The Institute of Paper Science and Technology

Atlanta, Georgia

Doctoral Dissertation Reprint

A MATHEMATICAL MODEL OF HIGH INTENSITY PAPER DRYING

A thesis submitted by

Joseph R. Pounder

B.S. 1979, Philadelphia College of Textiles and Science

M.S. 1982, Lawrence University

in partial fulfillment of the requirements
of The Institute of Paper Chemistry
for the degree of Doctor of Philosophy
from Lawrence University,
Appleton, Wisconsin

January, 1986

TABLE OF CONTENTS

ABSTRACT

High intensity paper drying is defined as any drying process in which the web is at or above the thermodynamic saturation temperature corresponding to the ambient pressure. Rapid generation of vapor under these circumstances causes the drying process to be driven by a gradient of total pressure and not by a gradient of partial vapor pressure. Therefore, the generated vapor leaves the web by a bulk (convective) flow mechanism rather than a slower diffusion mechanism. The vapor pressure build-up in the web also offers the opportunity for removal of moisture in liquid form, since the fast flowing vapor can displace and/or entrain liquid as it moves through the web. This can result in significantly lower energy usage relative to conventional drying, since only a fraction of the moisture has to be evaporated.

The thesis objective is a mathematical model simple enough to be easily modified or expanded but comprehensive enough to be applicable to a wide variety of process conditions and sheet variables.

Early experiments suggested that the high intensity drying process could be described effectively by a discrete "zone" model. The process is idealized by picturing the sheet as composed of different zones which contain various amounts of fiber, liquid water, and water vapor. The model is based on sets of equations which account for the heat and moisture transfer within and among the zones during three regimes: heatup, transition, and quasi-static. Once the hot surface temperature, boiling point temperature, basis weight, Canadian Standard Freeness, initial moisture ratio, and mechanical pressure pulse are specified, the equations may be solved to predict the moisture content as a function of time.

Comparisons between experimental data and the model's predictions demonstrate that the model qualitatively and quantitatively describes high intensity drying

behavior and provide indirect evidence that the mechanisms on which the model is based actually are in effect under high intensity conditions. An exploratory parametric study shows that the predicted drying behavior is most sensitive to changes in hot surface temperature and sheet basis weight. Peak pressure and freeness have a more moderate effect, and initial moisture ratio has almost no effect. Comparisons to laboratory data show that the model tends to overpredict the extent of liquid moisture removal and underpredict the heat flux. Changing the values of constants in the model modifies the predictions and suggests that a mathematical optimization of all constants, constrained by experimental data, would improve the predictive capability of the model.

INTRODUCTION

Low heat transfer rates, low drying rates, and low mechanical pressures characterize conventional can drying of paper. Moisture removal is dominated by a vapor diffusion mechanism, and average sheet temperatures are well below the boiling point.

In contrast, high intensity drying occurs at high surface temperatures and high mechanical pressures. Heat transfer rates and drying rates are orders of magnitude above those in the conventional process (see Fig. 1 and 2). Moisture removal is dominated by bulk (convective) vapor flow and liquid displacement or entrainment, and sheet temperatures frequently exceed the boiling point.

Mathematical modeling provides a convenient and comprehensive means for exploring the effects of temperature, pressure, freeness, and other factors on high intensity drying behavior. Mathematical modeling complements experimental study by identifying incomplete areas in knowledge of the physical system and suggesting areas for further research. Finally, mathematical modeling offers the opportunity for blending and balancing theoretical and empirical relationships to provide a fast, low-cost investigative tool.

Early experiments indicated that high intensity drying could be described effectively by a discrete "zone" model, since the drying behavior is consistent with other examples of phase change problems involving the development of zones. Initially, two zones of different moisture content were assumed to be present. As more information became available, additional zones were added to the model. Fundamental mass and energy balances for the zones are linked by the boundary conditions and the conditions at the interfaces between the zones. Solving the system of equations allows a prediction of the temperature distribution within

the sheet, the positions and rates of advance of the interfaces, and the moisture content of the sheet as functions of time.

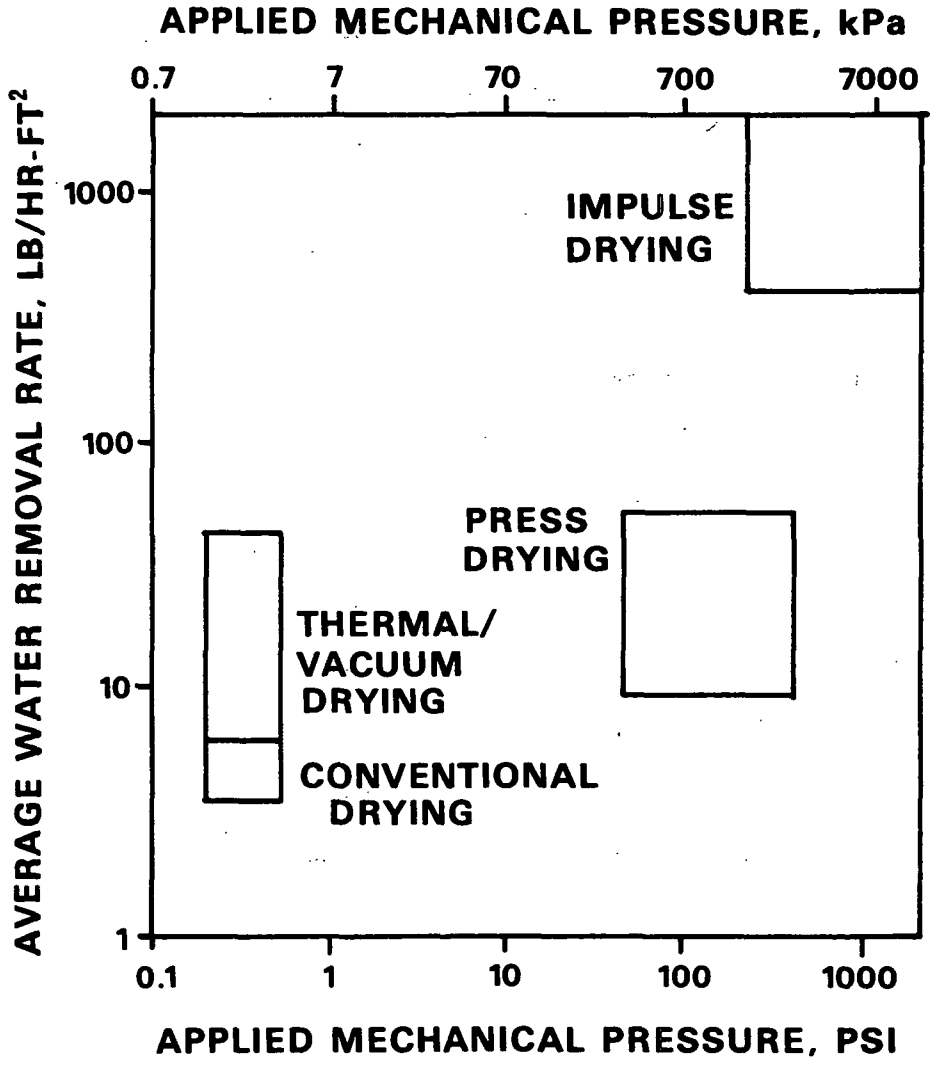

Figure 1. Water removal rates at different applied mechanical pressures for various drying methods.

This thesis presents the objective, experimental background, theoretical background, assumptions, and equations of the model. A parametric study details changes in the model's predictions resulting from changes in process variables. A sensitivity analysis shows the effects of varying certain model constants, and direct comparisons to experimental data demonstrate that the model qualitatively and quantitatively describes high intensity drying behavior.

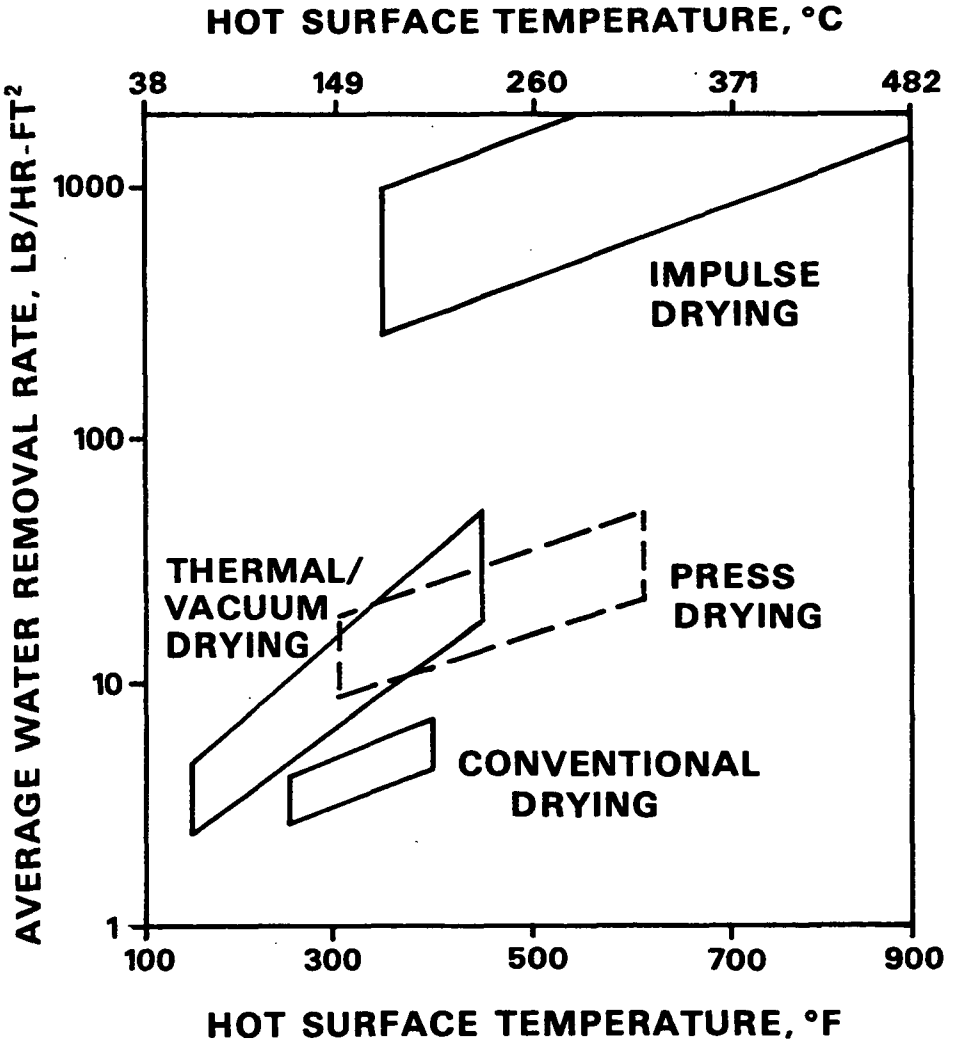

Figure 2. Water removal rates at different hot surface temperatures for various drying methods.

OBJECTIVE

The objective of this thesis is the creation of a mathematical model of high intensity drying simple enough to be easily modified or expanded but comprehensive enough to be applicable to a wide variety of process conditions and sheet variables. The mechanisms of bulk vapor flow and liquid displacement are analyzed within the framework of a moving boundary model, and comparisons to experimental data are used to verify that the model describes high intensity drying behavior.

EXPERIMENTAL BACKGROUND

INTRODUCTION

High intensity paper drying occurs when the web is at or above the thermodynamic saturation temperature corresponding to the ambient pressure. This definition encompasses press drying,[1] where the web is heated from both sides symmetrically, and the "one-sided" drying methods: thermal/vacuum drying,[2] where the web is dried in a reduced pressure environment; impulse drying,[3] where the web is dried in a heated press nip; and one-sided drying where temperatures and mechanical pressures are elevated above conventional conditions.[4] The conventional conditions are a reference state of surface temperatures from about 127 to 171°C (260 to 340°F) and mechanical pressures from 1.2 to 7 kPa (0.17 to 1 psi). High intensity conditions are on the order of 177 to 399°C (350 to 750°F) and 7 to 4826 kPa (1 to 700 psi).

Experimental investigations into high intensity drying are extensions of the mechanistic studies of conventional paper drying. Within the range of conventional operating conditions, increases in surface temperature and/or mechanical pressure lead to increases in drying rate. Recent publications[4,5] cite several references in this area, provide data at higher temperatures and pressures, and cite an example of press drying work at very high temperatures and pressures that shows the trend of increasing drying rate continues well beyond conventional conditions. It is clear that a dramatic increase in the drying rate is observed whenever the sheet temperature can be brought to or above the boiling point.

EXPERIMENTAL RESULTS

Figure 3 shows the configuration for the high intensity drying process modeled in this thesis. The paper contacts an impermeable heated surface directly. A felt, wire, or other highly porous material provides an escape path for the vapor and liquid to be removed from the paper, and another impermeable surface is used to exert mechanical pressure on the system. This arrangement causes one-sided heating of the paper. The overall heat and mass transfer are one-dimensional in the direction away from the hot surface. For experimental purposes, thermocouples are placed at various locations in the sheet so that the temperature distribution can be monitored throughout the course of drying.

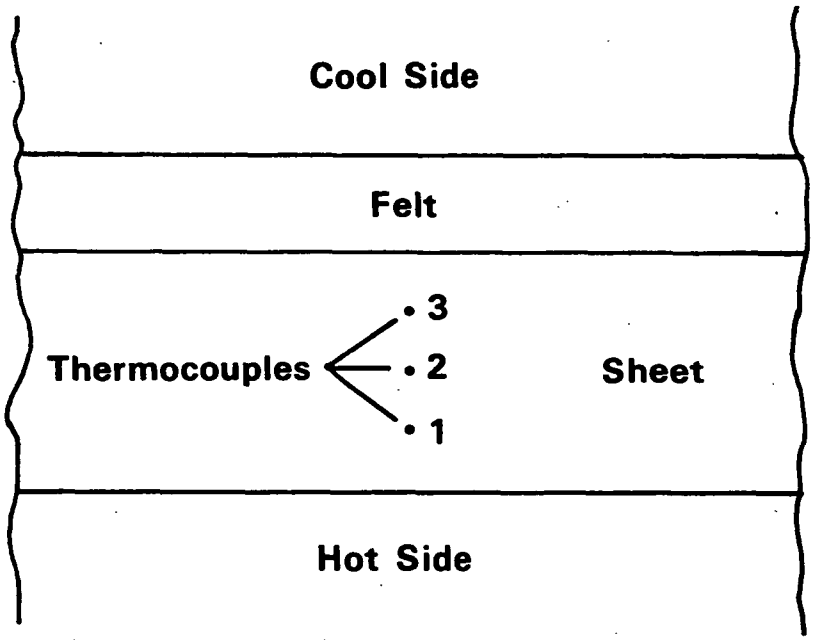

Figure 3. Configuration for one-sided high intensity drying.

Figure 4 depicts a typical sheet temperature history from several types of high intensity drying experiments.[6-8] It is important to note that all thermocouples reach a plateau value equal to or above the boiling point at approximately the same time and that this time is much shorter than the time needed to

simply conduct heat to the far thermocouples. The square roots of the times when the temperatures begin to rise above their plateaus are proportional to the distances of the thermocouples from the hot surface. When the temperature exceeds the boiling point, the vapor pressure exceeds the ambient pressure. The extent of the rise is related to the flow resistance of the sheet. The peak pressure is much higher in the high flow resistance cases than in the low flow resistance cases.[9]

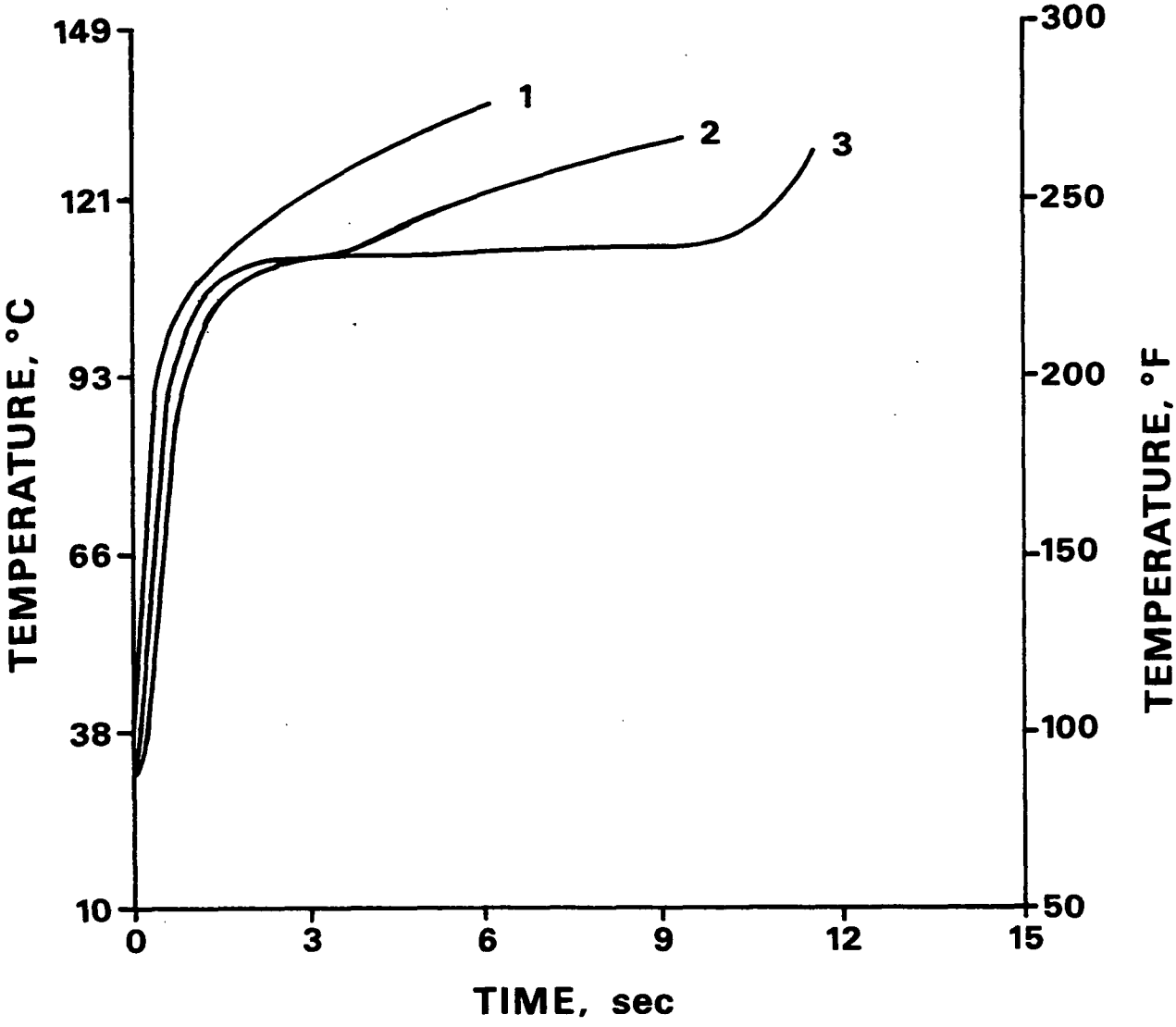

Figure 4. Internal sheet temperatures during high intensity drying.

Figure 5 shows a qualitative comparison between drying rates for conventional and high intensity drying. Four outstanding features differentiate the processes. In high intensity drying the peak drying rate is much greater than in conventional drying. In high intensity drying the peak rate is achieved (almost) instantaneously, but there is a significant heatup time required in conventional drying. The high intensity drying time is much shorter than the conventional drying time, and most importantly from a mechanistic point of view, high intensity drying does not exhibit a "constant rate" period as conventional drying does.

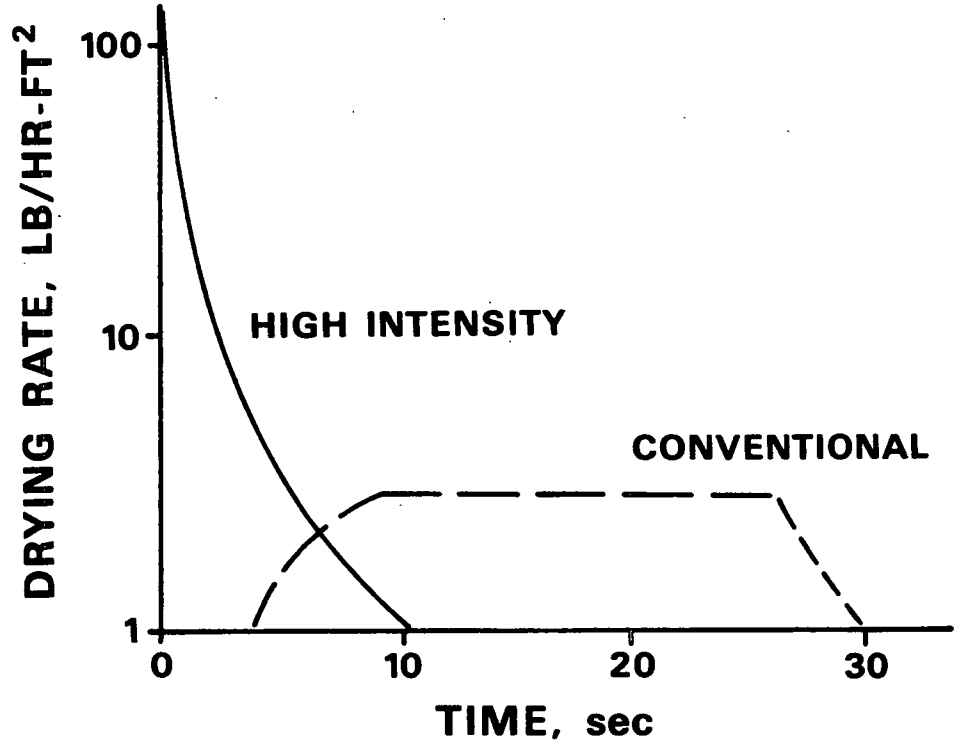

Figure 5. Comparison of high intensity and conventional drying rates.

Figure 6 depicts the results of a study designed to track the liquid distribution in the sheet.[8] A nonvolatile LiCl tracer is incorporated into the sheet during formation. This tracer moves with liquid water movement. After drying,

a cross section of the sheet is analyzed with the EDAX electron microscope technique to determine the location of the tracer. For conventional drying, most of the tracer is found near the side of the sheet which was adjacent to the hot surface. High intensity drying shows an opposite tracer distribution.

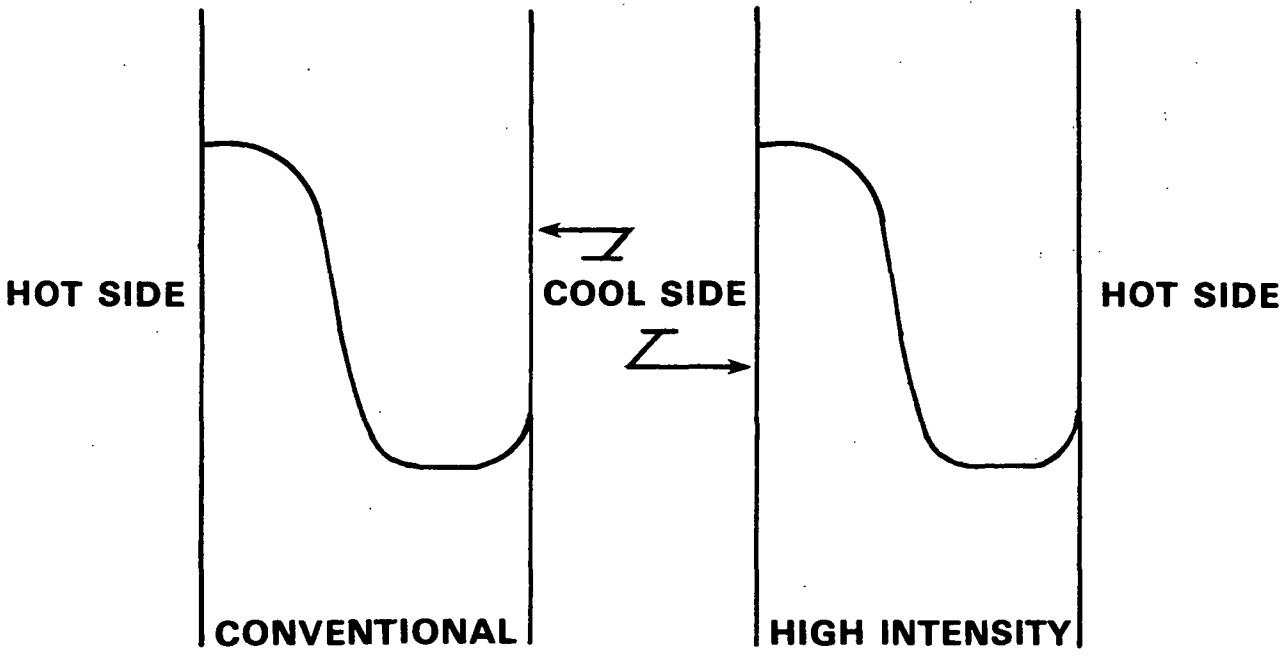

Figure 6. Comparison of tracer distributions for high intensity and conventional drying.

The experimental results lead to the postulation of three dominant mechanisms operative during high intensity drying: bulk vapor flow, liquid displacement and/or entrainment, and the development of zones within the sheet.

BULK VAPOR FLOW

Simple visual observation of a high intensity drying experiment is enough to suggest convective vapor flow. Vapor is forcibly ejected from the sheet. Even under impulse conditions where the nip residence time is as short as 0.005 second, a vapor pulse exiting the sheet is clearly visible. The rapid temperature rise

of thermocouples far from the hot surface supports this mechanism (see Fig. 4). The drying rate is insensitive to ambient air flow rate,[4] and this would not be true if diffusion were dominant since a diffusion mechanism would depend on convective transport external to the sheet. Finally, direct experimental evidence of vapor flow under a vapor-pressure-gradient driving force comes from a study of steady state heat transfer in a granular porous medium[10] and work involving heat pipes.[11] Darcy's law can be used to model the vapor flow in these cases, and while they are not examples of "drying," the fundamental transport mechanisms are identical.

LIQUID DISPLACEMENT

Liquid in the larger pores of a fibrous material can be displaced by a flowing gas. Devices for dewatering paper by passing air through the wet web were described in a patent filed for in March, 1963 and granted November 8, 1966.[12] Extensions of this concept[13-20] have shown that pressure differentials across the sheet on the order of 7 to 210 kPa (1 to 30 psi) can raise solids content from the 10 to 30% range up to the 40 to 45% range. For textile materials, steam pressurized at up to 700 kPa (100 psi) can be used to preheat the web, displace liquid, and raise solids content from around 20% to nearly 80%.[21]

High intensity drying achieves its pressure driving force by vaporizing some liquid in the vicinity of the hot surface. As the vapor tries to escape, it pushes or entrains interfiber liquid out of the sheet. Figure 6 indicates the flow of liquid away from the hot surface. Heat flux determinations reveal that the actual thermal energy input can be on the order of 50% or less than the energy which would be required to raise the sheet to the boiling point and then evaporate all the liquid at that temperature.[8]

Therefore, water has to be removed in liquid form. High intensity, vapor-induced expulsion of liquid droplets has been observed for other porous materials as well.[22] Note that since the necessary condition for liquid displacement is a vapor pressure differential across the web, the symmetrical heating of the press drying process precludes this mechanism.

Mechanical Dewatering

High-pressure, short-duration mechanical pressing of paper is a fundamental water removal method used prior to conventional drying. The extent of the dewatering is controlled by the relationship between the applied pressure and time and by either the flow resistance or compressibility of the sheet (or both). In addition to bulk vapor flow and vapor-induced liquid displacement, the temperature and pressure levels in impulse drying encourage effects similar to those found from pressing at higher than normal temperatures.

Pressing at up to 90°C (194°F) can take a sheet at ingoing solids content of 38% and raise it to nearly 50%, depending on temperature, basis weight, and freeness.[23,24] Additionally, hot pressing offers the possibility for moisture profile control.[25] Hot pressing and impulse drying use temperature to decrease the viscosity and surface tension of the water and to decrease the sheet compression resistance. Lower viscosity allows the liquid to flow more easily; this factor should be of key importance in a flow controlled situation. Lower compression resistance allows the sheet to be deformed more easily and should therefore be of key importance in a compression controlled case, particularly when a high percentage of lignin is present. Lower surface tension should benefit both cases by reducing capillary pressure and the possibility of rewetting.

ZONE DEVELOPMENT

Figure 6 indicates the presence of two main zones within the sheet at the end of drying: a zone of lower moisture content close to the hot surface and a zone of higher moisture content, created by liquid flow, far from the hot surface. This in itself is no guarantee of a uniform moving front that progresses through the sheet, but when there is no constant rate drying period (see Fig. 5) and the external boundary layer does not affect the drying,[4] then a simple approach to modeling the phenomenon is with a moving boundary or zone model.[26] The proportionality of the square roots of plateau rise times to thermocouple distances in Fig. 4 is compatible with the classical moving boundary problem called the Neumann problem[27] and suggests that an elementary model of high intensity drying might be based on a Neumann-like analysis.

SUMMARY

There is experimental evidence to indicate that high intensity drying might be conveniently described by a moving boundary or zone model based on the bulk vapor flow and liquid displacement mechanisms. In the case of impulse drying, the additional effects of high temperature pressing may contribute to the overall moisture loss by changing the physical properties of the liquid water and/or the sheet compressibility. The similarities between high intensity drying behavior and a classical moving boundary problem suggest a logical starting point for the mathematical modeling.

MOVING BOUNDARY MODELS

INTRODUCTION

Muehlbauer and Sunderland[28] present a brief summary of the Neumann problem and an excellent review of the mathematical investigations of moving boundary problems up until 1965. Substantial work in this area since then has centered on obtaining solutions to moving boundary problems with boundary and/or initial conditions or assumptions about key thermal properties which are different than those in the original and early analyses. Generally, the problems deal with one-dimensional heat transfer through one phase of a material to the interface with a different phase of the same material. The models usually treat melting or solidification problems, and mass transfer is not considered except in rare cases of convection in the liquid phase. The models either calculate the temperature or enthalpy distribution and position of the interface within the material or track the positions of isotherms that progress through the material.

TEMPERATURE-BASED MODELS

The original temperature-based model was formulated by Neumann. Details of the model are in.[27] Heat conduction equations for each phase or "zone" coupled with appropriate initial, boundary, and interface conditions allow a prediction of the temperature distribution and interface position within a semi-infinite medium. Extensions of this model allow for phase transitions over a range of temperatures[29,30] and a modified rate of interface advance due to the different densities of the two phases.[31] Simple dependence of thermal conductivity on temperature is treated analytically,[32] and clever numerical schemes handle more complicated dependencies of conductivity and density.[33,34]

The primary problems with these methods, with reference to drying, are that they deal only with semi-infinite media and that they deal only with the presence of a one-component (multiphase) system. Paper behaves as a finite medium with regard to heat transfer during drying and contains two or more components (fiber, water, air, etc.). Integral transform methods have been applied to solve the problem in finite media of various geometries and with boundary condtions of the first, second, and third kinds,[35] but the problem of multiple components remains.

ENTHALPY-BASED MODELS

When knowledge of the exact position of a phase change interface is not required, modeling the system in terms of an enthalpy equation often leads to greatly simplified (numerical) solution methods.[36] In elementary cases, the solution of the enthalpy-based analysis is identical to that of the analytical temperature-based problem. In this method, the temperature-based model is formulated and then converted to an enthalpy-based model by using a relationship between temperature and enthalpy.[37,38] This relationship describes the latent heat effect as a large jump in heat capacity over a very narrow temperature range. The advantages of this approach are: there are no conditions to be satisfied at the phase change boundary; there is no need to track the position of the phase change boundary accurately; there is no need to consider the regions on either side of the boundary separately; and it is possible to vary the range of temperatures over which the transition takes place.[38] It is also relatively easy to extend this technique to more than one dimension.[39]

The disadvantage of this method is that it can lead to problems when convective effects need to be considered. In a model of high intensity drying,

convection of vapor and liquid is a key mechanism, and so an enthalpy-based method is not directly applicable.

POSITION-BASED MODELS

The Isotherm Migration Method (IMM) and its modifications are alternatives to the temperature- and enthalpy-based approaches. IMM tracks the position of a given isotherm within the medium, and distance replaces temperature as the dependent variable.[40,41] It is another attempt to avoid calculating the exact position of the phase change front.

While IMM is flexible and capable of handling more than one moving front, it is limited because it requires some analytical solution to "start" the process. This analytical solution is an exact solution for very short times, places all isotherms in the slab, and sets an initial temperature profile to start the finite difference numerical scheme. Thus, IMM is somewhat limited in that an analytical solution may not exist to start the process. The lack of an analytical starting solution, however, is a relatively minor shortcoming compared to its inability to handle convective aspects of problem.

DRYING MODELS

Drying differs significantly from simple moving boundary problems, since drying involves simultaneous heat and mass transfer. Furthermore, drying takes place within a matrix of solid material from which a volatile component is evaporated. The strong coupling of heat and mass transfer in drying thus requires a careful extension of the general concepts of moving boundary problems.

An exact solution of an evaporation problem in porous media has been known since 1975.[42] This is the most elementary case involving constant surface

temperature, constant evaporation temperature, and a semi-infinite medium. Penetrating front models for finite media have evolved, generally for freeze drying applications.[43-47] The geometry of the models is such that the medium is heated either symmetrically or with one face perfectly insulated and impermeable. The heat and mass transfer occur in opposite directions, and therefore these models are directly applicable only to press drying or to drying in which the heated surface is permeable.

Most models do not account for the hygroscopic nature of the matrix, but models for drying of wood[48-50] and other materials[51] do include this factor. However, these also involve opposite heat and mass transfer.

Models which calculate the pressure rise inside the porous medium are not applicable because they either use a diffusion mechanism for vapor transport[52] or they assume a constant evaporation temperature but calculate the vapor flux based on a total pressure gradient.[53,54] These are also opposite heat and mass transfer cases.

Strek and Nastaj have used the moving boundary concept to model the falling rate period in vacuum drying of a bed of granular material.[55] Heat and mass transfer are in the same direction, but the experimental conditions are drastically different than those in high intensity paper drying. Mild temperature gradients and large bed thicknesses lead to very long drying times. The nature of the granular material is unlike that of cellulose papermaking fibers; the bed is not compressible and thickness is not sensitive to changes in moisture content.

Baines used a moving boundary concept to model a conventional drying process,[56] and Ahrens used the concept in modeling high intensity drying.[9,57] The Ahrens model is highly simplified and based on descriptions of the physical

processes dominant in high intensity conditions. The model is mathematically identical to an elementary analysis of the one-dimensional freezing of water.[58] The Ahrens model gives reasonable agreement with experimental data and serves as the starting point from which this thesis has been developed.

SUMMARY

Moving boundary models in general prove unsatisfactory for the description of high intensity drying because: they deal with only one component; they assume a constant phase transition temperature equal to the normal phase transition temperature of the one component; they model processes with heat and mass transfer in opposite directions; they usually deal only with boundary conditions of the first kind; they do not account for vapor-pressure-induced liquid convection; and/or they present analytical solutions only for semi-infinite media.

Of the drying models, an elementary one possesses the required characteristics to be used as a starting point for further development. The Ahrens model, which is mathematically identical to a simplified analysis of a freezing water problem, is the starting point of this thesis.

THE MATHEMATICAL MODEL

INTRODUCTION

For modeling purposes, the high intensity process is pictured as a series of linked mechanisms. As the sheet is brought into contact with the hot surface, heat flow into the sheet through a finite contact resistance raises its temperature in a "heatup" regime. The contact resistance depends on the mechanical pressure and on the degree of saturation of the sheet next to the hot surface. Because of the high thermal diffusivity of the (metal) hot surface, its temperature does not change much in reality and remains constant in the mathematical model.

If the sheet surface temperature adjacent to the hot surface becomes incrementally greater than the thermodynamic saturation temperature corresponding to the ambient pressure, then the vapor pressure difference across the sheet is assumed to cause slug flow of the interfiber liquid and air. The position of this slug flow interface defines the limit of linear temperature gradients and thermodynamic saturation so that no vapor flows into the outer zone until the temperature gradient there becomes linear due to heat transfer by conduction and liquid convection within the sheet.

If the sheet becomes saturated before the inner surface temperature exceeds the boiling point, liquid water starts to be mechanically expressed from the sheet and vapor induced liquid flow does not begin until the inner surface temperature exceeds the thermodynamic saturation temperature corresponding to the hydraulic pressure at the inner surface.

Once vapor induced liquid flow starts, the sheet is in the "transition" regime where zones of different moisture content develop inside the sheet. A dry zone is created by evaporation. A zone with water trapped inside the fibers is created

when interfiber water is pushed ahead and the evaporative front has not yet reached the trapped water. If the heat transfer is such that the sheet's outer surface temperature exceeds the boiling point, then a second evaporative front can move into the sheet if the rate of liquid flow toward the cool side is less than the rate of evaporation there.

The "linear" or quasi-static regime begins when all temperature gradients become linear due to heat transfer or when they become linear because all interfiber water has been removed (and the interface defining the limit of linear gradients no longer exists).

ELEMENTARY MODELS

The Ahrens model is formulated to describe macroscopic trends and is based on a few of the physical processes judged to be controlling under high intensity conditions. Figure 7 diagrams the configuration considered.

The paper is divided into a dry zone (devoid of liquid water) adjacent to the hot surface and a wet zone with stagnant liquid adjacent to the dry zone. δ is the time-varying dry zone thickness and δ_T is the total thickness of the fully dry sheet. The wet zone is assumed to be at the boiling point temperature (TB) that corresponds to the ambient pressure. Thus, there is no heatup or transition regime.

The process is considered to be controlled by the rate of heat transfer from the hot surface (at constant temperature TH) to the paper. The vapor generated at the dry-wet interface flows through the partially saturated wet zone and out of the sheet. The flow resistance of the wet zone is considered to be negligible so that the vapor is generated essentially at TB. (In any case, the difference between the interface temperature and TB would be much less than the

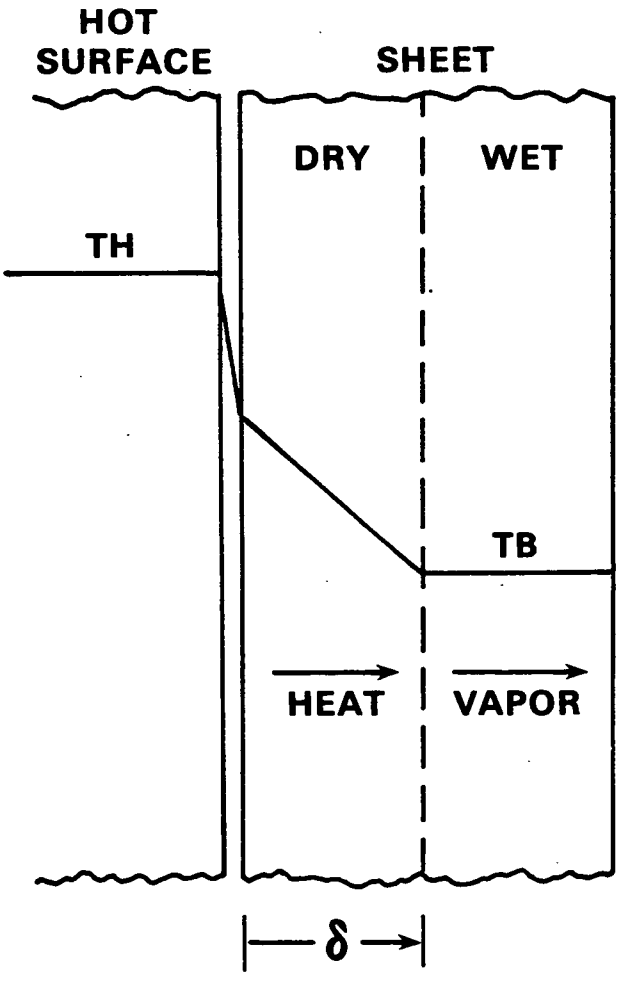

Figure 7. Configuration for Ahrens two zone model.

difference between TH and TB). The state of the system is described by an equation for heat flux

$$Q = U^*(TH - TB) \tag{1}$$

where Q is the heat flux and U is the overall heat transfer coefficient. As a consequence of assuming a linear temperature gradient in the dry zone, U is defined by

$$\frac{1}{U} = \frac{1}{Hc} + \frac{\delta}{Kd} \tag{2}$$

where Hc is the thermal contact coefficient between the hot surface and the sheet and Kd is the thermal conductivity of the dry zone (both assumed constant). The interface energy balance is

$$Q = \varepsilon * S * \rho_w * \Delta h * \frac{d\delta}{dt} \tag{3}$$

where ε and S are the porosity and saturation of the wet zone, ρ_w is the density of water, Δh is the latent heat (all assumed constant), and t is time; and the relative mass of water removed is

$$MREL = \frac{\delta}{\delta_T} \tag{4}$$

Equations (1) through (3) can be combined to solve for δ as a function of time by separating the variables and using the initial condition that $\delta = 0$ at time = 0. The moisture removal (drying curve) is then given by:

$$MREL = \sqrt{\frac{1}{BI^2} + \tau} - \frac{1}{BI} \tag{5}$$

where BI is the dimensionless Biot number defined by:

$$BI = \frac{Hc * \delta_T}{Kd} \tag{6}$$

and τ, a dimensionless time variable, is defined by:

$$\tau = \frac{2 * Kd * (TH - TB) * t}{\Delta h * Mo * \delta_T} \tag{7}$$

where Mo is the initial mass of water present per unit area.

The limiting case of "perfect" thermal contact between the sheet and hot surface (BI = ∞) reduces to a zone model with the interface location being directly proportional to the square root of time. Figure 8 graphs the results and[9] gives some comparisons to experimental data.

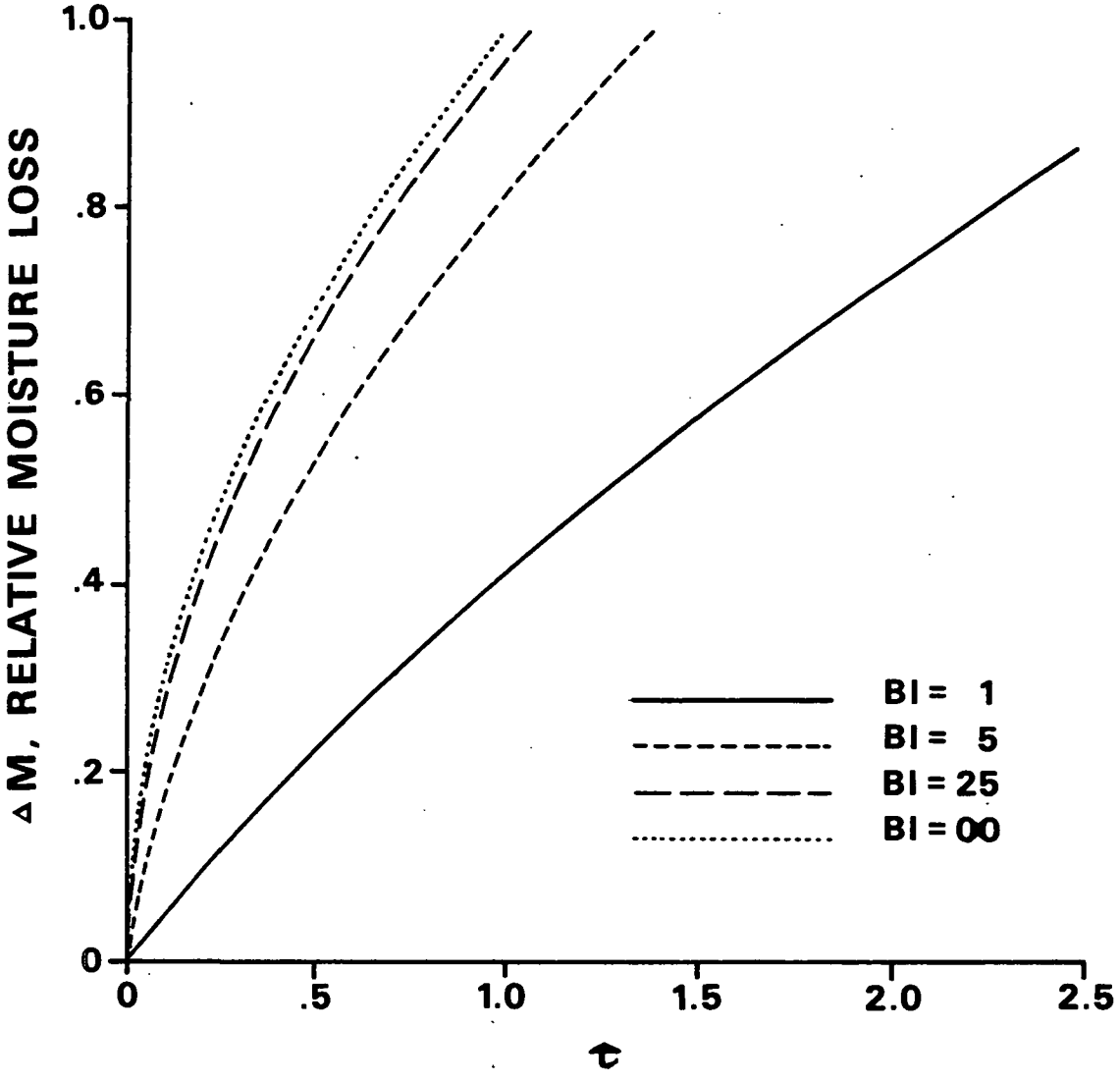

Figure 8. Moisture removal as a function of dimensionless time with Biot number as a parameter for the Ahrens model.

If the permeability of the wet zone were zero, heat transferred by conduction would cause an evaporative front to move into the sheet from the cool side

toward the hot side. Making the same assumptions as in the Ahrens model (stagnant liquid, constant properties, etc.) allows a calculation of moisture loss from:

$$MREL = 1 + \frac{1}{BI} - \sqrt{1 + \frac{2}{BI} + \frac{1}{BI^2} - \tau} \qquad (8)$$

where BI and τ are calculated based on the wet zone thermal conductivity and δ_T is the initial sheet thickness. Figure 9 shows the drying curves for this model.

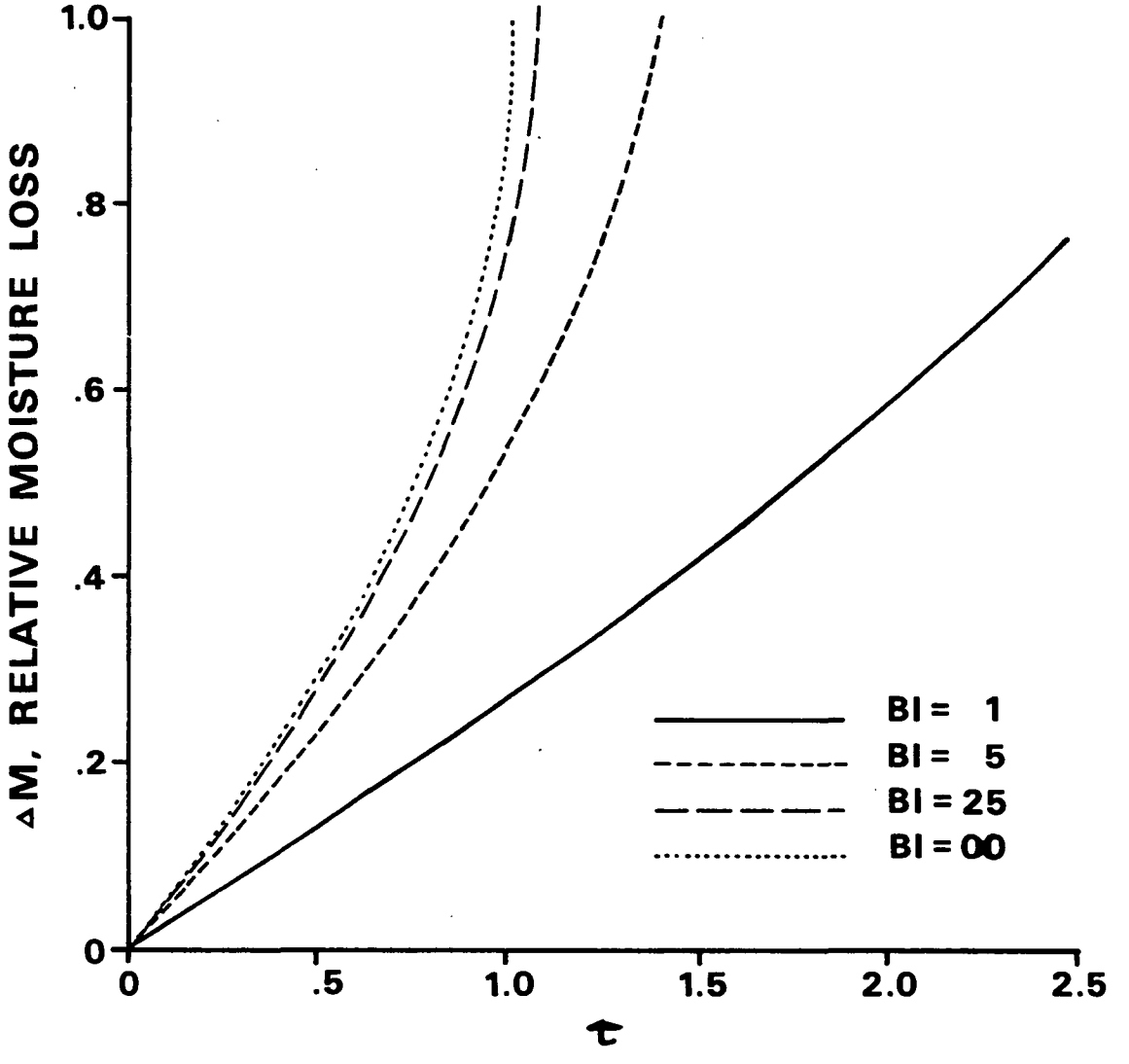

Figure 9. Moisture removal as a function of dimensionless time with Biot number as a parameter for the second limiting case.

DESCRIPTION OF THE ADVANCED MODEL

This thesis is developed from the Ahrens model of high intensity drying. The elementary analysis is extended by accounting for flowing liquid, elevated phase transition temperatures resulting from sheet flow resistance, and hygroscopic effects on latent heat at zone interfaces. The advanced model idealizes the high intensity paper drying process by picturing the sheet as composed of different zones which contain various amounts of fiber, liquid water, and water vapor. The model is based on sets of equations which account for the heat and moisture transfer within and among the zones during three regimes: heatup, transition, and quasi-static. Once the hot surface temperature, boiling point temperature, basis weight, Canadian Standard Freeness (CSF), initial moisture ratio, and mechanical pressure pulse are specified, the equations may be solved to predict the moisture content as a function of time.

The heat and mass balance equations are combined with supplementary equations that describe the nature of the pressure pulse; the liquid and vapor physical properties; and the thermal, compression, and permeability properties of the sheet. The complete model is converted to a FORTRAN program called HIDRYER1.

The program is used to run simulations of various drying conditions by calculating the rates of interface advance, multiplying the rates by a small time increment, and adding to the old values to obtain updated estimates of interface position, zone basis weight, and sheet moisture content.

ASSUMPTIONS

The fundamental assumptions of the model are listed in this section. Other assumptions are listed as they are invoked.

A1. Heat is transferred to the sheet from the hot surface by conduction only.

A2. The hot surface is an impermeable boundary.

A3. There is no conductive heat flux from the sheet to the felt.

A4. The vapor pressure at the sheet-felt interface is equal to the ambient pressure because of the negligible felt flow resistance.

A5. Heat and mass transfer occur only in one dimension.

A6. In the continuity equation, vapor and liquid storage terms within a zone are negligible.

A7. Change of phase occurs only at the zone interfaces.

A8. Porosity, saturation, and physical properties are uniform within a zone, but can differ from one zone to another and vary with time.

A9. Darcy's law is sufficient to describe liquid and vapor flow.

A10. The fiber flow can be described by a compression equation such that the fiber velocity at any point in a zone is linearly related to the velocities of the interfaces bounding the zone.

A11. Potential and kinetic energy contributions to the energy equation are negligible compared to thermal energy transfer.

A12. Conversion of mechanical energy to thermal energy is negligible.

A13. In energy calculations, the density, thermal conductivity, and specific heat of water vapor are negligible compared to those quantities for liquid water and fiber.

A14. Local thermal equilibrium exists at all points.

A15. Gravity effects are negligible.

A16. A representative value for the vapor and liquid physical properties of a zone may be obtained by calculating the values of

these properties at the temperatures of the interfaces bounding the zone and averaging the results.

A17. There is no net capillary force on a zone and there is no capillary pressure gradient within a zone.

A18. Fibers have a zero lumen volume and, in zones where water is present, a constant apparent cell wall density equal to 1.0 g/cc.[59]

A19. Hygroscopic effects on vapor pressure reduction and moisture distribution in the zones are neglected.

A20. As the inner zones develop, air is pushed ahead of the progressing interfaces so that the gas in zones with linear temperature gradients is composed of vapor only.

Assumptions A1 through A4 are the overall boundary conditions on the sheet. A1 simply states that radiation heat transfer to the sheet from the hot surface is negligible. Paper emissivity is low and the hot surface-to-sheet temperature difference declines rapidly after contact. A2 means that the hot surface is solid, not porous, and no mass is transferred through it. A3 indicates that the thermal contact from the sheet to the felt is minimal compared to the contact between the hot surface and sheet. A4 means that there is no substantial pressure differential across the felt. Note that this is a condition on the pressure at the outer surface, not a condition on the temperature there.

A5 is an approximation to the overall direction of heat and mass transfer because the thickness of the sheet is much less than the lateral dimensions.

A6 through A8 pertain to the continuity equations for the model. A6 is an assumption of slug flow to simplify the transport calculations. A7 and A8 allow each zone to be characterized by its own unique value of moisture content and

state that this moisture content is not altered by vapor condensing within the zone.

A9 and A10 are for the momentum equations. Darcy's law is the momentum equation for flowing liquid and vapor. Calculations show that the Reynolds number is well within the appropriate regime for suitable application of Darcy's law.[60] A10 allows the momentum equation for the deforming fiber bed to be replaced by a simple compression equation and states that each zone undergoes its own uniform compression.

Assumptions A11 through A15 pertain to the energy equation. All are standard assumptions used in drying models.[61,62]

A16 is made so that unique values can characterize a zone's vapor and liquid properties and variations with position in the zone can be neglected.

A17 might appear to be the most questionable approximation. The capillary pressure is typically calculated with the Laplace equation

$$Pcap = \frac{2 * \gamma * \cos \theta}{r} \qquad (9)$$

where Pcap is the capillary pressure, γ is the liquid surface tension, θ is the contact angle, and r is the pore radius. First, this applies to pores of circular cross section and therefore should NOT apply to paper since it has irregularly shaped pores. Second, at high drying temperatures the surface tension of water is drastically reduced and this serves to decrease Pcap. Third, even at elevated mechanical pressure there are still many pores in the sheet with large radii.[63] Fourth, the equation applies to a SATURATED pore, and it requires very

large mechanical pressures to achieve interfiber saturation. Therefore, at least in the initial stages of drying, the larger pores remain unsaturated.

When the sheet does become saturated, then a significant capillary pressure might be expected. However, it is exactly in this regime (wet pressing) that moisture loss by liquid expression dominates water removal and so the "drying" (evaporative) aspect becomes a secondary process. Thus, A17 may not be as bad an approximation as it would first appear to be. The net result is that the liquid pressure (and its gradient) is identical to the vapor pressure (and its gradient).

A18 is a means of trapping a certain fraction of liquid inside the fibers, thereby making it unavailable for vapor-induced displacement. Since the actual density of cellulose is about 1.55 g/cc, an apparent cell wall density of 1.0 g/cc means that roughly one-third of the fiber volume can contain liquid. Given the density of water and a "typical" fiber cross-sectional area, it is possible to determine the moisture ratio at which the fibers just become saturated.

Furthermore, by holding the apparent cell wall density fixed, a limit is placed on the minimum porosity attainable. Compressing the sheet is equivalent to moving the fibers closer together. The porosity of the zone can be no lower than the fiber wall porosity (about 0.33). In dry zones, A18 allows the porosity to go to zero by removing the apparent cell wall density restriction. Since there is no water there to occupy the space, the fiber wall can collapse.

A19 is made so that the moisture distribution in a zone can be treated as uniform and so that the vapor pressure is simply a function of the temperature. However, the hygroscopic effect on the heat of desorption is accounted for, since it strongly influences heat transfer calculations. This is detailed later in the thesis.

A20 is a convenience to simplify the mass and energy equations in zones of linear temperature gradient (zones where vapor flow is handled by Darcy's law) and to eliminate the need for a detailed gas continuity equation in the outer zone during the transition regime.

ADVANCED MODEL EQUATIONS

Continuity and energy equations determine the temperatures and rates of change of position of the interfaces and describe the heat and mass transfer within each zone. The interfaces separate zones of different moisture content. Figure 10 shows each kind of zone that may be present and the terminology for the zones, interfaces, and temperatures. Interface 1 separates zone 1 (no liquid moisture), which is adjacent to the hot surface, from zone 2 (liquid moisture only inside the fibers). Interface 2 separates zone 2 from zone 3 (liquid moisture inside and outside the fibers), or zone 2 from zone 4 (no liquid moisture), which can develop if heat is transferred to the far side of the sheet faster than interfiber liquid can flow there. Interface 3 separates zone 3 from zone 4. If zone 3 does not exist, either because there is initially not enough moisture present to saturate the fibers or because all the interfiber liquid is pushed out or evaporated, HIDRYER1 places interface 3 at δ_T.

The reasonable assumption of linear temperature gradients in zones 1 and 2 because of the low moisture contents and the porosities, and because of the low specific heat of cellulose, introduces a considerable simplification to the required calculations. For example, the energy equations for these zones are converted from partial differential equations to algebraic ones (which are easily solved provided the interface temperatures can be determined). Thus, the zone concept is a means of simplifying a more "continuous" type of model by limiting the regions over which detailed calculations have to be performed.

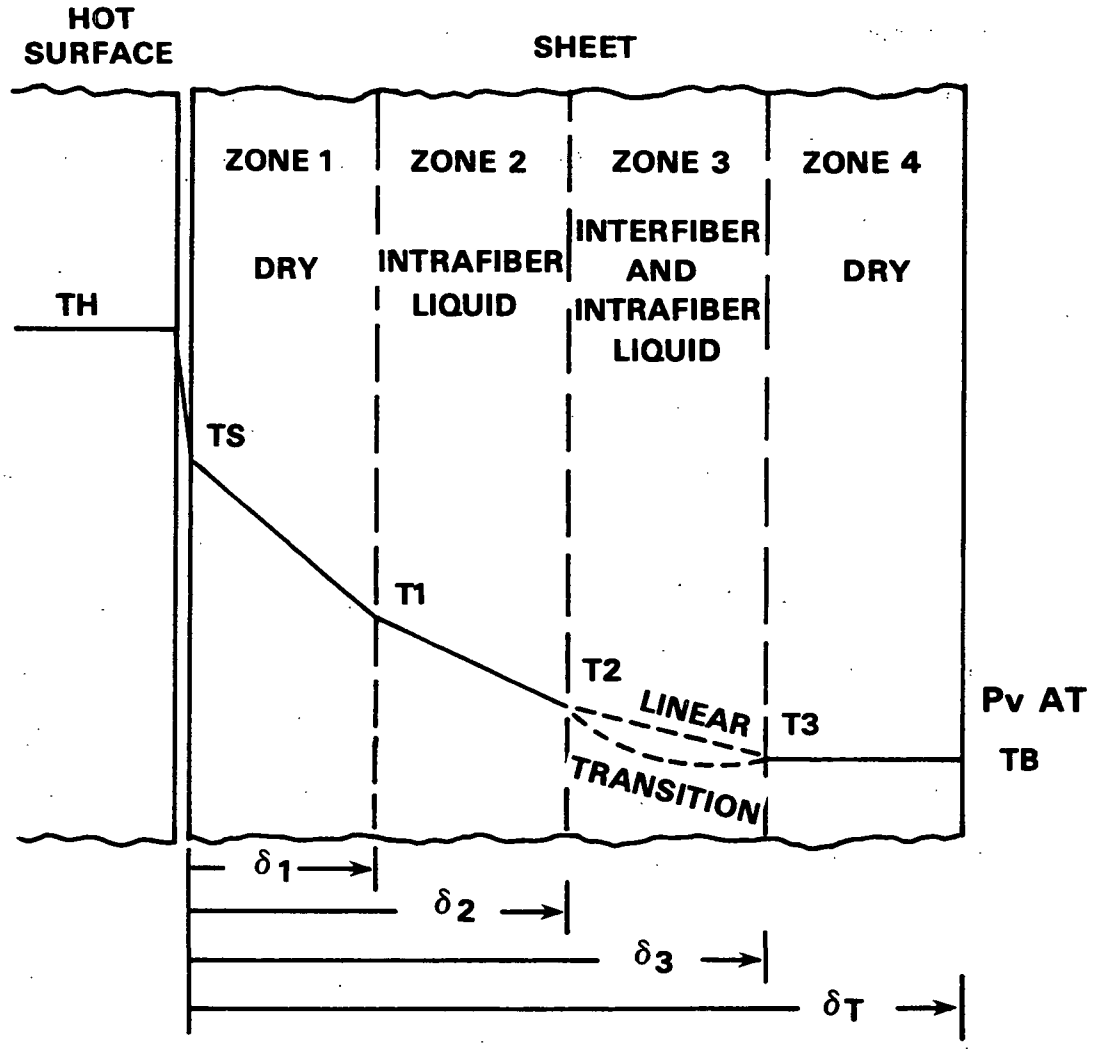

Figure 10. Zone, interface, and temperature designations for advanced model equations.

Zone Continuity and Momentum Equations

Consider the one-dimensional flow of a mixture of fibers, liquid water, and a gas composed of water vapor. Consider further that a certain fraction of the liquid water is trapped within the fibers and moves at the fiber velocity. The continuity equation is:

$$\frac{\partial}{\partial t}\left(\rho_F * (1-\varepsilon) + \rho_w * (1-a) * \varepsilon * S + \rho_w * a * \varepsilon * S + \rho_v * \varepsilon * (1-S)\right) =$$

$$-\frac{\partial}{\partial z}\left(\rho_F * (1-\varepsilon) * Vf + \rho_w * (1-a) * \varepsilon * S * Vf\right.$$

$$\left. + \rho_w * a * \varepsilon * S * Vwater + \rho_v * \varepsilon * (1-S) * Vgas\right) \qquad (10)$$

where ρ_F, ρ_w, and ρ_v are the fiber, water, and vapor densities; a is the fraction of liquid water external to the fibers; Vf, Vwater, and Vgas are the fiber, water, and vapor velocities relative to the fixed origin; z is the position coordinate and t is time.

Darcy's law, the momentum equation for the flowing gas and liquid, is used to describe the velocities of the flowing gas and liquid relative to the moving fibers.[64]

$$Vv = \varepsilon * (1-S) * (Vgas-Vf) = -\frac{Ka * Kv}{\mu_v} * \frac{\partial Pv}{\partial z} \tag{11}$$

$$Vw = a * \varepsilon * S * (Vwater-Vf) = -\frac{Ka * Kw}{\mu_w} * \frac{\partial Pw}{\partial z} \tag{12}$$

where Vv and Vw are the vapor and liquid superficial velocities relative to the moving fibers; Ka is the absolute permeability; Kv and Kw are the vapor and liquid relative permeabilities; Pv and Pw are the vapor and liquid pressures; and μ_v and μ_w are the vapor and liquid viscosities.

With these definitions, the continuity equation can be written as:

$$\frac{\partial D}{\partial t} = -\frac{\partial}{\partial z}(D * Vf + \rho_w * Vw + \rho_v * Vv) \tag{13}$$

where

$$D = \rho_F * (1-\varepsilon) + \rho_w * \varepsilon * S + \rho_v * \varepsilon * (1-S) \tag{14}$$

However, $\rho_v << \rho_w < \rho_F$, and with

$$S = \frac{(1-\varepsilon) * MR * \rho_F}{\rho_w * \varepsilon} \tag{15}$$

then

$$D = \rho_F * (1-\epsilon) * (1+MR) \tag{16}$$

where MR is the moisture ratio.

The momentum equation for each zone of the fiber matrix is replaced by a power law compression equation:

$$C = M * P^N \tag{17}$$

where C is the dry fiber concentration (mass/total volume), and where each zone has its own compression constants (M and N) and effective mechanical pressure (P); the assumption of uniform zone compressibility gives

$$Vf = \frac{\overline{L}}{L} * \frac{\partial L}{\partial t} + Vf' \tag{18}$$

where $\overline{L}$ is the distance inside the zone measured from the zone's interface closer to the origin, L is the zone thickness, $\partial L/\partial t$ is the "compression velocity" or change in zone thickness caused by P, and Vf' is the compression velocity of the zone interface closer to the origin with respect to that (fixed) origin.

For an unsaturated medium during the heatup regime, make the approximation that Vwater = Vf so that Vw = 0. (This is a compression model, not a wet pressing model.) For this case, and for an unsaturated or saturated zone in the transition or linear regimes, use assumption A6 so that the continuity equation becomes

$$\frac{\partial D}{\partial t} = - \frac{\partial}{\partial z} (D * Vf) \tag{19}$$

If the sheet becomes saturated during heatup, its compression is significantly affected by the buildup of a substantial internal hydraulic pressure. The overall continuity equation can be separated into its fiber and water components and combined with Darcy's law to produce:

$$\frac{\partial\ MR}{\partial\ t} = \frac{\rho_w * Ka * Kw}{(1-\epsilon) * \rho_F * \mu_w} * \frac{\partial^2 Pw}{\partial\ z^2} \tag{20}$$

Write $\partial MR/\partial t$ as $(\partial MR/\partial L)*(\partial L/\partial t)$ and when S = 1, $\partial MR/\partial L = \rho_w/BW$ where BW is the sheet basis weight. With $BW/L = (1-\epsilon)*\rho_F$ and Kw = 1 when S = 1, Eq. (20) becomes

$$\frac{1}{L} * \frac{\partial\ L}{\partial\ t} = \frac{Ka}{\mu_w} * \frac{\partial^2\ Pw}{\partial\ z^2} \tag{21}$$

Let

$$Pw = A1 + A2 * z + A3 * z^2 \tag{22}$$

so that

$$\frac{\partial\ Pw}{\partial\ z} = A2 + 2 * A3 * z \tag{23}$$

and

$$\frac{\partial^2\ Pw}{\partial\ z^2} = 2 * A3 \tag{24}$$

At z = 0, $\partial Pw/\partial z = 0$ and therefore A2 = 0. Integrating Eq. (22) from z = 0 to z = L and noting that at z = L $\partial Pw/\partial z = 2*A3*L$ and Pw = Patm (the ambient pressure) allows a calculation of A1 and A3 to yield:

$$Pw = Patm + \frac{\mu_w * (z^2-L^2)}{2 * Ka * L} * \frac{\partial\ L}{\partial\ t} \tag{25}$$

For simplicity, define an integral-average hydraulic pressure such that

$$\overline{Pw} = Patm - \frac{\mu_w * L}{3 * Ka} * \frac{\partial L}{\partial t} \tag{26}$$

and use P = Pmech - $\overline{Pw}$ in the compression equation, where Pmech is the absolute applied mechanical pressure. The applied mechanical pressure is the sum of Pmechg (the gage mechanical pressure) and ambient pressure and therefore

$$P = Pmechg + \frac{\mu_w * L}{3 * Ka} * \frac{\partial L}{\partial t} \tag{27}$$

With $C = M*P^N = BW/L$ and $Ka = 1/(R*C)$ then

$$\frac{\partial L}{\partial t} = \frac{3 *((C/M)^{1/N} - Pmechg)}{\mu_w * BW * R} \tag{28}$$

R, the specific filtration resistance, is a function of Pmechg; Pmechg is a prescribed function of time, so Eq. (28) is an initial value problem solvable by standard numerical techniques once L at t = 0 is specified.

Zone Thermal Energy Equation

Consider a one-dimensional energy equation where energy is transferred only by conduction or convection. Using the same kinds of manipulation as in the continuity equation gives:

$$\frac{\partial}{\partial t}(Dc * T) = -\frac{\partial}{\partial z}\left(-K * \frac{\partial T}{\partial z}\right.$$

$$\left. + (Dc * Vf + \rho_w * Cpw * Vw + \rho_v * Cpv * Vv) * T\right) \tag{29}$$

where T is temperature, K is thermal conductivity, Cpw and Cpv are the constant pressure specific heats of water and vapor, and where

$$Dc = \rho_F * (1-\epsilon) * Cpf + \rho_w * \epsilon * S * Cpw + \rho_v * \epsilon * (1-S) * Cpv \quad (30)$$

Cpf is the constant pressure specific heat of cellulose and with Eq. (15)

$$Dc = \rho_F * (1-\epsilon) * (Cpf + MR * Cpw) \quad (31)$$

Observe that Dc = b*D where

$$b = \frac{(Cpf + MR * Cpw)}{(1 + MR)} \quad (32)$$

Expand and rearrange Eq. (29) noting that b is independent of z within a given zone and use continuity Eq. (13) to simplify; divide by b*D to obtain

$$\frac{\partial T}{\partial t} + \frac{T}{b} * \frac{\partial b}{\partial t} + \frac{T}{D} * \frac{\partial}{\partial z}((\frac{Cpw}{b} - 1)* \rho_w * Vw + (\frac{Cpv}{b} - 1) * \rho_v * Vv) =$$

$$\frac{K}{b*D} * \frac{\partial^2 T}{\partial z^2} - (Vf + \frac{\rho_w * Cpw * Vw}{b*D} + \frac{\rho_v * Cpv * Vv}{b*D}) * \frac{\partial T}{\partial z} \quad (33)$$

For a nonsaturated medium $\partial b/\partial t = 0$ (Cpf and Cpw held constant). Using the slug flow assumption and the approximation $\rho_v * Cpv/(b * D) = 0$ gives

$$\frac{\partial T}{\partial t} = \frac{K}{b * D} * \frac{\partial^2 T}{\partial z^2} - Vf * \frac{\partial T}{\partial z} \quad (34)$$

for the nonsaturated heatup regime (with Vw = 0 as before) and

$$\frac{\partial T}{\partial t} = \frac{K}{b * D} * \frac{\partial^2 T}{\partial z^2} - (Vf + \frac{\rho_w * Cpw * Vw}{b * D}) * \frac{\partial T}{\partial z} \quad (35)$$

for the saturated heatup regime and the saturated or nonsaturated outer zone during the transition regime. Equations (34) and (35) must be solved to yield the temperature profiles.

For the inner zone during transition and all zones during the quasi-static regime no energy equation is required, since all temperature gradients are assumed linear.

Convective-Diffusion Equations

Two general methods available for the solution of Eq. (34) and (35) are transformation of variables and numerical solution. Transform Eq. (34) by defining $x = z/L$ and $t' = t$ so that $\partial x/\partial z = 1/L$, $\partial x/\partial t = -(z/L^2) * \partial L/\partial t$, $\partial t'/\partial z = 0$, and $\partial t'/\partial t = 1$. Thus, $\partial T/\partial z = (1/L) * \partial T/\partial x$, $\partial^2 T/\partial z^2 = (1/L^2) * \partial^2 T/\partial x^2$, and $\partial T/\partial t = \partial T/\partial t' - (z/L^2) * \partial L/\partial t * \partial T/\partial x$. Since $Vf = (z/L) * \partial L/\partial t$, substitution converts Eq. (34) to

$$\frac{\partial T}{\partial t'} = \psi * \frac{\partial^2 T}{\partial x^2} \tag{36}$$

where

$$\psi = \frac{K}{b * D * L} \tag{37}$$

The initial condition is $T = TI$ at $t' = 0$ for all x. The boundary conditions are: $BI * (TH - T) = -\partial T/\partial x$ at $x = 0$ and $\partial T/\partial x = 0$ at $x = 1$. The first BC is a statement of the imperfect thermal contact between the hot surface and sheet with $BI = Hc * L/K$. The second BC is the assumption of no conductive heat flux from the sheet to the felt.

Equation (35) requires different transformations depending on its application to the saturated heatup or saturated or nonsaturated transition regimes. For the saturated heatup regime continuity demands $Vw = -(z/L) * \partial L/\partial t$. The same transformation of variables as for Eq. (34) gives

$$\frac{\partial T}{\partial t'} = \psi * \frac{\partial^2 T}{\partial x^2} + \phi * \frac{\partial T}{\partial x} \tag{38}$$

with ψ as in Eq. (37) and

$$\phi = -\frac{\rho_w * Cpw * x}{b * D * L} * \frac{\partial L}{\partial t'} \tag{39}$$

The initial and boundary conditions are the same as before.

The application of Eq. (35) to the outer zone during transition requires a different transformation. The outer zone is designated as zone 3 and is bounded by interfaces 1 and 3 or 2 and 3. Define $x = (z - L2 - L1)/L3$ and $t' = t$ so that $\partial x/\partial z = 1/L3$, $\partial x/\partial t = -(\partial L1/\partial t + \partial L2/\partial t + x * \partial L3/\partial t)/L3$, and again $\partial t'/\partial z = 0$ and $\partial t'/\partial t = 1$. L1, L2, and L3 are the thicknesses of zones 1, 2, and 3. Substitution into Eq. (35) yields an equation of the form of Eq. (38) with

$$\psi = \frac{K}{b * D * L3} \tag{40}$$

and

$$\phi = \frac{\rho_w * Cpw * Vw}{b * D * L3} \tag{41}$$

The value of Vw is uniform in zone 3 by the slug flow assumption and is calculated using Darcy's law (with the pressure gradient given by the vapor pressure drop across zone 3). The initial condition for this case is the temperature distribution just after the heatup regime. The boundary conditions are that the heat conducted to interface 1 or 2 is just balanced by the sum of the heat conducted into zone 3 and a "source" or "sink" term composed of the latent heat and the net condensation or evaporation at interface 1 or 2. The other boundary condition is that there is no net conductive heat flux past interface 3.

A numerical scheme is needed to solve Eq. (38). A stable, high-order accuracy, finite difference method is available which uses weighted finite differences to overcome calculational instabilities.[65] This method also removes some severe restrictions on the time step-grid spacing combination typical of other convective-diffusion numerical solutions. The second spatial derivative is treated as a central difference:

$$\frac{\partial^2 T}{\partial x^2} = \frac{T(i+1,j) - 2 * T(i,j) + T(i-1,j)}{\Delta x^2} \tag{42}$$

where Δx is the grid spacing, i is the grid number (i = 1 to i = k), and j is the time increment number. The time derivative is treated as a forward difference:

$$\frac{\partial T}{\partial t'} = \frac{T(i,j+1) - T(i,j)}{\Delta t} \tag{43}$$

where Δt is the time increment. The temperature gradient is treated as an upstream weighted difference. Since $\phi > 0$ for the outer zone cases considered in this thesis,

$$\frac{\partial T}{\partial x} = \frac{2 * T(i+1,j) + 3 * T(i,j) - 6 * T(i-1,j) + T(i-2,j)}{6 * \Delta x} \tag{44}$$

Equations 42 through 44 are combined to give

$$T(i,j+1) = (A - B/3) * T(i+1,j) + (1 - 2 * A - B/2) * T(i,j) + (A + B) * T(i-1,j) - (B/6) * T(i-2,j) \tag{45}$$

where

$$A = \frac{\psi * \Delta t}{\Delta x^2} \tag{46}$$

and

$$B = \frac{\phi * \Delta t}{\Delta x} \tag{47}$$

and HIDRYER1 maintains

$$\Delta t < \frac{\Delta x}{2* \psi/\Delta x + \phi/2} \tag{48}$$

Equation 45 applies from i = 3 to i = k-1. At i = 2, a central difference operator is used for $\partial T/\partial x$ to give

$$T(2,j+1) = (A - B/2) * T(3,j) + (1 - 2 * A) * T(2,j) + (A + B/2) * T(1,j) \tag{49}$$

At the boundaries i = 1 and i = k the operative equation is derived by integrating the energy equation over a half interval.[66] At x = 0, integrate from 0 to $\Delta x/2$ to obtain:

$$\frac{\Delta x}{2} * \frac{\partial T}{\partial t'(avg)} = \psi * \frac{\partial T}{\partial x}\Bigg]_0^{\Delta x/2} - \overline{\phi} * T\Bigg]_0^{\Delta x/2} \tag{50}$$

$\overline{\phi}$ and $\partial T/\partial t'(avg)$ are averages over the half interval such that

$$\overline{\phi} = \frac{\phi\ (\Delta x/2) + \phi(0)}{2} \tag{51}$$

and

$$\frac{\partial T}{\partial t'(avg)} = \frac{1}{2} * \left(\frac{\partial T}{\partial t'(\Delta x/2)} + \frac{\partial T}{\partial t'(0)}\right) \tag{52}$$

Let

$$\frac{\partial T}{\partial t'(\Delta x/2)} = \frac{1}{2} * \left(\frac{\partial T}{\partial t'(\Delta x)} + \frac{\partial T}{\partial t'(0)}\right) \tag{53}$$

so that

$$\frac{\partial T}{\partial t'(avg)} = \frac{1}{4} * \left(\frac{\partial T}{\partial t'(\Delta x)} + 3 * \frac{\partial T}{\partial t'(0)}\right) \tag{54}$$

and Eq. (33) can be used to find the time derivatives at $x = \Delta x$ and $x = 0$. Let

$$\frac{\partial T}{\partial x(\Delta x/2)} = \frac{1}{2} * \left(\frac{\partial T}{\partial x(\Delta x)} + \frac{\partial T}{\partial x(0)}\right) \tag{55}$$

Apply the boundary condition $BI*(TH - T(1,j)) = -\partial T/\partial x(0)$ and

$$\frac{\partial T}{\partial x(0)} = \frac{2}{\Delta x} * T\Big]_{0}^{\Delta x/2} \tag{56}$$

to get $T(\Delta x/2)$. Let

$$\frac{\partial T}{\partial x(\Delta x)} = \frac{-2 * T(1,j) - 3 * T(2,j) + 6 * T(3,j) - T(4,j)}{6 * \Delta x} \tag{57}$$

to get

$$\begin{aligned} T(1,j+1) = {} & T(1,j) - (T(2,j+1) - T(2,j))/3 \\ & + 4 * B * BI * \Delta x * (TH - T(1,j))/3 + (2 * A/9) * (6 * BI * \Delta x \\ & * (TH - T(1,j)) - 2 * T(1,j) - 3 * T(2,j) + 6 * T(3,j) - T(4,j)) \end{aligned} \tag{58}$$

At the cold side, integrate from $x = 1 - \Delta x/2$ to $x = 1$. Apply the boundary condition $\partial T/\partial x(1) = 0$ and use similar averaging techniques to get

$$\begin{aligned} T(k,j+1) = {} & T(k,j) - (T(k-1,j+1) - T(k-1,j))/3 \\ & - (2*A/9) * (2 * T(k,j) + 3 * T(k-1,j) - 6 * T(k-2,j) + T(k-3,j)) \end{aligned} \tag{59}$$

Observe that when $\phi = 0$ Eq. (45), (49), (58), and (59) are solutions of Eq. (36) and so all cases are covered.

As δ_2 and δ_3 move into the sheet, a modification of the numerical method is employed. The first grid point in the transition zone is designated as i'. The last grid point of the transition zone is designated as i". δ' and δ" are the distances of these points from the origin. Because the distance between these special grid points and the interfaces closest to them may not correspond to the usual grid point spacing, temperatures at i', i", and the grid points adjacent to them must be calculated based on uncentered finite differences.

Taylor series expansions for the temperatures at the grid points around the one in question can be added, subtracted, and combined to give

$$\begin{aligned} T(i',j+1) = {} & T(i',j) - \phi * \Delta t * (T(i'+1,j) - Tx)/(\Delta x + DIFF') \\ & + 2 * \psi * \Delta t * (T(i'+1,j)/(\Delta x * (\Delta x + DIFF')) \\ & - T(i',j)/(\Delta x * DIFF') + Tx/(DIFF'*(\Delta x + DIFF'))) \end{aligned} \tag{60}$$

where Tx is either T1 or T2 depending on which interface is involved. The model treats the transition zone as if it were part of one large zone undergoing heating and compression. Instead of applying boundary conditions and calculating new temperatures for all the grid points, the model simply calculates the bounding interface temperatures from the interface equations and applies these temperatures directly. In terms of the relative (dimensionless) distance Δx

$$DIFF' = \frac{BW3 * (1 + BW4/BW)}{BW} - \Delta x * (1 - i' + i") \tag{61}$$

At the other end

$$\begin{aligned} T(i",j+1) = {} & T(i",j) - \phi * \Delta t*(Tx - T(i"-1,j))/(\Delta x + DIFF") \\ & + 2* \psi * \Delta t * (Tx/(DIFF" * (\Delta x + DIFF")) \\ & - T(i",j)/(\Delta x * DIFF") \\ & + T(i"-1,j)/(\Delta x * (\Delta x + DIFF"))) \end{aligned} \tag{62}$$

where

$$DIFF'' = \Delta x - \frac{BW3 * BW4}{BW} \qquad (63)$$

and Tx is either T2 or T3. The new temperature at i'+1 is found from Eq. (49). If DIFF' is equal to Δx or if the interface advances across a grid point, then Eq. (49) is also used at i' and Eq. (60) is bypassed. All other interior points are calculated with Eq. (45), but the temperature at i" is found with Eq. (62) if DIFF" is less than Δx and the interface does not cross a grid point.

Interface Equations

During the high intensity drying process zones of different moisture content develop inside the sheet. These zones are bounded by interfaces at various temperatures. The temperatures determine the rates of heat transfer and rates of change of interface position; since the interfaces separate zones of different moisture content, their positions are directly related to the overall sheet moisture content. Refer to Fig. 10 for the zones that may be present and the terminology for the zones, interfaces, and temperatures.

The "dry" zones contain water vapor. Zone 2 contains liquid water only inside the fibers. Zone 3 contains liquid water inside and outside the fibers.

Consider a "general" interface. Heat, liquid, and gas (vapor only) flow toward the interface on the (-) side close to the hot surface and flow away from the interface on the (+) side toward the felt. The net mass flux results in a change in interface position and is calculated from

$$(\rho_w * Vw(+) - \rho_w * Vw(-)) + (\rho_v * Vv(+) - \rho_v * Vv(-)) = \varepsilon * S * \rho_w * d\delta/dt \qquad (64)$$

for interfaces 1 and 2 and

$$\rho_w * Vw(-) - (\rho_v * Vv(+) - \rho_v * Vv(-)) = \varepsilon * S * \rho_w * d\delta/dt \qquad (65)$$

at interface 3. There is no liquid flow on the (+) side of interface 3 (unless $\delta_3 = \delta_T$) because any flow past δ_3 would be absorbed by the dry fibers in zone 4.

An energy balance gives

$$Q(-) = Q(+) + (\rho_v * Vv(+) - \rho_v * Vv(-)) * (\Delta h + \Delta h^*) \qquad (66)$$

at interfaces 1 and 2; at interface 3 the energy balance gives

$$Q(-) = (\rho_v * Vv(+) - \rho_v * Vv(-)) * (\Delta h + \Delta h^*) \qquad (67)$$

where Δh^* is the average heat of desorption at the interface.

Heatup and Transition Regimes

During the heatup regime there is only one zone (2 or 3) present, since the sheet starts and stays at uniform saturation. Interface 1 is at $z = 0$. Interface 2 is at δ_T if zone 2 is present and at $z = 0$ if zone 3 is present. Interface 3 is at δ_T. It is assumed that no evaporation takes place during heatup.

When TS is raised incrementally above the saturation temperature corresponding to the hydraulic pressure at $z = 0$, the liquid in the pores of the sheet sees the apparent pressure gradient corresponding to the vapor pressures at TS and TB. The liquid is assumed to flow in slug flow, and δ_2 defines the limit of thermodynamic saturation (and linear temperature gradient) so that no vapor flows past δ_2 in transition. For the first time increment the only nonzero term of Eq. (64) is $\rho_w * Vw(+)$. By assumption, the vapor and liquid pressures are identical and Darcy's law for the flowing liquid is

$$Vw = -\frac{Ka3 * Kw}{\mu_w} * \frac{\partial\ Pv}{\partial\ z} \qquad (68)$$

where Ka3 is the absolute permeability of zone 3. To link the mass and energy balance equations write $\partial Pv/\partial z$ as $(\partial Pv/\partial T) * (\partial T/\partial z)$. The correct expression for $\partial T/\partial z$ is $(TB - TS)/\delta_T$, the virtual gradient that the liquid experiences. Then, from Eq. (64) and (68)

$$\rho_w * KAKW * \frac{\partial Pv}{\partial T} * \frac{(TS - TB)}{(\mu_w * \delta_T)} = \varepsilon' * S' * \rho_w * D2 \qquad (69)$$

where KAKW = Ka3 * Kw, ε' and S' are the interfiber porosity and saturation (since only interfiber water flows), and D2 is the rate of change of position of δ_2 due only to vapor-induced liquid flow. This rate multiplied by BW * $\Delta t/\delta_T$ gives an increment in the basis weight of zone 2 and a corresponding decrement in the basis weight of zone 3. The increment or decrement is added to the old value of zone basis weight to get a new value at TIME(new) = TIME(old) + Δt. The liquid properties are evaluated at TS.

If no interfiber water exists, the transition regime is simply a continuation of the heatup regime calculation until the temperature at δ_T is raised incrementally above TB. Then, a dry zone propagates into the sheet toward the hot surface. This case is treated later.

After the first time increment, two cases can occur: δ_1 and δ_2 are either equal or they are unequal. When $\delta_1 = \delta_2$ the only nonzero term in Eq. (64) is $\rho_w * Vw(+)$. Since no vapor flows Q(-) = Q(+), where Q(-) = U * (TH - T2) and Q(+) = K3 * (T2 - T')/(δ' - δ_2). U is defined so that $1/U = 1/Hc + \delta_2/Kl$. T' is the temperature at the first finite difference grid point in zone 3, δ' is the distance of this grid point from the origin, and Kl and K3 are the thermal conductivities of zones 1 and 3. From the heat balance, a new value for T2 is isolated as

$$T2 = \frac{TH + I * T'}{1 + I} \tag{70}$$

where

$$I = \left(\frac{1}{Hc} + \frac{\delta_2}{K1}\right) * \left(\frac{K3}{\delta' - \delta_2}\right) \tag{71}$$

Of course, when $\delta_1 = \delta_2$, T1 = T2. The mass balance gives the rate of advance of interface 2 using Eq. (69) with the (virtual) temperature gradient (T2 - T3)/($\delta_3 - \delta_2$). If $\delta_3 = \delta_T$ then TB is used in place of T3.

If δ_1 and δ_2 are not equal, then equations are needed at both interfaces. At δ_1, ρ_v*Vv(+) is the only nonzero mass flow term. Thus,

$$\rho_v * \frac{Ka2}{\mu_v} * \frac{\partial\ Pv}{\partial\ T} * \frac{(T1 - T2)}{(\delta_2 - \delta_1)} = \varepsilon_2 * S2 * \rho_w * D4 \tag{72}$$

D4 is the rate of advance of δ_2 due solely to evaporation. ε_2 and S2 are the porosity and saturation of zone 2. Vapor properties are evaluated at T1 and T2 and then averaged. In the heat balance, Q(-) = U * (TH - T1) and Q(+) = K2 * (T1 - T2)/($\delta_2 - \delta_1$). Isolating for T1 gives

$$T1 = \frac{TH + I * T2}{1 + I} \tag{73}$$

where

$$I = \left(\frac{1}{Hc} + \frac{\delta_1}{K1}\right) * \frac{1}{(\delta_2 - \delta_1)} * \left(\frac{\rho_v * Ka2 * (\Delta h + \Delta h^*)}{\mu_v} * \frac{\partial\ Pv}{\partial\ T} + K2\right) \tag{74}$$

The vapor properties, except Δh, are averaged using T1 and T2. Δh is evaluated at T1 only and Δh^* is the latent heat correction factor based on the moisture ratios of zones 1 and 2.

At δ_2, ρ_w * Vw(+) and ρ_v * Vv(-) are the mass flow terms. ρ_v * Vv(-) at δ_2 is just ρ_v * Vv(+) at δ_1. ρ_w * Vw(+) is derived as for Eq. (68) and (69) so that

$$\frac{\rho_w * KAKW * (T2 - T3)}{\mu_w * (\delta_3 - \delta_2)} * \frac{\partial Pv}{\partial T} - \frac{\rho_v * Ka2 * (T1 - T2)}{\mu_v * (\delta_2 - \delta_1)}$$

$$* \frac{\partial P_v}{\partial T} = \varepsilon' * S' * \rho_w * D5 \qquad (75)$$

D5 is the net rate of motion of δ_2. Vapor and liquid properties are averaged with T2 and T3 or T1 and T2 as appropriate. In the heat balance, Q(-) is the same as Q(+) at δ_1. Q(+) = K3 * (T2 - T')/(δ' - δ_2), so that

$$T2 = \frac{II * T1 + T'}{1 + II} \qquad (76)$$

where

$$II = \left(\frac{K2}{K3} + \frac{\rho_v * Ka2 * (\Delta h + \Delta h^*)}{\mu_v * K3} * \frac{\partial Pv}{\partial T}\right) * \frac{(\delta' - \delta_2)}{(\delta_2 - \delta_1)} \qquad (77)$$

The vapor properties are evaluated in the usual way. Equations (73) and (76) then yield

$$T1 = \frac{(1 + II) * TH + I * T'}{1 + I + II} \qquad (78)$$

$$T2 = \frac{II * TH + (1 + I) * T'}{1 + I + II} \qquad (79)$$

HIDRYER1 calculates T' and then finds T1 and T2.

If $\delta_3 = \delta_T$ and T3 is equal to TB then

$$\frac{K3}{\Delta h + \Delta h^*} * \frac{(T3 - T'')}{\Delta x} = \varepsilon_3 * S3 * \rho_w * D6 \qquad (80)$$

where T" is the temperature of the first finite difference grid point just toward the origin relative to δ_3. If T3 is less than TB then D6 = 0.

The liquid mass flow to δ_3 is given by the first term of Eq. (75) so that

$$\varepsilon' * S' * D2 = \varepsilon_3 * S3 * D7 \tag{81}$$

The net change in the position of δ_3 is determined by the sum of D6 and D7. The new value of T3 comes from the finite difference temperature calculations.

If δ_3 is not equal to δ_T then

$$\frac{\rho_v * Ka4 * (T3 - TB)}{\mu_v * (\delta_T - \delta_3)} * \frac{\partial\ Pv}{\partial\ T} = - \varepsilon_3 * S3 * \rho_w * D6 \tag{82}$$

and Eq. (81) still applies. The heat balance yields

$$T3 = \frac{T" + III * TB}{(1 + III)} \tag{83}$$

where

$$III = \frac{\rho_v * Ka4 * (\Delta h + \Delta h^*)}{\mu_v * K3} * \frac{\partial\ Pv}{\partial\ T} * \frac{(\delta_3 - \delta")}{(\delta_T - \delta_3)} \tag{84}$$

δ" is the distance of the T" grid point from the origin. HIDRYER1 calculates T" and then T3.

Once the interface temperatures have been calculated, the change in interface position (zone basis weight) is performed. The rate of change of basis weights is found from:

$$DBW1DT = RATE1 * BW1/L1 \tag{85}$$

$$DBW2DT = RATE2 * BW3/L3 - DBW1DT \tag{86}$$

$$DBW3DT = (RATE3 - RATE2) * BW3/L3 \tag{87}$$

$$DBW4DT = -RATE3 * BW3/L3 \tag{88}$$

where RATE1 is either 0 or D4, RATE2 is either D2 or D5, and RATE3 is the sum of D6 and D7. These are multiplied by Δt and added to the old basis weight values to get new values. The temperatures at the new positions are calculated and the cycle continues.

If no interfiber water exists at the end of heatup, the transition regime is a continuation of heatup until the temperature at δ_T is raised incrementally above TB. δ_2 moves into the sheet toward the hot surface. There is no liquid flow term and all evaporation occurs at δ_2. Equation (82) is applicable with T3 replaced by T2, δ_3 by δ_2, and ε_3 and S3 by ε_2 and S2. T2 is calculated by Eq. (83) with appropriate substitutions.

Linear Regime

The linear (quasi-static) regime begins when $\delta_2 = \delta_3$ (if interfiber water is present) or when all the temperature gradients in the outer zone become linear due to heat transfer. Vapor can flow through all zones in this regime. Several possible cases exist. If $\delta_1 = \delta_2$ and δ_3 is not equal to δ_T then the heat balance gives:

$$T2 = \frac{(1 + I) * TH + II * TB}{1 + I + II} \tag{89}$$

$$T3 = \frac{I * TH + (1 + II) * TB}{1 + I + II} \tag{90}$$

where

$$I = \frac{\dfrac{K3}{\Delta h + \Delta h^*} + \dfrac{\rho_v * KAKV}{\mu_v} * \dfrac{Pv}{\partial T}}{\dfrac{\rho_v * Ka4}{\mu_v} * \dfrac{\partial Pv}{\partial T}} * \frac{(\delta_T - \delta_3)}{(\delta_3 - \delta_2)} \tag{91}$$

$$II = \left(\frac{1}{Hc} + \frac{\delta_2}{K1}\right) * \left(\frac{1}{\delta_3 - \delta_2}\right) * \left(K3 + \frac{\rho_v * KAKV * (\Delta h + \Delta h^*)}{\mu_v} * \frac{\partial\ Pv}{\partial\ T}\right) \qquad (92)$$

and KAKV = Ka3*Kv. The vapor properties in II and the numerator of I are evaluated using T2 and T3. The latent heat term in I is evaluated at T3 and corrected using the moisture ratios of zones 3 and 4. The latent heat term in II is evaluated at T2 and corrected using the moisture ratios of zones 1 and 3. The vapor properties in the denominator of I are evaluated using T3 and TB.

If δ_1 is not equal to δ_2 and δ_3 is not equal to δ_T then

$$T1 = \frac{(1 + IV) * TH + I * TB}{1 + I + IV} \qquad (93)$$

$$T2 = \frac{IV * TH + (1 + I) * TB}{1 + I + IV} \qquad (94)$$

$$T3 = \frac{II * III * TH + (1 + I + II) * TB}{1 + I + IV} \qquad (95)$$

where I is given by Eq. (74) and

$$II = \frac{\dfrac{K2}{\Delta h + \Delta h^*} + \dfrac{\rho_v * Ka2}{\mu_v} * \dfrac{\partial\ Pv}{\partial\ T}}{\dfrac{K3}{\Delta h + \Delta h^*} + \dfrac{\rho_v * KAKV}{\mu_v} * \dfrac{\partial\ Pv}{\partial\ T}} * \frac{(\delta_3 - \delta_2)}{(\delta_2 - \delta_1)} \qquad (96)$$

$$III = \frac{\dfrac{K3}{\Delta h + \Delta h^*} + \dfrac{\rho_v * KAKV}{\mu_v} * \dfrac{\partial\ Pv}{\partial\ T}}{\dfrac{\rho_v * Ka4}{\mu_v} * \dfrac{\partial\ Pv}{\partial\ T}} * \frac{(\delta_T - \delta_3)}{(\delta_3 - \delta_2)} \qquad (97)$$

and IV = II * (1 + III). Vapor properties in the numerator of II are evaluated with T1 and T2. The latent heat in II is at T2 and the correction is made with the moisture ratios of zones 2 and 3. The vapor properties in the denominator of II and the numerator of III are evaluated with T2 and T3; the denominator of III is evaluated with T3 and TB. The latent heat term is at T3 and corrected with the moisture ratios of zones 3 and 4.

If δ_1 is not equal to δ_2 and zone 3 does not exist, then

$$T1 = \frac{(1 + I) * TH + II * TB}{1 + I + II} \tag{98}$$

$$T2 = \frac{I * TH + (1 + II) * TB}{1 + I + II} \tag{99}$$

where

$$I = \frac{\frac{K2}{\Delta h + \Delta h^*} + \frac{\rho_v * Ka2}{\mu_v} * \frac{\partial\ Pv}{\partial\ T}}{\frac{\rho_v * Ka4}{\mu_v} * \frac{\partial\ Pv}{\partial\ T}} * \frac{(\delta_T - \delta_2)}{(\delta_2 - \delta_1)} \tag{100}$$

and II is given by Eq. (74). Vapor properties in the numerator of I are evaluated with T1 and T2. The latent heat is at T2 and corrected with the moisture ratios of zones 2 and 4. The vapor properties in the denominator of I are evaluated with T2 and TB.

The mass transfer terms for the linear regime are similar to those previously outlined for the transition regime with the additional consideration that when $\delta_1 = \delta_2$ there may be evaporation and flow of vapor. The mass transfer equations that apply when $\delta_1 = \delta_2$ are

$$\rho_v * \frac{KAKV}{\mu_v} * \frac{\partial\ Pv}{\partial\ T} * \frac{(T2 - T3)}{(\delta_3 - \delta_2)} = \varepsilon_3 * S3 * \rho_w * D1 \qquad (101)$$

$$\rho_w * \frac{KAKW}{\mu_w} * \frac{\partial\ Pv}{\partial\ T} * \frac{(T2 - T3)}{(\delta_3 - \delta_2)} = \varepsilon' * S' * \rho_w * D2 \qquad (102)$$

$$\rho_v * \frac{KAKV}{\mu_v} * \frac{\partial\ Pv}{\partial\ T} * \frac{(T2 - T3)}{(\delta_3 - \delta_2)} = \varepsilon_2 * S2 * \rho_w * D3 \qquad (103)$$

where D1 represents the evaporation of interfiber and intrafiber water, D2 is the slug flow of interfiber water, and D3 is the evaporation of intrafiber water accompanying D2. HIDRYER1 selects the larger of D1 or D2 (or D1 if they are equal) as the rate of advance. If D1 is equal to or larger than D2, δ_1 and δ_2 move according to D1. If D2 is larger, δ_2 moves according to D2 and δ_1 moves according to D3.

When δ_1 is not equal to δ_2, the mass balance gives

$$\rho_v * \frac{Ka2}{\mu_v} * \frac{\partial\ Pv}{\partial\ T} * \frac{(T1 - T2)}{(\delta_2 - \delta_1)} = \varepsilon_2 * S2 * \rho_w * D4 \qquad (104)$$

which is the evaporation of intrafiber water at δ_1 and

$$\rho_v * \frac{KAKV}{\mu_v} * \frac{\partial\ Pv}{\partial\ T} * \frac{(T2 - T3)}{(\delta_3 - \delta_2)} = \varepsilon' * S' * \rho_w * D5 \qquad (105)$$

which is the evaporation of interfiber liquid at δ_2. The expression for D2 also applies at δ_2 and HIDRYER1 selects the larger of D2 or D5 as the rate of advance of δ_2.

At δ_3

$$\frac{-K3}{(\Delta h + \Delta h^*)} * \frac{(T2 - T3)}{(\delta_3 - \delta_2)} = \varepsilon_3 * S3 * \rho_w * D6 \qquad (106)$$

and Eq. (81) also applies. Note that if D1 or D5 is greater that D2 then D2 is set = 0 and so D7 = 0. δ_3 is advanced according to the sum of D6 and D7.

In the special case where zone 3 is not present, the expression for D4 is used to advance δ_1 and

$$\frac{-K2}{(\Delta h + \Delta h^*)} * \frac{(T1 - T2)}{(\delta_2 - \delta_1)} = \varepsilon_2 * S2 * \rho_w * D8 \qquad (107)$$

is used for δ_2.

The size of the time increment used depends on the magnitudes of D1, D2, etc. δ_1 can never pass δ_2, and δ_2 can never pass δ_3. HIDRYER1 calculates the largest time increment which will not violate the interface position criterion or the finite difference stability criterion and compares it to DTO, the default time increment. The smaller of the two is chosen and used.

Because the interface temperature calculations involve vapor and liquid properties whose values depend on the temperatures, an iterative procedure is used such that a temperature is calculated and averaged with the previous temperature to obtain an updated value. The updated value is used for property calculations, and a new temperature is determined. The new temperature is averaged with the previously updated one and the cycle continues for a fixed number of iterations.

SUPPLEMENTARY RELATIONSHIPS

The following relationships are in the form of correlations which yield the required quantity, given an original input parameter or a value calculated in a previous step of the program.

Applied Mechanical Pressure

The nature of the applied mechanical pressure is specified in the form of input parameters. The peak pressure and time to achieve that pressure are required. HIDRYER1 offers the option of either a ramp-and-hold pressure pulse or a pulse that duplicates a press nip. The ramp-and-hold pulse rises linearly with time to the peak pressure value and maintains pressure at the peak value until drying is complete (at a final moisture content of 6%). An extremely short rise time mimics a step change in pressure.

The press-nip pulse uses a sinusoidal function to create a symmetrical pressure pulse that achieves its peak value at the input rise time. Thus, the "nip residence time" is twice the input rise time. HIDRYER1 terminates when the moisture content reaches its target value or when the nip residence time is exceeded.

The functional forms for the pressure options are:

$$P = A1 + A2 * \frac{TIME}{RISTIM} \tag{108}$$

and

$$P = A1 + \frac{A2}{2} * (1 + \text{sine}(\frac{A3 * TIME}{RISTIM} + A4)) \tag{109}$$

where A1 is some small but finite pressure value (contact pressure at time zero) required for the compressibility equation; A2 is the peak pressure, which is an

input parameter; A3 is the numerical constant π multiplied by 3600; and A4 is the numerical constant π multiplied by 1.5. The factor of 3600 is required since HIDRYER1 calculates TIME in hours and RISTIM, the time required to achieve the peak pressure, is specified in seconds.

Typical RISTIM values are on the order of 0.05 second. A1 is arbitrarily given the value of 0.7 kPa (0.1 psi), and A2 is specified in the input conditions.

Physical Properties

The vapor and liquid physical properties are derived by modeling steam table data with a multiple regression analysis program over the range from 0 to 232°C (32 to 450°F).[67] The functional form for the properties is:

$$PROP = B1 + T * (B2 + T * (B3 + T * (B4 + T * B5))) \quad (110)$$

where PROP is the property to be determined (latent heat, specific volume, etc.) and T is the temperature.

Latent Heat Correction Factor

The hygroscopic nature of cellulose requires that an additional quantity of energy above that of the latent heat (at a given temperature) be supplied during drying. This quantity is usually treated as a correction factor to the latent heat. Data on vapor pressure reduction in the presence of cellulose can be used to calculate the incremental heat of desorption at a given moisture ratio and temperature. Available data from[68] have been used to derive a functional relationship for the incremental heat of desorption over the range of 65 to 80°C (149 to 176°F) from moisture ratios of 0.01 up to 0.24.[69] Above moisture ratios of 0.24 the heat of desorption becomes infinitesimal relative to the latent heat.

The correlation has the form:

$$\Delta h' = C1 * \exp(C2 * MR) \tag{111}$$

where $\Delta h'$ is the heat of desorption, C1 has a value of 1157.5 kJ/kg (497.63 BTU/lbm), and C2 has a value of -14.9522.

Because HIDRYER1 assumes a step change in moisture ratio from one zone to the next, an integral-average latent heat increment at each interface is used as the correction factor and is defined by integrating Eq. (111) from the moisture ratio of one zone to the moisture ratio of the adjacent zone so that:

$$\Delta h^* = D1 * \frac{\exp(D2 * MRi) - \exp(D2 * MRf)}{MRf - MRi} \tag{112}$$

where D1 has a value of 77.4 kJ/kg (33.28 BTU/lbm) and D2 has a value of -14.9522.

Thermal Conductivity

The thermal conductivity is evaluated using the parallel conductor model[61,70] and neglecting the contribution of vapor conductivity. The thermal conductivity is given by:

$$K = E1 * (1-\varepsilon) + E2 * \varepsilon * S \tag{113}$$

where E1 and E2 are the thermal conductivities of cellulose and water, 0.24 W/m-K (0.14 BTU/ft-hr-°F) and 0.682 W/m-K (0.394 BTU/ft-hr-°F), and are assumed constant.

Contact Coefficient

The relationship for the contact coefficient between the sheet and the hot surface has the form:

$$Hc = F1 * (1-\epsilon) + F2 * \epsilon * S \quad (114)$$

where F1 is the contact coefficient for dry cellulose, obtained from data in,[71] that depends on the mechanical pressure[72] and F2 is a value typical of a boiling heat transfer coefficient between water and a flat plate that is on the order of 5678 W/m^2-K (1000 BTU/ft^2-hr-°F).

Compressibility

Mathematical descriptions of saturated sheet compression originate in the modeling of wet pressing. The sheet is modeled in one of three ways: a power law model relating the concentration of fibers to the mechanical pressure; a Kelvin body model describing the sheet thickness in terms of the applied pressure and certain viscoelastic constants; and a combination model using a power law to describe fiber bending and a time dependent expression for fiber compression.

Strictly speaking, a power law model applies only to an equilibrium conditon and not to a dynamic compression case. However, modification of the basic power law[73,74] to account for time dependent effects is possible.[75] A Kelvin body (spring and dashpot in parallel) exhibits a first order response to a step change in pressure and therefore only models flow-controlled pressing phenomena, which also exhibit a first order response.[76] The combination model treats fiber bending with a power law expression and models fiber compression as a rate process, since it is time dependent.[77] After short times (milliseconds), the rate of change of the fiber compression contribution is very small in comparison with the value of the bending contribution. Thus, it should be sufficient to describe the thickness in terms of just the bending term (power law) along with some slight correction which may amount to a nearly constant fraction of the bending term.

HIDRYER1 uses the power law compression model beacuse it is the simplest and most easily modified model and because the most data are available for relating

its constants to commonly measured sheet properties such as freeness and basis weight. The form of the power law is:

$$C = M * p^N \tag{115}$$

The coefficients M and N vary with the degree of beating[78,79] and the moisture ratio of the sheet.[79] Data from,[79] although limited to pressures on the order of 7 kPa (1 psi), demonstrated that the power law describes the compression behavior of unsaturated sheets as well as saturated sheets. Using this information, expressions for evaluating M and N at different moisture ratios are obtained by multiple linear regression.[80] The form is:

$$COEFF = G1 + G2 * MR + \frac{G3}{MR + 1.5} + \frac{G4}{(MR + 1.5)^2} + \frac{G5}{MR + 1} + \frac{G6}{(MR + 1)^2} \tag{116}$$

where COEFF is either M or N and the values of G1 through G6 change depending on whether M or N is to be calculated and on the freeness of the pulp in the sheet.

To account for the dependence on refining, the values for the regression constants in Eq. (116) are determined for the same pulp at two available freeness levels[79] and fit to a parabola with an assumed minimum at a freeness of 100 CSF. (Below 100 CSF, M and N are held fixed at the 100 CSF values.) Thus, each constant in Eq. (116) is found from an expresion of the form:

$$CONST = H1 + H2 * \frac{(CSF - H3)^2}{H4} \tag{117}$$

where CONST represents G1 through G6 and H1 through H4 change depending on which value of G is to be calculated.

The compressibility of a sheet is known to be highly temperature dependent. Data describing the overall gain in moisture removal by pressing at elevated

temperatures are available,[23] but no data are available on the specific changes in sheet compressibility constants. To account for this effect, the value of M calculated from Eq. (116) is (arbitrarily) multiplied by a function of the mean temperature of the zone such that:

$$M' = M * \left(\frac{TBAR}{TI}\right)^{I1} \tag{118}$$

where M' is the modified M value, TBAR is the average zone temperature, TI is the initial sheet temperature at which M and M' are identical, and I1 is an exponent less than unity (0.25 in HIDRYER1) so that the temperature effect moderates as TBAR increases.

A moist but unsaturated sheet can be brought to saturation if the mechanical pressure is high enough. To account for this observed behavior, the value of N is modified by making it a function of the effective mechanical pressure on the sheet. The effective mechanical pressure is the applied pressure minus the hydraulic pressure. Nsat, the value of N which would give a saturated sheet at a reference pressure equal to or greater than the peak pressure, is calculated and N becomes a function of this saturation value and the original value (Nref) calulated from Eq. (116) so that there is a smooth transition in the N value as effective pressure increases. N can never be greater than Nsat since the reference pressure is equal to or greater than the peak pressure. N can never be less than Nref since the pressure is never less than the A1 constant in the pressure function. The form is:

$$N = J1 + J2 * \left(\frac{P-J3}{J4}\right)^{J5} \tag{119}$$

where J1 and J2 depend on Nref and Nsat, and J3 and J4 depend on the value of the large reference pressure chosen. J5 is the reciprocal of an odd integer and

provides a smooth transition from Nref to Nsat as effective mechanical pressure changes.[81]

Permeability

The final supplementary relationship is that of permeability. Methods of characterizing permeability are based on theoretical or empirical relationships modeling permeability as a function of sheet porosity and/or fiber cross-sectional shape.[63,82-85] The empirical relationships are, of course, limited to the ranges of porosities and fiber types investigated. The theoretical approaches in this class are of limited applicability because the fiber is assumed to be of smooth (but not necessarily circular) cross sectional shape. Consequently, the theoretical relationships tend to predict permeabilities larger (by one or two orders of magnitude) than experimentally determined ones, except at high porosities and/or freenesses.

Paper fibers have many fibrils extending into the interfiber space. While the volume of the fibrils is generally small in comparison to the volume occupied by the bulk of the fiber, the effect of the fibrils on the flow properties is quite dramatic. The amount of fibrils depends on the extent to which the fiber has been physically degraded. Since Canadian Standard Freeness is a commonly performed test and gives a reasonable (but indirect) indication of the trend of the flow properties, it seems likely that a relationship between permeability and CSF would be both convenient and consistent with a model based on macroscopic trends.

An empirical linear relationship exists between ln(CSF) and the square root of specific filtration resistance[86,87] over a range of 100 to 700 CSF. The relationship has the form:

$$\ln(CSF) = K1 + K2 * \sqrt{R} \qquad (120)$$

The calculated value of R is for a given pressure drop across the mat. Data at a variety of pressure drops on the order of 7 kPa (1 psi) and a broad range of freeness values define a family of curves of R vs. pressure drop whose shape is roughly independent of freeness.[88] Thus, by selecting some reference pressure (Pref) and the specific filtration resistance (Rref) at this pressure, a generalized relationship can be developed,[72] such as:

$$R = L1 + L2 * P + L3 * \sqrt{P} \tag{121}$$

where L1 depends on Rref, and L2 and L3 depend on Rref and Pref. The pressure drop in a saturated flow experiment is equivalent to the effective mechanical pressure exerted on the mat, and the permeability is related to R by:

$$Ka = \frac{1}{R * C} \tag{122}$$

Therefore, there is a direct link between mechanical pressure and permeability (for a given CSF).

The permeability determined in saturated flow experiments is the absolute permeability; this is the permeability in the presence of only one flowing species. To adjust for the presence of two or more flowing species, the absolute permeability is generally multiplied by a correction factor called the relative permeability. Relative permeabilities vary between zero and unity and typical relationships are:[89]

$$Kw = S'^{M1} \tag{123}$$

and

$$Kv = (1 + N1 * S') * (1-S')^{N2} \tag{124}$$

where M1 is on the order of 4 and N1 and N2 are each on the order of 3. These relationships were developed for granular media. To be consistent with the

saturation concept for which they were developed, they are based here on the interfiber saturation of the paper, since it is the interfiber liquid (or intergranular liquid) that impedes the flow of vapor. This also makes them consistent with measurements of liquid relative permeability for paper at very low moisture ratios because below a critical but finite moisture ratio the liquid relative permeability becomes infinitesimally small.[90]

HIDRYER1 is organized so that the values for constants used in the supplementary relationships are grouped in DATA statements and/or COMMON statements. Therefore, modification of the model by changing the numerical value of a constant is a simple procedure. Most supplementary relationships are implemented in either the form of a SUBROUTINE or a FUNCTION so that changing the functional form also becomes simple. Refer to Appendix 1 for a detailed program listing.

MODEL VALIDATION

HIDRYER1 is the culmination of a series of drying models that began with a numerical implementation of the Ahrens model. First, the analytical solution to the Ahrens model was programmed to provide a reference for future comparisons. Next, the equations of the Ahrens model were programmed and solved numerically to duplicate the analytical result.[91] This numerical model was expanded by accounting for effects such as heat conduction into the outer zone, the influence of permeability on interface temperature, vapor-presure-induced liquid flow, and an initial heatup period. At each stage of development, the model's predictions were compared to the previous version of the model to demonstrate that the advanced case reduced to the simpler case if conditions consistent with the less stringent assumptions were introduced into the advanced model.

The result was a model called HIDRYER that assumed zones of constant permeability and porosity. It was based primarily on low mechanical pressure cases

where the thickness did not change much as drying progressed, but gave good agreement with experimental data even in higher pressure cases,[92] since any values for porosity, thickness, heat transfer coefficient, and permeability could be specified as inputs and held fixed through the drying simulation.

The final step was to convert HIDRYER to HIDRYER1 by specifying the required supplementary relationships that determine how porosity, etc., vary with pressure, temperature, moisture ratio, and freeness. Each relationship was tested separately before being incorporated into HIDRYER and then tested again after incorporation to verify that it had been implemented correctly. Thus, the model was validated at each stage of development so that the predictions of HIDRYER1 are a result of the model and its assumptions and not a result of problems in the FORTRAN coding of the equations.

SUMMARY

Fundamental heat and mass transfer relationships, with supplementary property equations, have been assembled into a model of high intensity paper drying. The model has been converted into a FORTRAN program called HIDRYER1.

The following sections describe simulations involving an exploratory or "parametric" study to determine the basic behavior of the model and direct comparisons to laboratory data to check on the values of constants used in the model.

PARAMETRIC STUDY

INPUT PARAMETERS

HIDRYER1 requires the user to provide values for hot surface temperature (TH), boiling point temperature (TB), basis weight (BW), Canadian Standard Freeness (CSF), initial moisture ratio (MRO), default time increment (DTO), peak mechanical pressure (PMAX), and pressure rise time (RISTIM). Additionally, the user must specify choices for the following options: ramp-and-hold or sinusoidal pressure pulse; English or SI units; and two options for a packaged subroutine used to calculate sheet thickness when the sheet becomes saturated during the heatup regime. These last two options select either a variable-order Adams predictor-corrector method or Gear's method for solving a differential equation and specify how the Jacobian matrix is to be calculated (analytically, by finite differences, etc.).

OUTPUT VARIABLES

HIDRYER1 produces two types of output: printed output and output stored on magnetic disk. The printed output consists of the input parameters and the following calculated values: time (SEC), amount of moisture removed relative to the initial amount present (MREL), sheet surface temperature (TS), temperatures at the various interfaces in the sheet (T1, T2, T3), positions of the interfaces relative to total sheet thickness (RATIO1, RATIO2, RATIO3), total sheet thickness (DELTAT), instantaneous heat flux (Q), overall heat transfer coefficient (OHTC), and the gage vapor pressure corresponding to T1 (PGAUGE). The disk output does not include the input parameters, but contains all the calculated values of the printed output plus the temperature at a point midway through the basis weight of the sheet (TMID). Other variables calculated in the program can be obtained by modifying the WRITE statements in the output subroutine.

DESIGN OF PARAMETRIC STUDY

The effect of various input parameters on drying behavior is determined by running the program at different sets of conditions for each of the two pressure pulse options. Table 1 lists the parameters and the values investigated. The center column gives the values for the base case. Results from all other cases are compared against this base case and are generated by varying the value of an individual parameter from its base value while maintaining all other parameters at their base case values. The pressure option is designated as either RAMP or SINE.

Table 1. Input parameter values for parametric study.

Parameter	Minimum	BASE	Maximum
TH, °C(°F)	148.9(300)	204.4(400)	260.0(500)
MRO	1.00	1.25	1.50
BW, g/m^2(lbm/ft^2)	50.25(0.0105)	102.50(0.0210)	205.00(0.0420)
CSF	300	450	600
PMAX, kPa(lbf/in^2)	2068(300)	3447(500)	4826(700)
RISTIM, s	0.005	0.010	0.050

RESULTS AND DISCUSSION

The HIDRYER1 program was allowed to run to completion or for one hour of CPU time, whichever was shorter. In general, the SINE cases took about 20 seconds to run. The exception is the SINE case with 0.050 second RISTIM, which took about 18 minutes of CPU time. The RAMP cases averaged around 30 minutes of CPU time, and no case took longer than 38 minutes.

Base Case

Figures 11 through 18 show the results of the base case with the RAMP pressure option. Figure 11 is the drying curve for this experiment. Two points on the curve are significant. The first point, at about 0.04 second, signals the onset of drying. Examination of the numerical output reveals that the transition regime actually started at about 0.02 second, but it takes several time increments of the transition regime before noticeable (on the graph) drying occurs. The second point, at about 0.13 second, signals the end of the transition regime and the onset of the linear regime. The steep slope of the drying curve in the transition regime indicates that the drying is dominated by liquid dewatering in this period. The abrupt change in slope at the start of the linear regime indicates a shift to an evaporation and bulk vapor flow dewatering mechanism.

Figure 12 traces the sheet thickness history. The rapid pressure rise during the heatup period causes a rapid sheet compression early in the process. As the pressure levels off and as the transition regime begins, the hydraulic pressure in the sheet builds and reduces the rate of compression. As more and more liquid is removed from the sheet, it becomes easier to compress and the rate of compresion increases until all the interfiber liquid is removed (which coincides with the onset of the linear regime in this case). Once the interfiber liquid is removed, the permeability of the sheet increases and results in low hydraulic (vapor) pressure. The rate of compression slows as the moisture removal becomes dominated by an evaporation mechanism and the sheet approaches its final (zero moisture content) thickness.

Figure 13 tracks the relative position of the various interfaces in the sheet. Interfaces 1 and 2 move together from the start of the transition regime for a short time. In this period, the heat transfer rate is able to keep up

with the liquid flow rate. At about 0.05 second the liquid dewatering rate becomes greater than the heat transfer (evaporation) rate and interface 2 progresses into the sheet faster than interface 1. When interface 2 reaches the cool side of the sheet, the linear regime begins and heat transferred to the cool side causes evaporation. Interface 2 then recedes back toward the hot side. As interface 2 reaches the far side of the sheet the inflection and change in slope of the curve for RATIO1 signals the shift from liquid dewatering and internal sheet evaporation to an evaporation-only mechanism. Interface 3 is held at DELTAT because evaporation at the outer surface does not occur until all interfiber water is removed.

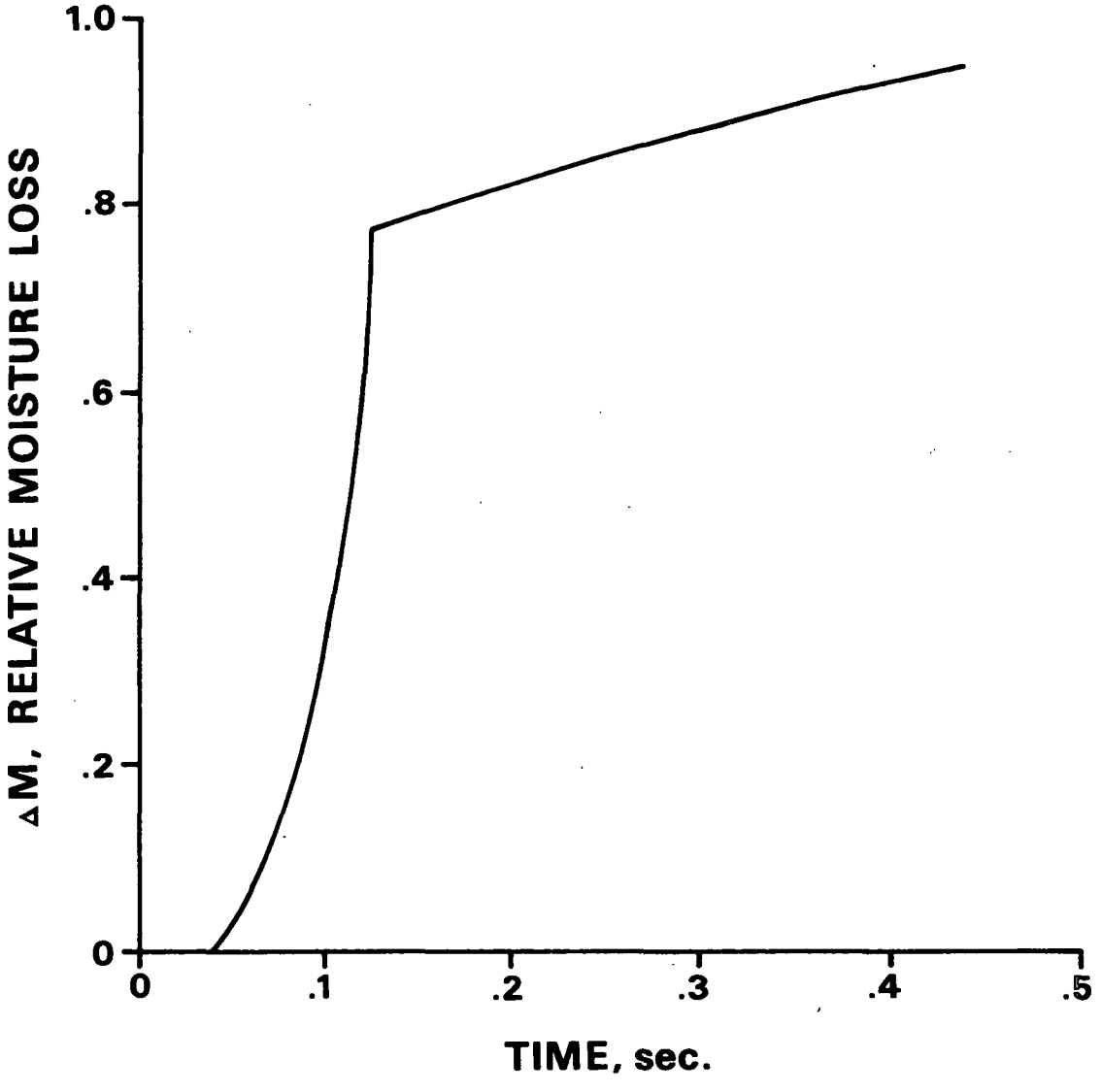

Figure 11. Moisture removal as a function of time for the RAMP base case.

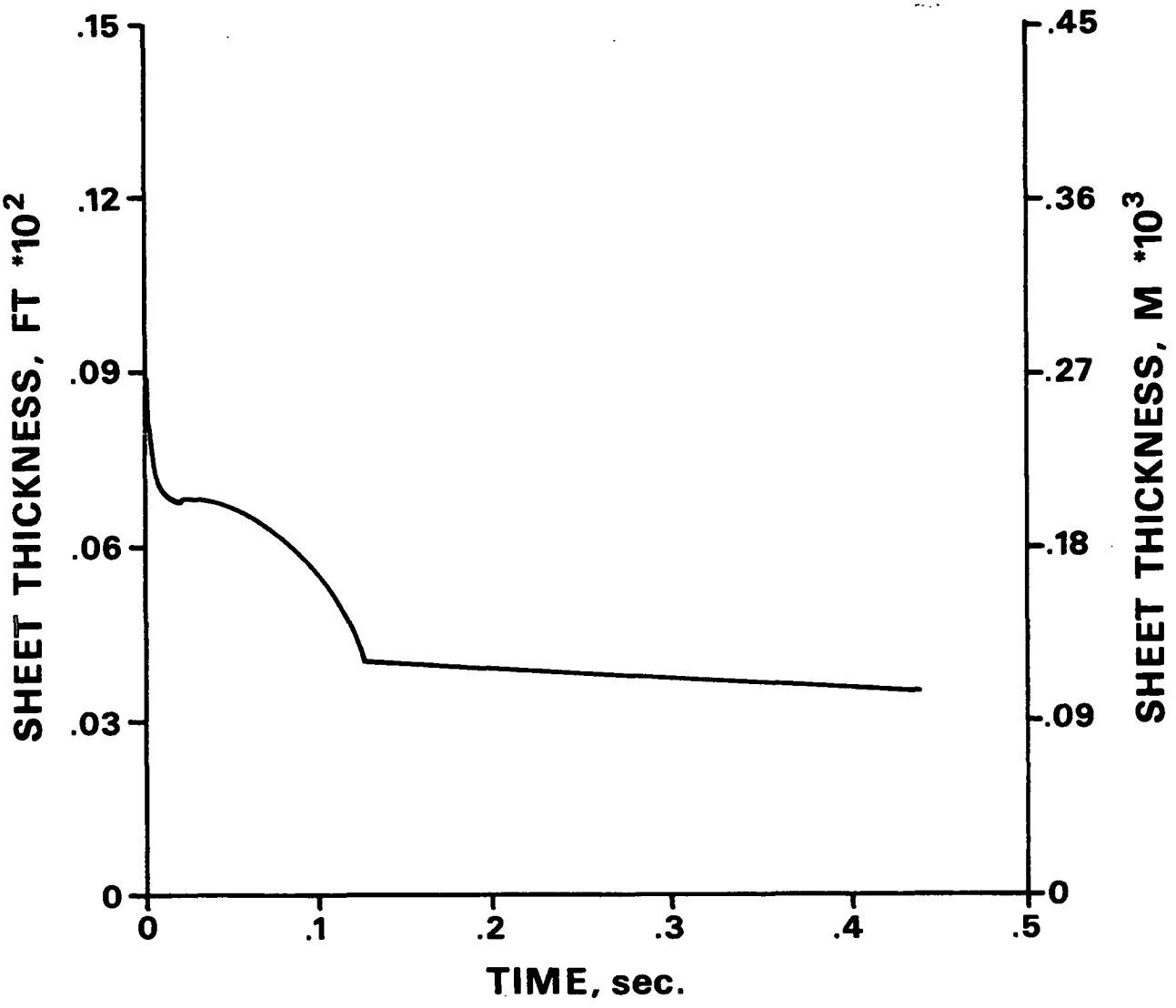

Figure 12. Sheet thickness as a function of time for the RAMP base case.

Figure 14 shows the temperature history of the interfaces. TS, T1, and T2 move together until the transition regime starts. T3 begins to rise then because of the quantity of heat transferred by convecting liquid. T1 and T2 remain together until interface 2 moves faster than interface 1. T2 and T3 become identical when interface 2 reaches DELTAT and the linear regime starts. T2 rises as interface 2 moves back into the sheet so that a vapor pressure gradient (determined by sheet permeability) can be maintained. T3 is fixed at TB since interface 3 is held at DELTAT.

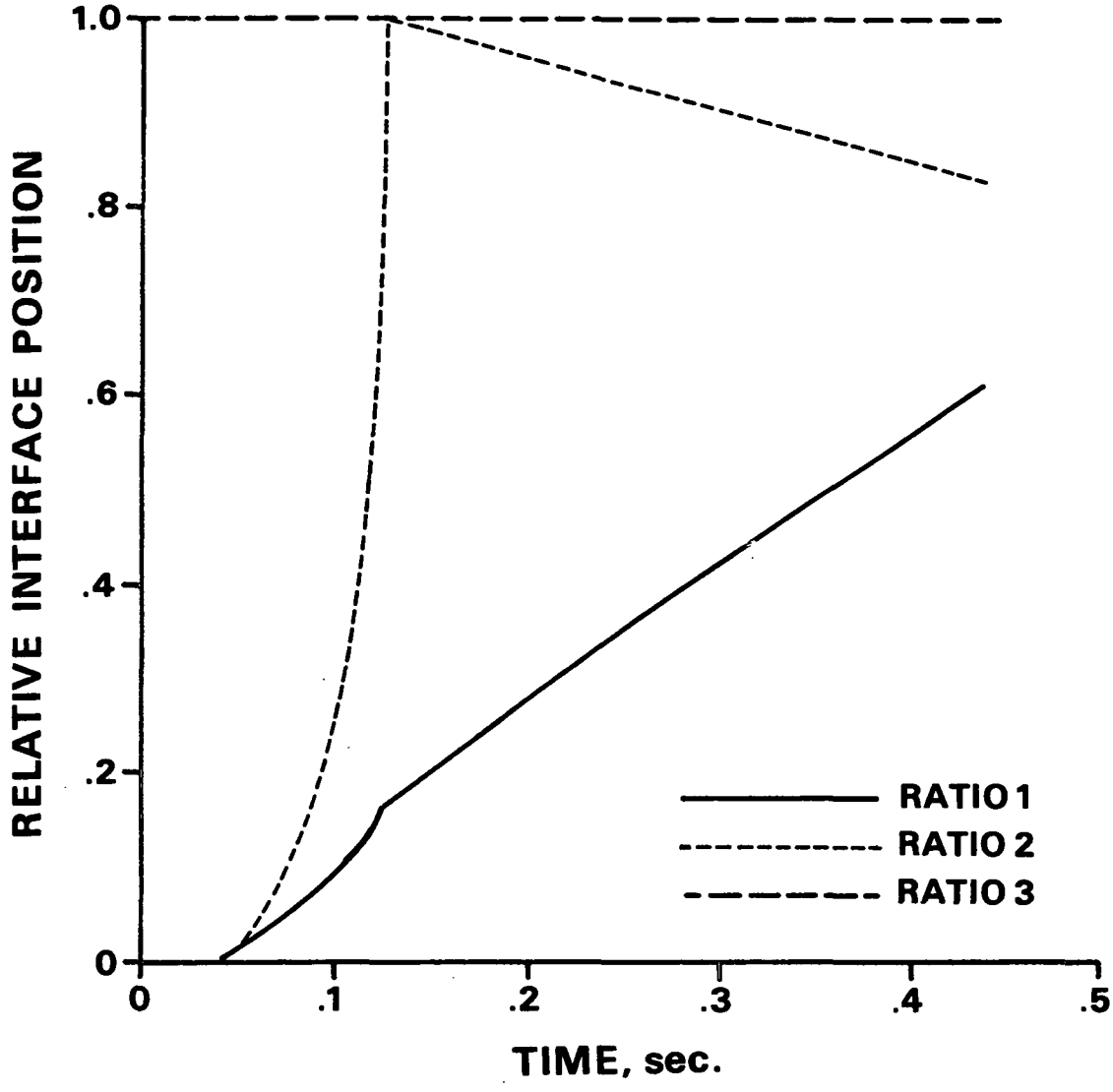

Figure 13. Interface positions relative to total sheet thickness as functions of time for the RAMP base case.

Figure 15 depicts the gage vapor pressure corresponding to the value of T1. The two abrupt drops and recoveries of vapor pressure occur at points where a slug of liquid is pushed through the sheet and the heat rate has to "catch up" to sustain continued flow. The first point occurs as interfaces 1 and 2 move into the sheet. The second point occurs as interface 2 moves ahead of interface 1. In both cases a zone of high vapor permeability (relative to zone 3) is suddenly created. This causes T1 (and the vapor pressure corresponding to T1) to

drop since the flow resistance is reduced. As the interfaces progress, T1 must increase to sustain continued vapor and liquid flow at points in the interior of the sheet.

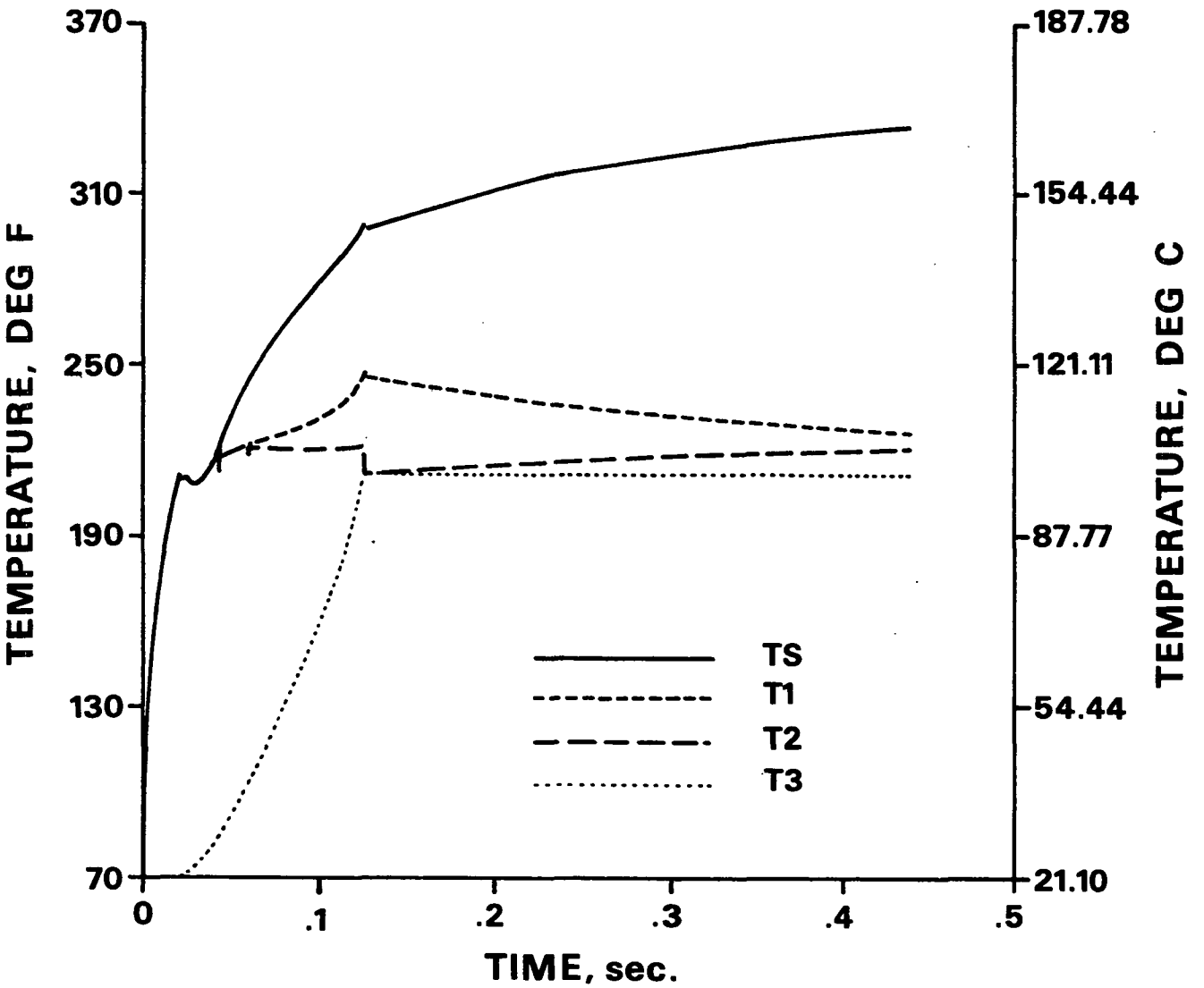

Figure 14. Sheet surface temperature and interface temperatures as functions of time for the RAMP base case.

Figure 16 traces the temperature at a point half way through the basis weight of the sheet. Since this does not always correspond to the instantaneous location of an interface, TMID has to be interpolated based on the positions of the interfaces relative to the total sheet basis weight. Conduction in the

compressing sheet during heatup causes the internal temperature to rise above its initial value earlier than the cool side does. The temperature rises steadily until the linear regime when the rate of compression and the drying rate slow significantly. TMID achieves a nearly constant level until interface 2 moves far enough back into the sheet to affect the thermal behavior of the sheet's interior.

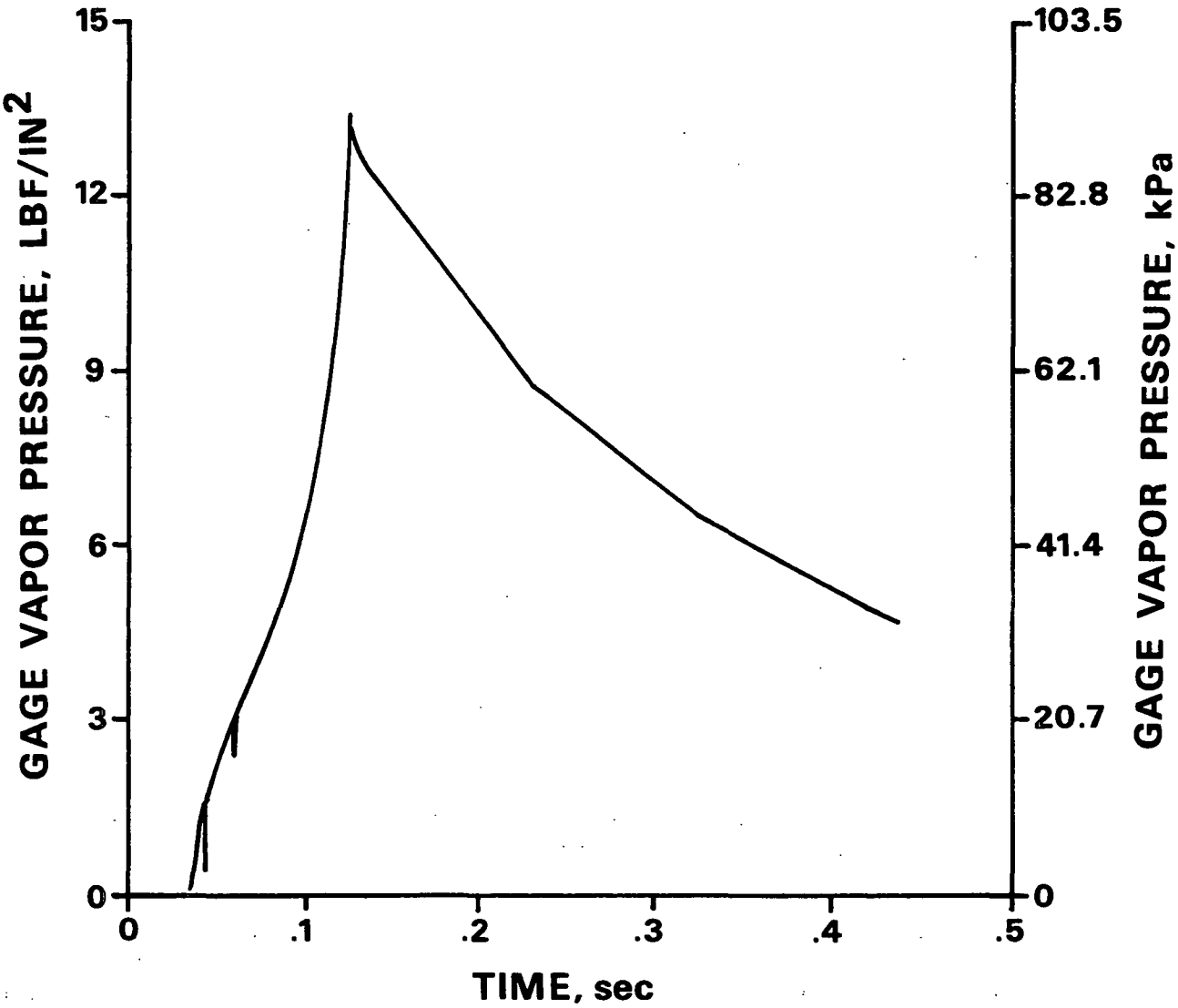

Figure 15. Gage vapor pressure corresponding to T1 as a function of time for the RAMP base case.

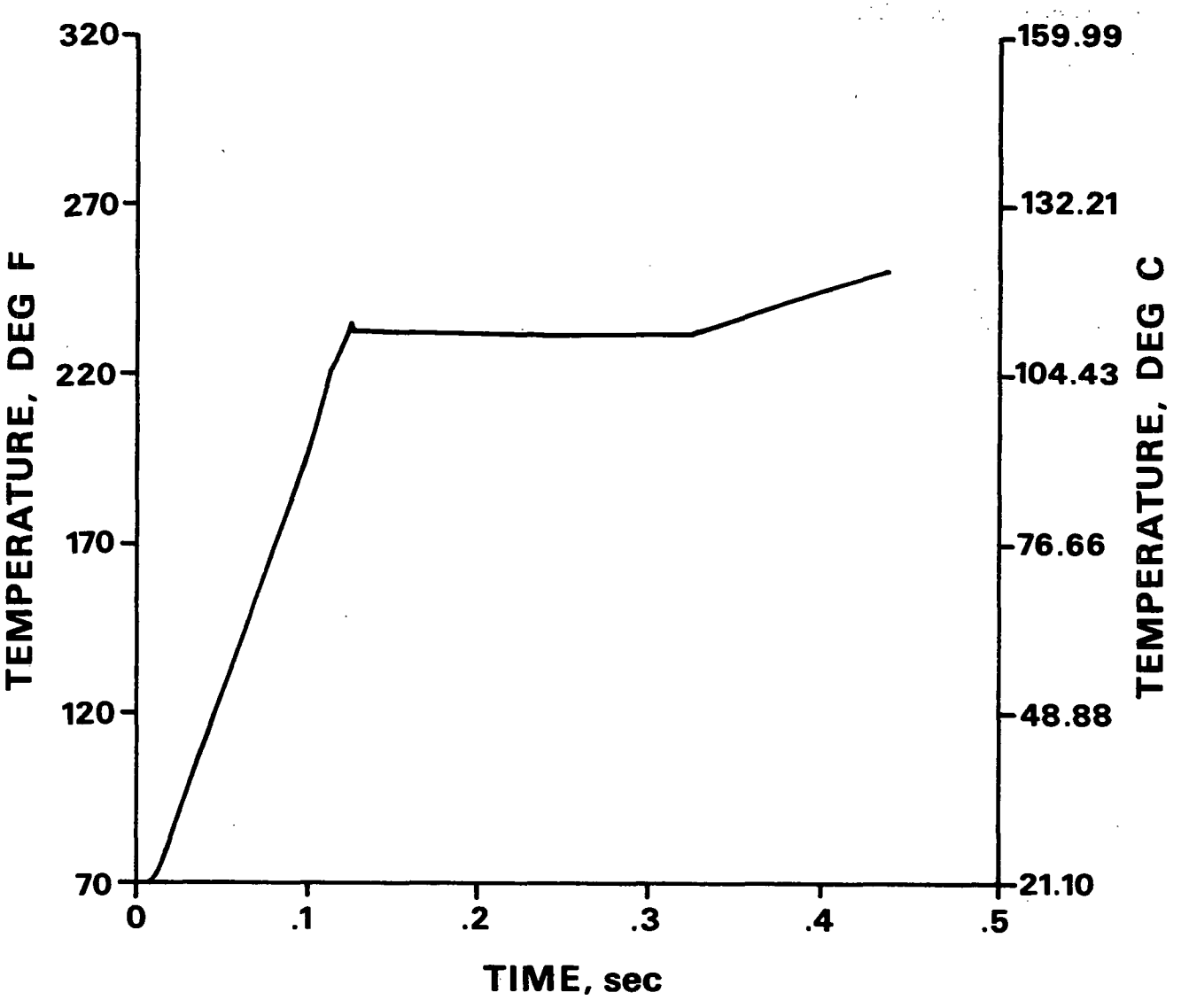

Figure 16. Temperature at one-half the sheet basis weight as a function of time for the RAMP base case.

Figure 17 graphs the heat flux from the hot surface to the sheet. Note that the hot surface temperature is assumed constant. The initial portion of the heat flux is controlled by the shape of the pressure pulse. The heat flux is initially zero and rises to its peak as the pressure peaks. When the pressure stabilizes, the heat penetrates the sheet, causing a temperature rise and a sharp drop in heat flux. Just as the transition regime begins, the drop in the heat flux moderates and when the linear regime begins the heat flux slowly

approaches an equilibrium value (zero) as the sheet approaches an equilibrium condition (dry).

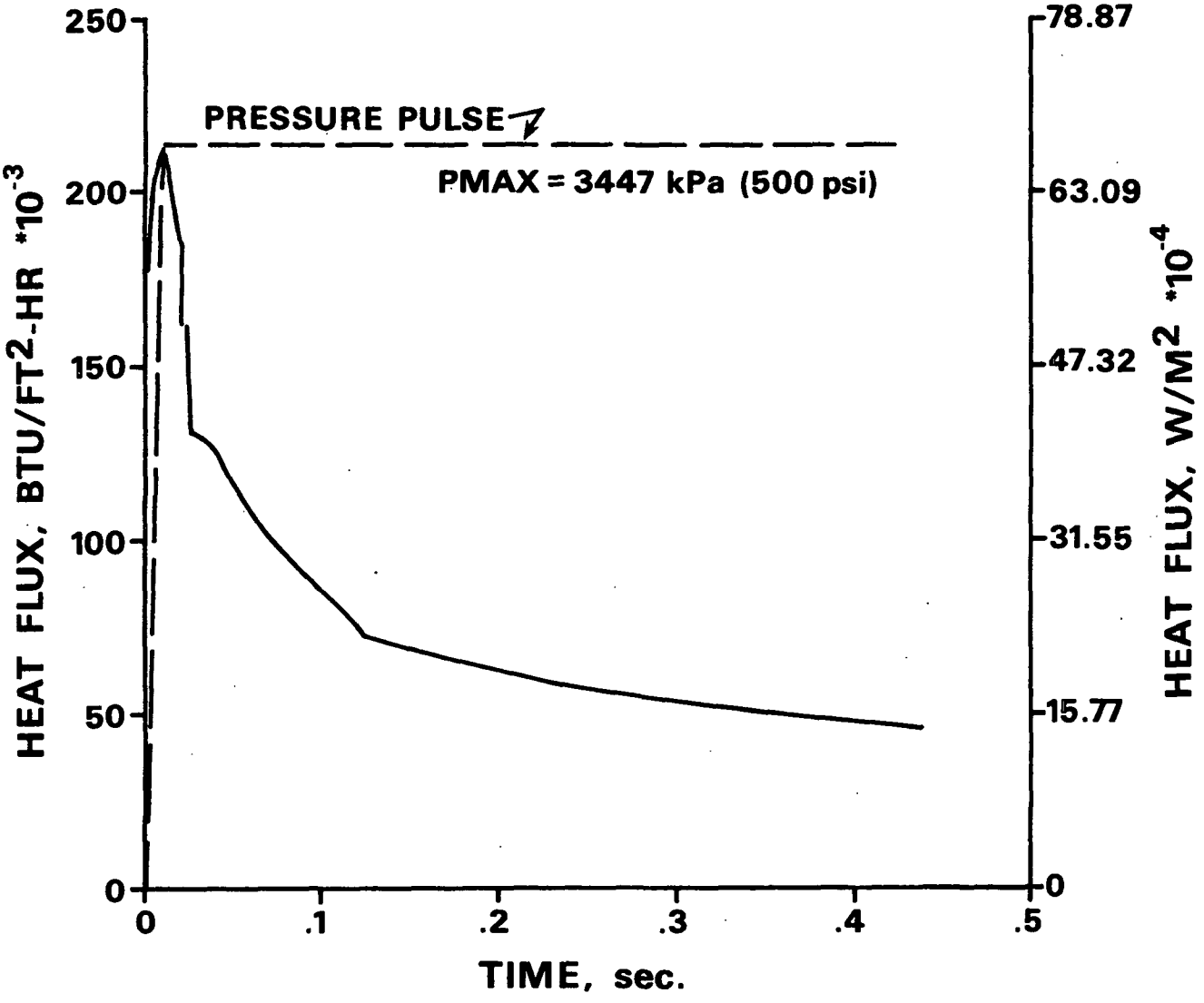

Figure 17. Heat flux as a function of time for the RAMP base case.

Figure 18 presents the history of the overall heat transfer coefficient. This quantity is calculated by dividing the heat flux by the difference between TH and TMID. OHTC parallels the heat flux curve until transition begins. As Q moderates and TMID continues to rise, OHTC remains somewhat constant. As the

linear regime begins, OHTC again parallels Q since TMID stabilizes. As TMID starts to rise again, its increase is offset by the decrease in Q to yield a constant OHTC value.

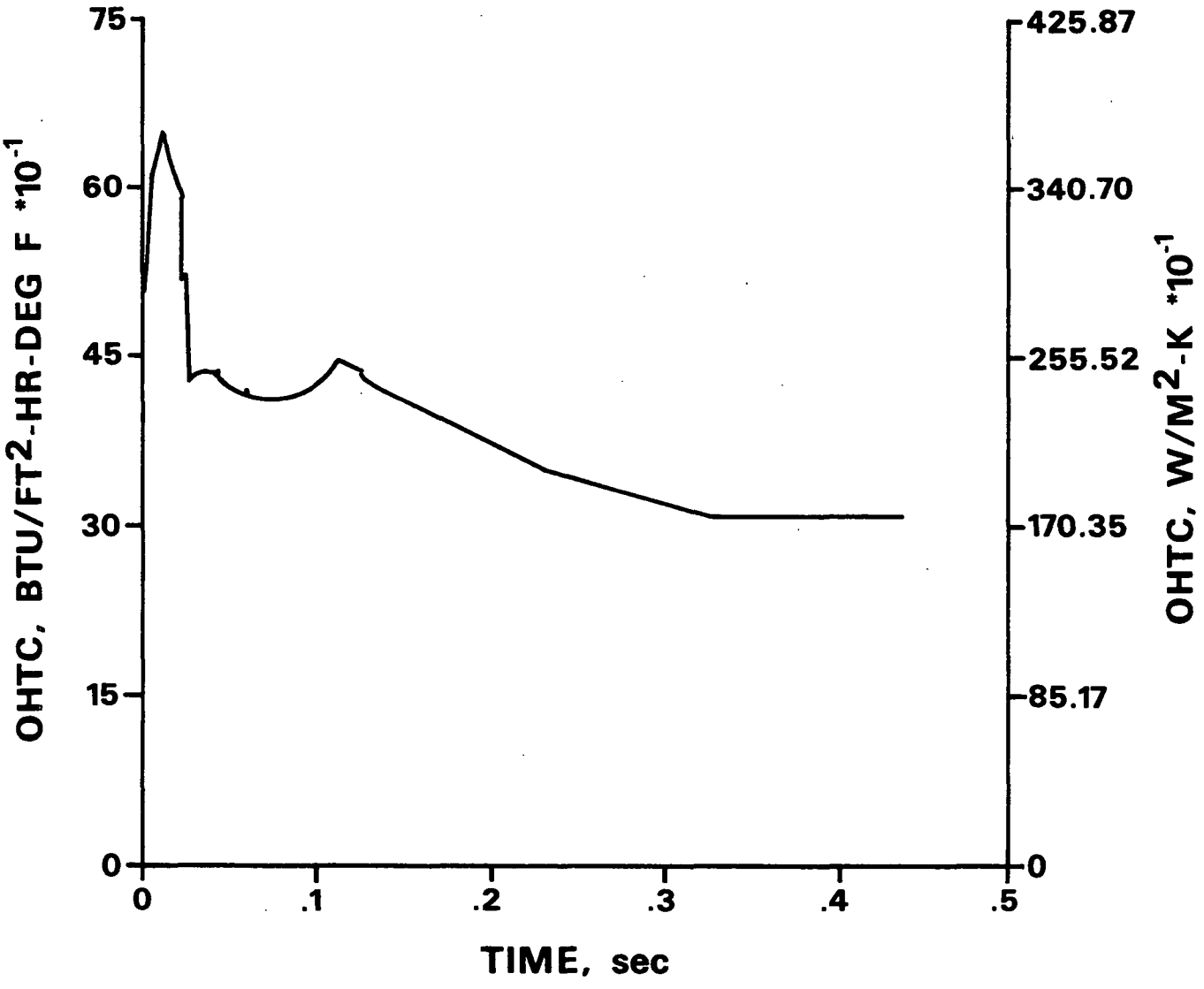

Figure 18. Overall heat transfer coefficient as a function of time for the RAMP base case.

The behavior of the base case for the niplike pressure pulse is not shown. The variables essentially match the RAMP pressure base case up until the peak

pressure is reached. After that, the values plateau and decline slightly as the pressure rapidly declines. The SINE case with 0.05 second RISTIM is the only niplike case that predicts any moisture removal. This is shown in a later figure in comparison with the moisture removal predicted for the various RAMP pressure rise times. (For the conditions selected the sheet is still in the heatup regime for all but this one SINE case.)

Comparisons of Drying Behavior

Figures 19 through 24 show comparisons of the drying behavior for the values of the input parameters given in Table 1. Results from all cases are compared against the base case and are generated by varying the value of an individual parameter from its base value while maintaining all other parameters at their base values. The drying curve stops when the sheet reaches 6% moisture content or, in one case, when the niplike pressure pulse drops to its starting value. The heatup regime accounts for 5 to 10% of the total drying time; the transition regime accounts for 10 to 45% of the total time; and the linear regime accounts for 50 to 80% of the total time. The base case results for drying time to 6% moisture content fall in between the times predicted for the minimum and maximum parameter values.

Figure 19 displays the effect of hot surface temperature on the drying curve. As anticipated, higher hot surface temperature results in shorter drying time and there is nearly a one-to-one correspondence between drying time and the driving force (TH-TB). The greatest benefits of higher hot surface temperature are reduction of the heatup time and higher driving force (drying rate) in the linear regime.

Figure 20 shows the effect of initial moisture ratio on the drying curve. There is little effect on total drying time because the moisture removal is

dominated by the (rapid) liquid dewatering mechanism. The time required to evaporate the remaining water during the linear regime is comparable for each initial moisture ratio case.

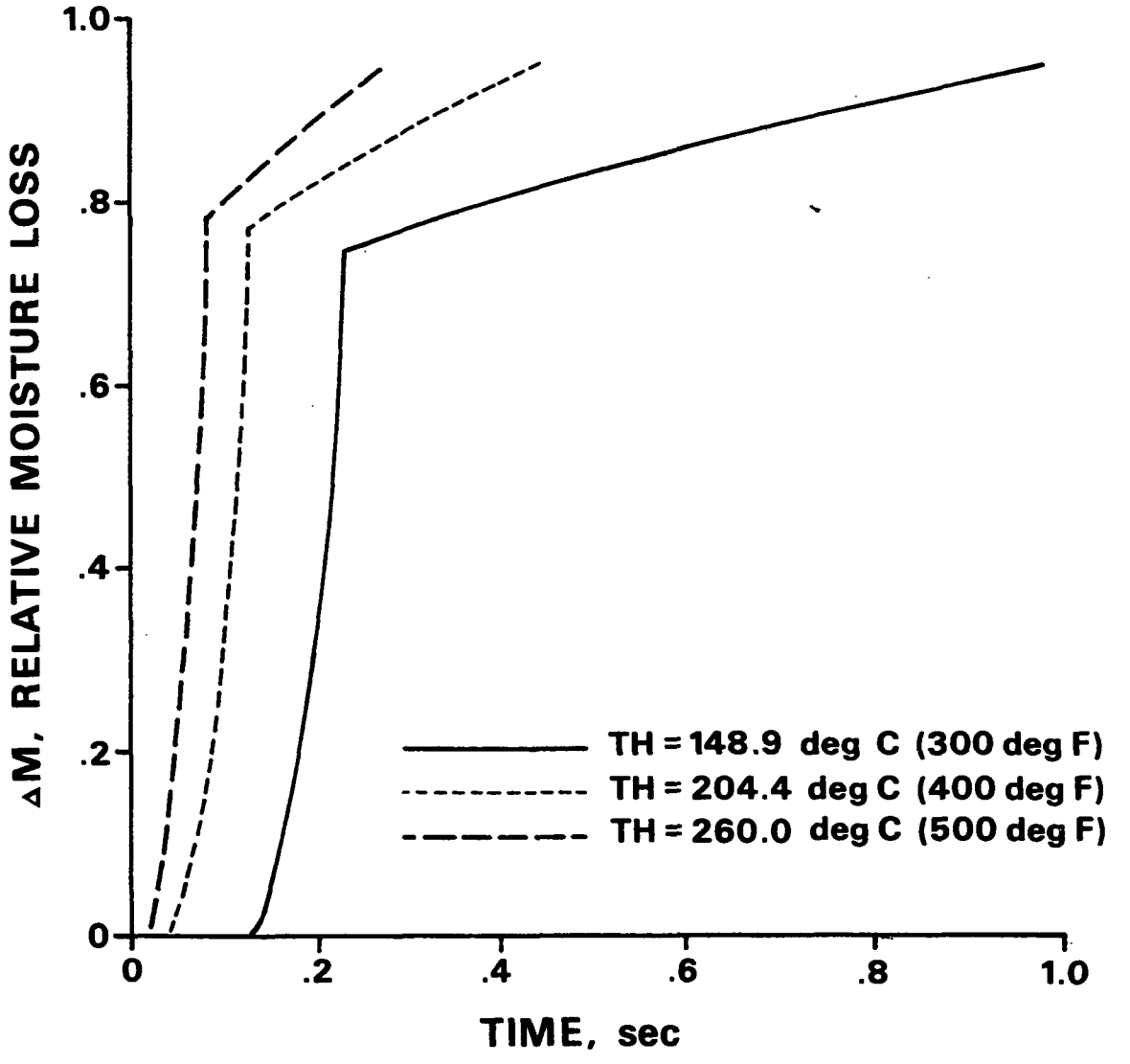

Figure 19. Effect of hot surface temperature on moisture removal for RAMP cases.

Figure 21 presents the effect of basis weight on drying. The heatup time for each basis weight is comparable, but the slopes of the liquid dewatering portion are distinctly different. In the lowest basis weight case, the heat can

penetrate far into the sheet in a short time and liquid motion can be sustained at its initial pace. In the heavier basis weights (thicker sheets), the heat only penetrates into a fraction of the total sheet thickness and after liquid motion starts, it takes some amount of time for a sufficient quantity of heat to penetrate further and sustain the flow. In the linear regime, the heat and mass have a shorter distance to travel in the lower basis weight cases and the drying rate is faster than in the heavier basis weight examples.

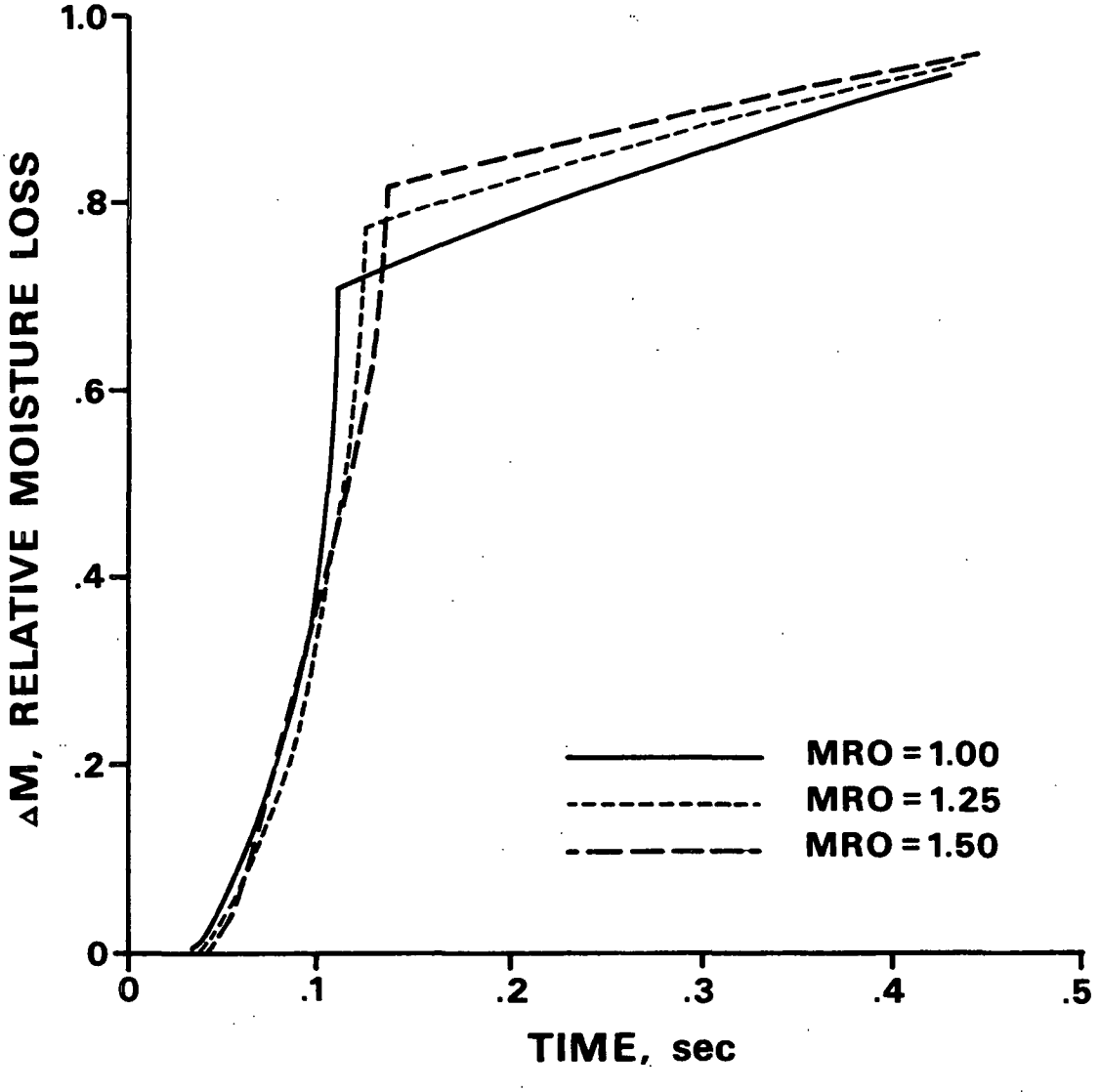

Figure 20. Effect of initial moisture ratio on moisture removal for RAMP cases.

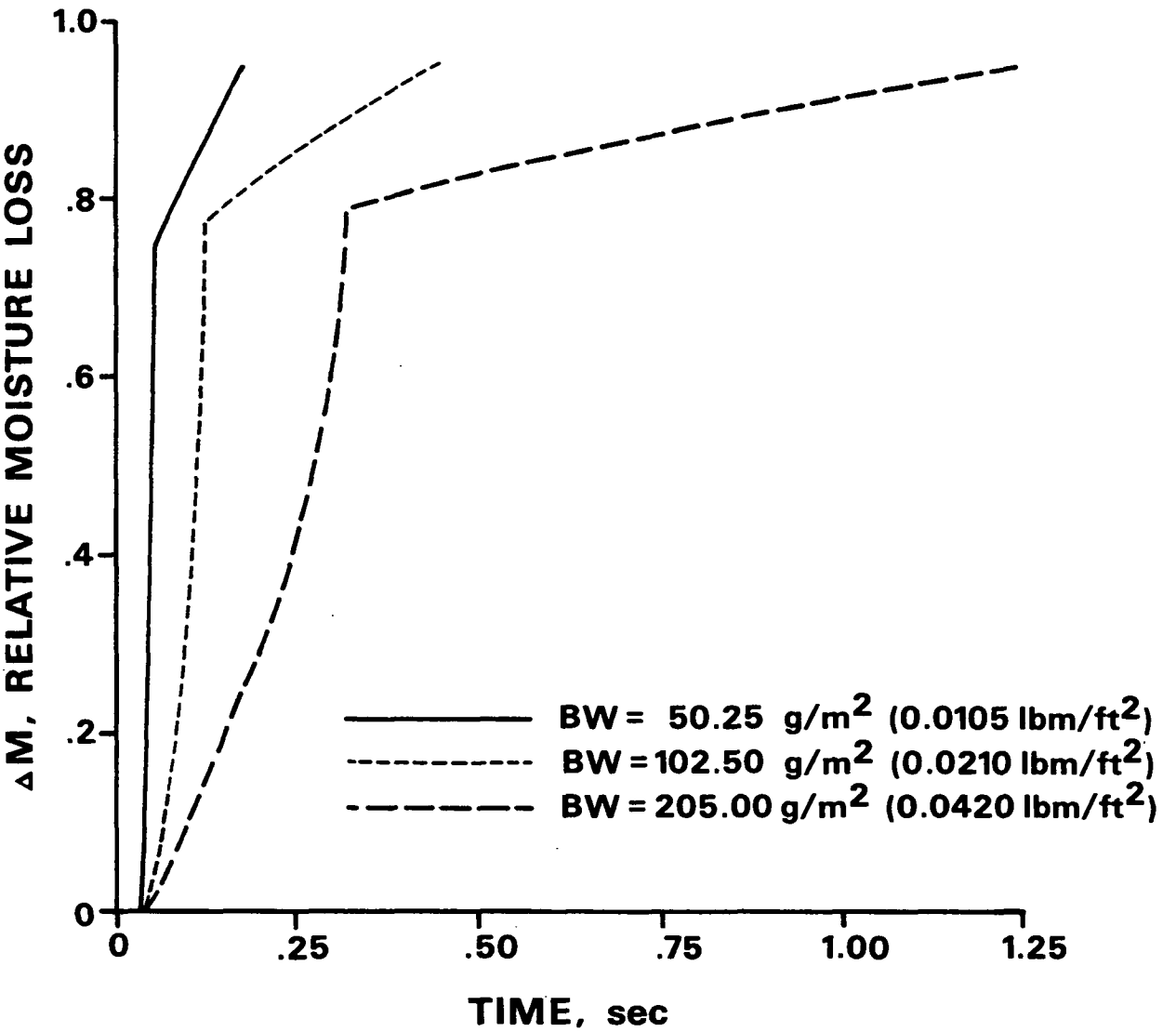

Figure 21. Effect of basis weight on moisture removal for RAMP cases.

Figure 22 shows how Canadian Standard Freeness affects drying. Lower CSF gives a more compressed sheet (at a given mechanical pressure), and in the case of 300 CSF liquid is removed from the sheet by mechanical dewatering in addition to the thermally induced liquid dewatering. The decrease in permeability accompanying lower CSF is not enough to offset the gains in drying resulting from a more compact sheet (which is better able to transfer heat) and the higher internal sheet temperatures going into the linear regime.

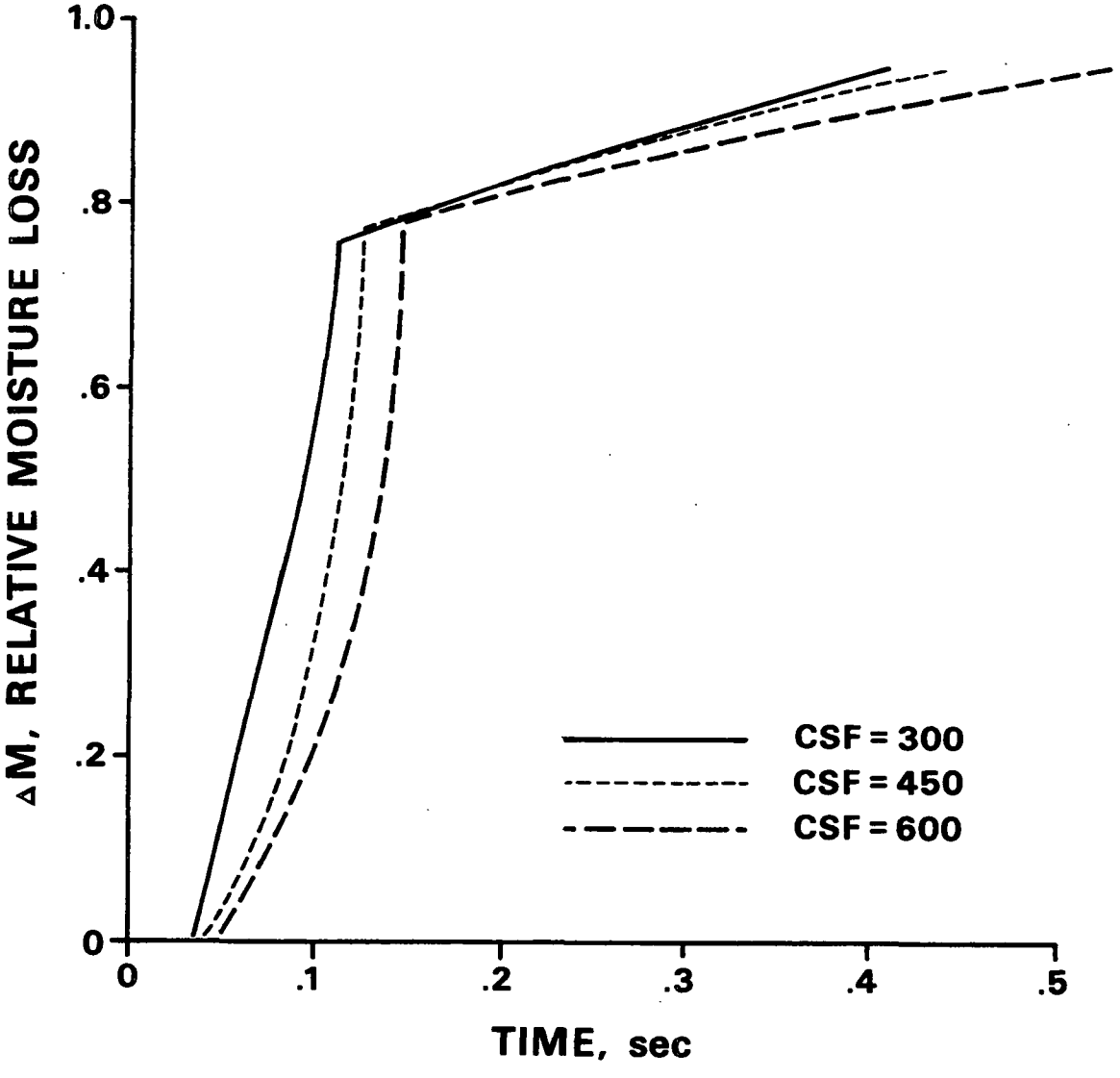

Figure 22. Effect of freeness on moisture removal for RAMP cases.

Figure 23 depicts the influence of peak pressure on drying. The curves are essentially parallel in slope but shifted in time. The results indicate that increasing pressure decreases drying time, but that the relative increase becomes smaller at higher pressures for the range of pressures examined here. This suggests that there may be some practical limit to the amount of pressure which is cost effective for a commercial implementation of high intensity drying technology.

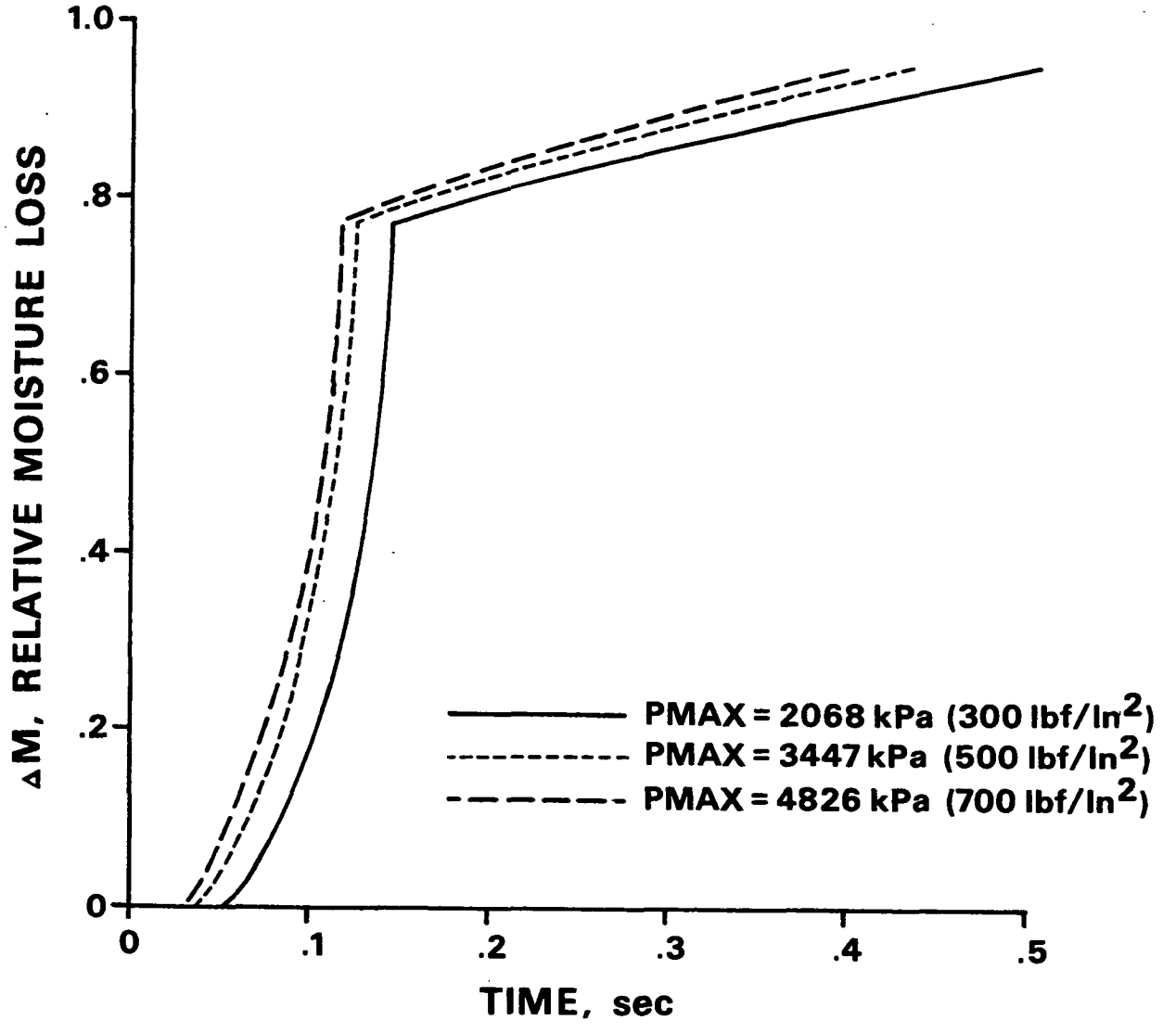

Figure 23. Effect of peak pressure on moisture removal for RAMP cases.

Figure 24 shows the effect of the pressure rise time, the time it takes to achieve the peak pressure. There is virtually no effect on drying time for the RAMP cases, since the rise time is such a small percentage of the total drying time needed. Comparing the SINE case to a RAMP case with the same rise time shows that they behave similarly until the SINE case pressure begins to drop rapidly. The SINE case continues to show a decreasing rate of dewatering as the

heat transfer to the sheet declines, and drying stops when the pressure reaches a point at which the heat transfer can no longer sustain liquid flow.

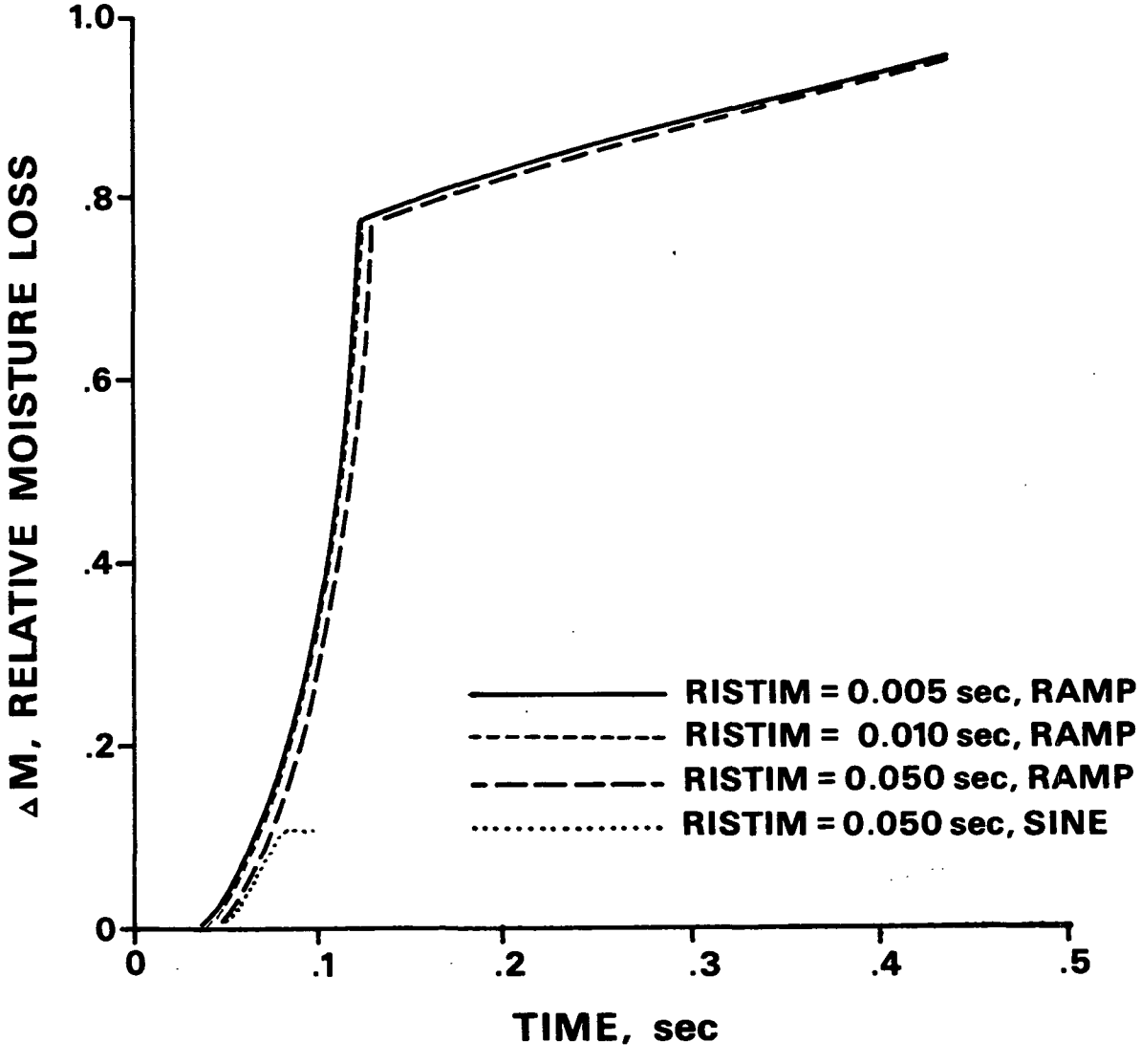

Figure 24. Effect of pressure rise time on moisture removal for RAMP cases and one SINE case.

The relative magnitudes of the changes are summarized in Table 2.

Table 2. Effect of changes in input parameters on drying time for RAMP cases.

Parameter	Value Relative to Base Case Value	Change in Drying Time
TH	- 25%	+123%
	+ 25%	- 39%
MRO	- 20%	- 2%
	+ 20%	+ 2%
BW	- 50%	- 60%
	+100%	+180%
CSF	- 33%	- 7%
	+ 33%	+ 18%
PMAX	- 40%	+ 16%
	+ 40%	- 9%
RISTIM	- 50%	<- 1%
	+400%	<+ 1%

SENSITIVITY ANALYSIS

The calculation method in HIDRYER1 requires that values be specified (in the program) for the number of grid points used in the finite difference equations (KMIN) and for the number of iterations used in determining the interface temperatures (IMAX). The default time increment (DTO) is an input parameter, and it too can influence the predicted drying output. There are no clear-cut methods of choosing appropriate values for these variables and so a sensitivity analysis is necessary to determine what numerical inputs give the best compromise between prediction accuracy and CPU ("computer") time.

Table 3 shows the results of variations in KMIN, IMAX, and DTO using the same inputs as for the RAMP base case (with the exception of DTO when sensitivity to DTO was tested, of course). The central line for each variable gives the value used in conducting the parametric study.

Table 3. Effect of grid spacing, iteration counter, and default time increment on drying time and CPU time.

Variable and Value		Predicted Drying Time, s	CPU Time, hr:min:s
KMIN	21	0.438	1:19:37
	101	0.432	0:28:20
	251	0.431	4:46:58
IMAX	5	0.432	0:22:26
	10	0.432	0:28:20
	15	0.432	0:35:34
DTO (hr)	10^{-5}	0.456	0:27:54
	10^{-7}	0.432	0:28:20
	10^{-10}	0.430	9:38:27

Changing the value of KMIN results in minor changes in predicted drying time and more drastic changes in CPU time. When KMIN is increased from 101 to 251, the increase in CPU time is a direct consequence of the increased amount of calculations required. When KMIN is decreased from 101 to 21, one might anticipate a reduction in calculation time. However, because HIDRYER1 uses a forward time difference procedure, interface 2 may be advanced to a location such that its temperature is less than TB. When this occurs, no drying takes place until heat transfer to the transition zone raises its temperature in the vicinity of interface 2 to the point at which T2 is calculated to be above TB. Thus, several time increments may elapse in which there is no drying. Using fewer grid points reduces the effective heat transfer by predicting a lower temperature at any given point inside the outer zone and therefore there are more time increments early in the process when the sheet is still heating up and not drying.

A change in the number of iterations for the interface temperature calculations is reflected directly in the amount of CPU time required. Since there is essentially no change in the predicted drying time or behavior, it appears that

5 iterations are sufficient and the system is "well behaved" with regard to interface temperature calculations.

Decreasing the default time increment has a tremendous effect on CPU time. Typically, the interface motion time increment restriction and the finite difference time increment stability criterion are more restrictive than the default time increment. These are dominant in the transition regime. In the linear regime the finite difference criterion is not operative and the interfaces are sufficiently separated that the default time increment becomes the more restrictive time step. It is in just this regime, however, that a larger time increment can be most useful, since the rate of drying slows relative to the liquid dewatering part of drying. Limiting the default time increment chiefly limits the number of calculations in the linear regime only. Clearly, maintaining DTO on the order of 10^{-7} hour produces a vast improvement in accuracy with little sacrifice in CPU time.

SUMMARY

The parametric study shows that hot surface temperature and basis weight have the greatest influence on drying time to 6% moisture content. Peak pressure and freeness have a more moderate effect, and initial moisture ratio and rise time have almost no effect.

Using about 101 finite difference grid points, 5 iterations for interface temperature calculations, and a default time increment on the order of 10^{-7} hour appears to be an adequate compromise for balancing prediction accuracy and CPU time.

EXPERIMENTAL COMPARISONS

PURPOSE

Comparisons between experimental results and the model's predictions can suggest changes and improvements, can validate the mechanisms assumed in the model, and can identify areas requiring further experimental study.

EXPERIMENTAL CONDITIONS

Two kinds of experiments were selected for comparisons to HIDRYER1 output based on the manner and magnitude of mechanical pressure application: ramp-and-hold high intensity drying and short duration (impulse) high intensity drying. Examination of the assumptions used in developing the model suggests that it should best predict cases of high hot surface temperature and moderate mechanical pressure (so that good thermal contact is promoted but capillary flow is discouraged by maintaining larger pores) and a ramp-and-hold pressure pulse (since a static compression equation is used).

HIDRYER1 appears to be impractical for modeling cases of mechanical pressure at or below 350 kPa (50 psi). HIDRYER, the earlier version of the program, gives reasonable results in much shorter times. At a mechanical pressure of 321 kPa (46.6 psi) and hot surface temperature of 274°C (525°F), HIDRYER requires about 2 minutes of CPU time but HIDRYER1 needs about 5 hours. HIDRYER gives a better estimate of the experimentally determined[9] drying time of 1.7 seconds: 1.4 seconds for HIDRYER and 0.68 second for HIDRYER1; and a better estimate of the peak vapor pressure of 120 kPa (17.4 psi): 125 kPa (18.1 psi) for HIDRYER and 24 kPa (3.5 psi) for HIDRYER1.

HIDRYER1 requires so much CPU time because it calculates all the properties and sheet behaviors, even when they change by only very small amounts. Conversely, HIDRYER has many built-in assumptions that eliminate the necessity for the

calculation of quantities that do not change much. For example, since HIDRYER takes values of thickness, absolute permeability, and the relative permeabilities as inputs and holds them fixed, it does not have to perform repetitive determinations of these quantities.

The chief drawback to using HIDRYER is that there are no simple guidelines for selecting valid "average" values representative of the quantities throughout the course of drying. Values for input parameters can be easily manipulated to produce good agreement with laboratory data, but the extent to which they reflect real sheet properties can always be questioned. HIDRYER1 attempts to provide an accurate picture at every instant of drying and was developed to address the chief drawback by removing the subjective aspect of running a simulation.

RAMP-AND-HOLD PRESSURE PULSE

Data are available[93] for a peak pressure of 4826 kPa (700 psi) at two hot surface temperatures: 149°C (300°F) and 274°C (525°F). Basis weight is 205 g/m^2 (0.042 lbm/ft^2); moisture ratio is 1.3256; and freeness is 625 CSF. The hydraulic system for application of the pressure pulse causes a small overshoot of PMAX before it settles to the designated value. RISTIM is selected as the time at which the mechanical pressure first reaches the target (about 0.12 second). It takes about an equal amount of time for the system to then settle and hold the target pressure value.

Figures 25 and 26 show predicted moisture removal curves with representative experimental points for the two cases. The experimental points are determined gravimetrically. The agreement appears to be better in the higher temperature case. This is probably due to the decrease in capillary effects at the higher temperature from lowered surface tension and viscosity and from the higher vapor pressure generated near the hot surface.

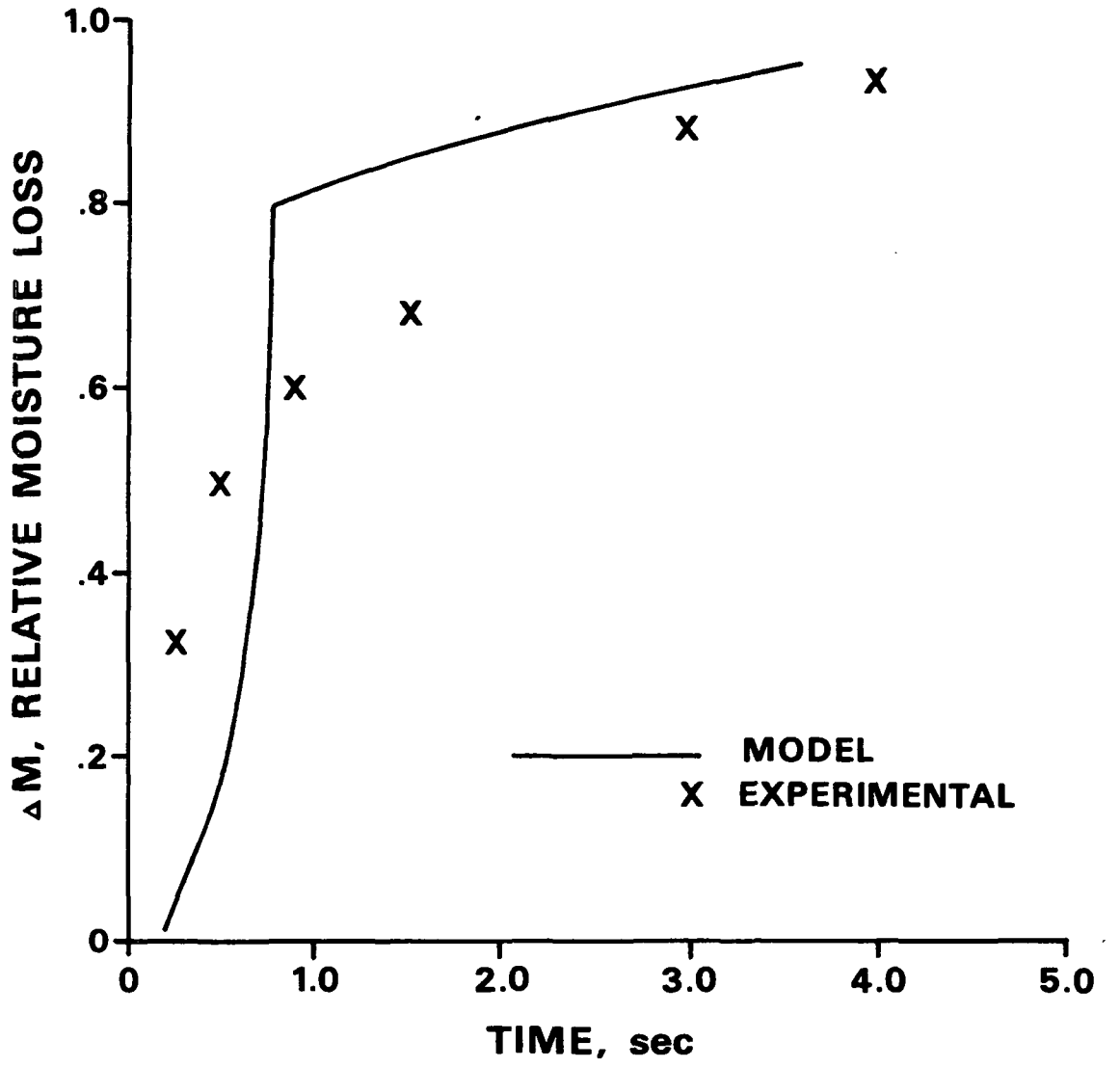

Figure 25. Predicted and measured moisture removal for 149°C (300°F) ramp-and-hold pressure pulse.

In both cases the model overpredicts the contribution of early liquid removal to overall moisture removal and underpredicts the rate of evaporative removal later in the process. Experimental results show liquid removal at about 30% of the total moisture removed,[8] but the model predicts values in the range of 80%. Also, the predicted drying times are about half the experimental ones. This behavior is probably a function of the uniform fiber wall density assumption, which fixes the amount of liquid available for flow; the assumption of no vapor

flow through the outer zone during transition, which limits the rate of rise of internal sheet temperature; and the calculated permeability for the outer zone, which controls the flow resistance.

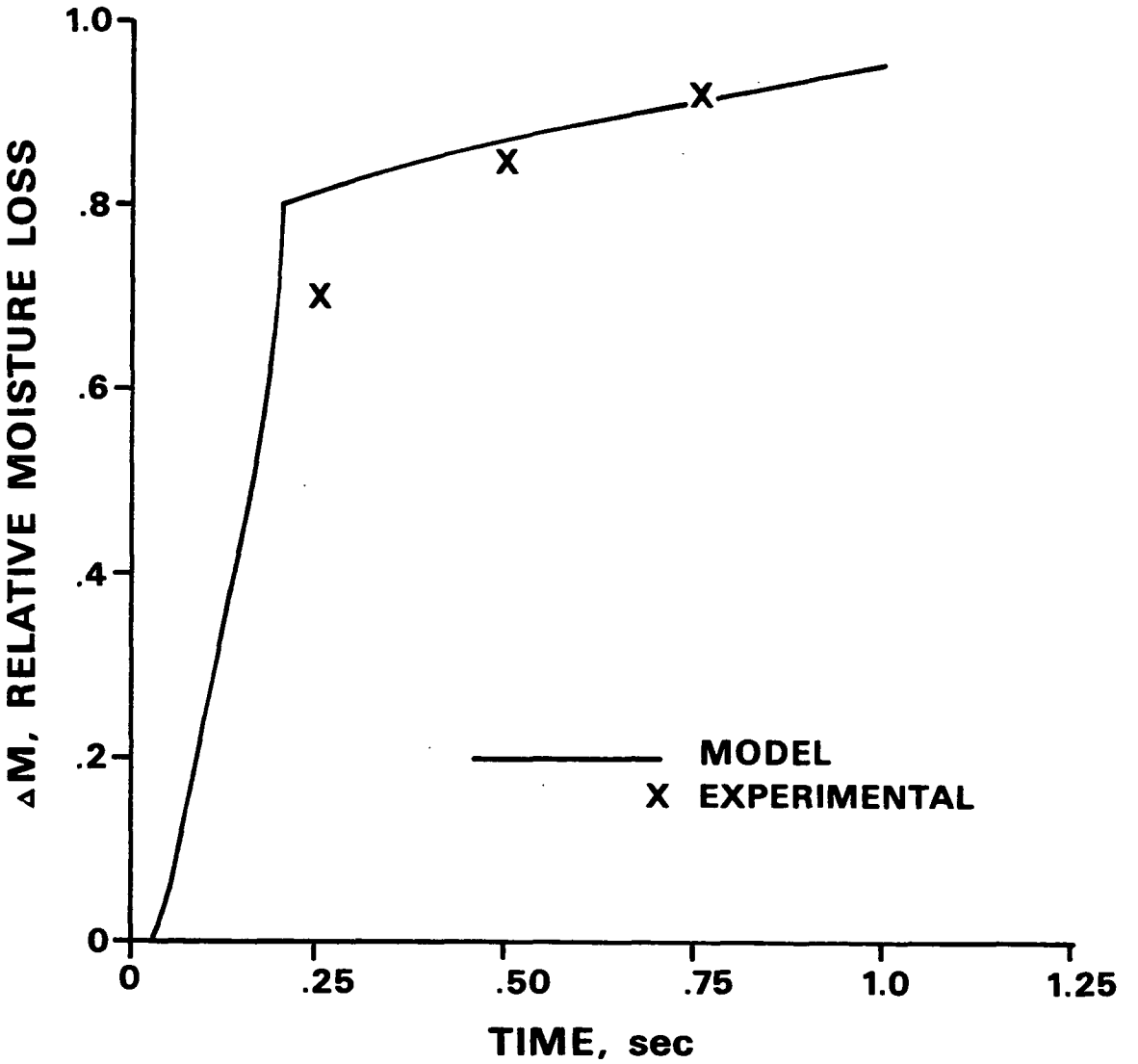

Figure 26. Predicted and measured moisture removal for 274°C (525°F) ramp-and-hold pressure pulse.

Figures 27 and 28 show heat flux comparisons for the two cases. The experimental heat flux is calculated from the measured hot surface temperature using Duhamel's Theorem. In both cases the model severely underpredicts the peak heat flux and less severely underpredicts the heat flux later in drying. The model curve also peaks before the experimental curve. This behavior is due to at

least two factors. First, the model assumes a constant hot surface temperature and determines heat flux by multiplying HC and the driving force (TH - TS). Experimentally, TH drops by about 4% of its initial value, therefore the value that the model predicts for HC must be low relative to the true value. Second, the experimental pressure actually exceeds the nominal target and this makes a contribution to the true value for HC but not for the calculated value for HC. Thus, the thermal and mechanical pressure lags of the physical system are not completely described by the model.

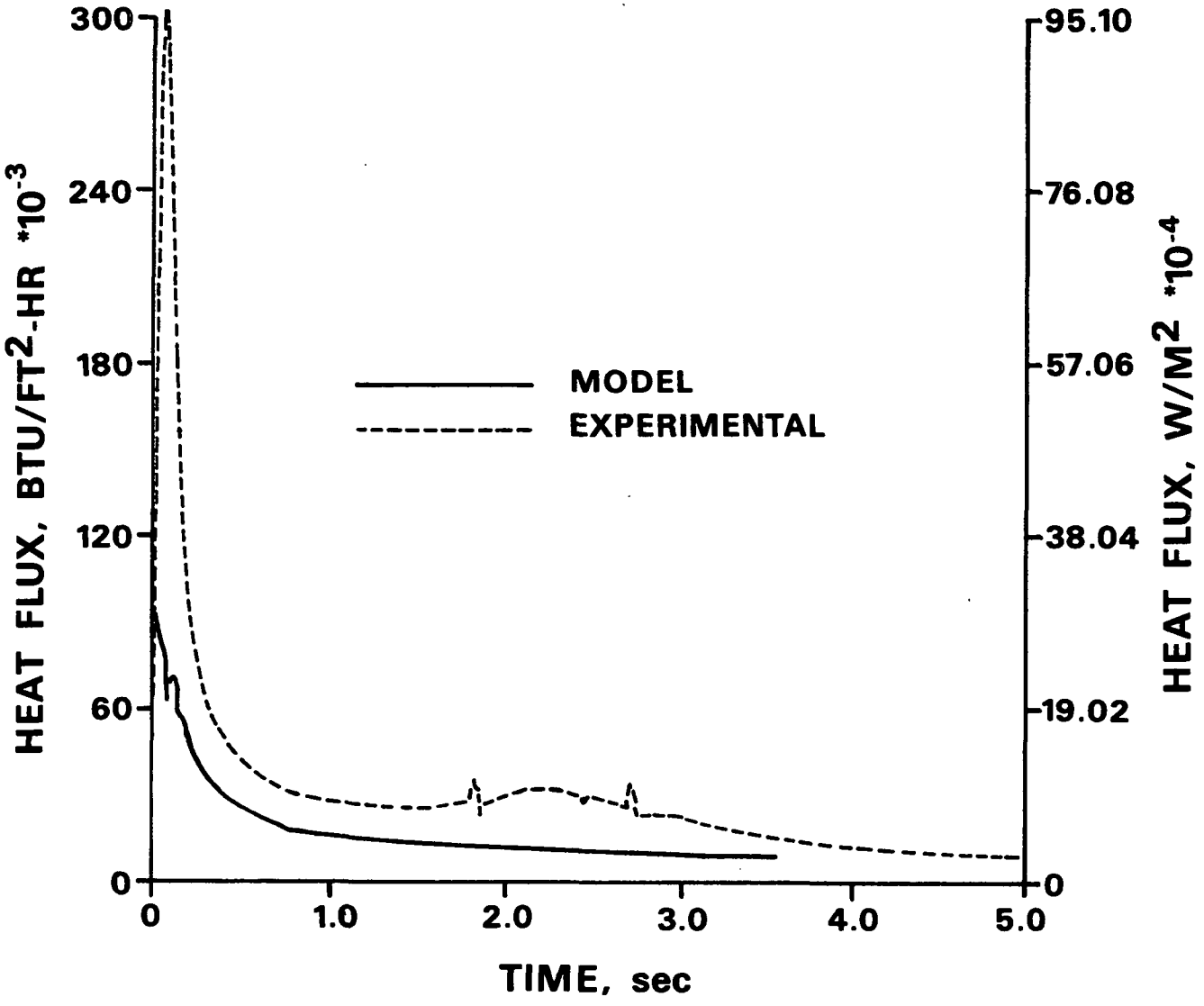

Figure 27. Predicted and measured heat flux for 149°C (300°F) ramp-and-hold pressure pulse.

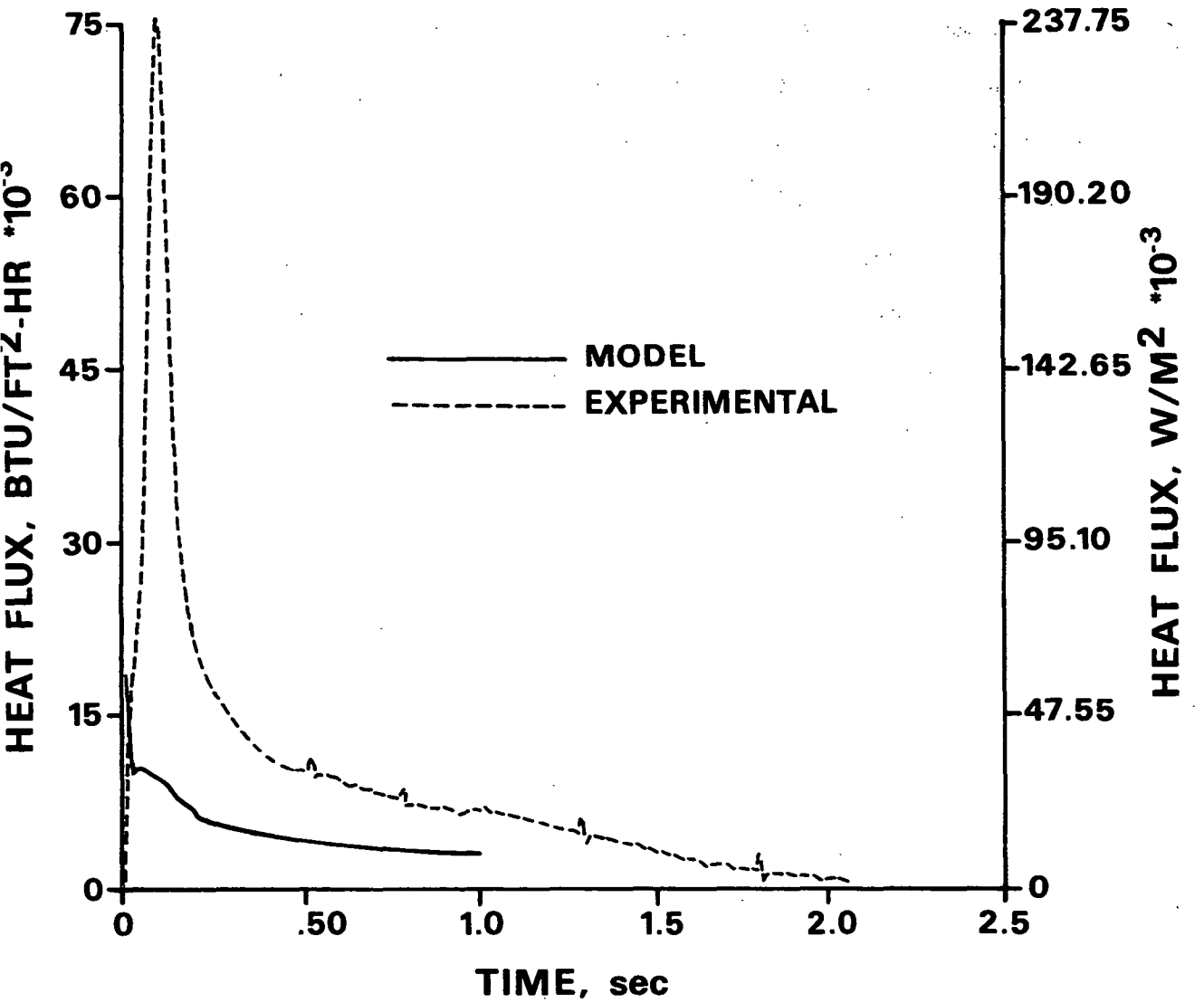

Figure 28. Predicted and measured heat flux for 274°C (525°F) ramp-and-hold pressure pulse.

Figures 29 and 30 show predicted and measured sheet thicknesses. The model curves qualitatively describe the compresssion pattern: a rapid compression ending in an abrupt change in compression rate followed by a moderate compression regime ending in an accelerating rate of compression followed by a quasi-equilibrium regime. The first regime results from the rapidly rising mechanical pressure. As the pressure attains the target value, heat transfer to the sheet begins to raise the hydraulic (vapor) pressure and the mechanical pressure plateaus, both of which slow the compression. Later, the heat flux drops, the interfaces move

into the sheet, moisture removal is dominated by liquid dewatering, and the vapor pressure decrease in the sheet increases the rate of compression. As the sheet enters the regime of drying by evaporation only the rate of moisture loss slows and the quasi-static compression regime starts. Quantitatively, the model underpredicts the initial sheet thickness and overpredicts the equilibrium thickness. This suggests a decrease in the M compression value and an increase in the N compression value would be appropriate so that the lower M value would dominate at lower pressures and the higher N value would dominate at higher pressures.

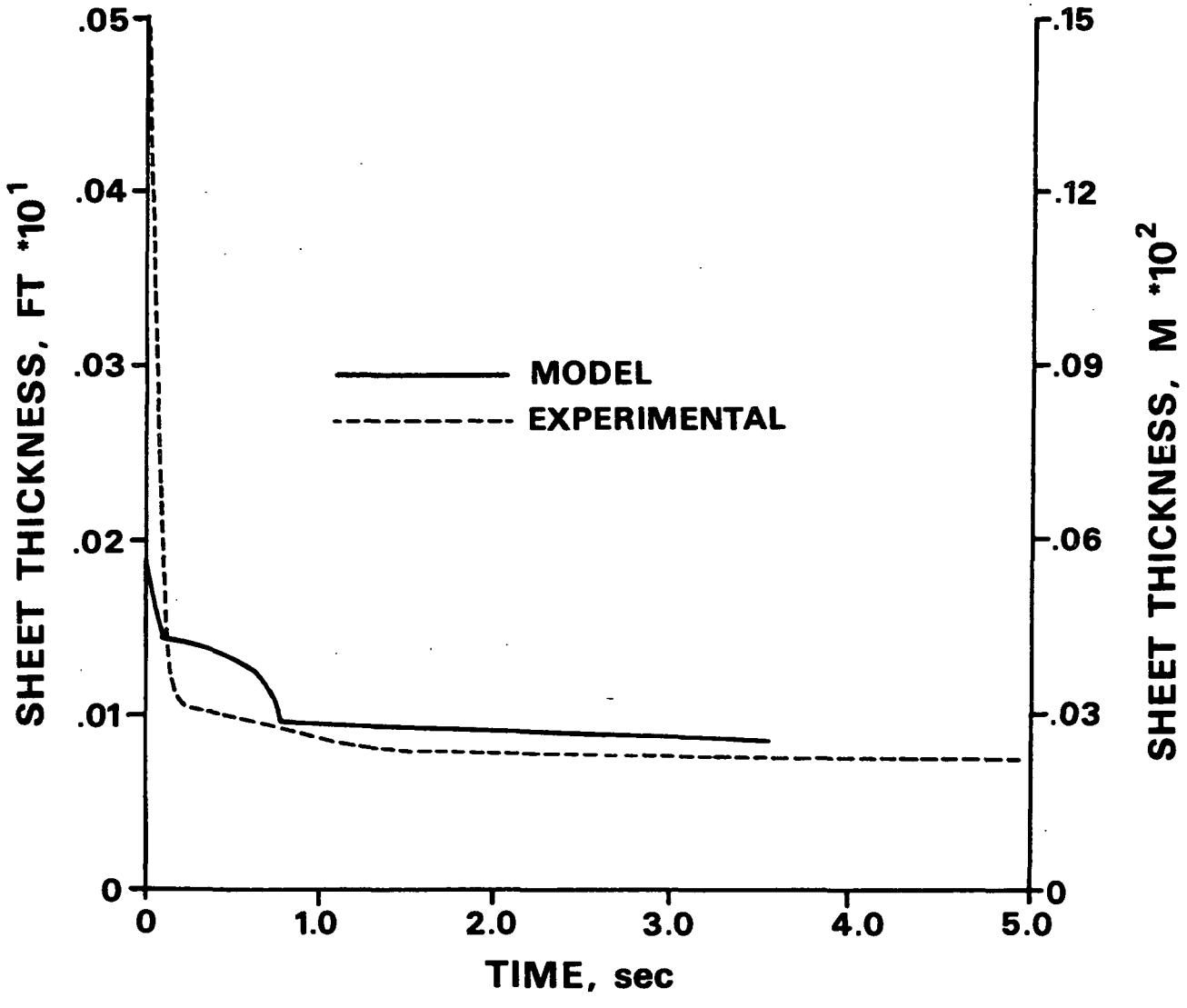

Figure 29. Predicted and measured sheet thickness for 149°C (300°F) ramp-and-hold pressure pulse.

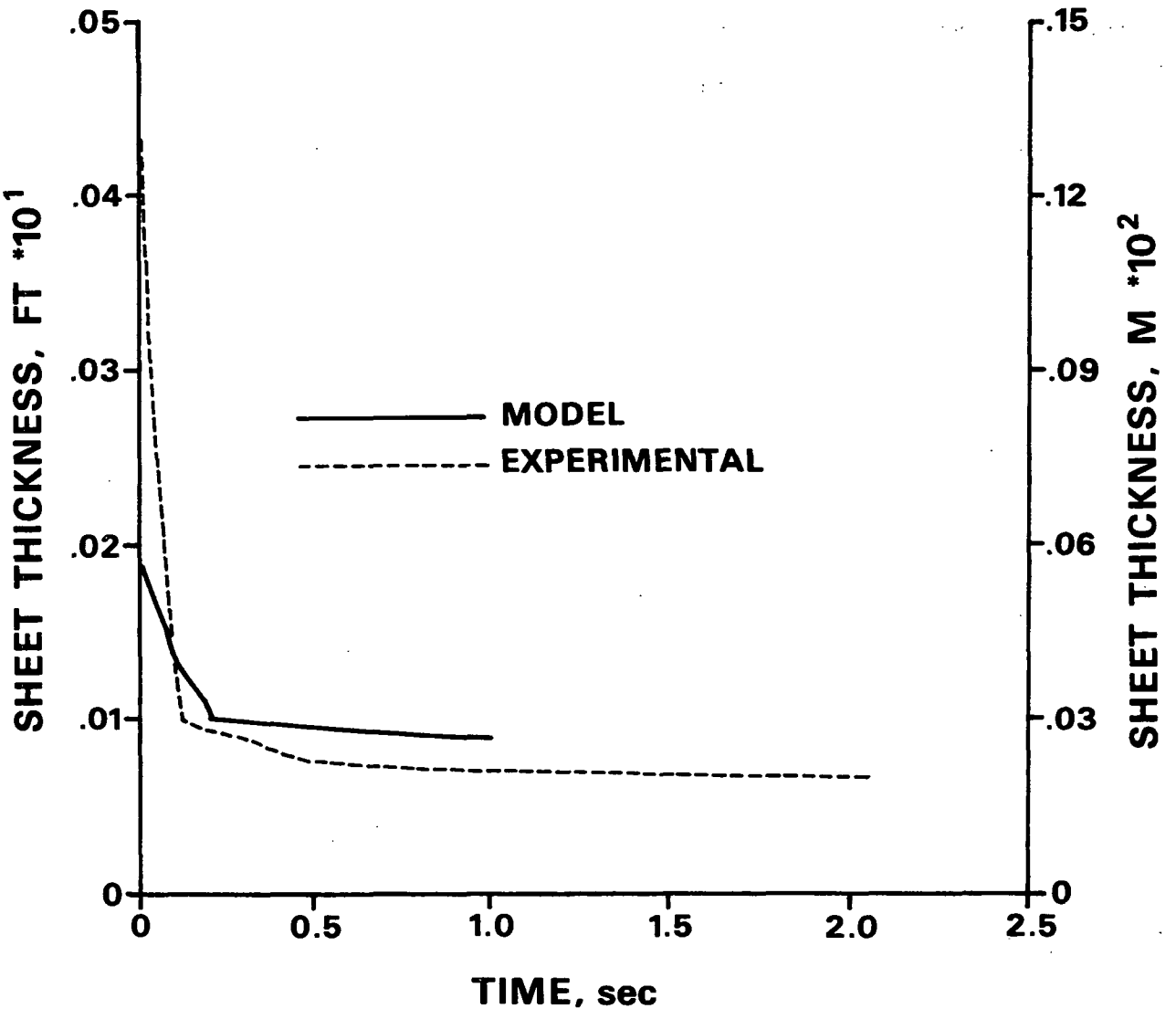

Figure 30. Predicted and measured sheet thickness for 274°C (525°F) ramp-and-hold pressure pulse.

Figures 31 and 32 again show that the model qualitatively describes these drying conditions. The temperature at a point midway through the basis weight of the sheet is plotted for both cases. The experimental curves indicate that the rate of heat transfer to the interior of the sheet is much higher than that predicted by the model. This is probably due to the model's assumption of no vapor flow through the outer zone during the transition regime. The large latent heat carried into the zone and released by vapor condensation raises the temperature there much faster than simple conduction would. Including this

effect would complicate the transition regime calculations by introducing a source term in the transient heat transfer equation and by requiring a more complicated mass balance (since the moisture ratio would be changing) but would be a reasonable next step in improving the model.

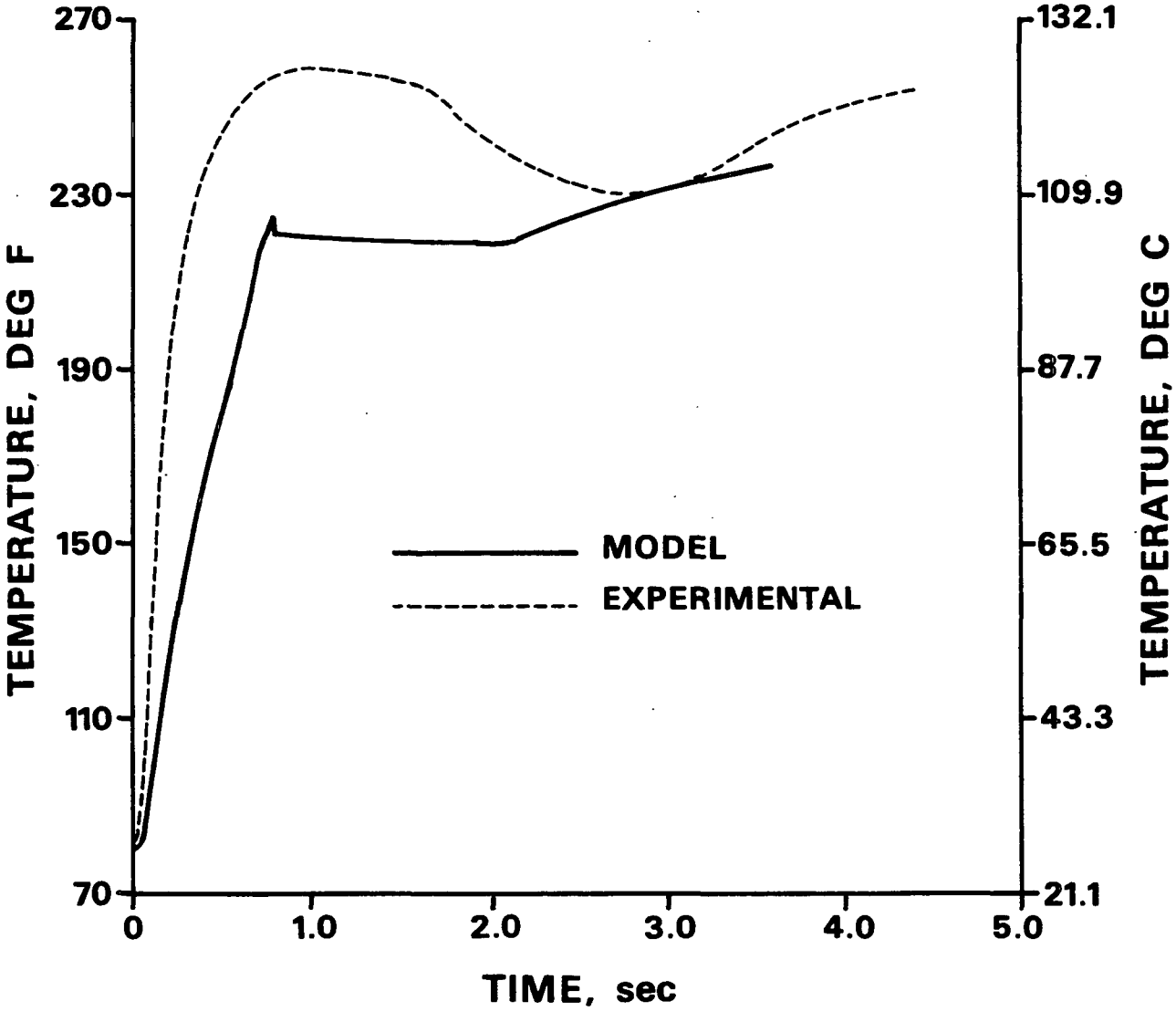

Figure 31. Predicted and measured midpoint temperature for 149°C (300°F) ramp-and-hold pressure pulse.

To demonstrate the effect of the proposed changes to the model, constants in the model were simultaneously modified by 10% of their original values. The reference values for contact coefficient and the N compression constant were increased. The apparent cell wall density, the absolute permeability, and the M

compression constant were decreased. To simulate the transport and condensation of vapor in the outer zone, the thermal conductivity was modified by the addition of a diffusion term for the heatup period[94] and a bulk vapor flow term for the transition period.[95] This combined "effective" conductivity can be orders of magnitude larger than the simple conductivity and should greatly increase heat transfer to the interior of the sheet. Note that no attempt was made to account for any changes in saturation from the condensing vapor. This approximation is reasonable because the large latent heat implies that only a small amount of condensation is necessary to produce a large change in temperature.

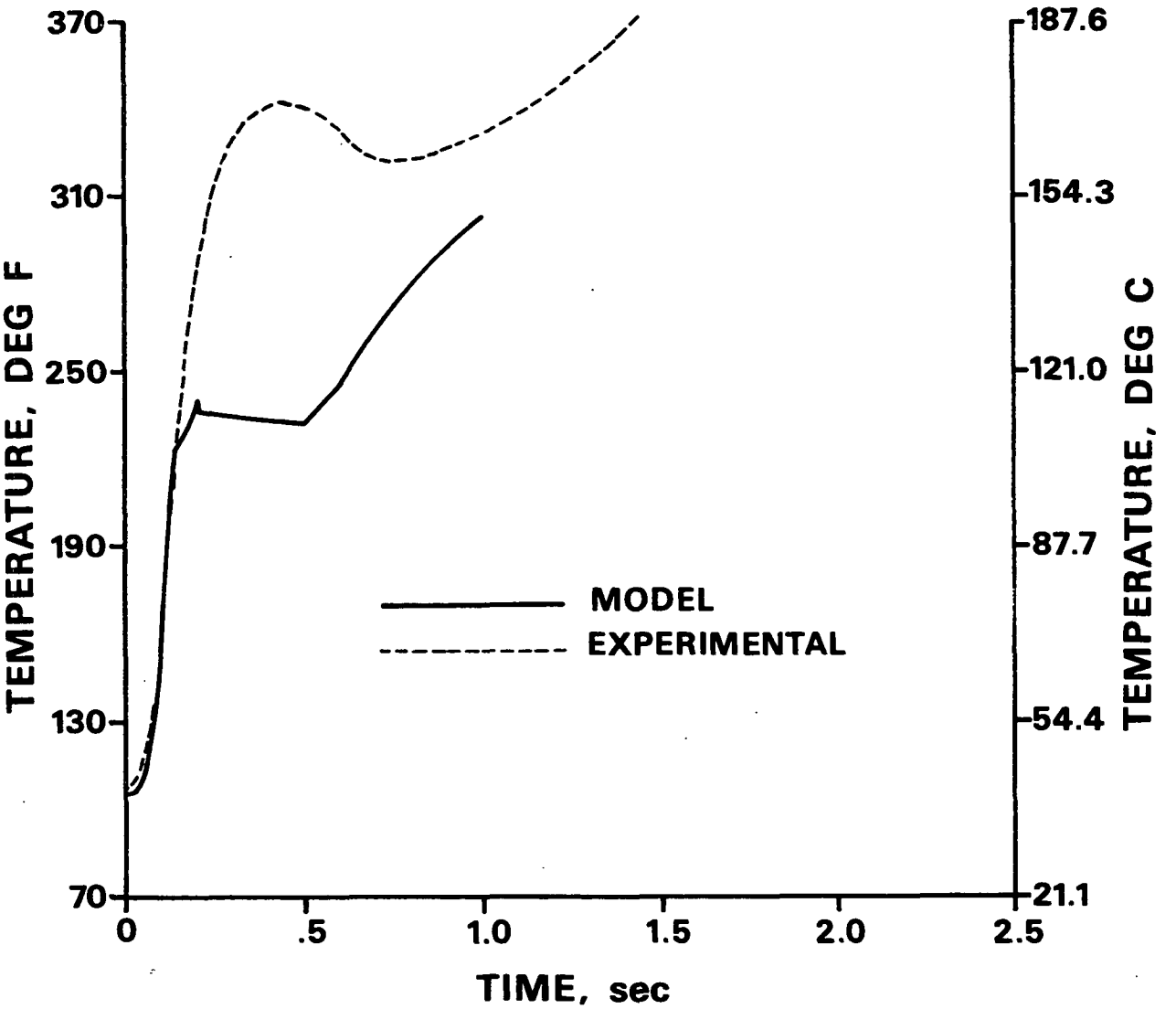

Figure 32. Predicted and measured midpoint temperature for 274°C (525°F) ramp-and-hold pressure pulse.

The results of this "optimization" are shown in Fig. 33 through 40 for the ramp-and-hold pressure cases. Figures 33 and 34 display the changes in drying behavior caused by the modifications. In both cases there is little effect on heatup time, since the diffusion term augmenting thermal conductivity is relatively small. The transition time is greatly reduced because the bulk flow term augmenting conductivity is very large. Trapping more water in the fibers causes a decrease in the amount of moisture removed in liquid form (from 80% down to 70%), and increases the drying time, since more moisture has to be removed by an evaporation mechanism.

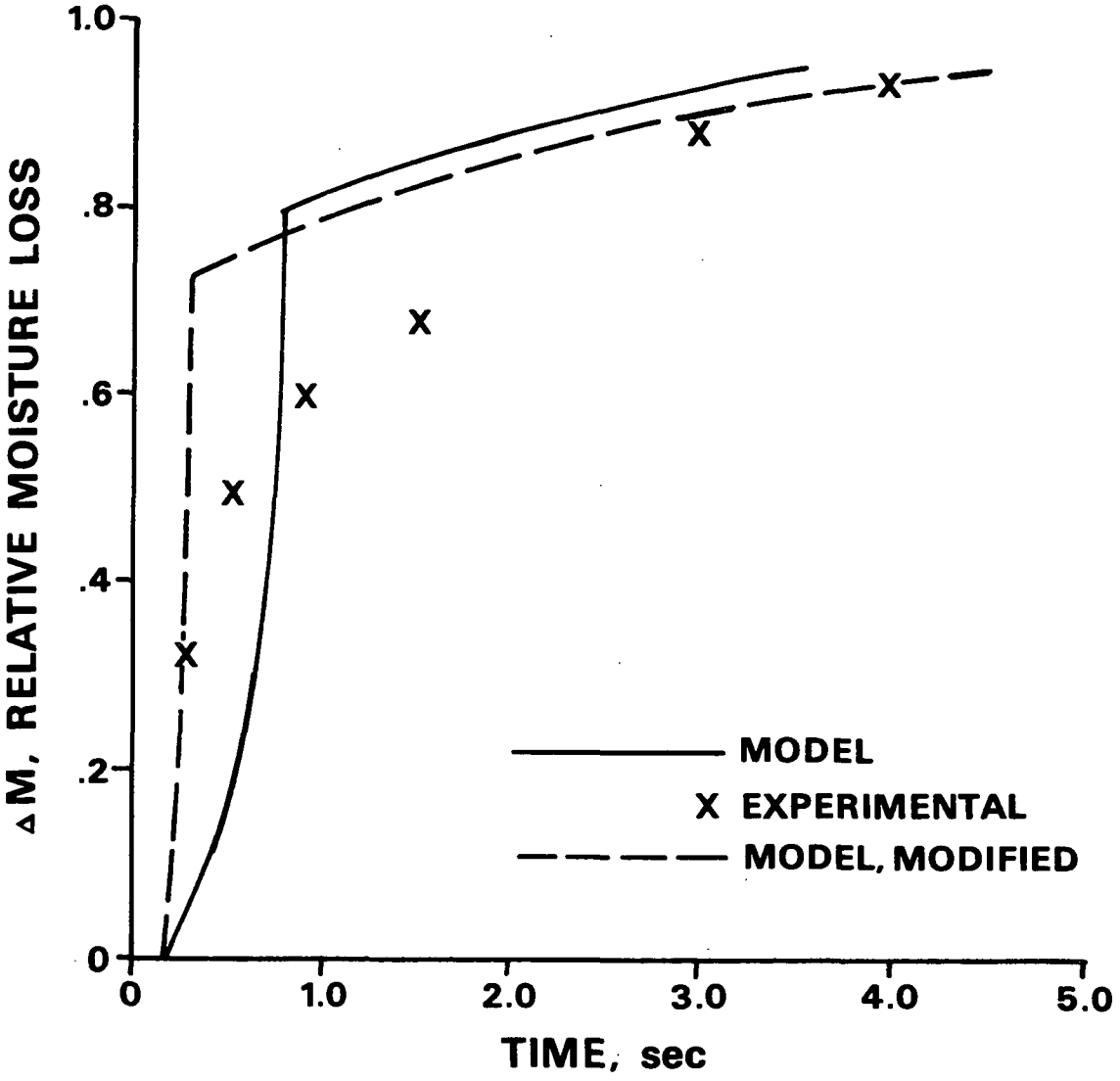

Figure 33. Predicted, measured, and modified model moisture removal for 149°C (300°F) ramp-and-hold pressure pulse.

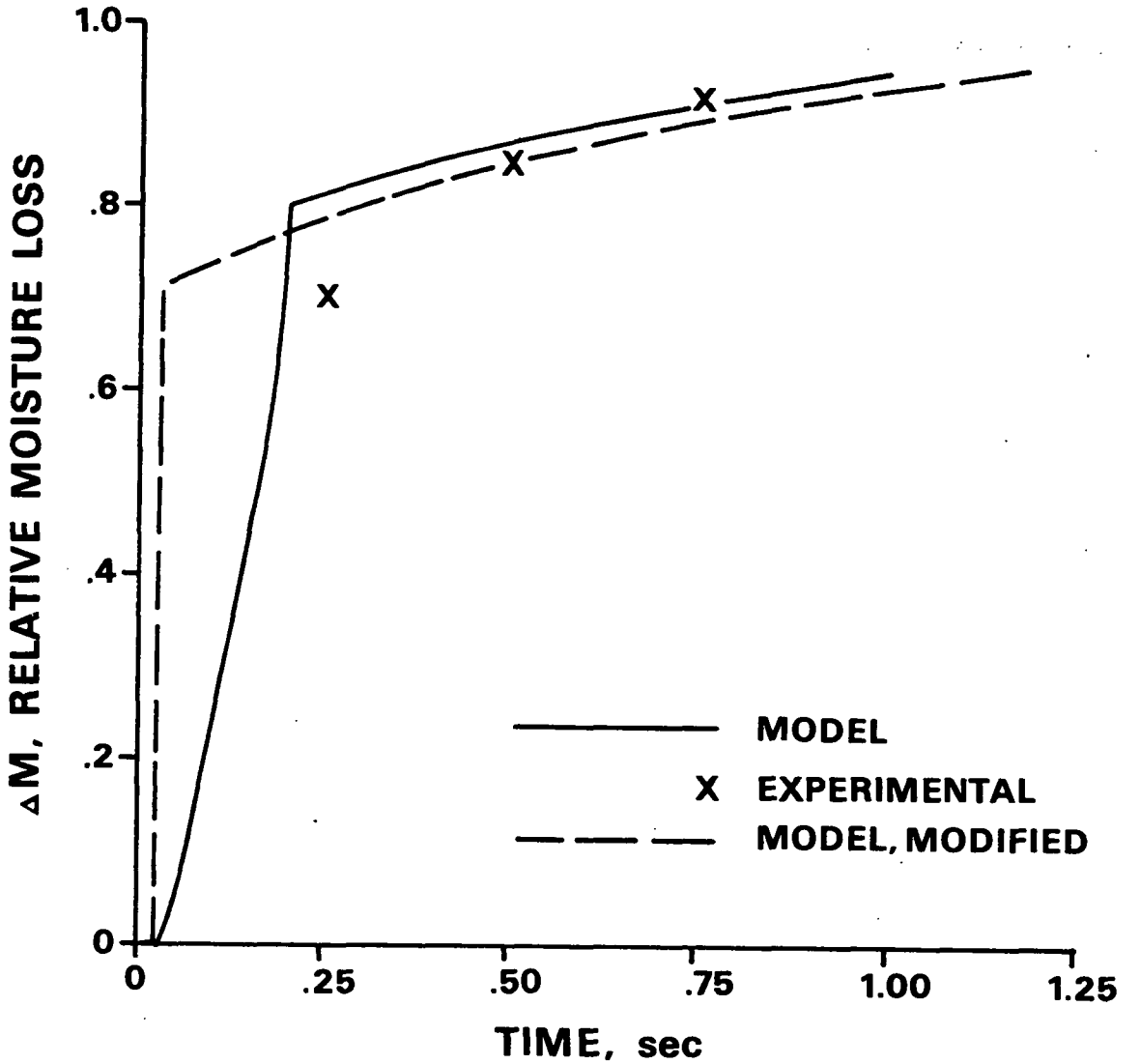

Figure 34. Predicted, measured, and modified model moisture removal for 274°C (525°F) ramp-and-hold pressure pulse.

Figures 35 and 36 show the influence on heat flux. In the 149°C (300°F) case the heat flux is decreased, which is the opposite of the anticipated trend. The change in compression constants causes a general increase in porosity and therefore an overall decrease in the contact coefficient even though the reference values for Hc were increased by 10%. In the 274°C (525°F) case, there is little effect because the higher driving force (TH - TS) tends to mask the influence of changes in the Hc reference values and compression constants.

Figures 37 and 38 depict the changes in predictions of sheet thickness. Changing the constants causes a slight increase in the initial thickness

prediction and significant changes in the slope and duration of the intermediate compression regime. The increase in N is not enough to offset the decrease in M and the modified model predicts an even higher thickness in the third compression regime. The slope is also changed in the third regime and shows a more rapid compression in the later stages of drying.

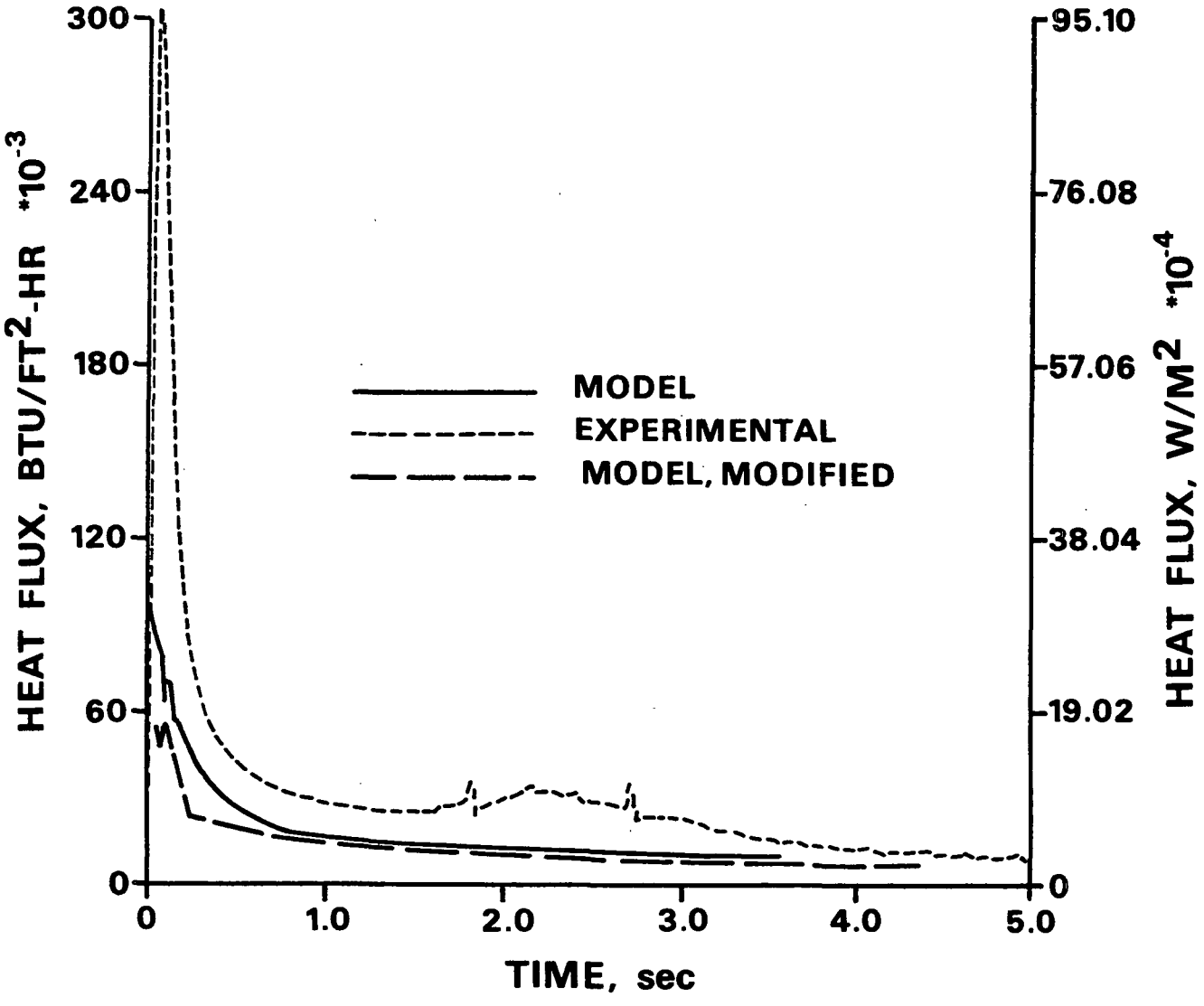

Figure 35. Predicted, measured, and modified model heat flux for 149°C (300°F) ramp-and-hold pressure pulse.

Figures 39 and 40 graph the effects of the modifications on the prediction of midpoint temperature. The first-peak midpoint temperature is significantly increased and the time required to achieve the peak is decreased. The duration of the predicted plateau period is increased. In a qualitative sense, the

changes benefit the lower temperature case more than the higher temperature case. This tends to indicate that the initial values for most constants were reasonable and that it is a change in mechanism going from lower temperature to higher temperature (such as the relative importance of capillary liquid flow) that causes the difference between measured and predicted behavior. Since the assumptions of HIDRYER1 are more appropriate to the higher temperature case, changing the constants should be expected to shift it away from its initially reasonable qualitative fit.

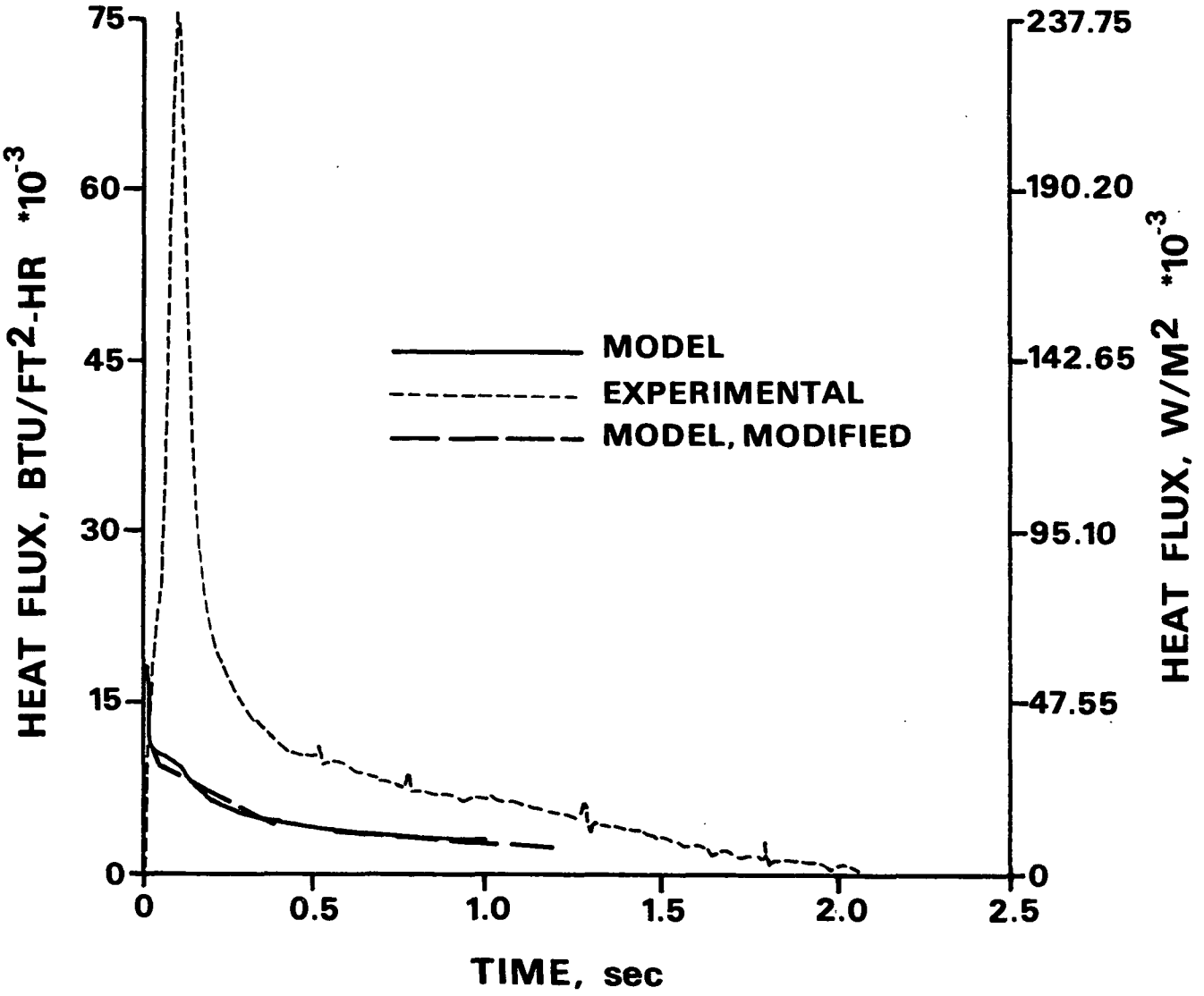

Figure 36. Predicted, measured, and modified model heat flux for 274°C (525°F) ramp-and-hold pressure pulse.

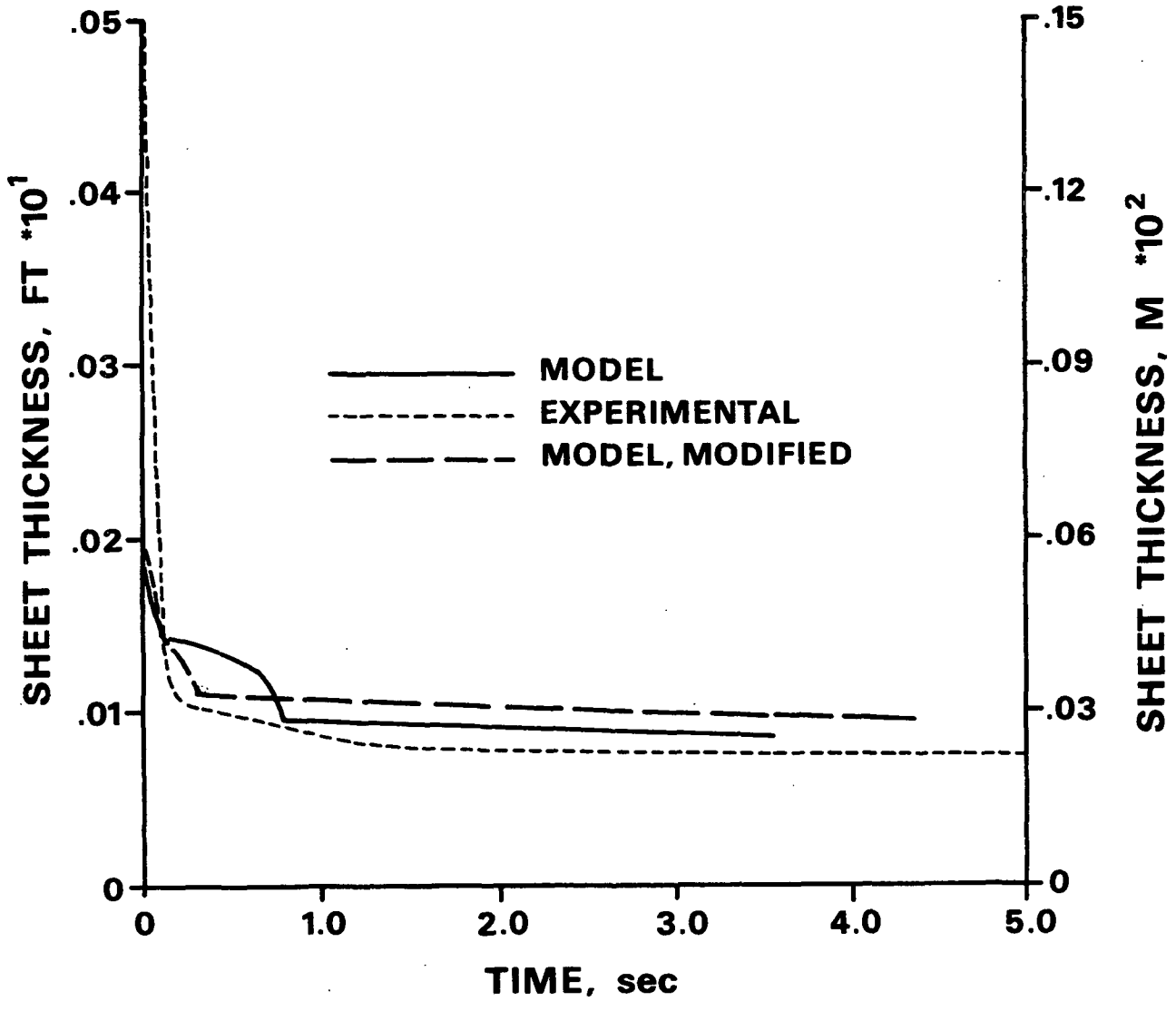

Figure 37. Predicted, measured, and modified model sheet thickness for 149°C (300°F) ramp-and-hold pressure pulse.

The previous figures clearly show that the model can be easily modified to alter its predictions by changing the constants in the model. An optimization of these constants in conjunction with further experimental information should be able to produce a highly accurate predictive tool.

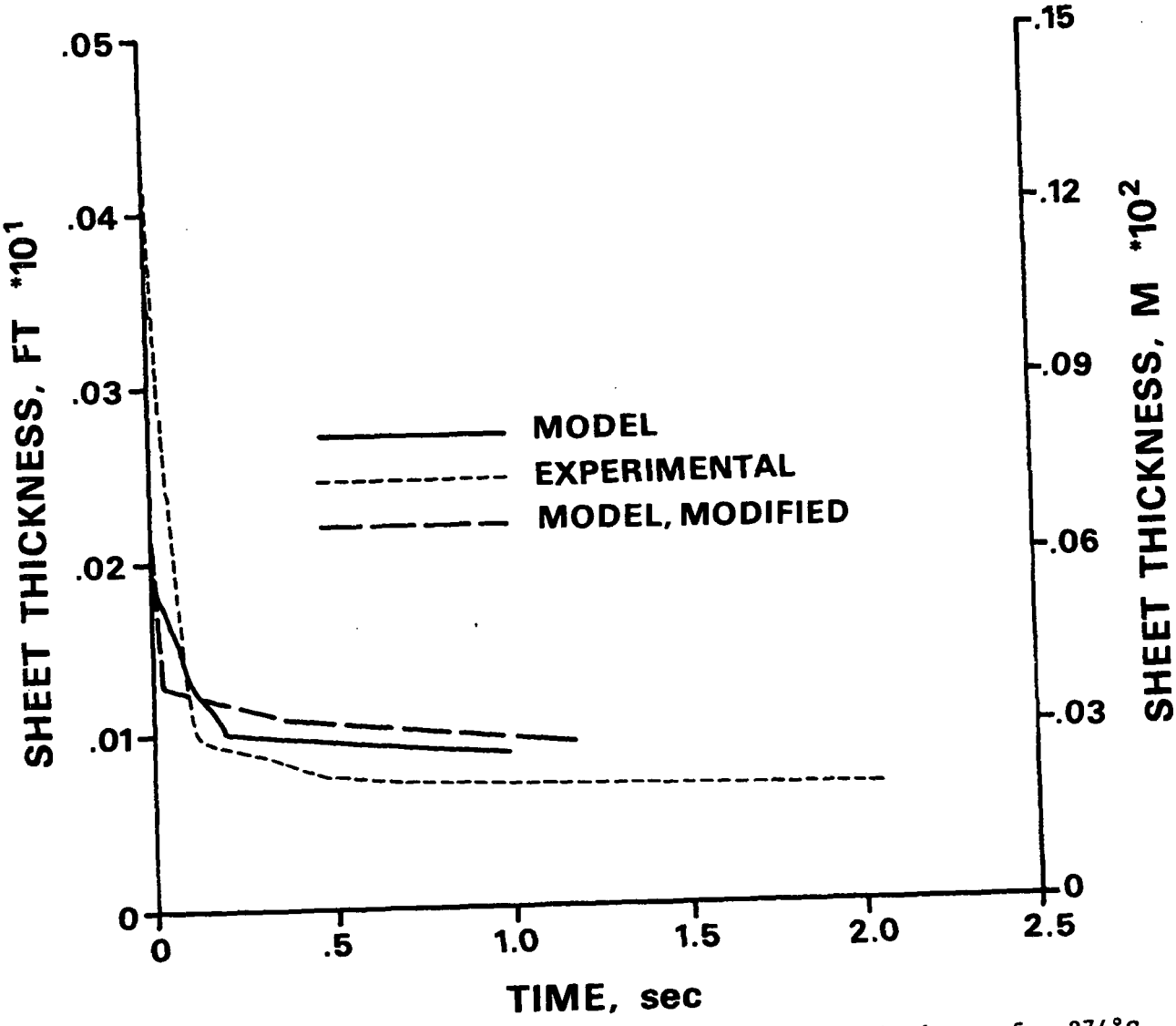

Figure 38. Predicted, measured, and modified model sheet thickness for 274°C (525°F) ramp-and-hold pressure pulse.

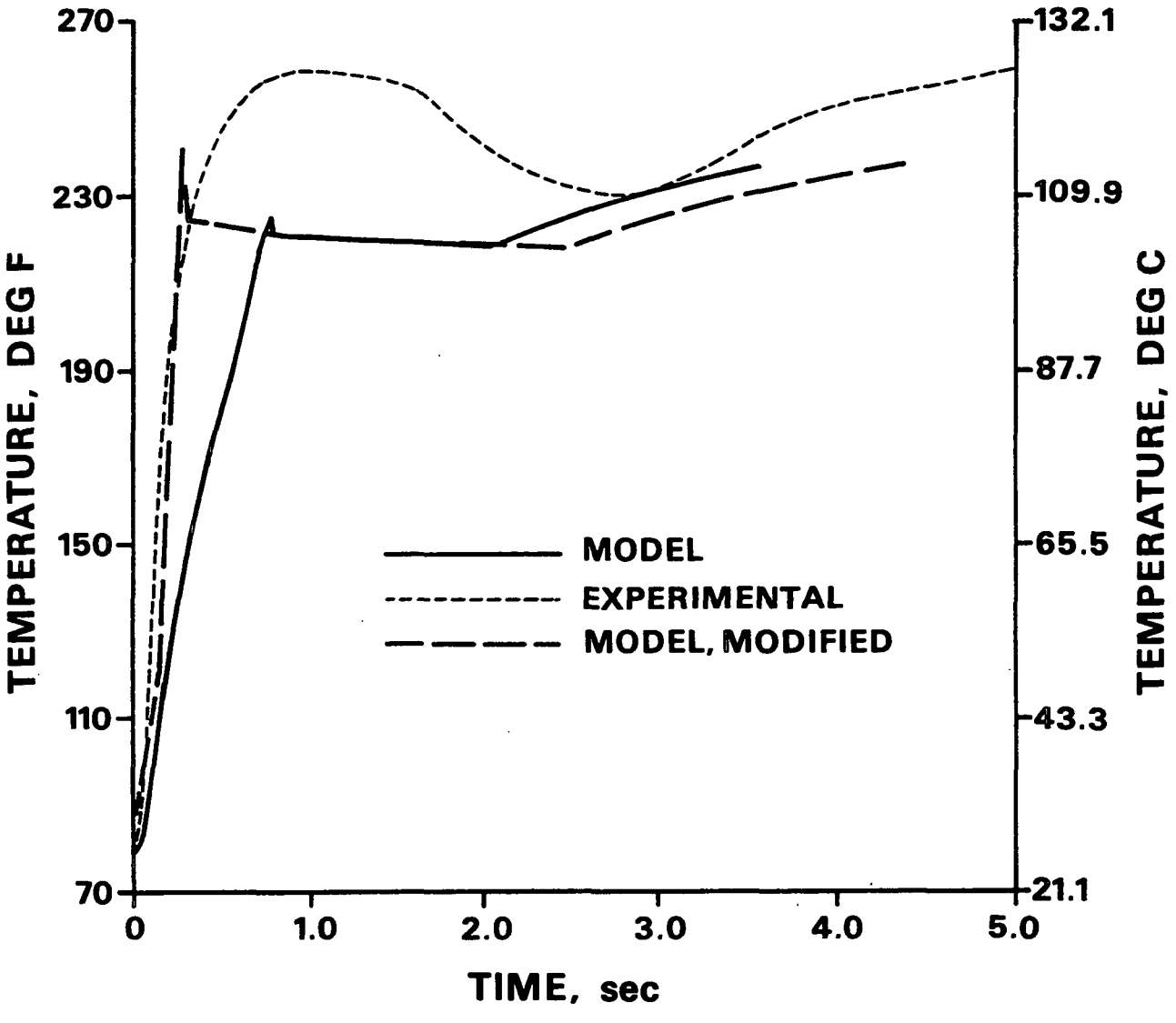

Figure 39. Predicted, measured, and modified model midpoint temperature for 149°C (300°F) ramp-and-hold pressure pulse.

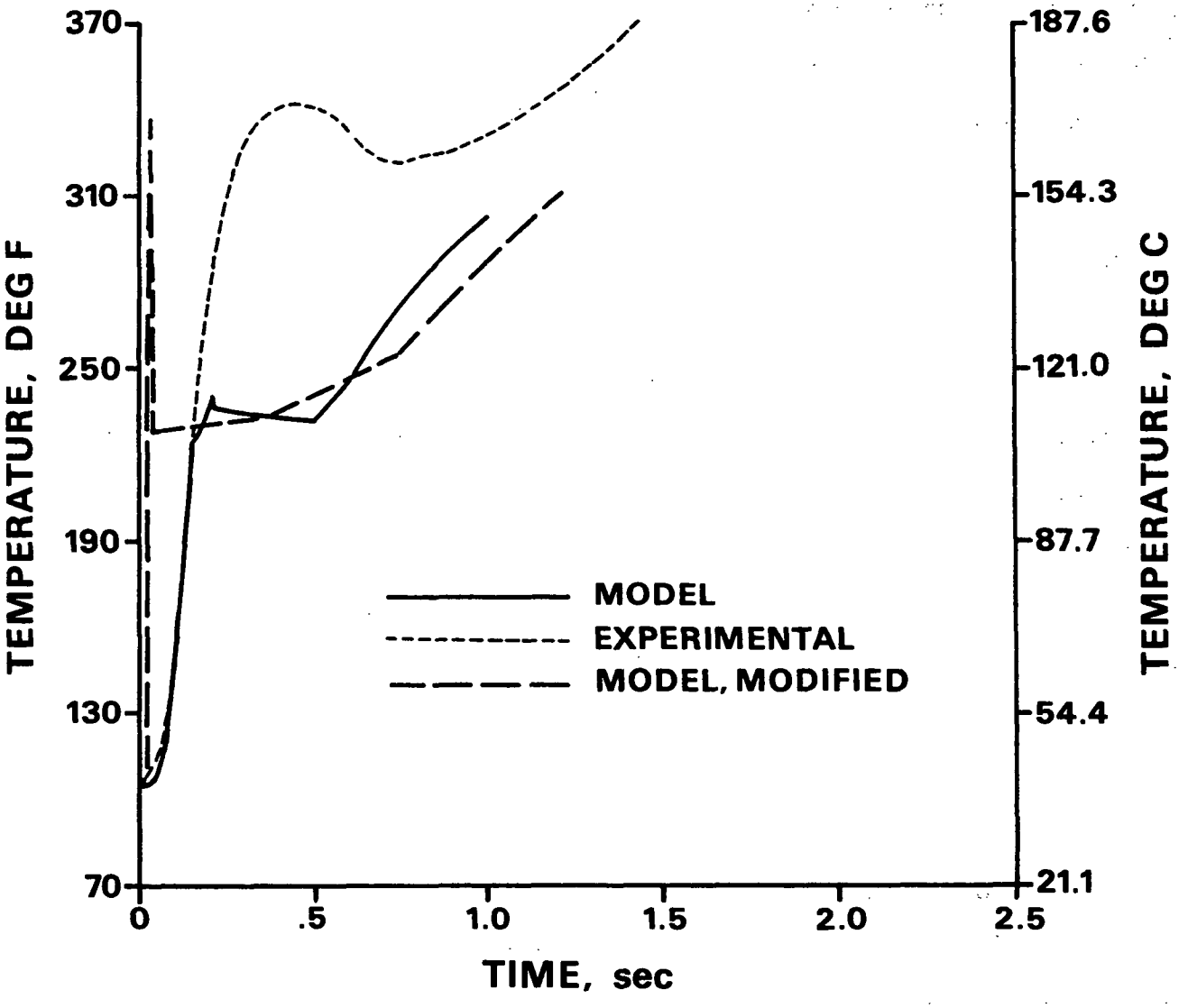

Figure 40. Predicted, measured, and modified model midpoint temperature for 274°C (525°F) ramp-and-hold pressure pulse.

SHORT DURATION (IMPULSE) PRESSURE PULSE

The time scale for the application of the mechanical pressure pulse in impulse drying is an order of magnitude shorter than the ramp-and-hold method. Rise times of a few milliseconds are possible. The heat and mass transfer phenomena that take place in both circumstances are fundamentally the same, but because of the dynamic nature of the impulse process the compression properties of the sheet assume great importance. The moisture loss by mechanical compression is

greater in the impulse case and the resulting sheet properties tend to be different. The impulse process is conceptually more identifiable with a (very high temperature) "heated wet pressing" operation than with a "drying" operation.

Figures 41 and 42 show comparisons of experimental and predicted sheet thicknesses for impulses delivered by a drop press simulator[3] at two hot surface temperatures.[96] Figure 42 corresponds to a wet pressing case since the temperature is only 18°C (65°F). The difference in magnitudes for the predicted and experimental results comes from the values used for M and N in the model and because the model calculates the thickness at every point in time (i.e., there is no initial thickness input to the model). If the model curve is simply shifted vertically so that the initial predicted thickness matches the initial measured thickness, a better comparison can be made. This is also shown in Fig. 41 and 42. Note that this method could be built into the model by supplying the initial thickness and correcting the model's predictions by a constant value equal to the difference between initial measured and predicted thicknesses. (An alternative would be to supply the initial measured thickness and modify M and N so that the initial predicted thickness would match.) Apart from the difference in magnitudes, the model exhibits an elastic type of behavior consistent with its compression equation. The experimental result shows how the paper fails to recover after the peak pressure has been achieved. This is due in part to the viscous nature of the fiber matrix and in part from irreversible alterations in the matrix structure. The depression in the center of the predicted curve results from the combination of rapid rate of change in pressure and N (which is a function of pressure) as the peak pressure is reached.

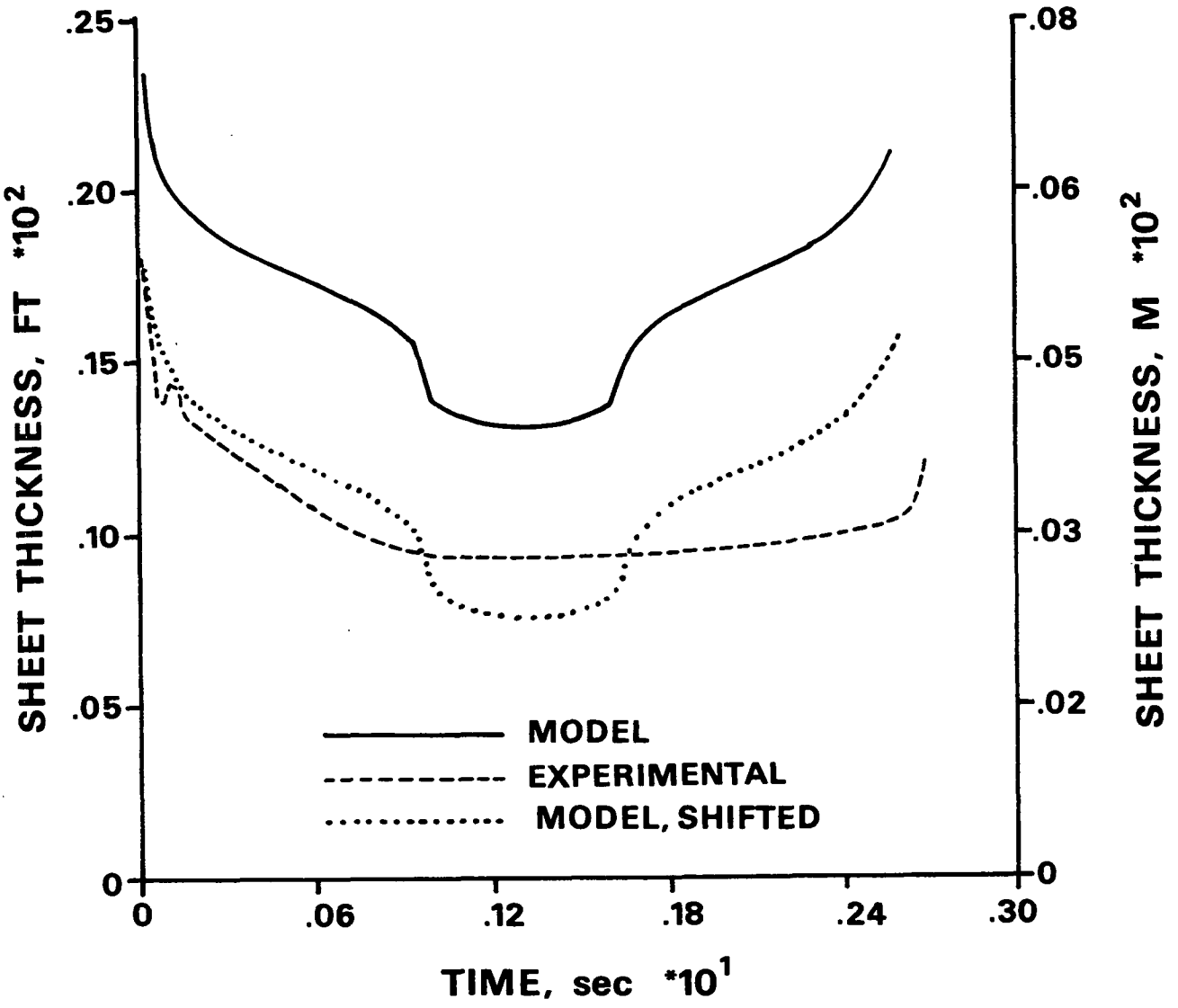

Figure 41. Predicted and measured sheet thickness for 18°C (65°F) impulse case.

In the 316°C (600°F) case, Fig. 42, the model more closely mimics the experimental result in a qualitative sense. Thermal softening at the elevated temperature moderates the rapid change in thickness as the peak pressure is attained. The model predicts a faster rate of compression in this case and a slower rate of thickness recovery relative to the lower temperature case. The experimental measurements show about the same rates in both cases. The model predicts a somewhat lower minimum thickness in the higher temperature case, which is the opposite of the experimental result. The model results are directly related to

the use of a compression equation in a drying model instead of using a heat transfer equation in a dynamic wet pressing model. A compression equation does not fully describe the internal sheet behavior to the extent necessary for direct application to impulse conditions.

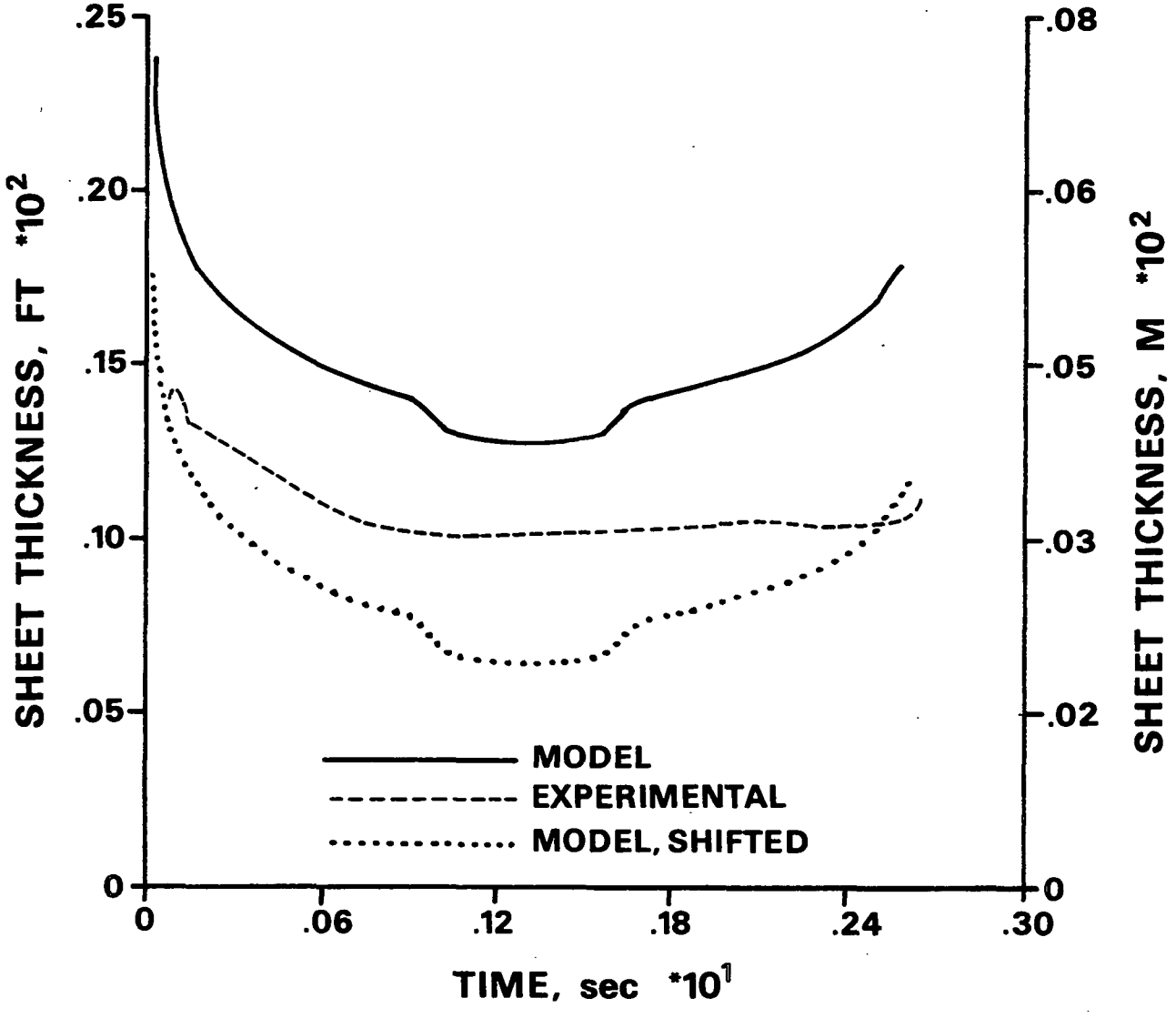

Figure 42. Predicted and measured sheet thickness for 316°C (600°F) impulse case.

Figure 43 shows the results from experiments in a heated, rotating roll press nip.[97] Equivalent dewatering can be achieved at many combinations of hot surface temperature and nip residence time.

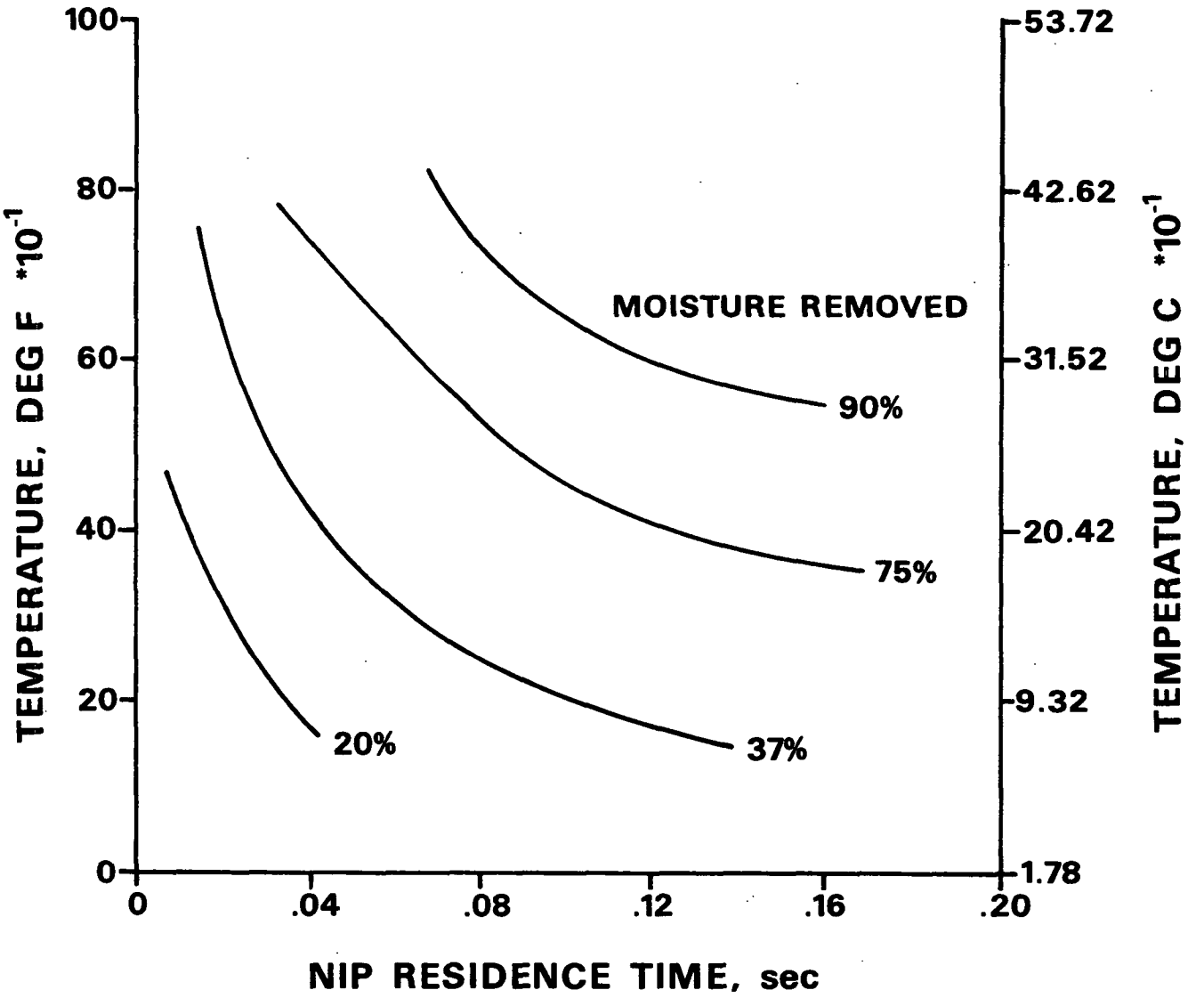

Figure 43. Impulse drying moisture removal for various combinations of hot surface temperature and nip residence time.

Table 4 summarizes the model's dewatering predictions for a variety of operating conditions selected from Fig. 43. The basis weight is 100 g/m^2 (0.0205 lbm/ft^2); moisture ratio is 1.381; freeness is 570 CSF; and PMAX is 12144 kPa (1760 psi). There are certain combinations of time and temperature which cause the model to predict an apparent zone 3 density which is greater than the (assumed constant) effective fiber wall density of 1 g/cc. The higher temperature cases can complete the calculations at shorter nip residence times than the lower temperature cases. This is a consequence of the rate of dewatering (rates of heat transfer and vapor pressure generation) relative to the rate of compression.

Table 4. Comparison of predicted and measured moisture removal for impulse drying conditions.

TH, °C (°F)	Nip Residence Time, s	Experimental Moisture Removal, %	Model Moisture Removal, %
149 (300)	0.020	20	55[a]
	0.060	37	33[a]
204 (400)	0.011	20	30[a]
	0.042	37	58[a]
	0.130	75	75
260 (500)	0.030	37	64[a]
	0.083	75	82
316 (600)	0.022	37	76
	0.063	75	83
	0.114	90	89
371 (700)	0.016	37	0[a]
	0.044	75	83
	0.082	90	88

[a] Computation terminated when zone 3 porosity becomes lower than the minimum allowable porosity.

Higher temperatures produce faster drying and higher hydraulic (vapor) pressures before the critical density is achieved by compression so that these cases can run to completion. At a basis weight of 50 g/m^2 (0.01025 lbm/ft^2) the model runs to completion but predicts no dewatering, even at 316°C (600°F) and 4137 kPa (600 psi), when the nip residence time is 5.4 milliseconds. Experimental moisture removals of up to 80% have been demonstrated for these conditions.[98]

In Table 4 all model cases overpredict the amount of moisture removed but the trend of increasing removal with increasing time is intact. The overprediction is a function of the assumed fiber wall density which determines the amount of (trapped) moisture unavailable for liquid flow. Decreasing the density would lower the amount available for flow but would raise the minimum porosity (lower

the effective critical density). The model therefore needs to be modified to treat both a compressible matrix, so that sheet thickness is a function of mechanical pressure; and compressible fibers, so that the liquid available for flow becomes a function of mechanical pressure and the limiting density is the density of cellulose (at a porosity of zero).

SUMMARY

HIDRYER1 gives good qualitative agreement with experimental results. The quantitative agreement could be improved by varying some of the constants used in the model and modifying the model to account for the phenomena of vapor flow and condensation during the transition regime and liquid expression from the fiber walls.

SUMMARY

This mathematical model is a significant first effort in the development of a convenient predictive tool for investigating high intensity drying options. The zone concept and simple solution method provide a methodology and framework for easy modification, expansion, and improvement.

The model requires few input parameters (hot surface temperature, boiling point temperature, basis weight, Canadian Standard Freeness, initial moisture ratio, mechanical pressure pulse) and qualitatively accounts for the observed macroscopic phenomena: internal sheet temperature, heat flux, sheet thickness, and moisture removal in liquid and vapor form. The degree of quantitative agreement varies with drying conditions. The agreement with all experimentally measured quantities could be improved by the specific suggestions in the thesis using a mathematical optimization procedure (with the empirical results as constraints on the output).

Capillary liquid flow appears to be significant at lower hot surface temperatures. Vapor flow with condensation appears to be significant during the transition regime under all conditions. A better model of dynamic sheet compression at high temperatures needs to be developed and tested.

RECOMMENDATIONS

The first extension of this work should be the modification of HIDRYER1 to run faster. This could be accomplished in several ways. The number of finite difference grid points could be reduced; the number of iterations for the calculation of the interface temperatures could be reduced; an alternative to the finite difference method could be used; or a reorganization of the computational algorithm could be performed. Any reduction in the CPU time would encourage more use of the model and allow a more comprehensive parametric investigation.

Second, a mathematical optimization of the model's constants would yield improvements in its quantitative predictions. There is already enough empirical evidence to make a reasonable effort in this area.

The third area for future research involves permeability. Transport models for paper have been limited in that a thorough investigation of the factors (freeness, moisture ratio, etc.) affecting permeability has not been performed. Isolated efforts are apparent, but are limited in scope and depth.

The fourth area is related to the compression properties of paper. The quantitative effects of moisture ratio, temperature, mechanical pressure, and freeness for a wide range of conditions are unknown. Each should be investigated individually and in combination to cover the complete range of process possibilities from wet pressing to high intensity drying.

ACKNOWLEDGMENTS

I would like to thank The Institute of Paper Chemistry for providing the facilities and financial support for this thesis.

The members of my advisory committee, Nai Chang, Peter Parker, and Douglas Wahren, offered many helpful insights and suggestions. My friend and principal adviser, Fred Ahrens, always found a way to keep me on the right track, whether by example, encouragement, or experience.

Finally, I would like to express my love and gratitude to my wife Deborah and my son Daniel for their endless supply of patience, support, love, and understanding.

NOMENCLATURE

The abbreviations for SI units in this section are: m (meter), s (second), kg (kilogram), K (kelvin), J (joule), N (newton), W (watt) , and Pa (pascal).

a	fraction of liquid water external to fibers
A1-4	equation constants
b	equation constant
B1-5	equation constants
BI	heat transfer Biot number
BW	mass of dry fibers per unit sheet area, kg/m^2
BW1-4	BW of individual zones, kg/m^2
C	mass of dry fibers per unit sheet volume, kg/m^3
C1,C2	equation constants
COEFF	arbitrary equation coefficient
CONST	arbitrary equation constant
Cpf	specific heat of cellulose, J/(kg K)
Cpv	specific heat of gas or vapor, J/(kg K)
Cpw	specific heat of liquid water, J/(kg K)
CSF	Canadian Standard Freeness
D	equation constant
D1-7	equation constants and rates of change
DBWxDT	rate of change of zone x basis weight, kg/m^2 s
Dc	equation constant
DIFF'	relative position increment
DIFF"	relative position increment
DTO	default time increment, s

E1,E2	equation constants
F1,F2	equation constants
G1-6	equation constants
H1-4	equation constants
Hc	hot surface to paper contact coefficient, $W/(m^2\ K)$
Δh	latent heat of vaporization, J/kg
$\Delta h'$	incremental latent heat of desorption, J/kg
Δh^*	average latent heat of desorption, J/kg
I1	equation constant
i'	grid point designation
i"	grid point designation
IMAX	iteration counter
J1-5	equation constants
K	thermal conductivity, W/(m K)
K1-3	equation constants or zone thermal conductivities
KAKV	product of Ka3 and Kv, m^2
KAKW	product of Ka3 and Kw, m^2
Ka	absolute permeability, m^2
Ka2-4	zone absolute permeabilities, m^2
Kd	dry zone thermal conductivity, W/(m K)
KMIN	minimum number of grid points
Kv	relative gas or vapor permeability
Kw	relative liquid permeability
$\overline{L}$	distance in zone, m
L	zone thickness, m
L1-3	equation constants or zone thicknesses
M	compression equation constant, $(kg/m^3)/Pa^N$

M'	modified M value, $(kg/m^3)/Pa^N$
M1	equation constant
Mo	initial mass of water per unit area, kg/m^2
MR	mass of water per unit mass of dry fiber
MRi	starting MR
MRf	ending MR
MREL	mass of water removed divided by initial mass
MRO	initial MR
N	compression equation constant
N1,N2	equation constants
OHTC	overall heat transfer coefficient, $W/(m^2\ K)$
P	pressure, Pa
Patm	ambient pressure, Pa
Pcap	capillary pressure, Pa
PMAX	maximum gage mechanical pressure, Pa
Pmech	absolute mechanical pressure, Pa
Pmechg	gage mechanical pressure, Pa
PROP	arbitrary vapor or liquid property
Pv	vapor pressure, Pa
Pw	liquid pressure, Pa
$\overline{Pw}$	average hydraulic pressure, Pa
Q	conduction heat flux, W/m^2
r	pore radius, m
R	specific filtration resistance, m/kg
RATE1-3	rates of advance, m/s
RATIO1-3	interface position divided by DELTAT
RISTIM	time required to attain PMAX, s

S	saturation
S'	interfiber saturation
S2,S3	zone saturations
SEC	time, s
t	time, s
Δt	time increment, s
t'	time, s
T	temperature, K
T'	grid point temperature, K
T"	grid point temperature, K
T1-3	interface temperatures, K
TB	boiling point temperature, K
TBAR	average zone temperature, K
TH	hot surface temperature, K
TI	initial sheet temperature, K
TIME	time, s
TS	sheet surface temperature, K
U	same as OHTC, $W/(m^2\ K)$
Vf	velocity of fibers, m/s
Vf'	interface velocity, m/s
Vgas	gas velocity, m/s
Vv	superficial vapor velocity relative to Vf, m/s
Vw	superficial liquid water velocity relative to Vf, m/s
Vwater	velocity of liquid water, m/s
x	relative position
Δx	relative position increment
z	position coordinate, m

γ	surface tension, N/m
δ	thickness, m
δ'	grid point coordinate, m
δ''	grid point coordinate, m
δ_{1-3}	interface positions, m
δ_T	total thickness, m
ε	porosity
ε'	interfiber porosity
$\varepsilon_{2,3}$	zone porosities
θ	contact angle, radians
μ_v	vapor viscosity, N s/m^2
μ_w	liquid viscosity, N s/m^2
ρ_F	fiber density, kg/m^3
ρ_v	vapor density, kg/m^3
ρ_w	liquid density, kg/m^3
τ	time parameter
ϕ	equation coefficient
$\overline{\phi}$	averaged equation coefficient
ψ	equation coefficient

LITERATURE CITED

1. Byrd, V. Drying and heat transfer characteristics during bench-scale press drying of linerboard. Drying 82. A. Mujumdar, ed., Washington, Hemisphere Publishing, 1982:83-90.

2. Lehtinen, J. A new vacuum-drying method for paper, board, and other permeable mats. Drying 80: Vol. 2 Proceedings of the 2nd International Drying Symposium. A. Mujumdar, ed., Washington, Hemisphere Publishing, 1980:347-54.

3. Arenander, S.; Wahren, D. Impulse drying adds new dimension to water removal. Tappi 66(9):123-6(Sept., 1983).

4. Ahrens, F.; Kartsounes, G.; Ruff, D. A laboratory study of hot surface drying at high temperature and mechanical loading. Preprints of the 68th annual CPPA Technical Section meeting, Montreal, Jan. 26-29, 1982, Vol. B, B93-B97 and Pulp Paper Canada 85(3):T63-7(March, 1984).

5. Ahrens, F. Heat transfer aspects of hot surface drying at high temperature and mechanical loading. J. Pulp Paper Sci. 9(3):TR79-82(July, 1983).

6. Fang, Y., The Institute of Paper Chemistry, Personal communication, April 4, 1983.

7. Burton, S. A dynamic simulation of impulse drying. A291 final report. Appleton, WI, The Institute of Paper Chemistry, 1983. 95 p.

8. Devlin, C., The Institute of Paper Chemistry, Personal communication, March 25, 1985.

9. Ahrens, F.; Astrom, A. High intensity drying of paper. Submitted to Drying Technology: An International Journal, December 31, 1984.

10. Udell, K. Heat transfer in porous media heated from above with evaporation, condensation, and capillary effects. J. Heat Transfer 105(3):485-92 (Aug., 1983).

11. Chi, S. Heat pipe theory and practice. Washington, Hemisphere Publishing, 1976.

12. Holden, G., U.S. pat. 3,284,285(Nov. 8, 1966).

13. Kawka, W.; Rogut, R., Przeglad Papier. 26(2):52-6(Feb., 1970).

14. Kawka, W.; Ingielewicz, H., Przeglad Papier. 28(11):381-7(Nov., 1972).

15. Kawka, W., Przeglad Papier. 30(1):10-18(Jan., 1974).

16. Kawka, W.; Ingielewicz, H., Przeglad Papier. 34(2):53-8(Feb., 1978).

17. Kawka, W.; Ingielewicz, H.; Marek, I., Przeglad Papier. 34(3):82-7(March, 1978).

18. Kawka, W.; Stepien, K., Przeglad Papier. 35(11):402-4(Nov., 1979).

19. Kawka, W.; Szwarcsztajn, E. EUCEPA-79 International Conference, London, May 21-24, 1979, Paper No. 31.

20. Kawka, W., Przeglad Papier. 39(11/12):403-7(Nov.-Dec., 1983).

21. Carr, W.; Holcombe, W.; Pearson, K.; Robertson, S.; Carter, W. Assessing the Machnozzle as a predrying device. Textile Chemist Colorist 15(8):21-6 (Aug., 1983).

22. Luikov, A.; Vasiliev, L. Heat and mass transfer in capillary porous bodies blown by a rarefied gas flow. Low Temperature Heat Mass Transfer 5(1970) as quoted in: Tolubinsky, V.; Antonenko, V.; Ostrovsky, Y.; Shevchuk, E. Drop carry-over phenomenon in liquid evaporation from capillary structures. Letters Heat Mass Transfer 5(6):339-47(Nov.-Dec., 1978).

23. Andersson, L.; Back, E. The effect of temperature up to 90°C on dewatering of wet webs, evaluated in a press simulator. TAPPI 1981 Engineering Conference Proceedings. Book 1:311-23(1981).

24. Andersson, L.; Back, E. Improvements in dewatering at increased pressing temperatures, a press simulator evaluation. Tappi 65(7):75-80(July, 1982).

25. Cutshall, K. Cross machine moisture control via hot pressing. TAPPI 1984 Engineering Conference Proceedings. Book 3:637-41(1984).

26. van Brakel, J.; Heertjes, P. Proceedings of the 1st International Drying Symposium. 70(1978) as quoted in: Brown, L.; Kashiwa, B.; Vanderborgh, N,; Corlett, R. The kinetic behavior of subbituminous coal drying; effects of confining pressure. Drying 80: Vol. 2 Proceedings of the 2nd International Drying Symposium. A. Mujumdar, ed., Washington, Hemisphere Publishing, 1980:425-433.

27. Ingersoll, L.; Zobel, O.; Ingersoll, A. Heat conduction with engineering, geological, and other applications. Madison, WI, University of Wisconsin Press, 1954:190-199.

28. Muehlbauer, J,; Sunderland, J. Heat conduction with melting or freezing. Applied Mechanics Reviews 18(12):951-9(Dec., 1965).

29. Tien, R.; Geiger, G. A heat transfer analysis of the solidification of a binary eutectic system. J. Heat Transfer 89(3):230-4(Aug., 1967).

30. Cho, S.; Sunderland, J. Heat conduction problems with melting or freezing. J. Heat Transfer 91(3):421-6(Aug., 1969).

31. Eckert, E.; Drake, R. Analysis of heat and mass transfer. New York, McGraw-Hill, 1972:224-8.

32. Cho, S.; Sunderland, J. Phase change problems with temperature dependent thermal conductivity. J. Heat Transfer 96(2):214-17(May, 1974).

33. White, R. A modified finite difference scheme for the Stefan problem. Mathematics of Computation 41(164):337-47(Oct., 1983).

34. Chawla, T.; Pedersen, D.; Leaf, G.; Minkowycz, W.; Shouman, A. Adaptive collocation method for simultaneous heat and mass diffusion with phase change. J. Heat Transfer 106(3):491-7(Aug., 1984).

35. Selim, M.; Seagrave, R. Solution of moving boundary transport problems in finite media by integral transforms, Parts I, II, III. I&EC Fundam. 12(1): 1-8, 9-13, 14-17(Feb., 1973).

36. Solomon, A. Some remarks on the Stefan problem. Mathematics of Computation 20:347-60(1966).

37. Bonacina, C.; Comini, G.; Fasano, A.; Primicerio, M. Numerical solution of phase change problems. Int. J. Heat Mass Transfer 16(10):1825-32(Oct., 1973).

38. Voller, V.; Cross, M. Accurate solutions of moving boundary problems using the enthalpy method. Int. J. Heat Mass Transfer 24(3):545-56(March, 1981).

39. Voller, V.; Shadabi, L. Enthalpy methods for tracking a phase change boundary in two dimensions. Int. Comm. Heat Mass Transfer 11(3):239-49(May-June, 1984).

40. Talmon, Y.; Davis, H.; Scriven, L. Progressive freezing of composites analyzed by isotherm migration methods. AIChE J. 27(6):928-37(Nov., 1981).

41. Talmon, Y.; Davis, H.; Scriven, L. Moving boundary problems in simple shapes solved by isotherm migration. AIChE J. 29(5):795-800(Sept., 1983).

42. Cho, S. An exact solution of the coupled phase change problem in a porous medium. Int. J. Heat Mass Transfer 18(10):1139-42(Oct., 1975).

43. Hilding, W.; Cheh, U. Transient temperature response during heating of an initially saturated plane porous wall. Heat Transfer 82: Vol. 6 Proceedings of the 7th International Heat Transfer Conference. U. Grigull; E. Hahne; K. Stephan; J. Straub, eds., Washington, Hemisphere Publishing, 1982:67-72.

44. Szentgyorgyi, S.; Molnar, K. Calculation of drying parameters for the penetrating evaporation front. Drying 84. A. Mujumdar, ed., Washington, Hemisphere Publishing, 1984:76-82.

45. Szentgyorgyi, S.; Molnar, K.; Orvos, M. Computer calculation method of the falling rate period of drying. Drying 84. A. Mujumdar, ed., Washington, Hemisphere Publishing, 1984:83-7.

46. Lin, S.; Chou, T. A parametric study of the freeze-dry process for preservation of activities of biological substances. Drying 84. A. Mujumdar, ed., Washington, Hemisphere Publishing, 1984:99-104.

47. Kisakurek, B.; Celiker, H. Modeling of simultaneous heat and mass transfer in freeze drying. Drying 84. A. Mujumdar, ed., Washington, Hemisphere Publishing, 1984:324-29.

48. Adesanya, B. Heat and mass transfer in a capillary porous body with particular reference to lumber. Doctoral Dissertation. Clemson, SC, Clemson University, 1982. 189 p.

49. Beard, J.; Rosen, H.; Adesanya, B. Temperature distributions and heat transfer during the drying of lumber. Drying Technology: An International Journal 1(i):117-40(Feb., 1983).

50. Dorri, B.; Emery, A.; Malte, P. Drying rate of wood particles with longitudinal mass transfer. J. Heat Transfer 107(1):12-18(Feb., 1985).

51. Hallstrom, A. Drying of porous hygroscopic materials: an extended shrinking core model. Drying 82. A. Mujumdar, ed., Washington, Hemisphere Publishing, 1982:19-24.

52. Sato, K.; Ishida, M.; Shirai, T. Prediction of pressure increase and evaporation temperature during the course of drying of porous solid soaked with water. J. Chem. Eng. Japan 9(1):35-9(1976).

53. Cross, M.; Gibson, R.; Young, R. Pressure generation during the drying of a porous half-space. Int. J. Heat Mass Transfer 22(1):47-50(Jan., 1979).

54. Gibson, R.; Cross, M.; Young, R. Pressure gradients generated during the drying of porous shapes. Int. J. Heat Mass Transfer 22(6):827-30(June, 1979).

55. Strek, F.; Nastaj, J. Mathematical modeling and simulation of vacuum contact drying of porous media in the falling rate period (boundary condition of the first kind). Drying 80: Vol. 2 Proceedings of the 2nd International Drying Symposium. A. Mujumdar, ed., Washington, Hemisphere Publishing, 1980:135-43.

56. Baines, W. Analysis of transient effects in drying of paper. Pulp Paper Can. 74(2):58-64(Feb., 1973).

57. Ahrens, F. Fundamentals of drying, project 3470. Status report to the Engineering and Colloid Science Research Advisory subcommittee. Appleton, WI, The Institute of Paper Chemistry, March 23-24, 1983:117-36.

58. Kreith, F. Principles of Heat Transfer. Scranton, Pa., International Textbook Company, 1958:430-6.

59. Yiannos, P. The apparent cell wall density of wood and pulp fibers. Tappi 47(8):468-71(Aug., 1964).

60. Devlin, C. An investigation of the drying mechanism of paper at high temperatures and mechanical pressures, A400 Revised Thesis Proposal. Appleton, WI, The Institute of Paper Chemistry, 1982:19.

61. Ahrens, F.; Journeaux, I. An experimental and analytical investigation of a thermally induced vacuum drying process for permeable mats. Drying 84. A. Mujumdar, ed., Washington, Hemisphere Publishing, 1984:281-91.

62. Han, S. Heat and mass transfer in hot-surface drying of fiber mats. Pulp Paper Can. 65(12):T537-49(Dec., 1964).

63. Carlsson, G.; Lindstrom, T.; Floren, T. Permeability to water of compressed pulp fiber mats. Svensk Papperstid. 86(12):R128-34(Sept., 1983).

64. Emmons, H. The continuum properties of fiber suspensions. Tappi 48(12): 679-87(Dec., 1965).

65. Leonard, B. A survey of finite differences of opinion in numerical muddling of the incomprehensible defective confusion equation. Finite Element Methods for Convection Dominated Flows, AMD Vol. 34. T. Hughes, ed., New York, ASME, 1979:1-17.

66. Patankar, S. Numerical heat transfer and fluid flow. Washington, Hemisphere Publishing, 1980:50-2.

67. Pounder, J. A400 Progress Report 5. Appleton, WI, The Institute of Paper Chemistry, Jan. 27, 1984. 26 p.

68. Prahl, J. Thermodynamics of paper fiber and water mixtures. Doctoral Dissertation. Cambridge, Harvard University, 1968. 159 p.

69. Pounder, J. A400 Progress Report 8. Appleton, WI, The Institute of Paper Chemistry, Oct. 19, 1984. 23 p.

70. Han, S. Drying of paper. Tappi 53(6):1034-46(June, 1970).

71. Fang, Y., The Institute of Paper Chemistry, Personal communication, March 20, 1983.

72. Pounder, J. A400 Progress Report 6. Appleton, WI, The Institute of Paper Chemistry, April 27, 1984. 24 p.

73. Campbell, W. The physics of water removal. Pulp Paper Can. 48:103-9, 122 ("Convention Issue", 1947).

74. Chang, N. Dynamic compression of handsheets. TAPPI 1978 Engineering Conference Proceedings. Book 1:93-106(1978).

75. Consolvo, W. Dynamic compression of a fiber mat. A291 final report. Appleton, WI, The Institute of Paper Chemsitry, 1981. 33 p.

76. Caulfield, D.; Young, T.; Wegner, T. The role of web properties in water removal by wet pressing. Tappi 65(2):65-9(Feb., 1982).

77. Ceckler W.; Thompson, E. Final Report of the University of Maine at Orono Wet Pressing Project. Washington, U.S. Department of Energy, 1982. 335 p.

78. Gren, U.; Ljungkvist, K. Compressibility and permeability of chemical pulps. Cellulose Chem. Tech. 17(5):515-23(Sept.-Oct., 1983).

79. Hung, J.; Holm, R. A study of the drying of linerboard, Progress Report 2, Project 2693. Appleton, WI, The Institute of Paper Chemistry, 1969. 69 p.

80. Pounder, J. IPC Research Notebook 3711, March 2, 1985:60-3.

81. Pounder, J. IPC Research Notebook 3711, March 2, 1985:63-5.

82. Davies, C. The separation of airborne dust and particles. Institution of Mechanical Engineers 1B:185-98(1952).

83. Labrecque, R. The effects of fiber cross-sectional shape on the resistance to the flow of fluids through fiber mats. Tappi 51(1):8-15(Jan., 1968).

84. Ellis, E. Compressibility and permeability of never dried bleached softwood kraft pulp and its application to the prediction of wet press behavior. Doctoral Dissertation. Orono, ME, University of Maine at Orono, 1981. 287 p.

85. Guzy, C. Flow and retention in fibrous porous media. Doctoral Dissertation. Albuquerque, NM, University of New Mexico, 1983. 259 p.

86. El-Hosseiny, F.; Yan, J. Analysis of Canadian Standard Freeness Part 1: theoretical considerations. Pulp Paper Can. 81(6):T113-16(June, 1980).

87. Boyd, K. Canadian Standard Freeness. A347 term report. Appleton, WI, The Institute of Paper Chemsitry, 1983. 26 p.

88. Ingmanson, W.; Whitney, R. The filtration resistance of pulp slurries. Tappi 37(11):523-41(Nov., 1954).

89. Wilder, J. Paper capillarity and rewetting during pressing. Tappi 51(2):104-9(Feb., 1968).

90. Robertson, A. The physical properties of wet webs, part 2, fiber properties and wet web behavior. Svensk Papperstid. 66(12):477-97(June 30, 1963).

91. Pounder, J. A400 Progress Report 4. Appleton, WI, The Institute of Paper Chemistry, Oct. 18, 1983. 29 p.

92. Pounder, J. A400 Progress Report 7. Appleton, WI, The Institute of Paper Chemsitry, July 20, 1984. 28 p.

93. Devlin, C., Institute of Paper Chemistry, Personal communication, May 9, 1985.

94. Herminge, L. Heat transfer in porous bodies at various temperatures and moisture contents. Tappi 44(8):570-5(Aug., 1961).

95. Ahrens, F. An analysis of a thermally induced vacuum drying process for permeable mats. Heat Transfer 82: Vol. 6 Proceedings of the 7th International Heat Transfer Conference. U. Grigull; E. Hahne; K. Stephan; J. Straub, eds., Washington, Hemisphere Publishing, 1982:509-14.

96. Burton, S. Dynamics of densification in impulse drying. Engineering Project Advisory Committee Report. Appleton, WI, The Institute of Paper Chemistry, April 3-4, 1985:24-45.

97. Ahrens, F. Fundamentals of drying, Project 3470. Engineering Project Advisory Committee Report. Appleton, WI, The Institute of Paper Chemistry, March 21-22, 1984:53-64.

98. Belisle, S. A study of the characteristics of impulse drying. A291 final report. Appleton, WI, The Institute of Paper Chemistry, 1984. 46 p.

APPENDIX I

HIDRYER1 PROGRAM AND DOCUMENTATION

HIDRYER1/USE

To run HIDRYER1 the user needs to have or must be able to access three files on the Burroughs B6900 main frame:

HIDRYER1/JOB, the WFL job deck to run the object code;

OBJECT/HIDRYER1, the compiled and saved FORTRAN object code; and

HIDRYER1/PARAMS, the data file containing input parameters.

HIDRYER1/JOB is the following WFL job deck:

```
BEGIN JOB HIDRYER1(INTEGER Q,STRING NAME1,STRING NAME2);
     QUEUE=Q;
     RUN OBJECT/HIDRYER1;
     FILE FILE1=#NAME1;
     FILE FILE2=#NAME2;
     STATION=MYSELF(SOURCESTATION);
END JOB
```

To run the program the user enters

```
START HIDRYER1/JOB(Q,"NAME1","NAME2")
```

where Q is the queue number, NAME1 is HIDRYER1/PARAMS (or other data file conforming to the correct input syntax), and NAME2 is the name of the disk data file to which the output information is written and saved.

OBJECT/HIDRYER1 is obtained by compiling HIDRYER1 and saving the result. HIDRYER1 and its documentation are listed later in this appendix. About 20 seconds of processor time and 60 seconds of elapsed time are required for compilation of HIDRYER1.

HIDRYER1/PARAMS is a data file containing the following numerical information separated by commas:

TH,TB,BW,CSF,MRO,DTO,PMAX,RISTIM,IOPTP,IOPTU,METH,MITER

For example:

525.0,212.0,0.0420,650,1.500,1.37E-07,750.0,0.025,1,1,2,2

The input parameters are defined in the thesis and in the HIDRYER1/DOC section of this appendix. HIDRYER1 performs all calculations in English units, but the input and output may be given in either English or SI units.

HIDRYER1/DOC

HIDRYER1 is a FORTRAN implementation of the equations in this thesis. It mathematically performs a drying "experiment" based on the inputs from HIDRYER1/PARAMS and outputs the results to the printer and to a disk file named by the user.

The main part of the program is divided into four sections. The first section contains the file declarations, statements for inclusion of packaged subroutines, real variable declarations, values for constants, common statements, and preliminary input and output statements. The next three sections contain the equations for the heatup, transition, and linear drying regimes.

The main program is followed by a SUBROUTINE section containing 13 subroutines and a FUNCTION section containing 12 functions. The subroutine names and their purposes are:

CALLER: calls property subroutines

CNSTMN: determines constants for calculation of M and N

CNVRT1: converts from English to SI units

CNVRT2: converts from SI to English units

DLDTFN: calculates the compression of a saturated sheet

DUMFUN: calculates the Jacobian matrix for DLDTFN

PRESSR: calculates applied pressure and time derivative

PROP12: calculates and averages physical properties at T1 and T2

PROP23: calculates and averages physical properties at T2 and T3

PROP3B: calculates and averages physical properties at T3 and TB

PROPTB: calculates the physical properties at TB

WARNIN: corrects error conditions or prints warning messages

WRITER: writes output to printer and disk

Subroutine DLDTFN calls a set of subroutines from the International Mathematical and Statistical Library package for the solution of an initial value problem. More information on these subroutines may be found in the appropriate IMSL documentation.

The function names and their purposes are:

DELHD : calculates latent heat of vaporization increment

DPVDT : calculates derivative of vapor pressure with temperature

EVALM : calculates the M compression constant

EVALN : calculates the N compression constant

HFG : calculates the latent heat of vaporization

HYDRAL: calculates the hydraulic pressure

SPRES : calculates the specific filtration resistance

VF : calculates the liquid water specific volume

VG : calculates the water vapor specific volume

VISF : calculates the liquid water viscosity

VISG : calculates the water vapor viscosity

PV : calculates the vapor pressure

The main program variable names and definitions are:

A	thermal diffusivity term
Ax	interface rate-of-advance terms
ALF	DELTA2 - DELTA1
ALFA	DELTA3 - DELTA1
BET	DELTA3 - DELTA2
BETA	DELTAT - DELTA3
BIDX	product of Biot number and DX
BW	sheet basis weight
BWx	basis weight of zone x
BWCORR	basis weight correction factor
BWSUM	sum of corrected zone basis weights
Cx	dry fiber concentration of zone x
COEFF	coefficient in mechanical pressure calculations
CONST	C3/DFIBER
CPF	specific heat of cellulose
CPW	specific heat of water
CSF	Canadian Standard Freeness
Dx	rates of interface advance
DBWxDT	rate of change of basis weight of zone x
DC	product of density, specific heat and moisture ratio
DELTAx	position of interface x
DELTAF	position of grid point closest to outer interface
DELTAI	position of grid point closest to inner interface
DELTAT	sheet thickness
DELTSI	DELTAT in SI units
DENOM	denominator term used in various calculations
DF	reciprocal of DFIBER
DFIBER	density of cellulose
DHx	constants in DELHD
DIFFF	relative distance term
DIFFFX	relative distance term
DIFFI	relative distance term
DIFFIX	relative distance term
DK	product of MR, DFIBER, and KWATER
DLDT	rate of change of saturated sheet thickness
DPDT	rate of change of mechanical pressure
DPDTxy	vapor pressure with temperature derivative over x and y
DPVDTB	vapor pressure at TB
DSTAR	interface rate of advance
DT	time increment

DTx	calculated time increments
DTDZxy	temperature gradient over x and y
DTMAX	maximum time increment
DTO	default time increment (in hours)
DW	density of liquid water
DX	relative position increment
DXX	relative position increment
Ex	porosity of zone x
EMIN	minimum allowable porosity
ESTAR	interfiber porosity
ESx	constants for calculation of ESTAR
Fx	factors for temperature calculations
F3X	product of F3 and DX
FACTOR	factor for conversion of English units
FLAG	signal for absence of zone 3
GAMM	DELTAT - DELTA3
H	time increment
HC	contact coefficient
HCx	constants for calculation of HC
HCDRY	contact coefficient of dry cellulose
HCREF	HCDRY at PREF2
HCWET	contact coefficient of water
HFGx	latent heat of vaporization at interface x
HFGTB	latent heat of vaporization at TB
I	loop iteration counter
IDUMMY	subroutine work vector
IER	subroutine error indicator
IFINI	number of grid point closest to outer interface
IMAX	maximum iteration counter
INDEX	subroutine call parameter
INIT	number of grid point closest to inner interface
IOPTx	interface motion indicators
IOPTP	pressure pulse option (1=ramp, 2=sine)
IOPTU	units option (1=English, 2=SI)
IWK	subroutine work vector
J	print control variable
K	loop iteration counter
Kx	thermal conductivity of zone x
KABSx	absolute permeability of zone x
KAKV	product of KABS3 and KV
KAKW	product of KABS3 and KW
KFIBER	thermal conductivity of dry cellulose
KK	grid point counter
KMIN	initial number of grid points
KV	vapor relative permeability
KW	liquid relative permeability
KWATER	thermal conductivity of water
L	print control variable
LIQDEW	mass of liquid water removed
LMAX	print control variable
M	number of points for internal temperature calculations
Mx	compression constant for zone x
MC	moisture content
METH	subroutine parameter (1=Adams method, 2=Gear's method)

MFINAL	target final moisture content
MITER	subroutine parameter (0=iteration, 1=analytic, etc.)
MO	initial mass of water present
MR	moisture ratio
MREL	relative amount of moisture removed
MREM	amount of moisture remaining
MRO	initial moisture ratio
MRSTAR	intrafiber MR
N	print control variable
Nx	compression constant for zone x
NEXP	exponent in calculation of Nx
OHTC	overall heat transfer coefficient
OHTCSI	OHTC in SI units
P	structural pressure
Px	structural pressure in zone x
PDENOM	denominator in pressure calculation
PGAGSI	PGAUGE in SI units
PGAUGE	gage vapor pressure at T1
PHx	hydraulic pressure in zone x
PHI	thermal diffusivity term
PMAX	maximum mechanical pressure
PMID	pressure midway between PMAX and PREF1
PREFx	reference menchanical pressures
PR3LOG	natural log of PREF3
PSI	velocity term
PS3	structural pressure of saturated sheet
PVTB	vapor pressure at TB
PW	liquid pressure
Q	instantaneous heat flux
QINIT	heat supplied during heatup regime
QSI	Q in SI units
QTHEOR	theoretical heat requirement
QTHERx	term in calculation of QTHEOR
QTOT	total heat input during drying
QTOTAL	heat supplied during transition and linear regimes
R	resistance factor
RATEx	rates of interface advance
RATIOx	DELTAx/DELTAT
REM	remainder in distance calculations
RISTIM	time required to attain PMAX (in seconds)
Sx	saturation of zone x
S3STAR	interfiber saturation
SDUMMY	subroutine work variable
SEC	time in seconds
SIGN	variable in LIQDEW calculation
STAR	variable in MRSTAR calculation
SUM12	sum of BW1 and BW2
SUM123	sum of SUM12 and BW3
Tx	temperature of interface x
TxSI	Tx in SI units
TB	boiling point temperature
TBARx	average temperature of zone x
TC	temperature at a fixed point in the sheet
TERMx	terms used in various calculations

TH	hot surface temperature
THICKx	thickness of zone x
TI	initial sheet temperature
TIME	time
TIMEND	time endpoint for initial value problem
TIMER	factor used in temperature calculations
TMID	temperature midway through the sheet basis weight
TMIDSI	TMID in SI units
TNEW	new temperature at a given grid point
TOL	subroutine convergence tolerance
TOLD	old temperature at a given grid point
TOx	old temperature at interface x
TS	sheet surface temperature
TSSI	TS in SI units
U	fractional basis weight
V	velocity term
VFxy	specific volume of liquid water over x and y
VFTB	specific volume of liquid water at TB
VGxy	specific volume of water vapor over x and y
VGTB	specific volume of water vapor at TB
VISFxy	viscosity of liquid water over x and y
VISFTB	viscosity of liquid water at TB
VISGxy	viscosity of water vapor over x and y
VISGTB	viscosity of water vapor at TB
W	product of MRSTAR and C2
WK	subroutine work variable
X	product of MR and C3
XX	grid point variable
Y	product of (MR-MRSTAR) and C3
YL	thickness of saturated sheet
Z	Y/X
ZTC	location of fixed points within the sheet

In the subroutines, the variables not linked to the main program by COMMON statements are:

CALLER

all variables in common with main program

CNSTMN

Ax	constants for calculation of CMx
Bx	constants for calculation of CMx
Cx	constants for calculation of CNx
CMx	constants for calculation of M compression constant

CNx	constants for calculation of N compression constant
Dx	constants for calculation of CNx
Ex	constants for calculation of TERM
TERM	constant for calculation of CMx and CNx

CNVRT1

Ax	constants in unit conversions

CNVRT2

Ax	constants in unit conversions

DLDTFN

YPRIME	rate of change of saturated sheet thickness

DUMFUN

PD	partial derivative of YPRIME with respect to YL

PRESSR

Ax	constants in sine pressure pulse calculation
PI	numerical value 3.14159...

PROP12

all variables in common with main program

PROP23

all variables in common with main program

PROP3B

all variables in common with main program

PROPTB

all variables in common with main program

WARNIN

all variables in common with main program

WRITER

all variables in common with main program

In the functions, the variables not linked to the main program by COMMON statements are:

DELHD

all variables in common with main program

DPVDT

Ax	constants used in property calculation

EVALM

A	constant used in calculation of M compression constant
Ax	constants used in calculation of A and B
B	constant used in calculation of M compression constant
CMx	constants in common with CNSTMN
CORRCT	correction in calculation of M compression constant

EVALN

A	constant used in calculation of N compression constant
Ax	constants used in calculation of A and B
B	constant used in calculation of N compression constant
C	uncorrected value for N compression constant
CNx	constants in common with CNSTMN

NDENOM denominator in correction of N compression constant

NMID value of N at PMID

NSAT value of N at PREF3

PTERM pressure term in correction of N compression constant

SIGN variable in correction of N compression constant

HFG

Ax constants used in property calculation

HYDRAL

all variables in common with main program

SPRES

Ax constants used in property calculation

RREF reference specific filtration resistance

X variable used in property calculation

VF

Ax constants used in property calculation

VG

Ax constants used in property calculation

VISF

Ax constants used in property calculation

VISG

Ax constants used in property calculation

PV

Ax constants used in property calculation

The following discussion of HIDRYER1 is divided into sections by program line numbers and headings. Refer to the program listing for the actual FORTRAN statements.

OPENING SECTION OF MAIN PROGRAM

1 : Format line.

Sets standard FORTRAN format.

5 - 23 : Headers

Program references and identification.

28 - 32 : File declarations.

File 1 is the parameter input file; file 2 is the disk output file; file 5 is the terminal; and file 6 is the line printer.

34 - 44 : Include statements.

Include the required subroutines from the IMSL package.

46 - 48 : Real variable declarations.

Sets variables ordinarily assumed to be integers to be real variables and dimensions some arrays.

50 : Dimension statement.

Sets dimension of an integer array.

52 : External statement.

Declares two subroutines external to the IMSL package.

55 - 64 : Fixed input assignment.

Assigns values to certain constants in the program.

67 - 85 : Subroutine common blocks.

Names common blocks for subroutines.

88 - 91 : Input statement.

Reads input parameters in free format from file 1.

94 - 101 : Write statements.

Write headings and repeat input parameters on line printer.

104 - 107 : Set print controls.

Set counters for frequency of printing output results.

110 - 114 : Set fixed internal points.

Set fixed fractions of basis weight at which temperatures are to be calculated. This is for direct comparison to experimental results.

117 - 120 : Compute properties at TB.

Convert to English units if necessary and compute vapor and liquid properties at TB for use later in the program.

HEATUP REGIME

129 - 168 : Initialize variables.

Set initial variable values for heatup regime and for use later in the main program.

171 - 223 : Calculate mechanical pressure and sheet properties.

Calculate mechanical pressure for nonsaturated or saturated sheets and determine sheet properties like thickness, porosity, etc.

226 - 232 : Calculate heat transfer parameters.

Determine contact coefficient, thermal conductivity and BIDX.

235 - 260 : Calculate interior temperatures.

Use finite difference methods to find internal temperatures for a nonsaturated or saturated sheet undergoing compression.

263 - 275 : Calculate boundary temperatures.

Use finite difference methods to calculate boundary temperatures for nonsaturated or saturated sheets.

278 - 282 : Reset old temperature values.

Reset TOLD for next set of finite difference calculations.

285 - 291 : Compute temperatures at fixed locations.

Use linear interpolation to find temperatures at fixed basis weight fractions in the sheet.

294 - 314 : Increment quantities and write results.

Calculate quantities which must be calculated at every time increment and determine if the output should be printed on this iteration. If the output needs to be printed, then calculate additional output quantities that do not have to be determined at every time step.

317 - 320 : Increment print control variables.

Increase the values of the counters for print control.

323 - 327 : Determine exit criteria.

Check time and physical criteria for exit to transition regime or program termination.

330 - 345 : Write heatup regime final output.

Calculate final values for quantities and write output if it is not a duplication of the last printed output.

TRANSITION REGIME

354 - 356 : Write transition regime heading.

Write heading on printer to signal onset of transition regime.

359 - 404 : Initialize variables.

Set initial values for transition regime variables.

407 -417 : Compute required derivatives.

Calculate the rates of advance for the different interfaces which may be present in the sheet.

420 - 460 : Set maximum allowable time increment.

Examine rates of interface advance and determine the maximum allowable time increment which will not violate the interface position criteria. Determine if new interface position permits the use of usual finite difference formulations or requires use of unequally spaced points. Increment the time and include the factor TIMER to account for round-off or truncation errors in the determination of DT.

463 - 501 : Calculate new temperature distribution.

Use finite difference methods to determine internal and "boundary" (INIT and IFINI) temperatures in the transition zone and in zone 4, if it exists.

504 -519 : Calculate rates of basis weight change.

Select the dominant rate at each interface and determine any liquid dewatering that takes place.

522 -535 : Calculate mechanical and hydraulic pressure.

Calculate applied mechanical pressure based on time and IOPTP and calculate the hydraulic (vapor) pressure for each zone. Obtain the effective structural pressure for each zone by subtraction.

538 - 585 : Calculate basis weight, concentration, and thickness.

Calculate rates of basis weight change and new basis weights. Correct basis weights for slight calculation errors. Evaluate the compression constants, dry fiber concentration, and thickness of each zone.

588 - 623 : Calculate porosity and saturation.

Calculate porosity based on dry fiber concentration, and saturation based on dry fiber concentration and moisture ratio. Correct zone 3 saturation if greater than unity.

626 - 645 : Increment interface positions.

Calculate new interface positions, locations of INIT and IFINI, and position increments for finite difference calculations.

648 - 658 : Compute thermal conductivity and contact coefficient.

Find thermal conductivity of each zone and contact coefficient.

661 - 669 : Calculate permeability factors.

Calculate specific filtration resistance, absolute permeability for the zones and KAKW.

672 - 680 : Set relative interface positions.

Compute the RATIOx values and calculate the remaining moisture and relative moisture loss.

683 - 735 : Compute new interface temperatures.

Calculate new interface temperatures based on equations appropriate for types and locations of interfaces present.

738 - 761 : Recompute variables for derivative calculations.

Calculate temperature gradient terms for zones and multipliers for rate expressions.

764 - 879 : Handle special case of intrafiber water only.

If FLAG = 1, then this section handles all calculations for the transition regime. The calculations are based on those of the previous sections and modified for this special case. If FLAG = 0, then this section is bypassed.

882 - 889 : Reset temperature distribution and time options.

Reset TOLD values for next finite difference calculations and reset IOPT1 and IOPT2 for the next time increment.

892 - 912 : Compute temperatures at fixed locations.

Same strategy as for lines 285 - 291.

915 - 934 : Increment quantities and write results.

Same strategy as for lines 294 - 314.

937 - 940 : Increment print control variables.

Same strategy as for lines 317 - 320.

943 - 949 : Determine exit criteria.

Same strategy as for lines 323 - 327.

952 - 968 : Write transition regime final output.

Same strategy as for lines 330 - 345.

LINEAR REGIME

977 - 979 : Write linear regime heading.

Same strategy as for lines 354 - 356.

982 - 989 : Set FLAG and go to first temperature calculation.

Set the value for FLAG and go directly to interface temperature calculation right from the transition regime.

992 -1005 : Compute required derivatives.

Same strategy as for lines 407 - 417, with additional calculations for other types of interfaces that may be present.

1008 - 1032 : Set maximum allowable time increment.

Same strategy as for lines 420 - 460, but no restriction on interface position relative to grid points.

1035 - 1053 : Calculate rates of basis weight change.

Same strategy as for lines 504 - 519.

1056 - 1070 : Calculate mechanical and hydraulic pressure.

Same strategy as for lines 522 - 535.

1073 - 1121 : Calculate basis weight, concentration, thickness.

Same strategy as for lines 538 - 585.

1124 - 1159 : Calculate porosity and saturation.

Same strategy as for lines 588 - 623.

1162 - 1169 : Increment interface positions.

Same strategy as for lines 626 - 645, but no finite difference grid spacings need to be calculated.

1172 - 1182 : Compute thermal conductivity, contact coefficient.

Same strategy as for lines 648 - 658.

1185 - 1194 : Calculate permeability factors.

Same strategy as for lines 661 - 669, with KAKV also determined.

1197 - 1204 : Set relative interface positions.

Same strategy as for lines 672 - 680.

1207 - 1286 : Compute new interface temperatures.

Same strategy as for lines 683 - 735, but with equations appropriate for linear regime (including vapor flow in zone 3).

1289 - 1317 : Recompute variables for derivative calculations.

Same strategy as for lines 738 - 761.

1320 - 1338 : Compute temperatures at fixed locations.

Same strategy as for lines 892 - 912.

1341 - 1357 : Increment quantities and write results.

Same strategy as for lines 915 - 934.

1360 - 1363 : Increment print control variables.

Same strategy as for lines 937 - 940.

1366 - 1369 : Determine exit criteria.

Same strategy as for lines 943 - 949, but time and moisture content are the only criteria for the linear regime.

1372 - 1385 : Write final output.

Calculate and write total values for cummulative variables.

1388 - 1410 : Format statements.

Statements for printer headings and output variable format.

1413 - 1416 : End main program.

STOP and END statements for main program.

The remainder of HIDRYER1 is composed of the SUBROUTINE and FUNCTION sections, which have been previously described.

```
IDRYER1 (05/21/85)

RESET FREE                                                              000001
                                                                        000002
                                                                        000003
                                                                        000004
            ******************************************                  000005
            **     HIGH INTENSITY DRYING PROGRAM    **                  000006
            **                                      **                  000007
            **              HIDRYER1                **                  000008
            **                                      **                  000009
            **     INSTITUTE OF PAPER CHEMISTRY     **                  000010
            **                                      **                  000011
            **           JOSEPH R POUNDER           **                  000012
            **                                      **                  000013
            **            MARCH 25, 1985            **                  000014
            ******************************************                  000015
                                                                        000016
                                                                        000017
                                                                        000018
 ************************************************************************ 000019
 *        PROGRAM DOCUMENTATION IS IN THE HIDRYER1/DOC FILE             * 000020
 *                                                                      * 000021
 *INSTRUCTIONS FOR RUNNING THE PROGRAM ARE IN THE HIDRYER1/USE FILE     * 000022
 ************************************************************************ 000023
                                                                        000024
                                                                        000025
                                                                        000026
                                                                        000027
FILE  1(KIND=DISK,NEWFILE=FALSE,FILETYPE=7,MYUSE=IN)                    000028
FILE  2(KIND=DISK,NEWFILE=TRUE,MAXRECSIZE=21,PROTECTION=SAVE,           000029
    * MYUSE=OUT)                                                       000030
FILE  5(KIND=REMOTE,MYUSE=IO)                                           000031
FILE  6(KIND=PRINTER)                                                   000032
                                                                        000033
INCLUDE "*IMSL/DGRCS"                                                   000034
INCLUDE "*IMSL/DGEAR"                                                   000035
INCLUDE "*IMSL/DGRIN"                                                   000036
INCLUDE "*IMSL/DGRPS"                                                   000037
INCLUDE "*IMSL/DGRSI"                                                   000038
INCLUDE "*IMSL/LUDATF"                                                  000039
INCLUDE "*IMSL/LUELMF"                                                  000040
INCLUDE "*IMSL/LEGT1B"                                                  000041
INCLUDE "*IMSL/UERTST"                                                  000042
INCLUDE "*IMSL/UGETIO"                                                  000043
INCLUDE "*IMSL/USPKD"                                                   000044
                                                                        000045
     REAL KABS2,KABS3,KABS4,KAKV,KAKW,KFIBER,KV,KW,KWATER,K1,K2,K3,     000046
    *K4,LIGDEN,MC,MFINAL,MO,MR,MREL,MREM,MRO,MRSTAR,M1,M2,M3,M4,NEXP,   000047
    *N1,N2,N3,N4,TC(10),TAEN(501),TOLD(501),WK(250),YL(2),ZTC(10)       000048
                                                                        000049
     DIMENSION IWK(1)                                                   000050
```

```
C                                                                       000051
      EXTERNAL DLOIFN,DUMFUN                                            000052
C                                                                       000053
C                                                                       000054
C*****FIXED INPUTS ARE:                                                 000055
C                                                                       000056
      DATA                                                              000057
     *DH1,DH2/33.2815,-14.9522/,   ES1,ES2/1.55,0.55/,   IMAX/10/,      000058
     *KMIN/101/,      M/3/,     DFIBER,KFIBER,CPF/96.76,0.14,0.346/,     000059
     *KWATER,CFW/0.394,1.00/,   FACTOR/1.6679002E+07/,   LMAX/25/,      000060
     *STAR/0.005684/, HFINAL/0.06/, TIMER/0.95/, TI/75.0/, J/ 25/,      000061
     *HCREF,HCRET/100.,1000./,  PREF1,PREF2,PREF3/0.10,1.,1000./,       000062
     *HC1,HC2,HC3/1.45159,0.33333333,0.479354/,      TOL/1.0E-05/,      000063
     *INDEX/1/,    NEXP/3.0/                                            000064
C                                                                       000065
C                                                                       000066
C*****SUBROUTINE COMMON BLOCKS ARE:                                     000067
C                                                                       000068
      COMMON   /GEAR/ DUMMY(48),SDUMMY(4),IDLMMY(38)                   000069
      COMMON /LABEL1/ TB,PVTB,DFVCTB,VFTB,VGTB,HFGTB,VISGTB,VISFTB      000070
      COMMON /LABEL2/ TH,T1,T2,T3,TI,TMID                               000071
      COMMON /LABEL3/ DPDT12,VF12,VG12,VISG12                           000072
      COMMON /LABEL4/ DPDT23,VF23,VISF23,VG23,VISG23                    000073
      COMMON /LABEL5/ DPDT3B,VG3B,VISG3B                                000074
      COMMON /LABEL6/ DXX,DIFFIX,CIFFFX,EMIN                            000075
      COMMON /LABEL7/ PREF1,PMAX,RISTIM,P,IOPTP,DPDT                    000076
      COMMON /LABEL8/ M1,M2,M3,M4,N1,N2,N3,N4                           000077
      COMMON /LABEL9/ DLOI,FACTOR,BW,DW,DFIBER,COEFF,PS3                000078
      COMMON /LABL10/ CSF                                               000079
      COMMON /LABL11/ SEC,MREL,TS,RATIO1,RATIO2,RATIO3,DELTAT,Q,DHTC,   000080
     * PGAUGE                                                           000081
      COMMON /LABL12/ TSSI,T1SI,T2SI,T3SI,DELTSI,QSI,DHTCSI,PGAGSI,     000082
     * TMIDSI                                                           000083
      COMMON /LABL13/ DH1,DH2,MR,MRSTAR                                 000084
      COMMON /LABL14/ NEXP,PR3LOG,PREF3,PMID,PDENOM,DF                  000085
C                                                                       000086
C                                                                       000087
C*****READ INPUT FROM DATA FILE                                         000088
C                                                                       000089
      READ(1,*) TH,TB,BW,CSF,MRO,DIO,PMAX,RISTIM,IOPTP,IOPTU,           000090
     * METH,MITER                                                      000091
C                                                                       000092
C                                                                       000093
C*****WRITE HEADINGS AND STARTING PARAMETERS                            000094
C                                                                       000095
      WRITE(6,900)                                                      000096
      WRITE(6,905)                                                      000097
      WRITE(6,910) TH,TB,BW,CSF,MRO,PMAX,RISTIM                         000098
      WRITE(6,915)                                                      000099
      WRITE(6,920) DIO,IOPTP,IOPTU,METH,MITER                           000100
      WRITE(6,925)                                                      000101
C                                                                       000102
C                                                                       000103
C*****SET VARIABLES FOR PRINTING OF RESULTS                             000104
```

```
      M=J                                                               000105
      L=1                                                               000106
                                                                        000107
                                                                        000108
                                                                        000109
*****SET POSITIONS FOR FIXED-POINT TEMPERATURE CALCULATIONS              000110
                                                                        000111
      DO 10 I=1,M                                                       000112
      ZIC(I)=I/(M+1.)                                                   000113
   10 CONTINUE                                                          000114
                                                                        000115
                                                                        000116
*****COMPUTE PROPERTIES AT SATURATION TEMPERATURE                       000117
                                                                        000118
      IF(ICPTG.EQ.2) CALL CNVRT1                                        000119
      CALL PROPT6                                                       000120
*************************************************************************000121
                                                                        000122
                                                                        000123
      *******************************                                   000124
      *****  THE HEATUP REGIME  *****                                   000125
      *******************************                                   000126
                                                                        000127
                                                                        000128
*****INITIALIZE VARIABLES                                               000129
                                                                        000130
      DW=1./VF(TI)                                                      000131
      VF23=1./DW                                                        000132
      DF=1./DFIBER                                                      000133
                                                                        000134
      PR3LOG=ALOG(PREF3)                                                000135
      PDENOM=(PREF3-PREF1)/2.                                           000136
      PMID=(PREF3+PREF1)/2.                                             000137
                                                                        000138
      MRSTAR=STAR*DW                                                    000139
      IF(MRSTAR.GT.MRO) MRSTAR=MRO                                      000140
      IF(MRSTAR.EQ.MRO) FLAG=1                                          000141
      PO=MRO*EW                                                         000142
      EMIN=ES2/ES1                                                      000143
      CALL CNSTMN(CSF)                                                  000144
                                                                        000145
      M=MMIN                                                            000146
      XX=(M-1)/(M+1)                                                    000147
      DX=1./(M-1)                                                       000148
                                                                        000149
      DO 20 I=1,M                                                       000150
      TOLD(I)=TI                                                        000151
   20 CONTINUE                                                          000152
                                                                        000153
      IF(FLAG.EQ.1) RATIO2=1.                                           000154
      RATIO3=1.                                                         000155
      PR=MRO                                                            000156
                                                                        000157
      P1=EVALP(0.,TB)                                                   000158
      P2=EVALP(MRSTAR,TB)                                               000159
```

```
      M4=M1                                                              000160
C                                                                        000161
      N1=EVALN(1,C.,0.)                                                  000162
      N2=EVALN(1,MRSTAR,0.)                                              000163
      N4=N1                                                              000164
C                                                                        000165
      CC=DFIBER*(CPF+MR*CPW)                                             000166
      CK=MR*DFIBER*KWATER                                                000167
      A=(KFIBER+DK/DW)/DC                                                000168
C                                                                        000169
C                                                                        000170
C*****CALCULATE MECHANICAL PRESSURE AND SHEET PROPERTIES                 000171
C                                                                        000172
   30 IF(S3.EQ.1.) GO TO 40                                              000173
      CALL PRESSR(TIME)                                                  000174
      TBAR1=(TOLD(1)+TOLD(K))/2.                                         000175
      M3=EVALM(MR,TBAR1)                                                 000176
      N3=EVALN(2,MR,F)                                                   000177
      DELTAT=BW/(M3*P**N3)                                               000178
      PSI=A/DELTAT**2                                                    000179
      DT=TIMER*DX**2/(2.*PSI)                                            000180
      PW=PWTB                                                            000181
      TIME=TIME+DT                                                       000182
      GO TO 50                                                           000183
C                                                                        000184
   40 YL(1)=DELTAT                                                       000185
      MR=CW*(YL(1)/BW-1./DFIBER)                                         000186
      TBAR1=(TOLD(1)+TOLD(K))/2.                                         000187
      M3=EVALM(MR,TBAR1)                                                 000188
      N3=EVALN(2,MR,F)                                                   000189
      CC=DFIBER*(CPF+MR*CPW)                                             000190
      CK=MR*DFIBER*KWATER                                                000191
      A=(KFIBER+DK/DW)/DC                                                000192
C                                                                        000193
      PHI=-CW*CPW*DLDT*DFIBER/(CC*BW)                                    000194
      PSI=A/(YL(1)**2)                                                   000195
C                                                                        000196
      DT=TIMER*DX/(2.*PSI/DX+ABS(PHI)/2.)                                000197
      F2=PSI*DT/(DX**2)                                                  000198
      F3=PHI*DT/DX                                                       000199
      TERM1=PHI*DT/3.                                                    000200
      TERM2=2.*F2/9.                                                     000201
C                                                                        000202
      H=DT/100.                                                          000203
      TIMEND=TIME+DT                                                     000204
      CALL DGEAR(1,DLDTFN,DUMFUN,TIME,H,YL,TIMEND,TOL,METH,MITER,        000205
     * INDEX,IWK,WK,IER)                                                000206
      IF(IER.GT.128) WRITE(6,/) TOL,YL(1),TIMEND,H,TIME,METH,MITER,      000207
     * INDEX                                                            000208
      P=(BW/(YL(1)*M3))**(1./N3)                                         000209
      PW=PWTB+1.5*DLDT/CGEFF                                             000210
      TIME=TIMEND                                                        000211
C                                                                        000212
   50 C3=M3*P**N3                                                        000213
      Y=(MR-MRSTAR)*C3                                                   000214
```

```
      DELTAT=EW/C3                                                      000215
      CONST=C3/DFIBER                                                   000216
      E3=1.-CONST                                                       000217
      IF(E3.LT.EMIN) CALL WARNIN(2,3,E3)                                000218
      IF(E3.LT.EMIN) GO TO 9999                                         000219
      ESTAR=ES1*E3-ES2                                                  000220
      S3=MR*C3/(E3*DW)                                                  000221
      IF(S3.GT.1.) S3=1.                                                000222
      S3STAR=Y/(ESTAR*DW)                                               000223
                                                                        000224
                                                                        000225
*****CALCULATE HEAT TRANSFER PARAMETERS                                 000226
                                                                        000227
      HCDRY=HCREF*(HC1*(P/PREF2)**HC2-HC3)                              000228
      HC=(HCDRY+MR*DFIBER*HCWET/DW)*CONST                               000229
      K1=KFIBER*CONST                                                   000230
      K3=K1+DK*CONST/DW                                                 000231
      BIDX=HC*DELTAT*DX/K3                                              000232
                                                                        000233
                                                                        000234
.....CALCULATE INTERIOR TEMPERATURES                                    000235
                                                                        000236
      IF(S3.EQ.1.) GO TO 70                                             000237
      DO 60 I=2,K-1                                                     000238
      TNEW(I)=TIMER*(TOLD(I+1)+TOLD(I-1))/2.+(1.-TIMER)*TOLD(I)         000239
   60 CONTINUE                                                          000240
      GO TO 110                                                         000241
                                                                        000242
   70 IF(PHI.LT.0.) GO TO 90                                            000243
      DO 80 I=3,K-1                                                     000244
      F3X=F3*(I-1)*DX                                                   000245
      TNEW(I)=(F2-F3X/3)*TOLD(I+1)+(1.-2.*F2-F3X/2.)*TOLD(I)+           000246
     * (F2+F3X)*TOLD(I-1)-(F3X/6)*TOLD(I-2)                            000247
   80 CONTINUE                                                          000248
      TNEW(2)=(F2-F3*DX/2.)*TOLD(3)+(1.-2.*F2)*TOLD(2)+(F2+F3*DX/2.)*   000249
     * TOLD(1)                                                         000250
      GO TO 120                                                         000251
                                                                        000252
   90 DO 100 I=2,K-2                                                    000253
      F3X=F3*(I-1)*DX                                                   000254
      TNEW(I)=(F2-F3X)*TOLD(I+1)+(1.-2.*F2+F3X/2.)*TOLD(I)+             000255
     * (F2+F3X/3)*TOLD(I-1)+(F3X/6)*TOLD(I+2)                          000256
  100 CONTINUE                                                          000257
      TNEW(K-1)=(F2-F3*(K-2)*DX/2.)*TOLD(K)+(1.-2.*F2)*TOLD(K-1)+       000258
     * (F2+F3*(K-2)*DX/2.)*TOLD(K-2)                                   000259
      GO TO 120                                                         000260
                                                                        000261
                                                                        000262
.....CALCULATE BOUNDARY TEMPERATURES                                    000263
                                                                        000264
  110 TNEW(1)=TOLD(1)-(TNEW(2)-TOLD(2))/3.+(TIMER/9.)*(6.*BIDX*(TH-     000265
     * TOLD(1))-2.*TOLD(1)-3.*TOLD(2)+6.*TOLD(3)-TOLD(4))               000266
      TNEW(K)=TOLD(K)-(TNEW(K-1)-TOLD(K-1))/3.-(TIMER/9.)*(2.*TOLD(K)+  000267
     * 3.*TOLD(K-1)-6.*TOLD(K-2)+TOLD(K-3))                            000268
      GO TO 130                                                         000269
```

```
C                                                                       000270
  12C TNEW(1)=TOLD(1)-(TNEW(2)-TOLD(2))/3.+TERM1*BIDX*(TH-TOLD(1))+     000271
     * TERM2*(6.*BIDX*(TH-TOLD(1))-2.*TOLD(1)-3.*TOLD(2)+6.*TOLD(3)-    000272
     * TOLD(4))                                                        000273
      TNEW(K)=TOLD(K)-(TNEW(K-1)-TOLD(K-1))/3.-TERM2*(2.*TOLD(K)+       000274
     * 3.*TOLD(K-1)-6.*TOLD(K-2)+TOLD(K-3))                           000275
C                                                                       000276
C                                                                       000277
C.....RESET OLD TEMPERATURE VALUES                                      000278
C                                                                       000279
  13C DO 140 I=1,K                                                      000280
      TOLD(I)=TNEW(I)                                                   000281
  14C CONTINUE                                                          000282
C                                                                       000283
C                                                                       000284
C*****COMPUTE TEMPERATURES AT FIXED-POINT LOCATIONS                     000285
C                                                                       000286
      DO 150 I=1,N                                                      000287
      KK=I*XX                                                           000288
      REM=I*XX-KK                                                       000289
      TC(I)=TNEW(1+KK)-REM*(TNEW(1+KK)-TNEW(2+KK))                      000290
  150 CONTINUE                                                          000291
C                                                                       000292
C                                                                       000293
C*****INCREMENT QUANTITIES AND WRITE RESULTS                            000294
C                                                                       000295
      TS=TNEW(1)                                                        000296
      QINIT=QINIT+(Q+HC*(TH-TS))*DT/2.                                  000297
      Q=HC*(TH-TS)                                                      000298
      IF(N.LT.J.AND.L.GT.LMAX.AND.TNEW(1).LT.TB) GO TO 160              000299
C                                                                       000300
      T1=TS                                                             000301
      T2=T1                                                             000302
      PGAUGE=PW-PVTB                                                    000303
      IF(PGAUGE.LT.0.) PGAUGE=0.                                        000304
      SEC=TIME*3600.                                                    000305
      TMIC=TC(1+N/2)                                                    000306
      CHTC=Q/(TH-TMIC)                                                  000307
      WREM=WR*BW                                                        000308
      WREL=1.-WRE)/WC                                                   000309
C                                                                       000310
      T3=TNEW(K)                                                        000311
      CALL WRITER(IOPTU)                                                000312
      N=1                                                               000313
      GO TO 170                                                         000314
C                                                                       000315
C                                                                       000316
C*****INCREMENT PRINT CONTROL VARIABLES                                 000317
C                                                                       000318
  16C N=N+1                                                             000319
  17C L=L+1                                                             000320
C                                                                       000321
C                                                                       000322
C*****DETERMINE EXIT CRITERIA                                           000323
C                                                                       000324
```

```
      IF(1800*TIME.GE.RISTIM.AND.IOPTP.EQ.2) GO TO 9999                 000325
      IF((FLAG.EQ.1.AND.TNEW(K).LT.TB).OR.                              000326
     * PV(TNEW(1)).LT.PW.OR.PV(TNEW(1)).LT.PVTB) GO TO 30               000327
                                                                        000328
                                                                        000329
******WRITE HEATUP REGIME FINAL OUTPUT                                 000330
                                                                        000331
      T1=TS                                                             000332
      T2=T1                                                             000333
      PGAUGE=PW-PVTB                                                    000334
      IF(PGAUGE.LT.0.) PGAUGE=0.                                        000335
      SEC=TIME*3600.                                                    000336
      THIC=TC(1*M/2)                                                    000337
      CHIC=G/(TH-THIC)                                                  000338
      MREM=MR*BW                                                        000339
      MREL=1.-MREM/MG                                                   000340
                                                                        000341
      T3=TNEW(K)                                                        000342
      IF(N.NE.1) CALL WRITER(IOPTU)                                     000343
      WRITE(6,930)                                                      000344
      WRITE(6,935) (I,TNEW(I),I=1,K)                                    000345
*************************************************************************000346
                                                                        000347
                                                                        000348
      ************************************                              000349
      *****  THE TRANSITION REGIME  *****                               000350
      ************************************                              000351
                                                                        000352
                                                                        000353
******WRITE TRANSITION REGIME HEADING                                   000354
                                                                        000355
      WRITE(6,940)                                                      000356
                                                                        000357
                                                                        000358
******INITIALIZE VARIABLES                                              000359
                                                                        000360
      L=1                                                               000361
      IF(FLAG.EQ.1) DELTA2=DELTA1                                       000362
      DELTA3=DELTAT                                                     000363
      THICK2=DELTA2                                                     000364
      THICK3=DELTA3                                                     000365
      IF(FLAG.EQ.1.) THICK3=0.                                          000366
                                                                        000367
      RATIO2=DELTA2/DELTAT                                              000368
      RATIO3=DELTA3/DELTAT                                              000369
      LIQDEW=MG-E3*S3*DW*DELTAT                                         000370
                                                                        000371
      R=SPRES(F)/FACTOR                                                 000372
      RANK=S3STAR**4/(R*C3)                                             000373
      EW3=BW                                                            000374
      IF(FLAG.EQ.1) EW3=0.                                              000375
      IF(FLAG.EQ.1) EW2=BW                                              000376
      C1=M1*P**N1                                                       000377
      C2=M2*P**N2                                                       000378
```

```
      C4=M4*P**N4                                                       000379
      W=MRSTAR*C2                                                       000380
      X=MR*C3                                                           000381
C                                                                       000382
      T3=TB                                                             000383
      Z=1.-MRSTAR/MR                                                    000384
      DXX=DX                                                            000385
      DIFFIX=DXX                                                        000386
      DIFFI=DX                                                          000387
      DIFFFX=DXX                                                        000388
      DIFFF=DX                                                          000389
      DELTAI=DIFFIX*THICK3                                              000390
      DELTAF=DELTAI-DIFFFX*THICK3                                       000391
C                                                                       000392
      INIT=2                                                            000393
      IFINI=K-1                                                         000394
C                                                                       000395
      IF(FLAG.EQ.1) GO TO 350                                           000396
C                                                                       000397
      DTDZ23=(T2-T3)/DELTAT                                             000398
C                                                                       000399
      CALL PROP23(1)                                                    000400
      A2=RAKW*CPDT23/(VISF23*VF23*Y)                                    000401
      V=A2*Y*CPW*DTDZ23/((1.-E3)*DC)                                    000402
      PSI=A/DELTAI**2                                                   000403
      PHI=V/DELTAI                                                      000404
C                                                                       000405
C                                                                       000406
C*****COMPUTE REQUIRED DERIVATIVES                                      000407
C                                                                       000408
  180 D2=A2*DTDZ23                                                      000409
      D4=A4*DTDZ12                                                      000410
      D5=D2-A5*DTDZ12                                                   000411
      D6=-A6*DTDZ38                                                     000412
      IF(RATIO3.EQ.1..AND.TNEW(K).GE.TB) D6=K3*(TNEW(K)-TNEW(K-1))/     000413
     * ((HFG(T3)+DELHD(3))*DXX*THICK3*X)                                000414
      D7=D2*Z                                                           000415
C                                                                       000416
      DENOM=D6+D7                                                       000417
C                                                                       000418
C                                                                       000419
C*****SET MAXIMUM ALLOWABLE TIME INCREMENT                              000420
C                                                                       000421
      DTMAX=TIMER*DX/(2.*PSI/DX+PHI/2.)                                 000422
C                                                                       000423
      DT1=DTMAX                                                         000424
      DT2=DTMAX                                                         000425
      DT3=DTMAX                                                         000426
      DT4=DTMAX                                                         000427
      DT5=DTMAX                                                         000428
C                                                                       000429
      IF(DELTA1.NE.DELTA2) GO TO 190                                    000430
      IF(D2.NE.DENOM) DT1=(DELTA3-DELTA2)/(D2-DENOM)                    000431
```

```
      DT=AMIN1(DT1,DTMAX)                                                   000432
      IF((D2*DT).GE.DIFFIX*THICK3) IOPT1=1                                  000433
      GO TO 200                                                             000434
                                                                            000435
  190 IF(D4.NE.D5) DT1=(DELTA2-DELTA1)/(D4-D5)                              000436
      IF(DT1.LT.0.) DT1=DTMAX                                               000437
      IF(D5.NE.DENOM) DT2=(DELTA3-DELTA2)/(D5-DENOM)                        000438
      IF(DT2.LT.0.) DT2=DTMAX                                               000439
      DT=AMIN1(DT1,DT2,DTMAX)                                               000440
      IF((D5*DT).GE.DIFFIX*THICK3) IOPT1=1                                  000441
                                                                            000442
  200 IF((-DENOM*DT).GE.DIFFFX*THICK3) IOPT2=1                              000443
      IF(ICPT1.EQ.1.AND.IOPT2.EQ.1) GO TO 210                               000444
                                                                            000445
      IF(IOPT1.EQ.0) DT3=DIFFI*DX/(2.*PSI)                                  000446
      IF(DENOM.LE.0.) DT4=DIFFF*DX/(2.*PSI)                                 000447
      IF(DENOM.GT.0..AND.RATIO3.NE.1.) DT5=(DXX-DIFFFX)*THICK3/DENOM        000448
      IF(DT5.EQ.0.) DT5=DXX*THICK3/DENOM                                    000449
      DT=AMIN1(DT1,DT2,DT3,DT4,DT5,DTMAX)                                   000450
                                                                            000451
      IF(DELTA1.EQ.DELTA2.AND.D2*DT.GE.DIFFIX*THICK3) IOPT1=1               000452
      IF(DELTA1.EQ.DELTA2.AND.D2*DT.LT.DIFFIX*THICK3) IOPT1=0               000453
      IF(DELTA1.NE.DELTA2.AND.D5*DT.GE.DIFFIX*THICK3) IOPT1=1               000454
      IF(DELTA1.NE.DELTA2.AND.D5*DT.LT.DIFFIX*THICK3) IOPT1=0               000455
      IF((-DENOM*DT).GE.DIFFFX*THICK3) IOPT2=1                              000456
      IF((-DENOM*DT).LT.DIFFFX*THICK3) IOPT2=0                              000457
                                                                            000458
      DT=TIMER*DT                                                           000459
  210 TIME=TIME+DT                                                          000460
                                                                            000461
                                                                            000462
*****CALCULATE NEW TEMPERATURE DISTRIBUTION                                000463
                                                                            000464
      DC=DFIBER*(CPF*MR+CPW)                                                000465
      DK=MR*DFIBER*KWATER                                                   000466
      A=(KFIBER+DK*VF23)/DC                                                 000467
      W=D2*W*CPW/((1.-E3)*DC)                                               000468
      PSI=A*(C3/BW)**2                                                      000469
      PHI=W*C3/BW                                                           000470
      F2=PSI*DT/DX**2                                                       000471
      F3=PHI*DT/DX                                                          000472
      TERM2=2.*F2/9.                                                        000473
                                                                            000474
      DO 220 I=INIT,INIT+1                                                  000475
      TNEW(I)=(F2-F3/2)*TOLD(I+1)+(1-2*F2)*TOLD(I)+(F2+F3/2)*TOLD(I-1)      000476
  220 CONTINUE                                                              000477
                                                                            000478
      DO 230 I=INIT+2,IFINI                                                 000479
      TNEW(I)=(F2-F3/3)*TOLD(I+1)+(1.-2*F2-F3/2)*TOLD(I)+(F2+F3)*           000480
     * TOLD(I-1)-(F3/6)*TOLD(I-2)                                           000481
  230 CONTINUE                                                              000482
                                                                            000483
      IF(IOPT1.EQ.0) TNEW(INIT)=TOLD(INIT)-PHI*DT*((TOLD(INIT+1)-T2)/       000484
     * (DX+DIFFI))+2.*PSI*DT*(TOLD(INIT+1)/(DX*(DIFFI+DX))-TOLD(INIT)       000485
```

```
     * /(DIFFI*DX)+T2/(DIFFI*(DIFFI+DX)))                                    000486
C                                                                            000487
      IF(IGPT2.EQ.0.AND.RATIO3.NE.1.) TNEW(IFINI)=TOLD(IFINI)-PHI*DT*        000488
     * ((T3-TOLD(IFINI-1))/(DX+DIFFF))+2.*PSI*DT*(T3/(DIFFF*                 000489
     * (DX+DIFFF))-TOLD(IFINI)/(DX*DIFFF)+TOLD(IFINI-1)/(DX*(DX+             000490
     * DIFFF)))                                                              000491
C                                                                            000492
      TNEW(K)=TOLD(K)-(TNEW(K-1)-TOLD(K-1))/3.-TERM2*(2.*TOLD(K)+            000493
     * 3.*TOLD(K-1)-6.*TOLD(K-2)+TOLD(K-3))                                  000494
      IF(TNEW(K).GT.TNEW(K-1)) TNEW(K)=TNEW(K-1)                             000495
      IF(TNEW(K).GE.TB) TNEW(K)=TB                                           000496
      IF(RATIO3.EQ.1.) GO TO 240                                             000497
C                                                                            000498
      DO 240 I=IFINI+1,K                                                     000499
      TNEW(I)=TB                                                             000500
  240 CONTINUE                                                               000501
C                                                                            000502
C                                                                            000503
C*****CALCULATE RATES OF BASIS WEIGHT CHANGE                                 000504
C                                                                            000505
      RATE1=0.                                                               000506
      IF(DELTA1.NE.DELTA2) RATE1=D4                                          000507
C                                                                            000508
      RATE2=D2                                                               000509
      IF(DELTA1.NE.DELTA2) RATE2=D5                                          000510
C                                                                            000511
      RATE3=DENOM                                                            000512
C                                                                            000513
      IF(FLAG.EQ.1) RATE3=0.                                                 000514
C                                                                            000515
      SIGN=0.                                                                000516
      IF(D6.EQ.0.) SIGN=1.                                                   000517
      IF(RATIO3.EQ.1.) LIQDEN=SIGN*MREL*MO+(1.-SIGN)*                        000518
     *(LIQDEN+RATE3*X)*DT)                                                   000519
C                                                                            000520
C                                                                            000521
C*****CALCULATE MECHANICAL AND HYDRAULIC PRESSURE                            000522
C                                                                            000523
      CALL PRESSR(TIME)                                                      000524
C                                                                            000525
      PH1=HYDRAL(T1,T1)                                                      000526
      PH2=HYDRAL(T1,T2)                                                      000527
      PH3=HYDRAL(T2,T3)                                                      000528
      PH4=HYDRAL(T3,TB)                                                      000529
C                                                                            000530
      P1=P-PH1                                                               000531
      IF(P1.LE.0.) P1=PREF1                                                  000532
      P2=P-PH2                                                               000533
      P3=P-PH3                                                               000534
      P4=P-PH4                                                               000535
C                                                                            000536
C                                                                            000537
C*****CALCULATE BASIS WEIGHT, CONCENTRATION AND THICKNESS                    000538
C                                                                            000539
```

```
      DBW1DT=C2*RATE1                                                   000540
      DBW2DT=C3*RATE2-DBW1DT                                            000541
      DBW3DT=C3*(RATE3-RATE2)                                           000542
      IF(RATIO3.EQ.1..AND.RATE3.GT.0.) DBW3DT=-C3*RATE2                 000543
      DBW4DT=-C3*RATE3                                                  000544
                                                                        000545
      BW1=BW1+DBW1DT*DT                                                 000546
      BW2=BW2+DBW2DT*DT                                                 000547
      BW3=BW3+DBW3DT*DT                                                 000548
      IF(FLAG.EQ.1) BW3=0.                                              000549
      BW4=BW4+DBW4DT*DT                                                 000550
                                                                        000551
      IF(BW1.LT.0.) BW1=0.                                              000552
      IF(BW2.LT.0.) BW2=0.                                              000553
      IF(BW3.LT.0..OR.FLAG.EQ.1) BW3=0.                                 000554
      IF(BW4.LT.0.) BW4=0.                                              000555
                                                                        000556
  250 BWSUM=BW1+BW2+BW3+BW4                                             000557
      BWCORR=BW/BWSUM                                                   000558
                                                                        000559
      BW1=BW1*BWCORR                                                    000560
      BW2=BW2*BWCORR                                                    000561
      BW3=BW3*BWCORR                                                    000562
      BW4=BW4*BWCORR                                                    000563
                                                                        000564
      TBAR1=(TS+T1)/2.                                                  000565
      TBAR2=(T1+T2)/2.                                                  000566
      TBAR3=(T2+TNEW(IFINI))/2.                                         000567
      TBAR4=(TNEW(IFINI)+TNEW(K))/2.                                    000568
                                                                        000569
      P1=EVALP(0.,TBAR1)                                                000570
      P2=EVALP(PRSTAR,TBAR2)                                            000571
      P3=EVALP(PR,TBAR3)                                                000572
      P4=EVALP(0.,TBAR4)                                                000573
                                                                        000574
      N3=EVALN(2,PR,P3)                                                 000575
                                                                        000576
      C1=M1*P1**N1                                                      000577
      C2=M2*P2**N2                                                      000578
      C3=M3*P3**N3                                                      000579
      C4=M4*P4**N4                                                      000580
                                                                        000581
      THICK1=BW1/C1                                                     000582
      THICK2=BW2/C2                                                     000583
      THICK3=BW3/C3                                                     000584
      THICK4=BW4/C4                                                     000585
                                                                        000586
                                                                        000587
*****CALCULATE POROSITY AND SATURATION                                  000588
                                                                        000589
      E1=1.-C1/DFIBER                                                   000590
      E2=1.-C2/DFIBER                                                   000591
      E3=1.-C3/DFIBER                                                   000592
      ESTAR=ES1*E3-ES2                                                  000593
```

```
      E4=1.-C4/DFIBER                                                   000594
      IF(C1.GT.DFIBER) CALL WARNIN(1,1,C1)                              000595
      IF(E2.LT.EMIN) CALL WARNIN(2,2,E2)                                000596
      IF(E3.LT.EMIN) CALL WARNIN(2,3,E3)                                000597
      IF(C4.GT.DFIBER) CALL WARNIN(1,4,C4)                              000598
      IF(C1.GT.DFIBER.OR.E2.LT.EMIN.OR.E3.LT.EMIN.OR.C4.GT.DFIBER)      000599
     * GO TO 9999                                                       000600
C                                                                       000601
      CALL CALLER(4)                                                    000602
      W=MRSTAR*C2                                                       000603
      X=MR*C3                                                           000604
      Y=(MR-MRSTAR)*C3                                                  000605
      Z=Y/X                                                             000606
C                                                                       000607
      S2=W*VF12/E2                                                      000608
      S3=X*VF23/E3                                                      000609
      S3STAR=Y*VF23/ESTAR                                               000610
      IF(S3.LE.1.) GO TO 270                                            000611
      IF(BW4.NE.0.) GO TO 260                                           000612
      S3=1.                                                             000613
      S3STAR=1.                                                         000614
      MR=E3/(VF23*C3)                                                   000615
      X=E3/VF23                                                         000616
      Y=(MR-MRSTAR)*C3                                                  000617
      Z=Y/X                                                             000618
      GO TO 270                                                         000619
  260 BW4=BW4-(S3-1.)*BW3                                               000620
      IF(BW4.LT.0.) BW4=0.                                              000621
      BW3=BW-BW1-BW2-BW4                                                000622
      GO TO 250                                                         000623
C                                                                       000624
C                                                                       000625
C*****INCREMENT INTERFACE POSITIONS                                     000626
C                                                                       000627
  270 DELTA1=THICK1                                                     000628
      DELTA2=DELTA1+THICK2                                              000629
      DELTA3=DELTA2+THICK3                                              000630
      DELTAT=DELTA3+THICK4                                              000631
      IF(THICK3.EQ.0.) DELTA3=DELTAT                                    000632
C                                                                       000633
      IF(DS.GT.0.) INIT=((BW1+BW2)/BW)*(K-1)*2                          000634
      IFINI=(K-1)-(K-1)*BW4/BW                                          000635
      IF(IFINI.LE.INIT) GO TO 450                                       000636
      DXX=DX*BW/BW3                                                     000637
      DIFFFX=DXX-EW4/BW                                                 000638
      DIFFIX=1.-DIFFFX-(IFINI-INIT)*DXX                                 000639
      IF(DIFFIX.GT.DXX) CALL WARNIN(3,1,0.)                             000640
      IF(DIFFFX.GT.DXX) CALL WARNIN(4,1,0.)                             000641
      DELTAI=DELTA2+DIFFIX*THICK3                                       000642
      DELTAF=DELTA3-DIFFFX*THICK3                                       000643
      DIFFI=DIFFIX*BW3/BW                                               000644
      DIFFF=DIFFFX*BW3/BW                                               000645
C                                                                       000646
C                                                                       000647
C*****CALCULATE THERMAL CONDUCTIVITY AND CONTACT COEFFICIENT             000648
```

```
      K1=KFIBER*(1.-E1)                                                 000649
      K2=KFIBER*(1.-E2)+KWATER*E2*S2                                    000650
      K3=KFIBER*(1.-E3)+KWATER*E3*S3                                    000651
      K4=KFIBER*(1.-E4)                                                 000652
                                                                        000653
      HCDRY=HCREF*(HC1*(P1/PREF2)**HC2-HC3)                             000654
      HC=HCDRY*(1.-E1)                                                  000655
      IF(DELTA1.EQ.0.) HC=HCDRY*(1.-E2)*E2*S2*HCWET                     000656
      IF(DELTA2.EQ.0.) HC=HCDRY*(1.-E3)*E3*S3*HCWET                     000657
                                                                        000658
                                                                        000659
*****CALCULATE PERMEABILITY FACTORS                                     000660
                                                                        000661
      R=SPRES(F)/FACTOR                                                 000662
                                                                        000663
      RABS2=1./(R*C2)                                                   000664
      RABS3=1./(R*C3)                                                   000665
      RABS4=1./(R*C4)                                                   000666
                                                                        000667
      RAK4=RABS3*S3STAR**4                                              000668
                                                                        000669
                                                                        000670
*****SET RELATIVE INTERFACE POSITIONS AND REMAINING MOISTURE            000671
                                                                        000672
      RATIO1=DELTA1/DELTAT                                              000673
      RATIO2=DELTA2/DELTAT                                              000674
      RATIO3=DELTA3/DELTAT                                              000675
                                                                        000676
      RREM=RR*BK3+RRSTAR*BK2                                            000677
      RREL=1.-RREM/RC                                                   000678
      IF(RATIO2.EQ.1.) GO TO 390                                        000679
                                                                        000680
                                                                        000681
*****COMPUTE NEW VALUES FOR T1, T2 AND T3                               000682
                                                                        000683
      IF(DELTA1.NE.DELTA2) GO TO 280                                    000684
      ALFA=DELTA3-DELTA1                                                000685
      TERM1=(1./HC*DELTA1/K1)*K3/(DELTA1-DELTA1)                        000686
      T1=(TH+TERM1*TKEK(INIT))/(1.+TERM1)                               000687
      T2=T1                                                             000688
      GO TO 290                                                         000689
                                                                        000690
 280  DO 290 I=1,IMAX                                                  000691
                                                                        000692
      TC1=T1                                                            000693
      TC2=T2                                                            000694
                                                                        000695
      CALL PROP12                                                       000696
      HFG1=HFG(T1)+DELHD(1)                                             000697
      HFG2=HFG(T2)+DELHD(2)                                             000698
                                                                        000699
      ALF=DELTA2-DELTA1                                                 000700
                                                                        000701
```

```
      EET=DELTA3-DELTA2                                                 000702
C                                                                       000703
      TERM1=(1./HC*DELTA1/K1)*(1./ALF)*(HFG1*KABS2*DPDT12/              000704
     * (VG12*VISG12)*K2)                                               000705
      TERM2=(KABS2*DPDT12*HFG2/(K3*VG12*VISG12)+K2/K3)*                 000706
     * (DELTA1-DELTA2)/ALF                                             000707
      DENOM=1.+TERM1+TERM2                                              000708
C                                                                       000709
      T1=((1.+TERM2)*TH+TERM1*TNEW(INIT))/DENOM                         000710
      T1=(T01+T1)/2.                                                    000711
      T2=(TERM2*TH+(1.+TERM1)*TNEW(INIT))/DENOM                         000712
      T2=(T02+T2)/2.                                                    000713
  290 CONTINUE                                                          000714
C                                                                       000715
      IF(RATIO3.EQ.1.) GO TO 310                                        000716
C                                                                       000717
      CALL PROP3B                                                       000718
      HFG3=HFG(T3)+DELHD(3)                                             000719
C                                                                       000720
      DO 300 I=1,IMAX                                                   000721
C                                                                       000722
      T03=T3                                                            000723
C                                                                       000724
      TERM1=(KABS4*HFG3*DPDT3B/(K3*VISG3B*VG3B))*(DELTA3-DELTAF)        000725
     * /(DELTAT-DELTA3)                                                000726
C                                                                       000727
      T3=(TNEW(IFIN)+TERM1*TB)/(1.+TERM1)                               000728
      T3=(T03+T3)/2.                                                    000729
  300 CONTINUE                                                          000730
      GO TO 320                                                         000731
C                                                                       000732
  310 T3=TB                                                             000733
C                                                                       000734
  320 IF((TNEW(IFIN)-T3)/DIFFFX.EQ.(T2-T3)) GO TO 450                   000735
C                                                                       000736
C                                                                       000737
C*****RECOMPUTE VARIABLES FOR DERIVATIVE CALCULATIONS                   000738
C                                                                       000739
      IF(DELTA1.NE.DELTA2) GO TO 330                                    000740
      DTDZ12=0.                                                         000741
      DTDZ23=(T2-T3)/ALFA                                               000742
      IF(T2.LE.TB) DTDZ23=0.                                            000743
      GO TO 340                                                         000744
C                                                                       000745
  330 DTDZ12=(T1-T2)/ALF                                                000746
      IF(T2.LE.TB) DTDZ12=(T1-TB)/ALF                                   000747
      IF(T1.LE.TB) DTDZ12=0.                                            000748
      DTDZ23=(T2-T3)/BET                                                000749
      IF(T2.LE.TB) DTDZ23=0.                                            000750
C                                                                       000751
  340 DTDZ3B=0.                                                         000752
      IF(RATIO3.NE.1.) DTDZ3B=(T3-TB)/(DELTAT-DELTA3)                   000753
C                                                                       000754
      CALL CALLER(1)                                                    000755
```

```
      A2=KAKW*DPDT23/(VISF23*VF23*Y)                                    000756
      A4=KABS2*DPDT12/(VISG12*VG12*W)                                   000757
      A5=A4*W/Y                                                         000758
      A6=KABS4*DPDT3B/(VG3B*VISG3B*X)                                   000759
      GO TO 400                                                         000760
                                                                        000761
                                                                        000762
*****HANDLE SPECIAL CASE OF INTRA-FIBER WATER                          000763
                                                                        000764
  35C DTMAX=TIMER*DX**2/(2.*PSI)                                        000765
      DIFFFX=DXX                                                        000766
      I1=INEW(1)                                                        000767
      I2=INEW(K)                                                        000768
      HFG2=HFG(T2)+DELHD(1)                                             000769
      D7=0.                                                             000770
      X=HR*C2                                                           000771
                                                                        000772
  36C D6=K3*(T2-TNEW(IFINI))/(HFG2*DXX*THICK2*X)                        000773
                                                                        000774
      DT1=DTMAX                                                         000775
      DT2=DTMAX                                                         000776
      DT1=(DELTA2-DELTA1)/(-D6)                                         000777
      DT=AMIN1(DT1,DTMAX)                                               000778
      IF((-D6*DT).GE.DIFFFX*THICK2) ICPT2=1                             000779
      IF(ICPT2.EQ.1) GO TO 37C                                          000780
      DT2=DX*DIFFF/(2.*PSI)                                             000781
      DT=AMIN1(DT1,DT2,DTMAX)                                           000782
      DT=TIMER*DT                                                       000783
  37C TIME=TIME+DT                                                      000784
                                                                        000785
      A=(KFIBER*DX*VF12)/DC                                             000786
      PSI=A*(C2/BK)**2                                                  000787
      F2=PSI*DT/DX**2                                                   000788
                                                                        000789
      DO 380 I=INI1,IFINI                                               000790
      TNEW(I)=F2*(TOLD(I+1)+TOLD(I-1))/2.+(1.-2.*F2)*TOLD(I)            000791
  38C CONTINUE                                                          000792
                                                                        000793
      TNEW(1)=TOLD(1)-(TNEW(2)-TOLD(2))/3.+(2.*F2/9.)*(6.*BIDX*(TH-     000794
     * TOLD(1))-2.*TOLD(1)-3.*TOLD(2)+6.*TOLD(3)-TOLD(4))               000795
      I1=INEW(1)                                                        000796
      TOLD(1)=TNEW(1)                                                   000797
                                                                        000798
      IF(ICPT2.EQ.0) TNEW(IFINI)=TOLD(IFINI)+2.*PSI*DT*(T2/(DIFFF*      000799
     * (DIFFF+DX))-TOLD(IFINI)/(DX*DIFFF)+TOLD(IFINI-1)/(DX*(DX+        000800
     * DIFFF)))                                                         000801
                                                                        000802
      RATE2=D6                                                          000803
      CALL PRESSR(TIME)                                                 000804
      PH2=HYDRAL(T1,T2)                                                 000805
      PH4=HYDRAL(T2,TB)                                                 000806
      F2=P-PH2                                                          000807
      P4=P-PH4                                                          000808
                                                                        000809
```

```
C                                                                       000810
      DBW2DT=C2*RATE2                                                   000811
      DBW4DT=-DBW2DT                                                    000812
C                                                                       000813
      BW2=BW2+DBW2DT*DT                                                 000814
      BW4=BW4+DBW4DT*DT                                                 000815
C                                                                       000816
      BWSUM=BW2+BW4                                                     000817
      BWCORR=BW/BWSUM                                                   000818
      BW2=BW2*BWCORR                                                    000819
      BW4=BW4*BWCORR                                                    000820
      TBAR2=(T1+T2)/2.                                                  000821
      TBAR4=(T2+T0)/2.                                                  000822
      P2=EVALM(PRSTAR,TBAR2)                                            000823
      P4=EVALM(0.,TBAR4)                                                000824
      C2=M2*P2**N2                                                      000825
      C4=M4*P4**N4                                                      000826
C                                                                       000827
      THICK2=BW2/C2                                                     000828
      THICK4=BW4/C4                                                     000829
C                                                                       000830
      E2=1.-C2/DFIBER                                                   000831
      E4=1.-C4/DFIBER                                                   000832
      IF(E2.LT.EMIN) CALL WARNIN(2,2,E2)                                000833
      IF(C4.GT.DFIBER) CALL WARNIN(1,4,C4)                              000834
      IF(E2.LT.EMIN.OR.C4.GT.DFIBER) GO TO 9999                         000835
C                                                                       000836
      CALL PROP12                                                       000837
      X=MR*C2                                                           000838
      Z=0.                                                              000839
      S2=X*VF12/E2                                                      000840
C                                                                       000841
      DELTA2=THICK2                                                     000842
      DELTAT=DELTA2+THICK4                                              000843
      IFINI=(K-1)-(K-1)*BW4/BW                                          000844
      CXX=CX*BW/BW2                                                     000845
      DIFFFX=CXX-BW4/BW                                                 000846
      IF(DIFFFX.GT.CXX) CALL WARNIN(4,1,0.)                             000847
      DELTAF=DELTA2-DIFFFX*THICK2                                       000848
      K2=KFIBER*(1.-E2)+KWATER*E2*S2                                    000849
      K4=KFIBER*(1.-E4)                                                 000850
      HCDRY=HCREF*(HC1*(P2/PREF2)**HC2-HC3)                             000851
      HC=HCDRY*(1.-E2)+E2*S2*HCWET                                      000852
      EIDX=HC*BW*CX/(K2*C2)                                             000853
C                                                                       000854
      R=SPRES(P)/FACTOR                                                 000855
      RABS2=1./(R*C2)                                                   000856
      RABS4=1./(R*C4)                                                   000857
C                                                                       000858
      RATIO1=0.                                                         000859
      RATIO2=DELTA2/DELTAT                                              000860
      RATIO3=1.                                                         000861
C                                                                       000862
      PREM=PRSTAR*BW2                                                   000863
      PREL=1.-PREM/PC                                                   000864
C                                                                       000865
```

```
      CALL PROP23(2)                                                    000866
      HFG2=HFG(T2)+DELHD(1)                                             000867
                                                                        000868
      IF(RATIO2.EQ.1.) GO TO 390                                        000869
      DO 390 I=1,IMAX                                                   000870
      T02=T2                                                            000871
      TERM1=(KAES4*HFG2*DPDT23/(R3*VISG23*VG23))*(DELTA2-DELTAF)/       000872
     * (DELTAT-DELTA2)                                                  000873
      T2=(TNEW(IFINI)+TERM1*TB)/(1.+TERM1)                              000874
      T2=(T02+T2)/2.                                                    000875
  390 CONTINUE                                                          000876
                                                                        000877
      IF(RATIO2.EQ.1.) T2=TB                                            000878
      IF((TNEW(IFINI)-T2)/DIFFF).EQ.(T1-T2)) GO TO 450                  000879
                                                                        000880
                                                                        000881
*****RESET TEMPERATURE DISTRIBUTION AND TIME OPTIONS                    000882
                                                                        000883
  400 DO 410 I=INIT,M                                                   000884
      TOLD(I)=TNEW(I)                                                   000885
  410 CONTINUE                                                          000886
                                                                        000887
      ICPT1=0                                                           000888
      ICPT2=0                                                           000889
                                                                        000890
                                                                        000891
*****COMPUTE TEMPERATURES AT FIXED-POINT LOCATIONS                      000892
                                                                        000893
      SUM12=BW1+BW2                                                     000894
      SUM123=SUM12+BW3                                                  000895
      DO 420 I=1,M                                                      000896
      U=ZTC(I)*BW                                                       000897
      NN=I*XX                                                           000898
      REM=I*XX-NN                                                       000899
      IF(U.LT.BW1.AND.BW1.NE.0.) TC(I)=TS-(TS-T1)*(U/BW1)               000900
      IF(U.GT.BW1.AND.U.LT.SUM12.AND.BW2.NE.0.) TC(I)=T1-(T1-T2)*       000901
     * (U-BW1)/BW2                                                      000902
      IF(U.GT.SUM12.AND.U.LT.SUM123.AND.BW3.NE.0.) TC(I)=TNEW(1+NN)-    000903
     * REM*(TNEW(1+NN)-TNEW(2+NN))                                      000904
      IF(U.GT.SUM123.AND.U.LT.BW.AND.BW4.NE.0.) TC(I)=T3-(T3-TB)*       000905
     * (U-SUM123)/BW4                                                   000906
                                                                        000907
      IF(U.EQ.BW1) TC(I)=T1                                             000908
      IF(U.EQ.SUM12) TC(I)=T2                                           000909
      IF(U.EQ.SUM123) TC(I)=T3                                          000910
      IF(U.EQ.BW) TC(I)=TB                                              000911
  420 CONTINUE                                                          000912
                                                                        000913
                                                                        000914
*****INCREMENT QUANTITIES AND WRITE RESULTS                             000915
                                                                        000916
      HC=HREM/(HREM+EW)                                                 000917
      TS=(TH*HC*DELTA1/K1+T1)/(1.+HC*DELTA1/K1)                         000918
```

```
      GTOTAL=GTOTAL+(Q+HC*(TH-TS))*DT/2.                                  000919
      G=HC*(TH-TS)                                                        000920
      IF(N.LT.J.AND.L.GT.LMAX.AND.MC.GT.MFINAL) GO TO 430                 000921
C                                                                         000922
      PGAUGE=PV(I1)-PVTB                                                  000923
      IF(PGAUGE.LT.0.) PGAUGE=0.                                          000924
      SEC=TIME*3600.                                                      000925
      TMID=TC(1+M/2)                                                      000926
      CHTC=G/(TH-TMID)                                                    000927
C                                                                         000928
      IF(RATIO3.EQ.1.) T3=TNEW(K)                                         000929
      IF(FLAG.EQ.1) T3=TB                                                 000930
      CALL WRITER(IOPTU)                                                  000931
      T3=TB                                                               000932
      K=1                                                                 000933
      GO TO 440                                                           000934
C                                                                         000935
C                                                                         000936
C*****INCREMENT PRINT CONTROL VARIABLES                                   000937
C                                                                         000938
  430 K=K+1                                                               000939
  440 L=L+1                                                               000940
C                                                                         000941
C                                                                         000942
C*****DETERMINE EXIT CRITERIA                                             000943
C                                                                         000944
      IF(1800*TIME.GE.RISTIM.AND.IOPTP.EQ.2) GO TO 9999                   000945
      IF(MC.LT.MFINAL) GO TO 9999                                         000946
      IF(RATIO2.EQ.1.) GO TO 450                                          000947
      IF(FLAG.NE.1.AND.MC.GT.MFINAL) GO TO 180                            000948
      IF(FLAG.EQ.1.AND.MC.GT.MFINAL) GO TO 360                            000949
C                                                                         000950
C                                                                         000951
C*****WRITE TRANSITION REGIME FINAL OUTPUT                                000952
C                                                                         000953
  450 MC=MREM/(MREM+EW)                                                   000954
      TS=(TH+HC*DELTA1/K1+T1)/(1.+HC*DELTA1/K1)                           000955
      GTOTAL=GTOTAL+(Q+HC*(TH-TS))*DT/2.                                  000956
      G=HC*(TH-TS)                                                        000957
      PGAUGE=PV(I1)-PVTB                                                  000958
      IF(PGAUGE.LT.0.) PGAUGE=0.                                          000959
      SEC=TIME*3600.                                                      000960
      TMID=TC(1+M/2)                                                      000961
      CHTC=G/(TH-TMID)                                                    000962
C                                                                         000963
      IF(RATIO3.EQ.1.) T3=TNEW(K)                                         000964
      IF(FLAG.EQ.1) T3=TB                                                 000965
      IF(N.NE.1) CALL WRITER(IOPTU)                                       000966
      WRITE(6,930)                                                        000967
C     IF(IFINI.LE.K) WRITE(6,935) (I,TNEW(I),I=INIT,IFINI)                000968
C*************************************************************************000969
C                                                                         000970
C                                                                         000971
C     *********************************                                   000972
C     *****  THE LINEAR REGIME  *****                                     000973
```

```
      ********************************                                  000974
                                                                        000975
                                                                        000976
*****WRITE LINEAR REGIME HEADING                                        000977
                                                                        000978
      WRITE(6,945)                                                      000979
                                                                        000980
                                                                        000981
*****SET FLAG AND GO TO FIRST TEMPERATURE CALCULATION                   000982
                                                                        000983
      L=1                                                               000984
      T3=TE                                                             000985
      MANV=MABS3*(1.-S3STAR)**3*(1.+3.*S3STAR)                          000986
      IF(RATIO2.EQ.1.) FLAG=1                                           000987
      DTMAX=DTO                                                         000988
      GO TO 550                                                         000989
                                                                        000990
                                                                        000991
*****COMPUTE REQUIRED DERIVATIVES                                       000992
                                                                        000993
  460 D1=A1*DTDZ23                                                      000994
      D2=A2*DTDZ23                                                      000995
      D3=A3*DTDZ23                                                      000996
      D4=A4*DTDZ12                                                      000997
      D5=A5*DTDZ23                                                      000998
      D6=-K3*DTDZ23/(HFG3*X)                                            000999
      D7=D2*Z                                                           001000
      D8=A8*DTDZ12                                                      001001
                                                                        001002
      IF(DELTA1.EQ.DELTA2.AND.D1.GE.D2) D7=0.                           001003
      IF(DELTA1.NE.DELTA2.AND.D5.GE.D2) D7=0.                           001004
      DENOM=D6+D7                                                       001005
                                                                        001006
                                                                        001007
*****SET MAXIMUM ALLOWABLE TIME INCREMENT                               001008
                                                                        001009
      DT1=DTMAX                                                         001010
      DT2=DTMAX                                                         001011
                                                                        001012
      IF(DELTA1.NE.DELTA2) GO TO 470                                    001013
      IF(D1.GE.D2.AND.D1.NE.D6) DT1=(DELTA3-DELTA1)/(D1-D6)             001014
      IF(D1.LT.D2.AND.D2.NE.DENOM) DT1=(DELTA3-DELTA2)/(D2-DENOM)       001015
      GO TO 490                                                         001016
                                                                        001017
  470 IF(FLAG.EQ.1) GO TO 480                                           001018
      DSTAR=AMAX1(D2,D5)                                                001019
      IF(DSTAR.NE.DENOM) DT1=(DELTA3-DELTA2)/(DSTAR-DENOM)              001020
      IF(D4.GT.DSTAR) DT2=(DELTA2-DELTA1)/(D4-DSTAR)                    001021
      GO TO 490                                                         001022
                                                                        001023
  480 DSTAR=0.                                                          001024
      IF(D4.NE.D8) DT1=(DELTA2-DELTA1)/(D4-D8)                          001025
                                                                        001026
  490 IF(DT1.LE.0.) DT1=DTMAX                                           001027
      IF(DT2.LE.0.) DT2=DTMAX                                           001028
```

```
      DT=AMIN1(DT1,DT2,DTMAX)                                          001029
C                                                                      001030
      DT=TIMER*DT                                                      001031
      TIME=TIME+DT                                                     001032
C                                                                      001033
C                                                                      001034
C*****CALCULATE RATES OF BASIS WEIGHT CHANGE                           001035
C                                                                      001036
      IF(DELTA1.NE.DELTA2) GO TO 500                                   001037
      IF(D1.GE.D2) RATE1=D1                                            001038
      RATE2=RATE1                                                      001039
      IF(D1.LT.D2) RATE2=D2                                            001040
      IF(D1.LT.D2.AND.D3.GE.D2) RATE1=RATE2                            001041
      IF(D1.LT.D2.AND.D3.LT.D2) RATE1=D3                               001042
      GO TO 510                                                        001043
C                                                                      001044
  500 RATE1=D4                                                         001045
      RATE2=DSTAR                                                      001046
      IF(FLAG.EQ.1) RATE2=D8                                           001047
C                                                                      001048
  510 RATE3=DENOM                                                      001049
      IF(FLAG.EQ.1) EW3=0.                                             001050
      IF(FLAG.EQ.1) RATE3=0.                                           001051
C                                                                      001052
      IF(BW4.EQ.0.) LIQDEW=LIQDEW+RATE3*X*DT                           001053
C                                                                      001054
C                                                                      001055
C*****CALCULATE MECHANICAL AND HYDRAULIC PRESSURE                      001056
C                                                                      001057
      CALL PRESSR(TIME)                                                001058
C                                                                      001059
      PH1=HYDRAL(T1,T1)                                                001060
      PH2=HYDRAL(T1,T2)                                                001061
      PH3=HYDRAL(T2,T3)                                                001062
      PH4=HYDRAL(T3,TB)                                                001063
      IF(FLAG.EQ.1) PH4=PH3                                            001064
C                                                                      001065
      P1=P-PH1                                                         001066
      IF(P1.LE.0.) P1=PREF1                                            001067
      P2=P-PH2                                                         001068
      P3=P-PH3                                                         001069
      P4=P-PH4                                                         001070
C                                                                      001071
C                                                                      001072
C*****CALCULATE BASIS WEIGHT, CONCENTRATION AND THICKNESS              001073
C                                                                      001074
C                                                                      001075
      DBW1DT=C2*RATE1                                                  001076
      DBW2DT=C3*RATE2-DBW1DT                                           001077
      IF(FLAG.EQ.1) DBW2DT=C2*(RATE2-RATE1)                            001078
      DBW3DT=C3*(RATE3-RATE2)                                          001079
      IF(RATIO3.EQ.1..AND.RATE3.GT.0.) DBW3DT=-C3*RATE2                001080
      DBW4DT=-C3*RATE3                                                 001081
      IF(FLAG.EQ.1) DBW4DT=-C2*RATE2                                   001082
```

```
                                                                        001083
      EW1=BW1+DBW1DT*DT                                                 001084
      EW2=BW2+DBW2DT*DT                                                 001085
      EW3=BW3+DBW3DT*DT                                                 001086
      EW4=BW4+DBW4DT*DT                                                 001087
                                                                        001088
      IF(BW1.LT.0.) BW1=0.                                              001089
      IF(BW2.LT.0.) BW2=0.                                              001090
      IF(BW3.LT.0..OR.FLAG.EQ.1) BW3=0.                                 001091
      IF(BW4.LT.0.) BW4=0.                                              001092
                                                                        001093
  520 BWSUM=BW1+BW2+BW3+BW4                                             001094
      BWCORR=BW/BWSUM                                                   001095
                                                                        001096
      BW1=BW1*BWCORR                                                    001097
      BW2=BW2*BWCORR                                                    001098
      BW3=BW3*BWCORR                                                    001099
      BW4=BW4*BWCORR                                                    001100
                                                                        001101
      TBAR1=(TS+T1)/2.                                                  001102
      TBAR2=(T1+T2)/2.                                                  001103
      TBAR3=(T2+T3)/2.                                                  001104
      TBAR4=(T3+TE)/2.                                                  001105
                                                                        001106
      P1=EVALP(0.,TBAR1)                                                001107
      P2=EVALP(PRSTAR,TBAR2)                                            001108
      P3=EVALP(PR,TBAR3)                                                001109
      P4=EVALP(0.,TBAR4)                                                001110
      IF(FLAG.EQ.1) P4=EVALP(0.,TBAR3)                                  001111
                                                                        001112
      C1=M1*P1**N1                                                      001113
      C2=M2*P2**N2                                                      001114
      C3=M3*P3**N3                                                      001115
      C4=M4*P4**N4                                                      001116
                                                                        001117
      THICK1=BW1/C1                                                     001118
      THICK2=BW2/C2                                                     001119
      THICK3=BW3/C3                                                     001120
      THICK4=BW4/C4                                                     001121
                                                                        001122
                                                                        001123
*****CALCULATE POROSITY AND SATURATION                                  001124
                                                                        001125
      E1=1.-C1/DFIBER                                                   001126
      E2=1.-C2/DFIBER                                                   001127
      E3=1.-C3/DFIBER                                                   001128
      ESTAR=ES1*E3-ES2                                                  001129
      E4=1.-C4/DFIBER                                                   001130
      IF(C1.GT.DFIBER) CALL WARNIN(1,1,C1)                              001131
      IF(E2.LT.EMIN) CALL WARNIN(2,2,E2)                                001132
      IF(E3.LT.EMIN) CALL WARNIN(2,3,E3)                                001133
      IF(C4.GT.DFIBER) CALL WARNIN(1,4,C4)                              001134
      IF(C1.GT.DFIBER.OR.E2.LT.EMIN.OR.E3.LT.EMIN.OR.C4.GT.DFIBER)      001135
     * GO TO 9999                                                       001136
                                                                        001137
```

```
      CALL CALLER(4)                                                    001138
      B=MRSTAR*C2                                                       001139
      X=MR*C3                                                           001140
      Y=(MR-MRSTAR)*C3                                                  001141
      Z=Y/X                                                             001142
C                                                                       001143
      S2=W*VF12/E2                                                      001144
      S3=X*VF23/E3                                                      001145
      S3STAR=Y*VF23/ESTAR                                               001146
      IF(S3.LE.1..OR.FLAG.EQ.1) GO TO 540                               001147
      IF(BW4.NE.0.) GO TO 530                                           001148
      S3=1.                                                             001149
      S3STAR=1.                                                         001150
      MR=E3/(VF23*C3)                                                   001151
      X=E3/VF23                                                         001152
      Y=(MR-MRSTAR)*C3                                                  001153
      Z=Y/X                                                             001154
      GO TO 540                                                         001155
  530 BW4=BW4-(S3-1.)*BW3                                               001156
      IF(BW4.LT.0.) BW4=0.                                              001157
      BW3=BW-BW1-BW2-BW4                                                001158
      GO TO 520                                                         001159
C                                                                       001160
C                                                                       001161
C*****INCREMENT INTERFACE POSITIONS                                     001162
C                                                                       001163
  540 DELTA1=THICK1                                                     001164
      DELTA2=DELTA1+THICK2                                              001165
      DELTA3=DELTA2+THICK3                                              001166
      DELTAT=DELTA3+THICK4                                              001167
      IF(THICK3.EQ.0.) FLAG=1                                           001168
      IF(THICK3.EQ.C.) DELTA3=DELTAT                                    001169
C                                                                       001170
C                                                                       001171
C*****CALCULATE THERMAL CONDUCTIVITY AND CONTACT COEFFICIENT             001172
C                                                                       001173
      K1=KFIBER*(1.-E1)                                                 001174
      K2=KFIBER*(1.-E2)+KWATER*E2*S2                                    001175
      K3=KFIBER*(1.-E3)+KWATER*E3*S3                                    001176
      K4=KFIBER*(1.-E4)                                                 001177
C                                                                       001178
      HCDRY=HCREF*(HC1*(P1/PREF2)**HC2-HC3)                             001179
      HC=HCDRY*(1.-E1)                                                  001180
      IF(DELTA1.EQ.0.) HC=HCDRY*(1.-E2)+E2*S2*HCWET                     001181
      IF(DELTA2.EQ.0.) HC=HCDRY*(1.-E3)+E3*S3*HCWET                     001182
C                                                                       001183
C                                                                       001184
C*****CALCULATE PERMEABILITY FACTORS                                    001185
C                                                                       001186
      R=SPRES(P)/FACTOR                                                 001187
C                                                                       001188
      KABS2=1./(R*C2)                                                   001189
      KABS3=1./(R*C3)                                                   001190
      KABS4=1./(R*C4)                                                   001191
```

```
      KAKV=KABS3*(1.-S3STAR)**3*(1.+3.*S3STAR)                          001192
      KAKW=KABS3*S3STAR**4                                              001193
                                                                        001194
                                                                        001195
                                                                        001196
*****SET RELATIVE INTERFACE POSITIONS AND REMAINING MOISTURE            001197
                                                                        001198
      RATIO1=DELTA1/DELTAT                                              001199
      RATIO2=DELTA2/DELTAT                                              001200
      RATIO3=DELTA3/DELTAT                                              001201
                                                                        001202
      WREM=WR*BW3+WRSTAR*BW2                                            001203
      WREL=1.-WREM/WC                                                   001204
                                                                        001205
                                                                        001206
*****COMPUTE NEW VALUES FOR T1, T2 AND T3                              001207
                                                                        001208
  550 IF(DELTA1.NE.DELTA2) GO TO 570                                    001209
                                                                        001210
      DO 560 I=1,IMAX                                                   001211
                                                                        001212
      T02=T2                                                            001213
      T03=T3                                                            001214
                                                                        001215
      CALL CALLER(2)                                                    001216
                                                                        001217
      HFG2=HFG(T2)+DELHD(3)                                             001218
      HFG3=HFG(T3)+DELHD(3)                                             001219
                                                                        001220
      ALFA=DELTA3-DELTA2                                                001221
      BETA=DELTAT-DELTA3                                                001222
                                                                        001223
      TERM1=(1./HC+DELTA1/K1)*(1./ALFA)*(HFG2*KAKV*DPDT23/              001224
     * (VG23*VISG23)+K3)                                               001225
      TERM3=(BETA*(KAKV*DPDT23/(VG23*VISG23)+K3/HFG3))/                 001226
     * (ALFA*KABS4*DPDT3B/(VG3B*VISG3B))                               001227
      DENOM=1.+TERM1+TERM3                                              001228
                                                                        001229
      T2=(TH*(1.+TERM3)+TB*TERM1)/DENOM                                 001230
      T2=(T02+T2)/2.                                                    001231
      T3=(TH*TERM3+TB*(1.+TERM1))/DENOM                                 001232
      T3=(T03+T3)/2.                                                    001233
  560 CONTINUE                                                          001234
                                                                        001235
      T1=T2                                                             001236
      GO TO 590                                                         001237
                                                                        001238
  570 DO 590 I=1,IMAX                                                   001239
                                                                        001240
      T01=T1                                                            001241
      T02=T2                                                            001242
      T03=T3                                                            001243
                                                                        001244
      CALL CALLER(3)                                                    001245
                                                                        001246
```

```
      HFG1=HFG(T1)+DELHD(1)                                              001247
      HFG2=HFG(T2)+DELHD(2)                                              001248
      IF(FLAG.EQ.1) HFG2=HFG(T2)+DELHD(1)                                001249
      HFG3=HFG(T3)+DELHD(3)                                              001250
C                                                                        001251
      ALF=DELTA2-DELTA1                                                  001252
      BET=DELTA3-DELTA2                                                  001253
      GAMM=DELTA1-DELTA3                                                 001254
      IF(BET.EQ.0.) FLAG=1                                               001255
      IF(FLAG.EQ.1) GO TO 580                                            001256
C                                                                        001257
      TERM1=(1./HC+DELTA1/K1)*(1./ALF)*(HFG1*KABS2*DPDT12/               001258
     * (VG12*VISG12)+K2)                                                001259
      TERM2=(BET*(KABS2*DPDT12/(VG12*VISG12)+K2/HFG2))/                  001260
     * (ALF*(KAKV*DPDT23/(VG23*VISG23)+K3/HFG2))                         001261
      TERM3=(GAMM*(KAKV*DPDT23/(VG23*VISG23)+K3/HFG3))/                  001262
     * (BET*KABS4*DPDT3B/(VG3B*VISG3B))                                  001263
      TERM4=TERM2*(1.+TERM3)                                             001264
      DENOM=1.+TERM1+TERM4                                               001265
C                                                                        001266
      T1=(TH*(1.+TERM4)+TB*TERM1)/DENOM                                  001267
      T1=(T01+T1)/2.                                                     001268
      T2=(TH*TERM4+TB*(1.+TERM1))/DENOM                                  001269
      T2=(T02+T2)/2.                                                     001270
      T3=(TH*TERM2+TERM3+TB*(1.+TERM1+TERM2))/DENOM                      001271
      T3=(T03+T3)/2.                                                     001272
      GO TO 590                                                          001273
C                                                                        001274
  580 TERM1=(1./HC+DELTA1/K1)*(1./ALF)*(HFG1*KABS2*DPDT12/               001275
     * (VG12*VISG12)+K2)                                                001276
      TERM2=(BET*(KABS2*DPDT12/(VG12*VISG12)+K2/HFG2))/                  001277
     * (ALF*KABS4*DPDT23/(VG23*VISG23))                                  001278
      DENOM=1.+TERM1+TERM2                                               001279
C                                                                        001280
      T1=(TH*(1.+TERM2)+TB*TERM1)/DENOM                                  001281
      T1=(T01+T1)/2.                                                     001282
      T2=(TH*TERM2+TB*(1.+TERM1))/DENOM                                  001283
      T2=(T02+T2)/2.                                                     001284
      T3=TB                                                              001285
  590 CONTINUE                                                           001286
C                                                                        001287
C                                                                        001288
C*****RECOMPUTE VARIABLES FOR DERIVATIVE CALCULATIONS                    001289
C                                                                        001290
      IF(DELTA1.NE.DELTA2) GO TO 600                                     001291
      DTDZ12=0.                                                          001292
      DTDZ23=(T2-T3)/ALFA                                                001293
      GO TO 610                                                          001294
C                                                                        001295
  600 DTDZ12=(T1-T2)/ALF                                                 001296
      DTDZ23=0.                                                          001297
      IF(FLAG.EQ.0) DTDZ23=(T2-T3)/BET                                   001298
C                                                                        001299
```

```
 61C CALL CALLER(4)                                                    001300
                                                                       001301
     HFG2=HFG(T2)+DELHD(1)                                             001302
                                                                       001303
     IF(FLAG.EQ.1) GO TO 620                                           001304
     A1=KAKV*DPDT23/(VISG23*VG23*X)                                    001305
     A2=KAKW*DPDT23/(VISF23*VF23*Y)                                    001306
     A3=KAKV*DPDT23/(VISG23*VG23*W)                                    001307
     A4=KABS2*DPDT12/(VISG12*VG12*W)                                   001308
     A5=KAKV*DPDT23/(VISG23*VG23*Y)                                    001309
     GO TO 630                                                         001310
                                                                       001311
 62C A1=0.                                                             001312
     A2=0.                                                             001313
     A3=0.                                                             001314
     A4=KABS2*DPDT12/(VISG12*VG12*W)                                   001315
     A5=0.                                                             001316
     A8=-K2/(HFG2*W)                                                   001317
                                                                       001318
                                                                       001319
*****COMPUTE TEMPERATURES AT FIXED-POINT LOCATIONS                     001320
                                                                       001321
 63C SUM12=BW1+BW2                                                     001322
     SUM123=SUM12+BW3                                                  001323
     DO 64C I=1,M                                                      001324
     L=ZTC(I)+BW                                                       001325
     IF(U.LT.BW1.AND.BW1.NE.0.) TC(I)=TS-(TS-T1)*(U/BW1)               001326
     IF(U.GT.BW1.AND.U.LT.SUM12.AND.BW2.NE.0.) TC(I)=T1-(T1-T2)*       001327
    * (U-BW1)/BW2                                                      001328
     IF(U.GT.SUM12.AND.L.LT.SUM123.AND.BW3.NE.0.) TC(I)=T2-(T2-T3)*    001329
    * (U-SUM12)/BW3                                                    001330
     IF(U.GT.SUM123.AND.U.LT.BW.AND.BW4.NE.0.) TC(I)=T3-(T3-TB)*       001331
    * (L-SUM123)/BW4                                                   001332
                                                                       001333
     IF(U.EQ.BW1) TC(I)=T1                                             001334
     IF(U.EQ.SUM12) TC(I)=T2                                           001335
     IF(U.EQ.SUM123) TC(I)=T3                                          001336
     IF(U.EQ.BW) TC(I)=TB                                              001337
 64C CONTINUE                                                          001338
                                                                       001339
                                                                       001340
*****INCREMENT QUANTITIES AND WRITE RESULTS                            001341
                                                                       001342
     HC=HREM/(HREM+BW)                                                 001343
     TS=(TH+HC*DELTA1/K1+T1)/(1.+HC*DELTA1/K1)                         001344
     QTOTAL=QTOTAL+(Q+HC*(TH-TS))*DT/2.                                001345
     Q=HC*(TH-TS)                                                      001346
     IF(N.LT.J.AND.L.GT.LMAX.AND.HC.GT.HFINAL) GO TO 650               001347
                                                                       001348
     PGAUGE=PV(T1)-PVTB                                                001349
     SEC=TIME*3600.                                                    001350
     TMID=TC(1+M/2)                                                    001351
     CHTC=Q/(TH-TMID)                                                  001352
                                                                       001353
```

```
      IF(L.NE.1) CALL WRITER(IOPTU)                                      001354
C     WRITE(6,*) MREL,LIQDEW,S3,MR,RATE1,RATE2,RATE3,X,D7,DT             001355
      N=1                                                                001356
      GO TO 660                                                          001357
C                                                                        001358
C                                                                        001359
C*****INCREMENT PRINT CONTROL VARIABLES                                  001360
C                                                                        001361
  650 N=N+1                                                              001362
  660 L=L+1                                                              001363
C                                                                        001364
C                                                                        001365
C*****DETERMINE EXIT CRITERIA                                            001366
C                                                                        001367
      IF(1800*TIME.GE.RISTIM.AND.IOPTP.EQ.2) GO TO 9999                  001368
      IF(MC.GT.MFINAL) GO TO 460                                         001369
C                                                                        001370
C                                                                        001371
C*****WRITE FINAL OUTPUT                                                 001372
C                                                                        001373
      IF(N.NE.1) CALL WRITER(IOPTU)                                      001374
      WRITE(6,950) QINIT                                                 001375
      WRITE(6,955) QTOTAL                                                001376
      QTOT=QINIT+QTOTAL                                                  001377
      WRITE(6,960) QTOT                                                  001378
      QTHER1=(QW*CPF+MO*CPW)*(TB-TI)                                     001379
      QTHER2=MO*HFGTB                                                    001380
      QTHEOR=QTHER1+QTHER2                                               001381
      IF(TB.LT.TI) QTHEOR=QTHER2                                         001382
      WRITE(6,965) QTHEOR                                                001383
      LIQDEW=LIQDEW*100./MO                                              001384
      WRITE(6,970) LIQDEW                                                001385
C                                                                        001386
C                                                                        001387
C*****FORMAT STATEMENTS                                                  001388
C                                                                        001389
  500 FORMAT("  ***** HIDRYER1 PROGRAM OUTPUT *****")                     001390
  505 FORMAT(1HO,"     TH        TB          BW        CSF       MRG"    001391
     *"      PMAX      RISTIM")                                          001392
  510 FORMAT(2F9.2,F11.5,I8,F9.2,F10.2,F9.3)                             001393
  515 FORMAT(1HO,"       DTO         IOPTP    IOPTU"                     001394
     *"        METH       MITER")                                       001395
  520 FORMAT(E13.5,2I8,2I11)                                             001396
  525 FORMAT(1HO,"    SEC      MREL       TS        T1        T2"       001397
     *"        T3     RATIO1  RATIO2  RATIO3   DELTAT       Q"         001398
     *"        OMIC    PGAUGE      SEC")                                001399
  530 FORMAT(1HO)                                                        001400
  535 FORMAT(10(I5,F8.3))                                                001401
  540 FORMAT(1HO," START OF TRANSITION REGIME")                          001402
  545 FORMAT(1HO," START OF LINEAR REGIME")                              001403
  550 FORMAT(1HO,1X,F6.2," BTU/FT2 REQUIRED TO HEAT THE SHEET")          001404
  555 FORMAT(1HO,1X,F6.2," BTU/FT2 REQUIRED FOR DEWATERING THE SHEET")   001405
  560 FORMAT(1HO,1X,F6.2," BTU/FT2 TOTAL THERMAL ENERGY INPUT")          001406
  565 FORMAT(1HO,1X,F6.2," BTU/FT2 THEORETICALLY REQUIRED FOR HEATUP"    001407
```

```
     *" AND EVAPORATION OF ALL LIQUID AT SATURATION TEMPERATURE")        001408
 570 FORMAT(1H0,1X,F6.2," PERCENT OF THE MOISTURE IS REMOVED IN"         001409
     *" LIQUID FORM")                                                    001410
                                                                         001411
                                                                         001412
*****END MAIN PROGRAM                                                   001413
                                                                         001414
9999 STOP                                                               001415
     END                                                                001416
*************************************************************************001417
                                                                         001418
                                                                         001419
     ******************************                                      001420
     *****  THE SUBROUTINES  *****                                      001421
     ******************************                                      001422
                                                                         001423
                                                                         001424
                                                                         001425
                                                                         001426
*****SUBROUTINE TO CONVERT FROM ENGLISH TO SI UNITS                      001427
                                                                         001428
     SUBROUTINE CNVRT1                                                  001429
                                                                         001430
     DATA A1,A2,A3,A4,A5/9,5,32,4.8224,6.8948/                          001431
                                                                         001432
     COMMON /LABEL1/ TB,PVTB,DFUDTB,VFTB,VGTB,HFGTB,VISGTB,VISFTB       001433
     COMMON /LABEL2/ TH,T1,T2,T3,TI,TMID                                001434
     COMMON /LABEL7/ PREF1,PMAX,RISTIM,P,IOPTP,DPDT                     001435
     COMMON /LABEL9/ DLDT,FACTOR,BW,CW,DFIBER,COEFF,PS3                 001436
                                                                         001437
     TH=A1*TH/A2+A3                                                     001438
     TB=A1*TB/A2+A3                                                     001439
     EW=BW/A4                                                           001440
     PMAX=PMAX/A5                                                       001441
                                                                         001442
     RETURN                                                             001443
     END                                                                001444
*************************************************************************001445
                                                                         001446
                                                                         001447
*****SUBROUTINE TO DETERMINE THE CONSTANTS FOR CALCULATION OF M AND N    001448
                                                                         001449
     SUBROUTINE CNSTMN(X)                                               001450
                                                                         001451
     DATA                                                               001452
    *A1,A2,A3,A4,A5,A6/2.9613453E+00,-2.8919415E-01,5.7420518E+01,      001453
    *                  -3.3796161E+01,4.411387E+00,1.2974508E+00/,      001454
    *B1,B2,B3,B4,B5,B6/2.005747E-01,2.2200153E-02,-8.3841418E+01,       001455
    *                  -3.5825139E+01,7.6054413E+01,-1.0786651E+01/,    001456
    *C1,C2,C3,C4,C5,C6/-1.992423E-02,-2.1085106E-03,-1.1519896E-01,     001457
    *                  -3.1081894E-01,3.5352481E-01,-4.1291326E-02/,    001458
    *D1,D2,D3,D4,D5,D6/1.405545E-02,9.497606E-04,-6.4943036E-02,        001459
    *                   3.5853945E-02,-2.7498142E-03,-1.305774E-03/,    001460
    *E1,E2/100.,540./                                                   001461
                                                                         001462
```

```
      COMMON /LABL15/ CM1,CM2,CM3,CM4,CM5,CM6                           001463
      COMMON /LABL16/ CN1,CN2,CN3,CN4,CN5,CN6                           001464
C                                                                       001465
      TERM=((X-E1)/E2)**2                                               001466
      IF(X.LT.0.) TERM=0.                                               001467
      CM1=A1+B1*TERM                                                    001468
      CM2=A2+B2*TERM                                                    001469
      CM3=A3+B3*TERM                                                    001470
      CM4=A4+B4*TERM                                                    001471
      CM5=A5+B5*TERM                                                    001472
      CM6=A6+B6*TERM                                                    001473
C                                                                       001474
      CN1=C1+D1*TERM                                                    001475
      CN2=C2+D2*TERM                                                    001476
      CN3=C3+D3*TERM                                                    001477
      CN4=C4+D4*TERM                                                    001478
      CN5=C5+D5*TERM                                                    001479
      CN6=C6+D6*TERM                                                    001480
C                                                                       001481
      RETURN                                                            001482
      END                                                               001483
C*************************************************************************001484
C                                                                       001485
C                                                                       001486
C*****SUBROUTINE TO CALCULATE PROPERTIES AT TB                          001487
C                                                                       001488
      SUBROUTINE PROPTB                                                 001489
C                                                                       001490
      COMMON /LABEL1/ TB,PVTB,DPVDTB,VFTB,VGTB,HFGTB,VISGTB,VISFTB      001491
C                                                                       001492
      PVTB=PV(TB)                                                       001493
      DPVDTB=DPVDT(TB)                                                  001494
      VFTB=VF(TB)                                                       001495
      VGTB=VG(TB)                                                       001496
      HFGTB=HFG(TB)                                                     001497
      VISGTB=VISG(TB)                                                   001498
      VISFTB=VISF(TB)                                                   001499
C                                                                       001500
      RETURN                                                            001501
      END                                                               001502
C*************************************************************************001503
C                                                                       001504
C                                                                       001505
C*****SUBROUTINE TO CALL PROPERTY SUBROUTINES                           001506
C                                                                       001507
      SUBROUTINE CALLER(I)                                              001508
C                                                                       001509
      COMMON /LABEL2/ TH,T1,T2,T3,TI,TMID                               001510
C                                                                       001511
      IF(I.EQ.4) GO TO 10                                               001512
C                                                                       001513
      CALL PROP3B                                                       001514
      IF(I.EQ.2) GO TO 20                                               001515
C                                                                       001516
   10 CALL PROP12                                                       001517
```

```
      IF(I.EQ.3) GO TO 20                                                   001518
                                                                            001519
      CALL PROP23(1)                                                        001520
      GO TO 30                                                              001521
                                                                            001522
   20 CALL PROP23(2)                                                        001523
                                                                            001524
   30 RETURN                                                                001525
      END                                                                   001526
C*********************************************************************      001527
                                                                            001528
                                                                            001529
C*****SUBROUTINE TO CALCULATE T1-T2 AVERAGE PROPERTIES                     001530
                                                                            001531
      SUBROUTINE PROP12                                                     001532
                                                                            001533
      COMMON /LABEL2/ TH,T1,T2,T3,TI,TMID                                   001534
      COMMON /LABEL3/ DPDT12,VF12,VG12,VISG12                               001535
                                                                            001536
      DPDT12=(DPVDT(T1)+DPVDT(T2))/2.                                       001537
      VF12=(VF(T1)+VF(T2))/2.                                               001538
      VG12=(VG(T1)+VG(T2))/2.                                               001539
      VISG12=(VISG(T1)+VISG(T2))/2.                                         001540
                                                                            001541
      RETURN                                                                001542
      END                                                                   001543
C*********************************************************************      001544
                                                                            001545
                                                                            001546
C*****SUBROUTINE TO CALCULATE T2-T3 AVERAGE PROPERTIES                     001547
                                                                            001548
      SUBROUTINE PROP23(I)                                                  001549
                                                                            001550
      COMMON /LABEL2/ TH,T1,T2,T3,TI,TMID                                   001551
      COMMON /LABEL4/ DPDT23,VF23,VISF23,VG23,VISG23                        001552
                                                                            001553
      GO TO (10,20) I                                                       001554
                                                                            001555
   10 VF23=(VF(T2)+VF(T3))/2.                                               001556
      VISF23=(VISF(T2)+VISF(T3))/2.                                         001557
      GO TO 30                                                              001558
                                                                            001559
   20 VG23=(VG(T2)+VG(T3))/2.                                               001560
      VISG23=(VISG(T2)+VISG(T3))/2.                                         001561
                                                                            001562
   30 DPDT23=(DPVDT(T2)+DPVDT(T3))/2.                                       001563
                                                                            001564
      RETURN                                                                001565
      END                                                                   001566
C*********************************************************************      001567
                                                                            001568
                                                                            001569
C*****SUBROUTINE TO CALCULATE T3-TB AVERAGE PROPERTIES                     001570
                                                                            001571
```

```
      SUBROUTINE PROP3B                                                 001572
C                                                                       001573
      COMMON /LABEL1/ TB,PVTB,DPVDTB,VFTB,VGTB,HFGTB,VISGTB,VISFTB      001574
      COMMON /LABEL2/ TH,T1,T2,T3,TI,TMID                               001575
      COMMON /LABEL5/ DPDT3B,VG3B,VISG3B                                001576
C                                                                       001577
      DPDT3B=(DPVDT(T3)+DPVDTB)/2.                                      001578
      VG3B=(VG(T3)+VGTB)/2.                                             001579
      VISG3B=(VISG(T3)+VISGTB)/2.                                       001580
C                                                                       001581
      RETURN                                                            001582
      END                                                               001583
C*********************************************************************  001584
C                                                                       001585
C                                                                       001586
C*****SUBROUTINE TO CALCULATE APPLIED PRESSURE AND ITS DERIVATIVE        001587
C                                                                       001588
      SUBROUTINE PRESSR(A)                                              001589
C                                                                       001590
      DATA PI,A2/3.1415927,4.712389/                                    001591
C                                                                       001592
      COMMON /LABEL7/ PREF1,PMAX,RISTIM,P,IOPTP,DPDT                    001593
C                                                                       001594
      GO TO (10,20) IOPTP                                               001595
C                                                                       001596
   10 DPDT=PMAX*3600./RISTIM                                            001597
      P=PREF1+A*DPDT                                                    001598
      IF(P.GT.PMAX) P=PMAX                                              001599
      IF(P.GE.PMAX) DPDT=0.                                             001600
      GO TO 30                                                          001601
C                                                                       001602
   20 A1=PI*3600./RISTIM                                                001603
      P=PREF1+PMAX*(1.+SIN(A1*A+A2))/2.                                 001604
      DPDT=A1*PMAX*COS(A1*A+A2)/2.                                      001605
      IF(1800.*A.GE.RISTIM) P=PREF1                                     001606
      IF(1800.*A.GE.RISTIM) DLDT=0.                                     001607
C                                                                       001608
   30 RETURN                                                            001609
      END                                                               001610
C*********************************************************************  001611
C                                                                       001612
C                                                                       001613
C*****SUBROUTINE TO CALCULATE THE THICKNESS OF A SATURATED MEDIUM        001614
C                                                                       001615
      SUBROUTINE DLDTFN(N,TIME,YL,YPRIME)                               001616
C                                                                       001617
      REAL YL(N),YPRIME(N),TIME                                         001618
C                                                                       001619
      COMMON /LABEL1/ TB,PVTB,DPVDTB,VFTB,VGTB,HFGTB,VISGTB,VISFTB      001620
      COMMON /LABEL7/ PREF1,PMAX,RISTIM,P,IOPTP,DPDT                    001621
      COMMON /LABEL8/ M1,M2,M3,M4,N1,N2,N3,N4                           001622
      COMMON /LABEL9/ DLDT,FACTOR,BW,DW,DFIBER,COEFF,PS3                001623
C                                                                       001624
      CALL PRESSR(TIME)                                                 001625
      PS3=(BW/(YL(1)*M3))**(1./N3)                                      001626
```

```
      R=SPRES(P)/FACTOR                                                 001627
      COEFF=3./(VISFTB*BW*R)                                            001628
      YPRIME(1)=(PS3-P)*COEFF                                           001629
      QLOT=YPRIME(1)                                                    001630
                                                                        001631
      RETURN                                                            001632
      END                                                               001633
C*****************************************************************     001634
                                                                        001635
                                                                        001636
C*****SUBROUTINE TO CALCULATE THE JACOBIAN FOR A SATURATED MEDIUM        001637
                                                                        001638
      SUBROUTINE DUMFUN(N,TIME,YL,PD)                                   001639
                                                                        001640
      REAL TIME,YL(N),PD(1,1)                                           001641
                                                                        001642
      COMMON /LABEL8/ M1,M2,M3,M4,N1,N2,N3,N4                           001643
      COMMON /LABEL9/ QLOT,FACTOR,BW,DW,DFIBER,COEFF,PS3                001644
                                                                        001645
      PD(1,1)=-COEFF*PS3/(N3*YL(1))                                     001646
                                                                        001647
      RETURN                                                            001648
      END                                                               001649
C*****************************************************************     001650
                                                                        001651
                                                                        001652
C*****SUBROUTINE TO WRITE OUTPUT                                        001653
                                                                        001654
      SUBROUTINE WRITER(I)                                              001655
                                                                        001656
      COMMON /LABEL2/ TH,T1,T2,T3,TI,TMID                               001657
      COMMON /LABL11/ SEC,MREL,TS,RATIO1,RATIO2,RATIO3,DELTAT,Q,QHTC,   001658
     * PGAUGE                                                          001659
      COMMON /LABL12/ TSSI,T1SI,T2SI,T3SI,DELTSI,QSI,QHTCSI,PGAGSI,     001660
     * TMIDSI                                                          001661
                                                                        001662
      IF(I.EQ.2) GO TO 10                                               001663
                                                                        001664
      WRITE(6,20) SEC,MREL,TS,T1,T2,T3,RATIO1,RATIO2,RATIO3,DELTAT,Q,   001665
     * QHTC,PGAUGE,SEC                                                 001666
      WRITE(2,20) SEC,MREL,TS,T1,T2,T3,RATIO1,RATIO2,RATIO3,DELTAT,Q,   001667
     * QHTC,PGAUGE,TMID                                                001668
      GO TO 30                                                          001669
                                                                        001670
   10 CALL CNVRT2                                                       001671
                                                                        001672
      WRITE(6,20) SEC,MREL,TSSI,T1SI,T2SI,T3SI,RATIO1,RATIO2,RATIO3,    001673
     * DELTSI,QSI,QHTCSI,PGAGSI,SEC                                    001674
      WRITE(2,20) SEC,MREL,TSSI,T1SI,T2SI,T3SI,RATIO1,RATIO2,RATIO3,    001675
     * DELTSI,QSI,QHTCSI,PGAGSI,TMIDSI                                 001676
                                                                        001677
   20 FORMAT(1X,F8.5,F8.4,4F9.3,3F8.4,F10.6,F11.1,F8.2,F8.3,F10.5)      001678
                                                                        001679
   30 RETURN                                                            001680
```

```
      END                                                                   001681
C*************************************************************************  001682
C                                                                           001683
C                                                                           001684
C*****SUBROUTINE TO CONVERT FROM ENGLISH TO SI UNITS                        001685
C                                                                           001686
      SUBROUTINE CNVRT2                                                     001687
C                                                                           001688
      DATA A1,A2,A3,A4,A5,A6,A7/5,32,9,0.3048,3.1546,5.6783,6.8948/         001689
C                                                                           001690
      COMMON /LABEL2/ TH,T1,T2,T3,TI,TMID                                   001691
      COMMON /LABL11/ SEC,HREL,TS,RATIO1,RATIO2,RATIO3,DELTAT,Q,QHTC,       001692
     * PGAUGE                                                              001693
      COMMON /LABL12/ TSSI,T1SI,T2SI,T3SI,DELTSI,QSI,QHTCSI,PGAGSI,         001694
     * TMIDSI                                                              001695
C                                                                           001696
      TSSI=A1*(TS-A2)/A3                                                    001697
      T1SI=A1*(T1-A2)/A3                                                    001698
      T2SI=A1*(T2-A2)/A3                                                    001699
      T3SI=A1*(T3-A2)/A3                                                    001700
      TMIDSI=A1*(TMID-A2)/A3                                                001701
      DELTSI=DELTAT*A4                                                      001702
      QSI=Q*A5                                                              001703
      QHTCSI=QHTC*A6                                                        001704
      PGAGSI=PGAUGE*A7                                                      001705
C                                                                           001706
      RETURN                                                                001707
      END                                                                   001708
C*************************************************************************  001709
C                                                                           001710
C                                                                           001711
C*****SUBROUTINE TO CORRECT ERROR CONDITION OR PRINT WARNING MESSAGE        001712
C                                                                           001713
      SUBROUTINE WARNIN(I,J,X)                                              001714
C                                                                           001715
      COMMON /LABEL6/ DXX,DIFFIX,DIFFFX,EMIN                                001716
      COMMON /LABEL9/ CLOT,FACTOR,BW,CW,DFIBER,COEFF,PS3                    001717
C                                                                           001718
      GO TO (10,20,30,40) I                                                 001719
C                                                                           001720
   10 WRITE(6,50) J,X,DFIBER                                                001721
      GO TO 70                                                              001722
C                                                                           001723
   20 WRITE(6,60) J,X,EMIN                                                  001724
      GO TO 70                                                              001725
C                                                                           001726
   30 DIFFIX=DXX                                                            001727
      GO TO 70                                                              001728
C                                                                           001729
   40 DIFFFX=DXX                                                            001730
C                                                                           001731
   50 FORMAT("***  ZONE ",I2," DENSITY ",E16.10," IS GREATER THAN THE"      001732
     *" MAXIMUM ALLOWABLE DENSITY ",E16.10," *** COMPUTATION"               001733
```

```
     *" TERMINATED")                                                    001734
                                                                        001735
   60 FORMAT("***  ZONE ",I2," POROSITY ",E16.10," IS LESS THAN THE"    001736
     *" MINIMUM ALLOWABLE POROSITY ",E16.10," *** COMPUTATION"          001737
     *" TERMINATED")                                                    001738
                                                                        001739
   70 RETURN                                                            001740
      END                                                               001741
C*************************************************************************001742
                                                                        001743
                                                                        001744
      ****************************                                      001745
      *****  THE FUNCTIONS  *****                                      001746
      ****************************                                      001747
                                                                        001748
                                                                        001749
C*****VAPOR PRESSURE FUNCTION                                           001750
                                                                        001751
      FUNCTION PV(T)                                                    001752
                                                                        001753
      DATA                                                              001754
     *A1,A2,A3,A4,A5/1.5284E+00,-6.42281E-02,9.7657E-04,-5.85595E-06,    001755
     * 1.91309E-08/                                                     001756
                                                                        001757
      PV=A1+T*(A2+T*(A3+T*(A4+T*A5)))                                   001758
                                                                        001759
      RETURN                                                            001760
      END                                                               001761
C*************************************************************************001762
                                                                        001763
                                                                        001764
C*****VAPOR PRESSURE DERIVATIVE FUNCTION                                001765
                                                                        001766
      FUNCTION DPVDT(T)                                                 001767
                                                                        001768
      DATA                                                              001769
     *A1,A2,A3,A4/-6.42281E-02,9.7657E-04,-5.85595E-06,1.91309E-08/     001770
                                                                        001771
      DPVDT=A1+T*(2.*A2+T*(3.*A3+4.*A4*T))                              001772
                                                                        001773
      RETURN                                                            001774
      END                                                               001775
C*************************************************************************001776
                                                                        001777
                                                                        001778
C*****LIQUID SPECIFIC VOLUME FUNCTION                                   001779
                                                                        001780
      FUNCTION VF(T)                                                    001781
                                                                        001782
      DATA                                                              001783
     *A1,A2,A3,A4,A5/1.60571E-02,-2.35188E-06,3.69301E-08,-6.94068E-11,  001784
     * 8.04005E-14/                                                     001785
                                                                        001786
      VF=A1+T*(A2+T*(A3+T*(A4+T*A5)))                                   001787
```

```
C                                                                       001788
      RETURN                                                            001789
      END                                                               001790
C*************************************************************************001791
C                                                                       001792
C                                                                       001793
C*****VAPOR SPECIFIC VOLUME FUNCTION                                    001794
C                                                                       001795
      FUNCTION VG(T)                                                    001796
C                                                                       001797
      DATA                                                              001798
     *A1,A2,A3,A4,A5/9.40601E+00,-4.37418E-02,9.59205E-05,-1.41015E-07,  001799
     * 9.35084E-11/                                                    001800
C                                                                       001801
      VG=EXP(A1+T*(A2+T*(A3+T*(A4+T*A5))))                              001802
C                                                                       001803
      RETURN                                                            001804
      END                                                               001805
C*************************************************************************001806
C                                                                       001807
C                                                                       001808
C*****LATENT HEAT FUACTION                                              001809
C                                                                       001810
      FUNCTION HFG(T)                                                   001811
C                                                                       001812
      DATA                                                              001813
     *A1,A2,A3,A4,A5/1.09351E+03,-5.6626E-01,8.20598E-05,-5.70484E-07,   001814
     * -6.91038E-10/                                                   001815
C                                                                       001816
      HFG=A1+T*(A2+T*(A3+T*(A4+T*A5)))                                  001817
C                                                                       001818
      RETURN                                                            001819
      END                                                               001820
C*************************************************************************001821
C                                                                       001822
C                                                                       001823
C*****LIQUID VISCOSITY FUNCTION                                         001824
C                                                                       001825
      FUNCTION VISF(T)                                                  001826
C                                                                       001827
      DATA                                                              001828
     *A1,A2,A3,A4/-1.3917E-04,1.85E-07,6.4841E-02,-7.0869E-01/          001829
C                                                                       001830
      VISF=A1+T*A2+A3/T+A4/T**2                                         001831
C                                                                       001832
      RETURN                                                            001833
      END                                                               001834
C*************************************************************************001835
C                                                                       001836
C                                                                       001837
C*****VAPOR VISCOSITY FUNCTION                                          001838
C                                                                       001839
      FUNCTION VISG(T)                                                  001840
C                                                                       001841
```

```
      DATA
     *A1,A2/5.499E-06,1.3908E-08/                                        001842
                                                                         001843
      VISG=A1*T**A2                                                      001844
                                                                         001845
      RETURN                                                             001846
      END                                                                001847
C*************************************************************************001848
C                                                                        001849
C                                                                        001850
C                                                                        001851
C*****M EVALUATION FUNCTION                                              001852
C                                                                        001853
      FUNCTION EVALM(X,T)                                                001854
C                                                                        001855
      DATA A1,A2,A3/1.5,1.,0.25/                                         001856
C                                                                        001857
      COMMON /LABEL2/ TH,T1,T2,T3,TI,TMID                                001858
      COMMON /LABL15/ CM1,CM2,CM3,CM4,CM5,CM6                            001859
C                                                                        001860
      A=X+A1                                                             001861
      B=X+A2                                                             001862
      CORRCT=(T/TI)**A3                                                  001863
      EVALM=(CM1+CM2*X+CM3/A+CM4/A**2+CM5/B+CM6/B**2)*CORRCT             001864
C                                                                        001865
      RETURN                                                             001866
      END                                                                001867
C*************************************************************************001868
C                                                                        001869
C                                                                        001870
C*****N EVALUATION FUNCTION                                              001871
C                                                                        001872
      FUNCTION EVALN(I,X,Y)                                              001873
C                                                                        001874
      REAL NDENOM,NMID,NSAT                                              001875
C                                                                        001876
      DATA A1,A2/1.5,1./                                                 001877
C                                                                        001878
      COMMON /LABEL4/ DPDT23,VF23,VISF23,VG23,VISG23                     001879
      COMMON /LABEL7/ PREF1,PMAX,RISTIM,P,IOPTP,DPDT                     001880
      COMMON /LABL16/ CN1,CN2,CN3,CN4,CN5,CN6                            001881
      COMMON /LABEL8/ M1,M2,M3,M4,N1,N2,N3,N4                            001882
      COMMON /LABL13/ DH1,DH2,MR,MRSTAR                                  001883
      COMMON /LABL14/ NEXP,PR3LOG,PREF3,PMID,PDENOM,DF                   001884
C                                                                        001885
      A=X+A1                                                             001886
      B=X+A2                                                             001887
      C=CN1+CN2*X+CN3/A+CN4/A**2+CN5/B+CN6/B**2                          001888
      EVALN=C                                                            001889
      IF(I.EQ.1) GO TO 10                                                001890
      IF(X.LE.MRSTAR) GO TO 10                                           001891
C                                                                        001892
      NSAT=ALOG(1./(M3*(X**VF23+DF)))/PR3LOG                             001893
      NMID=(NSAT+C)/2.                                                   001894
      NDENOM=NSAT-NMID                                                   001895
      PTERM=ABS(Y-PMID)/PDENOM                                           001896
```

```
C                                                                       001897
      SIGN=1.                                                           001898
      IF(Y.LT.PMID) SIGN=-1.                                            001899
      IF(Y.EQ.PMID) SIGN=0.                                             001900
      EVALN=NMID+SIGN*NDENOM*PTERM**(1./NEXP)                           001901
      IF(Y.LT.PREF1) EVALN=C                                            001902
      IF(Y.GT.PREF3) EVALN=NSAT                                         001903
C     WRITE(5,/) I,X,Y,C,NSAT,NMID,NDENOM,PTERM,PMID,PDENOM,EVALN       001904
C                                                                       001905
   10 RETURN                                                            001906
      END                                                               001907
C***********************************************************************001908
C                                                                       001909
C                                                                       001910
C*****SPECIFIC FILTRATION RESISTANCE FUNCTION                           001911
C                                                                       001912
      FUNCTION SPRES(P)                                                 001913
C                                                                       001914
      DATA A1,A2,A3,A4,A5,A6/7.027,2.013E-05,0.142,0.464,0.187,0.344/   001915
C                                                                       001916
      COMMON /LABL10/ CSF                                               001917
C                                                                       001918
      RREF=((A1-ALOG(CSF))/A2)**2
      X=P/A3                                                            001920
      SPRES=RREF*(A4+A5*X+A6*SQRT(X))                                   001921
C                                                                       001922
      RETURN                                                            001923
      END                                                               001924
C***********************************************************************001925
C                                                                       001926
C                                                                       001927
C*****HYDRAULIC PRESSURE FUNCTION                                       001928
C                                                                       001929
      FUNCTION HYDRAL(A,B)                                              001930
C                                                                       001931
      COMMON /LABEL1/ TB,PVTB,DPVDTB,VFTB,VGTB,HFGTB,VISGTB,VISFTB      001932
C                                                                       001933
      HYDRAL=(PV(A)+PV(B))/2.-PVTB                                      001934
C                                                                       001935
      RETURN                                                            001936
      END                                                               001937
C***********************************************************************001938
C                                                                       001939
C                                                                       001940
C*****LATENT HEAT INCREMENT FUNCTION                                    001941
C                                                                       001942
      FUNCTION DELHD(I)                                                 001943
C                                                                       001944
      COMMON /LABL13/ DH1,DH2,MR,MRSTAR                                 001945
C                                                                       001946
      GO TO (10,20,30) I                                                001947
C                                                                       001948
   10 DELHD=DH1*(1.-EXP(DH2*MRSTAR))/MRSTAR                             001949
      GO TO 40                                                          001950
```

```
                                                                      001951
 2C DELHC=DH1*(EXP(DH2*MRSTAR)-EXP(DH2*MR))/(MR-MRSTAR)               001952
    GC TC 4C                                                          001953
                                                                      001954
 3C DELHC=DH1*(1.-EXP(DH2*MR))/MR                                     001955
                                                                      001956
 4C RETURN                                                            001957
    END                                                               001958
*********************************************************************** 001959
```

The programs for the various stages of model development and the data files used to generate the graphs for this thesis are stored on magnetic tape in the Institute computer center.

The model equations, supplementary relationships, and data file information and names are in Institute research notebooks 3578 and 3711.