AN ABSTRACT OF THE THESIS OF

Endalkachew Sahle-Demessie for the degree of Master of Science in Chemical Engineering presented on August 30, 1989.

Title : Dynamic Modeling of Thermal Treatment of Timber Poles

Abstract approved: Redacted for Privacy

Keith Levien

The temperature-time-location relationships during steam conditioning and pressure treatment of timber poles have been studied and mathematical models that take into account both the thermal properties of the poles and the parameters of the treatment process have been developed. Although much work has been previously done in this area, the standard "recipe" to sterilize wood fails to bring the interiors of large diameter wood poles to the required temperature. Recent studies (DOST, 1984; NEWBILL et al.,1988) indicated that commonly used charts, initially made by MACLEAN (1930,1932,1935,1952), predict a much faster temperature increase than actually measured. In all previous modeling work it has been assumed that during pressure treatment, operational changes result in step changes of the surface temperatures of the poles. However, from actual measurements it was found that when operating conditions changed, there was a time interval, ' time lag', during which no effect was observed on the surface temperature of the poles. These time lags are due to the thermal capacity of the process equipment and were found to be an important element for

accurate prediction.

The unknown parameters of several mathematical models were estimated by fitting experimental data taken from commercial scale equipment (NEWBILL et al., 1988). The best model was discriminated among rival ones and the sensitivity and reliability of its estimated parameters were analyzed. Charts were made that show the minimum required steaming time that ensures that the center pith shall be heated to and remain above 150 ^{o}F (65.5^{o}C) for 2 hours according to the 1982 Rural Electrification Authority, REA, purchase specification.

Dynamic Modeling of Thermal Treatment of Timber Poles

by

Endalkachew Sahle-Demessie

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Completed August 30, 1989

Commencement June 1990

Approved:

Redacted for Privacy

Assistant Professor of Chemical Engineering in charge of major

Redacted for Privacy

Head of department of Chemical Engineering

Redacted for Privacy

Dean of Graduate School

Date thesis is presented August 30, 1989

Typed by: Endalkachew Sahle-Demessie

ACKNOWLEDGEMENTS

I wish to take this opportunity to express my appreciation to Dr. Keith Levien for his helpful advice, guidance and constant encouragement throughout the course of this study.

Especial thanks are extended to Dr. J.J. Morrell and M. Newbill for their congenial cooperation in providing raw data for this study and for their helpful advice.

Deep consideration is extended to the Addis Ababa University, in Ethiopia, and the Chemical Engineering Department at OSU for their financial support.

Particular acknowledgement is due to my parents and to Debbra Wallace for their encouragement and help during the the course of my studies.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

DYNAMIC MODELING OF THERMAL TREATMENT OF TIMBER POLES

CHAPTER 1.0

INTRODUCTION TO PROCESS OBJECTIVES AND CURRENT PRACTICE

1.1 GENERAL PRINCIPLES OF WOOD PRESERVATION

Timber poles are widely used by telephone and power companies in the construction of their overhead transmission and distribution lines. However, all timber is liable to attack and decay by wood-destroying organisms when exposed under environmental conditions favorable to their development and growth. These conditions include proper temperature, sufficient moisture, sufficient air, and a food supply. Some infection and decay may occur in a living tree but this infection is minor. When wood is in outdoor service there is no control over temperature, moisture, and air and untreated wood is therefore highly liable to decay. The wood preservation industry uses heat sterilization and chemical treatments to effectively poison the food supply of the microorganisms.

The main requirements for treating wood are that the physical properties, other than density, should not be materially altered and that the treatment should keep wood destroying insects and fungi inactive. Such treatments have made wood an economical material to use in many fields. The normal useful service life of a treated pole is 35 years, compared to 5 - 6 years if untreated. There are treated poles still in use 70 to 80 years after erection.

There are many factors that make treatment of wood quite complex. Some of these factors are:

- the properties and characteristics of wood vary with the species,
- the center of a tree trunk (heart wood) has quite different properties from that on the outside, near the bark (sapwood),
- differences in wood result from where the tree grows,
- the different ways the wood is processed (sawed, seasoned, chemically treated, machined, etc.,) will also affect characteristics of the final wood product.

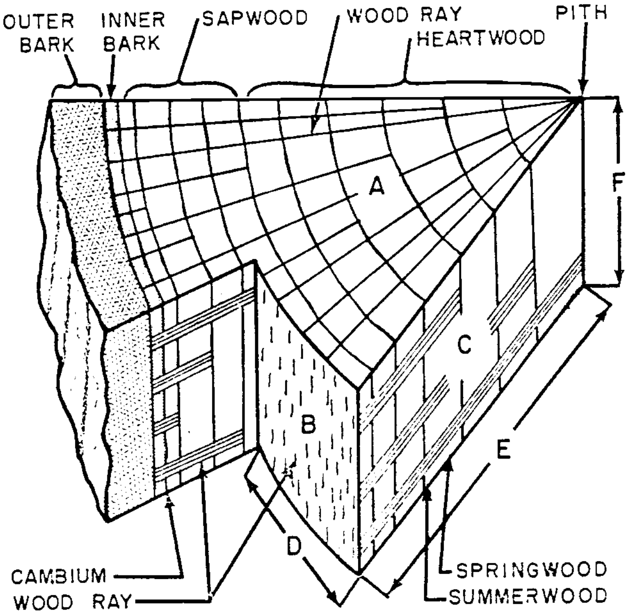
1.2 STRUCTURE OF WOOD

Wood is a complex cellular material. The cell walls are composed of cellulose and lignin upon which have been deposited residues,"extractives", of the physiological processes of the once living cells. The type of cell, their size, shape, arrangement, wall thickness, and wall openings vary with species. Hardwoods differ from softwoods. Considerable variation also occurs within a species and even within a tree as result of heredity and growing conditions.

Figure 1.1 shows a section of a softwood with the central wood portion surrounded by the bark. The outer bark has the functions of protection and conduction of food. The wood portion in most species is differentiated readily into *'sapwood'* and *'heartwood'* regions. Both are constructed basically of long, slender, fiber-like cells(tracheids) oriented parallel to the longitudinal axis of the of the tree. These tracheids are the water conducting units which resemble tubes with tapered ends. Most liquids pass through the cell cavity which is called the lumen. Passages are provided for the liquids to pass from one lumen to another by means of pits. To give a general idea as to the size of structure being dealt with, STAMM (1932) reported that conifers which have an average tracheid length of 0.3 cm and a diameter of 0.003 cm have from 30 to 300 pits connecting adjoining fibers, and there are from 50,000 to 100,000 such fibers in a square centimeter cross section. ELFRING (1882) and SCHEIT (1884) proved that even though the tracheids are hygroscopic, they are relatively impervious to rapid movements of liquids.

Other main anatomical components of wood are narrow bands of tissue, denoted as 'wood rays', which extend through the inner bark towards the pith perpendicular to the tree's axis. Wood rays serve to conduct manufactured food solutions radially from the inner bark to the living cells in the outer sapwood. Rays represent planes of weakness which contribute to the surface checking as the barked pole, or flat-grained lumber, dries in seasoning.

Fibers in outer sapwood are physiologically active in conducting water from the ground to leaves in the crown for the manufacture of food and its distribution. It is generally accepted that sapwood is more permeable to liquids than heartwood BAILEY (1915), GRIFFIN (1919), SCARTH (1928), ERICKSON et al. (1937), STONE (1939) and VERRALL (1957). To show the difficulty in obtaining reproducible results TEESDALE (1914) stated that "Results with a given species of wood cannot be applied to another species, however similar in structure the two may appear. Even wood of the same species will vary when grown under widely different conditions."



A -- CROSS SECTION
B -- TANGENTIAL SECTION
C -- RADIAL SECTION
D -- TANGENTIAL DIRECTION
E -- RADIAL DIRECTION
F -- LONGITUDINAL DIRECTION

Fig. 1.1 Inner Structure of a wood

1.3 TECHNIQUES FOR TIMBER PRESERVATION

Wood is a highly porous but not very permeable material. Dry wood in the normal specific gravity range of 0.3 to 0.6 has fractional void volumes ranging from 0.590 to 0.795 (STAMM, 1963). Treatment of wood involves sterilizing the wood with heat and impregnating the porous structure of the wood with preservative chemicals. The mechanisms involved in the conditioning and treating processes can be studied as mass and heat transfer problems in porous bodies. STAMM (1953) classified the methods of absorption of liquids by wood as one or a combination of more than one of the following: (a) by *capillary absorption*, (b) by *pressure permeability*, or (c) by *diffusion*.

There are also different methods of impregnating timber with a preservative. These methods are grouped into two general classes: atmospheric pressure treatment, in which the maximum pressure is atmospheric, and high pressure treatment, in which pressures above atmospheric are used. The term, atmospheric pressure treatment, is applied to those treatments in which a partial vacuum exists within the wood and the driving force is the difference between atmospheric and a partial vacuum. These processes include painting, cold soaking and diffusion types of treatments. In many of these processes, the chief take-up of preservative is by diffusion: the chemicals diffuse into the wood and water diffuses out. The method to obtain partial vacuum is either to subject the wood to a vacuum or to heat the wood and then cool it. Heating the wood drives out steam and air, and cooling condenses the steam remaining in the wood to create the vacuum. This method is often referred to as the non-pressure or open tank treatment.

Pressures above atmospheric are used to force a liquid preservative into the wood. There are two kinds of pressure treatments : *full-cell* and *empty-cell*. The first aims at filling the capillary structure of the wood with preservative liquid or solution, whereas in the second the bulk liquid is removed from the internal capillary structure after treatment, leaving only surface-adsorbed films. There are two commonly practiced empty-cell processes and one dominant full-cell process:

- Empty-cell (*Lowry Process*), in which the wood is placed in a cylinder, the preservative is introduced and then pressure is applied. After a predetermined amount of preservative is absorbed by the wood, which is indirectly measured by the length of time for the particular species, the applied pressure and the preservative used, the pressure is relieved, the liquid is pumped out and a vacuum is then applied to recover some of the preservative.

- Empty-cell *(Rueping Process)*- air pressure is applied to the wood before the introduction of the preservative, the preservative is introduced and the pressure is then further increased.

- Full-cell *(Bethell process)* - this is the more widely used treatment for Douglas-Fir poles. This method accomplishes higher net retentions. Details of this process are discussed in the next section.

1.4 PRESSURE TREATMENT OF POLES (FULL-CELL)

The pressure process consists of a series of carefully controlled steps by which wood is conditioned or prepared for treatment, then impregnated under pressure to obtain the optimum penetration and concentration of preservative and finally cleaned by vacuum.

To preserve wood adequately :

1) The preservative must be biologically active.

2) The timber must be in suitable condition to absorb the preservative.

3) The method of application must give satisfactory impregnation and retention of the preservatives.

1.4.1 SEQUENCE OF PROCESSES

REMOVAL OF BARK

Round timber should have all outer and inner bark removed, otherwise penetration may be negligible.

SEASONING

MACLEAN (1952) has indicated that green timber of Coastal Douglas-fir has an average moisture content, on an oven-dry weight basis, of 115 % in the sapwood and 37 % in the heartwood. If the cells of wood are full of moisture, as in green timber, it is very difficult to force in additional liquid. Whatever the shape or size of wood to be treated, preservatives can only enter from the outer side, thus the behavior of the outer cells is crucial. Seasoning of poles is the process to remove the water that is present as sap, especially in the sapwood layer of the living tree. The moisture moves transversely from fiber to fiber to the periphery of the pole. Water can move through wood in three forms: as *water vapor* through the cell cavities and permanent pit membrane pores, as *free liquid* water in the same structure, and as *bound water* in the wood structure. The moisture content at which the cell walls have all the bound water they can hold, yet the cell cavities contain no free water, is known as the *fiber saturation point* (F.S.P). At the F.S.P. the moisture content on an oven-dry weight basis is about 30% for most wood.

There are two frequently used methods to season or condition the wood:

i) air-seasoning,

ii) Boulton process, which is boiling-under-vacuum.

In the air seasoning of poles, the cut and peeled poles are placed in open horizontal stacks and are protected from rain. Good air circulation and ventilation give more satisfactory results. Usually several months are required to reduce the moisture content in the material to the proper level for preservative impregnation. Some of the important considerations in air-seasoning include species type, proportion of sapwood, time of cutting, peeling, climatic conditions, locality in which the timber is seasoned, and method of piling. If unfavorable climatic conditions make air-seasoning a decay hazard, the *Boulton process* is used. This conditioning treatment generally removes a substantial amount of moisture from the timber and also heats the wood to a more favorable treating temperature. Proper seasoning of poles is critical to the success of subsequent processes to produce pressure treated poles.

INCISING

Douglas-fir is very resistant to penetration by preservatives and pressure treatment may result in very uneven and inadequate penetration. To overcome this difficulty large dimension timber are incised. Incising is an effective means of getting uniform depth of penetration in heartwood and it was also found to reduce checking and splitting during subsequent processes.

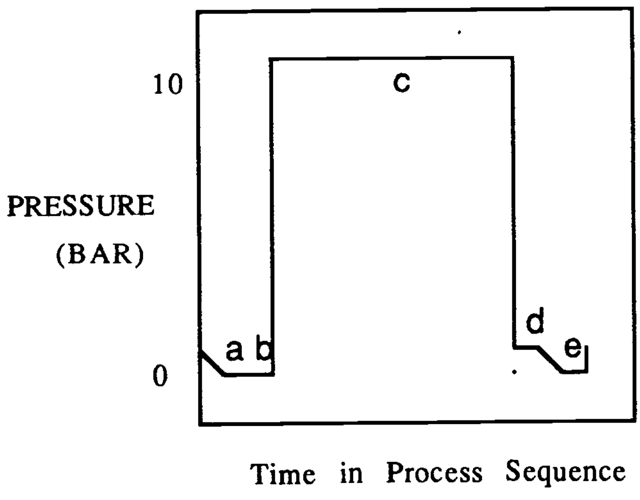
STEAMING

The next step in the conditioning process of poles is to heat a pile of poles in a closed cylinder with steam at a temperature of about 115 ^{o}C (240 ^{o}F). Steaming sterilizes the poles and apparently ensures subsequent proper penetration and distribution of the preservative. The poles are heated throughout until the temperature reaches 65.5 ^{o}C and remains above it for at least two hours, as required by the Rural Electrification Authority. Either live steam may be introduced or steam may be generated within the cylinder by the use of water overheating coils. Advantages of the steam conditioning process are that there is no need for special equipment, the process is simple to operate and easy to control.

WIRKA, 1924, proved that, in general, practically no reduction in moisture content of wood occurs during steaming. Depending on the initial moisture content, initial temperature and the dimensions of the pole, the wood even absorbed condensed steam initially. For green timber, however, steaming results in some loss of moisture and apparently has some other effects not well understood. Some researchers believe that even though the moisture content of the wood remains relatively high, steam conditioning enhances the treatability of green wood. During steaming mild hydrolysis of cellulose also takes place which can result in a slight strength reduction when wood is steamed without proper control.

PRESSURE TREATMENT (FULL-CELL)

After steaming is completed vacuum is applied in the cylinder as quickly as possible in order to utilize the maximum amount of heat available for moisture removal. This vacuum step done at the end of the conditioning process also serves as the initial vacuum step of the pressure treatment. Pressure is reduced to minus 0.75 bar or lower (560 mm Hg vacuum gauge reading) for about 22 minutes. Then, while maintaining the vacuum, the cylinder is filled with preservative fluid, which takes around 2 hours. The vacuum is then released and pressure applied hydraulically or by compressed air. Pressure is raised to between 10 and 14 bars and maintained for a few hours. Pressure is then released, the cylinder emptied of liquid and a final vacuum applied, which helps to dry the surface of the treated timber. The duration of the different steps, as well as the intensity of vacuum, pressure, and preservative temperature, varies widely according to the character and condition of the wood and the judgment of the plant operator or the particular purchaser.



FULL-CELL PROCESS

a- Initial vacuum

b- Filling cylinder

c- Pressure period

d- Emptying cylinder

e- Final vacuum

Figure 1.2 A typical pressure diagram for full-cell pressure treatment of poles.

1.4.2 RECOMMENDED PRACTICE

The American National Standards Association, the American Wood Preserver's Association and the Western Wood Preserving Operator's Association have all issued specifications or standards for the preservative treatment of timber by pressure process in closed vessels. Below is a summary of the recommended treatment schedule for Coastal Douglas-fir treated with ammoniacal copper arsenate, (ACA).

Table 1.1 Recommended process schedule for pressure treatment of poles

STEP	TIME [hr]	PRESSURE [bar]	TEMPERATURE [°C]
Conditioning	By air-seasoning, by kiln drying, by steaming, by heating in preservative, by Boultonizing		
Steaming	6	---	115
Initial Vacuuming (At sea level)	about 2	0.75	---
Pressure Treatment	(16 -30)*	about 11	60
Final Vacuum	2	---	---

* Depending on the diameter of the pole

1.4.3 CURRENT PRACTICES AND CONCERNS

As discussed in previous sections, for a satisfactory preservative impregnation, the wood should be seasoned to reduce its moisture content. Air-seasoning of poles is widely employed in the Pacific Northwest. This region has a wide range of climatic conditions: hot and cold, wet and dry, heavy and light ice load, high wind areas, lightning areas and a variety of fungi and insect enemies. Depending on the size of the poles the time required for air-seasoning of poles varies from a few months to more than a year. Large poles season more slowly than small ones because of the greater volume of wood in proportion to the surface and the longer distance through which the interior moisture must diffuse to reach the surface. MATHEWSON et al. (1949) reported that most of the seasoning that occurs in large-size timbers will be obtained within the first year. Studies by TAYLOR (1980), PRZYBYLOWICZ et al. (1986), MORRELL et al. (1987) and SMITH et al. (1987) all indicated that air-seasoned Douglas-fir poles are liable to substantial incipient decay even during short periods using the conventional air-seasoning method. ESTEP et al. (1966) have reported that in Douglas-fir the infection is practically assured in 3 to 6 months and significant decay occurs in 6 to 12 months. The susceptibility is greater while the moisture of the wood is above the fiber saturation content and during the warmer months of the year. TAYLOR (1980) reported that the Electric Power Research Institute is particularly concerned about the problems with Douglas-fir due to its thin sapwood, resistance to treatment by the heartwood and the seasoning checks that develop after treatment. The degree of seasoning for optimal penetration is not fully known. On the other hand, studies by ESLYN (1970) and ZABEL et al. (1970) showed that conventional treatments do not kill all the decay fungi that invade the poles during air seasoning. This was confirmed from an inspection of in-line Douglas-fir poles, which showed considerable early decay.

Since air-seasoning has potential problems, a better understanding of heat sterilization of wood prior to treatment is required. Heat conditioning not only sterilizes the poles, it also reduces the wide differentials in the moisture content of the poles in a treatment cylinder charge and within the individual poles as recognized by TAMBLYN (according to TAYLOR, 1980). MACLEAN (1951) indicated that the cost of pole installation is considerably greater than the the cost of the treatment of timber, which emphasizes the great importance of performing an effective treatment.

CHAPTER 2.0

EXPERIMENTAL PROCEDURE AND DATA ACQUISITION

2.1 EXPERIMENTAL METHOD

The data used in this study were taken from NEWBILL et al. (1988), where the experimental work was carried in commercial pole treating plants. Eighteen Douglas-fir poles which were air-seasoned for about 1 year and had diameters varying between 12 to 22 in (30 to 53.9 cm) were used. A representative log with length of 2.44 m was cut from each pole. Moisture contents were measured at 2.25, 5 and 7.25 cm from the surface using a resistance-type moisture meter. The sizes and moisture contents of the poles used in the experiments are given in Table 2.1. These moisture values are based on an oven-dry-weight basis which may be computed by using the formula:

$$M = (W_o - W_d)\,100 / W_d$$

where

M = moisture in percentage

W_o and W_d are the original and oven-dry weights respectively.

A series of 0.95 cm diameter holes were drilled perpendicular to the grain to depths of 5, 10, 15, 20, 25 cm from the surface along the pole length, depending on the pole diameter. Copper-constantan thermocouples were inserted through the holes, and were protected by a dowel that filled the rest of the holes. Two pole sections were then placed on the ram in a commercial cylinder and the thermocouples were threaded through a specially constructed flange and were connected to a CR-21X Micro Data Logger that collected readings every 10 seconds and averaged this data every 15 minutes to produce one value for a given thermocouple. The collected data was then recorded by an IBM PC. The experiments were carried out for steaming periods of 4, 5, 6 and 7 hours.

After the data was obtained it was important to review it, making plots of the recorded values in order to screen out those values which are not believed physically obtainable. This was necessary because in some cases the data recorder was disconnected from the thermocouples in the middle of the treatment process and recordings were lost. There were also cases in which the readings were taken near checks, which do not represent normal conditions. Since the modeling is not intended to predict temperatures near checks, these data sets were not used in the analysis.

2.2 EXPERIMENTAL RESULTS

The temperature versus time at different depths for all the Douglas-fir poles during preservative treatment with waterborne ACA are shown in Figures 2.1a, 2.1b, 2.2a, 2.2b .

1) The general pattern of the change in temperature was as described in the literature. When steam was discontinued and initial vacuuming was started, the surface temperature

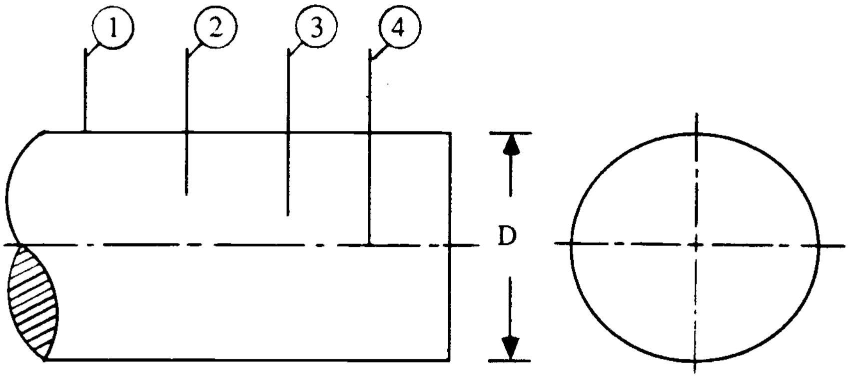
fell suddenly. However the interior temperatures continued to ascend until the early pressure period, i.e., for about 3-4 hours after steaming was stopped, depending on the size of the poles and the maximum surface temperature reached before cooling was started.

2) Figures 2.1b and 2.2d show that in some cases the inner temperatures never reached the required 65.5 ^{o}C, the sterilization temperature proposed by CHEDISTER (1937, 1939).

3) At positions near deep checks, Figure 2.3, the temperature increased very sharply and dropped sharply during the vacuuming period, resembling the changes seen in the surface temperature.

4) The moisture contents of the poles were measured before steaming and the values are shown in Table 2.1. The moisture contents were low and the range narrow, 16 - 24 %.

TABLE 2.1 Pole sizes and thermocouple positions used in the experiment



Thermocouple No	Radial Position (From the center)	Depth (cm)
1	R	0
2	R-5	5
3	R-10	10
4	R-15	15

TRIAL	POLE NUMBER	DIAMETER (cm.)		MOISTURE % AT DEPTH (cm.)		
		MININUM	MAXIMUM	2.5	5	7.5
ACA1	3	30.8	33.7	22	---	---
	4	30.5	33.	21	---	---
ACA2	5	31.8	34.3	20	---	---
	6	33.7	34.3	21	---	---
ACA3	7	31.1	32.4	12	21	---
	8	31.75	34.3	20	21	---
ACA4	9	29.8	31.8	18	21	---
	10	30.5	32.4	17	20	---
JAB1	15	47	54.61	21	22	---
	16	33.7	34.29	17	20	---

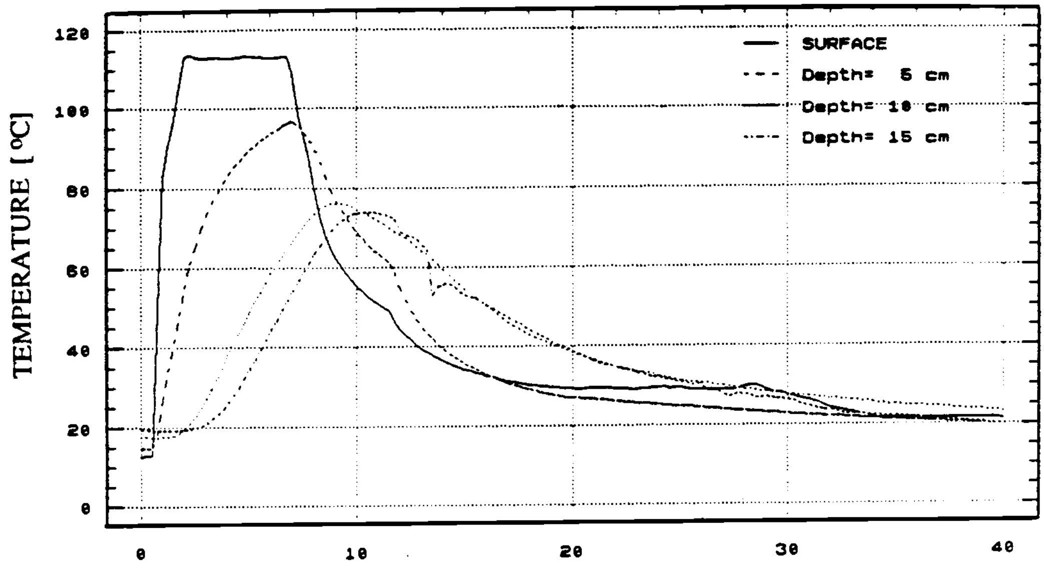


Figure 2.1a

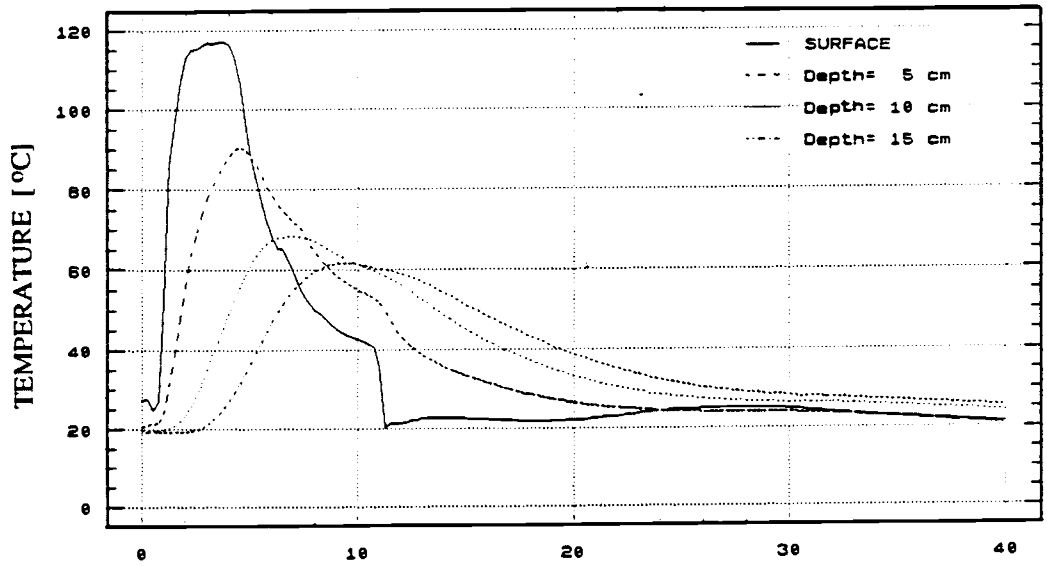


Figure 2.1b

Figures 2.1a,2.1b Temperature versus time relationship in Douglas-Fir pole sections during preservative treatment with waterborne ammoniacal copper arsenate for steaming periods of 6.75 and 4.25 hours for Figures 2.1a and 2.1b respectively.

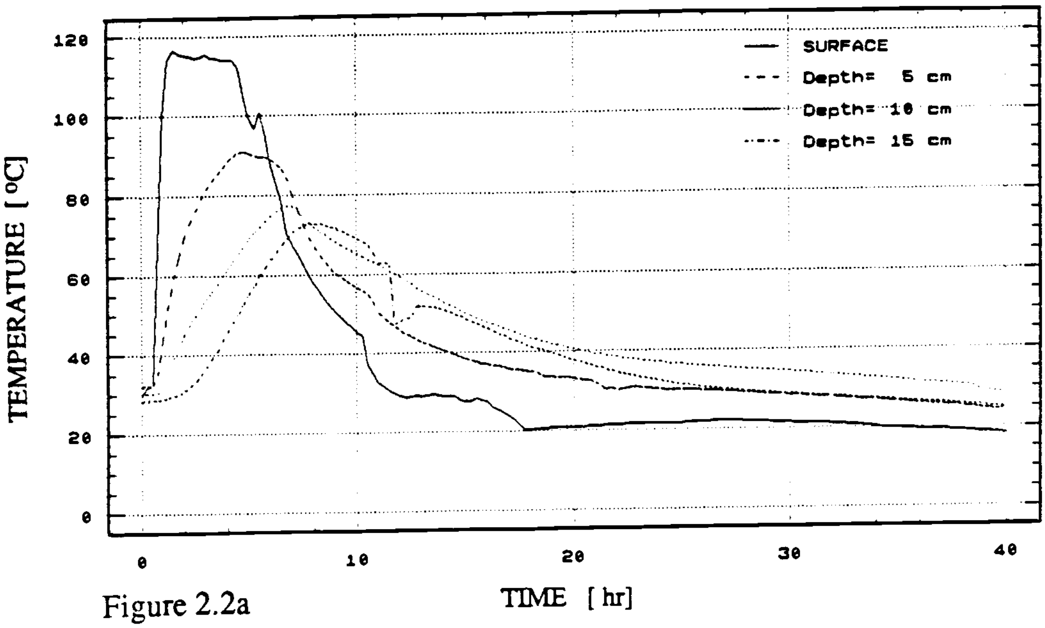


Figure 2.2a

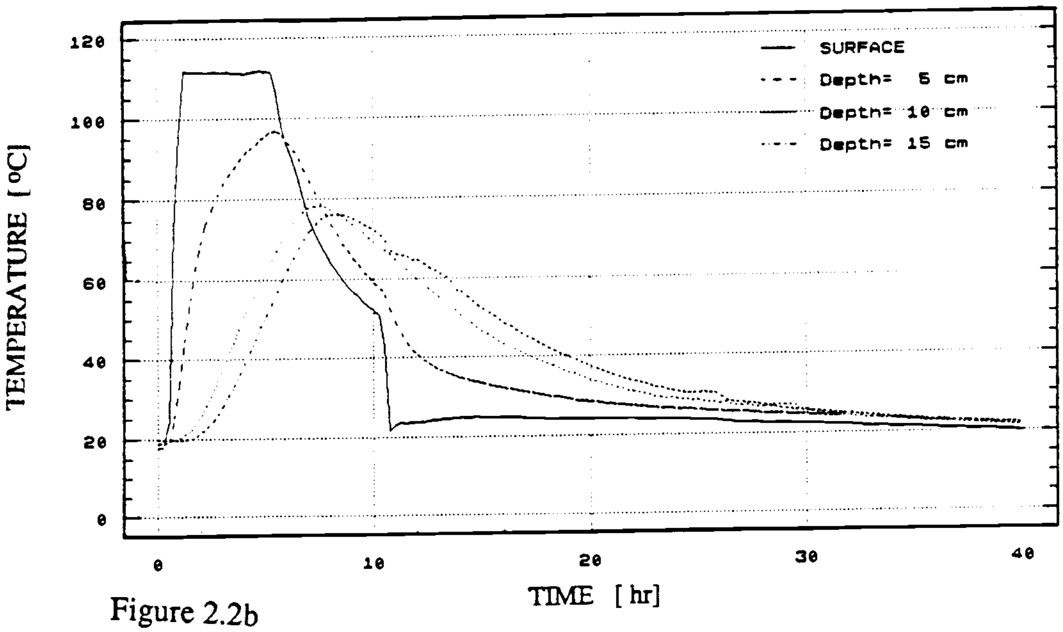


Figure 2.2b

Figures 2.2a,2.2b Temperature versus time relationship in Douglas-Fir pole sections during preservative treatment with waterborne ammoniacal copper arsenate for steaming periods of 4.5 and 5.25 hours for Figures 2.2a and 2.2b respectively.

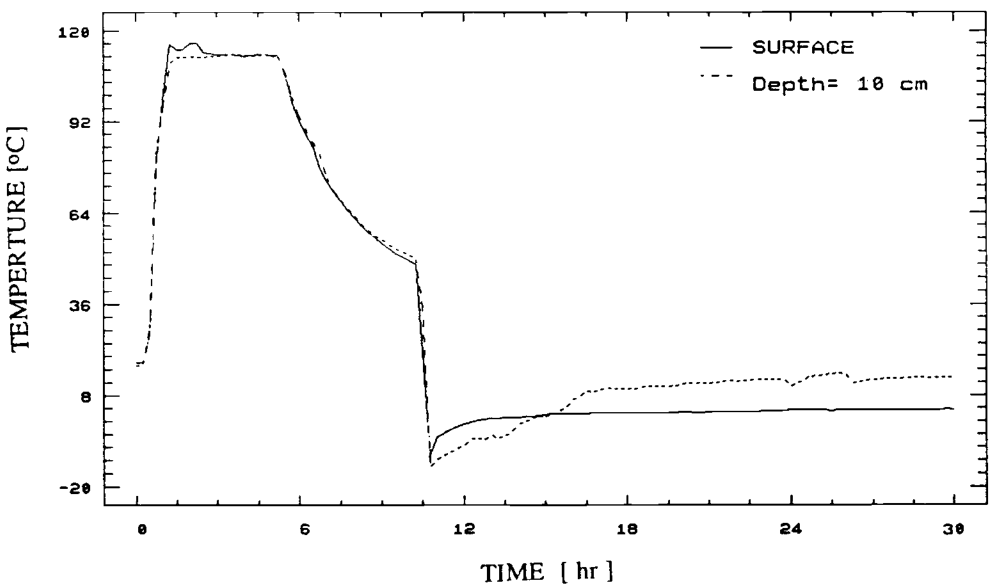


Figure 2.3 Temperature versus time relationship in Douglas-fir pole section when one thermocouple was near a check at 10 cm. depth and the other on the surface.

CHAPTER 3.0

MODEL FORMULATIONS AND SOLUTIONS

The purpose of the present work is to describe heat transfer to wood poles during the preservative treatment utilizing analytical methods. A wood treatment process is a batch process. Piles of poles pass through a sequence of processes in which little or no feedback control on the process is used. The inherent dynamic nature of the steaming process demands a model that can give a good prediction of internal temperatures for various operating conditions.

The study of heat or mass transfer in solids can be broadly classified into two levels. The first level of study assumes the internal solid structure to be homogeneous, where the heat and mass transfer rates are independent of the actual microstructure and the variations in properties of the solid are lumped together to yield an average or "effective" property of the solid. The next level of study considers the solid as a non-homogeneous material and characterizes the actual structure of the solid matrix, e.g. cell structure and orientation.

Many researchers (MACLEAN,1941, KOLLMANN and MALMQUIST , 1956, SIAU et al., 1968, MAKU, 1954) have attempted the geometrical modeling of wood cell in order to explain electrical and thermal conductivity, dielectric behavior and water-vapor diffusion. In this study, for the sake of simplicity and lack of data, such models of the internal geometrical structure of wood are not used.

3.1 BASIC ASSUMPTIONS

The following assumptions are made in the formulation of the heat transfer models:

i) Heat is assumed to flow only in the radial(transverse) direction. The poles used in the tests had a length to diameter ratio of more than 4.5. Based on Figure 7.13, page 114 (SIAU, 1971) this length was taken to be long enough to neglect the longitudinal direction of heat flow

ii) The timber poles are assumed to have uniform diameter equal to the average diameter. The tapering in the diameter of the poles used in the experiment was in most cases less than 8% .

iii) Wood is strictly a non-homogeneous and a non-isotropic substance. However, it is assumed to have sufficiently uniform structure, i.e. thermal properties are independent of position, to permit the application of the mathematical theory of heat conduction in homogeneous long cylinders in the radial direction.

iv) The poles are assumed to have uniform initial temperature, even though it was observed that there were 3 to 6 ^{o}C initial temperature variations within the poles.

v) The convective heat transfer coefficient is constant and uniform over the surface.

vi) The effects of vacuuming and the penetration of preservatives during the pressure period on the wood thermal diffusivity and heat transfer coefficient are not considered. Thermal expansion and shrinkage are also neglected.

vii) All analyses were made for a single pole and effects of neighboring poles are not considered explicitly, but only indirectly through effects on the measurable surface temperature of the instrumented pole section.

3.2 MATHEMATICAL FORMULATION OF THE PROBLEM

From the general energy balance with uniform thermal conductivity and no heat generation in the medium, the governing differential equation in cylindrical coordinates for unsteady-state heat flow in the radial direction is (Eqn. 3, pg. 188, CARSLAW and JAEGER, 1959) :

(The notations used in this section follow that of the book "Heat Conduction" by N. Ozisik)

$$1/r \, \partial(\partial(\kappa r T)/\partial r)/\partial r = \partial(\rho C_p T)/\partial t \qquad 3.1$$

Rearranging equation (3.1) for constant κ we get :

$$\partial^2 T/\partial r^2 + 1/r \, \partial T/\partial r = 1/\alpha \, \partial T/\partial t \qquad 3.2$$

where

$T = T(r, t)$ the temperature at radial position r and time t

r = radial location measured from the center line of the pole, (cm)

R = the outer radius of the pole, (cm)

t = time measured from onset of steaming (sec.)

ρ = average density of the wood (gm / cm^3)

Cp = heat capacity (cal / gm ^oC)

κ = thermal conductivity (cal / cm ^oC sec)

$\alpha = \kappa/(Cp\ \rho)$ = thermal diffusivity, (cm^2 / s)

The thermal diffusivity, α, measures the change of temperature that can be produced in a unit volume of a material when heat is added equivalent to the quantity of heat that flows in a unit time through unit area of a layer of unit thickness having unit difference of temperature between faces.

Other frequently used terms are the following:

Dimensionless solid temperature

$$\Theta = \frac{T - T_S}{T_O - T_S}$$

where

$T_S(t)$ = surface temperature, r =R

$T_O(t)$ = initial temperature, t = 0

Dimensionless radial coordinate

$$Z = r/R$$

Dimensionless time (Fourier number)

$$F_o = \frac{\alpha t}{R^2}$$

Surface coefficient (Biot number)

$$Bi = h R / \kappa$$

where h = surface heat transfer coefficient, cal /(cm^{2}s ^{o}C)

The relative resistance,

$$MR = 1 / Bi = \kappa / \dot{h} R$$

The solution of the differential equation (3.2), provides the variation of temperature with both time and radial position. The equation may be solved based on different assumptions for the boundary conditions(T_S) and initial conditions(T_o). The models used in this study differ in the assumptions taken for what is happening at the surface of the poles. Simulations are divided into two time ranges. *DURATION I* considers the time from the moment the steam valve is opened till the end of the steaming period. *DURATION II* starts from the moment the steam valve is opened includes initial vacuuming and pressure periods.

3.2.1 DURATION I FOR TIME RANGE UNTIL THE END OF STEAMING

Three different models were suggested for predicting the time-temperature curves in this time range. The first one was used by MACLEAN (1930,1932).

MODEL IA CONSTANT SURFACE TEMPERATURE.

In this case it is assumed that from the moment the treatment process starts the surface temperature makes a jump to the maximum steam temperature and remains constant.

Initial Condition : $T(r, 0) = T_o$, at $0 \leq r \leq R$

Boundary Condition $T(R, t) = T_s$, for $t > 0$,

This happens when the thermal capacity of the equipment is neglected and negligible surface heat transfer resistance, 1/h.

Therefore :

$1/h \Rightarrow 0$ and $Bi \Rightarrow \infty$ i.e., MR is negligible.

Solving Equation (3.2) for these conditions gives us the equation for model IA.

Model parameter : thermal diffusivity, α

Model solution (from Eqn. 10, pg 199, CARSLAW and JAEGER, 1959)

$$\Theta = 2 \sum_{n=1}^{\infty} \exp(-F_o \beta_n^2) A_n , \qquad \text{.......................... (3.3)}$$

where β_n are positive roots of the characteristic equation $J_o(\beta_n) = 0$

and, $$A_n = \frac{J_o(\beta_n Z)}{\beta_n J_1(\beta_n)}$$

MODEL IB This model assumes a constant surface heat transfer coefficient and constant steam temperature.

Initial Conditions: $T(r, 0) = T_o$, at $0 \leq r \leq R$

Boundary Condition: $\partial T / \partial r = -h(T - T_s)/\kappa$ for $t > 0$, at $r = R$

Model parameters : heat transfer coefficient, h

and thermal diffusivity , α

Model solution (from Eqn. 8, pg. 202, CARSLAW and JAEGER, 1959) :

$$\Theta = 2 \sum_{n=1}^{\infty} \exp(-F_o \beta_n^2)\ B_n \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.4)$$

where

$$B_n = \frac{J_o(\beta_n Z)\ Bi}{(Bi^2 + \beta_n^2)\ J_o(\beta_n)}$$

and β_n is the root of : $\beta_n J_1(\beta_n) = J_1(\beta_n)\ Bi$

MODEL IC Since it is not practically possible to step change the surface temperature of the pole at the moment steam flows into the cylinder, because of the high thermal capacity of the equipment , a third model considers the time required to heat up as an additional model parameter incorporated simply as a time delay to the surface step change.

Initial Conditions : $T(r, 0) = T_o$, at $0 \le r \le R$

Boundary Conditions : $T(R, t) = T_o$, for $t < \tau_d$

$T(R, t) = T_s$, for $t \ge \tau_d$

Model parameters : the thermal diffusivity , α and

the time delay, τ_d

The model solution are :

$$\Theta = 1 , \quad \text{for} \quad t < \tau_d$$

$$\Theta = 2 \sum_{n=1}^{\infty} \exp(-\alpha\beta_n^2 (t - \tau_d)/R^2)\, A_n \quad \text{for} \quad t \ge \tau_d \quad \ldots (3.5)$$

where A_n is as defined for Equation (3.3)

MODEL ID The last model for this time range takes the boundary conditions of Model IB and incorporates a time delay as an additional parameter.

Initial Condition : $T(r, 0) = T_o$, at $0 \le r \le R$

Boundary Condition: $T(R, t) = T_o$, for $t < \tau_d$

$\partial T / \partial r = -h(T - T_s)/\kappa$, for $t \ge \tau_d$

Model parameters : the thermal diffusivity of the wood , α

the surface heat heat transfer coefficient, h

the time delay, τ_d

The model solution :

$$\Theta = 1 , \qquad \text{for} \quad t < \tau_d$$

$$\Theta = 2 \sum_{n=1}^{\infty} \exp(-\alpha \beta_n{}^2 (t - \tau_d)/ R^2) B_n \qquad \text{for } t \geq \tau_d \text{.........} \quad (3.6)$$

where B_n is as defined for Equation (3.4)

3.2.2 DURATION II FOR THE TIME RANGE WHICH CONTAINS THE VACUUM AND PRESSURE PERIODS

As noted in previous studies (WIRKA ,1924, MACLEAN, 1946, DOST, 1984), the interior temperature of the poles during the treatment process reaches its maximum early in the pressure period after steaming has been stopped and then decreases gradually. It is therefore important to know the temperature-time-location relations after steaming is stopped. This leads to models for the second stage which contains the vacuuming and the pressure period.

The same governing equation and general assumptions are used in formulating these models. The models differ in the boundary conditions used with Equation (3.2).

MODEL IIA

When timbers are allowed to cool in contact with the heating medium while the temperature of the medium is gradually reduced, approximate internal pole temperatures may be calculated assuming a constant surface temperature that is the average between the initial and final temperature of the heating medium for that period of time (MACLEAN, 1946).

Model parameters : the thermal diffusivity of the wood, α

Initial condition : $T(r, 0) = T_o$ at $0 < r \leq R$

Boundary condition: $T(R, t) = T_s$ for $t < t_{vc}$,

$T(R, t) = T_{mid}$ for $t_{vc} \leq t < t_{cl}$,

$T(R, t) = T_f$ for $t \geq t_{cl}$,

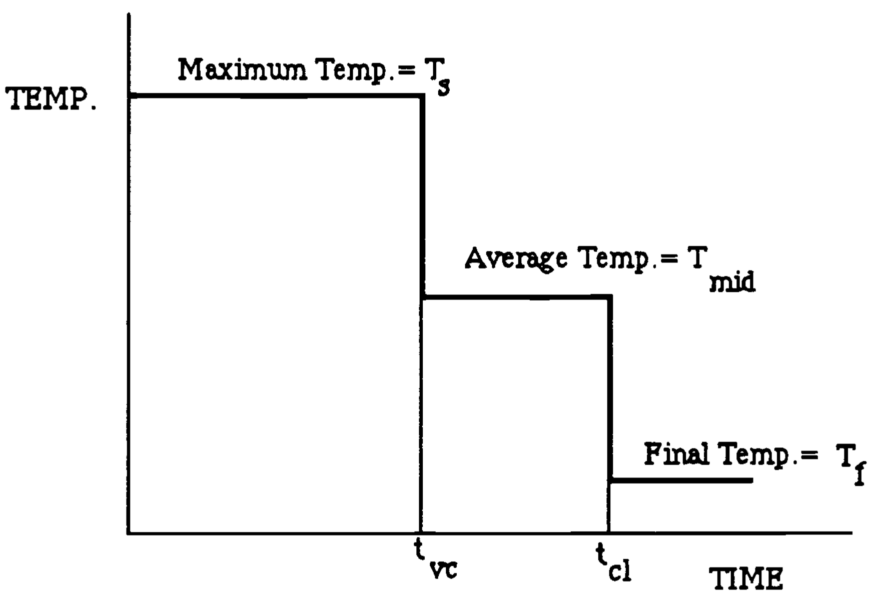


Figure 3.1 Assumed surface temperature profile for Model IIA.

The model solution :

$$T = T_s + 2(T_s - T_o)\sum_{n=1}^{\infty} \exp(-\beta_n^2\alpha/R^2)\, A_n$$

$$- 2(T_s - T_{mid})\sum_{n=1}^{\infty} \exp(-\beta_n^2\alpha(t - t_{vc})/R^2)\, A_n\, H(t - t_{vc})$$

$$- 2(T_{mid} - T_f)\sum_{n=1}^{\infty} \exp(-\beta_n^2\alpha(t - t_{cl})/R^2)\, A_n\, H(t - t_{cl}) \quad \ldots\ldots\ldots (3.7)$$

where

βn are positive roots of the characteristic equation $Jo(\beta n) = 0$

A_n as defined for Equation (3.3)

$H(t - t^*)$ - Heaviside unit function defined as:

$H(t - t^*) = 0$ for $t < t^*$

$= 1$ for $t \geq t^*$

MODEL IIB

The basis for formulating Models IIB and IIC are the surface temperature measurements taken from the NEWBILL (1988) experiments. Figures 3.4 to 3.7 show plots of these surface temperatures for different lengths of steaming periods. We can see that the assumption made in Model IIA, that the surface temperature varies according to step changes, is not realistic. Therefore, instead of assuming a step surface temperature drop when heating is stopped and vacuum is applied, the surface is now assumed to be cooled at a constant rate. The rate of cooling is taken as a model parameter.

Model parameters : thermal diffusivity, α [ft^2/hr]

initial time delay, τ_d [hr]

the rate of the surface temperature change after steaming,

$$k_c = (T_f - T_s) / (t_{cl} - t_{vc}) \quad [\,^oC / hr]$$

Initial conditions: $T(r, 0) = T_o,$ at $0 < r \le R$

Boundary conditions: $T(R, t) = T_o,$ for $t < \tau_d,$

$T(R, t) = T_s,$ for $\tau_d < t < t_{vc}$

$T(R, t) = T_s + k_c(t - t_{vc})$ for $t_{vc} < t < t_{cl}$

$T(R, t) = T_f$ for $t > t_{cl},$

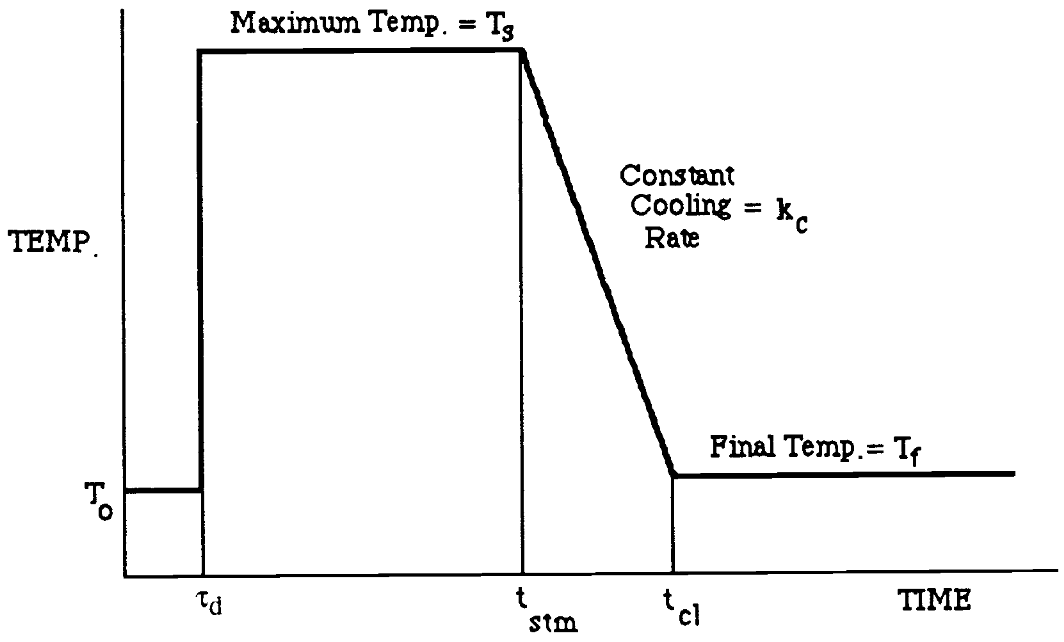


Figure 3.2 Assumed surface temperature profile for Model IIB.

The solution of Equation (3.2) for the above boundary and initial conditions is (Eqn. 24, pg 330, and Eqn. 10, pg 199, CARSLAW and JAEGER, 1959) :

$$T = \left[T_s + 2(T_s - T_o) \sum_{n=1}^{\infty} \exp(-\beta_n^2 \alpha (t-\tau_d)/R^2)\, A_n \right]$$

$$+ \left[k_c[(t-t_{vc}) - (R^2-r^2)/4\alpha] + 2k_c/\alpha \sum_{n=1}^{\infty} \exp(-\beta_n^2 \alpha (t-t_{vc})/R^2)\, B_n \right] H(t - t_{vc})$$

$$+ \left[k_c[(t-t_{cl}) - (R^2-r^2)/4\alpha] + 2k_c/\alpha \sum_{n=1}^{\infty} \exp(-\beta_n^2 \alpha (t-t_{cl}))/R^2)\, B_n \right] H(t-t_{cl})$$

........................(3.8)

where

βn are positive roots of the characteristic equation $J_o(\beta n) = 0$

$$A_n = \frac{J_o(\beta_n Z)}{\beta_n J_1(\beta_n)}$$

$$B_n = \frac{A_n R^2}{\beta_n^2}$$

$H(t - t^*) = 0$ for $t < t^*$

$= 1$ for $t \geq t^*$

MODEL IIC

One also may observe that the rate of the surface temperature decrease during the vacuuming period is faster than during the initial pressure period. The model IIC incorporates two rates of temperature change.

Model parameters : thermal diffusivity, α [ft^2/hr]

initial time delay, τ_d [hr]

the rate of surface temperature change during vacuuming, k_1 [°C /hr] = (TII - T_s) / (t_{pr} - t_{vc})

the rate of surface temperature change in the early

pressure period, k_2 [°C /hr] = (T_f -TII) / (t_{cl} - t_{pr})

Initial condition: $T(r, 0) = T_o$ at $0 < r \leq R$

Boundary condition: $T(R, t) = T_o$ for $t < \tau_d$

$T(R, t) = T_s$ for $\tau_d \leq t < t_{vc}$

$T(R, t) = T_s + k_1(t - t_{vc})$ for $t_v \leq t < t_{pr}$

$T(R, t) = T\,II + k_2(t - t_{pr})$ for $t_{pr} \leq t < t_{cl}$

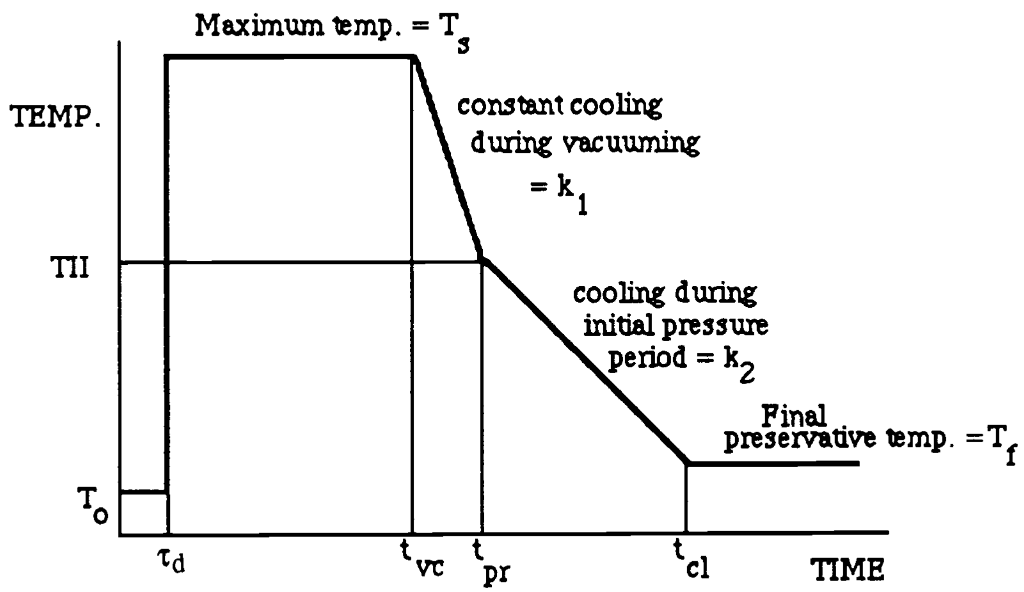


Figure 3.3 Assumed surface temperature profile for Model IIC.

Solving Equation (3.2) for this boundary conditions:

$$T = \left[T_s + 2(T_s - T_o)\sum_{n=1}^{\infty}\exp(-\beta_n{}^2\alpha(t-\tau_d)/R^2)\, A_n \right]$$

$$+ \left[k_1[(t-t_{vc}) - (R^2-r^2)/4\alpha] + 2k_1/\alpha\sum_{n=1}^{\infty}\exp(-\beta_n{}^2\alpha(t-t_{vc})/R^2)\, B_n \right] H(t-t_{vc})$$

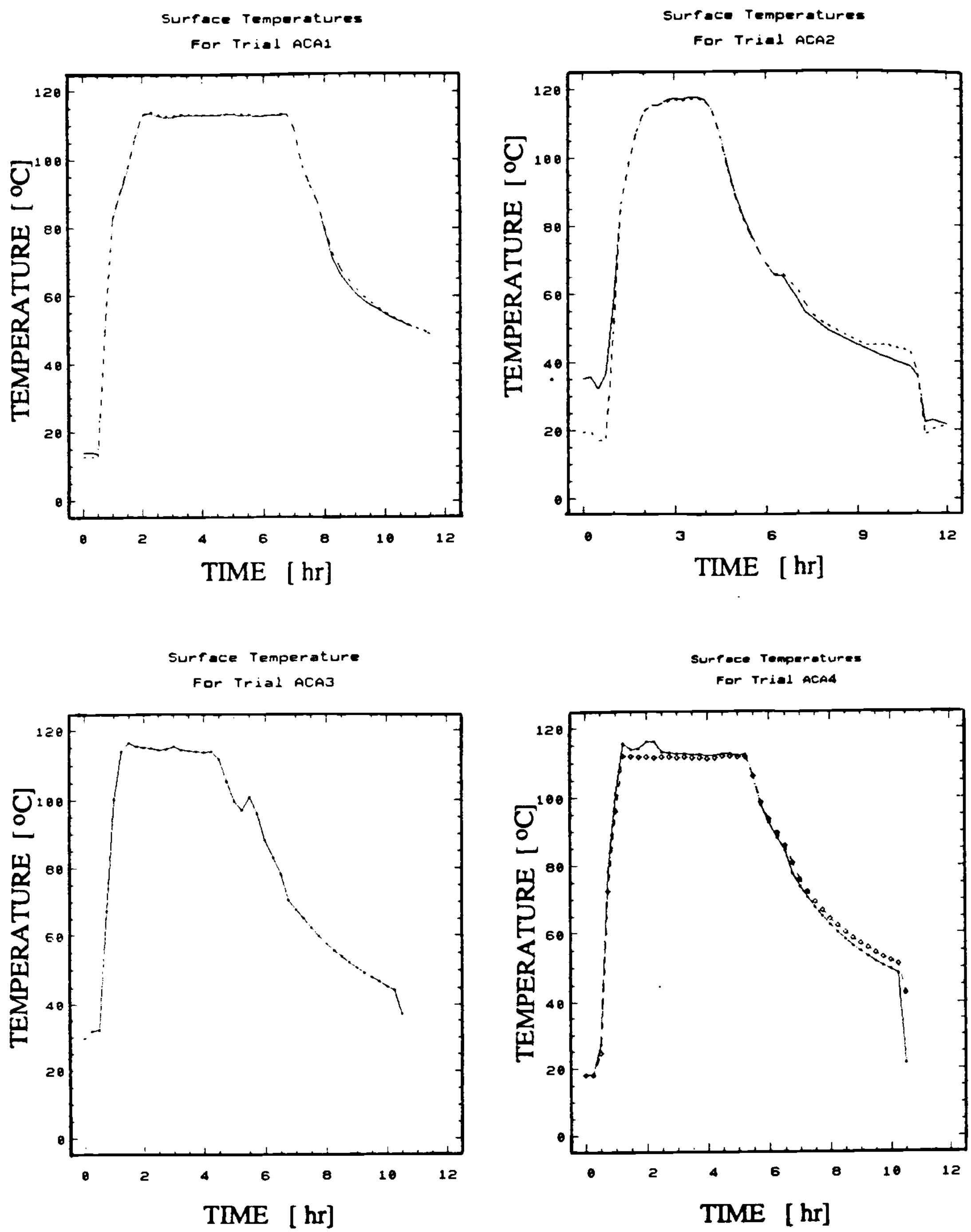
$$- \left[k_1[(t-t_{pr}) - (R^2-r^2)/4\alpha] + 2k_1/\alpha\sum_{n=1}^{\infty}\exp(-\beta_n{}^2(t-t_{pr})/R^2)\, B_n \right]H(t - t_{pr})$$

$$+ \left[k_2[(t-t_{pr}) - (R^2-r^2)/4\alpha] + 2k_2/\alpha\sum_{n=1}^{\infty}\exp(-\beta n^2(t-t_{pr})/R^2)\, B_n \right] H(t - t_{pr})$$

$$- \left[k_2[(t-t_{cl}) - (R^2-r^2)/4\alpha] + 2k_2/\alpha\sum_{n=1}^{\infty}\exp(-\beta_n{}^2(t-t_{cl})/R^2)\, B_n \right]H(t - t_{cl})$$

. . . . (3.9)

where A_n, B_n , β_n and $H(t-t^*)$ are as defined for Model IIB.



Figures 3.4a,3.4b, 3.4c, 3.4d Measured surface temperature versus time for trials ACA1, ACA2, ACA3 and ACA4 which were steamed for 6.75, 4.25, 4.5, and 5.25 hours respectively. Measurements for two independent thermocouples are shown for all cases except for ACA3.

CHAPTER 4.0

MODEL VALIDATION AND DISCRIMINATION

4.1 ESTIMATION OF MODEL PARAMETERS

The mathematical models for temperature formulated in the previous chapter are all non-linear in the parameters. Part of the boundary conditions, for example the initial time delay and the rates the surface of the poles cooled after steaming, are treated as additional unknown parameters. The parameters of the model equations are found by least-squares fitting of the dynamic models to the measured values. These measured temperatures were observed at various points in the pole and were recorded every 15 minutes.

Some of the questions that need to be answered are:

1) What are the best values for the model parameters ?

2) What are the uncertainties or the accuracy of the estimation of the parameters ?

3) How well do the calculated curves fit the data ? How can we discriminate between the models, i.e. how can we tell which model fits significantly better than the others ?

This chapter discusses the general method followed to answer the above questions. First the data were used to estimate the model parameters. Then it was necessary to check how well the prediction of each model agreed with the measured values from the experiments. Residual analysis was used as a criterion to choose the best model .

As an example of how the statement of the problem can be written, the model solution given for Model IC, Eqn 3.5, can be written for each of the N data points :

$$\Theta_i = 2\sum_{n=1}^{\infty} \exp(-\alpha\beta_n^2 (t_i-\tau_d)/R^2)\, A_n + \varepsilon_i , \quad i = 1,\ldots,N \quad (4.1)$$

and,

$$A_n = \frac{J_o(\beta_n r_i /R)}{\beta_n J_1(\beta_n)}$$

where

Θ_i = the dependent variable which is the ith predicted dimensionless temperature ,

t_i, r_i = the independent variables which are time and radial location ,

α , τ_d = model parameters to be estimated,

ε_i = is the error or the residual in the ith data point

The model has two parts, a deterministic part and a stochastic part. The deterministic part depends upon the the parameters α and τ_d and upon the independent variables time and radial location. The stochastic part, ε_i , is a disturbance which perturbs the temperature for that case.

An error or a residual is defined as the difference between the measured value, Θ_i^* , and the corresponding fitted value, Θ_i . The i th residual is :

$$\varepsilon_i = \Theta_i^* - \Theta_i , \quad i = 1, 2, \ldots . N.$$

Residuals play an important role in investigating the adequacy of the fitted regression model . An important function used to measure the adequacy of a fitted model is the the residual or the error sum of squares of (S):

$$S = \sum_{i=1}^{N} \varepsilon_i^2 = \sum_{i=1}^{N} [\ \Theta_i^* \ - \ \Theta_i\ ]^2 \ldots\ldots\ldots\ldots\ldots (4.2)$$

The residual sum of squares can be decreased by a suitable choice of model parameters. The assumptions necessary for the analysis are that the errors are uncorrelated, i.e. they are independent random variables, identically and normally distributed (IIND) and have a constant variance, σ^2, and an expected mean equal to zero.

To find parameters which minimize the residual sum of squares, S, it is differentiated with respect to the parameters and these partial derivatives are set to zero. These equations, which are usually known as the normal equations, are nonlinear and can be difficult to solve. Therefore an iterative method involving a series of linear approximations is used. Point estimates of and confidence intervals for the parameters were obtained using this method.

4.2 MEASUREMENTS OF FITTING

There is no automatic assurance that the model with the most parameters is best. It is necessary to examine the *residuals* of the the "best" model and compare them with residuals from the other models. To decide which is the simplest model to fit the measured values, statistical hypothesis tests were made that compared whether the residual values of the models differed significantly or not. The statement being tested in a test of significance is called the *null hypothesis,* NH. The test of significance is designed to assess the strength of the evidence against the null hypothesis.

If there are two rival models, models A and B, where model B has additional parameters beyond those of model A, and model A can be obtained from model B by setting some parameters equal to zero, equal to each other, or equal to some specific value, the two models are called *nested* models. To determine whether Model B contains an insignificant parameter it is necessary to test the adequacy of the fit of both models. The null hypothesis for this test will be: (from Eqn. 4.20, pg 96, WEISBERG, 1985)

$$\text{NH}: \quad \Theta = \text{Model A}$$

This means that the temperature is equal to the prediction given by model A. The degrees of freedom of the null hypothesis is, $df_{NH} = N - P_A$ where n is the number of data points and P_A is the number of parameters in model A.

The statement we hope or suspect to be true instead of NH is called the alternative hypothesis, AH.

$$\text{AH}: \quad \Theta = \text{Model B}$$

This means that the temperature is equal to the prediction given by model B. The degrees of freedom of the alternative hypothesis is $df_{AH} = N - P_B$, where P_B is the number of parameters in model B. Both models will be fitted to the observed data and their residual sum of squares, denoted as S_{NH} and S_{AH} will be evaluated. Clearly $df_{NH} > df_{AH}$ since the alternative hypothesis fits the data using more parameters. Also, $S_{NH} - S_{AH} \geq 0$, since the fit of the AH must be at least as good as the fit of the NH. The residual sum of squares contains two components one is due to the scatter in the experimental data and the other is due to the lack of fit of the model. In order to test the adequacy of the fit of the two models their residual sum of squares must be partitioned into its components. This procedure is called analysis of variance, which is summarized below.

Analysis of variance

Source of variance	Sum of Squares	Degrees of Freedom	Mean Squares	F-Ratio
Extra Parameters	$S_E = S_{AH}\text{-}S_{NH}$	$df_E = P_B - P_A$	$s_E{}^2 = S_E / df_E$	$s_E{}^2 / s^2{}_{AH}$
Model B	S_{AH}	$df_{AH} = N - P_B$	$s^2{}_{AH} = S_{AH} / df_{AH}$	
Model A	S_{NH}	$df_{NH} = N - P_A$		

The ratio of the variances $s^2{}_E / s^2{}_{AH}$ has an approximate F distribution with degrees of freedom of df_E and df_{AH}. If this ratio exceeds the tabulated value for α^*, df_E and df_{AH} then we would judge that the model B fits is a significantly better than fit model A.

For linear models the extra sum of squares analysis is exact. But the models formulated in the previous chapter were all nonlinear and we might expect the extra sum of squares analysis is only approximate because the calculated mean square ratio, $s_E{}^2$

$/s^2_{AH}$ will not have an exact F distribution. BATES and WATTS (1988) have shown that the mean square ratio is not affected by parameter nonlinearity. Another method to compare the 'goodness of fitting' between models is the likelihood ratio test (LRT) , (WEISBERG, 1985):

$$LRT = -N \left[\ln \left(\frac{S_{AH}}{S_{NH}} \right) \right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.3)$$

The likelihood ratio statistic can be compared to the chi-squared distribution with the degrees of freedom equal to the number of parameters in the larger model, model B, minus the number of parameters in the smaller model, model A.

The probability of getting an outcome at least as far from what we would expect if NH were true as was the actually measured outcome is called the P-value which is the level of significance of the statistical test. We need only say how small a P-value we will accept. This decisive value which is the probability of drawing a value of the test statistic that is contradictory to the null hypothesis is called the *Significance Level*, α^*. If the P-value is as small or smaller than α^*, we say that the data are statistically significant at level α^*.

4.3 ANALYSIS AND DISCUSSION OF PARAMETER VALUES AND RESIDUALS

1) Summary of the average parameter values and the confidence intervals of the estimates for all models are given in Table 4.1. The thermal diffusivities for most of the models are close to each other and are comparable to the value given by MACLEAN (1952), 0.00825 ft^2/hr for steam heated Douglas-fir pole. Models IA, IB, IC and ID proposed for the time range of DURATION I, were fitted to the data and a summary of the best parameters estimates is given in Tables 4.2, 4.3 and 4.4. Table 4.2 contains estimates of thermal diffusivities for each model. Table 4.3 contains the estimated time lags of models IC and ID and the surface thermal resistances of models IB and ID. As shown in Tables 4.3, the estimated surface thermal resistances are very low. The corresponding Biot numbers are greater than 1000, conforming negligible surface heat transfer resistance. Estimated model parameters for models IIA, IIB and IIC are contained in Table 4.6 and 4.8.

2) There was a concern that the estimated parameters may depend on radial position, but no pattern was found. This may be because the poles used in this study were all seasoned to moisture contents below the fiber saturation moisture content. Thus the assumptions that physical properties that could

affect thermal properties of the wood were uniform through the cross section appears to be reasonable.

3) Figures 4.1 and 4.3 compare the experimental data and computed model outputs. Figures 4.2 and 4.4 show examples of residuals versus time plots. These types of plots show useful information about the deficiencies of the models, for example the model IIA used by MACLEAN (1946), was found to overpredicts the temperature by 5 - 11°C at the end of the heating period in most cases.

4) Table 4.4 shows the average residual sum of squares and Table 4.5 the F- ratios for the models in the time range of DURATION I. The number of data points, N, is 24. The upper-tail F-ratio for 24-2 = 22 and 95 % confidence level is read from an F-chart to be 4.2. The observed F- ratios , shown in Table 4.5, are smaller than 4.2 using Models IA and IB and Models IC and ID. This indicates that there is no significant improvement brought to the modeling by including a surface heat transfer coefficient as a model parameter. On the other hand, comparing F-ratios of Models IA and IC, and IB and ID indicates that including the time delay as a model parameter significantly improves the fit. To compare the models in DURATION II, for 48 data points the values found in an F chart are

F(1,45; .05) = 3.23 and F(2,45;.05) = 4.08, while from a chi-square table the corresponding chi-squared values for degrees of freedom of 1 and 2 are 3.84 and 5.99. These values are compared to those ratios in Tables 4.7 and 4.9 and the results indicate that model IIC fits significantly better than both model IIA and IIB. For example, the residual sum of square values for pole number 6 of trial ACA2 at a 6 in. depth are 289.8, 20.6 and 8.23 for models IIA, IIB and IIC respectively. The corresponding F-ratios for model IIA and IIB is 293.3 and for models IIB and IIC is 66.6.

Table 4.1 Parameter summary for all models

Model IA	α = 0.0068 ± 3.9 E-3	[ft^2 / hr]
Model IB	α = 0.00698 ± 4.34E-3	[ft^2 / hr]
	MR = 1.325E-3 ± 1.17E-3	[-]
Model IC	α = 0.00884 ± 4.39E-3	[ft^2 / hr]
	τ_d = 0.817 ± 0.41	[hr]
Model ID	α = 0.00843 ± 4.114E-4	[ft^2 / hr]
	τ_d = 0.877 ± 0.442	[hr]
	MR = 1.498E-3 ± 1.527E-3	[-]
Model IIA	α = 0.007639 ± 2.136E-3	[ft^2 / hr]
Model IIB	α = 0.008355 ± 1.3723	[ft^2 / hr]
	τ_d = 0.8816 ± 0.224	[hr]
	k_c = 22.34 ± 2.97	[^oC / hr]
Model IIC	α = 0.008816 ± 1.3693	[ft^2 / hr]
	τ_d = 0.875 ± 0.223	[hr]
	k_1 = 27.34 ± 3.07	[^oC / hr]
	k_2 = 11.96 ± 2.18	[^oC / hr]

Table 4.2 Estimated thermal diffusivity of poles for Models IA, IB, IC and ID

Trial	Pole #	Data file	Radial pos. in.	Thermal Diffus. [ft^2/hr] Model IA	Model IB	Model IC	Model ID
ACA1	3	A161	0.033800	0.003200	0.006407	0.008144	0.008144
	3	A162	0.033800	0.005883	0.005897	0.007635	0.007635
	4	A163	0.028600	0.005950	0.005975	0.007500	0.007667
	4	A164	0.028600	0.008425	0.008452	0.008425	0.008454
	3	A141	0.200000	0.006680	0.006743	0.007925	0.007892
	4	A143	0.195300	0.006124	0.006147	0.007871	0.007898
	4	A144	0.195300	0.015728	0.015747	0.015700	0.015760
	3	A121	0.367160	0.007608	0.007646	0.009800	0.009800
	4	A123	0.361970	0.008487	0.008526	0.011285	0.011260
	4	A124	0.361970	0.001190	0.001200	0.001566	0.001858
	3	A171	0.049500	0.005577	0.005672	0.007165	0.008080
	4	A172	0.054690	0.005570	0.005595	0.007770	0.007800
ACA2	5	B271	0.061660	0.006345	0.006372	0.009726	0.006733
	6	B272	0.026000	0.004795	0.005000	0.008443	0.008925
	5	B261	0.051670	0.007061	0.007074	0.009579	0.006922
	5	B262	0.051670	0.006922	0.006959	0.009643	0.009038
	6	B263	0.057330	0.005968	0.006000	0.008626	0.008480
	6	B264	0.057330	0.022158	0.022148	0.022106	0.000818
	5	B241	0.208340	0.007271	0.007312	0.009540	0.009573
	5	B242	0.208340	0.008285	0.008320	0.009270	0.011190
	6	B243	0.224000	0.007226	0.007256	0.010581	0.010610
	6	B244	0.224000	0.003132	0.003172	0.005537	0.005681
	5	B221	0.375000	0.007125	0.001200	0.013329	0.013416
	5	B222	0.375000	0.009307	0.009373	0.019102	0.019218
	6	B223	0.390700	0.007875	0.007919	0.015870	0.015850
ACA3	7	C371	0.062500	0.008038	0.008066	0.008043	0.008073
	7	C361	0.020830	0.020000	0.019200	0.020223	0.020270
	7	C326	0.020830	0.007616	0.004455	0.007600	0.007640
	7	C341	0.187490	0.009480	0.009509	0.009480	0.009500
	7	C321	0.354160	0.008890	0.008935	0.011849	0.011851
	7	C322	0.354160	0.007900	0.007954	0.012450	0.012419
	7	C323	0.375000	0.009033	0.006890	0.013887	0.013950
ACA4	9	A461	0.005200	0.007316	0.007323	0.008853	0.008900
	9	A462	0.005200	0.008297	0.008804	0.009090	0.009122
	10	A463	0.015600	0.003200	0.020966	0.003200	0.003200
	10	A464	0.015600	0.006471	0.006509	0.006521	0.007148
	9	A442	0.171800	0.007440	0.002637	0.008464	0.008491
	10	A443	0.182270	0.005646	0.005673	0.006734	0.006773
	10	A444	0.182270	0.006280	0.006304	0.006881	0.006909
	9	A445	0.171800	0.007291	0.007306	0.008640	0.008672
	9	A421	0.338530	0.010530	0.010565	0.014774	0.014850
	10	A422	0.348900	0.007487	0.007532	0.009670	0.009732

Table 4.3 Estimated initial time delay and relative surface thermal resistance for Models IB, IC and ID

Trial	Pole #	Data file	Radial pos. in.	Time Delay [hr.] Model IC	Model ID	Realtive Resis. Model IB	Model ID
ACA1	3	A161	0.033800	1.310430	1.304981	0.000806	0.005150
	3	A162	0.033800	1.225800	1.217800	0.001120	0.000961
	4	A163	0.028600	1.170000	1.175500	0.000847	0.000872
	4	A164	0.028600	0.000000	0.000000	0.001475	0.001497
	3	A141	0.200000	0.818900	0.804953	0.002438	0.000660
	4	A143	0.195300	1.029500	1.030800	0.001236	0.001340
	4	A144	0.195300	0.000000	0.000000	0.000403	0.000690
	3	A121	0.367160	0.633700	0.636700	0.001200	0.000400
	4	A123	0.361970	0.610800	0.608700	0.001200	0.000550
	4	A124	0.361970	1.120000	1.700000	0.000942	0.001000
	3	A171	0.049500	1.120000	1.607600	0.000915	0.001488
	4	A172	0.054690	1.516000	1.532600	0.001361	0.000668
ACA2	5	B271	0.061660	1.277400	1.067630	0.001027	0.000767
	6	B272	0.026000	1.565400	1.738600	0.001000	0.001860
	5	B261	0.051670	0.951760	0.954800	0.001060	0.000760
	5	B262	0.051670	0.880700	0.848000	0.000820	0.000997
	6	B263	0.057330	1.154200	1.101360	0.000960	0.000825
	6	B264	0.057330	0.000000	0.000000	0.000818	0.000818
	5	B241	0.208340	0.757700	0.756170	0.000825	0.001449
	5	B242	0.208340	0.320000	0.807089	0.000409	0.000630
	6	B243	0.224000	1.008600	1.009230	0.000894	0.000850
	6	B244	0.224000	1.600000	1.641800	0.000839	0.001860
	5	B221	0.375000	0.978800	0.978700	0.001200	0.001400
	5	B222	0.375000	0.991800	0.991400	0.001200	0.001400
	6	B223	0.390700	1.018130	1.260000	0.001200	0.001600
ACA3	7	C371	0.062500	0.002000	0.002600	0.001731	0.001600
	7	C361	0.020830	0.000010	0.000000	0.001200	0.000800
	7	C326	0.020830	0.000000	0.000000	0.001655	0.007615
	7	C341	0.187490	0.000000	0.000000	0.001410	0.001410
	7	C321	0.354160	0.472450	0.472250	0.001200	0.000250
	7	C322	0.354160	0.746690	0.747800	0.001200	0.000400
	7	C323	0.375000	0.647000	0.649000	0.001200	0.000693
ACA4	9	A461	0.005200	0.509113	0.513448	0.001429	0.001318
	9	A462	0.005200	0.126860	0.131000	0.001460	0.001390
	10	A463	0.015600	0.000000	0.000000	0.000000	0.001200
	10	A464	0.015600	0.032000	0.383000	0.000806	0.007148
	9	A442	0.171800	0.443600	0.443831	0.002200	0.001304
	10	A443	0.182270	0.631640	0.640000	0.001000	0.001423
	10	A444	0.182270	0.318097	0.321120	0.001192	0.001280
	9	A445	0.171800	0.574880	0.574650	0.000700	0.001654
	9	A421	0.338530	0.561000	0.560230	0.001200	0.001400
	10	A422	0.348900	0.500200	0.499500	0.001200	0.001538

Table 4.4 Residual sum of squares for Models IA, IB, IC and ID

Trial	Pole #	Data file	Radial pos.[in.]	Residual sum of squares Model IA	Model IB	Model IC	Model ID
ACA1	3	A161	0.034	7784.400	1412.352	2.868	2.842
	3	A162	0.034	59.760	59.683	15.648	15.641
	4	A163	0.029	67.608	67.505	1.560	1.616
	4	A164	0.029	9.158	9.130	9.158	9.130
	3	A141	0.200	136.488	136.387	6.115	6.290
	4	A143	0.195	164.436	163.858	1.962	1.925
	4	A144	0.195	266.640	266.808	266.640	266.880
	3	A121	0.367	757.920	754.056	141.492	141.792
	4	A123	0.362	827.760	822.912	40.080	40.560
	4	A124	0.362	341.040	340.872	158.400	80.304
	3	A171	0.050	88.615	100.150	12.702	1.233
	4	A172	0.055	89.129	88.486	1.050	1.048
ACA2	5	B271	0.062	27.214	27.175	0.535	3.063
	6	B272	0.026	13.464	12.475	4.627	4.492
	5	B261	0.052	22.342	22.328	0.869	0.903
	5	B262	0.052	16.599	16.651	0.784	0.823
	6	B263	0.057	11.198	11.234	0.751	0.746
	6	B264	0.057	88.589	88.639	88.589	88.639
	5	B241	0.208	92.710	92.630	22.694	22.608
	5	B242	0.208	143.251	142.934	63.096	9.727
	6	B243	0.224	151.174	150.761	4.030	3.976
	6	B244	0.224	17.194	17.318	2.003	1.951
	5	B221	0.375	170.717	1703.328	67.944	67.315
	5	B222	0.375	2589.600	2585.040	85.920	87.528
	6	B223	0.391	2499.600	249.456	58.747	58.872
ACA3	7	C371	0.063	0.710	0.695	0.710	0.694
	7	C361	0.021	371.184	458.952	371.184	371.232
	7	C326	0.021	2.460	1127.856	2.460	2.410
	7	C341	0.187	72.000	72.350	72.000	72.348
	7	C321	0.354	408.288	406.464	5.148	5.203
	7	C322	0.354	862.752	860.088	24.312	24.468
	7	C323	0.375	847.200	854.400	15.547	15.528
ACA4	9	A461	0.005	21.348	21.297	2.213	2.253
	9	A462	0.005	7.115	6.845	5.160	5.131
	10	A463	0.016	664.296	1076.688	664.296	664.536
	10	A464	0.016	5.990	6.141	5.136	0.277
	9	A442	0.172	53.400	353.496	16.349	16.181
	10	A443	0.182	35.568	35.496	2.894	2.859
	10	A444	0.182	12.147	12.056	1.539	1.517
	9	A445	0.172	69.898	69.595	6.197	6.144
	9	A421	0.339	1030.824	1020.792	44.026	44.160
	10	A422	0.349	469.800	467.040	7.070	6.954

Table 4.5 F - ratios for comparing extra sum of squares for Models IA, IB, IC and ID

Trial	Pole #	Data file	Radial pos.	F-ratios from extra sum of squares IA - IB	IA - IC	IB - ID	IC - ID
	3	A162	0.0338	0.028	62.018	59.133	0.010
	4	A163	0.0286	0.034	931.446	856.011	-0.733
	4	A164	0.0286	0.067	0.000	-0.001	0.063
	3	A141	0.2000	0.016	469.028	434.318	-0.585
	4	A143	0.1953	0.078	1822.235	1766.500	0.398
	4	A144	0.1953	-0.014	0.000	-0.006	-0.019
	3	A121	0.3672	0.113	95.846	90.679	-0.044
	4	A123	0.3620	0.130	432.359	405.064	-0.249
	4	A124	0.3620	0.011	25.367	68.140	20.423
	3	A171	0.0495	-2.534	131.480	1684.877	195.361
	4	A172	0.0547	0.160	1845.674	1752.360	0.041
ACA2	5	B271	0.0617	0.031	1096.144	165.307	-17.329
	6	B272	0.0260	1.744	42.015	37.326	0.634
	5	B261	0.0517	0.013	543.553	498.144	-0.793
	5	B262	0.0517	-0.069	443.602	403.899	-0.986
	6	B263	0.0573	-0.070	305.850	295.325	0.159
	6	B264	0.0573	-0.013	0.000	0.000	-0.012
	5	B241	0.2083	0.019	67.873	65.040	0.080
	5	B242	0.2083	0.049	27.948	287.596	115.224
	6	B243	0.2240	0.060	803.347	775.352	0.285
	6	B244	0.2240	-0.157	166.873	165.439	0.561
	5	B221	0.3750	-19.795	33.277	510.379	0.196
	5	B222	0.3750	0,039	641.073	599.211	-0.386
	6	B223	0.3907	198.444	914.065	67.982	-0.045
ACA3	7	C371	0.0625	0.489	0.000	0.041	0.509
	7	C361	0.0208	-4.207	0.000	4.962	-0.003
	7	C326	0.0208	-21.952	0.000	9808.422	0.437
	7	C341	0.1875	-0.107	0.000	0.001	-0.101
	7	C321	0.3542	0.099	1722.821	1619.555	-0.222
	7	C322	0.3542	0.068	758.707	717.182	-0.134
	7	C323	0.3750	-0.185	1176.827	1134.487	0,026
ACA4	9	A461	0.0052	0.052	190.240	177.521	-0.374
	9	A462	0.0052	0.868	8.339	7.016	0.117
	10	A463	0.0156	-8.426	0.000	13.024	-0.008
	10	A464	0.0156	-0.538	3.660	443.999	367.923
	9	A442	0.1718	-18.677	49.860	437.779	0.218
	10	A443	0.1823	0.045	248.348	239.693	0.257
	10	A444	0.1823	0.167	151.687	145.900	0.301
	9	A445	0.1718	0.096	226.133	216.874	0.182
	9	A421	0.3385	0.216	493.112	464.431	-0.064
	10	A422	0.3489	0.130	1439.912	1389.291	0.349

Table 4.6 Estimated model parameters for Models IIA and IIB

			Model IIB	Model IIC		
Trial	Pole #	DEPTH [in.]	Theraml diffus. [ft^2/hr]	Therm. di [ft^2/hr]	Time delay[hr]	cool.rate [C/hr]
ACA1	3	2	0.0073	0.0096	0.7449	22.8000
	3	4	0.0066	0.0075	0.6833	32.9270
	3	6	0.0065	0.0075	1.0552	22.8285
	3	6	0.0063	0.0075	1.2000	22.8285
	3	7	0.0062	0.0081	1.6614	28.2815
	4	2	0.0081	0.0071	1.2000	22.8475
	4	2	0.0017	0.0060	1.2000	19.5700
	4	4	0.0063	0.0072	0.8465	22.9235
	4	4	0.0153	0.0092	0.6728	26.0110
	4	6	0.0062	0.0073	0.7849	
	4	6	0.0077	0.0071	0.8920	22.8380
	4	7	0.0057	0.0067	1.2000	22.6860
ACA2	5	2	0.0074	0.0098	0.7285	18.9335
	5	2	0.0095	0.0092		
	6	2	0.0081	0.0107	0.7069	18.1545
	6	2	0.0070	0.0094	0.7645	18.7340
	5	4	0.0089	0.0101	0.7044	20.5200
	6	4	0.0078	0.0092	0.7788	22.3915
	5	6	0.0082	0.0093	0.7691	22.8000
	5	6	0.0080	0.0092	0.8000	22.2490
	6	6	0.0067	0.0079	0.7986	22.8000
	6	6	0.0067	0.0081	1.1711	20.3585
ACA3	7	6	0.0077	0.0086	0.7783	22.8000
	7	4	0.0107	0.0089	0.8000	22.8000
	7	2	0.0085	0.0090	0.8000	21.6030
	8	2	0.0094	0.0095	0.7999	17.6225
ACA 4	9	6	0.0076	0.0086	0.7764	22.8000
	9	6	0.0066	0.0070	0.8000	22.8855
	9	4	0.0077	0.0090	0.7867	22.8000
	10	4	0.0060	0.0068	0.7901	21.4890
	9	2	0.0106			
	10	2	0.0075	0.0098	0.7537	20.8430

Table 4.7 Residual values, F - ratios and likelihood ratio values for Models IIA and IIB

			Model IIA	Model IIB		
Trial	Pole #	DEPTH [in.]	Residual sum sq.	Residual sum sq.	F STATIST	LRT
ACA1	3	2	2025.312	773.424	36.419	46.207
	3	4	270.557	52.598	93.236	78.614
	3	6	294.221	83.218	57.050	60.618
	3	6	356.640	75.600	83.643	74.461
	3	7	519.696	5.923	1951.629	214.770
	4	2	2100.288	92.746	487.028	149.759
	4	2	5115.360	20132.64	-16.783	-65.765
	4	4	396.110	129.216	46.474	53.770
	4	4	4720.176	555.312	168.751	102.723
	4	6	277.776	574.560	-11.622	-34.886
	4	6	1258.656	230.741	100.234	81.432
	4	7	763.200	154.080	88.949	76.802
ACA2	5	2	2512.272	930.672	38.237	47.666
	5	2	3210.720			
	6	2	3052.560	1291.728	30.671	41.280
	6	2	2367.792	857.424	39.634	48.757
	5	4	539.808	289.762	19.416	29.863
	6	4	580.752	241.387	31.633	42.140
	5	6	454.320	91.387	89.356	76.977
	5	6	379.248	66.811	105.219	83.343
	6	6	224.688	37.597	111.963	85.813
	6	6	289.882	20.654	293.284	126.794
ACA3	7	6	271.675	290.616	-1.466	-3.235
	7	4	1989.264	1228.272	13.940	23.144
	7	2	1942.896	1470.480	7.228	13.372
	8	2	2205.696	970.704	28.626	39.397
ACA 4	9	6	476.592	133.680	57.716	61.018
	9	6	215.486	164.016	7.061	13.101
	9	4	645.120	173.453	61.184	63.049
	10	4	247.166	28.805	170.567	103.177
	9	2	2757.312			
	10	2	1356.480	854.496	13.218	22.183

Table 4.8 Estimated model parameters for Model IIC

Model IIC

Trial	Pole #	DEPTH [in.]	Therm.Dif [ft^2/hr]	time delay[hr]	Cooling rates [deg C/hr] k1	k2
					(-)	(-)
ACA1	3	2	0.00982	0.768	29.913	12.000
	3	4	0.00762	0.741	39.000	0.002
	3	6	0.00757	1.057	24.090	14.400
	3	6	0.00757	1.200	24.083	14.400
	3	7	0.00819	1.695	32.220	0.002
	4	2	0.01110	0.800	27.980	14.400
	4	2	0.00600	1.200	24.000	9.600
	4	4	0.00750	0.947	30.000	14.400
	4	4	0.01120	0.667	30.180	14.400
	4	6	0.00737	1.076	30.333	14.400
	4	6	0.00892	0.800	31.521	14.400
	4	7	0.00677	1.186	30.180	14.400
ACA2	5	2	0.01035	0.749	24.344	9.600
	5	2	0.01120	0.667	24.123	9.600
	6	2	0.11070	0.691	23.805	9.600
	6	2	0.00987	0.782	24.126	9.600
	5	4	0.01035	0.737	24.115	11.914
	6	4	0.00925	0.786	24.115	12.850
	5	6	0.00946	0.800	24.676	14.400
	5	6	0.00921	0.792	24.000	14.400
	6	6	0.00818	0.950	24.000	14.400
	6	6	0.00824	1.198	24.115	10.516
ACA3	7	6	0.00881	0.790	30.180	13.696
	7	4	0.00936	0.800	30.000	9.600
	7	2	0.01002	0.800	28.600	9.600
	8	2	0.01054	0.800	27.515	9.600
ACA 4	9	6	0.00885	0.796	31.146	12.000
	9	6	0.00733	0.796	32.714	12.000
	9	4	0.00914	0.790	30.150	9.700
	10	4	0.00692	0.790	26.934	9.600
	9	2	0.01120	0.610	27.548	9.600
	10	2	0.01014	0.736	26.765	9.600

Table 4.9 Residual values, F- ratios and likelihood ratios for Models IIB and IIC

Trial	Pole #	DEPTH [in.]	Model IIB Residual sum sq.	Model IIC Residual sum sq.	F-ratio	Likelihood ratio test
ACA1	3	2	773.424	351.677	52.767	37.830
	3	4	52.598	20.993	66.244	44.088
	3	6	83.218	80.976	1.218	1.311
	3	6	75.600	74.400	0.710	0.768
	3	7	5.923	3.363	33.499	27.172
	4	2	92.746	605.280	-37.258	-90.040
	4	2	20132.64	19943.52	0.417	0.453
	4	4	129.216	32.438	131.271	66.343
	4	4	555.312	12115.68	-41.983	-147.971
	4	6	574.560	126.427	155.962	72.669
	4	6	230.741	1631.136	-37.776	-93.875
	4	7	154.080	138.000	5.127	5.290
ACA2	5	2	930.672	404.256	57.296	40.025
	5	2	0.000	933.264		
	6	2	1291.728	635.184	45.480	34.071
	6	2	857.424	361.618	60.327	41.441
	5	4	289.762	192.288	22.304	19.683
	6	4	241.387	208.685	6.895	6.988
	5	6	91.387	75.984	8.920	8.860
	5	6	66.811	50.174	14.589	13.746
	6	6	37.597	30.816	9.683	9.547
	6	6	20.654	8.237	66.333	44.127
ACA3	7	6	290.616	128.112	55.812	39.317
	7	4	1228.272	885.264	17.048	15.719
	7	2	1470.480	846.096	32.470	26.530
	8	2	970.704	1024.800	-2.323	-2.603
ACA 4	9	6	133.680	44.122	89.312	53.208
	9	6	164.016	30.619	191.692	80.560
	9	4	173.453	37.910	157.315	72.993
	10	4	28.805	8.700	101.679	57.467
	9	2		722.064		
	10	2	854.496	363.341	59.478	41.048

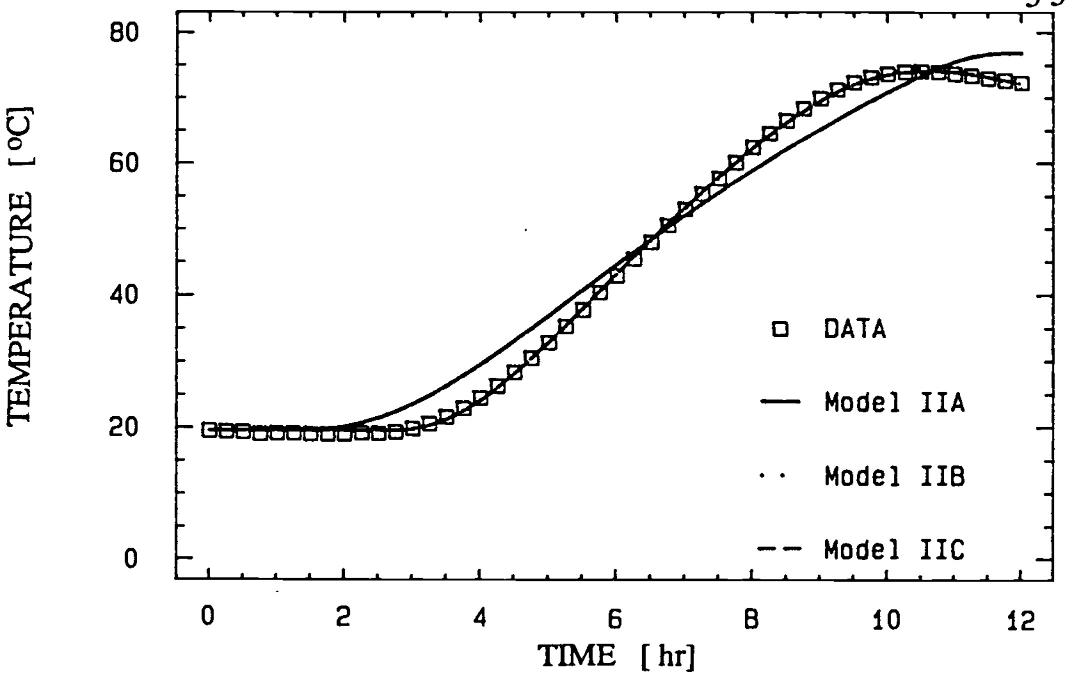


Figure 4.1 Comparison of experimental and calculated temperatures for Models IIA, IIB and IIC.

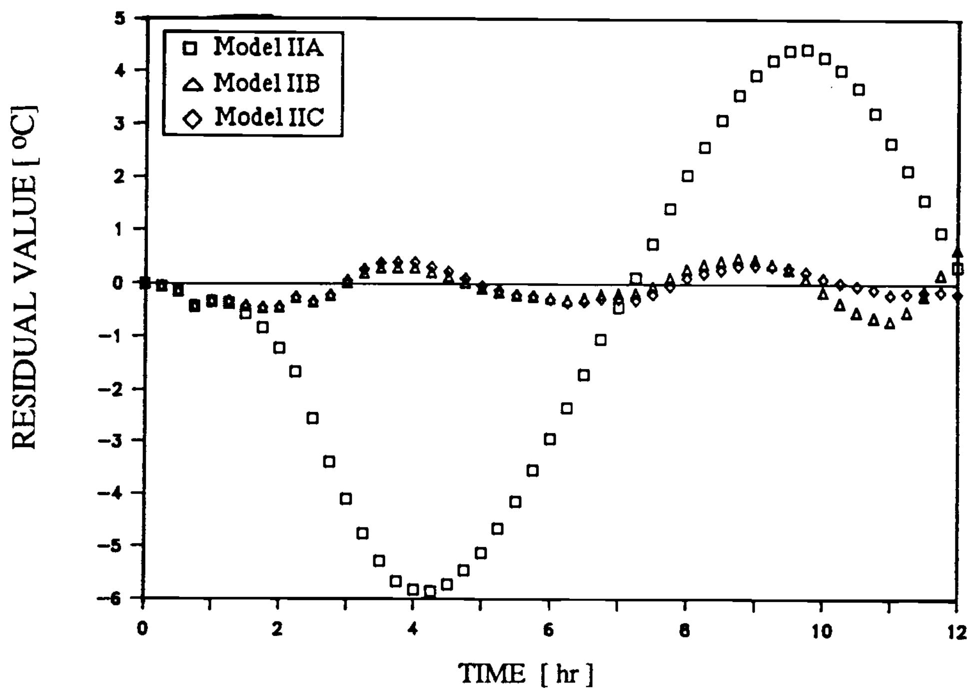


Figure 4.2 Residual values versus time for predictions of Models IIA, IIB and IIC.

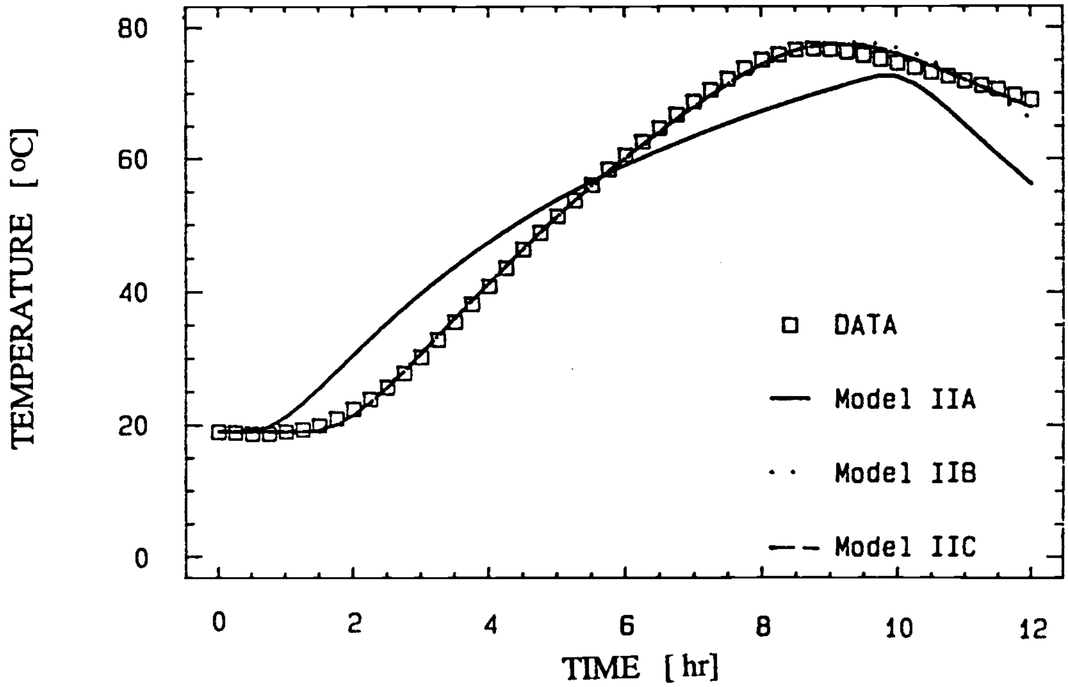


Figure 4.3 Comparison of experimental and model predictions of temperatures for Models II A, IIB and IIC for trial ACA1 .

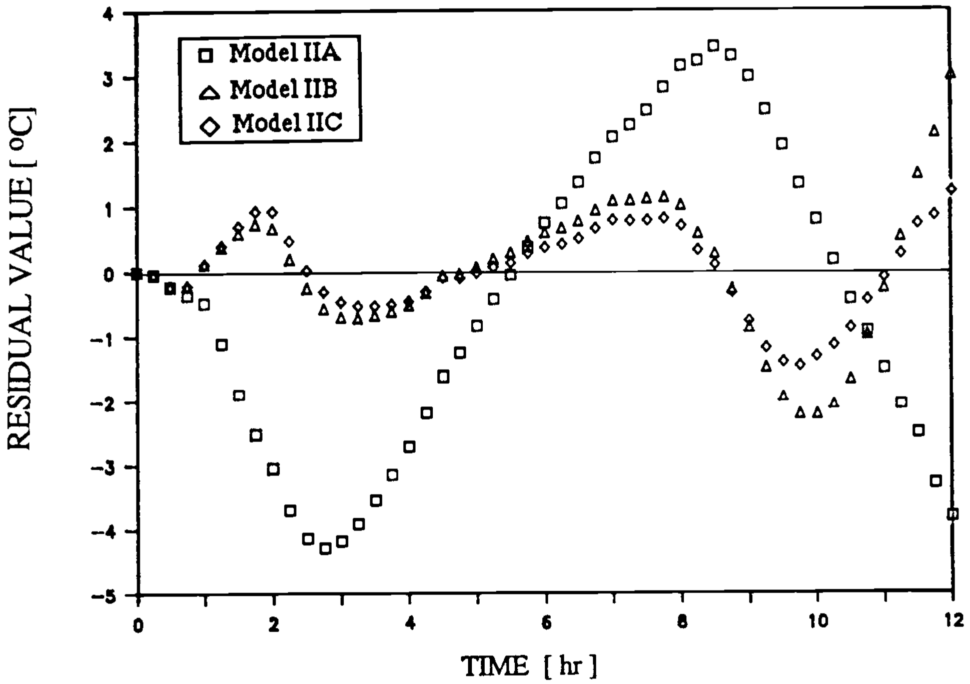


Figure 4.4 Residual values versus time for predictions of Models IIA, IIB and IIC.

4.4 SENSITIVITY ANALYSIS

The preceding analysis and recommendations have been based on a set of modeling assumptions. Although the assumptions are intended to be reasonable, operating at conditions different from the the assumptions may have major ramifications:

- the model parameters estimated with data could be inappropriate and consequently the prediction for minimum steaming time and the time required to reach it may be in error.
- a change in the process sequence, type of heating method or type of preservative or any other major conditions not accounted by the model would require further study.

These changes can be represented as uncertainty for the estimated temperature, (BARD, 1974). The temperature prediction for Model IIC as a function of parameter changes is shown in Figures 4.5, 4.6 and 4.7.

Let :

$$\Delta T = T - T_p$$

where T_p = temperature prediction for the mean parameter estimate .

T = temperature prediction for parameter values in the confidence interval of the parameter estimate.

The plots show that the temperature is sensitive to changes in the wood thermal diffusivity values, ± 9 ^{o}C changes, but not very sensitive to changes in the initial heating up time, ± 1 ^{o}C, or the cooling rate after steaming, ± 3 ^{o}C. Thus in order to use this model, the operating engineer must determine the thermal diffusivity of the pole as accurately as possible, but rough estimation of the time delay and the rates of cooling adequate.

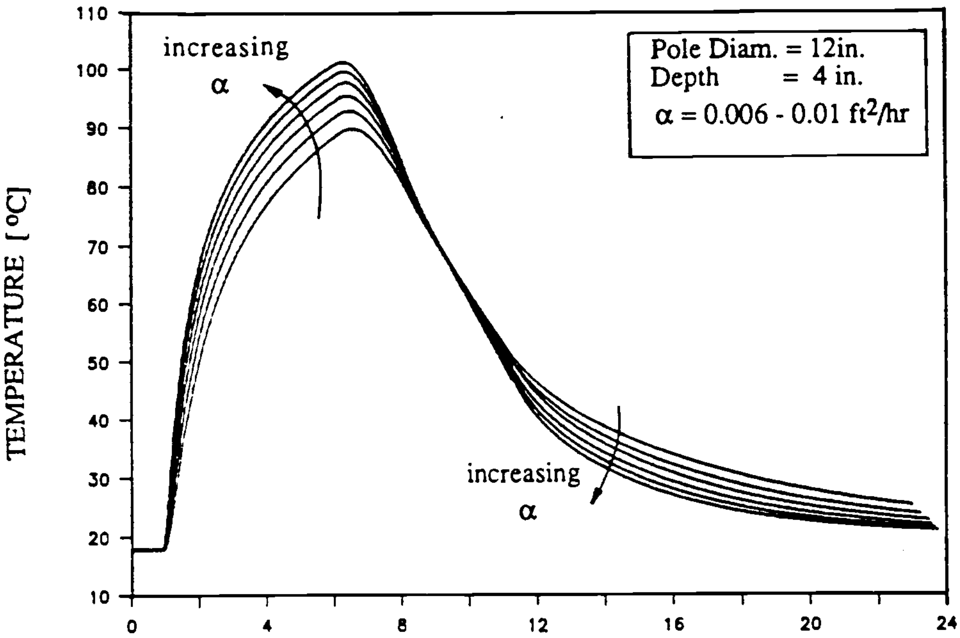


Figure 4.5a

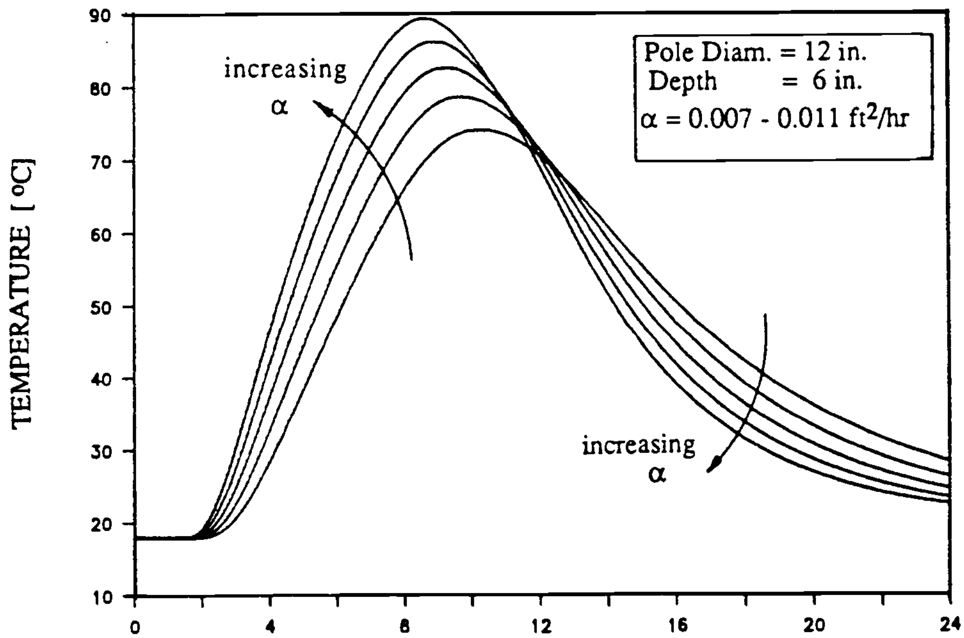


Figure 4.5b

Figures 4.5a, 4.5b Effect of thermal diffusivity on the predicted temperature for a 12 in. diameter pole during ACA treatment at a depth of 4 in. (a), and 6 in.(b).

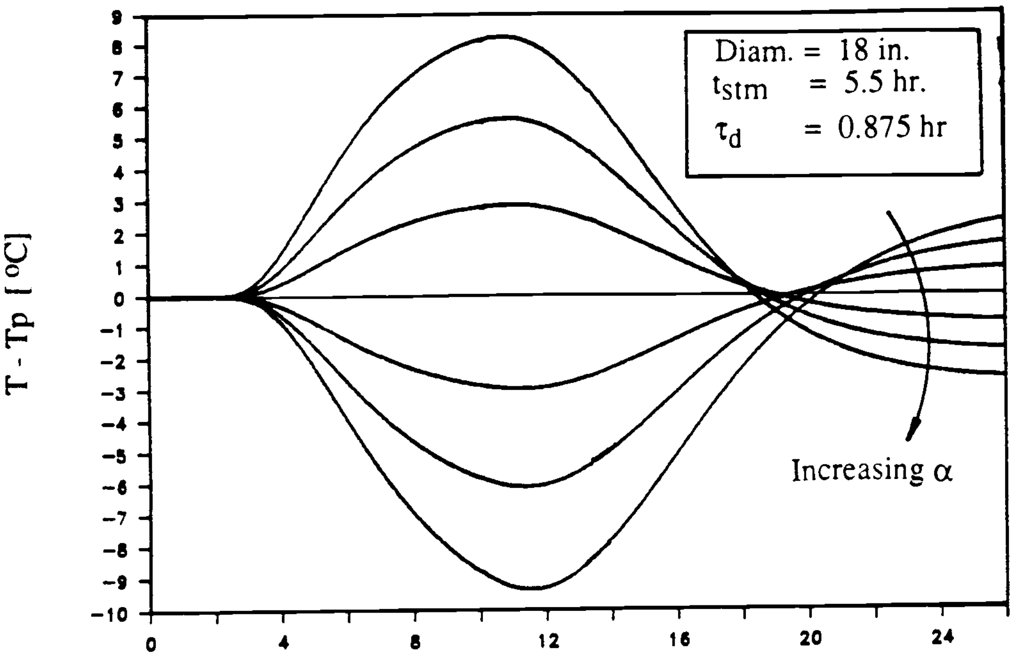


Figure 4.6a

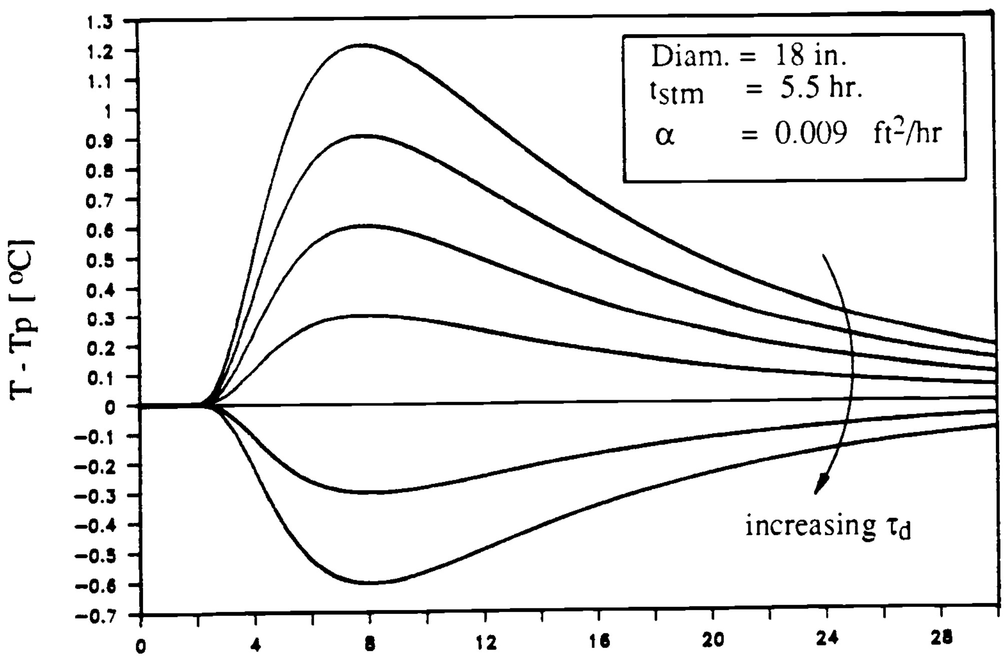


Figure 4.6b

Figure 4.6a, 4.6b The difference between the predicted center line temperatures for the average estimated parameter (α =0.0092 ft^2/hr for Fig. 4.6a, and τ_d =0.875 hr for Fig. 4.6b) and for parameters in the range of the confidence interval of estimation, α = 0.006 - 0.012 ft^2/hr and τ_d = 0.5 - 1.1 hr.

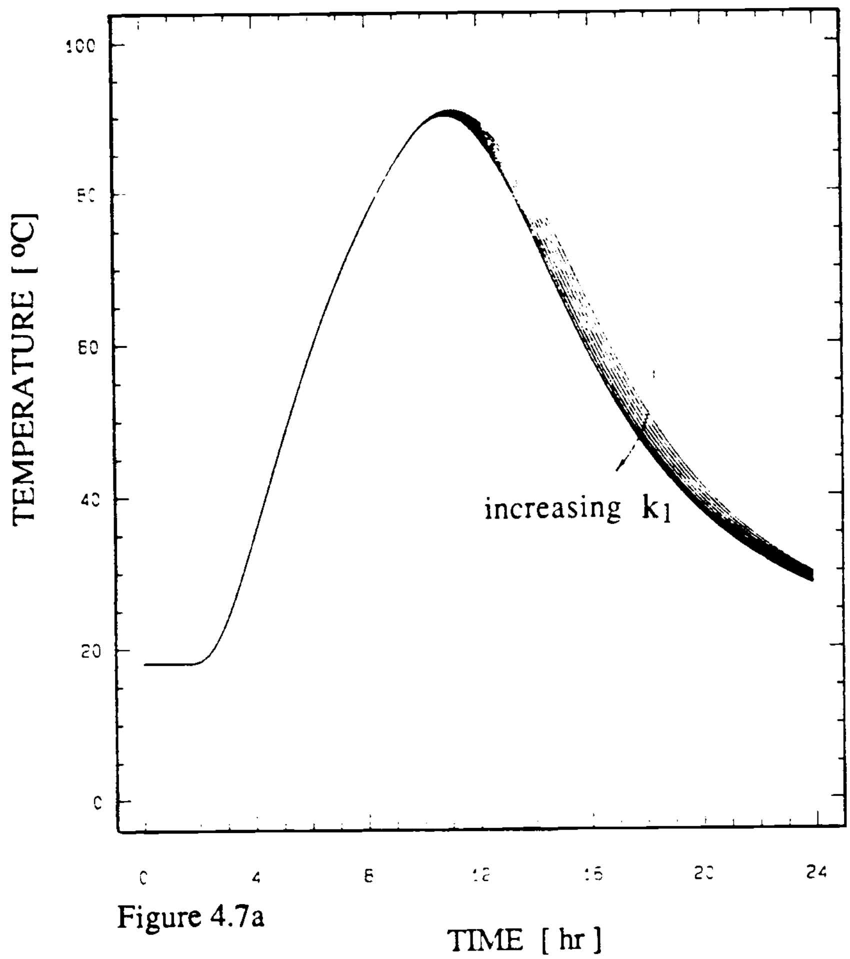


Figure 4.7a

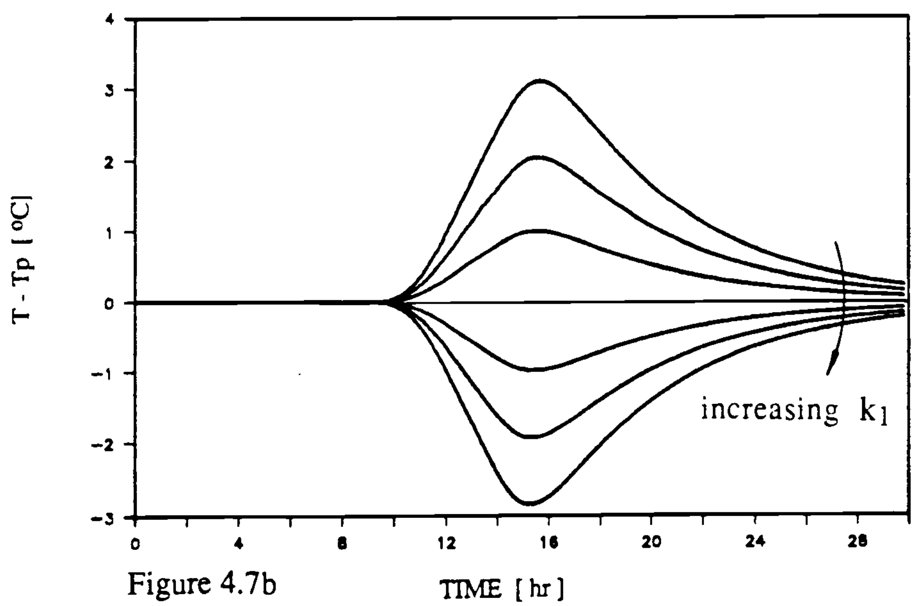


Figure 4.7b

Figure 4.7a, 4.7b Difference between the calculated temperatures for the estimated mean rate of surface cooling, k_1 = 27 °C/hr, and for the rates of cooling in the range of the confidence interval of the parameter estimate, k_1 = 24 - 30 °C/hr.

CHAPTER 5.0

PROCESS RECOMMENDATIONS

5.1 PREDICTION EQUATIONS FOR TIME-TEMPERATURE-LOCATION RELATIONS

Using Model IIC with the mean estimated parameters, Table 4.1, we can demonstrate important relations and make predictions. Based on the commonly used pressure treatment schedule for Douglas-fir poles, using waterborne ammoniacal copper arsenate (ACA), (Table 1.1 page 12), the following recommendations were obtained using the results of modeling.

1) One of the objectives in modeling is to determine whether the steam conditioning and pressure treatment used result in sterilization. The minimum steaming time required to reach 65.5°C for poles with diameters of 22.86, 30.48, 38.1, 45.72, 53.34, 60.96 cms. (9, 12, 15, 18, 21, 24 in.) are shown in Fig.5.1. From this plot one can easily find, for example, that at a constant depth of 15.24 cm (6 in.) the dimensionless radial distance, r/R, is equal to 1, 0.8 and 0.667 for poles with diameters of 30.48, 45.72, 53.34 cm respectively. The necessary times to reach 65.5°C, from Fig. 5.1, are about 6.8, 12, 14.3

hours respectively. This shows that for the same depth, depending on the diameter of the poles, the time required to reach 65.5 ^{o}C varies by more than a factor of 2. This result indicates that the time-depth relationship shown by DOST (1984) is questionable since it does not include the diameter of a pole as a variable and thus would predict the same required time of 9 hours for all these poles.

2) The minimum required steaming time to achieve two hours of temperature above 65.5 ^{o}C is plotted as a function of the diameter of the poles in Figure 5.2. These values are for an assumed initial pole temperature of 18 ^{o}C a steam temperature of 115 ^{o}C and, the best parameters with Model IIC. An approximate equation for this relationship was obtained by using the linear regression analysis after logarithmic transformation of power function. It is very important to note that, due to the various assumptions made, all the prediction equations given here have about a $\pm$ 15 percent accuracy.

$$t_{stm1} = 0.025 D^{2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5.1)$$

where

t_{stm1} = the minimum require steaming time to achieve two hours of the center line temperature above 65.5 ^{o}C [hr]

D = diameter of the poles [in.]

3) The time elapsed to first reach 65.5°C at the center line is also shown as a function of the diameter of a pole in Figure 5.1. These results were approximated by the equation shown below, obtained using linear regression after logarithmic transformation of the power function.

$$TIME_m = 0.11\ D^{1.67} \qquad \text{(5.2)}$$

where

$TIME_m$ = the time required to first reach 65.5 °C at center while achieving two hours of the center line temperature above 65.5 °C, [hr.]

D = diameter of the pole [in.]

4) There is relatively little effect on internal temperature of poles when the treating solution temperature varies between 20 to 60 °C (Figure 5.2). Warmer solution delays the loss of heat from the pole but didn't increase the internal temperature already reached during steaming (Figure 5.4). NEWBILL (1988) reported that heated solutions merely act as an insulator, thereby delaying the loss of heat from the pole surface.

5) All of the above results are based on an assumed initial pole temperature of 18 °C. Since there is considerable seasonal temperature variation, in the range of 0 °C to 40 °C,

it was important to analyze the effect of initial temperature on the required steaming time. Figure 5.3 shows the minimum required steaming time to achieve two hours of the center line temperature above 65.5 °C versus initial temperature of the pole. From Figures 5.1 and 5.4 the following relation was developed:

$$t_{stm2} = t_{stm1} - (0.0118\,D - 0.095)\,(T_o - 18) \qquad \text{.............} (5.3)$$

Similarly an approximate relationship for the time needed for the center line temperature to reach 65.5 °C for an initial temperature $10 \le T_o \le 30$ °C and diameter $9 \le D \le 24$ in. is :

$$\text{Time} = \frac{1}{1.4\,D - 35}\,T_o + 0.118\,D^{1.68} \qquad \text{............} (5.4)$$

where:

D = diameter of the pole [in.], $9 \le D \le 30$

T_o = the initial temperature of a pole, [°C]

t_{stm1} = time of steaming of a pole which has an initial temperature of 18°C to sterilization conditions. (To be read from Fig. 5.2) [hr]

t_{stm2} = time of steaming required to bring the center line of the pole which has initial temperature of T_{i2} to sterilization conditions. [hr]

Time = time required to reach 65.5 °C [hr]

6) The above results are obtained using the mean thermal diffusivity of 0.0088 ft^2/hr. The values of the minimum steaming time or the time required to reach 65.5 ^oC may be corrected for different diffusion coefficient using (MACLEAN 1952)

$$t = t^* \frac{0.0088}{\alpha} \quad \ldots\ldots\ldots\ldots\ldots\ldots (5.5)$$

where t = is either the minimum steaming time or the time required to reach 65.5 ^oC calculated using equations 5.1 to 5.4 . [hr]

t^* = the corrected time [hr]

α = thermal diffusion coefficient of pole [ft^2/hr]

7) Figure 5.4 shows the time the center line temperature remains above 65.5 ^oC versus the diameter of the poles which are initially at 18 ^oC. The curves are for 6 or 8 hour steaming periods and for preservative at 20 or 60 ^oC. This figure demonstrates that :

- as the diameter of poles increases from 6 in. for the same steaming time, the time the center of the poles remains above 65.5 ^oC, t_{above}, first increases, because the thermal capacity of the poles increase with their size and then decreases sharply. In all cases the rate of change of the time, t_{above}, with an increase in pole size, $\partial t_{above} / \partial r$, is very negative when t_{above} is less than 3 hours, i.e. close to the REA specification. For example, for 6 hours steaming period a 15 in. diameter pole is the critical size since poles larger than this size may not be steamed long enough to achieve the center line temperature remain for 2 hours above 65.5 °C. Similarly 18 in. is the critical pole diameter for 8 hour steaming.

- the temperature of the preservative only affect the shape of the curve, where the hotter preservative is the longer it keeps the poles above 65.5 °C. Preservative temperature is not an important factor in bringing the poles to the required sterilization condition.

8) The maximum temperatures obtainable at various locations when the center line is heated to 65.5 °C are shown in Figure 5.5 for various pole diameters. It was observed that in general by heating the center until it reaches 65.5 °C, less than 75 percent of the pole was heated above 100 °C.

This study recommends steaming periods longer than the standard practice when large diameter poles, i.e. poles with a diameter of 18 in and above, are steam treated. The question now is, would this expose the wood to excessively high temperatures which may affect its mechanical properties ?

Early studies on the effect of steaming on the mechanical properties of wood were reported by HATT (1906). There is a range of temperature above which wood undergoes chemical degradation, and some loss in strength. The effects are dependent upon the duration as well as the maximum temperature of exposure.

MACLEAN (1953) studied the steaming of Douglas-fir, sitka spruce and Southern yellow birch under temperatures of 121 °C, 149 °C, 177 °C. He showed that the average module of rapture (MOR) and work to maximum load decrease with an increase in steaming temperature or steaming period. STAMM (1963) has shown that the strength loss in small thin test specimens steamed at 115 °C was 2.5 percent in 3 hours and 4.5 percent in 6 hours. This would be approximately the strength loss at radial positions near the surface of poles. Therefore, as indicated above, increasing the steaming period to sterilize the entire pole would probably not endanger the strength of the pole, since only the outer fibers are exposed to such high temperatures.

5.2 EXAMPLES SHOWING HOW THE PREDICTION EQUATIONS AND CHARTS ARE USED

Example 1.

How long must a 15 in. diameter air-seasoned Douglas-fir pole, which is initially at 10°C, be steamed to achieve two hours of its center-line temperature above 65.5 °C ?

Solution

Using equation (5.1) the minimum steaming time for an initial pole temperature of of 18 °C is

$$t_{stm1} = 0.025\ (15)^2 = 5.625 \text{ hr}$$

From equation (5.3) for the given initial pole temperature of 10 °C the minimum steaming time will be

t_{stm2} = 5.625 - (0.0118 (15) - 0.095) (10 - 18) = 6.28 or approximately 6 hours and 17 minutes.

The pole reaches at the required temperature (equation 5.4)

$$\text{Time} = \frac{1}{1.4\,(15) - 35}\,(10) \quad + \quad 0.118\,(15)^{1.68} = \; 10.45 \text{ hr.}$$

Example 2

Date given :

Initial pole temperature, T_o = 22 °C

Diameter of pole, D = 22 in.

Species - Larch which has thermal diffusivity = 0.008 ft^2/hr, MACLEAN (1952)

Required

Find the heating period and the total time needed to obtain two hours of the center line temperature above 65.5 °C.

Solutions

From equation (5.1) the minimum steaming time for an initial temperature of 18 °C is

$$t_{stm1} = 0.025\,(22)^2 = 12.1 \text{ hr.}$$

Using equation (5.3), for the given initial pole temperature of 22 °C, the steaming time will be:

$$t_{stm2} = 12.1 - (0.0118\,(22) - 0.095)\,(22 - 18) = 11.44 \text{ hr.}$$

With this steaming time the required time to reach 65.5 °C from equation (5.4) is

$$\text{Time} = \frac{1}{1.4\,(22) - 35}\,(22) \quad + \quad 0.118\,(22)^{1.68} = \quad 16.\ \text{hr}$$

Since these values are all for thermal diffusion coefficient of 0.0088 ft^2/hr, the corrected steaming time and required time for $\alpha = 0.008\ ft^2/hr$ will be

$$t_{stm} = 11.44\ (0.0088 / 0.008) = 12.58\ \text{hr}$$

$$\text{Time} = 16(\ 0.0088 / 0.008) = 17.6\ \text{hr}$$

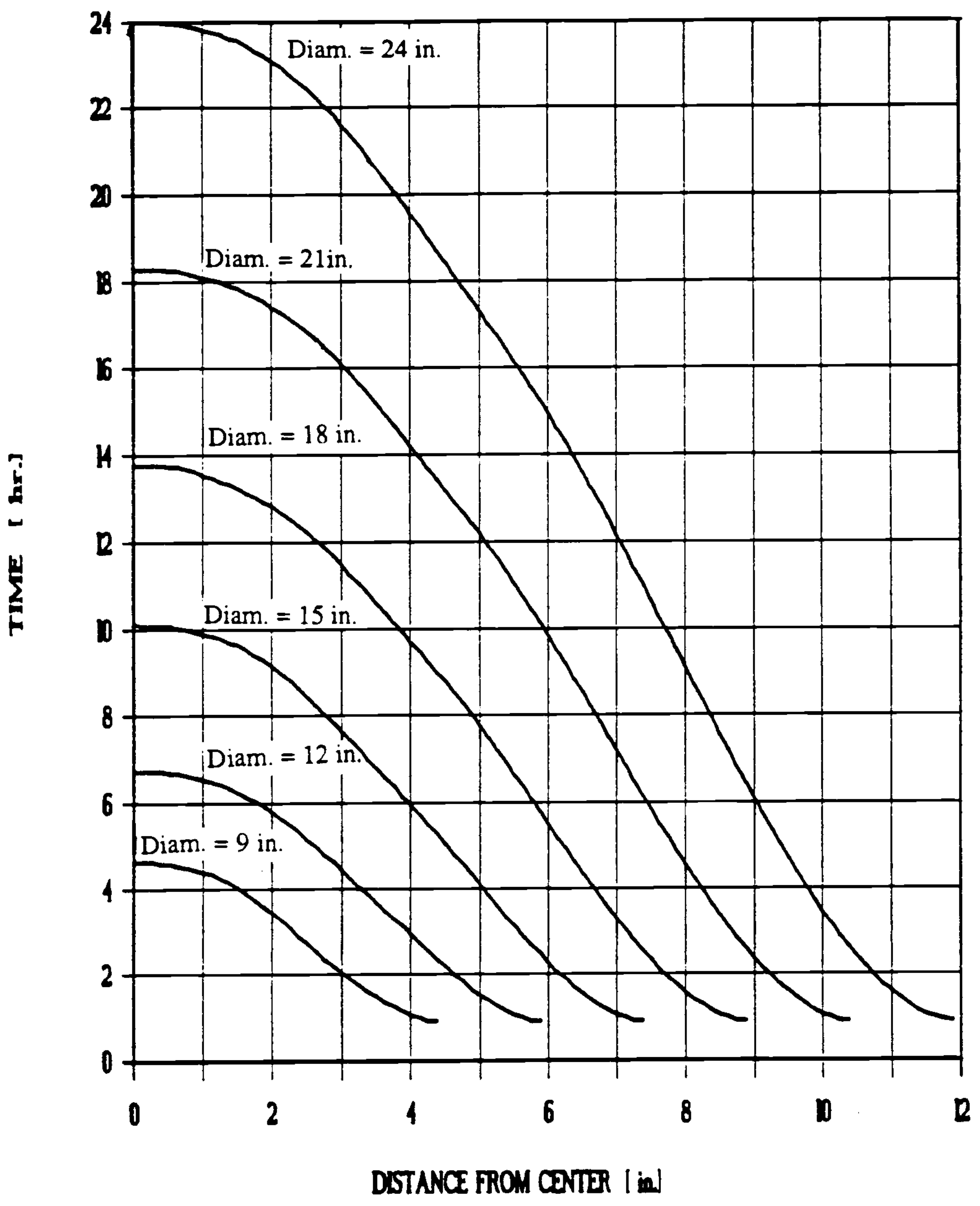


Figure 5.1 Time required for T_{max}= 65.5°C for various distances from the center of a pole treated with waterborne ACA and for assumed initial temperature of 18°C, steam temperature of 115 °C and final preservative temperature of 20 °C.

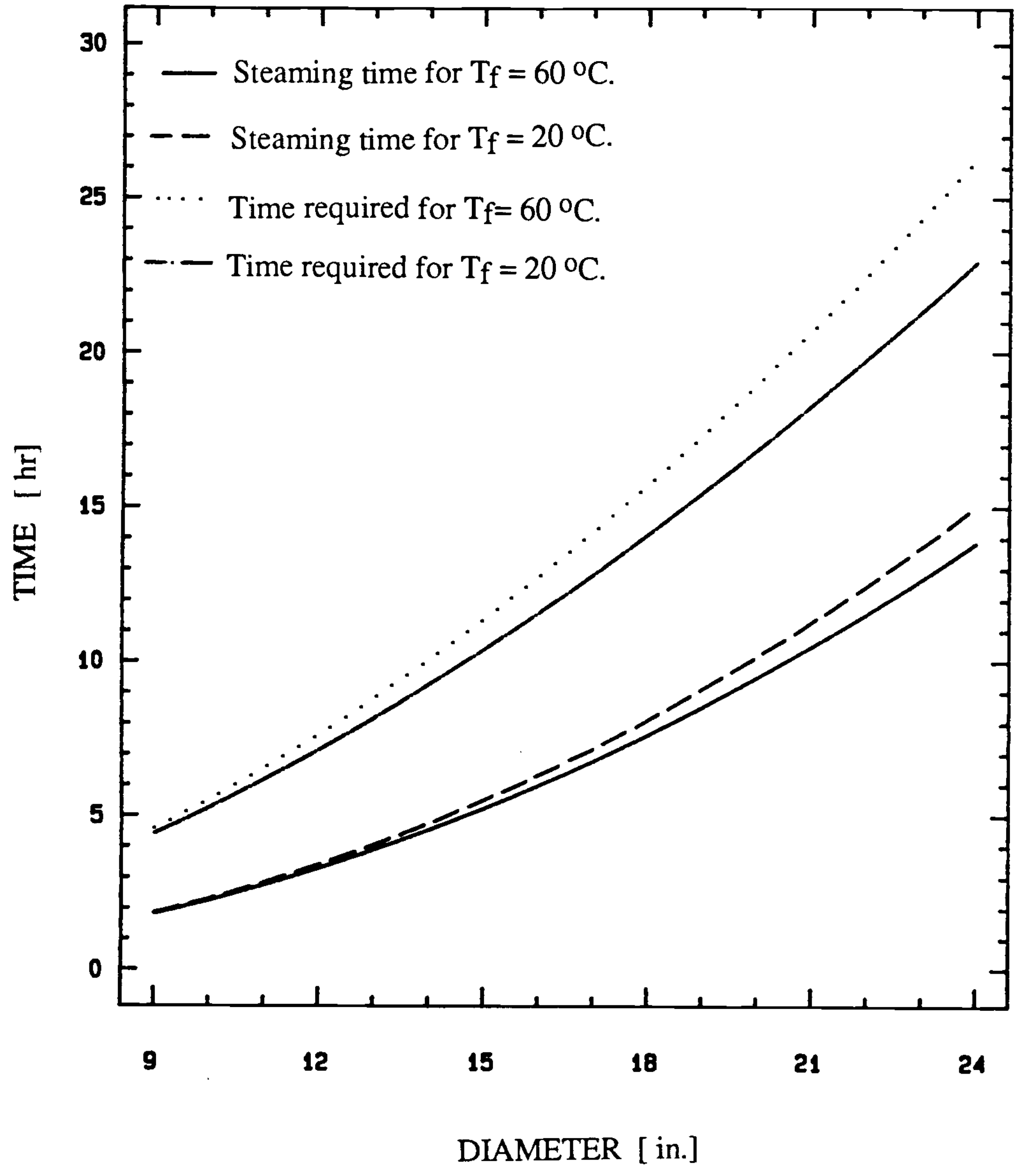


Figure 5.2 The minimum required steaming time to achieve two hours of the center line temperature above 65.5°C versus the diameter of the pole, treated with waterborne ACA for an assumed initial pole temperature of 18 °C, steam temperature of 115 °C and final preservative temperature of 20 or 60 °C.

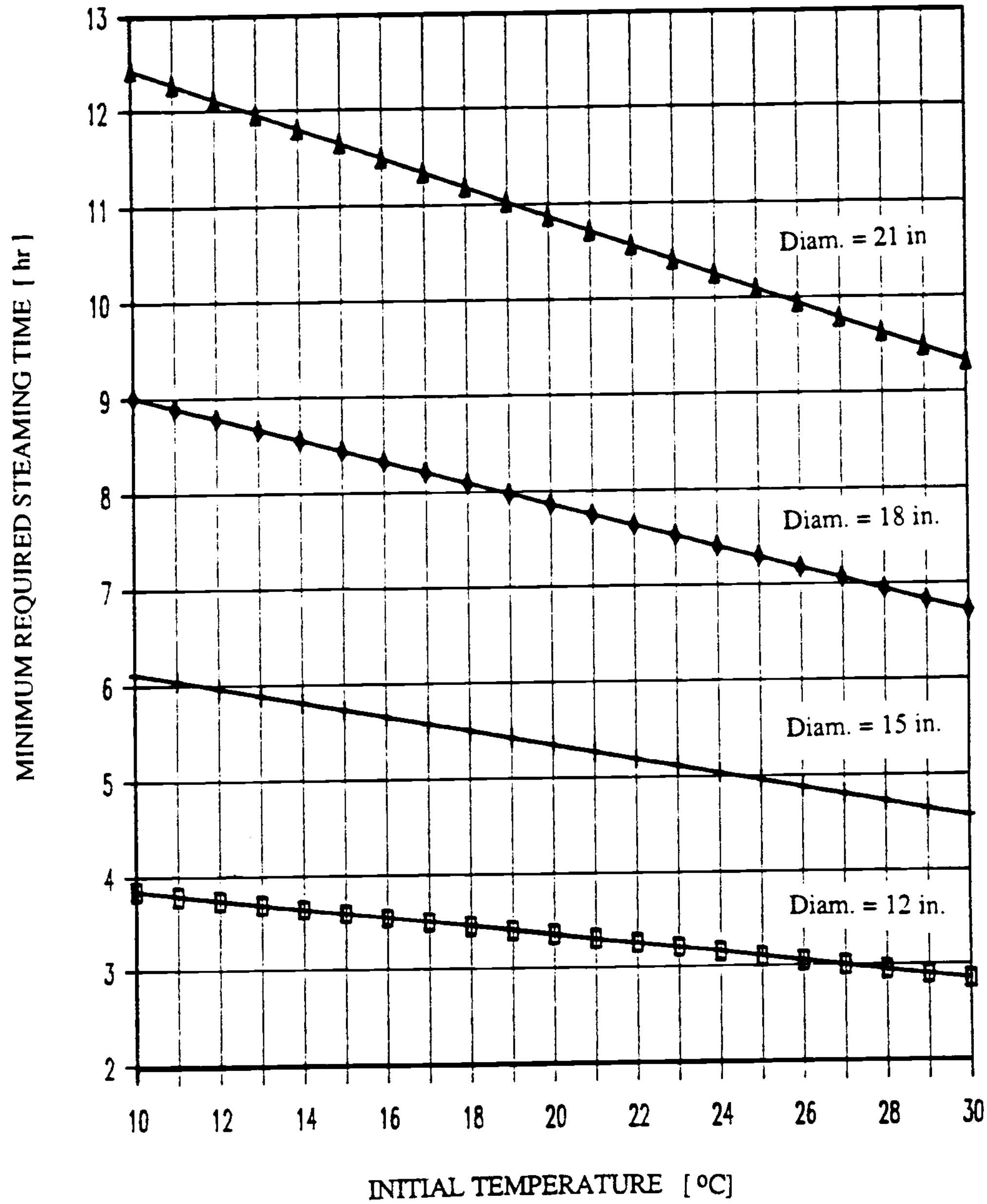


Figure 5.3 The minimum required steaming time to achieve two hours of center line temperature above 65.5°C versus initial temperature of poles treated with waterborne ACA for steam at a temperature of 115°C and final preservative temperature of 20°C.

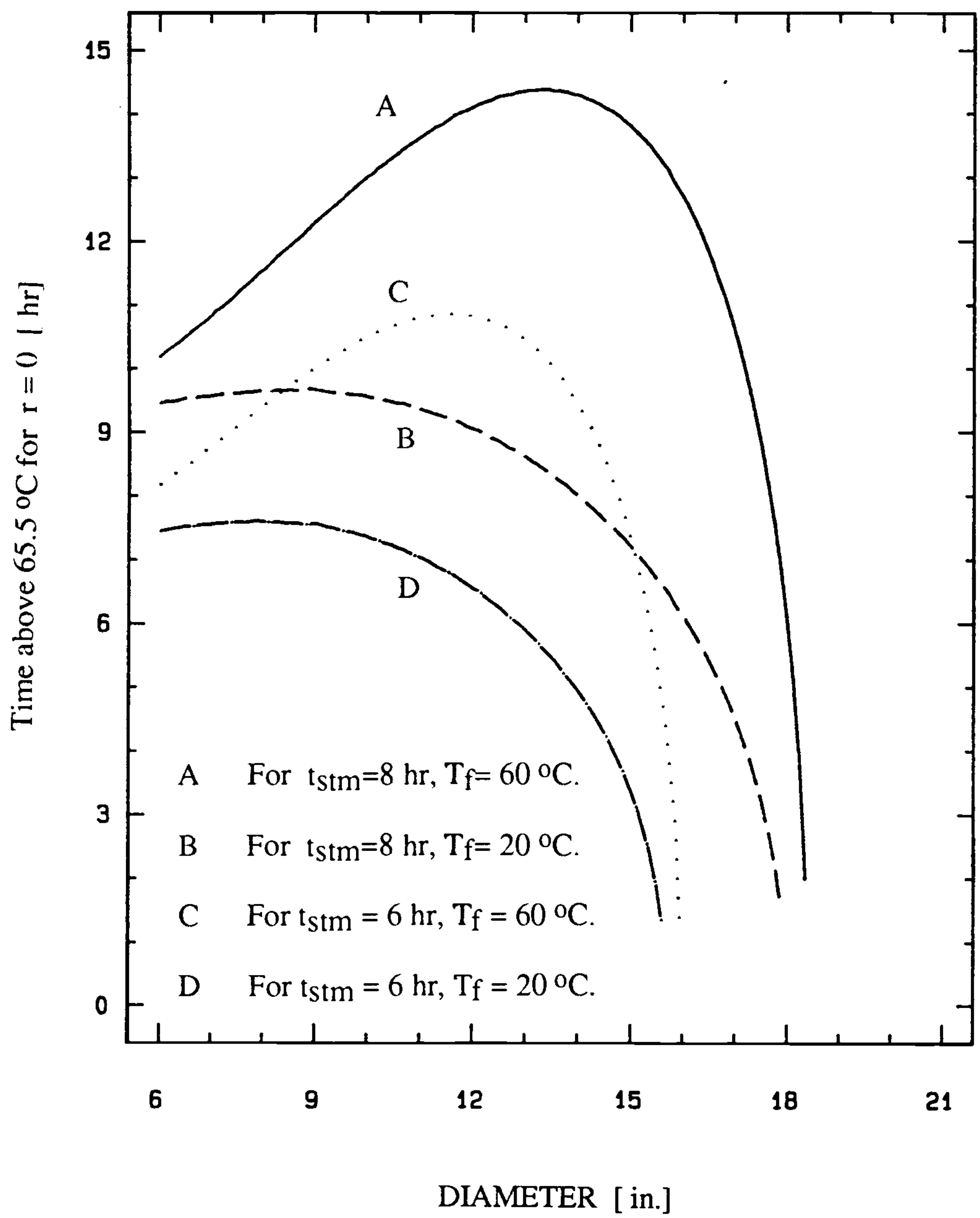


Figure 5.4 The time the center line temperature remains above 65.5 °C for 6 or 8 hour steaming versus the diameter of the poles which are initially at 18 °C and treated with waterborne ACA at 20 or 60 °C.

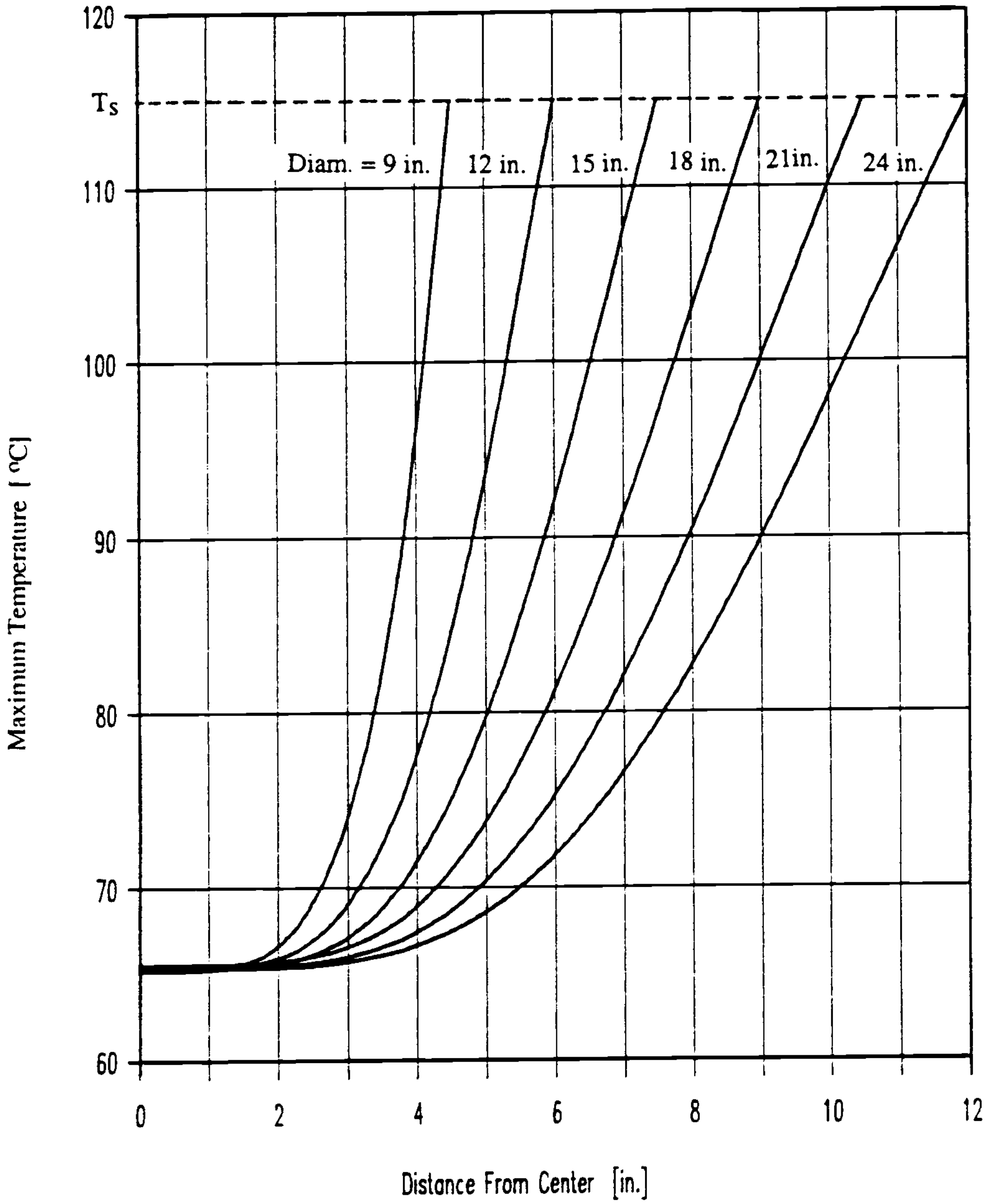


Figure 5.5 The maximum temperature reached in the interior of poles with diameter ranging from 9 to 24 in. when the pole is heated until the center line reaches approximately T_{max} = 65.5 °C.

CHAPTER 6.0

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

Modeling temperature-time-location relationships in round timbers during heat sterilization and pressure treatment is a complex problem. The process is not fully understood and there are a number of unanswered questions. This complexity makes it difficult to tailor a single treatment program that is suitable for various operational and climatic conditions. Bearing in mind the limitations of developing a model that can be used for generally acceptable prediction, the present method of analysis nevertheless brings some interesting facts to light. Following are some general conclusions from the present study :

- the standard six hour steaming time, currently used by the preservative industries was found to be too short to bring large diameter poles (poles larger than 15 in. in diameter) to the required sterilization condition. Therefore, longer steaming time is highly recommended according to the estimates provided by Eqn.(5.2) and (5.3).

- The recommendations by DOST,1984, for time-depth relation was questionable since it does not include the diameter of the poles in a simplified time-temperature relationship.

- Most of the earlier work was done before computers came into use and it was important then to make assumptions that simplify the computation involved, for example, step change boundary conditions. These assumptions were found to agree poorly with measurements and were a limitation on the accuracy of the results. By including elements in the model that account for heating up time and gradual cooling rates a better prediction was obtained.

- The large number of factors that are necessary to evaluate the required steaming time make it difficult to show all these effects on charts. Therefore, it is important to develop process simulation software to help engineers in the pole treatment industry to predict adequate treatment conditions.

6.2 RECOMMENDATIONS FOR POSSIBLE FUTURE WORK

1) Though this study is based on a large set of data taken from industrial equipment, the poles used for the study had low moisture contents in a narrow range. The effects of higher moisture content on the model parameters is not well known. Additional data with poles with a wide range of moisture content are needed to understand and characterize these effects.

2) Research efforts are also needed to better understand the mechanistic process involved in using different heating media, for example heating with steam, air or hot preservatives. What is known so far is only a qualitative comparison of the different heating media.

3) Until now there is not full agreement on the requirements for sterilizing the poles sufficiently. CHEDISTER (1937,1939) suggested the wood should be heated above 65.5^{o}C for 90 minutes. The Rural Electrification Authority purchase specification (1982) requires not less than 2 hours. An agreement on this point is necessary to to make a clear operational goal.

4) Another important point which seems to be overlooked in all the modeling work is the collective effect of the pile of poles; i.e., the geometry, number and sizes of poles in a single charge. There needs to be a more fundamental approach to characterize these collective effects of poles as well as differences due to type or size of cylinder used.

SYMBOLS USED

a_i - ith parameter value

Bi - Biot number = $k / C_p \rho$ [-]

C_p - specific heat [cal / gm ^oC]

D - diameter of pole [in.]

F - a test statistic used to compare variances from two normal distributions

k_c - rate of surface cooling after steaming, for Model IIB [^oC/hr]

k_1 - rate of cooling of the surface during vacuuming, for Model IIC [^oC/hr]

k_2 - rate of cooling of the surface in early the pressure period, Model IIC [^oC/hr]

F_o - Fourier number = dimensionless time = $\alpha t / R^2$ [-]

h - surface heat transfer coefficient [cal / ^oC cm^2]

J_o - Bessel's Function of the first kind of order zero

J_1 - Bessel's Function of the first kind of order one

LRT- likelihood ratio test

MR - dimensionless relative thermal resistance = $\kappa / R h$ [-]

M - moisture content [%]

N - number of data points [-]

p - number of parameter in a model [-]

r - radial location in a pole measured from the center line [in.]

R - radius of pole [in.]

S - residual sum of squares

s^2 - sample variance

T - temperature at an interior location of a pole during preservative treatment [^oC]

T_f - the final preservative temperature [^oC]

T_{mid}- the average temperature between the steam temperature and the temperature of the preservative [^oC]

T_o- initial temperature of a pole [^oC]

T_p - temperature prediction for mean parameter values [^oC]

T_s - temperature of the steam used for conditioning the poles [^oC]

t - time measured from the opening of the steam valve for steaming [hr]

t_{above} - time the center of a pole remained above 65.5 ^oC during preservative treatment [hr]

t_{cl} - the total time required for the surface temperature to reach the final steady-state temperature [^oC]

t_{pr} - the time elapsed at which initial vacuuming stops and pressure is applied [hr]

t_{stm} - the minimum required steaming time to achieve two hours of the center-line temperature above 65.5 ^oC for the given pole size [hr]

t_{vc} - the time elapsed at which initial vacuuming starts [hr]

v - degrees of freedom = n - p [-]

Z - dimensionless radius = r / R [-]

GREEK LETTERS

α - thermal diffusivity [ft^2 / hr]

α^* - significance level [-]

β_n - Roots of a particular characteristic equation [-]

ε - error= true value - measured value

κ = thermal conductivity [cal / ^oC cm]

ρ = density of wood [gm/ cm^3]

τ_d - the time delay needed for warming up [hr.]

σ - the standard error of an estimate

SUBSCRIPTS :

i = value for ith data point.

e = extra

NH = null hypothesis

AH = alternative hypothesis

BIBLIOGRAPHY

ANON, REA, Specification for Wood Poles, Studs and Anchore Logs, USDA, Rural Electrification Administration Bul. 44-2:345-1 46 pages (1982)

American National Standards Association , Specification for Wood Poles, ANSI 05.1 - (1979).

BARD, Y., Non-Linear Parameter Estimation, Academic Press, New York (1974).

BAILEY, I. W. "The Effect of the Structure of Wood Upon Its Permeability," Amer. Railway Engineering Assoc. Bulletin. No 174, 15 : 835-853 (1915).

BARNES, H. M. and J.E WINARIDY, " Effects of Seasoning and Preservatives on the Properties of Treated Wood," Amer. Wood Preservers' Assoc. Proc., 82 : 95 - 104 (1986).

BATES, D.M. and D. G. WATTS, Nonlinear Regression Analysis and Its Applications, John Wiley & Sons Inc., New York (1988).

BROWNLEE, K. A. Statistical Theory and Methodology in Science and Engineering, 2nd Edition, John Wiley & Sons Inc., New York (1965).

CHANG, H. L. and J. E. WINARIDY, " Effects of Steaming Ponderosa Pine on Its Mechanical and Chemical Properties," Amer. Wood Preservers' Assoc. Proc. 70 : 257 - 264 (1986).

CARSLAW, H. S. and J. C. JAEGER, Conduction of Heat in Solids, 2nd ed. Oxford Clarendon Press, London. (1959).

CHIDESTER, M. S.. "Temperatures Necessary to Kill Fungi in Wood," Amer. Wood Preservers' Assoc. Proc. 33 : 316 - 324 (1937).

CHIDESTER, M. S. "Further Studies on Temperatures Necessary to Kill Fungi in Wood," Amer. Wood Preservers' Assoc. Proc. 35 : 319 - 324 (1939).

DOST, W. A., "Internal Pole Temperature During ACA Treatment of Utility Poles," Amer. Wood Preservers' Assoc. Proc. 80:1-12 (1984).

DRAPER, N. R. and H. SMITH, Applied Regression Analysis, 2nd ed., John Wiley & Sons Inc., New York (1981).

ERICKSON, H. E., SCHMITZ, H. and GORTNER, R. A. "The Permeability of Wood to Liquids and the Factors Affecting the Rate of Flow," University of Minnesota Agricultural Experiment Station. Technical Bulletin No 122 (1937).

ESLYN, W. E., " Utility Pole Decay II. Basidiomycetes Associated with decay in poles," Wood Science and Technology 4: 97 - 103 (1970).

ESTEP, E. M., and R. D. GRAHAM, " Effect of Incising on Checking of Air-Seasoned and Boulton-Seasoned, Pressure-Treated Douglas-fir Poles," Forest Research Laboratories, OSU (1966).

GRIFFIN, G. J. " Bordered Pits in Douglas-Fir : A Study of the Position of the Torus in Mountain and Lowland Species in Relation to Creosote Penetration," Journal of Forestry 17: 813 - 822 (1919)

GALLANT, R., " Non-Linear Regression ," American Statistician vol. 29, pg. 73-81 (1975).

GURNY, H. P. and J. LURIE, "Charts of Estimating Temperature Distributions in Heating of Cooling Solid Shapes," Ind. Eng. Chem. 15, 1170 (1923).

HART, J. F., E. W. CHENEY, C. L. LAWSON, H. J. MACHLY, C. K. MESZTENYI, J. R. RICE and H. G. THACHER, JR, Computer Approximations, John Wiley & Sons Inc., New York (1968).

HATT, W. K. " Experiments on the Strength of Treated Timbers ," USDA. Forest Serv. Circ. No 39, (1906).

HUNT, G. M., "Temperature Changes in Wood Under Treatment," Amer. Wood Preservers' Assoc. Proc. 11: 85 - 99, illus. (1915).

HUNT, G. M., "Report of Committee on Steam Treatments," Amer. Wood Preservers' Assoc. Proc. 22, 225 - 230, (1926).

KENDEL, M. G. and A. STAURT, The Advanced Theory of Statistics , vol. 2, Hafner Pub. Co., New York (1958).

KENNEDY, W. J. and J. E. GENTLE, Statistical Computing, M. Dekker, New York (1980).

KITTRELL, J. R., "Mathematical Modeling of Chemical Reaction, " Advances in Chemical Engineering, vol. 8, Academic Press, (1970).

KNUDSON, M. R., " Production of Treated Poles," Wood Pole Conference, Oregon State Collage, Corvallis, OR, (March 21 and 22 1960).

KOLLMANN, F. P., A. WILFRED and COTE Jr., Principles of Wood Science and Technology, Vol.1, Springer-Verlag, Berlin / Heidelberg (1968).

KOLLMANN, F. and L. MALMQUIST, "Untersuchungen Uber das Strahlungsverhalten Trockender Holzer," Holzer als Roh und Werkstoff 14(6) : 201-204 (1956).

LINDGREN, R. and M. MARCH , "Temperature, Moisture and Penetration Studies of Wood Stains," Technical Bulletin 807 (1942).

MATHEWOS, J. S., MORTON, C. S. and BESCHER, R. H. " Air-Seasoning of Red Oak Cross Ties," Amer. Wood Preservers' Assoc. Proc. 45: 216-230, illus. (1949).

MACLEAN, J. D., "Studies of Heat Conduction in Wood; Result of Steaming Green Round Southern Pine Timbers," Amer. Wood Preservers' Assoc. Proc. 26: 197-219. (1930).

MACLEAN, J. D., "Studies of Heat Conduction in Wood. Part II : Results of Steaming Green Sawed Southern Pine Timers," Amer. Wood Preservers' Assoc. Proc. 28: 303-330 (1932).

MACLEAN, J. D., "Temperature in Green Southern Pine Timbers after Various Steaming Periods," Amer. Wood Preservers' Assoc. Proc., 30: 355-373 (1935).

MACLEAN, J. D., "Thermal Conductivity of Wood," Trans. Amer. Soc. Heating and Ventilating Engineering. 47: 323 - 354 (1941).

MACLEAN, J. D., " Temperatures Obtained in Timbers When the Surface Temperature is Changed after Various Periods of Heating," Amer. Wood Preservers' Assoc. Proc. 42: 87-139 (1946).

MACLEAN, J. D., " Preservative Treatment of Wood by Pressure Methods," Agricultural Handbook No 40 USDA (1952).

MACLEAN, J. D., " Effects of Steaming on the Strength of Wood," Amer. Wood Preservers' Assoc. Proc. 49: 88 -172 (1953).

MAKU, T., "Studies on the Heat Conduction in Wood," Wood Research Bull. No 13. Wood Research Institute, Kyoto University, Kyoto, Japan. (1954).

MANUK, C., R. TURTON and O. LEVENSPIEL, "Unsteady State Heat Transfer to Variously Shaped Objects," Heat Transfer Engineering, vol. 8, No 3-4 (1984).

MORRELL, J. J., M. E. CORDEN, M. A. NEWBILL and P. PRZYBYLOWICZ, "Controlling Decay Fungi Colonizing Air-Seasoned Douglas-fir Heart-Wood with High Temperature Exposures," Proceeding West Coast Dry Kiln Club. 1985: 90-96 (1985).

MORRELL, J. J., M. E. CORDEN, R. D. GRAHAM, B. R. KROPP, P. PRZYBYLOWIC, S. M. SMITH and C. M. SEXTON , " Basidiomycete colonization of air - seasoned, Douglas-fir poles," Amer. Wood Preservers' Assoc. Proc. 83: 284 - 296 (1987).

NEWBILL, M. A., J. J. MORELL and K. LEVIEN, "Internal Temperature in Douglas-fir Poles During Treatment with Ammoniacal Copper Arsenate or Pentachlorophenol," Amer. Wood Preservers' Assoc. Proc. 84: 48 - 54 (1988).

NEWMAN, A. B., " Heating and Cooling Rectangular and Cylindrical Solids," Industrial Eng.Chem. Vol. 28: No 5, 545- 553 (1936).

North Eastern Wood Utility Council, Inc. Economics in Seasoning Aug. (1948).

OZISIK, M. N., Heat Conduction, Wiley-Interscience Publication, New York (1980).

PANKEL, E., "Pretreatment for the Protection of Southern Yellow Pine Poles During Seasoning," Amer. Wood Preservers' Assoc. Proc. 59, p188 (1963).

PRESS, W. H., B. P. FLANNERY, S. A. TEAKOSKY and W. T. VETTERLING, Numerical Recipes: the Art of Scientific Computing, Cambridge University Press., Cambridge (1986).

PRZYBYLAWICZ,P. R, B. R. KROPP, M. E. CORDEN and R. D. GRAHAM "Colonization of Douglas-fir by Decay fungi during air-seasoning and its effects on wood strength," Forest Products Journal 37(4): 17 - 23 (1987).

RATKOWSKY, D. A., Non-Linear Regression Modeling, A unified practical approach M. Dekker, New York (1983).

RELLY,P. M., G. E. BLAU, "The Use of Statistical Method to Build Mathematical Model of Chemical Reacting Systems," Canadian Journal of Chemical Engineering, Vol. 52, (1974).

RICE, J. A., Mathematical Statistics and Data Analysis, Wadsworth & Brooks Advanced Brooks & Software Pacific Grove, CA. (1988).

ROSENBROCK, H. H. and C. STOREY Computational Techniques of Chemical Engineers , 1st ed., Pergamon Press, New York (1966).

SCARTH, G. W., " The Structure of Wood and its Penetrability," Technical Association Section of the Paper Trade Journal 86: 53 - 58 (1928).

SCHEIT, M., " Die Wasserbewegung im Holze," Bot. Zeit. (March 1884).

SIAU, J. F., Flow in Wood, Syracuse, Syracuse University Press, New York (1971).

SIAU, J. F., R. W. DAVIDSON, J.A. MEYER and C. SKAAR, "A Geometrical Model for Wood-Polymer Composites ", Wood Science 1(2) : 116-128 (1968).

SMITH, S. M., R. D. GRAHAM and J. J. MORELL," Influence of air-seasoning on fungal colonization and strength properties of Douglas-fir sections," Forest Products Journal 37(9) : 45 - 48 (1987).

STAMM, A. J., " Effect of Chemical Treatment on Wood Permeability, " Industrial Engineering Chemistry 24 : 51 - 53, (1932)

STAMM, A. J., Passage of Liquids, Vapors and Dissolved Materials Through Softwood, U.S. Department of Agriculture Technical Bulletin No 329 (1946).

STAMM, A. J. and E. E. HARRIS, Chemical Processing of Wood, Chemical Publishing Co. Inc., New York (1953).

STONE, C. D., " A Study on the Border Pits of Douglas-fir with Reference to the Permeability of the Wood to Liquids," Ph.D. Thesis, University of Washington. (1936).

TAYLOR, J. A., " Pretreatment Decay of Poles", Amer. Wood Preservers' Assoc. Proc., 76: 227-245 (1980).

TAYLOR, J. A., "Kiln Drying of Poles as a Means of Solving the Problem of Pretreatment Poles," International Research Group on Wood Preservation, IRG/ WP/1263 (1985).

TEESDALE, C. H., " Relative Resistance of various conifers to Injection with creosote," U.S.A.D. Bulletin, No 101 (1914).

VERRALL, A. F., " Absorption and Penetration of Preservatives Applied to Southern Pine Wood by Dips or Short Periods Soaks," Southern Forest Experiment Station Occasional Paper No 157 (1957).

WEISBERG, S. Applied Linear Regression , 2nd ed., John Wiley & Sons Inc., New York, (1985).

WEST, W. I., " Structure of Wood," Wood pole conference, Oregon State Collage, Corvallis, Oregon. March 21-22 (1960).

WETCH, A. F.," Wood Pole Maintenance, " Amer. Wood Preservers' Assoc. Proc., vol. 63: 198-202 (1967).

WIRKA, R. M., " Temperature and Moisture Changes in Wood Under Steaming Treatment ," Amer. Wood Preservers' Assoc. Proc., Exhibit A. 20: 285 - 303 (1924).

ZABEL,R. A., F. F. LOMARD and A. M. KENDERES, "Fungi Associated with Decay in Treated Douglas-fir Transmission Poles in the Northern United States," Forest Products Journal , 30(4): 51-56 (1980).

APPENDICES

APPENDIX A

SOLUTIONS FOR HEAT CONDUCTION PROBLEMS WITH TIME DEPENDENT BOUNDARY CONDITIONS

This appendix contains the solution of nonhomogeneous boundary-value problem of heat condition in the cylindrical coordinate system using Green's function. The model solutions shown in Chapter 3 are special cases of this general equation.

Let a solid cylinder, $0 \leq r \leq R$, be initially at temperature F(r). For times $t > 0$ there is heat generation in the medium at a rate of g(r,t) [W / m^3] while the boundary surface at r=R is kept at temperature f(t). The mathematical formulation of this problem is given as:

$$\partial^2 T / \partial r^2 + 1/r\, \partial T / \partial r + g(r,t) / \kappa = 1 / \alpha\, \partial T / \partial r$$

$$\text{in} \quad 0 \leq r \leq R,\ t > 0 \ldots\ldots\ldots\ldots (A)$$

$$T = f(t) \qquad \text{at } r = R, \text{ for } t > 0$$

$$T = F(r) \qquad \text{for } t = 0, \text{ in } 0 \leq r \leq R$$

The dimensionless parameters used are: $F_o = \alpha t / R^2$, $Z = r / R$

Using the appropriate Green's function, the expression for the temperature distribution T(r,t) in the cylinder for times $t > 0$ is obtained (from Eqn. (6-73), pg. 228, M. N. Ozisik , 1980) :

$$T(r,t) = \frac{2}{R^2} \sum_{n=1}^{\infty} \exp(-F_o\beta^2{}_n) \frac{J_o(\beta_n Z)}{J^2{}_1(\beta_n)} \int_{r'=0}^{R} r' J_o(\beta_n r'/R)\, F(r')\, dr'$$

$$+ \frac{2\alpha}{kR^2} \sum_{n=1}^{\infty} \exp(-F_o\beta^2{}_n) \frac{J_o(\beta_n Z)}{J^2{}_1(\beta_n)} \int_{\tau=0}^{t} \exp(-F_o\beta^2{}_n)\, d\tau$$

$$\int_{r'=0}^{R} r' J_o(\beta_n r'/R) g(r',\tau)\, dr' \quad + \quad f(t)$$

$$- \; 2 \sum_{n=1}^{\infty} \frac{J_o(\beta_n Z)}{\beta_n J_1(\beta_n)} \Big[f(0) \exp(-F_o\beta^2{}_n) + \int_0^t \exp(-\alpha\beta^2{}_n R^2 (t-\tau))\, df(\tau) \Big]$$

where βn 's are the positive roots of $J_o(\beta_n) = 0$.

Special cases are obtainable from this solution.

Case 1. Cylinder is initially at zero temperature; there is no heat generation, the boundary surface at $r = R$ is maintained at a constant temperature T_s. For this special case:

$F(r) = 0$, $g(r,t) = 0$, and $f(t) = T_s$.

Equation (A) reduces to [Eqn. 6-74, M. N. Ozisik , 1980]

$$T(r,t) = T_s - 2\; T_s \sum_{n=1}^{\infty} \frac{J_o(\beta_n Z)}{\beta_n J_1(\beta_n)} \exp(-F_o\beta^2{}_n) \quad \ldots\ldots\ldots\ldots\ldots (C)$$

Case 2. Cylinder is initially at zero temperature; there is no heat generation, the boundary surface at $r = R$ is kept at temperature $f(t)$ [Eqn. (5-59a), M. N. Ozisik , 1980] :

$$F(r) = 0, \quad \text{and} \quad g(r,t) = 0,$$

$$T(r,t) = f(t) - 2 \sum_{n=1}^{\infty} \frac{J_0(\beta_n Z)}{\beta_n J_1(\beta_n)} \left[f(0)\exp(-F_o\beta^2_n) + \int_0^t \exp(-F_o\beta^2_n) \right]$$

for $f(t) = \psi t$ where ψ = constant

$$T(r,t) = \psi \left[t - \frac{R^2 - r^2}{4\alpha} \right] + \frac{2\psi}{\alpha} \sum_{m=1}^{\infty} \exp(-F_o\beta^2_n) \frac{J_0(\beta_n Z) R^2}{\beta^3_n J_1(\beta_n)} \quad \ldots (D)$$

Case 3. Cylinder is initially at zero temperature; there is no heat generation and heat conducted to the boundary surface is equal to the heat dissipation by convection from the surface into the surrounding, i.e.

$$F(r) = 0, \qquad g(r,t) = 0,$$

$$\partial T / \partial r + HT = 0 \quad \text{at} \quad r = R, \quad t > 0$$

where $H = h / \kappa$

The solution for equation (A) become (from Equation (3-63), pg. 102 , Heat conduction, M. N. Ozisik, 1980) :

$$T(r,t) = 2 \sum_{n=1}^{\infty} \exp(-F_o \beta^2_n) \frac{J_o(\beta_n Z)\ \beta_n^2}{(\beta^2_n + Bi^2)\ J^2_o(\beta_n)} \int_0^R r'\ J_o(\beta_n r' / R) F(r') dr' \qquad \text{.......... (E)}$$

where β_n's are the positive roots of

$$\beta_n J_1(\beta_n) = Bi\ J_o(\beta_n)$$

$$Bi = H R = h R / \kappa$$

For the special case of $F(r) = T_o$ = constant, the solution of equation (E) reduces to :

$$T(r,t) = 2 T_o \sum_{n=1}^{\infty} \exp(-F_o \beta^2_n) \frac{J_o(\beta_n Z)\ \beta_n^2}{(\beta^2_n + Bi^2) J^2_o(\beta_n)} \qquad \text{........ (F)}$$

APPENDIX B: COMPUTER PROGRAM

```
$LARGE
      PROGRAM FIT
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C *                                                             *
C *           H E A T   C O N D U C T I O N                     *
C *                                                             *
C * * * * * * * * * * * MAIN PROGRAM * * * * * * * * * * * * * *
C
C     THIS FORTRAN PROGRAM SOLVES FOR RADIAL TEMPERATURE
C     DISTRIBUTION RESULTING FROM CONDUCTION HEAT TRANSFER.
C     BOUNDARY CONDITIONS ARE EITHER THE SURFACE TEMPERATURE
C     PROFILE ASSUMED FOR MODEL IIC OR WITH A CONSTANT HEAT
C     TRANSFER COEFFICIENT AT THE SURFACE.  THE CONSTANT SURFACE
C     TEMPERATURE PROBLEM IS SOLVED IN THE DIMENSIONLESS
C     ACCOMPLISHED TEMPERATURE CHANGE AS SHOWN IN FIG 11.1-2 IN
C     BIRD, STEWART AND LIGHTFOOT, 'TRANSPORT PHENOMENA',
C     PG 357. THE HEAT TRANSFER COEFFICIENT CONDITION IS
C     SOLVED AS DEFINED IN A.B. NEWMAN'S PAPER, IND. ENG. CHEM.
C     VOL. 28, NO. 5PG 545.  BETAN(I) VALUES ARE FROM
C     CARSLAW AND JAEGER TABLE III OF APPENDIX IV,
C     PG 493 OF 'CONDUCTION OF HEAT IN SOLIDS'.
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
C     DEFINITIONS OF FORTRAN VARIABLES
C     ALPHA -  THERMAL DIFFUSIVITY
C     BETAN -  ROOTS OF BESSEL FUNCTIONS
C     DIMLSR - DIMENSIONLESS RADIAL PISITON = R/RAD
C     R -  RADIAL POSITION, DENOTED AS r IN MODEL SOLUTIONS.
C     RAD -  RADIUS OF THE POLE,DENOTED AS R IN MODEL SOLUTIONS
C     OBS(I) - VECTOR OF DATA VALUES
C     ERR(I) - VECTOR OF ERROR VALUES
C     PAR(I) - THE PARAMETER VECTOR
C     NPAR(I) - NUMBER OF PARAMETERS
C     SL1 - THE RATE OF SURFACE COOLING DURING VACUUMING
C     SL2 - THE RATE OF SURFACE COOLING DURING THE INITIAL
C           PRESSURE PERIOD
C     TEMDAT(I) - VECTOR OF COMPUTED TEMPERATURE VALUES
C     TINIT - INITIAL TEMPERATURE OF THE POLE
C     TBATH - THE MAXIMUM SURFACE TEMPERATURE=STEAM TEMPERATURE
C   TII    - THE SURFACE TEMPERATURE AFTER THE INITIAL VACUUMING
C   TFIN   - THE FINAL PRESERVATIVE TEMPERATURE
C   TTDLAY - TIME DELAY
C   TTSTM  - LENGTH OF STEAMING TIME
C   TTVAC  - TIME AT THE END OF VACUUMING
C   TTCOOL - LENGTH OF TIME WHEN THE SURFACE TEMPERATURE COOLS
C            DOWN TO THE TEMPERATURE OF THE PRESERVATIVE DURING
C            INITIAL PRESSURE PERIOD.
C
```

```
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
       PARAMETER (MAXRTS = 100)
       PARAMETER (NOBMX =  200)
       PARAMETER (NPARMX = 4)
C      PARAMETER (NSCMX = 6+2*NOBMX+NPARMX*(17+2*NPARMX+NOBMX))
       PARAMETER (NSCMX = 1306)
C
       DIMENSION ISC(20),SC(NSCMX),PAR(NPARMX)
       DIMENSION BETAN(MAXRTS),OBS(NOBMX),TIME(NOBMX),
      *           TEMDAT(NOBMX)
C
       CHARACTER*10 NFILE
       CHARACTER*1 IDUM
C
       COMMON TTSTM,TFIN,TINIT
       COMMON/SETUP/R,TBATH,RAD,DIMLSR
       COMMON/PASS/BETAN
C
       WRITE(*,*)'ENTER TEMPERATURE DATA FILE NAME'
       READ(*,1) NFILE
     1 FORMAT(A)
       OPEN(1,FILE=NFILE,STATUS='OLD')
       REWIND (1)
          DO 2 I=1,MAXRTS
          READ(1,*,END=3) TIME(I),OBS(I)
     2    CONTINUE
     3    NOB = I-1
       CLOSE (1)
C
       WRITE (*,*)'ENTER 0 FOR PROBLEM SPECIFICATIONS IN FIT.DAT'
       READ(*,*) IDAT
C      INPUT SECTION FOR THE INITIAL GUESES OF PARAMETERS
       IF (IDAT.EQ.0) THEN
          OPEN(1,FILE='FIT.DAT',STATUS='OLD')
          REWIND (1)
          READ(1,*)  TBATH,ALPHA,TTDLAY,SL1,SL2
          CLOSE (1)
       ELSE
         WRITE(*,*)'ENTER TEMP OF HEATING BATH OR STEAM, DEG C '
          READ(*,*) TBATH
          WRITE(*,*) 'ENTER THERMAL DIFFUS ALPHA,TTDLAY,SL1,SL2'
          READ(*,*)  ALPHA,TTDLAY,SL1,SL2
       ENDIF
          WRITE(*,*) 'ENTER INITIAL TEMPERATURE OF POLE, DEG C'
          READ(*,*) TINIT
          WRITE(*,*)'ENTER RADIUS OF POLE IN FEET'
          READ (*,*) RAD
          WRITE(*,*)'RADIAL POSITION OF THERMOCOUPLE FROM CENTER'
          READ (*,*) R
       WRITE(*,*) 'ENTER THE LENGTH OF THE STEAMING TIME, HR'
       READ(*,*) TTSTM
```

```
      WRITE(*,*) 'ENTER THE FINAL PRESERVATIVE TEMPERATURE'
      READ(*,*) TFIN
C
 11       WRITE(*,10)
 10       FORMAT(1X,'ENTER CHOICE OF BOUNDARY CONDITION :',
     1 //1X,5X,'(1)=BOUNDARY CONDITION AS ASSUMED MODEL IIC',
     2 /1X,5X,'(2)=CONSTANT HEAT TRANSFER COEFFICIENT,MODEL IB'
     3          /1X,5X,'          ENTER 1 OR 2 : ',$)
C
          READ(*,*)IBC
          IF (IBC.EQ.2) THEN
          WRITE(*,12)
 12       FORMAT(/,1X,'ENTER RELATIVE RESISTANCE = MR ',
     1          /,1X,'  = KPAR/(H*RAD) = ',$)
          READ(*,*) MR
          PAR(1) = ALPHA
          PAR(2) = MR
          NPAR = 2
          ENDIF
       ENDIF
C
       IF (IBC.EQ.1) THEN
          OPEN(1,FILE='BETA.INF',STATUS='OLD')
          REWIND (1)
          DO 22 I=1,60
             READ(1,*) BETAN(I)
 22       CONTINUE
       PAR(1) = ALPHA
       PAR(2) = TTDAT
       PAR(3) = SL1
       PAR(4) = SL2
       NPAR   = 4
       ENDIF
       DIMLSR = R/RAD
       NSC = 6+2*NOB+NPAR*(17+2*NPAR+NOB)
C
       WRITE(*,*)'ENTER 0 FOR PARAMETER SEARCH'
       WRITE(*,*)'       1 FOR LEAST SQUARES FIT'
       READ(*,*) ISRCH
C
C **************************************************
C  THE ONE PARAMETER (ALPHA) SEARCH OPTION
C **************************************************
       IF (ISRCH.EQ.0) THEN
          WRITE(*,*)'ENTER MIN VALUE OF ALPHA'
          READ(*,*) ALPMIN
          WRITE(*,*)'ENTER MAX VALUE OF ALPHA'
          READ(*,*) ALPMAX
          WRITE(*,*)'ENTER NUMBER OF ALPHA VALUES'
          READ(*,*) NUMALP
          DELALP = (ALPMAX-ALPMIN)/(NUMALP-1)
          OPEN(1,FILE='SEARCH.DAT',STATUS='NEW')
```

```
        DO 200 I=1,NUMALP
        PAR(1)= ALPMIN + DELALP*(I-1)
           CALL MODEL (PAR,TEMDAT,NOB,NPAR)
           SUMSQR = 0.
           DO 190 J = 1,NOB
           SUMSQR = SUMSQR + (TEMDAT(J)-OBS(J))**2
 190       CONTINUE
           WRITE(1,*) PAR(1),SUMSQR
 200    CONTINUE
        STOP
      ENDIF
C
C *********************************************
C       THE LEAST SQUARES FIT OPTION
C *********************************************
      CALL LSGEN (NOB,OBS,NPAR,PAR,ISC,SC,NSC)
      CALL MODEL (PAR,TEMDAT,NOB,NPAR)
C
      ERRI = 0.0
      SUMERR = 0.0
      SUMSIG = 0.0
      DO 300 I=1,NOB
         ERRI = ABS(OBS(I)-TEMDAT(I))
         SUMERR = SUMERR + ERRI
         SUMSIG = SUMSIG + ERRI*ERRI
  300 CONTINUE
      ERR = SUMERR/NOB
      SIGMA = (SUMSIG/NOB)
C
      WRITE(*,310) ERR
  310 FORMAT(1X,'AVERAGE ABS RESIDUAL = ',E11.5)
      WRITE(*,320) SIGMA
  320 FORMAT(1X,'AVERAGE RESIDUAL SQUARED = ',E11.5)
      WRITE(*,330) PAR(1)
  330 FORMAT(/,1X,'FITTED VALUE OF THERMAL DIFF,ALPHA = ',F10.6)
C     FOR MODEL IB
C
      IF(IBC .EQ. 2) THEN
      WRITE(*,340) PAR(2)
  340 FORMAT(1X,'FITTED VALUE OF REL RESIST,KPAR/H*RAD**2=
     *  ',F10.6)
C     FOR MODEL IIC
      ELSEIF(IBC .EQ. 1) THEN
      WRITE(*,331) PAR(2)
      WRITE(*,332) PAR(3)
      WRITE(*,333) PAR(4)
 331  FORMAT(/,2X,'DELAY TIME = ', F8.4)
 332  FORMAT(/,2X,'RATE OF COOLING DURING VACUUMING=',F10.6)
 333  FORMAT(/,2X,'RATE OF COOLING DURING INITIAL
     *  PRESS.=',F10.6)
      OPEN (1,FILE='FITTED.DAT',STATUS='NEW')
C
```

```
      WRITE(*,*)'HIT ''RETURN'' TO LIST DATA AND FITTED VALUES'
      READ(*,350)IDUM
  350 FORMAT(A)
      DO 400 I=1,NOB
         WRITE(1,390)TDAT(I),OBS(I),TEMDAT(I)
         WRITE(*,390)TDAT(I),OBS(I),TEMDAT(I)
  390    FORMAT(1X,3(F12.7,1X))
  400 CONTINUE
      CLOSE (1)
      END
C
C
            SUBROUTINE MODEL(PAR,TEMDAT,NOB,NPAR)
C
C     THIS SUBROUTINE IS USED TO FIND OPTIMAL ALPHA ALONE ORWITH
C      KPAR/(H*RAD) TO FIT POLE DATA (CYLINDRICAL COORDS.).
C      BETAN(I) VALUES ARE AS GIVEN IN
C      CARSLAW AND JAEGER TABLE III OF APPENDIX IV,
C      PG 493 OF 'CONDUCTION OF HEAT IN SOLIDS'.
C      THOSE TABULATED VALUES OF 'C' ARE USED AS INITIAL VALUES
C      FOR SUCCESSIVE USE OF NEWTON'S METHOD ON THE EQUATION
C      GIVEN IN TABLE III. ROOTS ARE SOLVED IN DOUBLE PRECISION.
C
      REAL MR
      DOUBLE PRECISION CPAR
      DIMENSION BETAN(300),PAR(4),TDAT(100),TEMDAT(NOB)
      COMMON/SETUP/R,TBATH,RAD,DIMLSR
      COMMON/PASS/BETAN,IBC
      COMMON TTSTM, TIFIN,TINIT
C
      WRITE(*,*) 'MODEL HAS BEEN CALLED'
C     THE BOUNDARY CONDITIONS USED
C     IBC=2 IS CONSTANT HEAT TRANSFER COEF.,= 1 IS FOR MODEL IIC
C
      IF( IBC .EQ. 2) THEN
      ALPHA = PAR(1)
      MR = PAR(2)
      ENDIF
C
      IBC = NPAR
C
      TIME = 0.
      NTERMS = 60
C
      IF(IBC.EQ.2) THEN
         OPEN (1,FILE='ALPHA1.DAT',STATUS='OLD')
         REWIND (1)
         CPAR = 1.D0/MR
   28    READ(1,*,END=29) CEST,A1
         IF (SNGL(CPAR).GT.CEST) GO TO 28
   29    CONTINUE
C
```

```
         CALL ROOTS (CPAR,A1,NTERMS)
      ENDIF
C
C
      IF(IBC .EQ. 1) THEN
      ALPHA  = PAR(1)
      TTDLAY = PAR(2)
      SL1    = PAR(3)
      SL2    = PAR(4)
      GO TO 98
      END IF
C     SL1 AND SL2 ARE SLOPES OF THE SURFACE TEMPERATURE
C     WHERE SL1 IS RATE OF TEMPERATURE DROP VACUUM IS PULLED
C     AND SL2 IS RATE OF TEMPERATURE DROP AFTER VACUUMING
98      TII      = TBATH + 2*SL1
        TTVAC    = TTSTM + 2.0
        TTCOOL   = TTVAC + (TFIN-TII)/SL2
        NTERMS   = 60
        DA       = (RAD**2 - R**2)/(4*ALPHA)
C
       DO 142 J = 1, 49
       TIME(J) = (J-1)/4.
       YR =  0.
       YR1 = 0.
       YR2 = 0.
       YR3 = 0.
       YR4 = 0.
C FOR TIME LESS THAN OR EQUAL TO THE TIME DELAY
C
        IF (TIME(J) .LE. TTDLAY) THEN
         TEMDAT(J) = TINIT
C FOR TIME BETWEEN THE DELAY TIME TILL THE STEAMING IS STOPPED
C
      ELSEIF (TIME(J) .LE. TTSTM) THEN
          XR = ALPHA*(TIME(J) - TTDLAY)/RAD**2
          DO 100 I = 1,NTERMS
          AN   = 1./(BETAN(I)*DBESJ1(BETAN(I)))
          EX   = DEXP(-XR*BETAN(I)**2)
          TERM = AN*EX*DBESJ0(BETAN(I)*DIMLSR)
          IF(DABS(TERM) .LT. 1.D-37) GO TO 101
          YR = YR + TERM
 100  CONTINUE
 101  YR = YR*2
      TEMDAT(J) = TINIT*YR + TBATH*(1.-YR)
C FOR TIME UNTILL VACUUMING IS COMPLETED
C
       ELSEIF (TIME(J) .LE. TTVAC) THEN
         XR1 = ALPHA*(TIME(J) - TTDLAY)/RAD**2
         XR2 = ALPHA*(TIME(J) - TTSTM )/RAD**2
         DO 123 I = 1,NTERMS
         AN  = 1./(BETAN(I)*DBESJ1(BETAN(I)))
```

```
          AN1=(DBESJ0(BETAN(I)*DIMLSR))/(BETAN(I)*
     *       DBESJ1(BETAN(I)))
       EX1    = DEXP(-XR1*BETAN(I)**2)
       EX2    = DEXP(-XR2*BETAN(I)**2)
          TERM1 = AN*EX1*DBESJ0(BETAN(I)*DIMLSR)
          TERM2 = AN1*EX2/((BETAN(I)/RAD)**2)
          IF (DABS(TERM2) .LT. 1.D-40) GO TO 221
          YR1 = YR1 + TERM1
 123      YR2 = YR2 + TERM2
 221      YR1 = YR1*2
         TEMDAT(J) = TINIT*YR1 + TBATH*(1.- YR1)
     *    + SL1*((TIME(J)-TTSTM)-DA) + 2*YR2*SL1/ALPHA
C
C FOR TIME UNTILL THE SURFACE TEMPERATURE COOLS DOWN TO THAT OF
C  THE PRESERVATIVE TEMPERATURE
C
        ELSEIF(TIME(I) .LE. TTCOOL) THEN
           XR1 = ALPHA*(TIME(J)  - TTDLAY)/RAD**2
           XR2 = ALPHA*(TIME(J)  - TTSTM)/RAD**2
           XR3 = ALPHA*(TIME(J)  - TTVAC)/RAD**2
        DO 124 I = 1, NTERMS
        AN = 1./(BETAN(I)*DBESJ1(BETAN(I)))
      AN1= (DBESJ0(BETAN(I)*DIMLSR))/(BETAN(I)*DBESJ1(BETAN(I)))
C
      EX1 = DEXP(-XR1*BETAN(I)**2)
      EX2 = DEXP(-XR2*BETAN(I)**2)
      EX3 = DEXP(-XR3*BETAN(I)**2)
           TERM1 = AN*EX1*DBESJ0(BETAN(I)*DIMLSR)
           TERM2 = AN1*EX2/((BETAN(I)/RAD)**2)
           TERM3 = AN1*EX3/((BETAN(I)/RAD)**2)
        IF (ABS(TERM3) .LT. 1.D-40) GO TO 345
           YR1 = YR1 + TERM1
           YR2 = YR2 + TERM2
 124     YR3 = YR3 + TERM3
 345      YR1 = YR1*2.
          TEMDAT(J) = TINIT*YR1 + TBATH*(1.- YR1)
     *   + (SL1*((TIME(J)-TTSTM)-DA)+2*YR2*SL1/ALPHA)
     *   - (SL1*((TIME(J)-TTVAC)-DA)+2*YR3*SL1/ALPHA)
     *   + (SL2*((TIME(J)-TTVAC)-DA)+2*YR3*SL2/ALPHA)
C
C FOR TIME AFTER THE SURFACE TEMPERATURE IS QUAL TO THAT OF THE
C  PERESERVATIVE
C
        ELSE
           XR1 = ALPHA*(TIME(J)  - TTDLAY)/RAD**2
           XR2 = ALPHA*(TIME(J)  - TTSTM)/RAD**2
           XR3 = ALPHA*(TIME(J)  - TTVAC)/RAD**2
           XR4 = ALPHA*(TIME(J)  - TTCOOL)/RAD**2
        DO 128 I = 1, NTERMS
        AN   = 1./(BETAN(I)*DBESJ1(BETAN(I)))
       AN1 =  (DBESJ0(BETAN(I)*DIMLSR))/(BETAN(I)*DBESJ1(BETAN(I)))
        EX1 = DEXP(-XR1*BETAN(I)**2)
```

```
      EX2 = DEXP(-XR2*BETAN(I)**2)
      EX3 = DEXP(-XR3*BETAN(I)**2)
      EX4 = DEXP(-XR4*BETAN(I)**2)
      TERM1 = AN*EX1*DBESJ0(BETAN(I)*DIMLSR)
      TERM2 = AN1*EX2/((BETAN(I)/RAD)**2)
      TERM3 = AN1*EX3/((BETAN(I)/RAD)**2)
      TERM4 = AN1*EX4/((BETAN(I)/RAD)**2)
        IF (DABS(TERM3) .LT. 1.D-17) GO TO 222
         YR1 = YR1 + TERM1
         YR2 = YR2 + TERM2
         YR3 = YR3 + TERM3
 128     YR4 = YR4 + TERM4
 222     YR1 = YR1*2
         TEMDAT(J) = TINIT*YR1 + TBATH*(1.-YR1)
     * + (SL1*((TIME(J)-TTSTM)-DA)+ 2*YR2*SL1/ALPHA)
     * - (SL1*((TIME(J)-TTVAC)-DA)+ 2*YR3*SL1/ALPHA)
     * + (SL2*((TIME(J)-TTVAC)-DA)+ 2*YR3*SL2/ALPHA)
     * - (SL2*((TIME(J)-TTCOOL)-DA)+ 2*YR4*SL2/ALPHA)
        END IF
C
      WRITE(*,233)  TIME(J),J,TEMDAT(J)
 233  FORMAT(2X,'TIME = ',F8.3,2X,'TEMP(',I3,')=',F14.4)
 142   CONTINUE
C
      WRITE(*,*) 'COUNTER'
      END
C
C
      SUBROUTINE ROOTS (CPAR,ALP1,NROOTS)
C
C  THIS PROGRAM CALCULATES THE ROOTS OF THE EQN IN TABLE III
C  OF CARSLAW AND JAEGER
C
      DOUBLE PRECISION CPAR,EPS,EPSS,X
      EXTERNAL CALC
      DIMENSION ROOT(300)
      COMMON/PASS/ROOT
C
      PI = 3.141592654
C
      MAXIT = 50
      EPSS = 0.0000001D0
C
      K = 0
      ROOT(1) = ALP1
C
      DO 100 I=1,NROOTS
         NT = MAXIT
         EPS = EPSS
         X = ROOT(I)
         CALL NEWTON(CPAR,X,NT,EPS,CALC,K,NTUSED)
         ROOT(I) = SNGL(X)
```

```
         IF (I.EQ.1) THEN
            ROOT(2) = ROOT(1)+3.5
         ELSEIF (I.EQ.2) THEN
            ROOT(3) = ROOT(2)+3.3
         ELSEIF (I.EQ.3) THEN
            ROOT(4) = ROOT(3)+3.15
         ELSE
            ROOT(I+1) = ROOT(I)+PI
         ENDIF
  100 CONTINUE
      END
C
      SUBROUTINE CALC(CPAR,X,FX,DFDX)
C
      DOUBLE PRECISION CPAR,X,FX,DFDX,DBESJ0,DBESJ1
      FX = X*DBESJ1(X) - CPAR*DBESJ0(X)
      DFDX = X*DBESJ0(X) + CPAR*DBESJ1(X)
      RETURN
      END
C
      SUBROUTINE NEWTON(CPAR,X,NT,EPS,SFNC,K,NTUSED)
C
C
C     X    : INITIAL GUESS OF THE ROOT ON INPUT, BUT THE BEST
C            ESTIMATE OF THE ROOT ON OUTPUT.
C     NT   : TOTAL NUMBER OF ITERATIONS ALLOWED.
C     EPS  : RELATIVE ERROR CRITERION FOR CONVERGENCE.
C            FOR 4-DIGIT ACCURACY SPECIFY EPS=0.0001 .
C     SFNC : NAME OF THE SUBROUTINE THAT CALCULATES THE FUNCTION
C            VALUE "F" AND THE DERIVATIVE "DFDX" AT X. USER MUST
C            PROVIDE SUBROUTINE SNFC(X,F,DFDX) AND PUT THEACTUAL
C            NAME OF THE SUBROUTINE IN EXTERNAL STATEMENT
C            WHICH MUST BE LOCATED IN THE PROGRAM THAT CALLS
C            NEWTON. K : A USER SPECIFIED PARAMETER TO CONTROL
C            THE PRINTING OF ITERATION RESULTS. EVERY K TH
C            ITERATION IS PRINTED. NO PRINTING FROM THE
C            SUBROUTINE NEWTON IF K=0.
C            NTUSED : NUMBER OF ITERATIONS ACTUALLY USED
C
C
C   PRINT HEADINGS AND CALL SUBROUTINE TO CALCULATE F AND DFDX
C
      DOUBLE PRECISION EPS,CPAR,X,F,DFDX,XN,XDEN,E
C
      IF(K.GE.1) THEN
         WRITE(*,20)
   20    FORMAT(//5X,'ITERATION RESULTS FOR NEWTON METHOD :'/
     1    4X,'ITER',8X,'X',13X,'F',12X,'DFDX')
         CALL SFNC(CPAR,X,F,DFDX)
         WRITE(*,25) 0,X,F,DFDX
   25    FORMAT(2X,I5,3D14.4)
      ELSE
```

```
         CALL SFNC(CPAR,X,F,DFDX)
      ENDIF
C
      J=0
      DO 100 I=1,NT
         J=J+1
C
C  CALCULATE NEW X BY NEWTON'S METHOD
C
         XN=X-F/DFDX
         XDEN=X
         IF(DABS(X).LT.1.0D-10) XDEN=SIGN(1.0E-10,SNGL(X))
         E=DABS((XN-X)/XDEN)
C
C  TEST FOR CONVERGENCE
C
         IF(E.GE.EPS) THEN
            X=XN
            CALL SFNC(CPAR,X,F,DFDX)
C
C  PRINT ITERATION
C
            IF(K.GE.1.AND.J.GE.K) THEN
               WRITE(*,25) I,X,F,DFDX
               J=0
            ENDIF
         ELSE
            X=XN
            IF(K.GE.1) WRITE(*,25) I,X,F,DFDX
            NTUSED = I
            RETURN
         ENDIF
  100 CONTINUE
C
C  OUTPUT IF NO CONVERGENCE
C
      WRITE(*,110) NT,X,F
  110 FORMAT(//2X,'NO CONVERGENCE IN',I5,3X,'ITERATIONS',
     +       /5X,'X= ',E14.4,5X,'F= ',E14.4)
      NTUSED = NT
      RETURN
      END
C
C
       FUNCTION DBESJ0(X)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C THE METHOD USED IN THE FOLLOWING SUBROUTINE IS ADAPTED FROM
C    THE BOOK "NUMERAL RECIPES", BY B. FLANNERS et al. AND THE
C    DOUBL PRECISION VERSION IS TAKEN FROM "COMPUTER
C    APPROXIMATIONS", BY J. HART et al..
C
      DATA P1,P2,P3,P4,P5/1.D0,-.1098628627D-2,.2734510407D-4,
```

```
     *  -2073370639D-5,.2093887211D-6/,Q1,Q2,Q3,Q4,Q5/
     *  -.1562499995D-1,.1430488765D-3,-.6911147651D-5,
     *  .7621095161D-6,-.934945152D-7/
        DATA R1,R2,R3,R4,R5,R6,R7,R8/
     +     .185962317621897803528399944 9D18,
     +    -.441458293918159818345844871 8D17,
     +     .233448917187786974457158669 8D16,
     +    -.477655594426735877546571316 1D14,
     +     .462172225031718026369418683D12,
     +    -.227149043955360326742219039 6D10,
     +     .551358456477075215411675931 7D07,
     +    -.529261713038455736490774717 6D04/,
     +  S1,S2,S3,S4,S5,S6,S7,S8/
     +     .185962317621897733129457400 9D18,
     +     .234475001365899675688114277 4D16,
     +     .150154624497697519723857558D14,
     +     .643986745351332562784646887 7D11,
     +     .204251483521343573615936589 9D09,
     +     .494030794918139724177275433 6D06,
     +     .884720367561755040118670129 3D03,
     +     .1D01/
       IF(DABS(X).LT.8.D0)THEN
         Y=X**2

       DBESJ0=(R1+Y*(R2+Y*(R3+Y*
     *        (R4+Y*(R5+Y*(R6+Y*(R7+Y*R8)))))))
     *     /(S1+Y*(S2+Y*(S3+Y*(S4+Y*(S5+Y*(S6+Y*(S7+Y*S8)))))))
       ELSE
         AX=DABS(X)
         Z=8.D0/AX
         Y=Z**2
         XX=AX-.785398164D0

DBESJ0=DSQRT(.636619772D0/AX)*(DCOS(XX)*(P1+Y*(P2+Y*(P3+Y
     * *(P4+Y*P5))))-Z*DSIN(XX)*(Q1+Y*(Q2+Y*(Q3+Y*(Q4+Y*Q5)))))
       ENDIF
       RETURN
       END
C
       FUNCTION DBESJ1(X)
       IMPLICIT DOUBLE PRECISION (A-H,O-Z)
       DATA R1,R2,R3,R4,R5,R6,R7,R8/
     +    .221488788042196313920764780 3D18,
     +   -.251237421470321278951327648 2D17,
     +    .848242074478127265409227071 4D15,
     +   -.124982036726202485305938640 4D14,
     +    .931656529672467320494156909D11,
     +   -.368666898702298162605736073 4D09,
     +    .743702381711999644103397156 8D06,
     +   -.607953017960741359942216258 9D03/,
     + S1,S2,S3,S4,S5,S6,S7,S8/
     +    .442977576084392621306860643 1D18,
```

```
     +   .51247127164848721123551908 33D16,
     +   .29898363077254871599748638 05D14,
     +   .11581921274668893293933519 64D12,
     +   .32819403445341964444997237 99D09,
     +   .69885861844850757440337717 49D06,
     +   .10777412894333043573129956 18D04,
     +   .1D01/
      DATA P1,P2,P3,P4,P5/1.D0,.183105D-2,-.3516396496D-4,
     * .2457520174D-5, -.240337019D-6/,
     *  Q1,Q2,Q3,Q4,Q5/.04687499995D0,-.2002690873D-3,
     * .8449199096D-5,-.88228987D-6,.105787412D-6/
       IF(DABS(X).LT.8.D0)THEN
       Y=X**2
C
      DBESJ1=X*(R1+Y*(R2+Y*(R3+Y*(R4+Y*
     *     (R5+Y*(R6+Y*(R7+Y*R8)))))))
     *    /(S1+Y*(S2+Y*(S3+Y*(S4+Y*(S5+Y*(S6+Y*(S7+Y*S8)))))))
       ELSE
       AX=DABS(X)
       Z=8.D0/AX
       Y=Z**2
       XX=AX-2.356194491D0
C               DBESJ1=DSQRT(.636619772D0/AX)*
     *   (DCOS(XX)*(P1+Y*(P2+Y*(P3+Y
     *    *(P4+Y*P5))))-Z*DSIN(XX)
     *    *(Q1+Y*(Q2+Y*(Q3+Y*(Q4+Y*Q5)))))
     *    *SIGN(1.,SNGL(X))
      ENDIF
      RETURN
      END
C
$LARGE
      SUBROUTINE LSGEN(NOB,OBS,NPAR,PAR,ISC,SC,NSC)
C     THE SIZE OF THE SCRATCH ARRAY, SC, MUST BE AT LEAST
C     6 + 2*NOB + NPAR*(17 + 2*NPAR + NOB)         IF IZA = 0
C     6 +   NOB + NPAR*(17 + 2*NPAR)               IF IZA = 1
C     6 +   NOB + NPAR*(17 + 2*NPAR) + 2*NCO
C       + NPRECB*(NPAR1 + NNPAR)*(1 + NNCO)        IF IZA = 2
C     THE SIZE OF THE ARRAY, ISC, MUST BE AT LEAST
C     5          IF IZA = 0 OR 1
C     7 + NCO    IF IZA = 2
      DIMENSION SC(NSC), ISC(20), OBS(NOB), PAR(NPAR)
      NPRECB = 2
      NCO = ISC(6)
  IF(ISC(6).EQ.0)NCO=1
  NCO1=NCO+1
      NNCO = NCO*(NCO + 1)/2
      NNPAR = NPAR*(NPAR + 1)/2
      IZA = ISC(5)
      NPAR1 = NPAR + 1
      NPAR2 = NPAR + 2
      N1 = NPAR + 3
```

```
      N2 = NPAR + N1
      N3 = NPAR + N2
      N4 = NPAR + N3
      N5 = NPAR + N4
      N6 = NPAR + N5
      N7 = NPAR + N6
      N8 = NPAR + N7
      N9 = NPAR + N8
      N10 = NOB + N9
      N11 = 2*NPAR + N10
      N12 = 2*NPAR1*NPAR2 + N11
  N13=1
  N14=1
  N15=1
  N16=1
  N17=1
  N18=1
  N19=1
  N20=1
      LZ = 0
      IF(IZA.EQ.0) LZ = NOB*NPAR1
      NSCRQ = LZ + N12 - 1
      IF(IZA.NE.2) GO TO 10
      N13 = LZ + N12
      N14 = NCO + N13
      N15 = NCO + N14
      LV = NPRECB*NNCO
      N16 = LV + N15
      N17 = LV*NPAR + N16
      N18 = LV*NNPAR + N17
      N19 = NPRECB + N18
      N20 = NPRECB*NPAR + N19
      NSCRQ = NPRECB*NNPAR + N20 - 1
10      WRITE(*,12) NSCRQ, NSC
   12 FORMAT('0A SCRATCH ARRAY, SC, OF ',I10,' WORDS IS
     * REQUIRED' A ' FOR THIS PROBLEM.'/25XI10,' WORDS WERE
 * ALLOCATED.')
      IF(NSCRQ.GT.NSC) STOP
      N21 = N11 + 2*NPAR1**2 - 2
      N22 = N11 + 2*NPAR*NPAR1
      N23 = N11
                                 C     A     L     L
LSB(NOB,OBS,NPAR,PAR,ISC(1),ISC(2),ISC(3),ISC(4),ISC(5),
     A      ISC(7),SC,SC(3),SC(N1),SC(N2),SC(N3),
     B      SC(N4),SC(N5),SC(N6),SC(N7),SC(N8),SC(N9),
     C      SC(N10),SC(N11),SC(N12),SC(N13),SC(N14),SC(N15),
     D      SC(N16),SC(N17),SC(N18),SC(N19),SC(N20),SC(N21),
     E      SC(N22),SC(N23),NPAR1,NCO,NNCO,NNPAR,NSC,NCO1)
      RETURN
      END
```