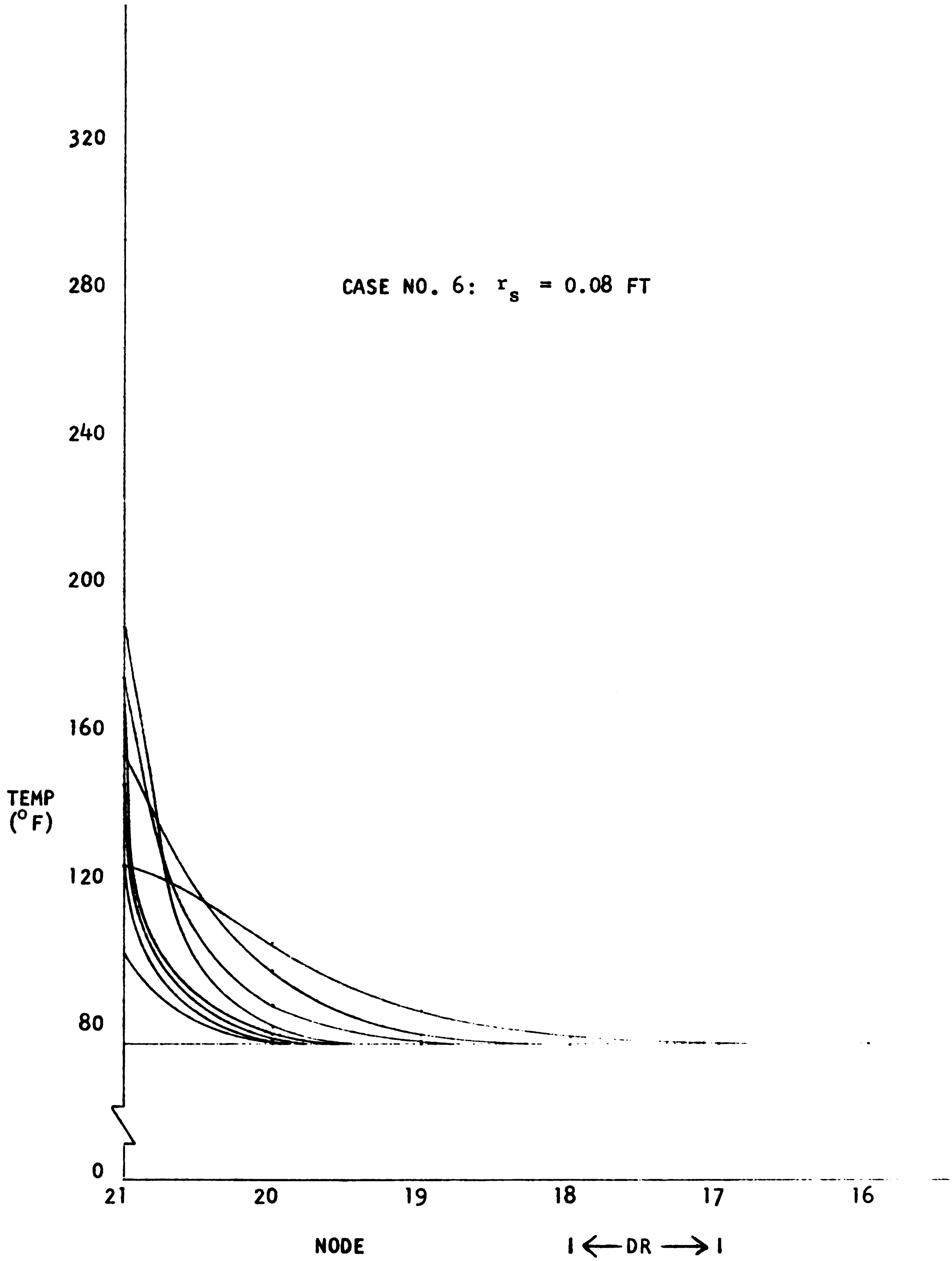
320
280
240
200
160
120
80
0
TEMP
(°F)
CASE NO. 3: ρ₁ = 65.0 LB/FT³
21
20
19
18
17
16
NODE
I← DR → I



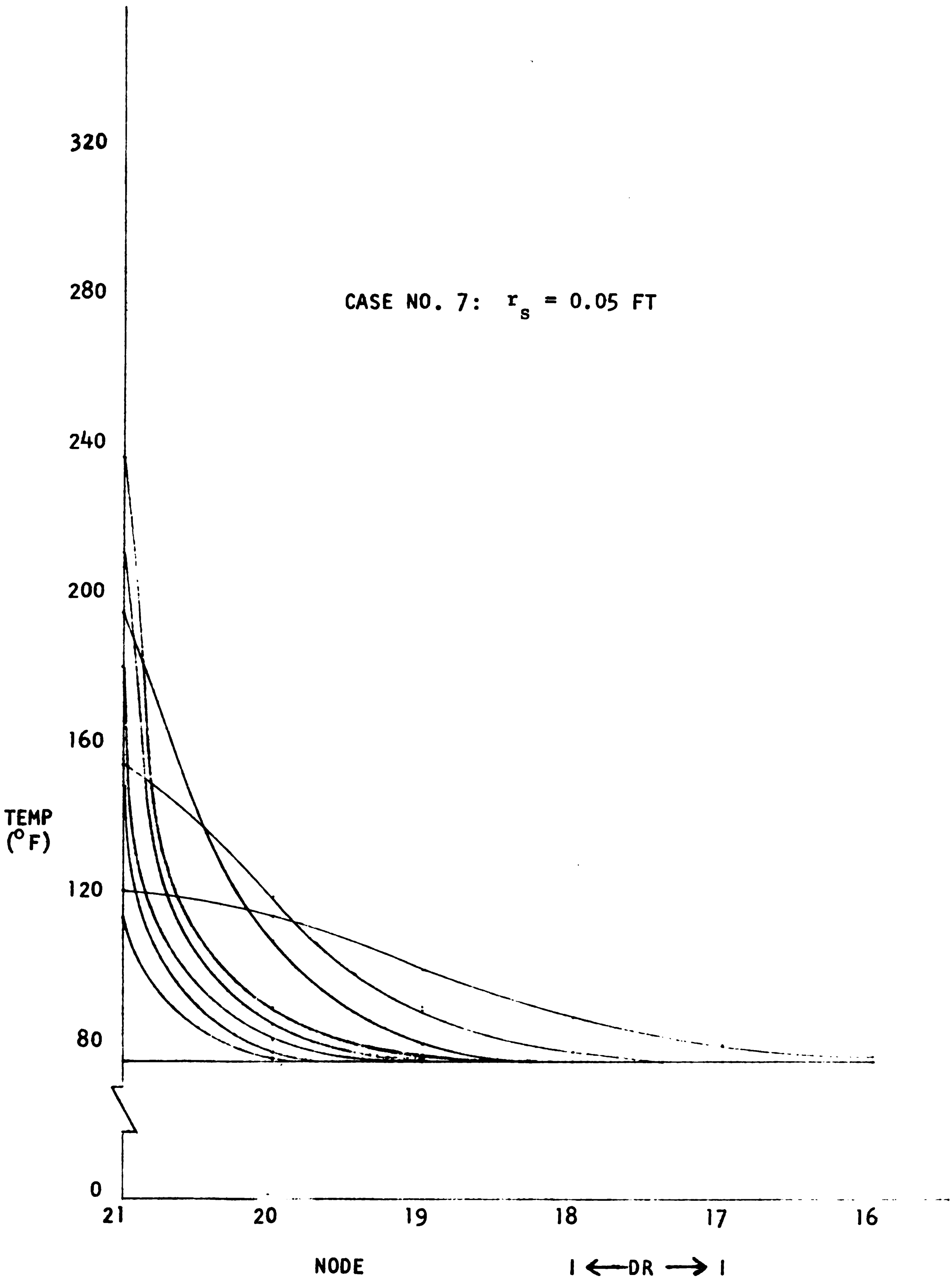
CASE NO. 4: ρ_2 = 40 LB/FT^3
TEMP (°F)
320
280
240
200
160
120
80
0
21
20
19
18
17
16
NODE
I ← DR → I

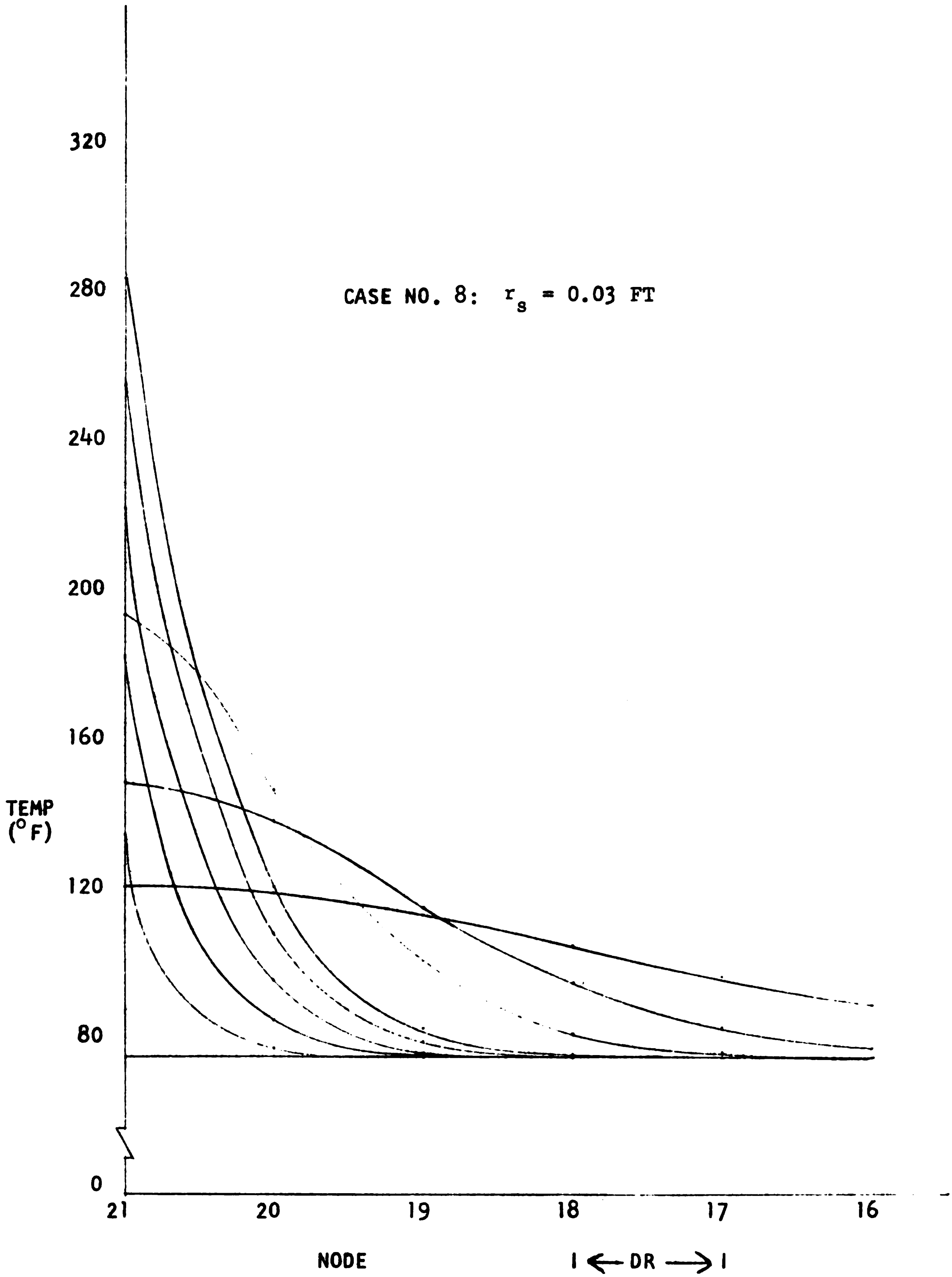

CASE NO. 5: ρ_2 = 65 LB/FT^3
320
280
240
200
160
120
80
0
TEMP
(°F)
21
20
19
18
17
16
NODE
I ← DR → I

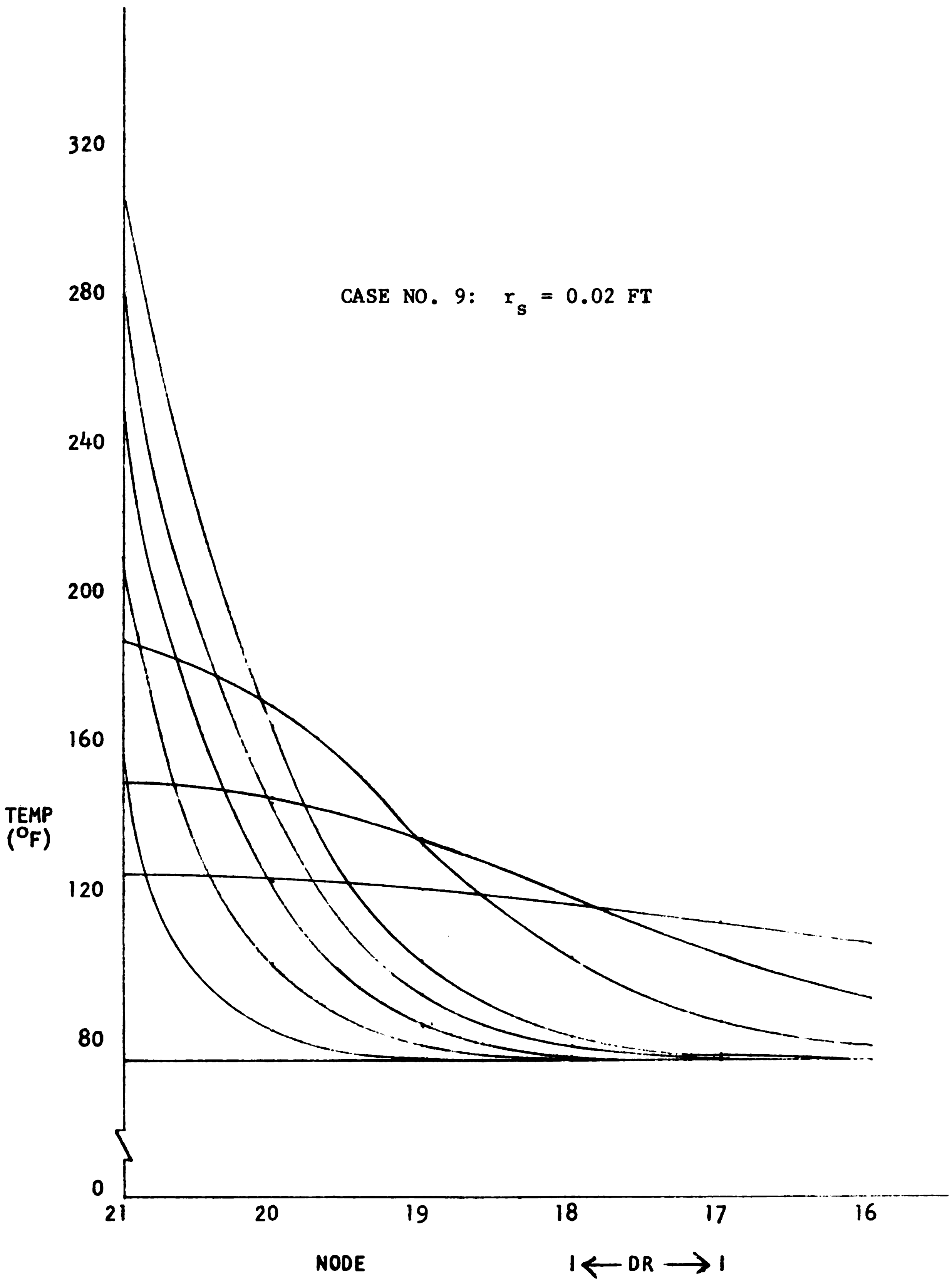

CASE NO. 35: r_s = 0.1 FT
320
280
240
200
160
120
80
0
TEMP
(^{o}F)
21
20
19
18
17
16
NODE
I← DR →I

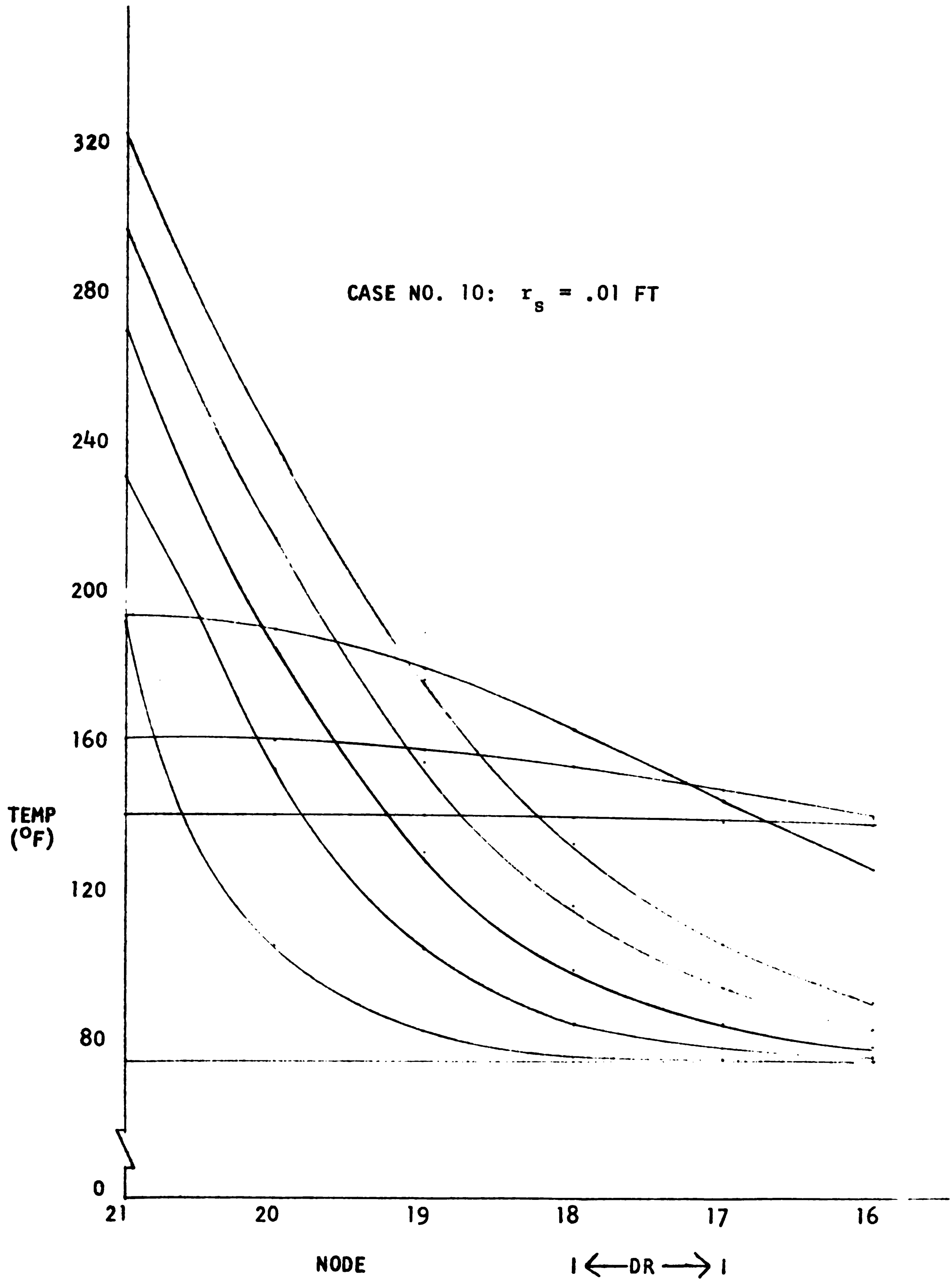


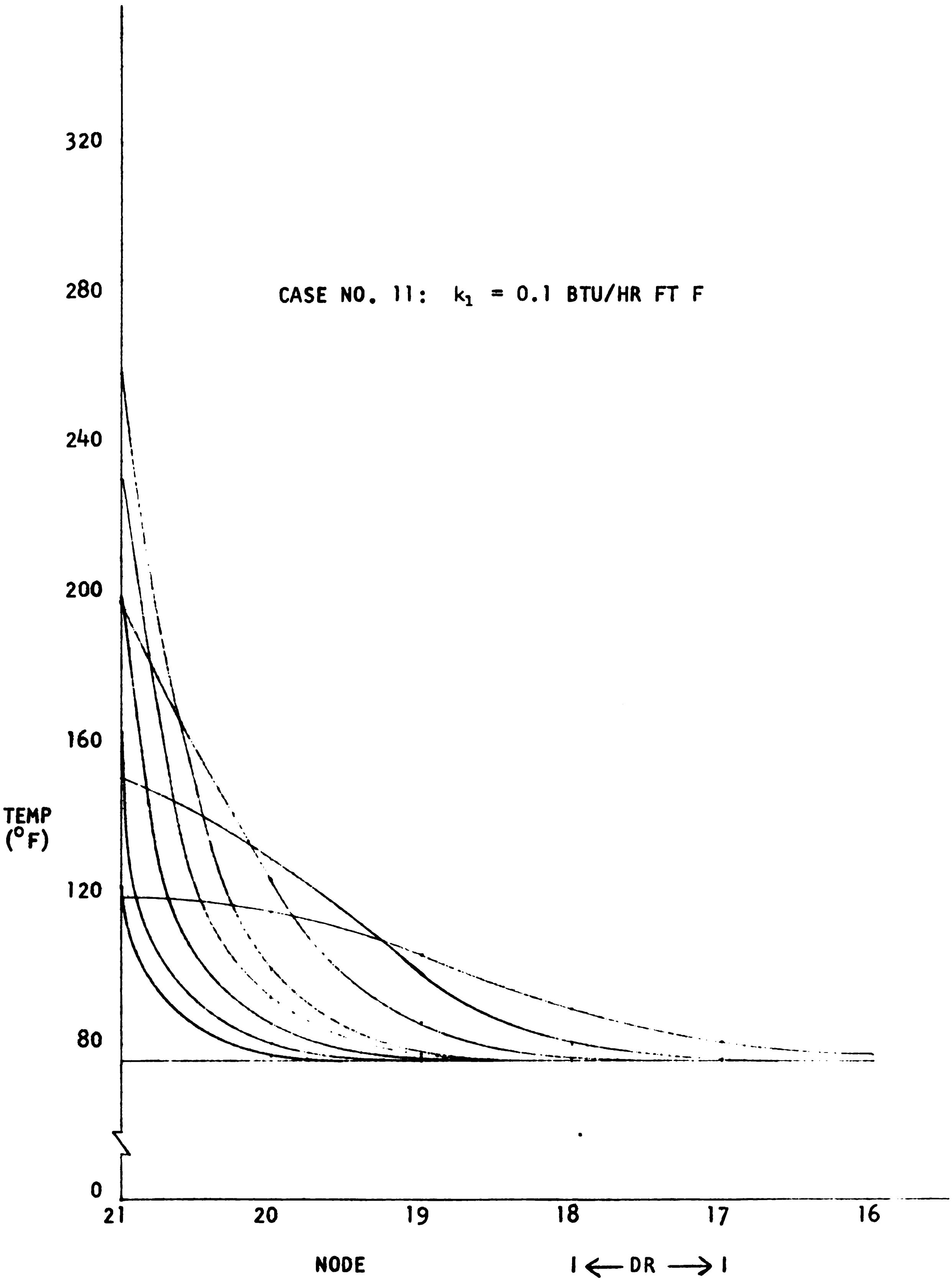
CASE NO. 6: r_s = 0.08 FT
320
280
240
200
160
120
80
0
TEMP
(°F)
21
20
19
18
17
16
NODE
I ← DR → I

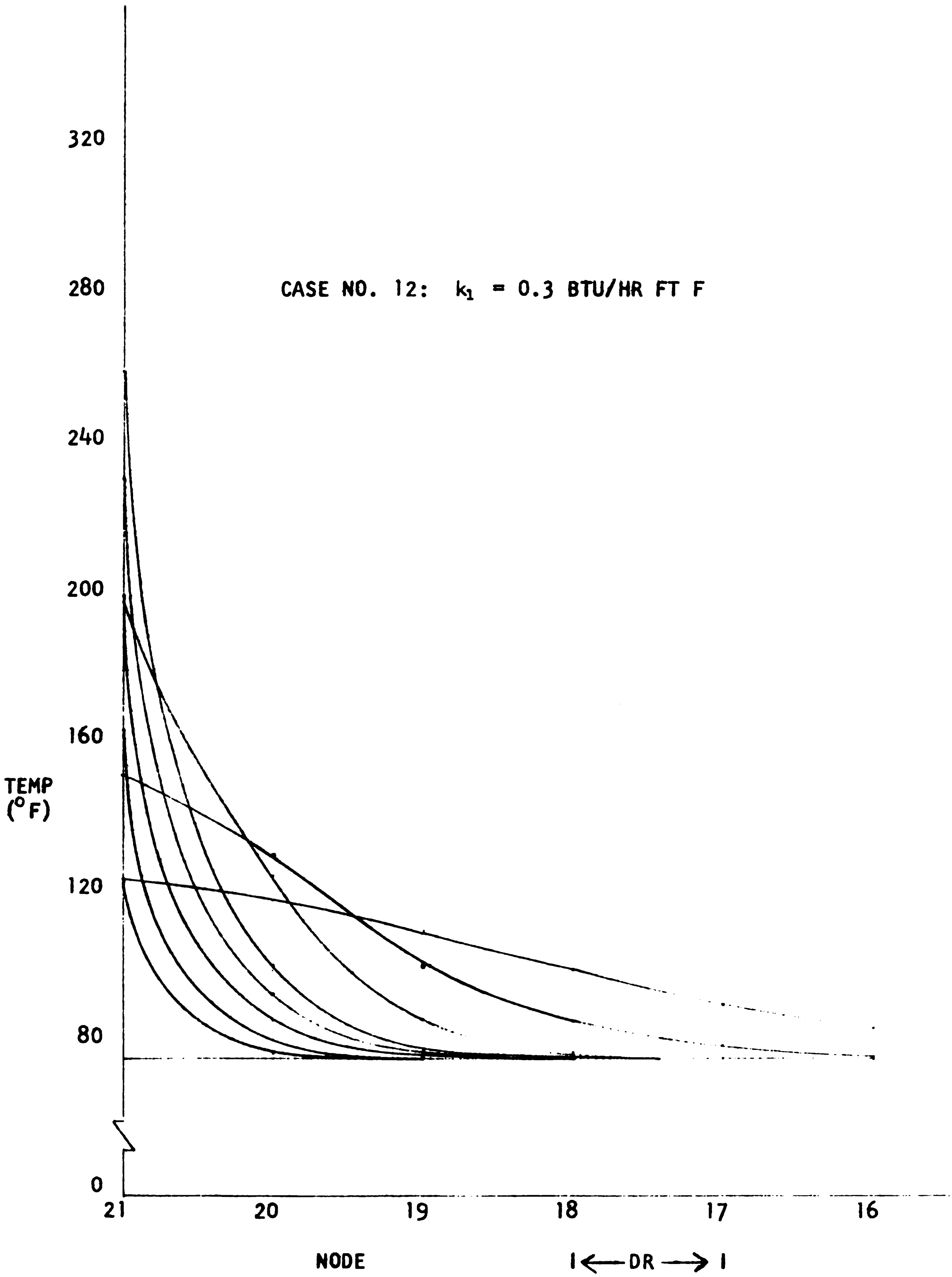

CASE NO. 7: r_s = 0.05 FT
320
280
240
200
160
TEMP
(°F)
120
80
0
21
20
19
18
17
16
NODE
| ← DR → |

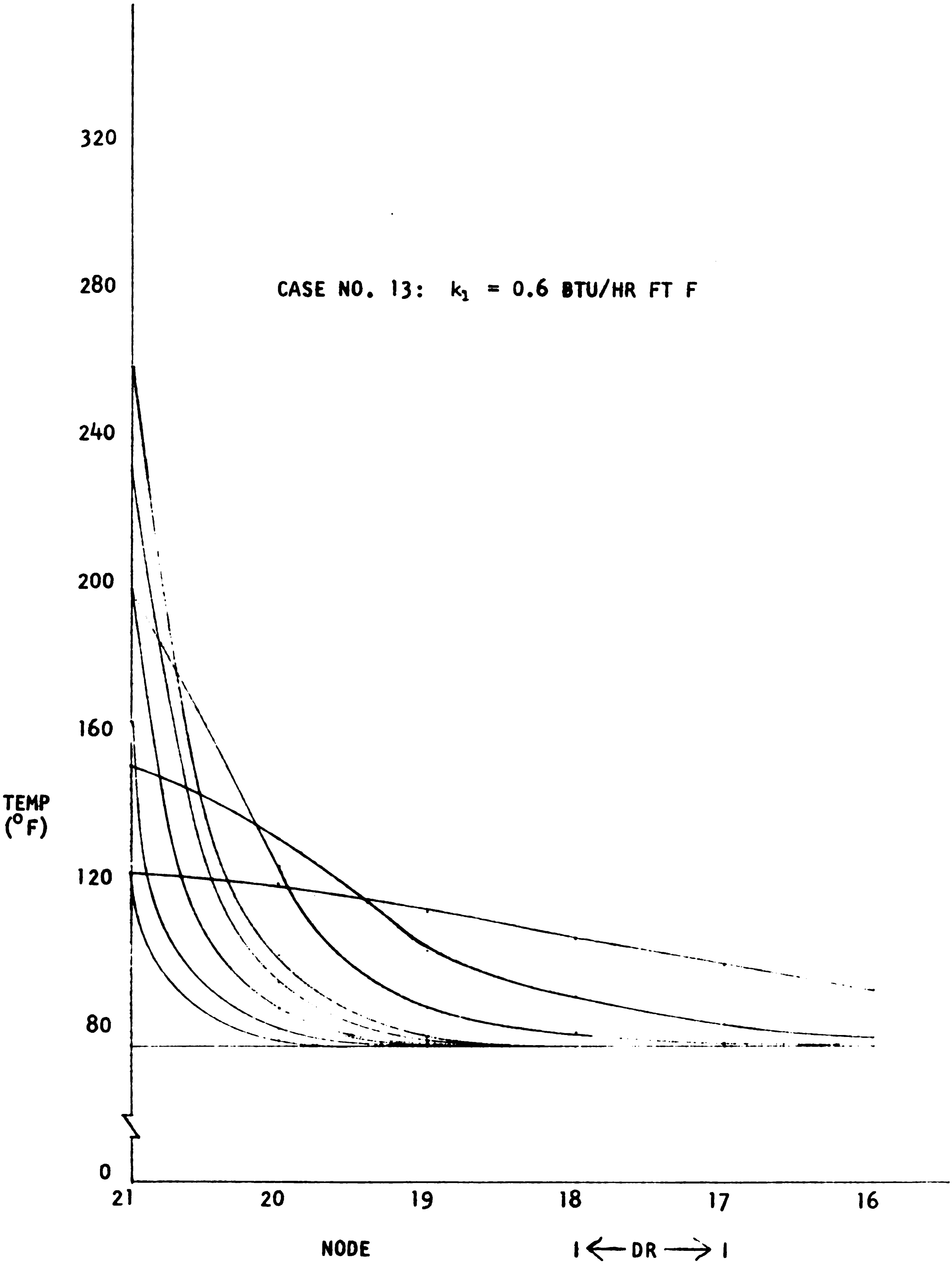

CASE NO. 8: r_s = 0.03 FT
320
280
240
200
160
TEMP
(°F)
120
80
0
21
20
19
18
17
16
NODE
I ← DR → I

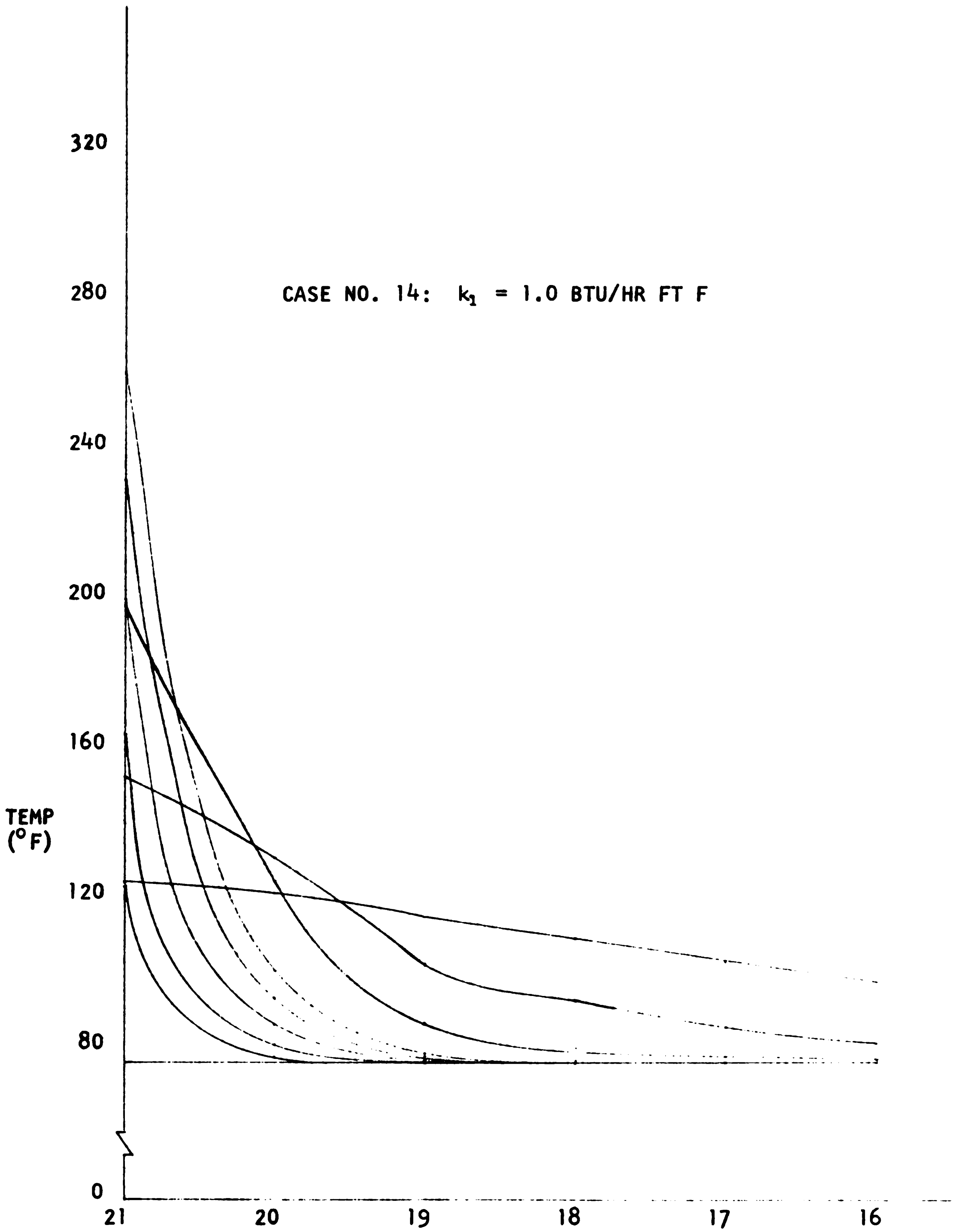

CASE NO. 9: r_s = 0.02 FT
TEMP
(^oF)
320
280
240
200
160
120
80
0
21
20
19
18
17
16
NODE
I← DR →I

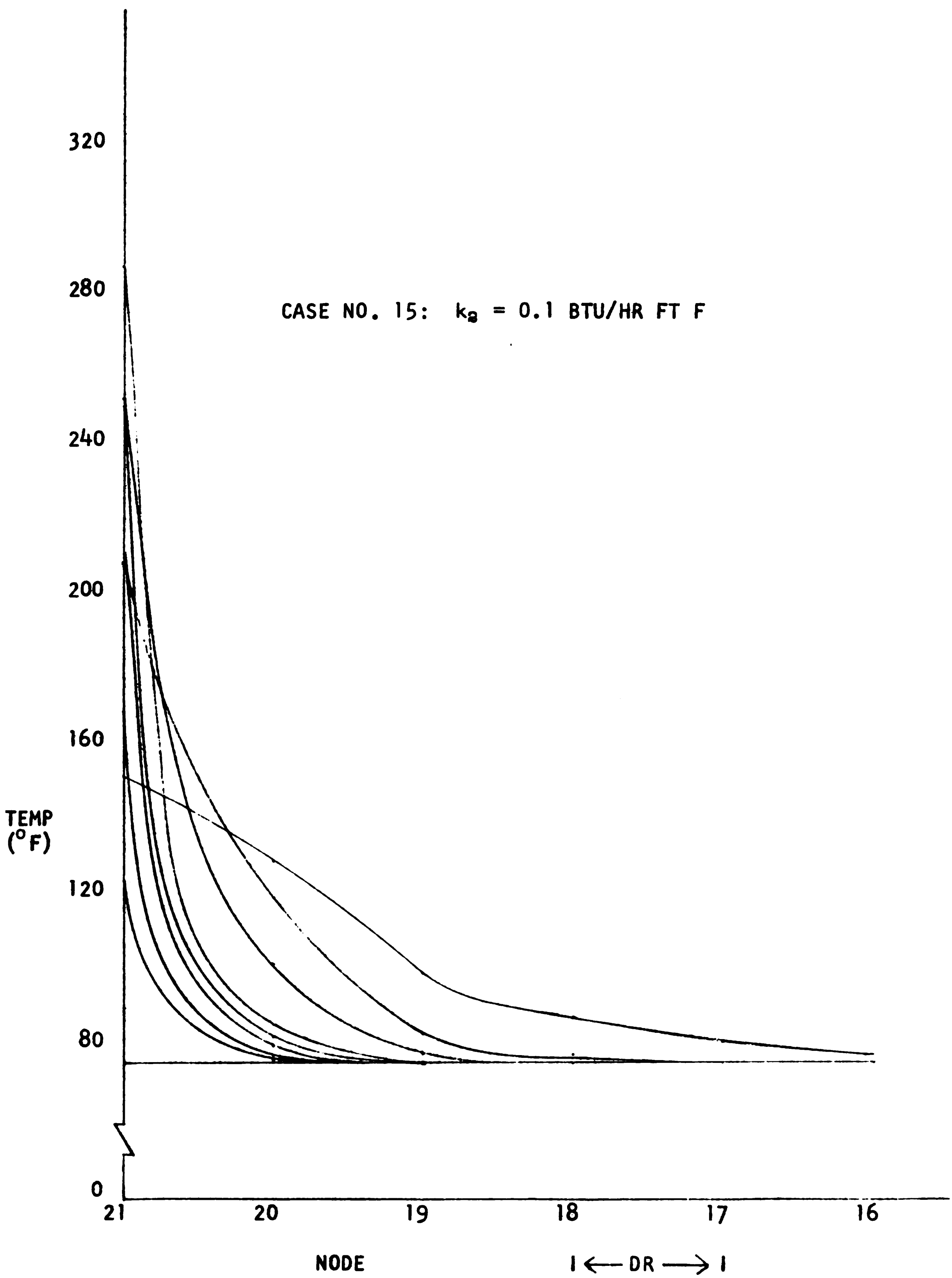

CASE NO. 10: r_s = .01 FT
320
280
240
200
160
TEMP
(°F)
120
80
0
21
20
19
18
17
16
NODE
I ← DR → I

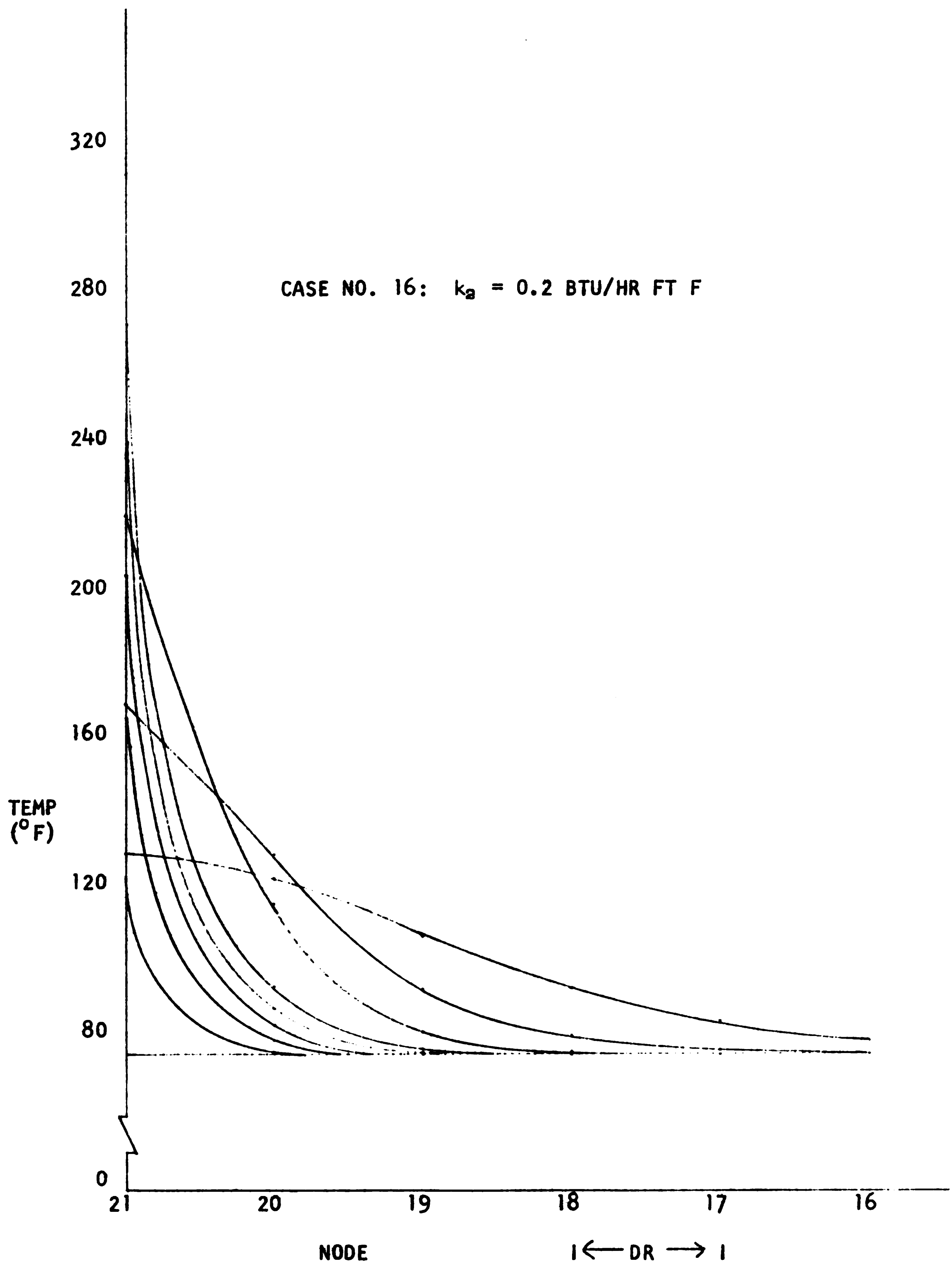

CASE NO. 11: k_1 = 0.1 BTU/HR FT F
320
280
240
200
160
120
80
0
TEMP
(°F)
21
20
19
18
17
16
NODE
I ← DR → I

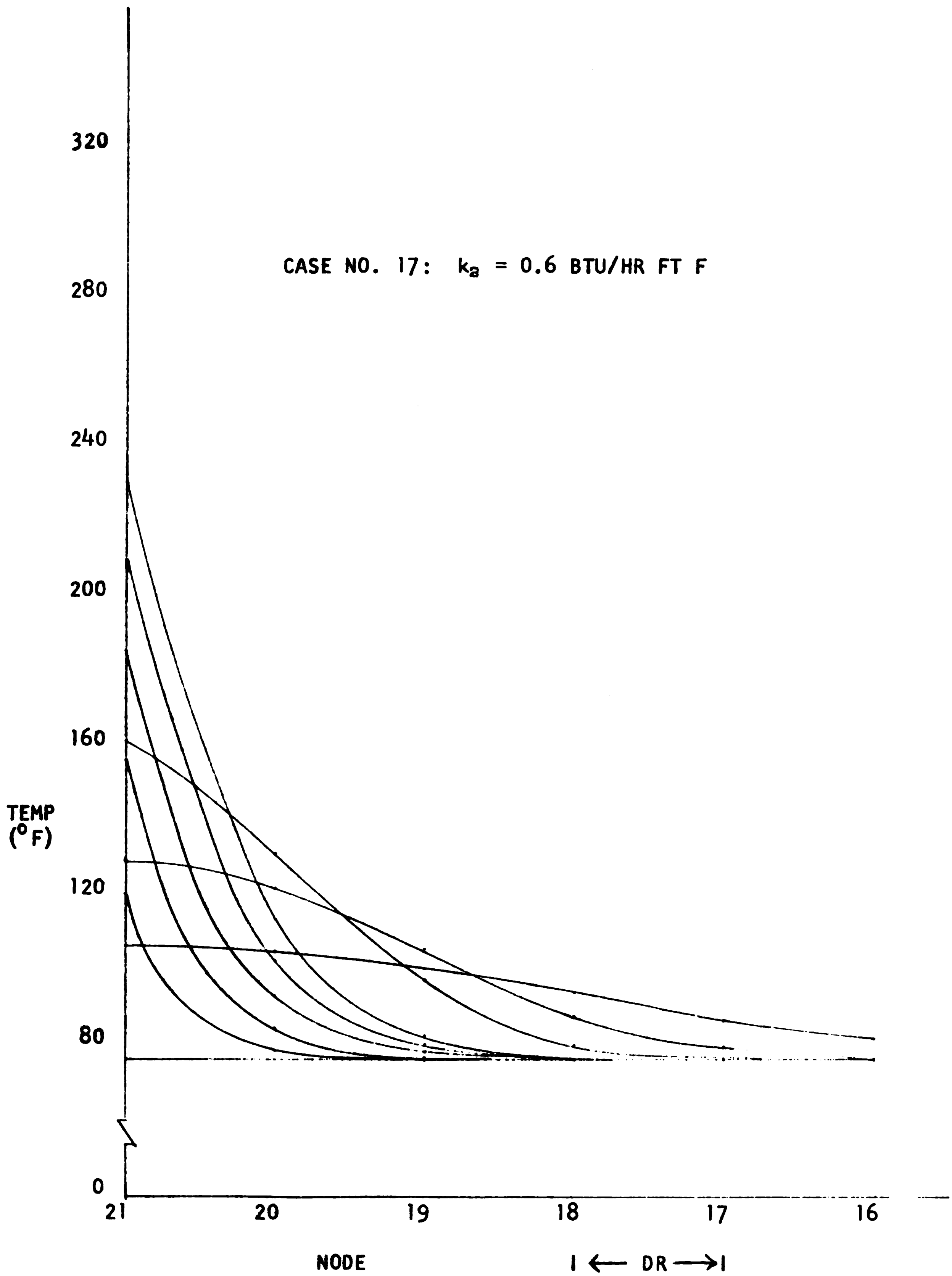

CASE NO. 12: k_1 = 0.3 BTU/HR FT F
320
280
240
200
160
120
80
0
TEMP
(°F)
21
20
19
18
17
16
NODE
I←DR→I


CASE NO. 13: k_1 = 0.6 BTU/HR FT F
TEMP
(°F)
320
280
240
200
160
120
80
0
21
20
19
18
17
16
NODE
I ← DR → I

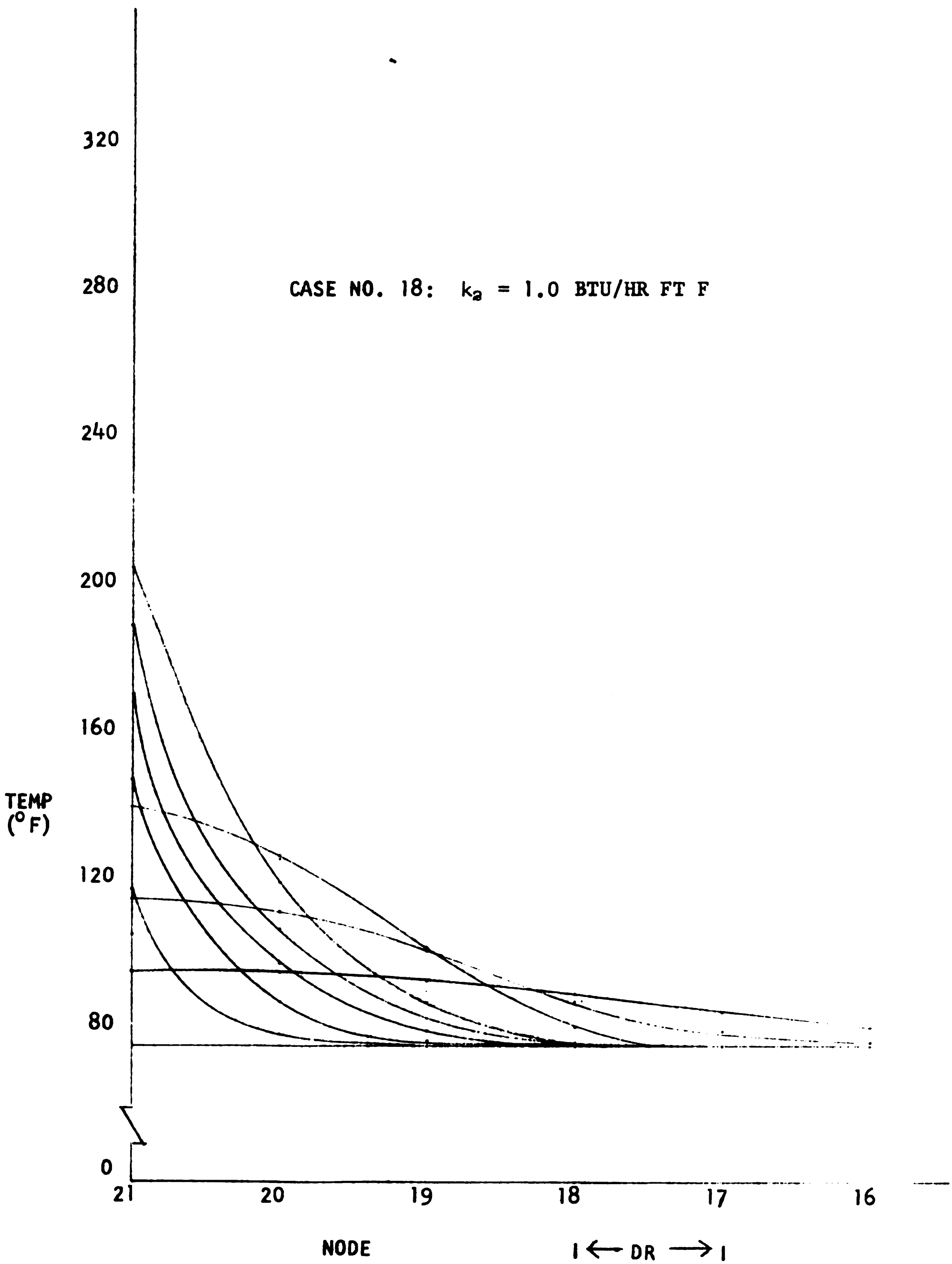

CASE NO. 14: k_1 = 1.0 BTU/HR FT F
320
280
240
200
160
120
80
0
TEMP
(°F)
21
20
19
18
17
16
NODE
I ← DR → I

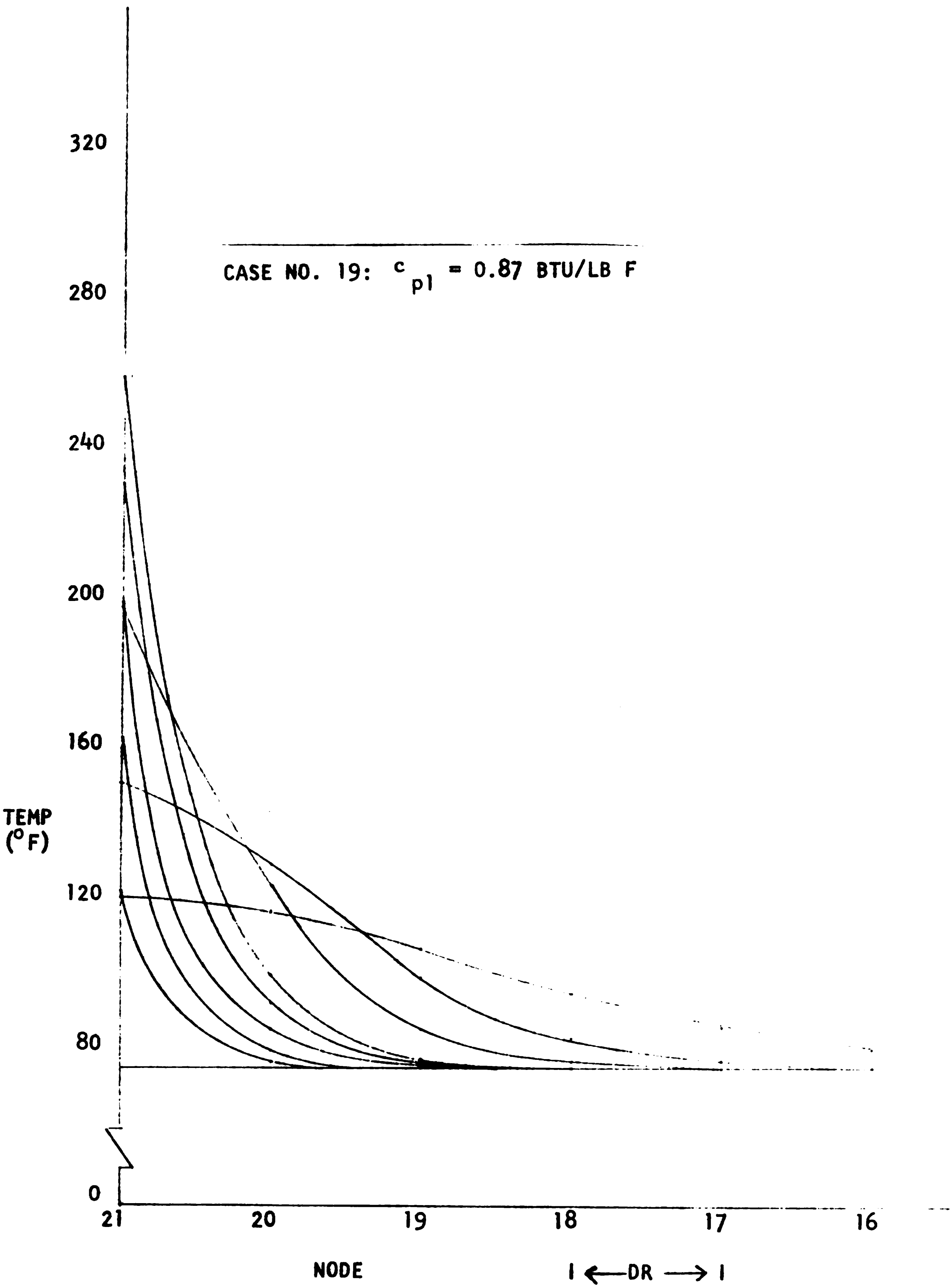

CASE NO. 15: k_s = 0.1 BTU/HR FT F
TEMP
(°F)
320
280
240
200
160
120
80
0
21
20
19
18
17
16
NODE
I ← DR → I


CASE NO. 16: k_a = 0.2 BTU/HR FT F
320
280
240
200
160
120
80
0
TEMP
(°F)
21
20
19
18
17
16
NODE
|← DR → |

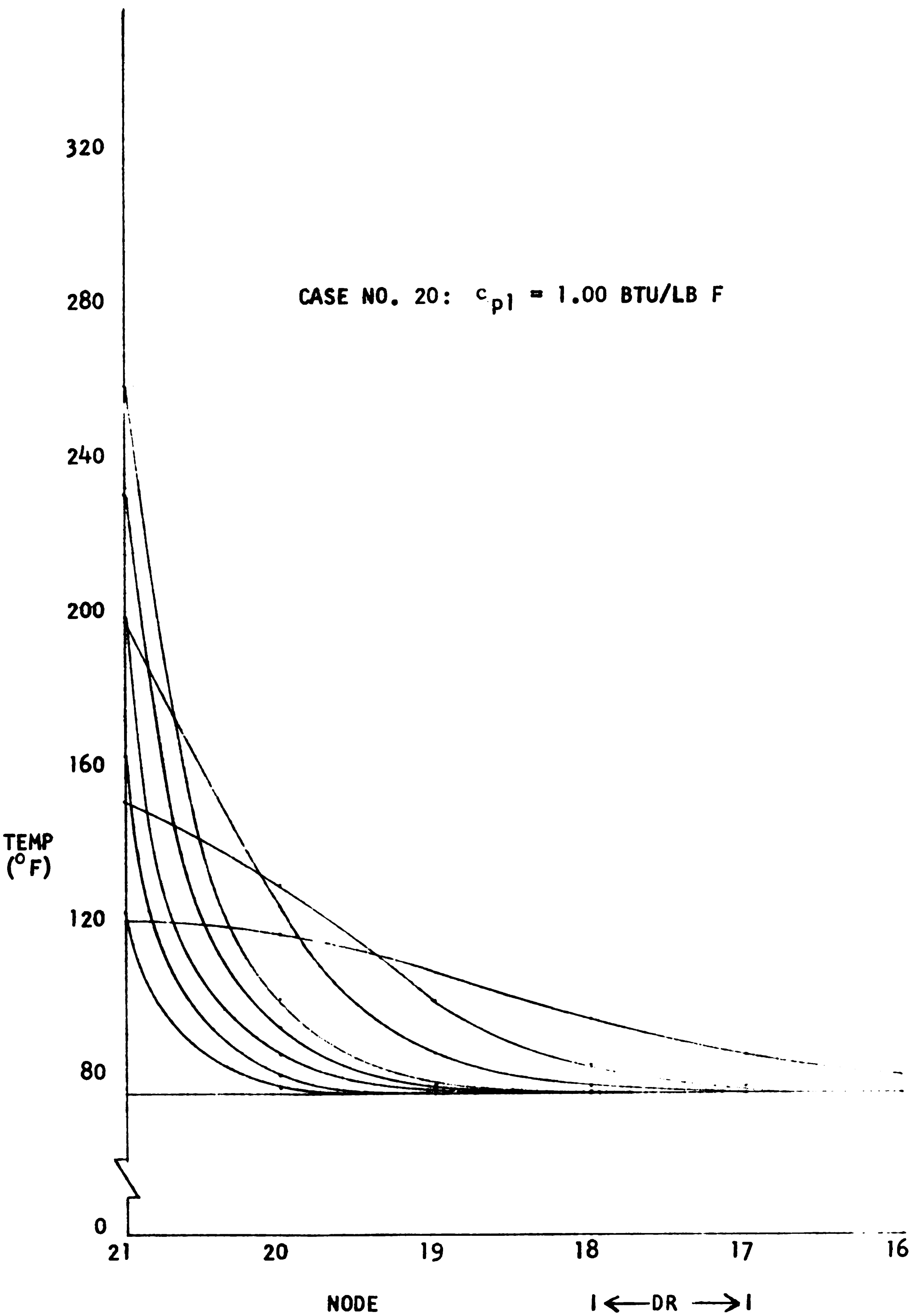


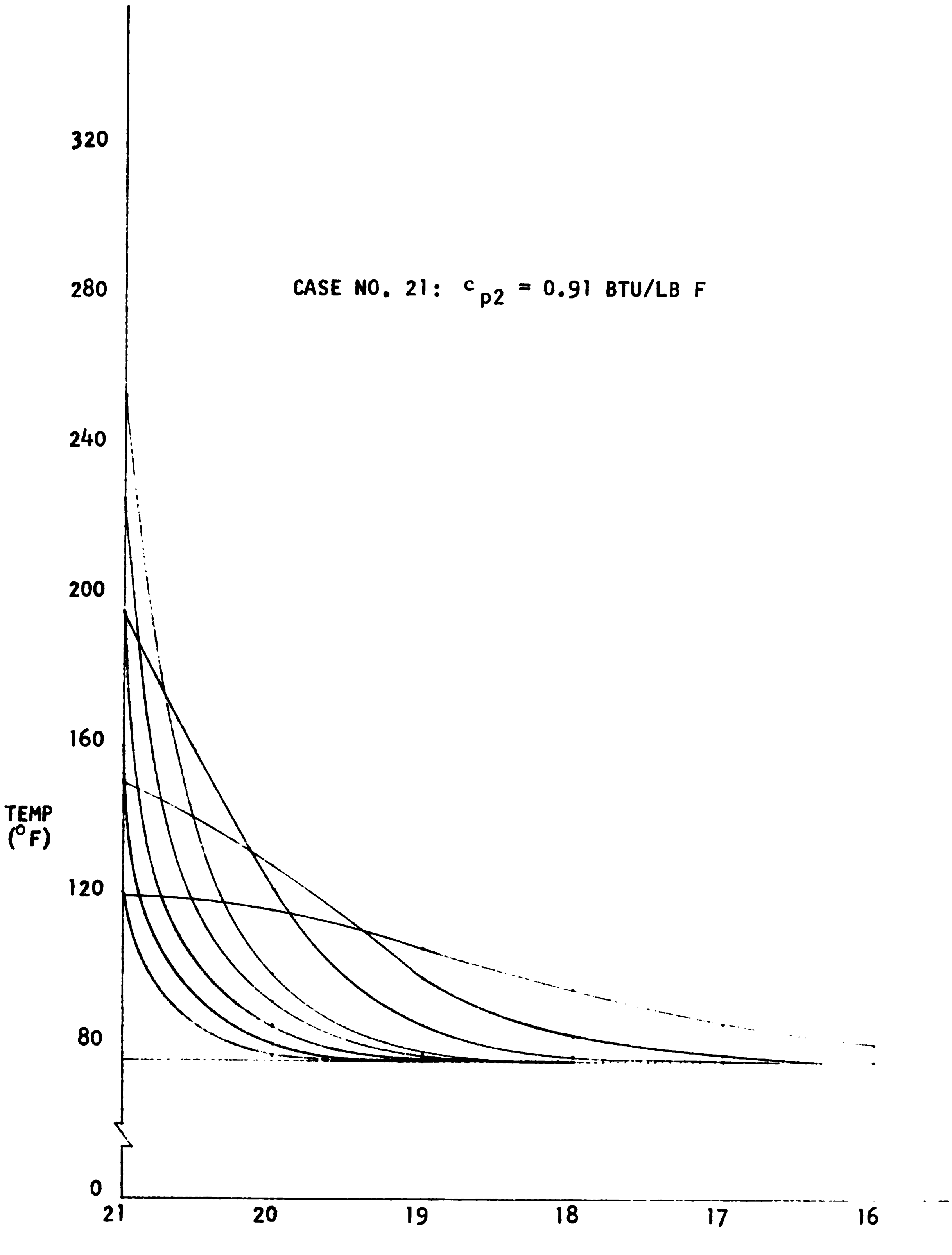
CASE NO. 17: k_a = 0.6 BTU/HR FT F
TEMP (°F)
320
280
240
200
160
120
80
0
21
20
19
18
17
16
NODE
I ← DR → I

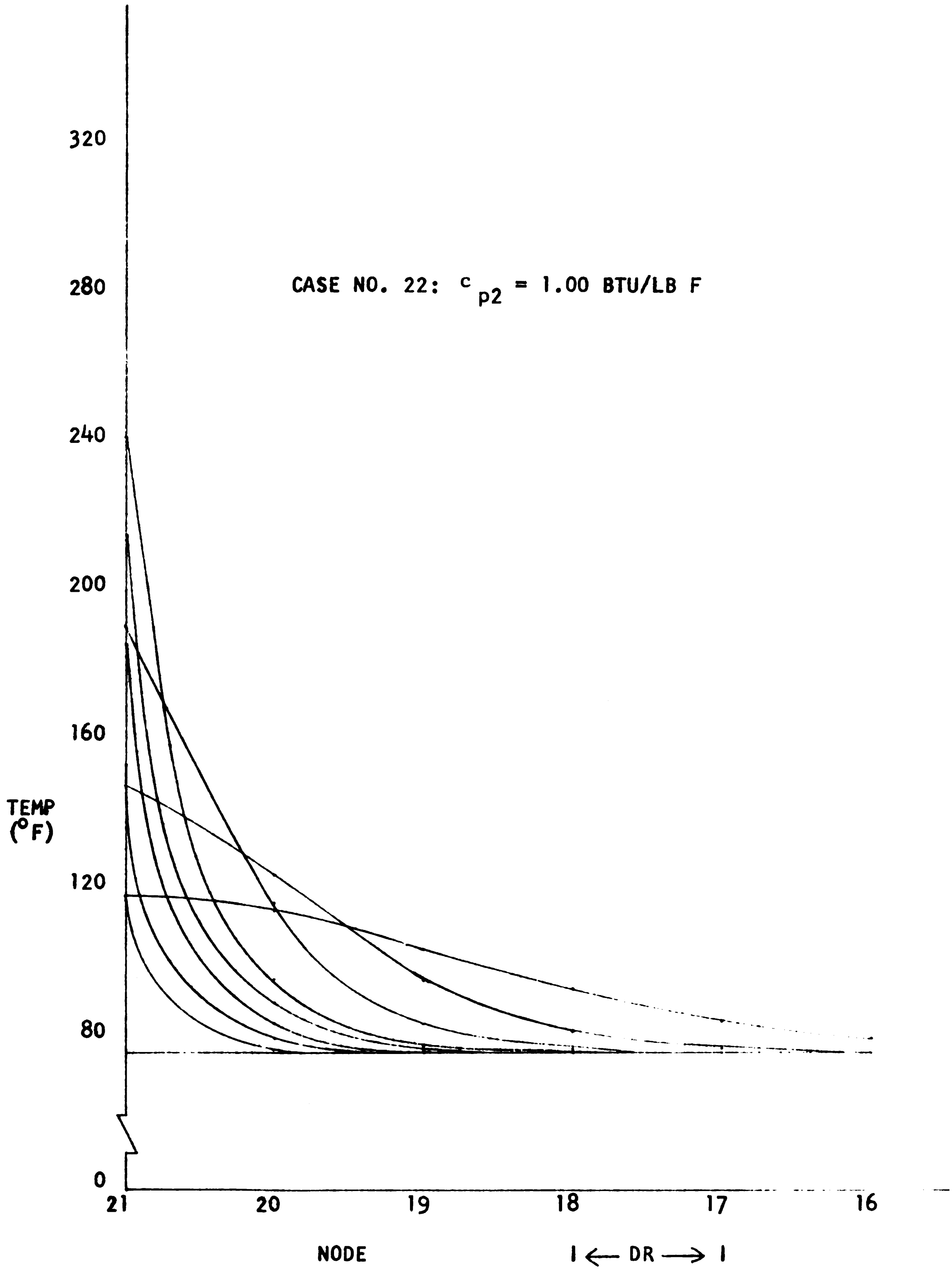

CASE NO. 18: k_a = 1.0 BTU/HR FT F
320
280
240
200
160
TEMP (°F)
120
80
0
21
20
19
18
17
16
NODE
← DR →



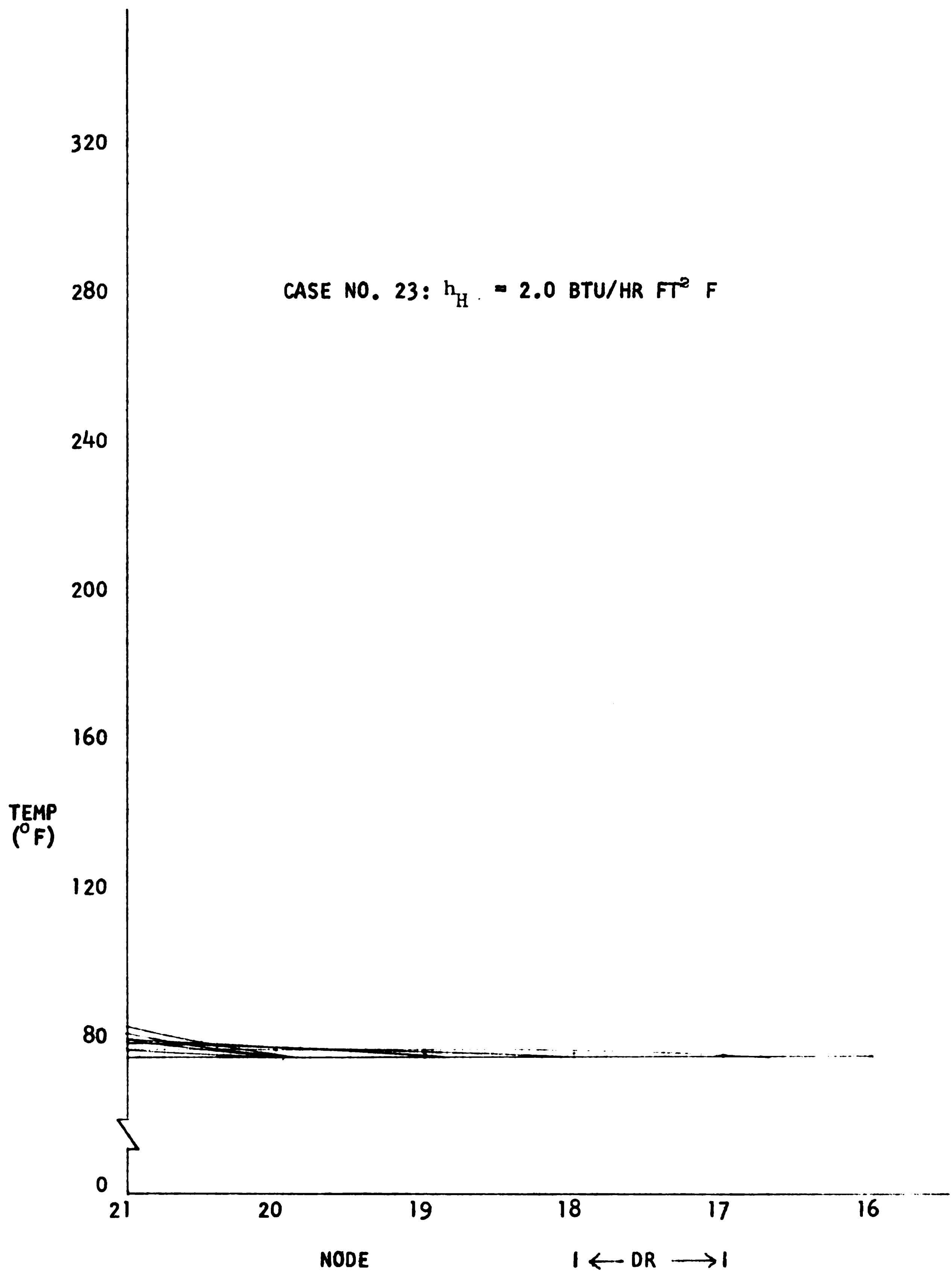
CASE NO. 19: c_{p1} = 0.87 BTU/LB F
320
280
240
200
160
120
80
0
TEMP
(°F)
21
20
19
18
17
16
NODE
I ← DR → I


CASE NO. 20: c_{p1} = 1.00 BTU/LB F
TEMP
(^oF)
320
280
240
200
160
120
80
0
21
20
19
18
17
16
NODE
I ← DR → I

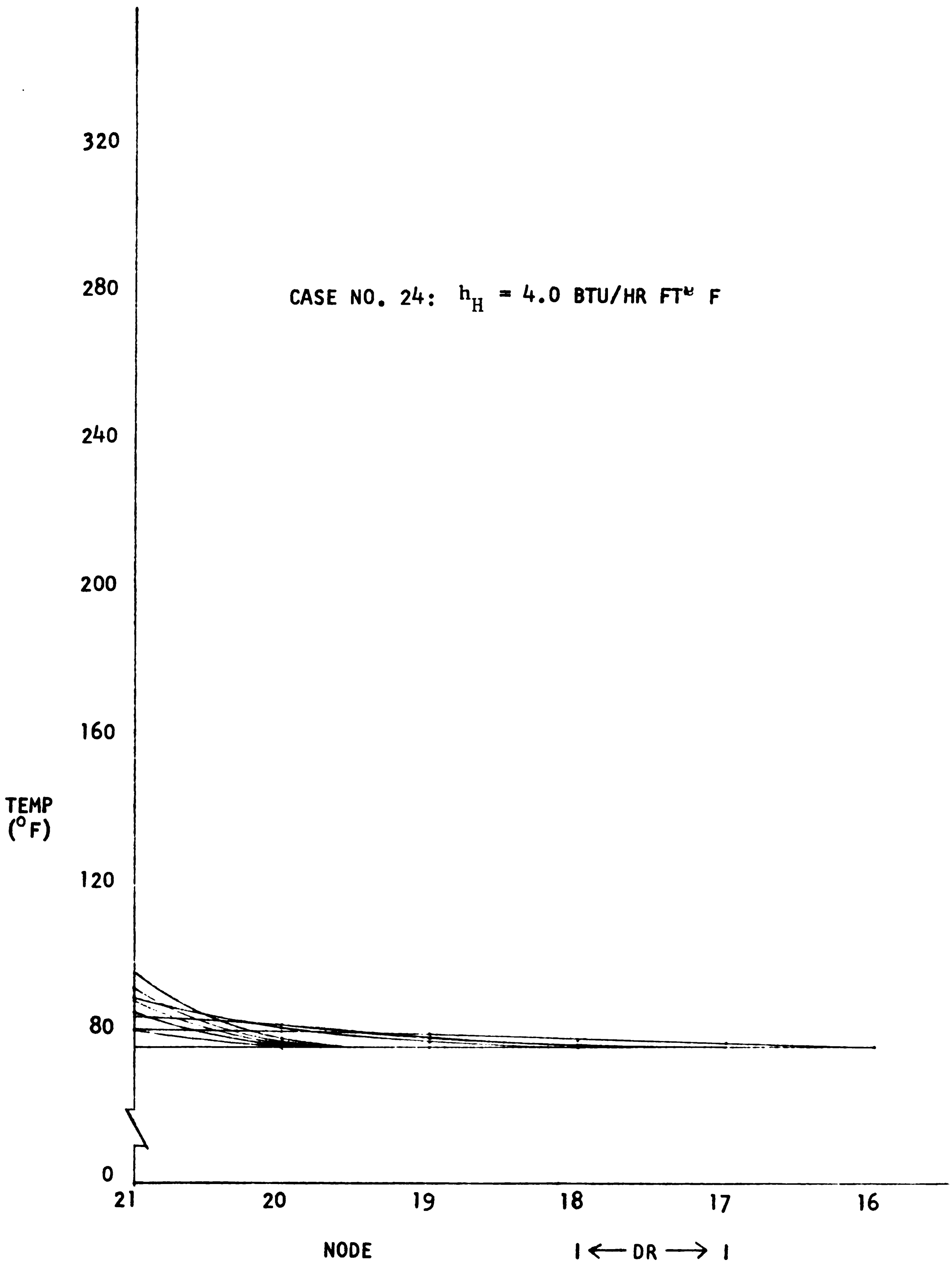

320
280
CASE NO. 21: c_{p2} = 0.91 BTU/LB F
240
200
160
TEMP (°F)
120
80
0
21
20
19
18
17
16
NODE
I ←DR→ I

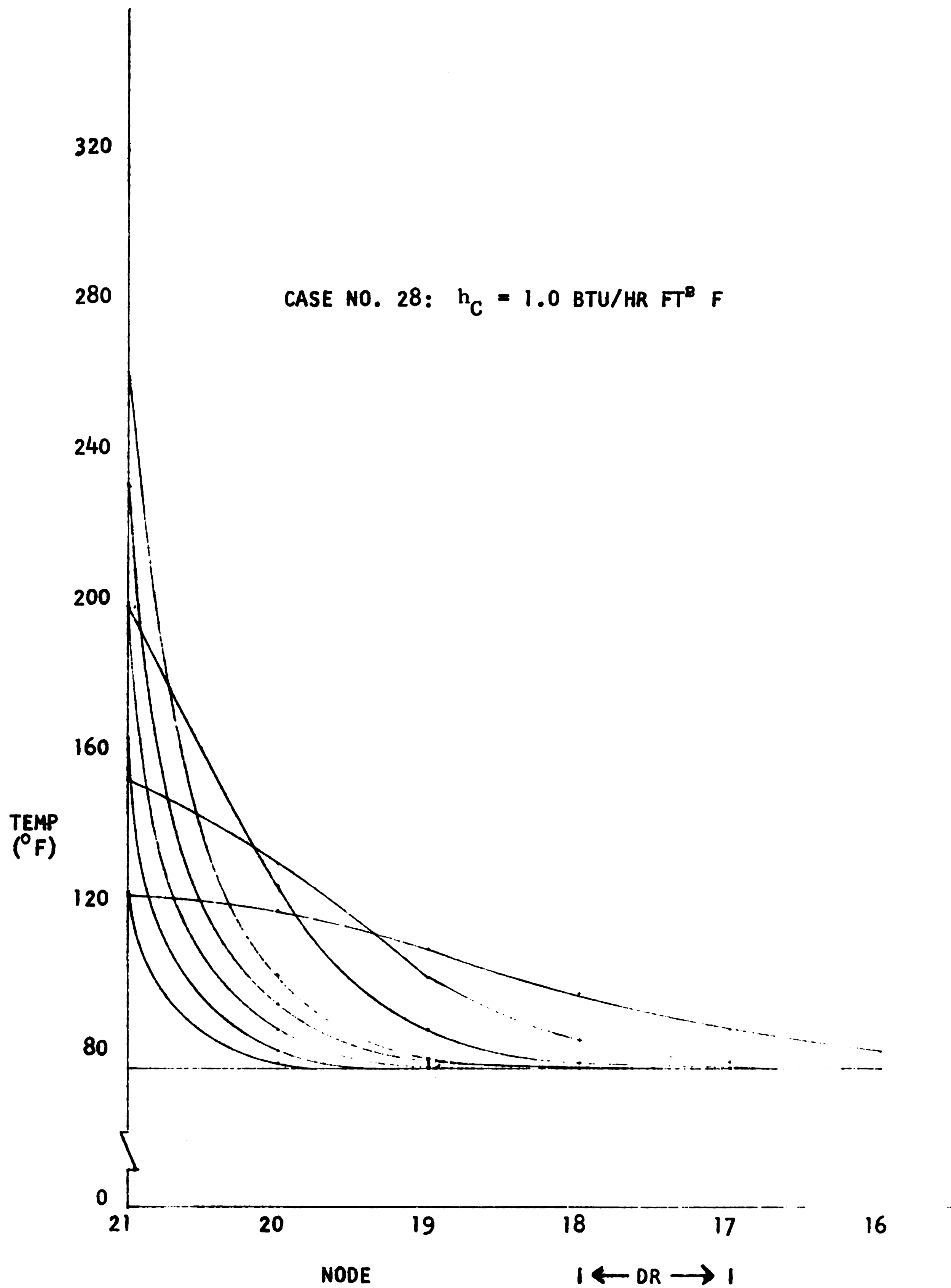


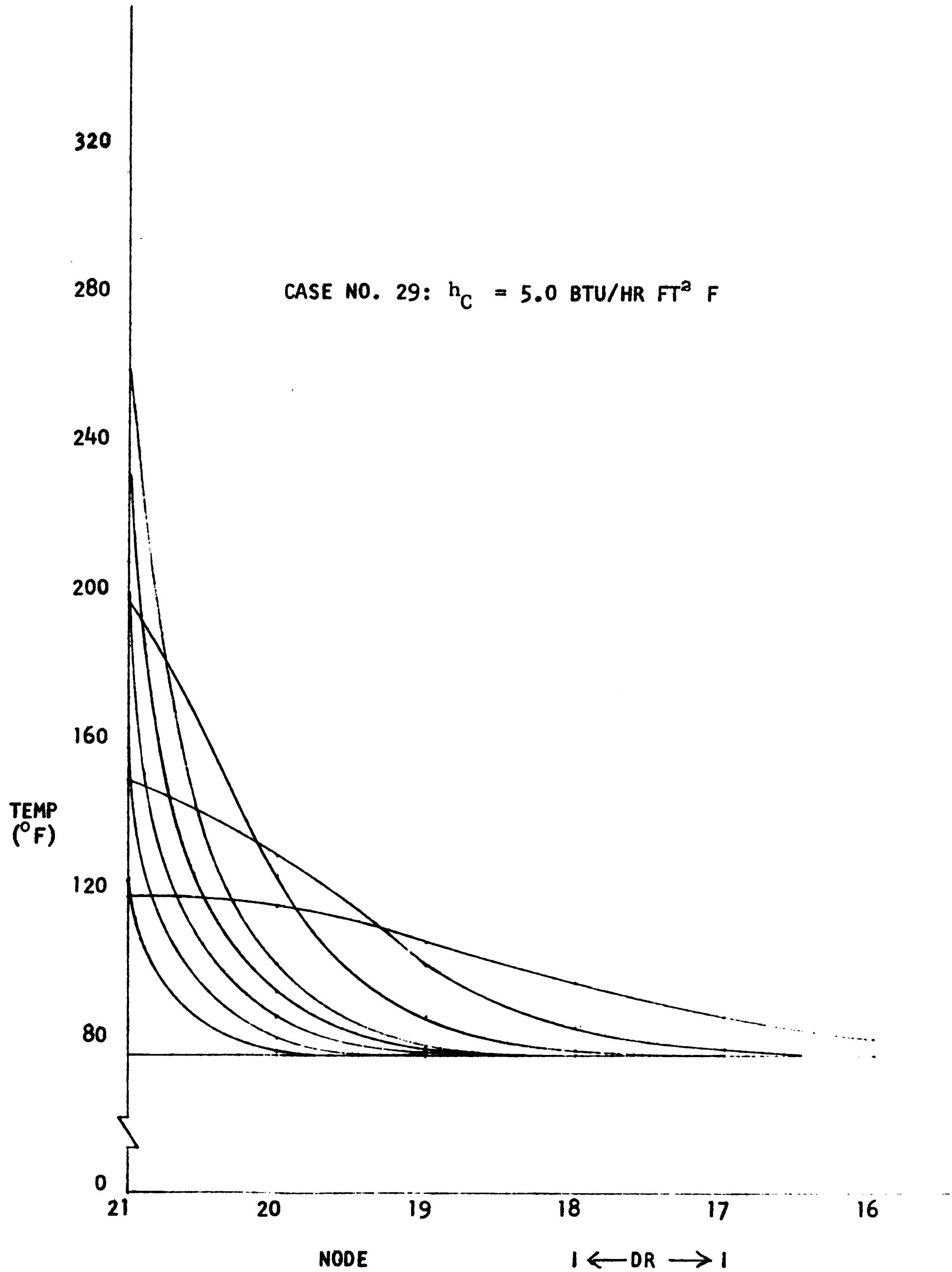
CASE NO. 22: c_{p2} = 1.00 BTU/LB F
TEMP (°F)
320
280
240
200
160
120
80
0
21
20
19
18
17
16
NODE
I ← DR → I

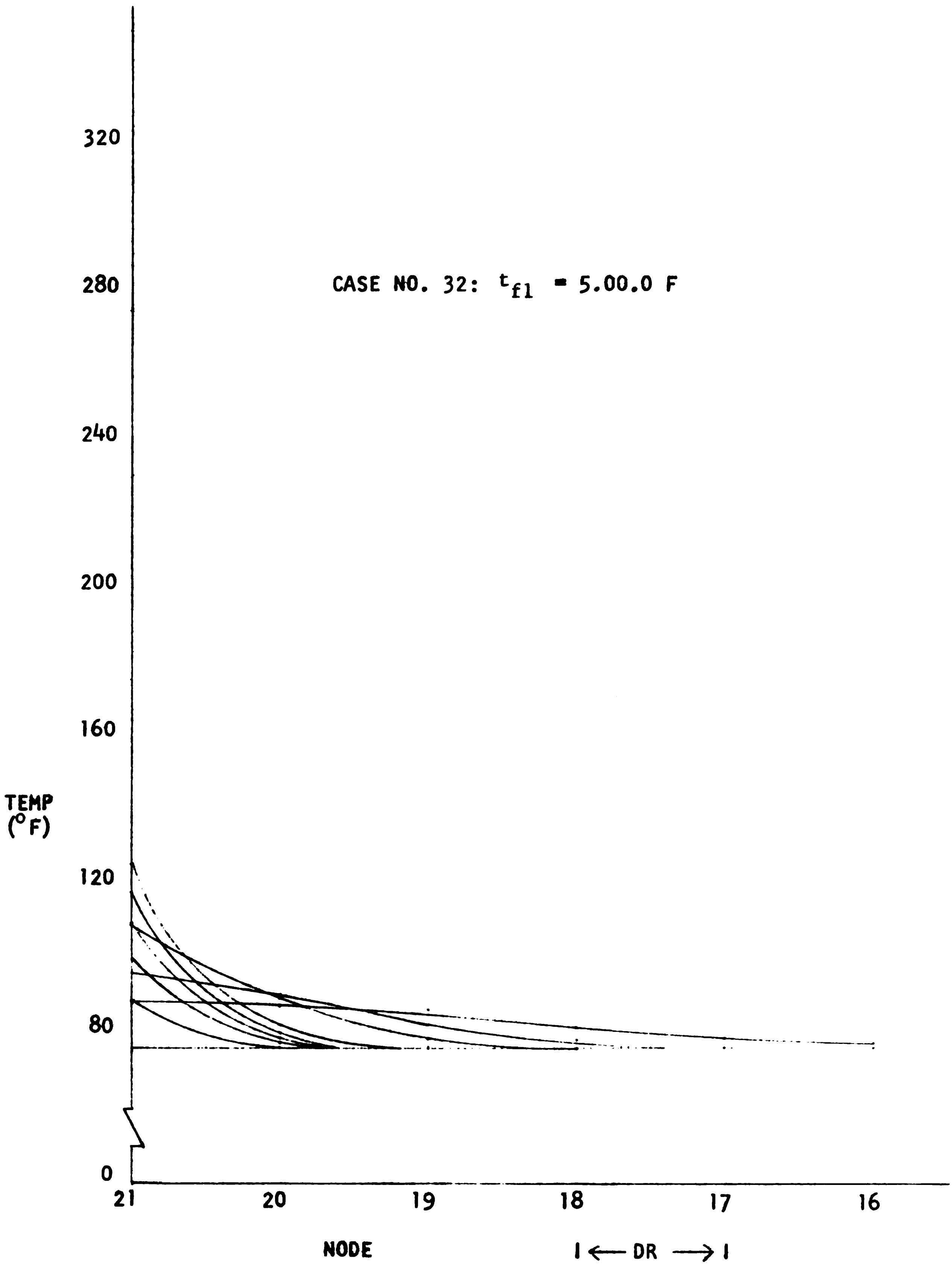


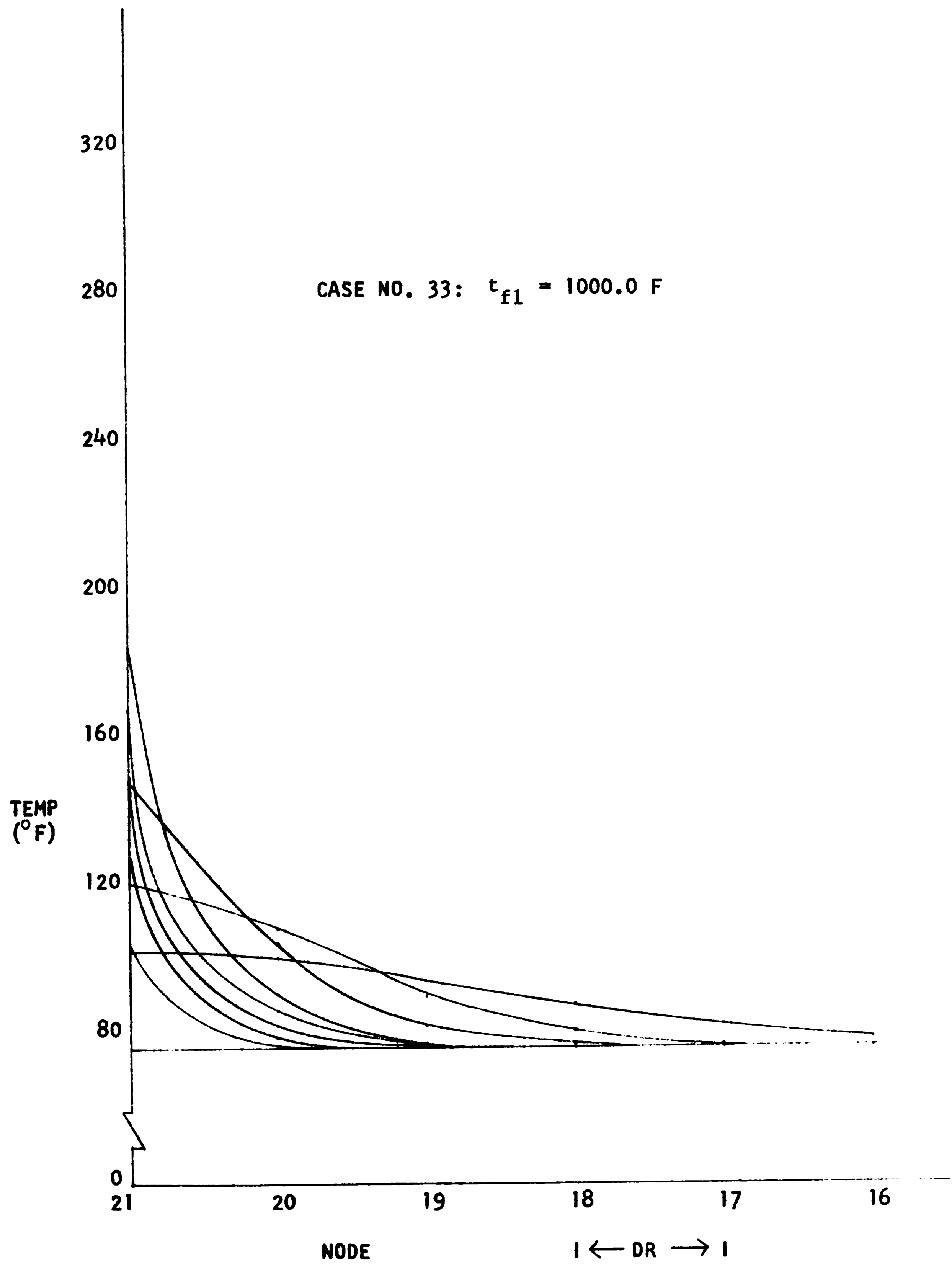
CASE NO. 23: h_H = 2.0 BTU/HR FT^2 F
320
280
240
200
160
120
80
0
TEMP
(^oF)
21
20
19
18
17
16
NODE
I ← DR → I

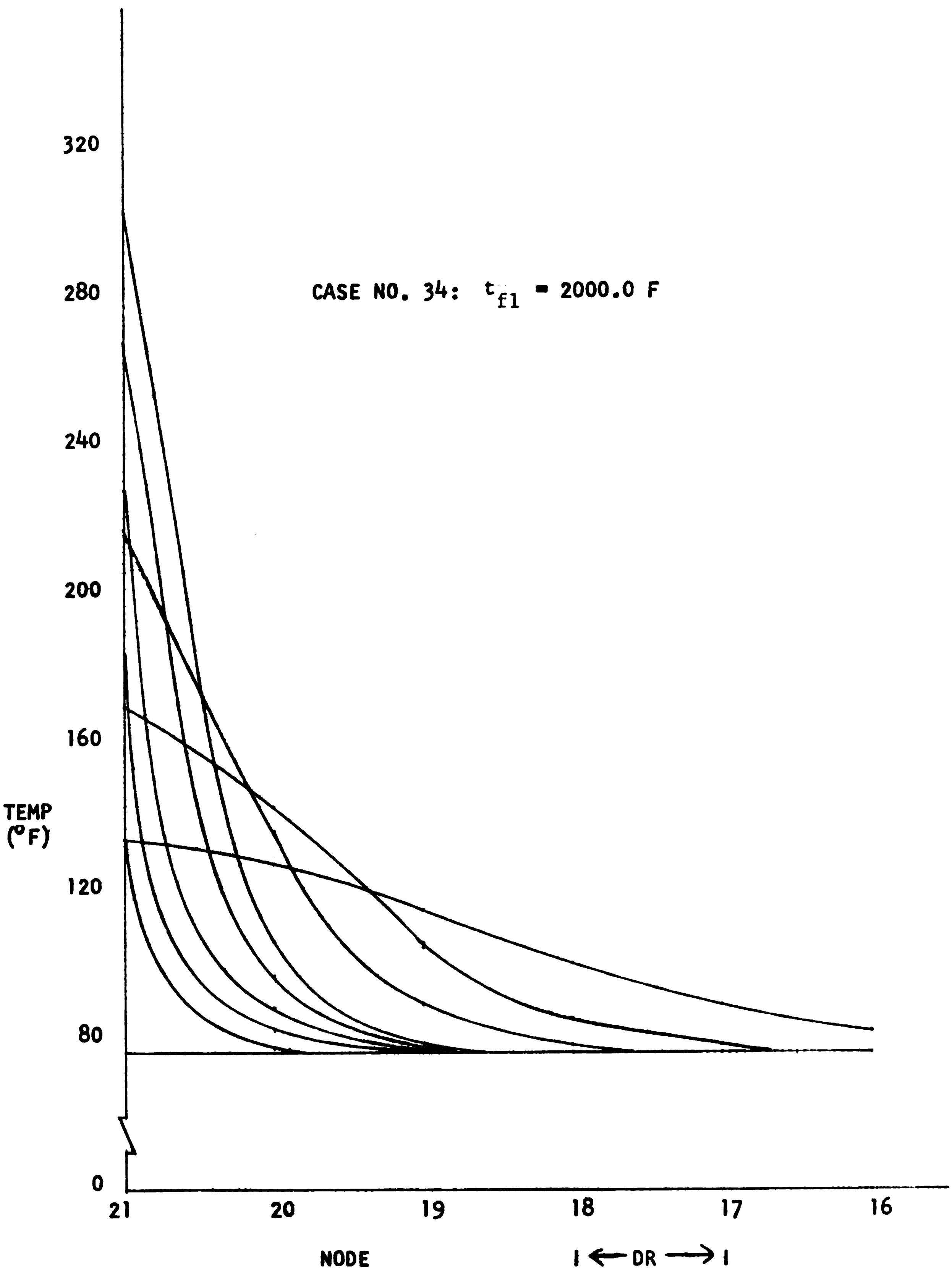

CASE NO. 24: h_H = 4.0 BTU/HR FT² F
TEMP (°F)
320
280
240
200
160
120
80
0
21
20
19
18
17
16
NODE
I ← DR → I


CASE NO. 28: h_C = 1.0 BTU/HR FT² F
320
280
240
200
160
120
80
0
TEMP
(°F)
21
20
19
18
17
16
NODE
I ← DR → I


CASE NO. 29: h_C = 5.0 BTU/HR FT² F
320
280
240
200
160
120
80
0
TEMP
(°F)
21
20
19
18
17
16
NODE
I ⟵ DR ⟶ I


CASE NO. 32: t_{f1} = 5.00.0 F
320
280
240
200
160
120
80
0
TEMP
(°F)
21
20
19
18
17
16
NODE
I ← DR → I


CASE NO. 33: t_{f1} = 1000.0 F
320
280
240
200
160
120
80
0
TEMP
(°F)
21
20
19
18
17
16
NODE
I ← DR → I



CASE NO. 34: t_{f1} = 2000.0 F
320
280
240
200
160
120
80
0
TEMP (°F)
21
20
19
18
17
16
NODE
I ← DR → I

LIST OF SELECTED REFERENCES

Bakker-Arkema, F.W. and Bickert, W.G. (1967). Computer Simulation of the Cooling of a Deep Bed of Cherry Pits. 1. Analysis, Quarterly Bulletin, Michigan Agricultural Experiment Station, Michigan State University, East Lansing, Michigan, Vol. 50, No. 2, pp. 204-211.

Bakker-Arkema, F.W.; Bickert, W.G.; and Patterson, R.J. (1967). Simultaneous Heat and Mass Transfer During the Cooling of a Deep Bed of Biological Products Under Varying Inlet Air Conditions. Journal of Agricultural Engineering Research, Vol. 12, No. 4, pp. 297-307.

Beck, J.V. (1962). Calculation Surface Heat Flux from an Internal Temperature History. ASME Paper No. 62-HT-46, presented at the ASME-AICHE Heat Transfer Conference, Houston, Texas.

Beck, J.V. (1963). Calculation of Thermal Diffusivity from Temperature Measurements. Journal of Heat Transfer, Transactions of the ASME, May, 1963, pp. 181-182.

Beck, J.V. (1964). The Optimum Analytical Design of Transient Experiments for Simultaneous Determinations of Thermal Conductivity and Specific Heat. Ph.D. Thesis, Mechanical Engineering Department, Michigan State University, East Lansing, Michigan.

Bennett, A.H.; Chace, W.G., Jr.; and R.E. Cubbedge. (1962) Estimating Thermal Conductivity of Fruit and Vegetable Components -- The Fitch Method. ASHRAE Journal, Vol. 4, No. 9, pp. 80-85.

Carslaw, H.S. and Jaeger, J.C. (1965). <u>Conduction of Heat in Solids</u>. Oxford University Press, London, Reprinted by D. R. Hillman and Sons, Ltd.

Crank, J. and Nicholson, P. (1947). A Practical Method for Numerical Evaluation of Solutions of Partial Differential Equations of the Heat Conduction Type. Proceedings The Cambridge Philosophical Society, Vol. 43, pp. 50-67.

Dusinberre, G.M. (1961). <u>Heat Transfer Calculations by Finite Differences</u>. International Textbook Co., Scranton, Pa., pp. 64-71.

Eucken, A. (1940). Allgemeine Gesetzmassigkeiten fur das Warmeleitvermogen verschiedener Stoffarten und Aggregatzustande, Forschungsgebiete Ingenieur, Ausgabe A., Vol. 11, No. 1, pp. 6-20.

Finch, D.I. (1962). General Principles of Thermoelectric Thermometry. Research and Development Department, Leeds and Northrup Co., published by Reinhold Publishing Corporation, pp. 34-43.

Fitch, A.L. (1935). A New Thermal Conductivity Apparatus. American Physics Teacher, Vol. 3, p. 135.

Freed, N.H. and Rallis, C.J. (1961). Truncation Error Estimates for Numerical and Analog Solutions of the Heat Conduction Equation. Journal of Heat Transfer, Vol. 83, pp. 383-384.

Gurney, H.P. and Lurie, J. (1923). Charts for Estimating Temperature Distributions in Heating or Cooling Solid Shapes. Industrial and Engineering Chemistry, Vol. 15, pp. 1170-1172.

Hartree, D.R. (1958). Numerical Analysis Oxford at the Clarendon Press.

Kardas, A. (1964). Errors in a Finite-Difference Solution of the Heat Flow Equation. Journal of Heat Transfer, Vol. 86, pp. 561-562.

Kethley, T.W.; Cown, W.B.; and Bellinger, F. (1950). An Estimate of the Thermal Conductivities of Fruits and Vegatables. Refrigerating Engineering, Vol. 58, pp. 49-50.

Kopelman, I.J. (1966). Transient Heat Transfer and Thermal Properties in Food Systems. Ph. D. Thesis, Food Science Department, Michigan State University, East Lansing, Michigan.

Kreith, F. (1958). Principles of Heat Transfer. International Text-Book Co., Scranton, Pa.

Lalor, W.F., and Buchele, W.F. (1966). The Development and Preliminary Testing of an Air-curtain Flame Weeder. Report to Iowa LP-Gas Association, Des Moines, Iowa.

Lentz, C.P. (1961). Thermal Conductivity of Meats, Fats, Gelatin Gels and Ice. Food Technology, Vol. 15, pp. 243-247.

Lentz, C.P. (1964). The Role of Engineers in Food Research. Food Technology, Vol. 18, No. 14, p. 104.

Luikov, A.V. (1964). Heat and Mass Transfer in Capillary-Porous Bodies. Advances in Heat Transfer, Academic Press, Vol. 1, pp. 123-184.

Matthews, F.V., Jr. (1966). Thermal Diffusivity by Finite Differences and Correlation with Physical Properties of Heat Treated Potatoes. Ph. D. Thesis, Agricultural Engineering Department, Michigan State University, East Lansing, Michigan.

Maxwell, J.C. (1904). A Treatise of Electricity and Magnetism. Dover Publications, Inc., New York, New York, Vols. 1 and 2. (1954)

Mironov, V.F. (1962). Inzh. Fiz. Zh., Vol. 5, p. 10.

Moore, R.P. (1960). Tetrazolium Testing Techniques. Proceedings of 38th Annual Meeting, Society of Commercial Seed Technologists, pp. 45-51.

Parker, R.E. and Stout, B.A. (1967). Thermal Properties of Tart Cherries. Transactions of the ASAE, Vol. 10, No. 4, pp. 489-491, 496.

Patin, T.R. (1967). Internal Temperature in Cotton Stalks Induced by Flame Cultivation and the Resulting Cell Damage. M.S. Thesis, Agricultural Engineering Department, Louisiana State University, Baton Rouge, Louisiana.

Perumpral, J. (1965). Determination of Temperative Patterns of Flame Cultivator Burners. M.S. Thesis, Agricultural Engineering Department, Purdue University, Lafayette, Indiana.

Reidy, G.A. (1968) Thermal Properties of Foods and Methods of Their Determination. M.S. Thesis, Food Science Department, Michigan State University, East Lansing, Michigan.

Richtmeyer, R.D. (1957). Difference Methods for Initial-Value Problems. Interscience Tracts in Pure and Applied Mathematics, No. 4.

Riedel, L. (1951). The Refrigerating Effect Required to Freeze Fruits and Vegetables. Refrigerating Engineering, Vol. 59, pp. 670-673.

Schneider, P.J. (1957). Conduction Heat Transfer. Addison-Wesley, Inc., Reading, Massachusetts.

Smilie, J.L.; Thomas, C.H.; and Standifer, L.C., Jr. (1964). Farm With Flame. Louisiana Agricultural Extension Publication 1364, Louisiana State University, Baton Rouge, Louisiana.

Smith, G.D. (1965). Numerical Solution of Partial Differential Equations. Oxford University Press, London.

Watson, H. (1961). A Study of Flame Patterns Obtained from a Flame Cultivator Burner as Affected by Fuel Pressure. Special Problem Report, Agricultural Engineering Department, Louisiana State University, Baton Rouge, La.

Weber, W.J., Jr. and Rumer, R. R., Jr. (1965). Intraparticle Transport of Sulfonated Alkylbenzenes in a Porous Solid: Diffusion with Nonlinear Adsorption. Water Resources Research, Vol. 1, No. 3, pp. 361-373.

Woodams, E.E. and Nowrey, J.E. (1968). Literature Values of Thermal Conductivities of Foods. Food Technology, Vol. 22, pp. 494-502.

, National Bureau of Standards, Thermal Conductivity of Sample of Silastic Silicone Rubber. Submitted by the U.S.D.A., Test Report, Test Folder G28359.