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THE DRYING OF POROUS FIBROUS MATERIALS

USING MICROWAVE HEATING

A THESIS

Presented to

The Faculty of the Graduate Division

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THE DRYING OF POROUS FIBROUS MATERIALS

USING MICROWAVE HEATING

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Chairman

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SUMMARY

The drying of bulky, porous, fibrous materials using microwave heating was investigated analytically and experimentally. Analytical equations were obtained in general form which described the heat and mass transfer processes throughout the sample during drying. The equations were simplified in light of the experimental findings and the solutions to the simplified equations used to predict and explain the drying characteristics during the constant rate period of drying.

The experimental study consisted of measuring the variation of the internal temperature, pressure, and moisture content during the drying of packages of cotton yarn using microwave heating at both 915 megacycles per second and 2450 megacycles per second. In addition to the internal property variations, the total moisture content of the sample was monitored throughout the drying process. The results of these measurements showed that the temperature of the entire sample rose rather uniformly to the local water boiling temperature and then remained at this temperature throughout the majority of the drying process. The moisture content remained uniform throughout the sample during drying, i.e., the center dried as rapidly as the surface. The drying process consisted primarily of vaporization of the moisture throughout the product and the flow of this vapor from the product to the surrounding atmosphere. The rapid internal vapor generation caused an internal pressure gradient to be established and the pressure gradient provided the

potential for moisture flow. The drying rate and the vaporization rate were proportional to the rate of energy addition to the sample with the constant of proportionality being the latent heat of vaporization of water.

Samples of cotton yarn, identical to samples dried with microwave heating, were dried using conventional convective hot air heating in order to provide a basis for comparison of drying processes with two types of heating. It was found that when microwave heating was used the constant rate period comprised the majority of the drying process. The point of critical moisture content occurred at a much lower moisture content with microwave heating than with conventional heating. Using microwave heating, a "liquid movement period" of drying was sometimes observed towards the end of the initial adjustment period. During the liquid movement period, liquid water is "blown" from the sample by the buildup in internal pressure accompanying the rapid moisture vaporization as the internal temperatures approach the boiling temperature. No corresponding drying period exists with conventional heating. The most significant variation between drying using microwave heating and using conventional heating is the possibility of a much more rapid drying rate using microwave heating. During this research, three-pound samples of cotton yarn were dried from over 200 percent initial moisture content in two hours using microwave heating. The results of this research indicate that this drying rate could be increased many times, without the danger of product damage, by increasing the energy output of the microwaves oven. Identical samples dried using convective hot air at 300°F took over 24 hours to dry with considerable product damage due to overheating of the prod-

uct's surface.

In order to study the internal moisture movement, a measurement technique was developed which allowed the measurement of internal moisture. The technique consisted of shining a collimated gamma ray beam through the sample and measuring the attenuation of the beam due to the water in the beam's path. This technique of moisture measurement is particularly useful during microwave heating as the gamma ray beam is unaffected by the microwave field.

NOMENCLATURE

a   experimental microwave attenuation coefficient, 1/in

b   pore filling factor

c_f vapor concentration factor, in^2/lb_f

c_m specific mass capacity, 1/MPU

$\overline{c}_m$ average specific mass capacity, 1/MPU

c_{pk} specific heat of kth component, Btu/lb °F

D   microwave penetration depth, in

D_k concentration diffusion coefficient of the kth component, in^4/sec

E   electromagnetic field voltage gradient, volts/in

E_v volumetric concentration of energy, Btu/in^3

f   frequency of the microwave field, cycles/sec

h_k enthalpy per unit mass of kth component, Btu/lb

h_t external heat transfer coefficient, Btu/hr ft^2 °F

h_m external mass transfer coefficient, lb_m/hr ft^2 °MPU

H_r volumetric concentration of enthalpy, Btu/in^3

I   intensity of a radiation beam, photons/sec

I_{dr} intensity of a radiation beam after shining through a dry product, photons/sec

I_r intensity of a radiation beam after shining through a reference attenuator, photons/sec

$\overline{J}_{mk}$ mass flux of kth component, lb_m/sec

$\bar{j}_q$ heat flux by conduction, Btu/sec

k_t thermal conductivity of the material, Btu/hr ft °F

K_f permeability of the material, lb_m in

N number of counts per counting period recorded when measuring the radiation beam intensity

N_{dr} number of counts per counting period recorded when measuring the radiation beam intensity through dry product

N_r number of counts per counting period recorded when measuring the radiation beam intensity through a reference material

p pressure, lb_f/in^3

p_∞ pressure of surrounding atmosphere, lb_f/in^3

P power per unit volume, watts/in^3

q_s internal energy generation within sample, Btu/sec in^3

R the value of the dimension, x, at the surface, in

t temperature, °F

t_∞ temperature of surrounding atmosphere, °F

u_k mass concentration of the kth component lb_m/lb_m

W_{kr} strength of source of the kth component from the rth component per unit volume, lb_m/in^3

x generalized distance outward from center of the sample, in

Z atomic number of the nuclear radiation absorber

α plane wave attenuation factor, 1/in

β pair-production attenuation coefficient, 1/in

γ photoelectric effect attenuation coefficient, 1/in

δ loss angle

δ Soret coefficient of thermal diffusion

ϵ' dielectric constant or real part of the complex dielectric constant

ϵ'' loss factor

$\epsilon*$ complex dielectric constant

ϵ_O dielectric constant of free space

θ_k mass transfer potential of the kth component, mass potential unit (MPU)

λ_k coefficient of mass transfer potential of kth component

λ'_k coefficient of thermal mass transfer potential of kth component

λ''_k coefficient of molar or filtration mass transfer potential of kth component

μ_k viscosity of the kth component, lb/sec in

μ_O total radiation attenuation coefficient, 1/in

Π porosity of the dry body

σ Compton effect attenuation coefficient, 1/in

ρ_k density of the kth component, lb_m/in^3

τ time, sec

CHAPTER I

INTRODUCTION AND BACKGROUND

General

Drying generally refers to the removal of a liquid, usually water, from a solid by evaporation of the liquid.[1] For many years the drying of thick bulky fibrous products such as textiles, paper, and grains has been a problem of industrial concern. The moisture removing process is generally expensive and time-consuming. Therefore, improvements in drying methods are continuously sought.

Problem

It is especially difficult to remove moisture from thick, bulky textile-like materials such as spools or cylinders of fabric or yarn. The conventional method used for drying is to circulate hot dry air around the product to be dried. As this type of drying proceeds, a dry outer layer will form around the product, surrounding the still wet inner core. In order for drying to proceed rapidly, it is necessary to raise the vapor pressure of the product's internal moisture. In order to increase the vapor pressure, energy must be added to the internal moisture to raise its temperature. In conventional drying this energy is conducted into the inner portions of the product from the heated surface by the process of heat conduction. Textile-like materials are generally good insulators, however, and this heat conduction process can be very slow. The rate of energy conduction could be increased by raising the surface tem-

perature, but the maximum allowable surface temperature is limited as product damage is observed at high temperatures. For textile products, the limitation on the surface temperature is often below 200°F. In general, the factor limiting the drying rate for bulky fibrous materials is the difficulty of supplying the energy to the moisture deep within the product.

Microwave Heating

One method that may be used to increase the energy addition rate to the moisture within the product involves the application of microwave heating. Microwave energy is a form of electromagnetic energy. Radar systems, television stations, and the like transmit electromagnetic energy at microwave frequencies. Microwave generators can be manufactured which will produce this electromagnetic energy at a number of specific microwave frequencies suitable for commercial heating applications.

Electromagnetic energy at microwave frequencies is much more penetrating than radiant heat of infrared frequencies. During the process of microwave heating the electromagnetic energy penetrates deeply throughout the material. Dielectric materials such as water absorb electromagnetic energy and convert it to its thermal equivalent. This energy appears as internal thermal heat generation within the sample. By using microwave heating it is possible to add large amounts of energy to internal portions of the sample very rapidly. Textile-like products are much poorer absorbers than water and therefore the wetter portions of the product tend to absorb the most energy. This is usually the desired situation during a drying process. By using microwave heating it is possible to dry many materials much faster than it is possible to do using conventional heating.

An example of this is the drying of packages (cakes) of viscose rayon yarn. Electromagnetic energy of the low microwave (radio) frequencies is presently used to dry viscose rayon.[2] In this application the commercial electromagnetic dryer dries three-pound cakes of rayon yarn in twenty minutes, with an improvement of product quality over the conventional drying process which takes up to 120 hours.

Microwave heating is not presently widely used for commercial drying applications. However, the design of microwave generators has for many years been of great interest to the radar and communications industries. In recent years it has become obvious that larger, more powerful microwave generators are required for these applications. Because of the defense and space requirements, the Federal Government supports much research for the development of larger, better generating devices. Great advancements have recently been made in the design of high power, high efficiency, microwave generators for radar and communications equipment. Several electronic equipment manufacturing companies have observed the potential commercial applications and are applying this previously developed experience and technology to the construction of microwave generating equipment for commercial applications. The transition from generating equipment designed for radar applications to equipment for commercial usage is not a simple one. However, each year microwave equipment manufacturers are offering for sale new, more powerful, and more efficient generating equipment suitable for commercial applications.

One of the predominant factors limiting the commercial application of microwave heating to drying problems is the lack of design data for the design of microwave heating chambers. Although technology developed for

radar and communications applications may be applicable to the design of the microwave generating equipment, such technology is only indirectly applicable to the design of the heating chamber for applying this microwave energy to a specific product. Some specific information required for the design of a microwave dryer is information concerning the heat and mass transfer situation inside the material being dried. The heating processes with microwave heating vary considerably from the processes with conventional heating. Consequently the drying processes vary considerably. Very little published data exists on the transport processes occurring inside textile-like products when they are heated using microwave energy. The research described in this dissertation is primarily an investigation of these internal transport processes.

Review of the Literature

A review of the literature may be divided into two separate sections. One consists of a review of the area concerning the heat and mass transfer processes during drying. The second consists of a review of the application of microwave energy for the purpose of heating.

The pioneer statements regarding drying were published by Lewis[3] in the early 1920's. About the same time, Carrier[4] presented a theory of evaporation from a thermodynamic standpoint and also pointed out how the chemical and physical behavior of the material being dried affects the drying rate. Several papers by Sherwood[5,6,7] and his co-workers further extended the understanding of the mechanism of the drying of solids by explanations of the propagation of moisture through solids during drying. The work of these early authors was extended and applied to the particular

application of the drying of thick bulky fibrous materials by McCready and
McCabe.[8] The drying of wound cylinders or spools of textile fabric or yarns
was investigated by Bell and Grosberg.[9] Further work by Bell and his co-
workers, (Nissan, Kaye and Bell,[10] Bell and Nissan[11]), described in great
detail the processes occurring inside bulky textile materials during dry-
ing. These investigations included a thorough investigation of the tempera-
ture and moisture profiles inside the sample during drying using conventional
hot air heating. Much of the work done by these and other investigators is
summarized and compared by Perry.[1] Perry presents a very thorough biblio-
graphy of the works of the numerous people interested in the various pro-
cesses of drying.

The diffusion of moisture throughout the drying body is an important
part of the drying process. The moisture diffusion process through a por-
ous media is discussed in detail by Barrer.[12] Carman[13] discusses the dif-
fusion of gases through a porous media due to a pressure gradient and this
work is quite helpful in analyzing the diffusion process of water vapor
during drying employing microwave heating.

A. V. Luikov and his co-workers in the U.S.S.R. presented a set of
differential equations which approximated the internal heat and mass trans-
fer situation inside a porous textile body during drying. A discussion of
the development of these equations is presented by Luikov in one chapter
of a book edited by Irvine and Harnett.[14] Solutions to simplifications of
these equations for several geometries and boundary conditions were compiled
in a book by Luikov and Mikhaylov.[15]

All of the works referenced above concern themselves with drying
using conventional hot air heating. None of the investigators was speci-

fically concerned with drying situations employing microwave heating but their work is quite useful in analyzing all drying situations.

The investigations mentioned above were concerned with the analysis of the heat and mass transfer situation inside the drying material. Many other investigators have studied the external heat and mass transfer problem by investigating the boundary layer buildup, etc., about bodies drying in an air stream. The work of these investigators will not be cited here, as an investigation of the external drying situation is not directly applicable to drying using microwave heating.

Historically, the area of microwave heating developed separately from the area of drying. Much of the earlier work in microwave heating considered such heating an adverse effect. As a consequence, microwave or dielectric heating is often referred to as a dielectric loss. Most investigations were concerned with the heating of the dielectric materials used in the construction of capacitors and with the attenuation of microwaves during their transmission through various materials.

The basic interpretation of the dielectric phenomena, which includes the phenomena of microwave heating, is usually attributed to Debye.[16] This basic work has been extended considerably by many investigators. Some have been concerned primarily with the dielectric behavior of the substances themselves, and, through the actions of the molecules in the electric fields, they have derived information on the chemical structure. A comprehensive work by Smyth[17] summarizes the theory and experimental data of this area. Another book discussing the molecular behavior of materials in a microwave field is presented by Frohlich.[18] Frohlich discusses the dielectric loss theory with respect to the variation of temperature and atomic structure of

the material and the frequency of the applied field. Further treatment of
the theory of dielectric heating is presented by von Hipple[19] and his asso-
ciates. In addition to discussing the heating phenomena, von Hipple pre-
sents an extensive tabulation of the dielectric properties of many materials.
An excellent reference discussing the transmission of microwave energy is
a book by Moreno.[20] All of the previously referenced authors have been
concerned with microwave phenomena in general. Other investigators have
been primarily interested in the heating aspects of microwave energy and
have discussed the application of such heating to particular materials.
Cable[21] discusses a number of possible applications of low frequency micro-
wave heating. Another thorough discussion of the theory of low frequency
microwave heating is presented by the German author Goldstein.[22] Micro-
wave heating at the higher microwave frequencies is discussed by Feiker
and Gittinger[23] and by Schmidt et al.[24] These authors were primarily in-
terested in the heating of materials for purposes other than drying, however.

Very little work has been published concerning the application of
microwave heating to the problem of drying. Copson[25] has authored a very
fine book concerning the application of microwave heating to the food in-
dustry. He discusses in some detail the principle of using microwave heat-
ing to sublime frozen moisture during the freeze drying of food products.
His book also provides an excellent bibliography in the field of microwave
heating. Harper and Chichester[26] also have published their investigation
concerning the application of microwave heating to freeze-drying processes.
Birks[27] discusses some specific applications of microwave heating for the
drying of textiles but he deals mainly with the dielectric properties of
the material rather than with the heat and mass transfer phenomena.

This writer knows of no published comprehensive discussion concerning the heat and mass transfer situation during the drying of bulky fibrous materials using microwave heating.

Statement of Intent

It is the intent of the research investigation described in the following chapters to study the heat and mass transfer situation inside large packages of cotton yarn as these packages are dried using microwave heating. The yarn packages are obtained by winding the yarn on a small paper core. The package size ranges up to five and one-half inches in length and eight inches in diameter and with a dry weight of three and one-half pounds. The packages are of the geometry used throughout the yarn industry during package dyeing or bleaching. Although this research has been conducted using the particular textile material described above, it is believed that the results are directly applicable to the microwave drying of many bulky, fibrous textile and paper products.

The research investigation is divided into two parts, a theoretical investigation and an experimental investigation. During the theoretical investigation, equations are developed which describe the internal heat and mass transfer situation. These equations are then simplified in light of the experimental findings and the solutions to the simplified equations compared with the experimental results. The primary value of the theoretical results is that they predict and substantiate the general shape of the temperature, pressure, and moisture profiles measured experimentally. Also, the significance of the measured parameters may be analyzed by examining how they affect the theoretical equations.

The experimental investigation consists of the measurement of the temperature, pressure, and moisture profiles inside the drying yarn package. The total weight loss of the sample is also recorded during the drying process. By moisture sealing different boundaries of the sample, it is possible to examine different one-dimensional drying situations. The drying characteristics are examined for samples of different sizes. Also, drying using microwave heating is compared with drying using conventional heating.

In order to measure the moisture profile inside a drying material, it is necessary to develop a technique for measuring the local moisture content inside the sample. The requirements of such a technique are particularly stringent for this application. Because of the microwave field, no conductors, such as copper wire, can be placed in the sample. A technique for measuring the local moisture content using a beam of gamma rays was developed. It is felt that this is a very useful technique for studying the internal moisture content for many drying situations. A discussion of the principles of using gamma rays to measure the internal moisture profile is presented in Chapter VI.

CHAPTER II

DRYING PRINCIPLES

Definition of Terms

Drying refers to the removal of liquid from a solid by thermal means. This definition distinguishes drying from mechanical methods of removing liquids from solids. Drying generally involves the removal of a liquid by evaporating the liquid and diffusing this vapor into the atmosphere surrounding the drying body. The evaporation process may take place at the surface of the body or within the body. In the general sense, the term drying may apply to the removal of all types of liquids from a solid. However, throughout this discussion the term drying will be restricted to mean only the removal of water from a solid into an air atmosphere.

The following definitions which are presented in Perry[1] are useful when discussing drying.

> Bound moisture is that liquid held by the solid which exerts a vapor pressure less than that of the pure liquid at the same temperature. Liquid may become bound by retention in small capillaries, solution in cell fiber walls, homogeneous solution throughout the solid, and by chemical or physical absorption on solid surfaces. Bound moisture can be removed from a solid only under specific conditions of humidity in the external surroundings.

> Unbound moisture is moisture which exerts a vapor pressure equal to that of a pure liquid at the same temperature. Unbound moisture is that moisture in excess of the equilibrium moisture content.

> Equilibrium moisture content is the moisture content at which the drying body is in equilibrium with the surrounding air under a specific air temperature and humidity. Once the equilibrium moisture content is established, moisture will no longer flow from the body into the air.

Free moisture content is that liquid which is removable at a given air temperature and humidity. It may include both bound and unbound moisture.

Hygroscopic material is one that may contain bound moisture.

Non-hygroscopic material is one that can contain no bound moisture. All water in a non-hygroscopic material is unbound water.

Initial moisture distribution refers to the moisture content throughout the material at the start of drying.

Dry weight basis indicates that the moisture content of the wet solid is expressed as pounds of water per pound of dry solid.

Constant rate period is that drying period during which the rate of water removal per unit drying surface is constant.

Falling rate period is that drying period during which the instantaneous drying rate continuously decreases.

The drying of bulky textile materials using conventional hot air drying has been investigated in some detail by McCready and McCabe,[8] Nissan, Kay, and Bell,[10] Bell and Nissan,[11] and others. The processes of moisture and energy migration with this type of heating are quite well understood. A review of the characteristics of drying using conventional heating is discussed in the following paragraphs.

In order to analyze the drying process, it is convenient to divide the process into several drying regions. A typical curve describing the change in the moisture content of a drying body with respect to time, when the body is heated and dried by circulating hot air over the body surface, is shown in Figure 1. The variation of the drying mechanisms during the different periods of drying can better be explained by plotting the drying rate as a function of the moisture content of the material. Such a curve is shown in Figure 2. The different periods of drying may be analyzed by observing the shape of this curve. The period A-B represents an initial
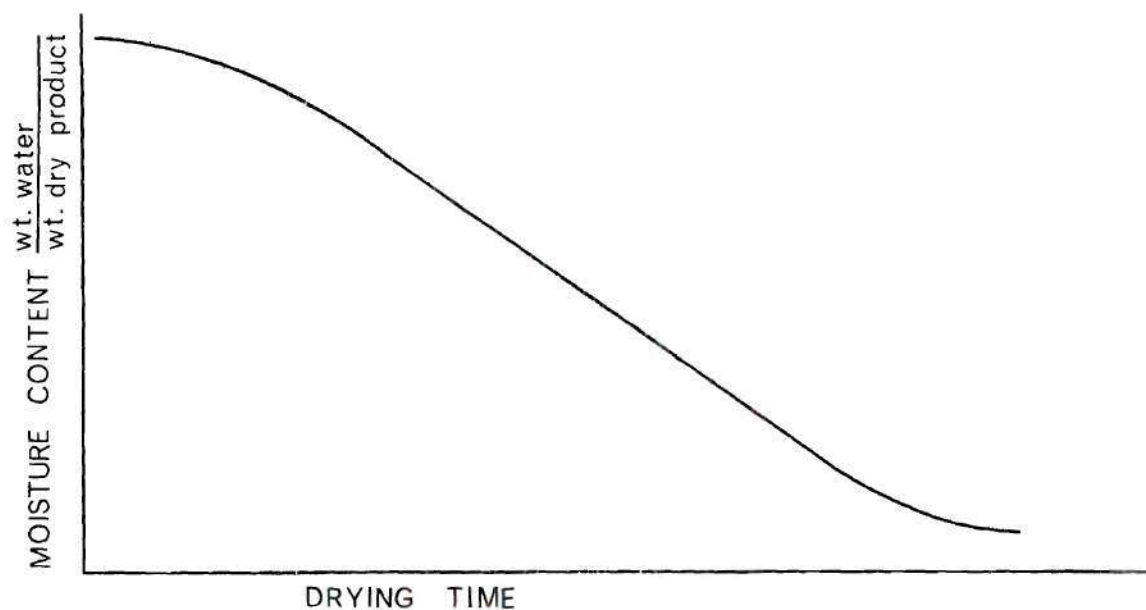
Figure 1. Typical Drying Curve for Drying Using Conventional Heating.
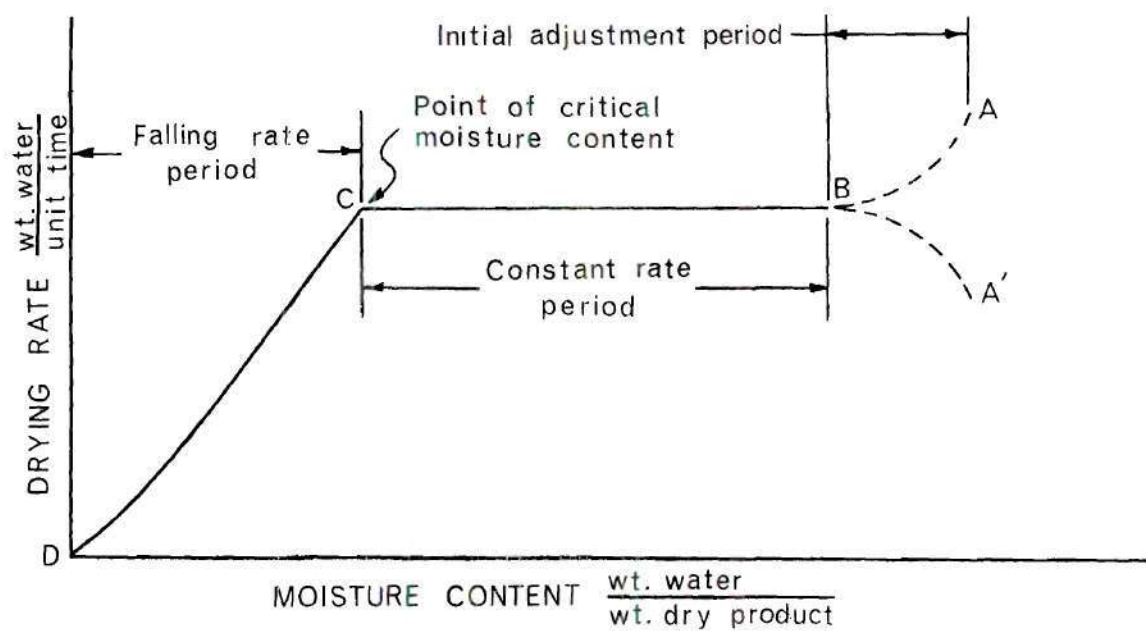
Figure 2. Typical Drying Rate Curve for Drying Using Conventional Heating.

adjustment period. During this period the sample is being heated to a pseudo-equilibrium temperature with the surrounding atmosphere. If the sample surface is very wet, rapid drying may be experienced during this period.

The period B-C represents the constant rate drying period. During this period the drying rate is relatively constant regardless of the moisture content of the body. This period of drying is typified by evaporation from a free water surface at the surface of the solid. The rate of drying is essentially equivalent to the rate of evaporation for the same external conditions from the surface of a container of water with no solid present. For such a case, the rate of drying is determined by the rate of diffusion of energy and water vapor through the air film surrounding the surface of the solid. The moisture leaving the surface is replenished by moisture migrating from within the sample to the surface in liquid form. All of the vaporization takes place at the surface and consequently the energy providing the latent heat of vaporization must be transferred only through the air boundary layer surrounding the product.

During this constant rate period, the temperature of the surface of the solid tends to remain constant. When the heat transfer mechanism from the surface into the surrounding atmosphere is primarily by convection (negligible radiation and conduction), the surface temperature will be near the wet bulb temperature.[1] If the effects of radiation and conduction to the surface of the material are sizable, the surface temperature will lie between the wet bulb temperature and the surrounding air temperature.

As drying proceeds it becomes impossible for liquid water to migrate to the surface as fast as this water may be evaporated at the surface. As

such migration becomes slower and slower the drying rate is reduced. This period is defined on the drying rate curve by that portion of the curve, C-D, and is called the falling rate period. During this period the drying rate is continuously decreasing.

The moisture content that separates the falling rate period from the constant rate period (point C) is designated as the critical moisture content. If the critical moisture content is less than the required final moisture content, the constant rate period will constitute the whole drying process. On the other hand, if the initial moisture content is less than the critical moisture content, as is the case for slow drying materials such as wood, the whole drying process will be in the falling rate period. The textile materials analyzed experimentally during this research investigation showed drying characteristics of both periods.

During the falling rate period, the drying rate is continuously decreasing. During the first phase of the falling rate period, the drying rate is decreased because only portions of the surface are saturated, decreasing the effective drying area. As drying proceeds, the moisture front recedes into the material leaving a dry outer layer. The temperature of the dry layer will be greater than the wet-bulb temperature of the vaporization front and, consequently, no free water can exist in this zone. In hygroscopic materials, some bound water may be present however. Typical temperature and moisture profiles for this situation are diagrammed in Figure 3. This figure represents a symmetrical body of infinite height with moisture flow perpendicular to the centerline of the body.
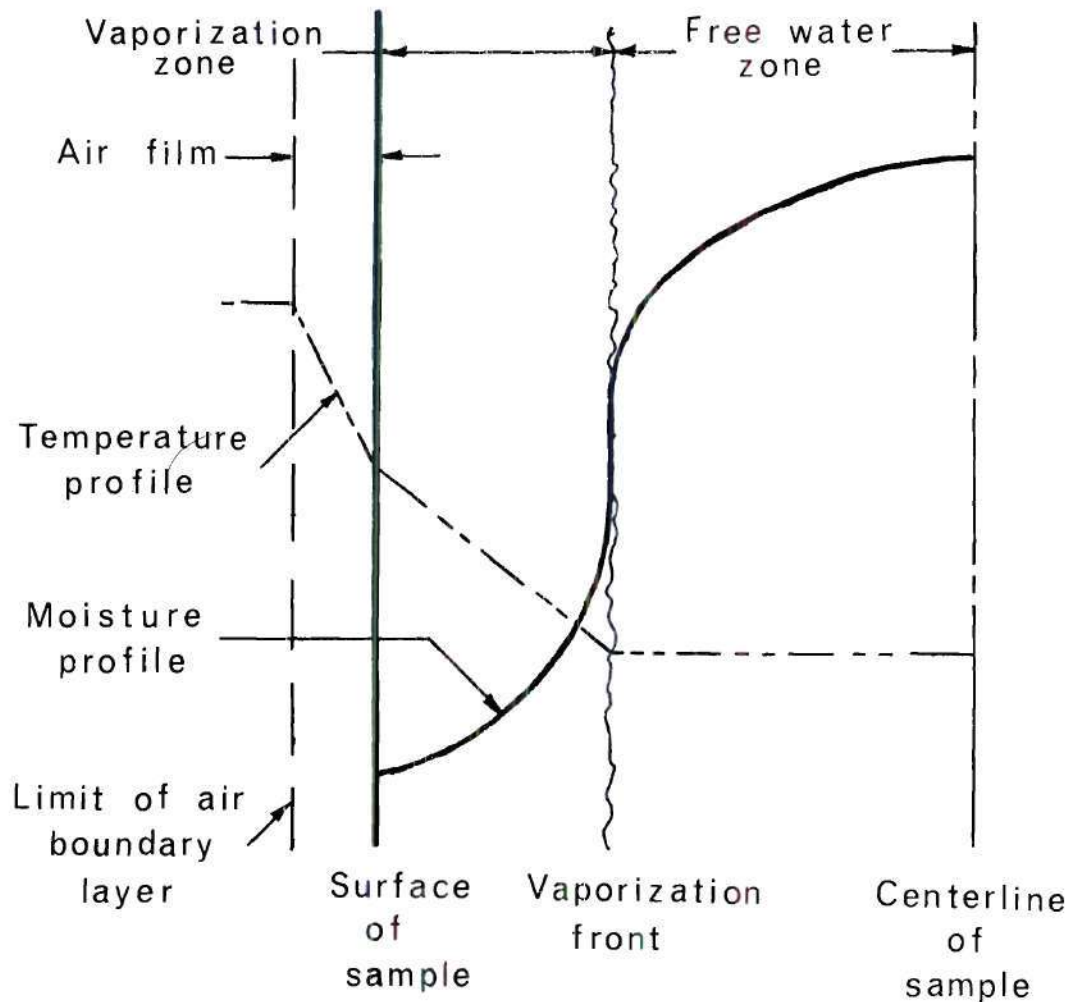
Figure 3. Temperature and Moisture Profiles During the Falling
Rate Period for Drying with Conventional Heating

In order to vaporize the moisture within the product, it is neces-
sary to add the heat of vaporization to the moisture below the product's
surface. In conventional hot air drying of thick materials, a temperature
gradient is established between the surface of the material and the va-
porization front, and energy is transferred by the process of heat con-
duction. The moisture vaporized within the body must diffuse out through
these dry outer layers. A balance is established with the outward

vapor flow proportional to the rate of inward heat conduction, the proportionality constant being the latent heat of vaporization. If the moisture diffusion process can not keep pace with the heat conduction, the temperature of the moisture within the material will increase. Accompanying the temperature increase will be an increase in the partial pressure of the vapor within the body, increasing the outward diffusion and thereby re-establishing a balance. It is even possible for the moisture to vaporize so rapidly that an internal pressurization occurs; the pressure gradient further increasing the moisture diffusion. Should the heat conduction process not keep pace with the vapor diffusion, the flow of vapor will be restricted to less than that potentially attainable, thereby limiting the drying rate.

In the case of textile-like products such as packages of yarn wound in cylindrical shape, the permeability of the yarn package is quite high. There is little restriction to the flow of vapor. On the other hand, the thermal conductivity of the material is quite low. The heat conduction process is therefore very slow. The heat conduction process may be increased by increasing the temperature of the surface of the material. However, most textile materials have a maximum surface temperature above which damage to the product occurs. For some textile yarns the maximum allowable temperature is quite low. Therefore, using conventional heating, the maximum drying rate may be very slow.

When microwave heating is used, the heat transfer problem is quite different and the heat and mass transfer theory described above must be modified. When analyzing the drying situation using microwave heating, a familiarity with the principles of drying using conventional heating is use-

ful for comparing the similarities and differences in the two situations.

During drying using microwave heating, the primary mechanism providing the heat of vaporization is the thermal heat generation due to microwave absorption. The heat conduction process is a minor energy transfer mechanism. In many instances the temperature profile is reversed from that typical of conventional drying. The surface is cooler than the internal portions of the product indicating that the heat conduction acts in the opposite direction from that typical of conduction processes using conventional heating.

The use of microwaves allows rapid addition of thermal energy inside the drying body without danger of overheating the surface of the material. Thus, using microwave heating, it is possible to heat the moisture within the material to temperatures approaching 212°F. This means that the internal vaporization will be quite rapid. Often the vapor is generated faster than it can diffuse out of the body due to partial pressure differences alone. Therefore, there may be a buildup in the total pressure inside the sample. When the total pressure gradient becomes large enough, the vapor movement may be primarily due to this total pressure gradient. In extreme cases it is possible to rupture the product by establishing a very large internal pressure.

Curves describing the drying rate versus the moisture content, which were useful for describing conventional drying processes, are also quite useful when describing microwave drying. During microwave drying, the constant rate period generally extends to a much lower moisture content than in conventional drying. A comparison of the drying rate curves for the two

heating situations is discussed in Chapter VIII. The mechanisms and characteristics of microwave drying are discussed in detail in Chapters IV, VII, and VIII.

CHAPTER III

MICROWAVE HEATING PRINCIPLES

Principles of Microwave Absorption

Microwave energy is a form of electromagnetic energy. Electro-
magnetic energy is classified by its frequency, which is the rapidity
with which the wave form occurs. The electromagnetic spectrum can be
considered as an array of energy sources at frequencies extending from
sound waves to cosmic rays. A breakdown of the spectrum is shown in
Figure 4. Microwaves consist of that portion of the spectrum at higher
frequencies than sound waves but lower than infrared rays. Generators
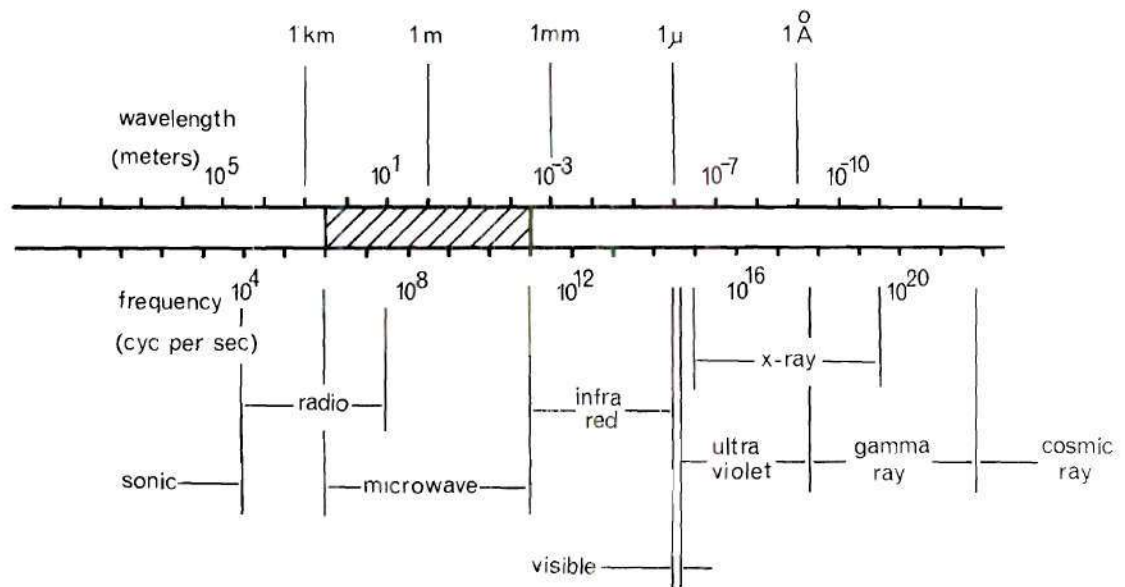
Figure 4. Electromagnetic Spectrum

are available which produce radiation within this frequency band. Energy
from these generators possesses electromagnetic properties; microwave heating
is the process of converting this electromagnetic energy to its thermal
equivalent. The energy is transported by the waves from the generator to
the material being heated. Some dielectric materials absorb a portion of
the electromagnetic energy which appears as thermal heat generation within
the product. Most materials that are not good electrical conductors can be
considered as dielectric materials and will under proper circumstances ab-
sorb energy from the electromagnetic field. Good conductors are good re-
flectors of microwaves and therefore will not absorb appreciable energy.

Dielectric or microwave heating should not be confused with induction
heating[21] which is used to heat electrical conductors such as metals. The
principle of induction heating is that the applied high-frequency magnetic
field causes the free electrons of the metal to flow in eddy currents with
heat being generated by ohmic and hysteresis losses. In contrast to metals,
dielectric materials have few free electrons. The frequencies used for in-
duction heating are in general much lower than those used for dielectric
heating. For example, metals are used to build guides, baffles, and oven
cavities to contain or control microwave energy. During dielectric heating
the absorption by the metal walls is negligible and no heating of the metal
is observed.

A true description of the absorption of electromagnetic energy by
dielectric materials is quite complex. Detailed descriptions of various
phases of the process are discussed by Birks,[27] Smyth,[17] Frohlich,[18] and
A. von Hipple.[19,31] In general, at microwave frequencies, the absorption
of electromagnetic energy is the result of contributions from four mechanisms:

(1) Electronic Polarization

(2) Atomic Polarization

(3) Orientation of Permanent Dipoles

(4) Ionic or Electronic Conduction

The first three of these involve strain or movement of molecules or atoms. Through this strain, energy is absorbed from the applied electromagnetic field. As long as the frequency of the applied energy is below the resonant frequency of the molecule (the general circumstance at microwave heating frequencies) this absorbed energy appears as internal heat generation within the material.

Electronic polarization is the slight displacement of the electrons in the individual atoms and molecules due to the applied electric field. When an electric field is applied to a dielectric the negatively charged electrons are displaced slightly relative to the heavier positively charged atomic nuclei. Hence, each molecule acquires an induced dipole moment. When atoms combine to form molecules, the charge distribution in the atoms is usually asymmetric, with the valence electrons localized in the region of the chemical bonds. The applied electric field thus acts on the atoms in the molecules similar to the action on the electrons of the individual atoms. A slight distortion in the normal charge distribution occurs, causing a relative displacement of the atoms of the molecule. This effect is termed "atomic polarization." Electronic and atomic polarization occur in all dielectric materials.

In many materials the molecules possess a permanent polarization due to distribution of the atoms of the molecule. Typical of this type of material is liquid water. For water, the two hydrogen atoms are attached

to the oxygen atom asymmetrically. Because of the asymmetric arrangement of
the hydrogen atoms, the whole molecule has a polarity. When an electric
field is applied the molecule will try to align itself with this electric
field. This molecular alignment is opposed by the statistical motions of
the molecules due to their temperature. The average amount of distortion
will be a function of the viscosity, and as a result the temperature of the
material. This molecular alignment is termed dipole orientation.

The electronic, atomic, and dipole polarizations all result from
displacements of charges bound to the atoms or molecules. In addition,
there is some migration of free electrons. Although the resistivity of
dielectric materials is very high, it is not infinite and there will be
some free electron movement due to the applied electric field. This elec-
tron movement causes resistance heating.

These mechanisms describe the electronic, atomic, and molecular
movements that occur when an electronic field is applied across a dielectric
material. Associated with each type of dielectric polarization is a charac-
teristic relaxation time. The relaxation time represents the time necessary
for the polarization to respond to the applied electric field. The energy
absorption of the material from the electric field will be a maximum when
the field is alternating at a frequency corresponding to one over the relax-
ation time of the polarization process. If the electric field is alternat-
ing much faster, the polarization will be only partially or insignificantly
established before the field reverses. If the field is alternating much
slower, the electrons or molecules have a resting period between each
distortion and consequently maximum absorption is not achieved. Some
characteristic relaxation times are: for electronic polarization, $\approx 10^{-16}$

sec; for atomic polarization, $\approx 10^{-12}$ to 10^{-13} sec; for dipole orientation in polar materials, $\approx 10^{-3}$ to 10^{-10} sec. Tables of dielectric relaxation times may be found in Digest of Literature on Dielectrics.[28] Because of the effect of the relaxation time, the amount of energy absorption by each of the polarization processes is frequency dependent. Often several of these energy absorption mechanisms have significant effects at a particular microwave frequency. The total effect is the sum of the individual effects.

If the electric field applied across the material is too large (i.e., large voltage gradient) a breakdown of the insulation resistance of the material will occur. Loosely bound charges which do not migrate at low electric fields are liberated at high fields and become free charges, thus increasing the conductivity of the material. The conductivity increases with the applied field until ultimately breakdown occurs. This breakdown is characterized by arcing within the material. This arcing usually causes product damage. An excellent reference on the dielectric breakdown strength of solid materials is a review article on this subject by Mason[29] published in Volume I of Progress in Dielectrics. The dielectric breakdown of liquids is discussed by Lewis.[30]

The energy absorbed by a dielectric material is a function of both the material and the applied field. Although the expression for the power absorbed by a dielectric material may be written in several forms, the following expression is common

$$P = \pi \, \epsilon'' \, f \, E^2 \tag{3.1}$$

where   P is the power absorbed per unit volume, watts per cubic inch

f is the frequency of the field, cycles/sec

E is the rms voltage gradient of the field, volts per inch

ϵ'' is the loss factor of the material, farads per inch.

The loss factor of the material, ϵ'', is a property of the material and lumps together the effect of the different loss mechanisms. For a given electromagnetic field the loss factor specifies the absorption characteristic of the material. The loss factor is generally a function of frequency.

When discussing the dielectric properties of a material it is customary to define a complex dielectric constant, ϵ^*.

$$\epsilon^* = \epsilon' - j\epsilon'' \qquad (3.2)$$

A complex dielectric constant so defined has the same significance as the dielectric constant defined when considering the ordinary capacitor. The loss factor is the imaginary part of the complex dielectric constant. The real part of the complex dielectric constant is often called "dielectric constant," omitting the designation "real part."

For the purpose of measurement and tabulation, the complex dielectric constant is often considered in polar form. This leads to the definition of the phase angle of the complex dielectric constant, δ. This angle is designated as the "loss angle." The "loss tangent" of the material is then defined as

$$\tan \delta = \frac{\epsilon''}{\epsilon'} \qquad (3.3)$$

The loss factor for a material can then be written as

$$\epsilon'' = (\text{dielectric constant}) \cdot (\text{loss tangent}) \tag{3.4}$$

$$\epsilon'' = \epsilon' \tan \delta$$

Usually the dielectric constant and loss tangent are tabulated separately for a material. A. von Hipple,[19,32] Moreno,[20] Smyth,[17] Birks,[27] all tabulated these quantities for a number of materials at microwave frequencies. Both the dielectric constant and loss tangent are, in general, functions of frequency. However, for some materials in the microwave frequency range, the dependence of the dielectric constant on frequency is small.

Another quantity sometimes mentioned in the literature instead of the loss tangent is the "power factor". The power factor is the cosine of the complementary angle of the loss angle, i.e., $\cos(90° - \delta)$. If the loss angle, δ, is small, which is usually the case, the power factor will approximate the loss tangent as seen by the following trigonometric relations.

$$\tan \delta \cong \sin \delta = \cos(90° - \delta)$$

For the purpose of tabulation the dimensionless ratio is often formed.

$$\epsilon_r' = \frac{\epsilon'}{\epsilon_0}$$

Where ϵ_0 is the dielectric constant of free space and has a value $\frac{1}{36\pi} \times 10^{-9}$ farads per meter of 2.25×10^{-13} farads per inch. The dimensionless dielectric parameter, ϵ_r', is called the "relative dielectric constant" of the

material.

An examination of the equation describing the power absorption of a given material indicates that the absorption increases with both frequency and voltage gradient. The maximum voltage gradient that may be used is often limited by the breakdown voltage of the microwave generating equipment. The higher the frequency of the waves, the lower is the required voltage to obtain a given heating rate. Because the power absorption is a function of the frequency, some materials which do not heat at all at lower frequencies can be heated at higher frequencies. Since the power absorption is proportional to the frequency, there is a reduction in penetration with increasing frequency. The relationship between power absorption and frequency is not a simple direct relationship because the loss factor is a function of frequency.

In the microwave range, the loss factor of water is large enough that water will absorb considerable energy from the field regardless of the specific frequency. For heating water, the choice of frequency is mainly based upon selecting penetration depth and specifying generating equipment geometry. For microwave frequencies, the loss factor of water is many times greater than the loss factor of such textile materials as cotton, rayon, nylon, etc. Therefore, microwave heating is especially attractive for drying textiles as the energy of the field is absorbed mainly by the moisture and only to a minor extent by the dry product. This means that energy can be rapidly added to moisture within the product.

One important consideration in analyzing a potential microwave heating application is the penetration depth. In analyzing the penetration, it is convenient to consider the effect of a plane wave radiated in one

direction only. If a plane wave is propagating through a lossy dielectric material there will be an attenuation of the field strength of the wave as it passes through the material. This attenuation is conventionally described in terms of the attenuation factor, α, and the voltage gradient, by

$$E_x = E_o \, e^{-\alpha x}$$

where E_x is the voltage gradient at a penetration depth x and E_o is the voltage gradient of the microwave field incident upon the material surface. The power absorbed from the microwave field by the lossy dielectric material is proportional to the square of the voltage gradient (equation 3.1). Therefore, the relationship between the power absorbed at the surface and that absorbed at some inner volume is

$$P_x = P_o \, e^{-2\alpha x} . \tag{3.5}$$

The attenuation factor, α, can be related to the dielectric properties of the material and the frequency of the field.[19] For dielectric materials the attenuation factor is

$$\alpha = 0.376 \times 10^{-9} \, f \, \sqrt{\epsilon'/\epsilon_o} \left[\sqrt{1 + \tan^2 \delta} - 1 \right]^{\frac{1}{2}} \frac{1}{\text{inches}} .$$

A convenient quantity to consider as a measure of the attenuation effect is the penetration depth. The penetration depth is the depth at

which the field strength (voltage gradient) has been attenuated to 1/e of the incident strength. The penetration depth, D, will then be

$$D = \frac{1}{\alpha} = 2.66 \times 10^{-9} \ \frac{1}{f \ \sqrt{\epsilon'/\epsilon_0} \left[\sqrt{1 + \tan^2 \delta} - 1 \right]^{\frac{1}{2}}} \ \text{inches.} \quad (3.6)$$

For many low loss materials such as textiles and paper the loss tangent is considerably less than one, i.e.,

$$\tan \delta \ll 1.$$

A good approximation for the penetration depth then becomes

$$D = 3.76 \times 10^{-9} \ \frac{1}{f \sqrt{\epsilon'/\epsilon_0} \ \tan \delta} \ \text{inches.} \quad (3.7)$$

Calculations for the penetration depth for specific materials at two of the common microwave frequencies are shown in Table 1.

The power absorption from the microwave field varies as the square of the microwave field strength (voltage). The power absorption within a lossy material will attenuate with penetration twice as fast as does the voltage gradient. The depth of penetration at which the power absorption will be 1/e of that absorbed at the surface will be one-half the values presented in Table 1, as Table 1 lists penetration depth with respect to field strength.

Table 1. Approximate Plane Wave Penetration Depth.

Material	Frequency (mc/s)	Penetration (inches)
Water (25°C)	915	9.7
	2450	1.4
Dry Cotton	915	307
	2450	122
Nylon	915	130
	2450	74

Microwave Generating Equipment

There are three types of equipment geometries that are commonly used to establish an electromagnetic field at microwave frequencies. These three can be designated as the parallel plate type, the nonresonant cavity type, and the waveguide type. The heating chamber geometry and the microwave generating equipment design are different for each type.

The equipment used for low frequency heating resembles an ordinary electrical capacitor. A microwave generator is connected across two parallel capacitor plates and the product to be heated is placed between the two plates. An electromagnetic field is established between the two plates and energy from the field is absorbed by the product.
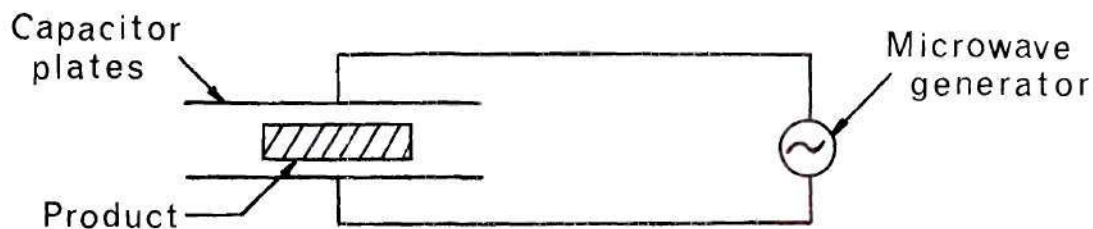
Figure 5. Capacitor Type Electromagnetic Heating Device

A requirement for this geometry to work is that the wave length of the alternating voltage placed across the capacitor plates be long compared to the size of the plates and the distance between them. For most products, a plate spacing of several inches is required. This limits the use

of this geometry to frequencies of the order of one hundred megacycles per second or less. (The wave length of a one megacycle per second wave is 984 feet; a one hundred megacycle per second wave is 98.4 feet.)

There are several disadvantages to this type of equipment geometry. One disadvantage is that, in order to get good power absorption at these low microwave frequencies, it is necessary that the voltage placed across the plates be large. This leads to arcing problems between the plates or between the plates and the side walls of the heating chamber and also within the product. Another disadvantage of this equipment is the low efficiencies of microwave generators at these frequencies. The generating equipment is generally of the type used by radio stations and has a line power to microwave power conversion efficiency in the neighborhood of fifty percent, when used for industrial heating applications. One of the problems of designing this type of equipment to operate at peak efficiency is that the parallel plates and the drying product itself are part of the tuned resonant circuit which is used for generating the microwaves. Whereas radio stations operate into a constant load (antenna), a constant loading is not possible in the case of drying products since the load changes with drying. The reason for the change in the electrical properties of the load is that the dielectric constant of the drying material changes as water is removed.

The capacitor-type geometry has been used extensively in the past because not until the last few years could high power microwave generators be built for frequencies above one hundred megacycles per second. This capacitor-type geometry is used for the drying of glue in the manufacture of plywood and laminated furniture. This geometry is particularly suited

for this application because the capacitor plates may be used to hold or shape the wood material as the glue is heated by the electromagnetic field. This type of geometry is also used for the drying of "cakes" of rayon yarn and has been used in the setting of nylon tire cord. A good reference on this type of dielectric heating is a book by Cable.[21]

In recent years, much effort has been spent developing high frequency generating equipment at frequencies higher than were attainable with the radio frequency type generating system. The incentive for this development has been from the radar and telemetry fields which require such equipment. Because of this concentrated development effort, equipment is anticipated or has now been developed that will produce energy at the high microwave frequencies (500 to 20,000 mc/s) at high power levels and with efficiencies above those common with the radio frequency equipment.

In general the equipment used for the generation of microwaves at the higher frequencies consists of a DC power supply, a microwave generating tube, and a chamber for applying the microwaves to the product. The DC power supply is required to operate the microwave generating tube. The power supply design is straightforward; its stability, ripple, etc. specified by the type of microwave generating tube it supplies. There are several types of microwave generating devices, such as a magnetron, klystron, amplitron, and resnatron. The name of the device specifies its principle of operation. From a user's standpoint, they all produce continuous electromagnetic energy at microwave frequencies. Microwave generating tubes are now available which operate continuously at power levels above 400 KW. The microwave generating tube constitutes the major expense

of microwave heating equipment.

The heating chamber geometry at these higher frequencies must be different from the capacitor-type design used at lower frequencies because the wavelength at these higher frequencies is too short to allow practical plate size or spacing. One geometry commonly used is to build an enclosed metal box with dimensions such that the dimension in the direction of propagation is larger than a half wavelength. (The wavelength at 900 mc/s is 13 inches; at 3,000 mc/s is 4 inches.) The microwave energy is then beamed into the box by an antenna inserted through one wall. If the walls of the box are metallic, the microwaves
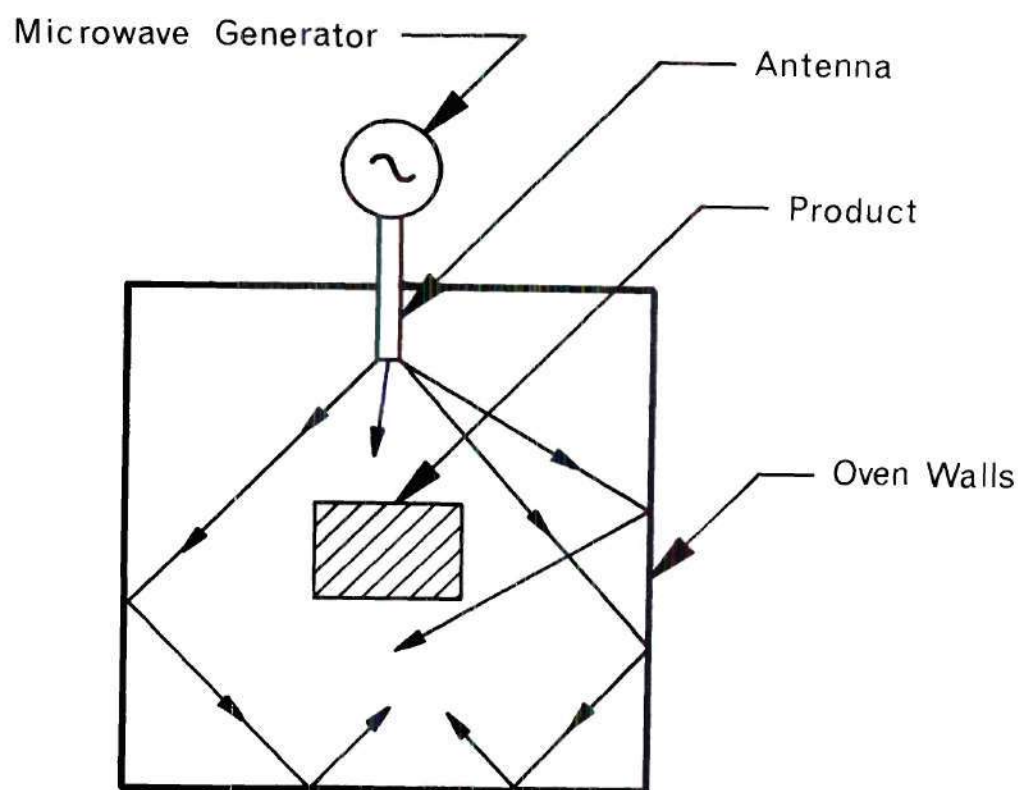
Figure 6. Microwave Oven Cavity

will not penetrate or be absorbed by the walls but will be reflected. If the box dimensions are such that the reflections are out of phase with the incident waves, a jumbled electromagnetic field with minimum standing waves is obtained. To aid in randomizing the waves within the box, a stirrer is sometimes used. This consists of a metal blade similar to a fan blade which is slowly rotated within the box giving random reflections of the microwaves from the blade faces. Another randomizing technique is to vibrate one wall of the box. Because the field is jumbled in the sense that there are no standing waves, the average electric field distribution throughout the oven over an interval of time will be nearly uniform. (It would not be uniform if there were standing waves, as the electric field would go from a maximum to a minimum between node and antinode of the wave.) At any point within the box, the components of all the reflections add to produce an electromagnetic field that will be converted to thermal energy by a lossy dielectric present at the point.

The walls of the box may be made partially from porous metal such as metal screen or grid sheeting. The loss of microwaves through the holes in the screen will be very slight and can be neglected if the hole size is small compared with the wave length of the waves. The use of such a porous wall has the advantage of allowing scavenging air to be circulated through the oven cavity to blow out the moisture from the drying product.

One advantage of the box geometry is that it allows the heating of large products. Within reason, the box can be made as large as the product requires. If the field in the box is not uniform enough, the heating may still be made uniform by moving the product about within the field during the heating cycle.

The box-type geometry is presently used by restaurants and auto-matic food dispensing machines to quickly heat and cook foods.[25] General Electric expects to market an oven for household use equipped with a micro-wave unit.[33] This type of geometry has been used to add the heat of sub-limation during the freeze-drying of meats and other food products.[25,26]

A disadvantage of the box-type geometry is the difficulty in estab-lishing a uniform microwave field. A third geometry suitable for indus-trial microwave heating is to beam the microwaves through a wave guide and pass the product through the center of the wave guide. A detailed discussion of the wave propagation in a wave guide is given by von Hipple.[19] Some properties of wave guides will be reviewed here.

A wave guide is a metal conduit of specific dimensions through which microwaves will propagate without appreciable loss of attenuation. The dimensions of a wave guide are specified by the frequency of the wave it is desired to propagate. Typical dimensions for a rectangular wave guide for a 915 mc/s wave would be 7.9 inches by 4.1 inches in cross sec-tion. For a 2450 mc/s wave, typical dimensions would be 4.4 inches by 2.3 inches in cross section. The electric field distribution along the length direction of the wave guide will be uniform if there is no attenuation or back reflection within the wave guide. The electric field distribution across a cross section is similar to that shown in Figure 7, having a maximum at the center and declining to zero at the sides. If the product is placed in the middle of the wave guide, it will be at a point of maxi-mum field intensity. A long slot can be cut in each side of the wave guide without appreciably affecting the electrical characteristics of the guide and the internal field. A thin product such as sheet fabric or

paper may be passed through these slots. The product will be passing through the guide at a position of maximum electric field intensity and will absorb energy from the electromagnetic field. Because wave guides can be constructed to turn 180° corners, it is possible to design the guide such that the product makes several passes through the same guide

Half sin wave
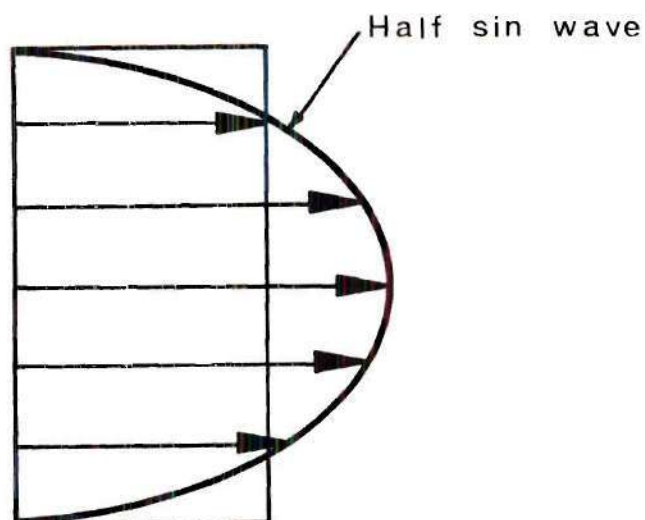
Figure 7. Electric Field Distribution Across the Cross Section of a Rectangular Wave Guide

by doubling back the guide several times. Other investigators have indicated that a maximum slot width of 3/4 inch can be tolerated at

2450 mc/s and a maximum slot width of 3-1/2 inches tolerated at 915 mc/s. A schematic diagram of a slotted wave guide heater is shown in Figure 8.

Slot

Sheet
Material
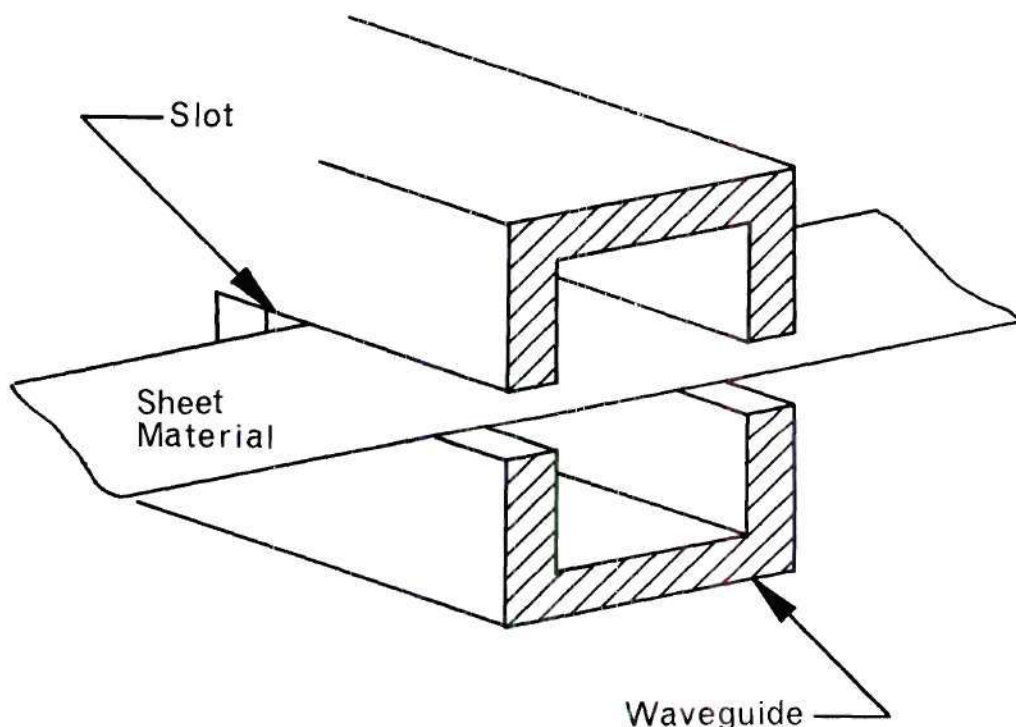
Waveguide

Figure 8.   Slotted Wave Guide Microwave Heater

No matter what type of geometry is used to establish a microwave field, parallel plates, nonresonant cavity, or wave guide, it is impossible to continuously generate microwave energy within the confines of a chamber without providing some means whereby the energy can dissipate. Some means of matching the load with the output of the generator must be included in the design of the apparatus. This creates a sizeable design problem if the product load is nonuniform. In the case of a radiant

thermal oven, should the heating element put more energy into the oven than the product could absorb, the excess energy is dissipated by heating the oven walls and radiating to the surroundings. Negligible microwave energy is absorbed by the metal walls of the wave guide or oven and from a safety and efficiency standpoint the equipment is designed so that energy leakage is negligible. If an attempt is made to generate more microwave energy than can be dissipated within the enclosure, the electrical potential gradient established by the generating tube will increase in an attempt to increase the power absorption of the load, as demonstrated by equation 3.1. This increase may continue until there is a breakdown or arcing within the chamber. Also, if there are reflections of standing waves back to the generating tube, the magnitude of these reflections will increase with increasing voltage gradient, increasing the possibility of tube damage from reflections. One alternative in the design of equipment to heat fluctuating loads is to provide the generator with a dummy load which will absorb energy when the regular load is not present. In the case of the wave guide geometry, this can be accomplished by placing a suitably designed water or ceramic load at the end of the guide which will absorb the microwave energy that has not been absorbed by the drying sample. In the case of the nonresonant cavity or box geometry, a similar dummy load may be inserted into the oven cavity. It is possible to control the output of some microwave generating tubes and this allows the construction of a feedback system which will match the tube output to the product load minimizing the energy absorbed by the dummy load.

Economic Considerations of Microwave Heating

The principal drawback preventing the widespread use of electro-magnetic heating is economic. In general, it costs more to use electro-magnetic heating than to use conventional heating. There are two reasons for the high cost; equipment cost and fuel cost. As a general rule, micro-wave energy generating equipment costs $1,000 per kilowatt of microwave energy output. In addition, the life of microwave generating equipment is limited. A typical microwave tube life guarantee would be 10,000 hours, which is 416 twenty-four-hour days. (The generating tube is about one-third of the total equipment cost.) As the market for microwave equipment grows, these prices will fall and, as the technology in the field expands, the equipment life will be extended. At present, most microwave generating tubes for high power level operation are manufactured on a single unit basis. It is this writer's opinion that the cost of many microwave gener-ating units may decrease by as much as 50 percent in the next ten years as the production volume and the manufacturers' competition increases.

The second reason microwave heating is expensive is that the basic fuel for such equipment is electricity while conventional heating allows the use of cheaper fuels such as gas or coal. A good conversion effi-ciency from 60 cycle line power to heat within the product of present day microwave equipment is 70 percent. The attainable efficiency will improve as the technology in the field expands, but this writer does not expect large improvements in the near future. Typical operation costs exclud-ing the capital cost of the equipment but including depreciation, peri-odic maintenance, and fuel costs are 6 to 8 cents per kwh output of micro-wave energy.

Because of these economic restrictions, microwave heating for drying processes will not replace conventional heating except in situations where the advantage of faster heating rates justifies the higher cost of microwave heating. Even then, many of the applications of microwave heating will be in combination with conventional hot air heating rather than replacing conventional heating. When conventional heating is used, as the moisture content of a product decreases, it becomes more and more difficult to remove the remaining moisture. There are circumstances where it is feasible to use microwave heating for the last stages of drying after much of the moisture has been removed by conventional drying. A possible instance of this is at the dry end of a paper machine or at the dry end of a process of drying a hygroscopic textile. Other applications exist where the savings in drying time justify the extra heating costs through the reduction of product handling and storage equipment. There are also applications where the energy requirement is so low that the increased fuel cost is not a factor. Typical of this situation is the use of microwaves for food preparation in the home or in restaurants. A similar application might be for the drying of clothes in a household dryer.

It is this writer's opinion that many feasible applications of microwave heating for the purpose of drying exist throughout the textile and paper industries. Although microwave generators have been built for many years, it has not been until the last year or so that high power, high efficiency microwave equipment could be purchased commercially. It is expected that within the next five years, as the technology of microwave heating develops and the newness of the area wears off, many applications will be realized and microwave heating will become commonplace.

Microwave Hazards

Microwave energy of the form discussed here as a heating mechanism is used also for communications and similar uses. To prevent interference the Federal Communications Commission has set aside certain frequencies which may be used for industrial, scientific, and medical (ISM) uses. These frequencies are shown in Table 2. Equipment operating at these

Table 2. ISM Frequencies[37]

13,560	±	6.78	kc/s
27,120	±	160.0	kc/s
40,680	±	20.0	kc/s
915	±	25.0	mc/s
2,450	±	50.0	mc/s
5,800	±	75.0	mc/s
22,125	±	125.0	mc/s

frequencies does not require an FCC licensed operator. However, the equipment must be certified to operate with the tolerance of these frequency bands and also with a maximum leakage below the established safe level. The danger of commercial heating equipment interfering with communications equipment is emphasized by the realization that commercial heating equipment may require a power output of several hundred kilowatts and the size

of some commercial radio stations is less than one kilowatt.

Microwave radiation, like nuclear radiation, is usually not sensed by a person being irradiated until damage to his body has already occurred. This means that strict precautions must be taken to prevent the possibility of microwave exposure. The U. S. Air force[34] uses 10 milliwatts per square centimeter as the maximum safe energy field intensity over the entire body. Additional special care should be taken to prevent exposure of the eyes or testes. Mumford[35] summarizes the area of microwave hazards.

It is not difficult to properly shield a microwave heating unit such that the hazard to operating personnel and communications is negligible; such shielding, of course, adds to the expense of the heating unit. Openings such as doors in microwave heating chambers must be designed so that a microwave seal is insured when the door is closed. Safety devices must be included in the design so that it is impossible for an operator to accidently open the door while the oven is on. Further shielding of the microwave unit may be constructed by surrounding the unit with a metal screen. As long as the holes in the screen are small in comparison with the wavelength of the microwaves, the leakage through the screen will be negligible. This writer has used 1/4 × 1/4 inch hardware cloth for shielding at 915 mc/s and 2450 mc/s.

Microwave Generating Equipment Manufacturers

There are several companies which build microwave generating equipment suitable for industrial heating. Some of them are Litton Industries, Raytheon Company, General Electric, Phillips Company, Deutsche Electronik, and Amperex. A good reference on microwave generating equipment manufacturers is The Microwave Engineers' Handbook and Buyers Guide[36] published

annually by Horizon House-Microwave, Inc. and distributed to subscribers of The Microwave Journal.

It is not possible to divorce the microwave generating equipment design from the design of the heating chamber. For this reason, most of the work in applications of microwave equipment to industrial processes has been done by the generating equipment manufacturers.

Because of the newness of the field and the exclusiveness of the microwave generating companies, much of the work that has been done towards applications of microwave heating has been done on a company confidential arrangement between the generating equipment manufacturer and the user. Although all manufacturers work differently, depending upon the circumstances, a typical arrangement in the past has been for a large company desiring to use microwave heating to go to the equipment manufacturer and ask him to develop equipment for the user's particular application. The user then pays for the direct development costs of the equipment. The equipment manufacturer agrees that, for a certain number of years, the company will not reveal the development to competitors of the user; but, at the end of this agreed upon "exclusive" time, the equipment manufacturer has the right to market the technology developed. This writer expects that within the next five years competition among equipment manufacturers and the fact that many of the exclusive contracts will have expired will make microwave equipment available to all users.

Today it is possible to purchase directly from most equipment manufacturers microwave generating tubes and power supplies with the intent of designing the heating chamber oneself. Some difficulty is encountered in arranging a guarantee on the life of the generating equipment since its life is a function of the application.

CHAPTER IV

THEORETICAL ANALYSIS

Development of the Transport Equations

Consider the situation of a capillary-porous body such as a thick spool (cheese) of textile yarn being heated and dried in an electromagnetic field. The drying body can be divided into four convenient components, fibrous material, moisture in vapor form, moisture in liquid form, and an inert gas (air). A model showing these components is given in Figure 9.

Textile

Connecting pores partially filled with liquid water and partially with water vapor and air.

x
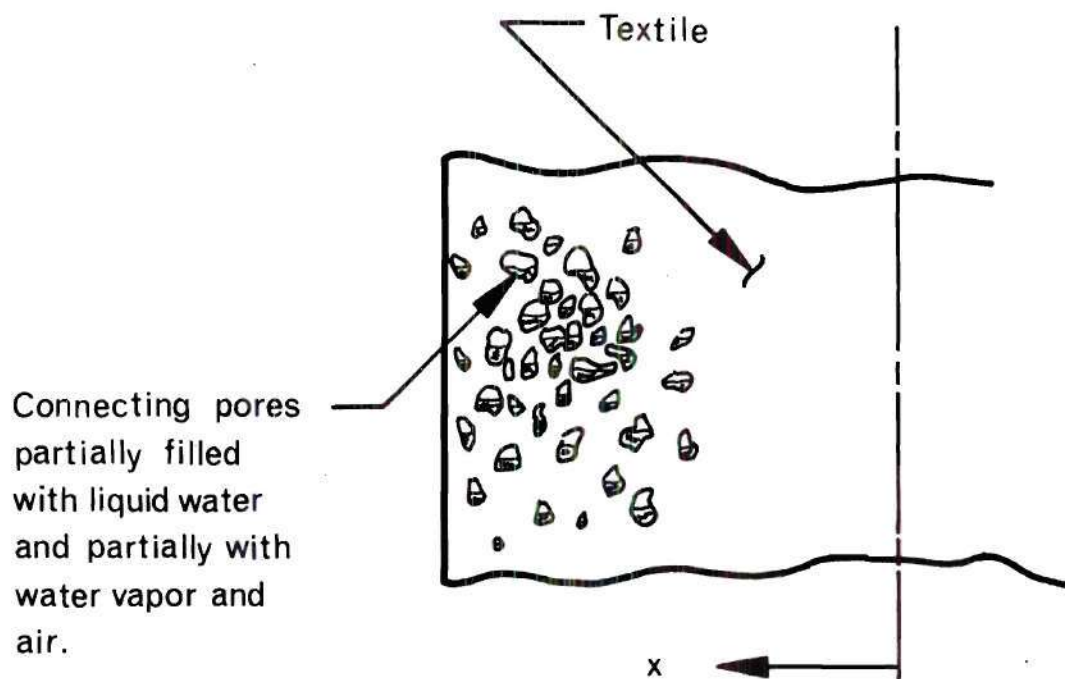
Figure 9. Analytical Model

As the body dries there is no movement of dry fibers but there is a mass flux of moisture and air. There is an energy flux inside the sample due to conduction and convection and also internal energy generation due to energy absorption from the electromagnetic field. The equations describing the heat and mass transports will be developed in the following paragraphs.

Consider first the equations describing the mass transfer. Within the drying sample consider a control volume as shown in Figure 10. Denote the unit normal to the surface of the control volume by the subscript n.
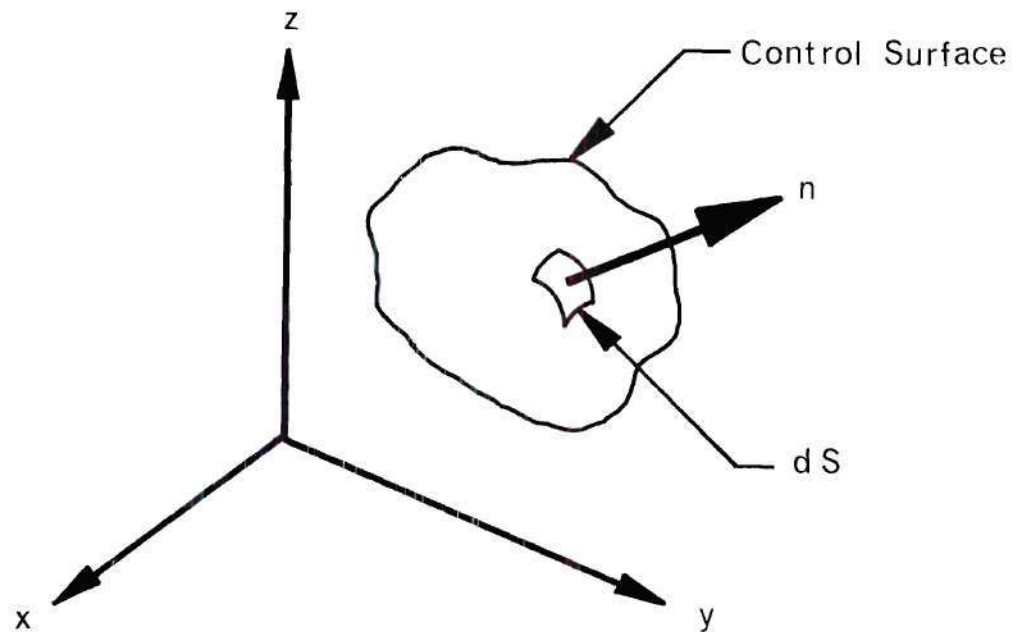
Figure 10. Control Volume

The integral equations stating the continuity of mass of each component of matter within the control volume can be written as follows

$$\left\{ \begin{array}{l} \text{Time rate of change} \\ \text{of mass inside the} \\ \text{control volume} \end{array} \right\} = \left\{ \begin{array}{l} \text{Rate of} \\ \text{mass flow} \\ \text{in} \end{array} \right\} - \left\{ \begin{array}{l} \text{Rate of} \\ \text{mass flow} \\ \text{out} \end{array} \right\} + \left\{ \begin{array}{l} \text{Rate of} \\ \text{mass} \\ \text{generation} \end{array} \right\}$$

or

$$\int_V \frac{\partial \rho_k}{\partial \tau} \, dV = - \oint_S (\bar{J}_{mk})_n \, dS + \int_V \sum_r W_{kr} \, dV \tag{4.1}$$

where

ρ_k is the density of the kth component

$\bar{J}_{mk}$ is the mass flux of the kth component through the control surface. It is a space vector.

W_{kr} is the strength of a source (or sink) of mass of the kth component. In the case of a source it is rate of change per unit time of the rth component into the kth component.

V is the volume of the control volume

S is the surface area of the control volume

τ is time

Applying Gauss' divergence theorem to equation 4.1 allows the transformation of the surface integral to a volume integral.[38]

$$\oint_S (\bar{J}_{mk})_n \, dS \equiv \int_V \nabla \cdot \bar{J}_{mk} \, dV$$

Using this result, equation 4.1 becomes

$$\int_V \left[\frac{\partial \rho_k}{\partial \tau} \, dV + \nabla \cdot \bar{J}_{mk} - \sum_r W_{kr} \right] dV = 0 \, .$$

Since an arbitrary control volume was considered, the integrand of the volume integral must be zero for the integral to be zero, indicating

$$\frac{\partial \rho_k}{\partial \tau} = - \nabla \cdot \overline{j}_{mk} + \sum_r W_{kr} \; . \tag{4.2}$$

It is convenient to consider mass concentrations in terms of specific concentration rather than density. Therefore, define the specific concentration of the kth component as

$$u_k = \frac{\rho_k}{\rho_o} \; . \tag{4.3}$$

The specific concentration is the ratio of the amount of the kth component to the amount of dry product present at any point. The total specific concentration, u, can be defined as

$$u = \sum_{k=1}^{3} u_k \tag{4.4}$$

where the subscripts 1, 2, and 3 represent vapor, liquid, and air respectively.

The differential equation for mass transfer, 4.2, can be rewritten in terms of the specific concentration.

$$\frac{\partial (\rho_o u_k)}{\partial \tau} = - \nabla \cdot \overline{j}_{mk} + \sum_r W_{kr} \tag{4.5}$$

Because of the law of conservation of mass, the following equalities must hold between sources and sinks.

$$W_{kr} + W_{rk} = 0 \qquad (4.6)$$

$$\sum_k \sum_r W_{kr} = 0 \qquad (4.7)$$

For the drying situation under consideration there is no source of component three (air). The source of vapor and sink of liquid are related according to equation 4.6.

$$W_{12} = - W_{21} \qquad (4.8)$$

Taking into account the above considerations, the differential equation for mass transfer, 4.5, may be written for each component:

$$\frac{\partial(\rho_0 u_1)}{\partial \tau} = - \nabla \cdot \bar{j}_{m1} + W_{12} \qquad (4.9)$$

$$\frac{\partial(\rho_0 u_2)}{\partial \tau} = - \nabla \cdot \bar{j}_{m2} - W_{12} \qquad (4.10)$$

$$\frac{\partial(\rho_0 u_3)}{\partial \tau} = - \nabla \cdot \bar{j}_{m3} \; . \qquad (4.11)$$

Equations 4.9, 4.10, and 4.11 may be added yielding

$$\frac{\partial[\rho_0(u_1 + u_2 + u_3)]}{\partial \tau} = -\nabla \cdot (\bar{J}_{m1} + \bar{J}_{m2} + \bar{J}_{m3}). \tag{4.12}$$

It is reasonable to assume that the mass flux of air is small in comparison to the mass flux of moisture, i.e.,

$$\bar{J}_{m1} + \bar{J}_{m2} \gg \bar{J}_{m3} . \tag{4.13}$$

Making this assumption allows us to write the differential equation for mass transfer in terms of the mass fluxes as follows:

$$\frac{\partial(\rho_0 u)}{\partial \tau} = -\nabla \cdot (\bar{J}_{m1} + \bar{J}_{m2}) . \tag{4.14}$$

The equation for the conservation of energy can be developed following a procedure similar to that used in developing the above mass transfer equation. Consider a control volume as described by Figure 9. The integral equations relating the conservation of energy within the volume to that passing through the surface can be written as follows.

$$\left\{\begin{array}{l}\text{Rate of}\\\text{accumulation}\\\text{of}\\\text{internal energy}\end{array}\right\} = \left\{\begin{array}{l}\text{Rate of}\\\text{energy}\\\text{in}\end{array}\right\} - \left\{\begin{array}{l}\text{Rate of}\\\text{energy}\\\text{out}\end{array}\right\} + \left\{\begin{array}{l}\text{Rate of}\\\text{energy}\\\text{generation}\end{array}\right\}$$

In terms of mathematical symbols, this equation is

$$\int_V \frac{\partial E_v}{\partial \tau} \, dV = - \oint_S (\bar{J}_e)_n \, dS + \int_V q_s \, dV \qquad (4.15)$$

where

E$_v$ is the concentration of energy inside the control volume per unit volume

$\bar{J}_e$ is the flux of energy through the control surface

q$_s$ is the energy generated inside the control volume per unit volume

S is the surface area of the control volume

V is the volume of the control volume.

Applying Gauss' divergence theorem[38] relating volume and area integrals to equation 4.15 yields

$$\frac{\partial E_v}{\partial \tau} = - \nabla \cdot \bar{J}_e + q_s. \qquad (4.16)$$

For constant pressure processes, the energy may be approximated by the enthalpy; other contributors to the energy such as changes in elevation and kinetic energy are considered small. The differential equation for energy transfer, 4.16, can be written

$$\frac{\partial H_v}{\partial \tau} = - \nabla \cdot \bar{J}_h + q_s \qquad (4.17)$$

where

H$_v$ is the volumetric concentration of enthalpy

$\bar{J}_h$ is the enthalpy flux.

When the substance within the control volume consists of several components (i.e., dry product, vapor, liquid, water, and air), the enthalpy of the com-

bination is equal to the sum of the enthalpy of the separate constituents, i.e.,

$$H_v = \rho_0 h_0 + \rho_1 h_1 + \rho_2 h_2 + \rho_3 h_3 \qquad (4.18)$$

$$= \rho_0 h_0 + \sum_{k-1}^{3} \rho_k h_k \; .$$

Expressing this in terms of specific concentration rather than density gives

$$H_v = \rho_0 h_0 + \sum_{k=1}^{3} \rho_0 u_k h_k \; . \qquad (4.19)$$

The enthalpy flux, $\bar{J}_h$, can be divided into two terms. It is possible for energy to cross the control surface by two different means. It can be conducted through the surface and can be convected through the surface by the mass flow of the different components. Therefore, the enthalpy flux can be written as

$$\bar{J}_h = \bar{J}_q + \sum_{k=1}^{3} h_k \bar{J}_{mk} \qquad (4.20)$$

where

$\bar{J}_q$ is the flux of energy by heat conduction

$\bar{J}_{mk}$ is the mass flux of the kth component.

The partial differential equation for energy transfer, 4.17, can be re-written using the definitions of equation 4.19 and 4.20, giving

$$\frac{\partial}{\partial \tau}\left(\rho_0 h_0 + \sum_{k=1}^{3} \rho_0 h_k u_k\right) = - \nabla \cdot \left(\bar{J}_q + \sum_{k=1}^{3} h_k \bar{J}_{mk}\right) + q_s \; . \qquad (4.21)$$

Expanding the derivative terms of this equation yields

$$\frac{\partial}{\partial \tau}(\rho_o h_o) + \sum_{k=1}^{3} u_k \frac{\partial(\rho_o h_k)}{\partial \tau} + \sum_{k=1}^{3} \rho_o h_k \frac{\partial u_k}{\partial \tau} \qquad (4.22)$$

$$= - \nabla \cdot \bar{J}_q - \sum_{k=1}^{3} h_k \nabla \cdot \bar{J}_{mk} - \sum_{k=1}^{3} \bar{J}_{mk} \nabla h_k + q_s .$$

It is convenient to express the energy equation in terms of temperature rather than enthalpy. Define, therefore, the specific heat for each component

$$c_k = \frac{dh_k}{dt} \qquad\qquad k = 1, 2, 3 \qquad (4.23)$$

$$c_o = \frac{dh_o}{dt} . \qquad (4.24)$$

For moderate temperature changes the specific heat may be considered constant. The assumption may also be made that, at any point within the product, all components present at that point are in temperature equilibrium. That is to say

$$t_o = t_1 = t_2 = t_3 = t. \qquad (4.25)$$

These assumptions allow the energy equation to be rewritten in terms of the temperature

$$\frac{\partial t}{\partial \tau} (\rho_o c_o + \sum_{k=1}^{3} \rho_o c_k u_k) + \sum_{k=1}^{3} \rho_o h_k \frac{\partial u_k}{\partial \tau} \qquad (4.26)$$

$$= -\nabla\cdot\overline{J}_q - \sum_{k=1}^{3} h_k \nabla\cdot\overline{J}_{mk} - \sum_{k=1}^{3} \overline{J}_{mk} c_k \nabla t + q_s \; .$$

It is convenient to combine several terms by making use of the equation for mass transfer of the kth component, equation 4.5. If equation 4.5 is multiplied by h_k, the following is obtained:

$$h_k \frac{\partial(\rho_o u_k)}{\partial\tau} = -h_k \nabla\cdot\overline{J}_{mk} + \sum_r h_k W_{kr} \; . \tag{4.27}$$

Summing each term of this equation with respect to k yields

$$\sum_{k=1}^{3} h_k \frac{\partial(\rho_o u_k)}{\partial\tau} = -\sum_{k=1}^{3} h_k \nabla\cdot\overline{J}_{mk} + \sum_{k=1}^{3}\sum_{r=1}^{3} h_k W_{kr} \; . \tag{4.28}$$

Combining this equation with equation 4.26 yields

$$\frac{\partial t}{\partial\tau}\left(\rho_o c_o + \sum_{k=1}^{3}\rho_o c_k u_k\right) = -\nabla\cdot\overline{J}_q - \sum_{k=1}^{3}\overline{J}_{mk} c_k \nabla t - \sum_{k=1}^{3}\sum_{k=1}^{3} h_k W_{kr} + q_s . \tag{4.29}$$

The third term on the right side of the above equation may be expanded as follows using equation 4.8:

$$\sum_{k=1}^{3}\sum_{r=1}^{3} h_k W_{kr} = h_1 W_{12} + h_2 W_{21} \tag{4.30}$$

$$= (h_1 - h_2) W_{12}$$

$$= L\, W_{12}$$

where L represents the latent heat of vaporization of water.
Using equation 4.30, the differential equation for energy transfer may be written as

$$\left(\rho_0 c_0 + \sum_{k=1}^{3} \rho_0 c_k u_k\right) \frac{\partial t}{\partial \tau} = - \nabla \cdot \overline{J}_q - \sum_{k=1}^{3} \overline{J}_{mk} c_k \nabla t - L\, W_{12} + q_s. \qquad (4.31)$$

This represents the energy equation written in terms of the energy and mass fluxes.

In addition to the energy equation and mass transfer equation, a third equation may be developed which also describes the physical conditions inside the sample. This equation describes the pressure variation throughout the sample. When a sample is heated using electromagnetic heating, portions of the sample may approach 212°F. When this occurs, the transition from liquid to vapor is so rapid that the vapor can not escape from within the sample as rapidly as it is produced. The sample may become pressurized internally. When a pressure gradient exists within the sample, there may be a mass flux of both liquid and vapor due to this pressure gradient.

The effect of this internal pressurization may be examined by writing a mass balance for the compressible components, i.e., air and vapor. The rate of change in the concentration of the air and vapor will be proportional to the gradient of their mass flux plus the contribution due to generation of the component. There will be no generation of air but there will be generation of vapor. Writing such a mass balance for the vapor and

air gives

$$\rho_0 \frac{\partial(u_1 + u_3)}{\partial \tau} = - \nabla \cdot (\overline{J}_{m1} + \overline{J}_{m3}) + W_{12} \qquad (4.32)$$

Define a vapor concentration factor, c_f, which relates the total pressure to changes in the concentration of compressible components:

$$c_f = \frac{1}{\rho_0} \frac{\partial(\rho_1 + \rho_3)}{\partial p} = \frac{\partial(u_1 + u_3)}{\partial p} \qquad (4.33)$$

where p represents the total pressure. In order to investigate the significance of the vapor concentration factor so defined, it is necessary to examine the equation of state for the compressible components within the body. The densities, ρ_1 and ρ_3, are not directly suitable for comparison with the equation of state. These densities represent the amount of compressible component present per total unit volume. However, these components do not fill the entire volume, as some of the volume is taken up by the other components present within the sample (dry fibers and liquid water). The available volume for these compressible components is dependent upon porosity of the material, Π, and the pore filling factor b. The porosity represents the ratio of the volume of pores to the volume of the bulk sample. A portion of the pores will be filled with liquid water, however. The pore filling factor represents the fraction of the pores available to be filled with vapor or air. The volume available for vapor and air is related to the total volume of the sample as follows

$$V_{avail.} = V_{total} \Pi \; b \qquad (4.34)$$

Therefore, the densities based upon total volume and those based on available volume are related

$$\rho_1 + \rho_3 = \frac{m_1 + m_3}{V_{total}} = \frac{m_1 + m_3}{V_{avail.}} \Pi b = \left(\rho_1 + \rho_3\right)_{avail.} \Pi b$$

The density defined with respect to the available volume is the appropriate one for the equation of state. Assuming that humid air is governed by the perfect gas equation of state, then

$$\left(\rho_1 + \rho_3\right)_{avail.} = \frac{p}{Rt} \qquad (4.35)$$

where

R is the gas constant for the vapor and air mixture

p is the absolute pressure of the vapor and air

t is the absolute temperature of vapor and air.

Using the relationships previously developed gives

$$\rho_1 + \rho_3 = \left(\rho_1 + \rho_3\right)_{avail.} \Pi b = \frac{p \Pi b}{Rt} . \qquad (4.36)$$

The vapor concentration factor is then seen to be

$$c_f = \frac{1}{\rho_o} \frac{\partial(\rho_1 + \rho_a)}{\partial p} = \frac{\Pi b}{\rho_o Rt} . \qquad (4.37)$$

Making use of the vapor concentration factor as defined in equation 4.33,

the mass balance equation, 4.32 can be written as follows:

$$\rho_0 \frac{\partial(c_f p)}{\partial \tau} = - \nabla \cdot (\bar{J}_{m1} + \bar{J}_{m3}) + W_{12} \, .$$

This equation describes the pressure distribution within the drying body.

For convenience the mass transfer, heat transfer, and pressure equations are rewritten here. The mass transfer equations are

$$\frac{\partial(\rho_0 u)}{\partial \tau} = - \nabla \cdot \sum_{k=1}^{2} \bar{J}_{mk} \tag{4.38}$$

$$\frac{\partial(\rho_0 u_k)}{\partial \tau} = - \nabla \cdot \bar{J}_{mk} + \sum_{r=1}^{3} W_{kr} \qquad k = 1, 2, 3. \tag{4.39}$$

The energy equation is

$$\left(\rho_0 c_0 + \sum_{k=1}^{3} \rho_0 c_k u_k\right) \frac{\partial t}{\partial \tau} = - \nabla \cdot \bar{J}_q - \sum_{k=1}^{3} \bar{J}_{mk} c_k \nabla t - L W_{12} + q_s. \tag{4.40}$$

The pressure equation is

$$\rho_0 \frac{\partial c_f p}{\partial \tau} = \nabla \cdot (\bar{J}_{m1} + \bar{J}_{m3}) + W_{12} \, . \tag{4.41}$$

Thermodynamic Driving Force

According to the theory of irreversible thermodynamics, the velocity, v, at which a system approaches equilibrium is proportional to the thermo-

dynamic driving force X, which can be expressed in terms of a potential gradient.[39] This linear law is a generalization established for a system whose state approaches equilibrium. Consequently, the linear law is an experimental law and does not have a strict theoretical basis. It may, however, be derived from the statistical theory of fluctuations if the state of the system is close to equilibrium.[40]

In accordance with this linear law the flux is proportional to the thermodynamic driving force. The driving force for the transfer of energy by heat conduction is the temperature gradient. The relationship expressing the energy conduction is then

$$\bar{J}_q = - k_t \nabla t \qquad (4.42)$$

where k_t is designated as the thermal conductivity of the material. This expression is commonly designated as Biot's law of heat conduction.[41]

The transfer of moisture is proportional to the diffusion driving force (the gradient of the potential of moisture transfer, θ), the thermal driving force (the temperature gradient), and the pressure driving force (the gradient of the pressure). The mass flux of each component of moisture can thus be expressed

$$\bar{J}_{mk} = - \lambda_k \nabla \theta_k - \lambda_k' \nabla t - \lambda_k'' \nabla p \qquad k = 1, 2, 3 \qquad (4.43)$$

where

θ_k is the diffusion transfer potential of the bound matter in phase k

λ_k is the ordinary diffusion coefficient of bound matter

$\lambda_k{'}$ is the thermal diffusion coefficient of bound matter

$\lambda_k{''}$ is the coefficient of the molar or filtration transfer of mass.

In addition to these stated driving forces, there is the possibility of other effects such as external body forces, pressure effects on molecular diffusion, and others, but these effects are small for the problem under consideration and will not be considered.

A. V. Luikov[40] suggested that the moisture content, u, of a body is not the potential of moisture transfer. One of the main properties of a transfer potential is that the potentials of contacting bodies in equilibrium will be equal. The moisture content does not satisfy this property. Luikov points out, for example, that moist peat with a moisture content of 210 percent will exist in equilibrium with paper containing a moisture content of 50 percent. Consequently, at the boundary of contact there exists a discontinuity in the moisture content. Luikov suggests the introduction of the moisture transfer potential, θ. The moisture transfer potential is related to the moisture content in much the same way as enthalpy is related to the temperature. Continuing this analogy prescribes the introduction of the specific mass capacity, c_m, defined in a manner similar to the specific heat of a body.

$$c_{mk} = (\frac{\partial u_k}{\partial \theta_k})_t \qquad (4.44)$$

Over some range of moisture content c_m may be assumed constant allowing a linear relationship between mass transfer potential and the moisture content, that is,

$$u_k = A_k + \bar{c}_{mk} \, \theta_k \qquad (4.45)$$

where A_k is a constant for given material properties and $\bar{c}_m$ is the average specific mass capacity. The equation for the mass flux may be written in terms of the moisture content rather than in terms of the mass transfer potential by using the above, that is,

$$\bar{j}_{mk} = - \frac{\lambda_k}{\bar{c}_{mk}} \nabla u_r - \lambda_k' \nabla t - \lambda_k'' \nabla p. \qquad (4.46)$$

It is worthwhile to examine the significance of the mass diffusion coefficients. The flux of moisture through a solid body due to concentration variations is commonly described by Fick's law[12] which describes the proportionality between the mass flux and the volumetric concentration gradient. Fick's law is

$$\bar{j}_{mk}^c = - D_k \nabla \rho_k \qquad (4.47)$$

where $\bar{j}_{mk}^c$ is the mass flux due to the concentration gradient and D_k is designated as the diffusion coefficient for the kth component. In terms of the moisture content, Fick's law is then

$$\bar{j}_{mk}^c = - D_k \, \rho_0 \, \nabla u_k \qquad (4.48)$$

Comparing this equation with the first term of equation 4.46 indicates that the coefficient of the first term of equation 4.46 is

$$\frac{\lambda_k}{\overline{c}_{mk}} \equiv D_k \, \rho_o \, . \qquad\qquad (4.49)$$

The mass diffusion due to the temperature gradient is generally designated as the Soret effect and denoted by the Soret coefficient,[42] δ. Mass transport due to this effect can then be expressed as

$$\vec{j}^t_{mk} = - \, D_k \, \rho_o \, \delta_k \, \nabla t \, . \qquad\qquad (4.50)$$

Comparing this with the second term of equation 4.46 indicates that

$$\lambda'_k \equiv D_k \, \delta_k \, \rho_o. \qquad\qquad (4.51)$$

Because of the internal pressurization of the drying sample due to rapid internal vaporization, a total pressure gradient may exist within the body. The flow of a liquid or a gas through a porous material due to a pressure gradient is often designated as filtration and described by Darcy's law[13] which is

$$\vec{j}^f_{mk} = - \, \frac{K_f}{\mu_k} \, \nabla p \qquad\qquad (4.52)$$

where K_f is the permeability of the material and μ_k is the viscosity of the migrating fluid. Comparing Darcy's law with the last term of equation 4.46 indicates that

$$\lambda_k'' \equiv \frac{K_f}{\mu_k},$$ (4.53)

The equation 4.46 expressing the mass flux may be rewritten making use of the more familiar expressions for the flux coefficients,

$$\bar{J}_{mk} = - D_k \rho_0 \nabla u_k - D_k \rho_0 \delta_k \nabla t - \frac{K_f}{\mu_k} \nabla p .$$ (4.54)

Microwave Energy Absorption

The energy absorption from the electromagnetic field, q_s, is in general a function of a number of variables as indicated in Chapter III. The equation describing the power absorption per unit volume by a dielectric material was presented in Chapter III and is repeated here.

$$P = \Pi \epsilon'' f E^2 \qquad watts/in^3$$ (3.1)

In order to analyze the energy absorption within the sample, it is necessary to examine the variation of the terms in this equation throughout the drying material.

Microwave generating equipment for commercial heating applications will generally be designed to operate at a fixed frequency. Therefore for each application, variations in frequency may generally be neglected. The voltage gradient of the microwave energy emitted from the generating equipment will be a function of the load the absorbing material presents to the generating equipment. If the electrical properties of the microwave ab-

sorber (load) do not vary appreciably during the heating process, the voltage gradient of the microwave energy emitted from the generator will be relatively constant. At any point within the sample, however, the voltage gradient of the microwave field will be attenuated by the outer layers of the sample. If the microwave energy incident upon the sample is the form of a plane wave and the materials' dielectric properties do not vary in the direction of propagation, then the attenuation in the direction of propagation is described by the equations presented in Chapter III, i.e.,

$$P_x = P_o \, e^{-2\alpha(R-x)} \tag{3.5}$$

where x is measured from the center of the sample out towards the edge, R is the value of x at the surface, P_o represents the power absorption at the surface and P_x the power absorption at a distance (R-x) below the surface. The attenuation coefficient, α, is defined in terms of the dielectric properties in Chapter III.

In actual practice the microwave energy incident upon the sample is not a simple plane wave but rather a multitude of random reflections striking the surface of the material from all directions. This makes the definition of microwave field strength at a point within the sample quite difficult. If the material is quite thick and has a high dielectric loss, there will undoubtedly be some attenuation of field with penetration and the inner portions of the material will receive less energy than the outer portions. Since the incident radiation is not necessarily a plane wave for which the attenuation equation 3.5 was derived, the attenuation coefficient

may require modification in order to agree with the physical situation. In order to consider this attenuation, the power absorption at any point within the material may be assumed to follow the general form

$$P_X = P_O\, e^{-2a(R-x)} \tag{4.55}$$

where a is an attenuation coefficient defined from experimental considerations.

The task of finding an expression for the power absorption at any point within the sample is further complicated because the dielectric properties of the drying material vary considerably both with time and with position throughout the sample. The power absorption is a direct function of the loss factor of the material. The loss factor of the material will in general be a function of the liquid moisture content and the temperature of the absorbing material. The relationship between the change in local liquid moisture content or temperature and the change in the local dielectric constant will in general be quite complicated. As a first approximation, a linear relationship is proposed,

$$P_X = P_X^n + a_1 u_2 + a_2 t \tag{4.56}$$

where P_X^n represents the power absorption at some nominal temperature and moisture, say the initial conditions, and the coefficients a_1 and a_2 describe the linearized effect of changes in these varying properties.

As an approximation, the power absorption at a particular location

within the sample would be given by an expression combining the effects of attenuation and property variation. Such an expression would have the form

$$q_s \cong P_x = [P_o^n + a_1 u_2 + a_2 t] \, e^{-2a(R-x)} \qquad (4.57)$$

Analysis of Equations

The equations expressing the continuity of mass, energy, and pressure may be rewritten using the expressions developed in the previous two sections for the thermodynamic driving forces and microwave power absorption. Substituting into equations 4.38, 4.39, 4.40, and 4.41, the expressions for the energy and mass flux, equations 4.42 and 4.54, and the equation for the microwave power absorption, equation 4.57, yields for the mass continuity equations

$$\rho_o \frac{\partial u}{\partial \tau} = \nabla \cdot [\sum_{k=1}^{2} D_k \rho_o \nabla u_k + D_k \rho_o \delta_k \nabla t + \frac{K_f}{\mu_k} \nabla p] \qquad (4.58)$$

$$\rho_o \frac{\partial u_k}{\partial \tau} = \nabla \cdot [D_k \rho_o \nabla u_k + D_k \rho_o \delta_k \nabla t + \frac{K_f}{\mu_k} \nabla p] + \sum_{r=1}^{2} W_{kr} \qquad (4.59)$$

for the energy equation

$$(\rho_o c_o + \sum_{k=1}^{3} \rho_o c_k u_k) \frac{\partial t}{\partial \tau} = \nabla \cdot k_t \nabla t + \sum_{k=1}^{2} [(D_k \rho_o \nabla u_k \qquad (4.60)$$

$$+ D_k \rho_o \delta_k \nabla t + \frac{K_f}{\mu_k} \nabla p) c_k \nabla t] - L W_{12}$$

$$+ [P_o^n + a_1 u_2 + a_2 t] \, e^{-2a(R-x)}$$

and for the pressure equation

$$\rho_0 \frac{\partial c_f p}{\partial \tau} = \nabla \cdot [\sum_{k=1,3} D_k \rho_0 \nabla u_k + D_k \rho_0 \delta_k \nabla t + \frac{K_f}{\mu_{13}} \nabla p] + W_{12} \, . \quad (4.61)$$

It is of interest to review the significance of the terms in these equations. The first term in equation 4.58 is $\rho_0 \frac{\partial u}{\partial \tau}$ which represents the rate of change of the total concentrations of air, vapor, and liquid water. The first term of equation 4.59, $\rho_0 \frac{\partial u_k}{\partial \tau}$, represents the rate of change of the concentration of the kth component. The first term on the right hand side of each of these equations is $\nabla \cdot D_k \rho_0 \nabla u_k$. This represents the flux of the kth component due to concentration differences within the material, i.e., concentration diffusion. The second term, $\nabla \cdot D_k \rho_0 \delta_k \nabla t$, represents the flux of the kth component due to the temperature gradient within the material, i.e., thermal diffusion. The third term, $\nabla \cdot \frac{K_f}{\mu_k} \nabla p$, represents the flux of the kth component due to a total pressure gradient within the material, i.e., filtration. The last term of equation 4.59, $\sum_r W_{kr}$, accounts for the accumulative effects of sources or sinks of the kth component. This term is either W_{12} (for the vapor component) or $-W_{12}$ (for the liquid component).

Similarly for the energy equation, the left hand side is $(\rho_0 c_0 + \sum_{k=1}^{3} \rho_0 c_k u_k) \frac{\partial t}{\partial \tau}$ which represents the rate of change of the internal energy of the material. The first term on the right hand side, $\nabla \cdot k_t \nabla t$, represents energy flux by the process of heat conduction. The second term, $(D_k \rho_0 \nabla u_k + D_k \rho_0 \delta_k \nabla t + \frac{K_f}{\mu_k} \nabla p) c_k \nabla t$, represents energy flux by the

process of convection due to movement of the kth component. The third

term, $L W_{12}$, designates the internal energy absorption due to the latent

heat of vaporization of the water. The last term, $(P_o^n + a_1u_2 + a_2t) e^{-2a(R-x)}$,

describes the thermal energy generation by absorption from the microwave

field accounting for the change in the dielectric constant during heating

and drying and for field attenuation with penetration.

For the pressure equation, the left hand side, $\rho_0 \dfrac{\partial c_f p}{\partial \tau}$, represents

the rate of change of the total pressure within the sample. The first group

of terms on the right hand side is similar to the corresponding grouping in

the mass continuity equation and represents the flow of the compressible

components, air and vapor. The last term, W_{12}, represents the vapor gene-

ration within the material.

For convenience the assumptions and restrictions implied in deriving

these equations are also compiled here.

The flux of air is small in comparison with the flux of moisture.

The contribution to the energy of each component by such effects as
surface tension, magnetism, etc. may be neglected.

The specific heat of each component is constant.

Temperature equilibrium exists between all components at any point
within the material.

The flux of mass may be approximated as linearly proportional to the
gradient of the concentration, temperature, and pressure.

The microwave energy absorption can be approximated as proportional
to the penetration depth, liquid moisture content, and temperature
of the material.

It is interesting to observe that the equations presented in this

section reduce to those customarily used to represent flow situations

other than drying. For instance, the continuity equation for one component

of a binary gas mixture where the total density of the mixture is fairly constant is presented by Bird[42] as

$$\frac{\partial \rho_A}{\partial \tau} = \nabla \cdot \mathcal{D}_{AB} \nabla \rho_A + \nabla \cdot \frac{\mathcal{D}^T_{AB}}{t} \nabla t - \nabla \cdot \rho_A \bar{v} + W_{AB} \tag{4.62}$$

where ρ_A is the density of component A, $\bar{v}$ is the bulk average velocity of the mixture, and $\mathcal{D}_{AB}$ and $\mathcal{D}^T_{AB}$ are the concentration and thermal diffusion coefficients for the gas mixture of A and B. The term, $\nabla \cdot \rho_A \bar{v}$, is considered the bulk flow term. Using Darcy's law to represent this term indicates that

$$\rho_A \bar{v} = \bar{J}_{mA} = - \frac{K_f}{\mu_A} \nabla p . \tag{4.63}$$

Substituting this into the equation presented by Bird gives

$$\frac{\partial \rho_A}{\partial \tau} = \nabla \cdot \mathcal{D}_{AB} \nabla \rho_A + \nabla \cdot \mathcal{D}^T_{AB} \frac{1}{t} \nabla t + \nabla \cdot \frac{K_f}{\mu_A} \nabla p + W_{AB} . \tag{4.64}$$

The mass continuity equation presented in this section as representing the drying situation may be reduced to a similar form by assuming only two components, air and vapor. Such an assumption and the notational substitution

$$\rho_1 = \rho_0 u_1$$

yields the following reduction of equation 4.59

$$\frac{\partial \rho_1}{\partial \tau} = \nabla \cdot D_1 \nabla \rho_1 + D_1 \delta_1 \nabla t + \frac{K_f}{\mu_1} \nabla p + W_{12} \qquad (4.65)$$

Comparing this with the equation for mass continuity of a binary gas mixture shows that except for a slightly different notational definition of the diffusion coefficients, the equations are the same.

Similar comparisons may be made for the energy equation. The Fourier-Kirchhoff equation for heat transfer in a flowing liquid is[41,42]

$$\rho c_p \frac{\partial t}{\partial \tau} = \nabla \cdot k_t \nabla t - c_p \bar{J}_m \nabla t . \qquad (4.66)$$

The energy equation for the drying situation (equation 4.60) may be reduced to a similar form if only a liquid component is assumed present and heat generation and latent heat effects are assumed negligible.

$$\rho_2 c_2 \frac{\partial t}{\partial \tau} = \nabla \cdot k_t \nabla t - c_2 \bar{J}_{m2} \nabla t . \qquad (4.67)$$

The energy equation representing heat conduction in a solid body with internal heat generation[41] may be obtained from the energy equation for the drying situation by assuming negligible energy contribution from the moisture and air. Such a reduction yields

$$\rho_0 c_0 \frac{\partial t}{\partial \tau} = \nabla \cdot k_t \nabla t + q_s . \qquad (4.68)$$

Boundary Conditions

In order to consider a particular problem, boundary conditions must be defined. The partial differential equations presented in the last section describe the variation of the dependent variables, specific concentration, temperature and pressure, with respect to the independent variables of time and position. In order to discuss typical boundary conditions, it is convenient to consider a one-dimensional drying situation. Let the dimension, x, represent the distance from the center of the body towards the drying surface. Consider the case of one-dimensional flux of mass and energy, the flux being along the direction x. For the case of a semi-infinite slab, the distance x is measured from the center outward towards the surface (see Figure 11). For the case of a long cy-
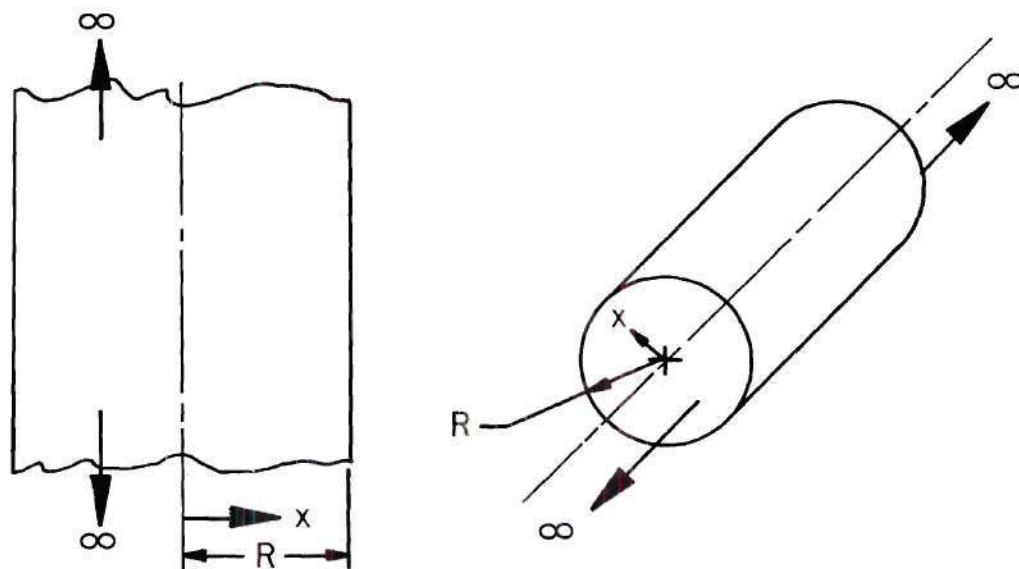
Figure 11. One-dimensional Models

linder, the dimension x represents the distance along a radius. If the drying material is spherical, x again represents radial distance. Denote

the magnitude of the distance from the center to the edge of the sample as R, i.e., the magnitude of x at the drying surface is R.

In order to solve the equations for this one-dimensional model, it is customary to specify as boundary conditions, relationships describing the specific concentration, temperature, and pressure at the surface and center of the drying sample (i.e., x = 0 and x = R). Relationships describing the heat and mass flux of the boundaries are also required.

In general there are three classes of surface boundary conditions that may be used in specifying the heat and mass flux at the boundaries. These are designated as boundary conditions of the first, second, and third kind. Boundary conditions of the third kind specify the situation at the drying surface in terms of external heat and mass transfer coefficients. Define then the external heat transfer coefficient h_t and the external mass transfer coefficient h_m such that the flux of heat from the surface into the surrounding atmosphere is given by

$$h_t(t(R, \tau) - \tau_\infty) .$$

(4.69)

The flux of water vapor from the surface into the surrounding atmosphere is given by

$$h_m(\theta(R, \tau) - \theta_\infty)$$

(4.70)

where

$\quad$ $t(R, \tau)$ is the surface temperature of the body

$\quad$ t_∞ is the temperature of the surrounding atmosphere

$\theta(R, \tau)$ is the vapor diffusion potential of the body at its surface

θ_∞ is the vapor diffusion potential of the surrounding atmosphere.

In order to obtain the boundary conditions of the third kind, it is convenient to write a temperature, pressure, and mass balance for a small control volume at the surface of the body. Consider first the surface mass balance. There is a flux of liquid and vapor from inside the body to the surface, described by the relationship below.

$$- D_k \, \rho_0 \, \frac{\partial u_k(R, \tau)}{\partial x} - D_k \, \delta_k \, \frac{\partial t(R, \tau)}{\partial x} - \frac{K_f}{\mu_k} \frac{\partial p}{\partial x} \qquad k = 1, \, 2 \qquad (4.71)$$

It is realistic to assume that all liquid moisture arriving at the surface is vaporized before it diffuses into the surrounding atmosphere. Therefore, there is no liquid moisture flow from the surface. The flux of vapor from the surface will depend upon the difference in the moisture diffusion potentials between the surface and the surrounding atmosphere. The moisture flux from the surface is then

$$h_m (\theta(R, \tau) - \theta_\infty) \, . \qquad (4.72)$$

Recall from a previous section that the mass diffusion potential is defined in terms of the moisture content by

$$u_k = A_k + \bar{c}_{mk} \, \theta_k \, . \qquad (4.45)$$

The vapor concentration at the surface has contributors from both the liquid and vapor flow to the surface, as at the surface the liquid becomes vapor. The moisture concentration at the surface, u_m, is

$$u_m = [u_1(R,\tau) + u_2(R,\tau)] = \bar{c}_{m1}\, \theta_1(R,\tau) . \tag{4.73}$$

Using these expressions, a mass balance may be written at the surface of the drying body.

$$\sum_{k=1,\,2} \left[- D_k\, \rho_o\, \frac{\partial u_k(R,\tau)}{\partial x} - D_k\, \rho_o\, \delta_k\, \frac{\partial t(R,\tau)}{\partial x} - \frac{K_f}{\mu_k}\, \frac{\partial p(R,\tau)}{\partial x} \right] \tag{4.74}$$

$$= h_m\, (\theta(R,\tau) - \theta_\infty).$$

This equation provides one surface boundary condition of the third kind.

A boundary condition concerning the energy flux may be obtained by writing an energy balance at the surface of the drying body. Energy may be transported to the surface of the body from within the body by the processes of convection and conduction. The energy transport to the surface by these mechanisms can be expressed by the following mathematical expressions.

The energy flowing to the surface by conduction is

$$-k_t\, \frac{\partial t(R,\tau)}{\partial x} . \tag{4.75}$$

The energy flowing to the surface by convection is

$$- \sum_{k=1,2} \left[D_k \, \rho_o \, \frac{\partial u_k(R, \tau)}{\partial x} + D_k \, \rho_o \, \delta_k \, \frac{\partial t(R, \tau)}{\partial x} + \frac{K_f}{\mu_k} \, \frac{\partial p(R, \tau)}{\partial x} \quad c_k t(R, \tau). \right]$$

$$(4.76)$$

Energy is absorbed at the surface by the vaporization of the liquid water which diffuses to the surface (i.e., it is assumed that all moisture leaves the surface as vapor). The expression for this energy absorption is

$$\left[D_2 \, \rho_0 \, \frac{\partial u_2(R, \tau)}{\partial x} + D_2 \, \rho_0 \, \delta_2 \, \frac{\partial t(R, \tau)}{\partial x} + \frac{K_f}{\mu_2} \, \frac{\partial p(R, \tau)}{\partial x} \right] \, L.$$

$$(4.77)$$

The energy transport from the surface to the surrounding atmosphere may be described by

$$h_t (t(R, \tau) - t_\infty) .$$

$$(4.78)$$

The terms describing the energy flux to the surface may be summed and equated to the energy flux leaving the surface, giving the following boundary condition:

$$- k_t \, \frac{\partial t(R, \tau)}{\partial x} - \sum_{k=1,2} \left[D_k \, \rho_o \, \frac{\partial u_k(R, \tau)}{\partial x} + D_k \, \rho_o \, \delta_k \, \frac{\partial t(R, \tau)}{\partial x} \right.$$

$$(4.79)$$

$$\left. + \frac{K_f}{\mu_k} \, \frac{\partial p(R, \tau)}{\partial x} \right] c_k t(R, \tau) - \left[D_2 \, \rho_0 \, \frac{\partial u_2(R, \tau)}{\partial x} \right.$$

$$+ D_2\, \rho_0\, \delta_2\, \frac{\partial t(R,\tau)}{\partial x} + \frac{K_f}{\mu_2}\, \frac{\partial p(R,\tau)}{\partial x} \Bigg]\, L = h_m \big(t(R,\tau) - t_\infty\big)\ .$$

The two boundary conditions, 4.74 and 4.79, relate the fluxes of heat and mass transfer at the surface to the external heat and mass transfer coefficients. Boundary conditions of this type are called boundary conditions of the third kind.

Boundary conditions of the first kind are boundary conditions which represent constant heat and mass transfer potentials at the surface. The moisture potential at the surface and the temperature at the surface are assumed constant, giving the boundary conditions

$$t(R,\tau) = t_0 = \text{constant} \tag{4.80}$$

$$\theta(R,\tau) = \theta_0 = \text{constant}. \tag{4.81}$$

In comparison with boundary conditions of the third kind, those of the first kind represent infinite h_m and h_t.

Boundary conditions of the second kind are used when the heat and mass transfer fluxes from the surface are known functions of time. Such boundary conditions are useful when the fluxes are known but they can not be described conveniently by equations. The boundary conditions of the second kind for the heat and mass transfer at the drying surfaces are

$$\sum_{k=1,2} \Bigg[- D_k\, \rho_0\, \frac{\partial u_k(R,\tau)}{\partial x} - D_k\, \rho_0\, \delta_k\, \frac{\partial t(R,\tau)}{\partial x} - \frac{K_f}{\mu_k}\, \frac{\partial p(R,\tau)}{\partial x} \Bigg] = q_m(\tau) \tag{4.82}$$

and

$$k_t \frac{\partial t(R,\tau)}{\partial x} - \sum_{k=1,2} \left[D_k \rho_o \frac{\partial u_k(R,\tau)}{\partial x} + D_k \rho_o \delta_k \frac{\partial t(R,\tau)}{\partial x} \right. \tag{4.83}$$

$$\left. + \frac{K_f}{\mu_k} \frac{\partial p(R,\tau)}{\partial x} \right] c_k t(R,\tau) - \left[D_2 \rho_o \frac{\partial u_2(R,\tau)}{\partial x} + D_2 \rho_o \delta_k \frac{\partial t(R,\tau)}{\partial x} \right.$$

$$\left. + \frac{K_f}{\mu_k} \frac{\partial p(R,\tau)}{\partial x} \right] L = q_m(\tau) .$$

where $q_m(\tau)$ and $q_t(\tau)$ are the fluxes of external mass and heat transfer known as functions of time.

In addition to these boundary conditions on the heat and mass fluxes at the surface, other boundary conditions may be stated which are quite general and apply whether boundary conditions on the fluxes of the first, second, or third kind are used.

The pressure on the surface of the drying body will be the same as that of the surrounding atmosphere, i.e.,

$$p(R,\tau) = p_\infty . \tag{4.84}$$

Assuming symmetry about the center line (x = 0) of the body, it follows that

$$\frac{\partial t(0,\tau)}{\partial x} = 0 \tag{4.85}$$

$$\frac{\partial u_k(0,\tau)}{\partial x} = 0 \qquad k = 1, 2, 3$$

$$\frac{\partial p(0, \tau)}{\partial x} = 0 .$$

Three other boundary conditions which are useful for some types of solutions may be obtained at the position $x = 0$ by stipulating that the dependent variables remain finite at this position.

$$t(0, \tau) < \infty \tag{4.86}$$

$$u_k(0, \tau) < \infty \qquad k = 1, \ 2, \ 3$$

$$p(0, \tau) < \infty$$

In addition to these boundary conditions, initial conditions concerning the temperature, mass, and pressure profiles may be specified as

$$t(x, 0) = t^*(x) \tag{4.87}$$

$$u_k(x, 0) = u^*(x) \qquad k = 1, \ 2, \ 3$$

$$p(x, 0) = p^*(x)$$

where the starred terms represent known functions of position at time zero. These boundary conditions are sufficient to permit the solution of the mass, pressure, and energy equations. They are typical of boundary conditions that may exist for a physical problem but they are not unique and each physical situation must be individually analyzed.

Reduction of Equations

As is often true for mass transfer problems, these equations describ-

ing the physical situation when written in complete form can not be solved mathematically. The problem of finding a solution is particularly difficult for the situation of a drying body as it is generally unrealistic to assume constant properties. The properties of the material vary considerably between the wet and dry states. Also, properties such as thermal conductivity, coefficients of mass diffusion, and permeability generally have not been tabulated for textile materials. Unless specific experimentation is carried out to measure these properties for each product, even approximate values of these properties are difficult to obtain.

There is considerable value in analyzing reduced forms of these equations obtained by restricting the applicability of the equations to specific drying situations. The results obtained from analyzing these reduced equations are helpful in explaining the physical mechanisms involved during the drying process. In the following paragraphs, several simplifying assumptions which are generally reasonable approximations for most drying situations are discussed. The equations resulting from applying these approximations are presented.

The energy equation may be reduced if the energy transport by convection is small in comparison with the other energy terms: heat conduction, heat generation, and latent heat. For most drying situations, the energy convection is small because the mass flux is small. (A rough comparison of the magnitude of the convective term and the latent heat term may be made. The vaporization of a pound of water requires a latent heat of nearly 1000 Btu and the transport of energy due to the flux of a pound of water through a 100°F temperature differential is 100 Btu.)

Neglecting the energy transport by convection reduces the energy equation to the following

$$(\rho_0 \ c_0 + \sum_{k=1}^{3} \rho_0 \ c_k \ u_k) \frac{\partial t}{\partial \tau} = \nabla \cdot k_t \ \nabla \ t - L \ W_{12} + q_s \ . \qquad (4.88)$$

Another reasonable approximation, for most drying problems, is to assume the mass concentration of liquid moisture is considerably greater than the concentration of water vapor and air, i.e.,

$$u_2 \gg u_1 + u_3 \ . \qquad (4.90)$$

This allows the approximation

$$u = u_1 + u_2 + u_3 \cong u_2 \ . \qquad (4.91)$$

The primary change in moisture content is due to the loss of liquid water, i.e.,

$$\frac{\partial u}{\partial \tau} \cong \frac{\partial u_2}{\partial \tau} \ . \qquad (4.92)$$

which indicates that

$$\frac{\partial u_1}{\partial \tau} \cong 0 \qquad (4.93)$$

$$\frac{\partial u_3}{\partial \tau} \cong 0 \ .$$

The mass continuity equations, 4.58 and 4.59, are reduced by this approximation to the following:

$$\rho_0 \frac{\partial u}{\partial \tau} = \nabla \cdot [D_1 \; \rho_0 \; \nabla \; u_1 + D_2 \; \rho_0 \; \nabla \; u_2 + (D_1 \; \delta_1 \; \rho_0 + D_2 \; \delta_2 \; \rho_0) \qquad (4.94)$$

$$\nabla \; t + (\frac{K_f}{\mu_1}) \; \nabla \; p]$$

and

$$0 = \nabla \cdot [D_1 \; \rho_0 \; \nabla \; u_1 + D_1 \; \delta_1 \; \nabla \; t + \frac{K_f}{\mu_1} \; \nabla \; p] + W_{12}. \qquad (4.95)$$

Comparing equation 4.95 with the pressure equation 4.61 indicates that the pressure equation becomes

$$\frac{\partial (c_f p)}{\partial \tau} = 0. \qquad (4.96)$$

Equations 4.88, 4.94, 4.95, and 4.96 were obtained by the assumptions that energy transport by convection could be neglected and the mass concentration of liquid water is much greater than that of air or water vapor. These assumptions are reasonable approximations for many drying problems.[40,15] When considering the special drying situation with microwave heating, it is possible to further reduce the equations by taking into account some of the experimentally observed drying characteristics which are discussed in Chapter VII.

During most of the drying process it was found experimentally that the temperature throughout the sample remained uniform and constant at

210°F. It was also found experimentally that the moisture gradient remained uniform throughout the majority of the drying process. The assumptions, constant and uniform temperature and uniform moisture content, may be applied to the equations. The applicability of these assumptions to the physical situation is discussed in Chapters VII and VIII.

The energy equation 4.88 is first considered term by term. The first term

$$\left(\rho_0 \, c_0 + \sum_{k=1}^{3} \rho_0 \, c_k \, u_k\right) \frac{\partial t}{\partial \tau} = 0$$

because of the assumption of constant temperature. The second term

$$\nabla \cdot k_t \, \nabla \, t = 0$$

because of the assumption of uniform temperature. The energy equation is thus reduced to the following form

$$L \, W_{12} = q_s \tag{4.97}$$

which specifies that the evaporation rate times the latent heat of water equals the internal microwave energy absorption.

The mass continuity equations can also be examined term by term. The first three terms on the right hand side of equation 4.94

$$D_1 \, \rho_0 \, \nabla \, u_1 + D_2 \, \rho_0 \, \nabla \, u_2 + (D_1 \, \delta_1 \, \rho_0 + D_2 \, \delta_2 \, \rho_0) \, \nabla \, t = 0$$

because of the assumption of uniform temperature and moisture content. This equation thus reduces to

$$\rho_0 \frac{\partial u}{\partial \tau} = \nabla \cdot \frac{K_f}{\mu_1} \nabla p \tag{4.98}$$

which specifies that all of the moisture lost by the drying sample is diffused by hydrodynamic diffusion in the vapor state. The second mass continuity equation 4.95 is similarly reduced as the first two terms are zero, i.e.,

$$D_1 \rho_0 \nabla u_1 + D_1 \delta_1 \nabla t = 0 .$$

This equation thus reduces to

$$\nabla \cdot \frac{K_f}{\mu_1} \nabla p = - W_{12} \tag{4.99}$$

which specifies that all of the vapor which is generated diffuses through the sample by hydrodynamic diffusion.

For convenience, these reduced equations are summarized below.

$$L W_{12} = q_s \tag{4.97}$$

$$\rho_0 \frac{\partial u}{\partial \tau} = \nabla \cdot \frac{K_f}{\mu_1} \nabla p \tag{4.98}$$

$$\nabla \cdot \frac{K_f}{\mu_1} \nabla p = - W_{12} . \tag{4.99}$$

These equations specify that the drying rate is proportional to the internal heat generation. If the internal heat generation is a constant, the drying rate will be a constant. The pressure distribution is then specified by the solution to the following equation:

$$\nabla \cdot \frac{K_f}{\mu_1} \nabla p = - \frac{q_s}{L} = \text{constant.}$$

The solution to this equation is known provided the product geometry is such that spatial coordinates, which yield useful boundary conditions, can be specified. In order to actually perform the second integration, some information must also be known about the variation of K_f, the permeability throughout the sample. The permeability of the dry sample is uniform and the permeability of the wet sample is proportional to the moisture content of the sample. Since the moisture content has been assumed uniform, the permeability may be assumed uniform. However, it is known that the permeability of the sample varies with drying time such that different values must be used depending upon the average moisture content of the sample at the time of interest.

The above equation may be solved for the particular one-dimensional cases pictured in Figure 11. If the moisture flow situation can be approximated by flow through a semi-infinite slab of thickness 2R, the equation reduces to the form shown below:

$$\frac{d^2p}{dx^2} = - \frac{q_s u_1}{L\, K_f} .$$

Some of the samples examined experimentally approximated this particular geometry. This equation can be solved applying the typical boundary conditions shown below.

$$p = 0 \quad \text{at} \quad x = 0$$

$$\frac{dp}{dx} = 0 \quad \text{at} \quad x = R$$

The solution for the pressure distribution is

$$p = \frac{q_s \mu_1}{L \, K_f} \left(Rx - \frac{x^2}{2} \right) . \tag{4.100}$$

If a sample with only radial moisture flow is considered, the pressure equation reduces to the form

$$\frac{d^2 p}{dx^2} + \frac{1}{r} \frac{dp}{dx} = - \frac{q_s \mu_1}{L \, K_f} .$$

Samples with this type of flow pattern were also examined experimentally. Assuming boundary conditions

$$p = 0 \quad \text{at} \quad x = R$$

$$\frac{dp}{dx} = 0 \quad \text{at} \quad x = 0$$

allows the solution of the equation yielding

$$p = \frac{q_s\,\mu_1\,R^2}{L\,K_f\,4}\,(R^2 - x^2).$$

(4.101)

It is observed that the predicted pressure profile is parabolic in shape with the highest pressure at the center of the sample for either axial or radial flow. As drying progresses and the permeability increases, the pressure profile shifts downward but remains parabolic.

The reasonableness of the assumptions applied in reducing the general drying equations and the results of experiments to examine the drying characteristics are discussed in Chapters VII and VIII.

CHAPTER V

EXPERIMENTAL APPARATUS

Introduction

A number of different experimental apparatuses were used in the course of the research. The details of each specific apparatus and the procedures used in running the experiments are discussed in the following sections.

The experimental investigation of the heating and drying characteristics of textile materials during microwave heating was conducted using two microwave ovens. Some experiments were conducted using a 915 megacycles per second oven; however, the majority of the experimentation was conducted using a microwave oven operating at 2450 megacycles per second.

2450 Megacycles per Second Oven

The 2450 megacycles per second oven chamber consists of an aluminum box with dimensions 18 inches wide, 17.5 inches deep and 15 inches high. A Raytheon model QK 390 magnetron which was specially designed for direct coupling to a wave guide or oven cavity was used as the microwave generator. A small antenna surrounded by a glass bulb protudes from the base of the tube allowing the tube to be mounted on the top of the oven chamber such that the antenna protrudes into the oven chamber.

The magnetron is designed to operate at a fixed frequency between 2425 and 2475 megacycles per second with a microwave energy output of

approximately 600 watts. An input of 6000 volts and approximately 350 milliamperes direct current is required to drive the magnetron. In addition, the cathode heater requires a 9 volt 35 ampere alternating current. These input power requirements are supplied by a Raytheon model 2170 power supply which is specifically designed to drive this microwave tube.

Aluminum sheet material 1/16 inch thick was used to construct the oven chamber. After the chamber was constructed, all seams were welded on the inside of the box, thereby rounding and filling all inside corners. This was done to reduce the chance of arcing in the microwave field which could possibly occur along a crack formed by the junction of two sheets of material.

Access was provided to the oven chamber by constructing the front of the chamber so it could be quickly removed and reinserted, thus providing a door. In order to minimize the microwave leakage from the edges of the door, the door edges and oven chamber walls form a tongue and groove assembly with the tongue part of the door and the sides of the grooves part of the oven chamber. The tongue protrudes approximately 4 inches into the groove with less than 1/32 inch gap between the tongue and the walls of the groove.

In order to provide air circulation and allow visual observations into the oven, windows 7 by 5 inches were cut into the front and back of the oven chamber. To prevent leakage of the microwave energy, the window openings were covered with aluminum window screen (household type). Two thicknesses of screen, separated by a 1/2 inch space, were placed over each window opening.

Measurements of the microwave field distribution showed that the

field could be made more uniform by inserting a stirrer into the oven chamber. The stirrer consists of a four bladed aluminum fan, approximately 10 inches in diameter. The blade is mounted on a plexiglass shaft which protrudes through the top of the oven chamber. The blade is located approximately 2-1/2 inches from the top of the oven and slightly to one side of and below the protruding magnetron antenna. The stirrer is rotated by a small motor at approximately 50 revolutions per minute. Several stirrer speeds were tried but the speed did not seem to affect the electrical performance of the device. The stirrer speeds used are much too slow to cause appreciable air movement. The benefit of the stirrer results from the establishment of a continually changing surface from which the microwaves reflect. This helps to reduce the standing waves that might be established in a fixed geometry oven. The Raytheon Company makes use of a stirrer of similar design to aid in producing a uniform field distribution in some of its commercial ovens designed for restaurant use. Some details of a stirrer design are described in U. S. patent number 2,813,185.

A schematic of the equipment layout including the microwave oven and associated microwave components is shown in Figure 12. A photograph of the actual equipment showing the 2450 megacycles per second oven is presented in Figure 13.

915 Megacycles per Second Oven

The 915 megacycles per second oven is a slightly modified version of the General Electric oven model CE21A, which is a prototype of an oven designed for restaurant food heating. The oven heating chamber is 5 in-

1. MICROWAVE FIELD STIRRER
2. LINE OF γ-RAY BEAM
3. FLORESCENT LIGHT BULB
4. COBALT 60 SOURCE SURROUNDED BY LEAD SHIELD
5. TABLE POSITIONING ROLLERS AND WAYS

6. POLYSTYRENE SAMPLE HOLDER
7. TABLE POSITIONING CRANK
8. CANTALEVERED WEIGHING BEAM
9. STRAIN GAGES ON WEIGHING BEAM

10. NaI CRYSTAL AND PHOTOTUBE
11. SAMPLE
12. SCREEN COVERED WINDOW
13. MAGNETRON

MAGNETRON HIGH VOLTAGE SUPPLY

PHOTOTUBE HIGH VOLTAGE

LINEAR AMPLIFIER

DISCRIMINATOR

COUNTER
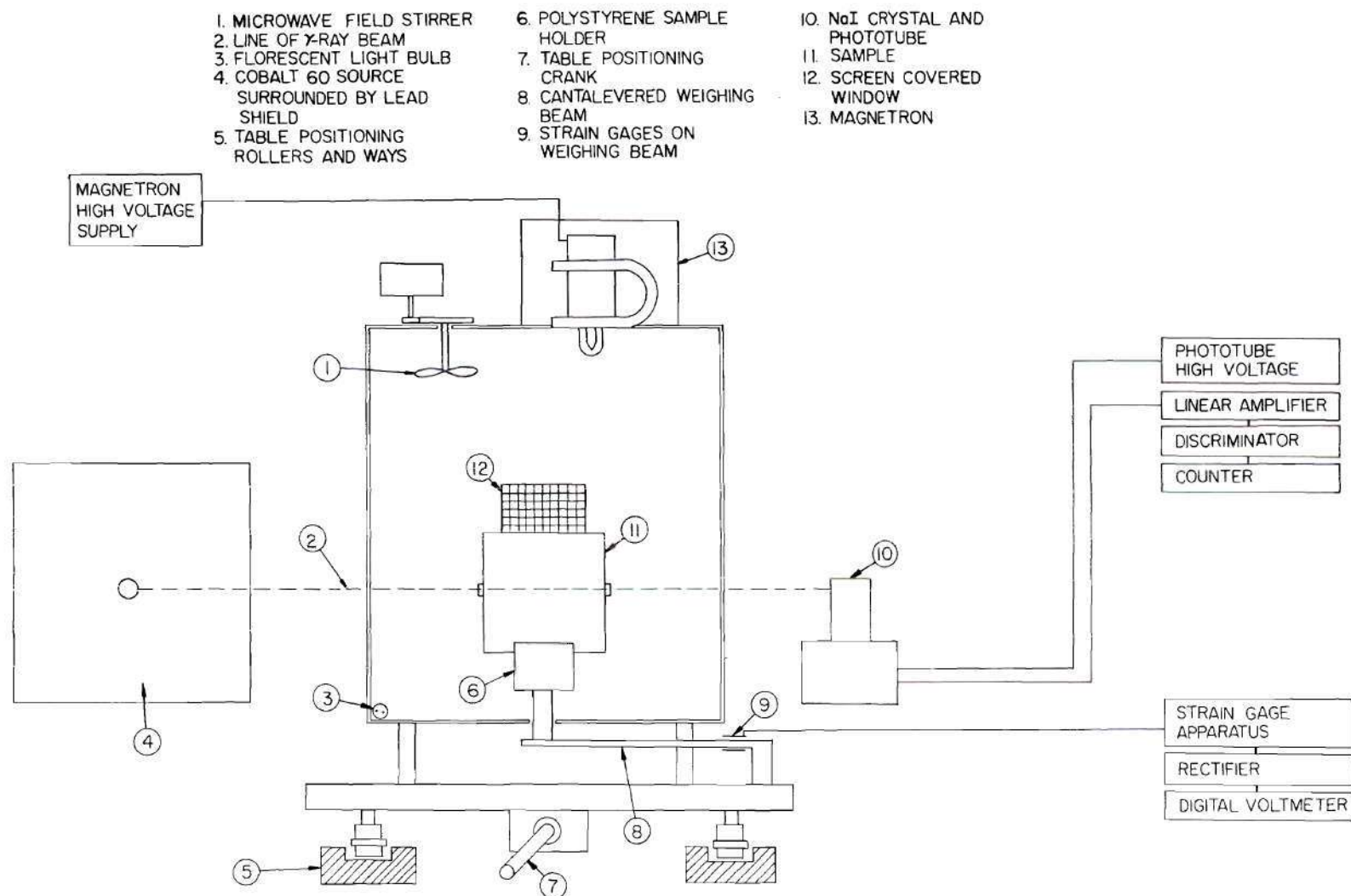
STRAIN GAGE APPARATUS

RECTIFIER

DIGITAL VOLTMETER

Figure 12.   Schematic of Equipment Layout Showing 2450 mc/s Oven.
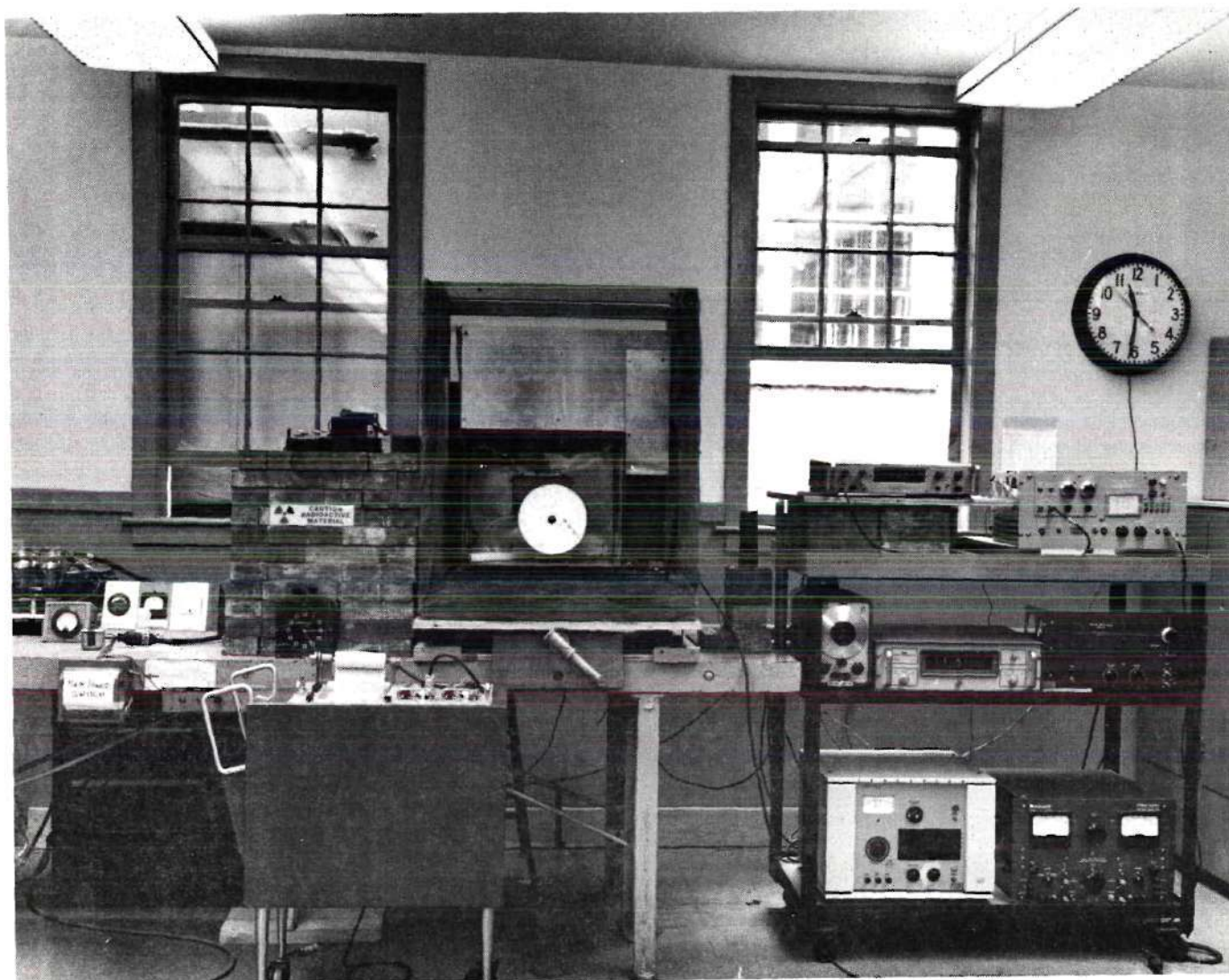
Figure 13. Photograph of Equipment Layout Showing 2450 mc/s Oven.

ches high, 12 inches wide, and 12 inches deep. The microwave output of the modified oven is approximately 400 watts. All of the components, the magnetron, power supply, and oven chamber, are mounted in a single chassis with the magnetron connected to the oven cavity by a co-axial transmission line. Microwave energy is introduced into the heating chamber by means of several resonant dipole antenna elements coupled in the proper phase relationship for establishing a uniform field in a non-resonant cavity. The dimensions of the cavity are such that none of the resonant wave-lengths of the microwave energy at the operating frequency corresponds to a cavity dimension and, therefore, the microwave field created is generally free of resonant modes. The front and the back of the oven chamber are constructed from perforated metal with approximately 1/8 inch square holes comprising approximately 1/3 of the surface area. Through these perfo-rated end plates it is possible to visually observe the sample and to circulate scavenging air through the chamber. Access to the chamber can be obtained by swinging down a hinged door which is normally sealed against a bradded metallic gasket.

The usefulness of this oven as a laboratory heating oven is limited by the small heating chamber. The largest sample volume that can be heated effectively in the oven chamber is 3 inches high and 8 inches wide and 8 inches deep. Because of this limitation on sample size, the majority of the experiments to examine drying characteristics were conducted using the larger 2450 megacycles per second oven. The tests run using the 915 mega-cycles per second oven were conducted to determine the effect of frequency change on the drying characteristics.

Oven Scavenging Air

Air circulation through the ovens is established by placing a centrifugal fan such that room air is forced through one of the oven windows. By adjusting the fan output it is possible to adjust the air flow rate through the oven and out the window on the opposite side. The air flow rate was usually adjusted such that the vapor leaving the drying product was removed from the oven at a rate similar to the generation rate. Tests showed that the air flow rate has little effect on the drying characteristics, but when no scavenging air was used the atmosphere within the oven became so saturated with water that it was difficult to visually observe the sample. Also, there is a tendency for arcing to occur within the microwave field when the oven atmosphere becomes extremely wet.

Oven Cavity Lighting

The screened windows allow visual observation of the drying material inside the oven chambers. In order to provide lighting inside the oven, a fluorescent bulb was placed on the floor of the oven chamber. This bulb absorbs energy from the microwave field and will glow although there are no electrical connections to the bulb. The amount of energy absorbed by the bulb is small in comparison with the total energy of the field, so that the bulb causes a negligible disturbance in the microwave field. The bulb provides sufficient lighting to allow good observation of the sample inside the oven. The bulb also provides a good safety device in that it glows whenever there is a microwave field in the oven, thus reducing the chance that the door of the oven might be accidentally opened before first shutting off the microwave energy.

Oven Field Distribution and Energy Output

The microwave energy input into the ovens can be calculated by observing the amount of energy that is absorbed by a load placed in the microwave field. It was found that the energy output of the microwave generator varied slightly depending upon the electrical characteristics of the load. The total microwave energy input to the oven and the uniformity of the field distribution were measured by observing the amount of energy absorbed by the various amounts of water placed in open beakers at various locations throughout the oven. The energy absorbed by the water was obtained using measurements of the change in temperature of the water and the amount of water which boiled away. The microwave power input to the 2450 megacycles per second oven was found to be between 550 and 600 watts. The microwave power input to the 915 megacycles per second oven was found to be between 400 and 500 watts. A more detailed presentation of the measurements and results concerning the microwave power output of the ovens is given in Chapter VIII.

An investigation of the field uniformity within the oven chamber was made by two different methods. With no other load in the oven, the field distribution was measured by observing the energy absorbed by a number of small beakers of water arranged in a grid throughout the oven chamber. The water in the beakers provided the load for the microwave energy. The relative energy absorption between the different beakers was indicative of the microwave field distribution only for that particular load geometry. If the beakers were rearranged, the field distribution changed.

With a load (such as a cake of wet yarn) in the oven, the field

distribution was examined by observing the light intensity of a grid of 12.5 watts, 115 volts electric light bulbs (the type used on Christmas trees). The bulbs will absorb energy from the microwave field and glow with an intensity proportional to the field intensity. It was observed that the microwave field distribution, when there was a concentrated load in the oven, was different from the distribution when there was a distributed load. When the load was concentrated at the center of the oven, the field concentrated about the load and was weaker in areas of the oven far from the load.

The microwave leakage from the 2450 megacycles per second oven was measured using a calibrated horn and a bolometer. It was found that the leakage from the oven was small such that there was negligible loss in microwave energy due to leakage. In spite of the precautions taken in designing the tongue and groove door seal, it was found that microwave leakage from the edges of the door was sufficient to cause a possible personnel hazard. Since in the course of taking data much time had to be spent directly in front of the oven door, it was decided that further shielding was necessary. A cage of 0.25 inch squares hardware cloth was constructed around the oven. The door of the cage was held in place by two spring catches. The cage door was sealed by using steel wool stripping along the junction of the cage door to the rest of the oven. With the addition of the cage about the oven, the microwave leakage was several orders of magnitude less than the industrially safe standard. The microwave leakage from the 915 megacycles per second oven was measured using a calibrated dipole antenna. The leakage was found to be within the industrially safe limits and no modification to insure safety was required.

Conventional Drying

In order to have a direct comparison between conventional convective hot air drying and microwave drying, experiments were run using hot air drying of yarn packages identical to some that were examined using microwave heating. Samples 6 inches in diameter and 5-3/8 inches long were prepared from absorbent cotton yarn. Thermocouples were placed within the sample enabling the continuous monitoring of the temperature distribution throughout the sample as drying progressed. The sample was placed in a 12 inch diameter wind tunnel. A detailed discussion of the wind-tunnel dryer construction is given in a thesis by Brook.[44] A schematic of the wind-tunnel dryer is shown in Figure 14. Hot air at 300°F was circulated over the sample which was positioned in the center of the wind tunnel with the cylindrical axis vertically oriented. The sample was held in position by a metal rod which fit snugly through the paper core of the sample, positioning the sample such that air could circulate about all sides of the sample. The supporting rod was attached to a platform held in position by four cantilever beam supports such that the deflection of the supports is proportional to the weight of the sample. The deflection was measured by a strain gauge bridge which was connected to a Bruel and Kjaer model 1516 strain gauge apparatus. This allowed the continuous reading of the weight of the sample. It was thus possible to determine the total moisture content and temperature distribution throughout the drying process.

Test Samples

The drying characteristics of both absorbent cotton, non-absorbent cotton, and viscose rayon yarn packages were studied. The non-absorbent
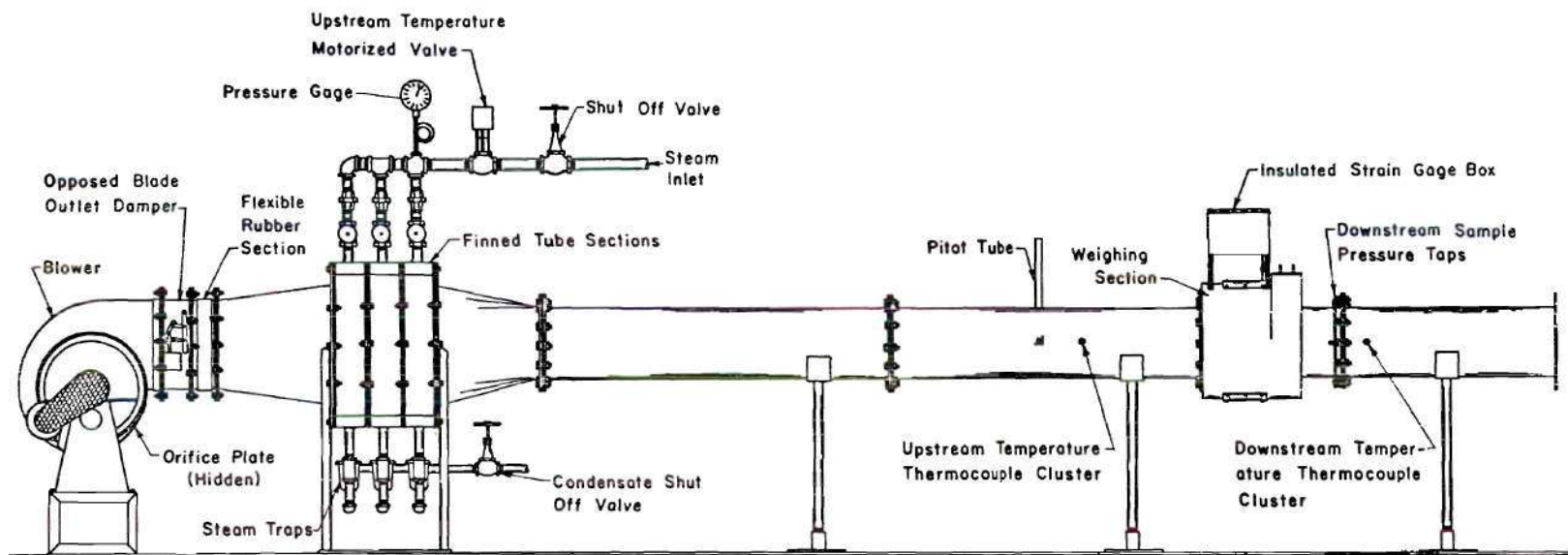
Figure 14. Schematic Diagram of Wind-Tunnel Dryer

cotton yarn was obtained from the Textile Department, Georgia Institute of Technology. The yarn was 24 count single ply, and had not been exposed to any bleach treatment.

The absorbent cotton yarn had been made absorbent by subjecting it to a caustic bleach process. The majority of the cotton yarn was obtained from the Standard-Coosa-Thatcher Company in Chattanooga, Tennessee. This yarn was 28 count, two ply, unmercerized, treated with a special "V" bleach process to make it specially absorbent. A typical commercial use for this particular yarn is to make terry cloth "after a bath" robes.

In addition to the tests made using cotton yarn, some experiments were conducted using absorbent viscose rayon yarn. The drying characteristics appeared to be similar to the characteristics of absorbent cotton yarn. The viscose rayon yarn was obtained from Celanese Corporation, Rome, Georgia Plant. It was dried in the form of two-pound cakes, 4 inches long, 6 inches in diameter and without a center core.

The drying characteristics of several size samples of the different cotton and viscose rayon yarns were studied. Typically, the samples were prepared by winding the yarn on a cylindrical paper core, forming a cylindrical yarn package. The cores are the type standard to the textile industry, made of rolled and glued paper, 7/8 inch in diameter. Such a core is relatively impervious to moisture movement, forming a moisture seal along the center of the sample. When wetting the yarn package, the core was soaked in water but it did not appear to absorb an appreciable amount of water. The paper core did not heat appreciably in the microwave field. Some drying runs were made with the same sample geometry but with the paper core removed from the sample, leaving no center cylindrical support.

Except for considerable distortion of the yarn package due to uneven shrinkage of the drying yarn, no changes in the drying characteristics were observed.

Several different size yarn packages were dried with an attempt to determine the effect of sample size on drying characteristics. There appeared to be little difference in the drying characteristics of the different size samples. The effect of sample size is discussed in detail in Chapter VII. The majority of the tests were run using one of three different sizes. The largest size consisted of a cylinder approximately 8 inches in diameter and 5-3/8 inches long with a dry weight of approximately 3.4 pounds. A shorter cylinder, 2-1/2 inches long and 8 inches in diameter with a dry weight of 1.0 pound was also used. The third sample size was 6-3/8 inches in diameter and 4-1/4 inches long with a dry cotton weight of approximately 1.75 pounds. All three sample sizes were dried in the 2450 megacycles per second oven, but only the two smaller sizes were dried in the 915 megacycles per second oven.

In order to study the moisture movement within the sample, it was necessary to make some tests in which the moisture movement was in one direction only. Moisture flow was restricted to one direction by coating one or more surfaces of the sample with a thermal plastic which was impervious to moisture. To restrict the moisture movement to the axial direction only, the circumference of the yarn cylinder was coated with the plastic. To restrict the moisture flow to the radial direction, the ends of the yarn cylinder were coated. The particular plastic used was a polyester resin manufactured by Marco Chemical Corporation, Linden, New Jersey, and sold under the name MR-455. The resin comes in liquid form with a

consistency similar to Karo syrup. The resin is activated by the addition of methyl ethyl ketone peroxide as a catalyst. It can then be painted onto the yarn sample with a brush and will harden in a few hours forming a hard shell surface. The plastic soaked or penetrated into the cotton sample less than 1/16 inch. Several coats of the plastic were usually applied, forming a plastic shell 1/32 to 1/16 inch thick.

The plastic has a very low microwave loss factor. No heating of the plastic could be observed when a block of the plastic was placed in the oven and the oven turned on. It is thus assumed that the plastic is transparent to the microwaves such that microwave penetration into the sample was unaffected by the plastic. Figure 15 shows three typical samples prepared for different experiments. One sample has the ends sealed with plastic and one the circumference sealed.

The samples were wound on a winding machine and then allowed to come to moisture equilibrium in a known temperature and humidity room. (The average equilibrium moisture content for the absorbent cotton yarn was five percent.) The sample was then weighed and the dry weight of cotton determined. The desired probes such as thermometers and pressure probes were then inserted into the sample and, if applicable, the sample coated with plastic. The added weight to the sample was recorded and then the sample was allowed to soak submerged in a tank of tap water for a minimum of 24 hours. Measurements of the moisture content throughout the sample showed that the largest samples of absorbent cotton were uniformly wet when soaked for this period of time. The non-absorbent cotton required a considerably longer wetting time and some difficulty was encountered in trying to wet uniformly a large non-absorbent cylinder of unbleached cotton.
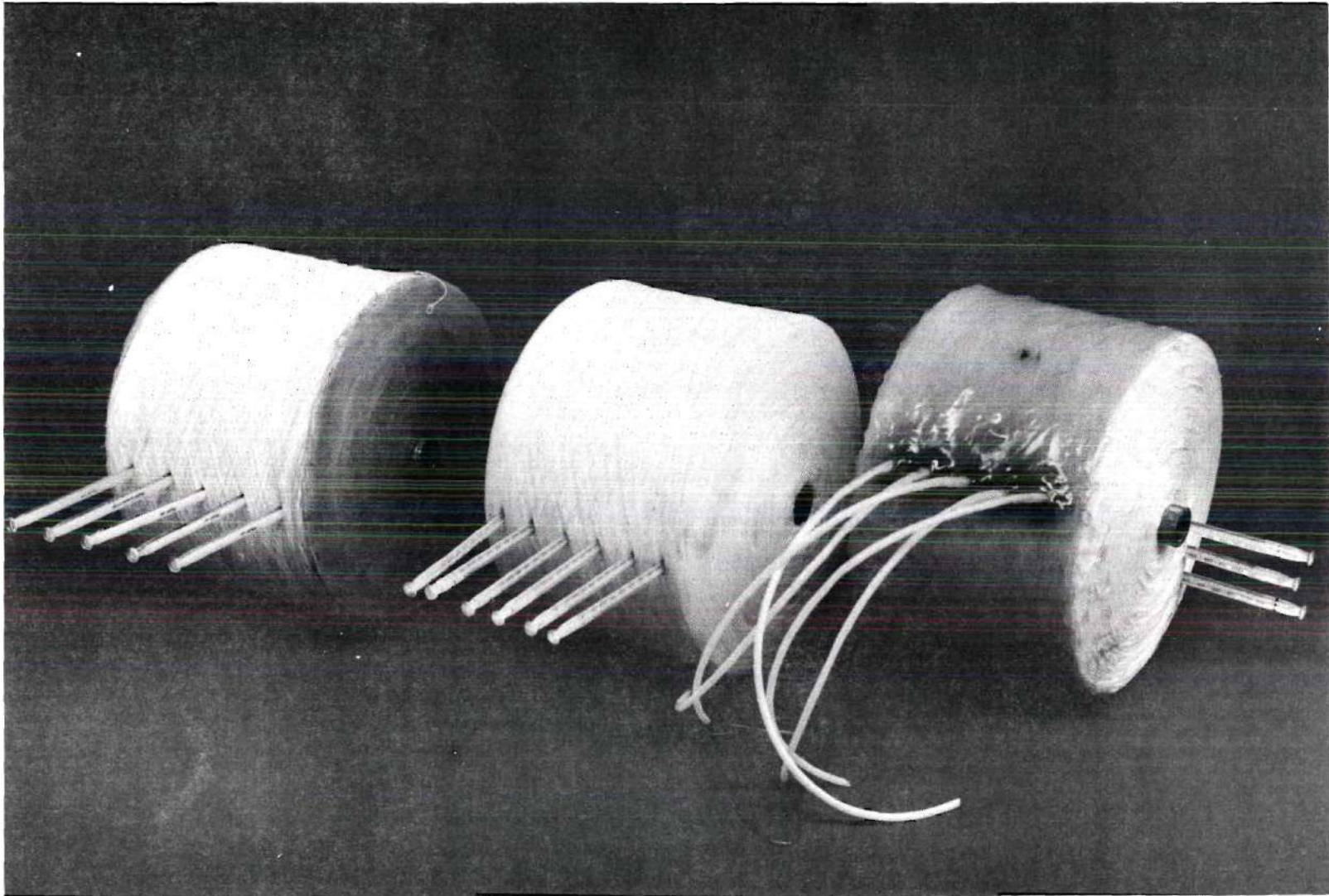
Figure 15.   Three Typical Test Samples.

Typically, the samples were dried starting at an extremely wet state, being allowed only to drain 5 to 10 minutes after being removed from the soaking tank. The initial moisture content of the absorbent cotton samples was typically approximately 2.2 pounds of water per pound of dry cotton and that of the non-absorbent samples approximately 1.1 pounds of water per pound of dry cotton.

Some tests were run starting with samples at lesser moisture contents. The lesser moisture content was obtained by partially soaking the sample and then sealing it in a plastic bag and letting it set until a uniform moisture content throughout the sample was achieved. It was typical to achieve a uniform moisture distribution throughout a package of absorbent cotton in less than 24 hours. In non-absorbent cotton, very little moisture would diffuse through the sample from a wet portion to a dry portion in a 24 hour period, and obtaining uniformity was difficult.

Tests were conducted to examine the moisture conduction or wicking rate. A cylindrical sample of dry cotton yarn approximately 8 inches in diameter and 2-1/2 inches long was wound. One portion of the sample was submerged in a tray of water and the moisture content at locations throughout the unsubmerged portion of the sample monitored. Throughout a 24 hour period of continuous soaking, the moisture content one inch above the submerged surface of a sample of non-absorbent cotton yarn remained less than 0.10 pound of water per pound of dry cotton. The moisture content at a similar location above the submerged surface of an absorbent cotton sample increased to over 1.0 pound of water per pound of dry cotton in less than 15 minutes of soaking. It was concluded from these experiments that liquid water conducted or wicked through an absorb-

ent sample quite rapidly but that there is almost no liquid moisture
conduction through a sample of non-absorbent yarn.

Sample Weight Measurement

In order to determine the total moisture content of the sample
throughout the drying process, it is necessary to continuously measure
the weight of the sample. When the sample is placed in the oven, it is
supported by a small plexiglass platform. This platform is supported
from below by a plexiglass rod, which protrudes through the bottom of the
oven chamber. The plexiglass rod is attached to the end of a 15 inch
long metal beam located below the floor of the oven. The beam is canti-
levered from a rigid support at the opposite end. The beam material is
cold rolled steel and the beam has dimensions approximately 1/8 inch thick
and one inch across. It is rigid enough such that the deflection of the sam-
ple platform is less than 3/16 inch under maximum changes in sample weight.
Four strain gauges are attached near the root of the beam and the strain
gauges are connected into a four terminal strain gauge bridge which is
connected to a Bruel and Kjaer model 1516 strain gauge apparatus. The
voltage output of the strain gauge apparatus is proportional to the sample
weight. The system can easily be calibrated by placing known weights upon
the sample platform and observing the voltage output of the strain gauge
apparatus. The overall sensitivity of the weighing device is 0.01 pound,
with a range of 0 to 15 pounds. The weighing mechanism is shown schema-
tically in Figure 12.

The strain gauges and associated wiring have a tendency to pick up
stray microwave voltages emanating from the oven and generator. By wrap-

ping the gauges with steel wool sheeting and shielding the lead out wires, it was possible to eliminate the microwave pickup.

Temperature Measurement

In order to study the heat and mass transfer characteristics of the drying sample, it is necessary to measure the temperature distribution throughout the sample as drying progresses. The presence of the microwave field restricts the types of temperature measurement devices which may be used. The presence of metallic devices, such as thermocouple wires or thermister wires, causes a large disturbance to the microwave field. Arcing occurs between the wires and the walls of the oven chamber. Alcohol-filled glass thermometers were found to work satisfactorily. The thermometers used throughout the tests were manufactured by the Taylor Instrument Company, Catalog No. 21420. These thermometers are approximately 6 inches in length with a bulb length of approximately 3/8 inch and a diameter of approximately 1/8 inch. The thermometers have a temperature scale range of 0 to 220°F in two degree increments. Using a known temperature bath, it was possible to extend the range of calibration to 250°F and to mark the extended temperature scale on the thermometer stem. Tests consisting of placing the thermometers in the microwave field indicated that the thermometer reading is unaffected by the field and that negligible heating of the alcohol or thermometer glass occurs.

Typically, the thermometers were inserted into the sample after the sample had been wound to the proper size. The thermometers were inserted by slightly pushing aside the yarn fibers using a sharp probe or the thermometer itself. If it was desired to coat the surface of the sample with

plastic, this was done after the thermometers had been inserted. Figure 15 shows three typical samples with the thermometers in position.

A number of tests were performed to determine whether the presence of the thermometers affects the heating characteristics of the sample. The sample was heated for various lengths of time and then quickly removed from the oven and probed with needle-type probes with thermocouples on the end. The temperature distribution in the sample appeared to be unaffected by the presence of the thermometers.

The thermometer readings were found to be affected by the insertion depth of the thermometer into the sample. This effect was most predominant for nearly dry samples. In an attempt to determine the effect of insertion depth, several thermometers were inserted into the sample approximately one inch, leaving a large amount of stem exposed. Some of the thermometer stems were wrapped with 1/4 inch of wet textile material which heated to a temperature similar to the sample temperature. A maximum temperature variation of 5°F was found between exposed stem and unexposed stem thermometers. The variation in the thermometer reading due to the exposed stem appeared to be a function of the position of the thermometer with respect to the oven scavenging air flow as well as a function of the insertion depth. Evidently the thermometer stem temperature varied depending upon the amount and velocity of scavenging air passing the stem. Because of this variation, it was not possible to establish a reliable stem correction procedure. No correction for insertion depth has been made for any of the reported test results. A discussion concerning the reliability and accuracy of all measurements is presented in Appendix D.

Local Boiling Point Temperature

Experiments were run to determine the boiling temperature of tap water in the laboratory. It was found that the average local boiling point of tap water was approximately 210°F.

Pressure Measurement

The pressure distribution throughout the sample was measured by inserting pressure probes into the sample. These probes consisted of lengths of Teflon tubing which were inserted into the wound sample. The Teflon tubing was then led out through one of the observation windows in the wall of the oven and connected to manometer tubes mounted outside the oven chamber. Teflon was chosen as the probe material because its extremely low microwave loss factor makes it invisible to the microwave field.

Several problems were encountered in trying to measure the pressure distribution. One problem was leakage or flow of moisture along the outside of the pressure probes as they extended through the outer layers of the sample. The insertion of the pressure probe distorted the yarn fibers thereby forming a possible flow channel along the edge of the probe. Should flow occur, this would affect the pressure distribution near the probe. Meaningful pressure readings could be obtained only when the surface of the sample through which the probe protruded was coated with moisture sealing plastic. This limited the pressure measurements to cases where at least one side of the sample was sealed with plastic and to measurements at positions along the direction of moisture flow.

A second problem encountered concerned the size of the pressure

probe. Ideally, the probe diameter should be as small as possible. However, it was found that as the manometer fluid level is displaced due to the pressure variation, the vapor from inside the sample is drawn into the tubing. When the vapor fraction in the tubing protruding from the sample becomes large, there is a tendency for the vapor to condense back into a liquid. The surface effects of the liquid drops thus formed could cause a relatively large pressure variation along the probe tubing. It is possible to minimize the effects of moisture condensation in the lead out tubes by using relatively large tubes and keeping their length to a minimum. Satisfactory results were obtained using 0.106 inch internal diameter tubing inside the sample and a short distance from the sample surface expanding to 0.250 inch internal diameter tubing. The 0.250 inch diameter tubing was used for both the lead out tubing and for manometer tubing. The manometer fluid used was water. Using these tubing sizes, negligible condensation could be observed in the probes or lead out lines. No condensation was observed within the manometer tubes. Figure 15 shows a typical sample with the Teflon pressure probes and lead out tubes in position.

Moisture Measurement

In order to study the drying characteristic, it is necessary to measure the moisture content at locations throughout the sample. The measurement of moisture content inside drying bodies is generally difficult and the presence of a microwave field further complicates the measurement problem. The measurement device must not be affected by the microwave field and also not distort or disturb the field. A method developed allow-

ing the measurement of internal moisture content consists of shining a collimated beam of photons (gamma rays) through the sample and measuring the attenuation of the beam. The photons are uncharged particles and are, therefore, unaffected by the microwave field. The basis for this technique is that the intensity of the beam of radiation decreases as it passes through the sample. The more molecules of material in the path of the beam of photons, the more likely the collision of the photons with the material. The more water present in the path of the beam, the less will be the intensity of the exiting beam. Therefore, the amount of water along a line through the sample can be measured by observing the attenuation of the radiation beam shined through the sample. The beam will also be attenuated by material other than water such as the oven walls, dry cotton, etc., but this attenuation will not vary as the sample dries. The difference between the attenuation through a wet sample and through a dry sample will be proportional to the amount of moisture in the wet sample. A detailed discussion of the principles of moisture measurement using gamma radiation is given in Chapter VI. Only general comments and descriptions of the specific equipment used in this research are discussed in this chapter.

Although this method of moisture measurement yields the average amount of water along a line through the sample rather than a more desirable localized point measurement, the line measurement tells much about the moisture content of the sample. If the moisture movement can be restricted such that there is no variation of moisture content in one dimension, the moisture distribution throughout the sample can be measured by shining the beam parallel to the uniform direction.

A schematic diagram showing the equipment layout for moisture mea-

surement (along with other equipment used in the tests) is shown in Figure 12.

The gamma ray source used was cobalt-60. The cobalt-60 was contained within a small pellet roughly 1/8 inch in diameter and 1/4 inch long. The source had a radioactivity of approximately 10 curies. To facilitate the handling of the source, the radioactive pellet was mounted in a cylinder 1.06 inches in diameter and 12 inches long. The portion of the cylinder above and below the pellet is filled with lead. When the cylinder holding the source is snugly inserted into a cylindrical hole bored from the top into a large lead-filled container, the pellet is completely surrounded by lead (see Figure 16). A small hole 1/16 inch in diameter was drilled horizontally from the wall of the container intersecting the center of the container along the centerline of the cylindrical cobalt-60 source holder. The length of the hole is 9 inches. By raising the cobalt-60 holder slightly above its bottoming position, it is possible to align the cobalt pellet with the 1/16 inch hole, allowing a beam of radiation to escape through the hole.

The lead container was formed by welding a steel outer shell and pouring this full of molten lead. Approximately 1000 pounds of lead was required. A 1-1/16 inch diameter hole was drilled and reamed from the top of the cylinder for the source holder. Some difficulty was encountered in drilling a 9 inch long, 1/16 inch diameter straight hole through the side of the container. A 1-1/2 inch hole was drilled and reamed along the line of the desired 1/16 inch hole. Lead spacers approximately three inches long and sized to fit snugly in the larger hole were machined. A 1/16 inch hole was drilled through the center of these spacers using a 1/16 inch dia-
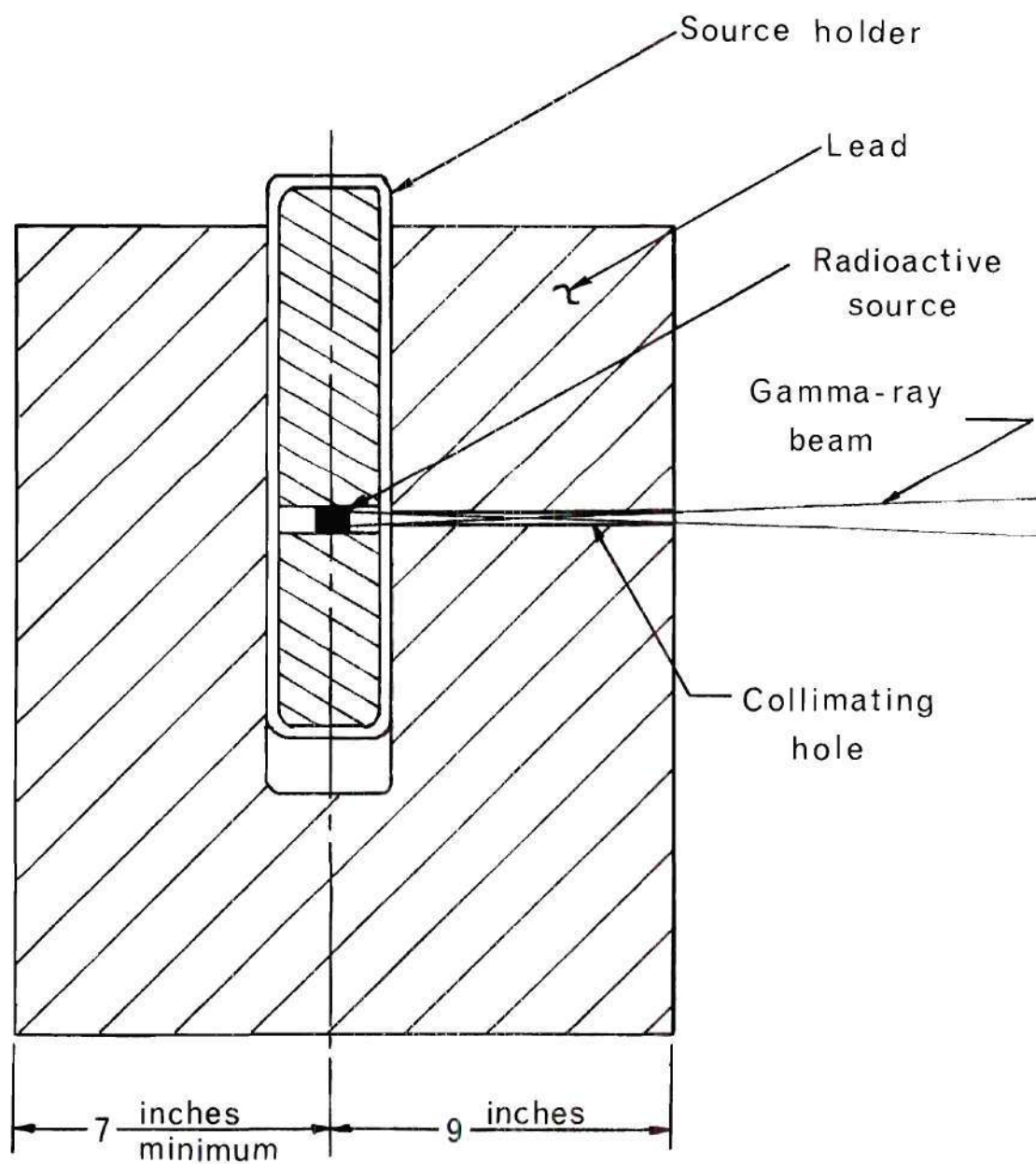
Figure 16.   Radioactive Source, Collimator, and Container.

meter drill rod as a bit. These spacers were then stacked into the 1-1/2 inch diameter hole.

The intensity of the gamma ray beam was measured by the scintillation technique. A Harshaw NaI(TI) Scintillation Detector was placed in the path of the beam. Both two and three inch diameter crystals were used. It was found that the three inch diameter crystal worked better than smaller crystals because of the tendency for the high energy (1.33 MeV) photons from the cobalt-60 to pass through the smaller crystals without a collision. The scintillation detectors were powered by a Tracerlab Versamatic II power supply.

The output of the scintillation detector was fed into a Franklin Electronics Linear Amplifier and Discriminator. The output from the discriminator, which is a 24 volt pulse corresponding to each input pulse within the discrimination band, was fed into a Hewlett Packard Digital Counter model 5233L. In order to obtain the desired counting time intervals (generally 50 seconds), it was necessary to supply the counter with an external time base. A Hewlett Packard model 202C Audio Oscillator was used for this purpose.

Cobalt-60 has two primary photon emission energies, 1.17 and 1.33 MeV. The pulse height discriminator was set such that photon energies between 1.0 and 1.4 MeV were counted. It was found that the count rate of the beam after passing through the sample and the oven walls surrounding the sample was in the order of one to five million counts per minute. A higher count rate was possible with the particular source and geometry, but at higher count rates the counting equipment used appeared to saturate slightly so the higher count rate was not used.

In order to measure the moisture content at many locations through-out the sample, it is necessary to move the sample with respect to the radiation beam. Because of the tremendous weight of the lead radiation source container, it is more practical to move the oven than to move the radiation beam. The entire oven was located on a sliding table which allowed the horizontal positioning of the sample with respect to the beam.

CHAPTER VI

THE USE OF GAMMA RADIATION TO MEASURE MOISTURE CONTENT

Introduction

In order to examine the characteristics of the drying processes, it is desirable to be able to determine the local moisture content throughout the drying body during transient drying conditions.

The determination of the local moisture content must be conducted in such a manner that the heat and mass transfer within the body is insignificantly disturbed by the measuring device. Also, the volume of the sample over which the measurement is taken should be small such that the measurement can be considered a local measurement. There are two types of moisture contained in many hygroscopic materials, bound moisture entrained in the cell of fiber walls or in very small capillaries, and free moisture.[8] It is usually desirable for the measuring device to measure both types of moisture.

A useful technique for measuring the moisture content of a drying sample is to shine a collimated beam of photons or other radioactive emissions through the sample and measure the attenuation of this beam. The basis of this technique is the fact that the intensity of radiation decreases as it passes through the sample. If the source intensity of the beam is constant and if the amount of dry product in the path of the beam remains constant, the change in the intensity of the attenuated beam can be related to the change in moisture content of the sample.

This technique has the convenience of not requiring a physical connection to the drying sample. The radioactive beam may be shone through the sample and through the walls of the oven, wind tunnel, bell jar, etc. in which the sample is being dried. Since the amount of attenuation of the beam by the surrounding container does not change as the sample dries, this attenuation can be differentiated from attenuation due to moisture content.

Types of Radiation

The collimated beam may consist of several different types of radioactive emissions, neutrons, alphas, betas, gamma rays, or x-rays. Alpha particles are absorbed by a sample in a very short distance of penetration. For example, a sheet of paper will absorb most of the incident alpha particles. This makes the use of alpha particles impractical for the moisture measurement of thick samples.

Beta particles are more penetrating than alpha particles, but they are also absorbed very easily. They have the disadvantage that their absorption by the sample is not truly an exponential function of penetration depth but rather a complicated function including the molecular arrangement of the sample. This makes correlation of attenuation to moisture content more difficult than with some other types of radiation. Dreshfield[45] has shown that the use of betas gives good results for thin samples such as paper.

Neutrons have an affinity to the hydrogen atom; therefore, their attenuation in the sample is greatly affected by the number of hydrogen atoms in the beam's path. The use of neutrons works well for measuring

the moisture of materials where the only hydrogen present is in water. Belcher et al.[43] have shown that the use of neutrons works well for detecting the moisture content of sand. However, when the drying sample contains a material like cellulose, which has a very high hydrogen count, this method does not work as well. The attenuation of the neutron beam becomes primarily a function of the amount of dry product in the beam's path and less a function of the moisture present. Another disadvantage to using neutrons is that neutron bombardment has the effect of activating (making radioactive) the sample. Like beta particles, the attenuation of the neutron beam is not an exponential function of moisture content.

X-rays are low energy photons and in this way behave similar to gamma rays, which are described in following paragraphs. The potential penetration of a photon is a function of the energy of the photon. Since x-rays are low energy photons, they have low penetration and are limited in their use to thin samples. X-rays are usually generated by electrical equipment. Equipment which will provide the necessary photon flux is often expensive compared to similar techniques using photons obtained from radioactive decay.

Photons are classified according to their mode of origin, not their energy. Gamma rays are defined as electromagnetic radiation accompanying nuclear transitions. Radioactive isotopes provide a convenient source of gamma rays. Although most radioactive isotopes emit photons at a multitude of energy levels, many isotopes have one or more energy levels at which they emit the bulk of their photons. By selecting different isotopes, the energy range available is quite broad, extending to much higher energies than x-rays. Thus, when gamma rays are used, there is little

limitation as to sample thickness. If more penetration is required, it may be obtained by choosing an isotope which emits higher energy gamma rays. It should be observed that too high an energy must not be used or the amount of attenuation due to the moisture might be too small to be conveniently measured. Since gamma rays can be obtained by the decay of inexpensive radioisotopes, obtaining a gamma ray source is relatively inexpensive.

Relationship Between Attenuation and Moisture Content

Unlike charged particles such as alpha and beta rays, a well-collimated beam of gamma rays shows a truly exponential absorption behavior in matter. The reason for this lies in the fact that photons are absorbed or scattered in a single event. That is, the collimated photons that pass through the absorber have not interacted with the absorbing material, while the ones absorbed have been eliminated from the beam in a single event.

There are a number of processes that cause gamma rays to be scattered or absorbed. The three types of interactions that are of importance in the energy range from 0.1 to 6 MeV are the Compton effect, the photoelectric effect, and the pair production effect. A detailed discussion of other minor effects is presented by Evans.[46] The Compton effect is one in which a photon is deflected by an electron of the atom in the absorbing material. The collision is elastic and not only is the direction of the photon changed, but the energy of the photon is also reduced, some of the energy being transferred to the electron. The photoelectric effect is the process in which a photon gives all its energy to a bound electron. This electron uses part of the energy to overcome its binding to the atom and

the rest as kinetic energy. Pair production is a process in which a photon strikes an atom and produces an electron-positron pair. This process can only take place when the energy of the photon is equal to or greater than the mass energy of the electron-positron pair. These three processes act independently with some being more dominant at different energy levels of the incident photons.

The basis of all measurements of the absorption of gamma rays is the fact that the intensity of radiation decreases as it passes through material. The probability of a given photon passing through a distance x of the absorber without any interaction with the absorber is the product of the probabilities of survival of the photon for each of the possible interactions. Therefore, the probability of the photon traversing the thickness x without a Compton collision is $e^{-\sigma x}$, without a pair-production is $e^{-\beta x}$, and likewise without a photoelectric effect is $e^{-\gamma x}$. The coefficient σ is the linear attenuation coefficient for the Compton process, β is the linear attenuation coefficient for the pair-production effect, and γ is the linear attenuation coefficient for the photoelectric effect. A collimated beam of gamma rays of intensity I_O will have a residual intensity, I, after the beam has traversed a distance, x, through a particular material. The intensity, I, is given by

$$I = I_O \, e^{-\sigma x} \, e^{-\gamma x} \, e^{-\beta x}.$$ (6.1)

Equation 6.1 may be reduced to

$$I = I_O \, e^{-(\sigma+\gamma+\beta)x}$$

or

$$I = I_O \, e^{-\mu_O x}$$

where μ_O is the total attenuation coefficient. For gamma rays of a given level, the total attenuation coefficient can be expressed as the following:

$$\mu_O = C \, N_a \, Z \, \rho$$

where Z is the atomic number of the absorber, N_a is Avogadro's number, ρ is the density of the absorber, and C is the constant of proportionality.

It is seen that a given material will have a constant total mass absorption coefficient if the energy of the incident radiation is constant. If a collimated beam is incident upon a material in which the density is changing, then the change in the residual intensity is a direct function of the change in density of the absorber. Generally during drying processes, the change of density is caused only by a change in the moisture content. Therefore, if a collimated beam of gamma rays passes along some line through the product during the drying process, the change in the attenuation of the gamma rays can be related directly to the change in moisture content along this path.

Since gamma ray absorption is exponential, the equation for absorption can be written in terms of the wet and dry states of the sample. The equation is

$$I = I_{dr} \, e^{-kux} \qquad\qquad (6.2)$$

where I is the intensity of a gamma ray beam after passing through a wet sample and I_{dr} is the intensity of the same gamma ray beam passing through the same dry sample; where k is a constant that is determined experimentally, u is the average moisture content, and x is the distance through the product. The constant k incorporates the density of dry product, Z, N_a, and all the constants involved in the exponent of equation 6.1. The moisture content is then given by the equation

$$ux = \frac{1}{k} \ln \frac{I_{dr}}{I} \quad . \tag{6.3}$$

The intensity of the beam when shining through the dry product can be determined by measuring the beam intensity at the measurement locations before the sample is wetted. If the beam intensity is measured at one other known moisture content, the proportionality constant, k, can be calculated. Throughout this research the moisture content was nearly uniform throughout the sample after wetting but before starting the drying process. Since the moisture content was uniform throughout the sample, it could be obtained by calculation, knowing the weight of dry cotton and the weight of water. Measurements of this known moisture content provided the necessary information for the calculation of the proportionality constant.

Beam Intensity Measurement

It is customary to determine the radiation intensity by counting the number of photons in the beam. The intensity, I, is proportional to the number of counts divided by the time interval of counting and divided by the efficiency of the counting instrumentation. It is convenient to

use consistent counting intervals for all measurements during a drying experiment. It is not always possible to rely upon the counting efficiency to remain constant for long periods of time. The counting efficiency is particularly sensitive to drift because of the use of a pulse height discriminator. Slight changes in the scintillation tube power supply voltage or the gain of the linear amplifier will cause a shift in the voltage magnitude of the pulses approaching the discriminator. Since the discriminator window may not shift correspondingly, the window may look at a different level of photon energies. Instrumentation is available which allows a minimum drift in counting efficiency, but besides being quite expensive it usually requires constant temperature surroundings. Typical drying laboratories do not have a precisely controlled atmosphere.

It is possible to compensate for a slow drift in counting efficiency. Periodically throughout the drying process the beam is positioned such that it shines through an unchanging media that will give a constant amount of attenuation from the beginning through the end of the experiment. The number of counts per counting interval at this location is periodically recorded. If there is no drift in the number of counts when the beam is shining through this unchanging media, no drift in the counting efficiency is occurring.

If a drift is observed the effect of it can be nullified by using a modified equation for calculation of the moisture content. Since the amount of attenuation by the unchanging media is constant, both the dry intensity and the wet intensity may be divided by this reference intensity, I_r, giving

$$u = \frac{1}{k} \ln \frac{I_{dr}/I_r}{I/I_r} \; .$$

If the counting efficiency of the measurement system does not drift too rapidly, the counting efficiency during some of the periodic reference measurements can be assumed to be the same as that during test measurements taken during the same period of time. The number of counts recorded on the counter is proportional to the beam multiplied by the counting efficiency and the time interval of counting. If the time interval and counting efficiency are the same when the test measurement and reference measurement are made, the ratio of intensities is equal to the ratio of the number of counts. This leads to the modified equation for moisture content

$$u = K \ln \frac{N_{dr}/N_{rdr}}{N/N_r} \tag{6.4}$$

where N is the measured number of counts when the beam is shone through the sample. N_r is the best estimate of the number of counts that would be measured were the beam shining through the reference media, obtained by interpolating between the periodic measurements taken through this media. N_{dr} is the number of counts observed when the beam was shone through the dry sample at the measurement position, and N_{rdr} is the number of counts through the reference media at the time the dry sample count was measured.

Statistical Variations

An inherent limitation of the accuracy of the gamma-ray method to determine moisture content lies in the nature of gamma radiation emission. Although the average emission rate of the source may be predicted by the half life of the material, the rate at any instant is subject to fluctuations about a mean value due to the random nature of gamma ray emission. As the events of emission become larger, the distribution of the measured emission rate approaches the Poisson distribution,[47] for which the standard deviation of the number of emissions in any given time is equal to the square root of the number of emissions. One can predict with a confidence level of 68.2 percent that the variation from the mean number of counts will not be more than one standard deviation. That is to say that the statistical variation in the number of counts during any counting period will not be more than the square root of the number of counts, 68.2 percent of the time. In order to increase the confidence level, the number of standard deviations must also be increased. To have a confidence level of 95.4 percent, two standard deviations in the count rate must be tolerated. For a confidence level of 99.73 percent (which is sufficient for most engineering problems), the statistical variation in the count rate will be three times the square root of the number of counts. It should be noted that the larger the number of counts, the smaller the percent statistical variation.

It should be pointed out that the percent error in the moisture content measurement due to statistical variations is not the same quantity as the percent statistical variation in the count. For example, suppose that one million counts are obtained during one counting period

through a wet sample of approximately 50 percent moisture content. Suppose also that through the same sample when dry, the mean number of counts, averaged over many counting periods (thereby reducing statistical variations), is one and one-half million counts. With a confidence level of 99.73 percent, the statistical error in the measured count through the wet sample would be three times the square root of one million or ± 3,000 counts. Using equation 6.3 shows that, due to this statistical fluctuation, the observed moisture content could vary from 49.6 percent to 50.3 percent. This error is a result of random statistical variation alone and is in addition to more common errors introduced by counting circuit nonlinearities, timers, and relays. The common errors are reduced by good design practices but the statistical error is only reduced by increasing the number of counts per counting period. The number of counts per counting period may be increased by either lengthening the counting period or increasing the source intensity. Measurement instrumentation has a limit on what rate pulses may be counted. The average period between pulses must be less than the response time of the instrument or many pulses will not be counted as they occur while the instrument is counting the previous pulse. Lengthening the counting period has the disadvantage that the sample characteristics might change during the measurement period.

Experimental Equipment

The necessary experimental equipment can be categorized as a source, a collimator, a radiation detector, a discriminator, and a counter. Each of these is considered individually below.

Collimator

The emission from the source is normally spherical and must be collimated. This can be accomplished by surrounding the source with sufficient shielding to reduce the radiation intensity to a satisfactory, safe level and by providing a small hole through the shielding. The radiation from this container will be insignificant in all directions except directly in line with the hole. The longer and smaller the diameter of the hole, the smaller will be the diameter of the collimated beam.

An easy way to check the size and geometry of the beam is to place a piece of Polaroid film in a light-sealed packet in the path of the beam and observe the spot on the film which is exposed by the gamma radiation. The required exposure time is a function of the beam intensity and photon energy. The writer has used exposure times of one to four hours.

Only the portion of the source directly in line with the hole will emit a significant number of photons which find their way through the hole. Therefore, the smaller the hole, the less the effective intensity of the source. It is desirable to minimize the total intensity of the source as this minimizes the amount of shielding required when using or handling the source; but, the required beam intensity is set by the sample thickness, density, etc., and the allowable statistical variations. This points out the need for a small compact source such as a pellet or needle.

Radiation Detector

The intensity of the beam of photons after it passes through the sample can be observed by means of a scintillation detector. A commonly

used detector consists of a sodium iodide crystal and a photoelectric tube surrounded by a thin light shielding container. When a photon strikes the sodium iodide crystal, a light pulse with an intensity proportional to the photon's energy is emitted. The photoelectric tube converts this light pulse into an electrical signal. The magnitude of the signal will be proportional to the energy of the photon.

Rather than a scintillation crystal, gas filled tubes are often used to detect radiation intensities. When a photon strikes a molecule of gas in the tube, the gas is ionized and this causes an electrical discharge to occur between two charged plates within the tube. This discharge provides an electrical signal which can be supplied to a counter. This type of detection device is often cheaper than a scintillation type detector. For the application being considered, the gas filled tube has two disadvantages, however. The detector has a low efficiency as many of the photons pass through the gas in the tube without a collision. Therefore, to get the required number of recorded pulses, the beam intensity must be greater than in the case of a more efficient sensor. Secondly, the signal from the tube is not proportional to the energy of the photon triggering the signal. This makes it electronically impossible to separate for consideration those photons within a limited energy range. Being able to consider photons of a particular energy range greatly increases the sensitivity of the count rate to moisture changes.

Discriminator

When a scintillation detector is used, a pulse height discriminator can be used to eliminate from consideration all photons except those

of a particular energy band, generally the primary emission energy of the
source. The pulses from the scintillation detector are fed into the input
of the discriminator. The discriminator observes these pulses and generates
an output pulse for each input pulse of voltage magnitude such that it falls
within the preset "window." The discrimination of photons with higher
energy than this particular energy band eliminates high energy radiation
from outer space as well as that from the source which might be of such
high energy that it is not stopped by the shielding about the source. The
discrimination of photons with lower energy than this particular band
eliminates low energy background radiation and also eliminates pulses
caused by products of photons which collided with a molecule of matter
when passing through the sample. The products of collision are of lesser
energy than the original photon.

Counter

The output of a pulse height discriminator is generally a train
of constant amplitude pulses with one pulse corresponding to each discrimi-
nator input pulse that fell within the band of acceptance. The time spac-
ing between these pulses will be random, corresponding to the scintilla-
tion input. Due to the random spacing of the pulses, the response time
of the counting and recording instrument must be considerably faster than
if the instrument counted evenly spaced pulses. The writer's experience
has indicated a response time of one-sixtieth of that required for evenly
spaced pulses works satisfactorily.

Several types of counters may be used to count the output pulses
of the discriminator. If continuous readings are desired, a count rate

meter which continuously calculates and displays the count rate may be useful. One disadvantage of such a device is that it is difficult to obtain a rate meter that has a scale sufficiently expanded to allow precise readings.

If a digital counter is used to display the discriminator output, either a counter which counts for a preset time and then records the counts during this period, or a counter which counts a preset number of counts and displays the counting time may be used. Either method works satisfactorily provided the display from the counter can be read to enough significant figures to make the readout error insignificant with respect to the change in count rate between wet and dry samples.

Source

The source used must emit the bulk of its photons at an energy level which gives appropriate penetration through the sample under study. The source intensity must be such that in this energy range the required number of photons are emitted to give an allowable statistical error.

Two isotopes quite useful for measuring the moisture content of samples of textile, meat, sand, etc. are cobalt-60 and cesium-137. Both radioisotopes emit primarily at definite energy levels, cesium-137 at 0.661 MeV and cobalt-60 at the two levels 1.17 and 1.33 MeV. Because of cesium-137's lower emission energy, it is ideal for thin or less dense materials. Both radioisotopes can be obtained in the necessary radiation quantity at a relatively low cost. Both isotopes have a half life (time to decay to one-half intensity) which is sufficiently long for most applications. Cobalt-60's half life is 5.27 years and cesium-137's is 33 years.

These decay rates are well known and the actual average intensity at any time can be easily computed from the original average intensity. Since neither isotope is a neutron emitter, there is no danger of activating the product.

Hazards

It should be pointed out that, due to the hazards involved, the Atomic Energy Commission requires that the user take certain precautions before purchasing or using appreciable quantities of radioactive materials. However, to make measurements, it is not necessary to remove the source from its container, and, therefore, very little special handling equipment is necessary once the initial source installation is made. Because the radiation beam is concentrated along one line, it is quite easy to minimize the possibility of accidental personnel exposure.

CHAPTER VII

EXPERIMENTAL RESULTS

Introduction

Packages of yarn were dried and measurements were performed during drying to determine the drying characteristics. The temperature, moisture content, and pressure at various points within the drying sample as well as the total weight of the sample were recorded during drying. Experimental tests were performed during the drying of yarn samples using convective hot air heating as well as microwave heating at 2450 megacycles per second and 915 megacycles per second. The results of each of these types of heating is discussed separately in the following sections. The majority of the experiments were conducted using an 8 inch diameter, 5-3/8 inch long sample of absorbent cotton. The results of experiments concerning other size samples and other types of yarns are discussed in separate, following sections.

Graphs presenting the experimental results are dispersed throughout this chapter. The run number corresponding to the particular experimental test is given on each graph. Specific details concerning the sample, the oven, and the drying situation are given in tabular form by run number in Appendix A. A discussion of the precision of the various measurements and the possible errors in the data is presented in Appendix B.

<u>Convective Air Heating</u>

Although drying using convective hot air heating was not the primary concern of this research, some experiments were conducted so that data would be available for comparison with the identical yarn packages which were dried using microwave heating.

Packages of bleached cotton yarn were wound in a cylindrical shape on a 7/8 inch diameter paper core. The packages thus formed had an outside diameter of 8 inches and a length of 5-3/8 inches. The total dry weight of the yarn was approximately 3.4 pounds. The samples were soaked in water for approximately twenty-four hours during which they absorbed approximately 6.8 pounds of water. They were then placed in a 12 inch diameter wind tunnel and dried by circulating 300°F air about the packages. (For a more detailed discussion of the dryer or the yarn package see Chapter V.) The temperature at several locations within the sample and the weight of the sample were recorded.

The variation of total moisture content of the package as a function of drying time is shown in Figure 17. Using the information presented in Figure 17, it is possible to plot drying rate versus moisture content. This result is shown in Figure 18. These curves follow very closely the results obtained by previous investigators[8] examining drying using convective heating (see Chapter II).

A plot of the temperature profile within the sample in the radial direction at fixed times is shown in Figure 19. The temperature of the inner portions of the sample remains lower than that of the surface, with the temperature rising rapidly in the layer near the surface. This corresponds with the drying mechanisms explained in Chapter II. For the
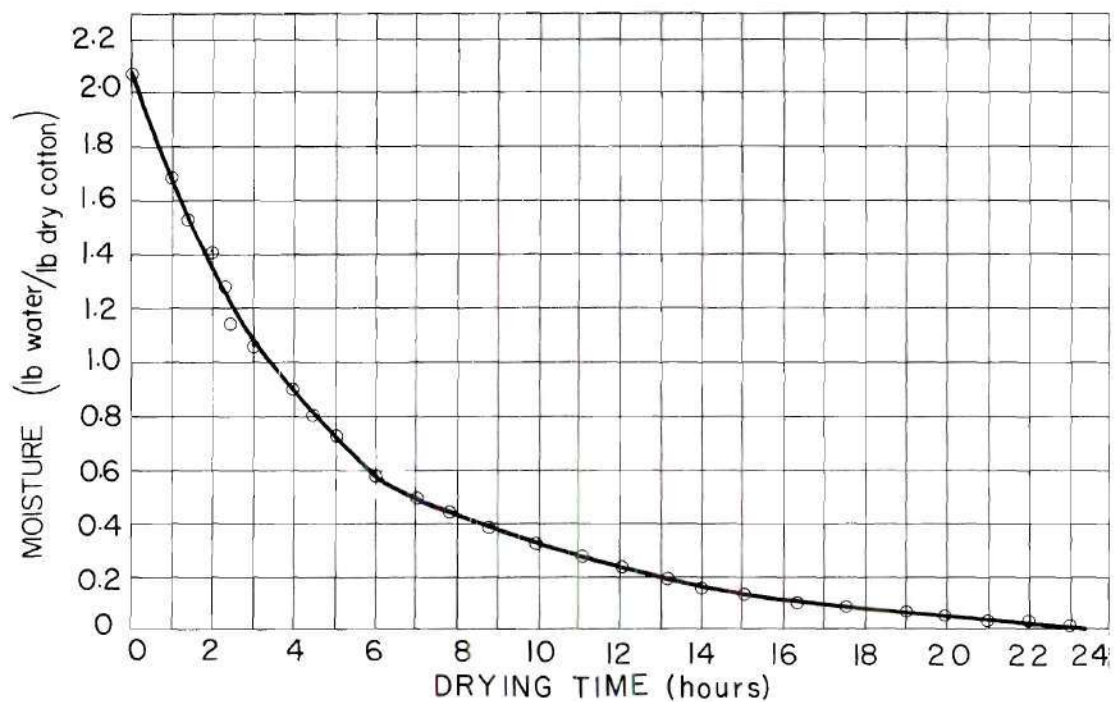
Figure 17. Total Moisture Content Variation During
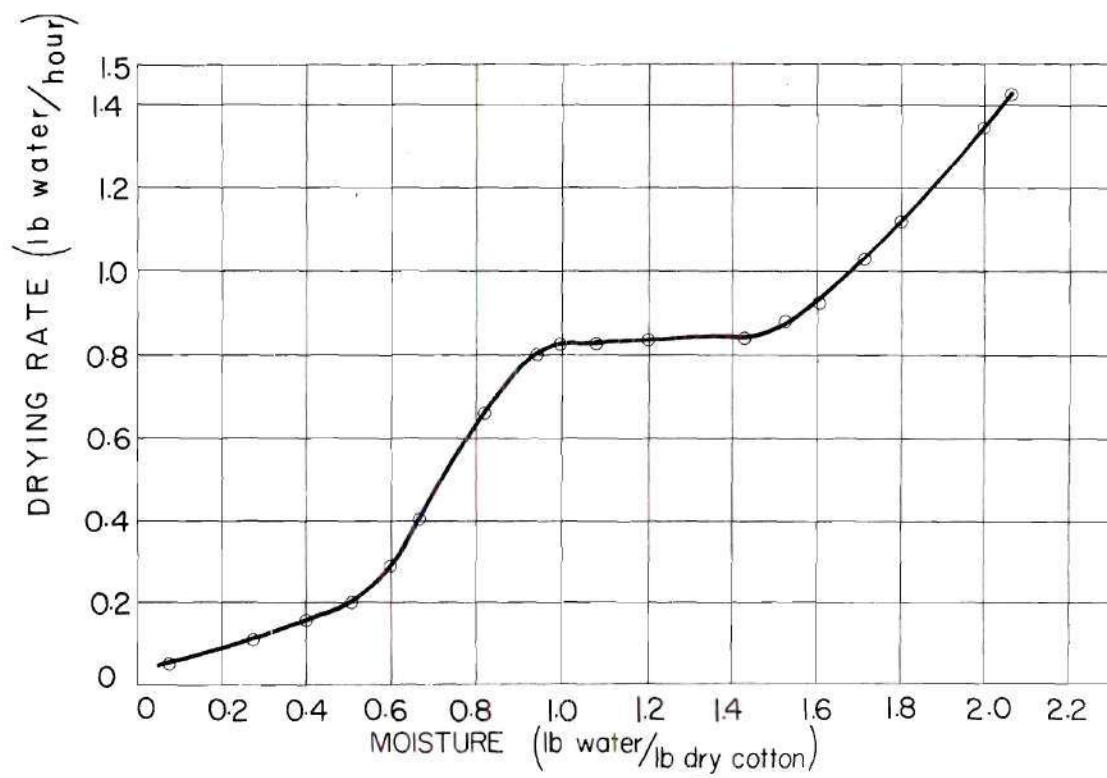Drying Using Conventional Heating--Run 40.

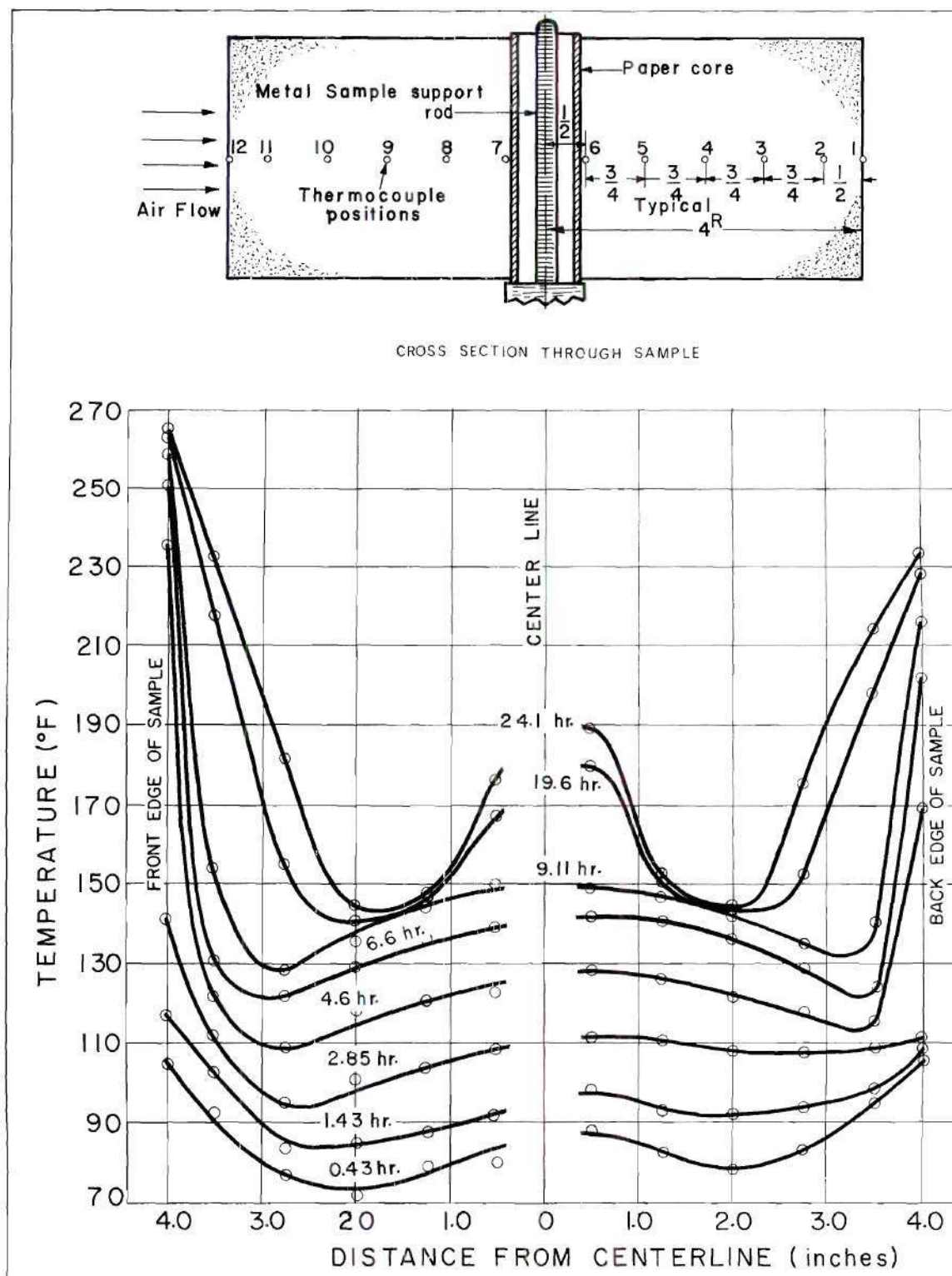Figure 18. Drying Rate Curve for Drying Using Conventional
Heating--Run 40.

Figure 19. Temperature Profiles During Drying Using
Conventional Heating--Run 40.

particular experimental data presented in Figure 19, the temperature of the center core of the sample is slightly higher than the temperature a short distance from the center. This temperature increase is because of energy addition at the center of the sample due to conduction along a metal rod which protruded through the center of the sample. The rod was used to support the sample within the wind tunnel.

It is significant to note that it took over twenty-four hours to dry the sample using conventional heating. The temperature of the circulating air was 300°F and, therefore, portions of the sample surface reached this temperature. Some surface discoloration of the cotton was observed due to overheating. The product damage could be reduced by lowering the air temperature but this would further slow the drying process.

Microwave Heating

Packages of cotton yarn were dried using microwave heating. The temperature, moisture, and pressure at various positions within the package and the total weight of the package were measured during the drying process.

The sample packages were prepared, as described in Chapter V, by winding the yarn on a 7/8 inch paper core. Some of the samples were wetted and dried with no further preparation, but the surface of some of the samples was sealed with plastic before wetting and drying. The plastic was impervious to water and by sealing one or more surfaces it is possible to restrict the moisture flow to either the radial or axial direction. The plastic has negligible effect on the microwave field pene-

tration. The results of each of the flow situations, sides sealed, ends sealed, and unsealed, are presented individually in following sections. However, before discussing the specific characteristics of each type of sample, some of the general microwave drying characteristics of packages of textile yarn are presented in the following section.

Characteristics of Microwave Drying

The characteristics of drying using microwave heating are generally the same whether the sample is sealed or unsealed, absorbent or nonabsorbent, large or small. The parameters such as temperature, moisture content, pressure, and drying rate vary in a similar manner regardless of the type sample. The runs or experiments used as examples throughout this section represent several of the different type samples. For specific details concerning each run see Appendix A.

Figure 20 shows a typical plot of the total moisture variation during a drying process using microwave heating. A typical drying rate versus moisture content plot is shown in Figure 21. During the first portion of the drying process, the moisture content changes very slowly. Much of the moisture loss during this initial drying period is due to drainage of liquid water from the extremely wet sample. Samples with an initial moisture content so low that there is very little drainage have an extremely low drying rate during this period. A graph of the total moisture content variation for a sample with a low initial moisture content is shown in Figure 22.

This initial period has been designated as the "initial adjustment period." During this period, the temperature throughout the sample rises.
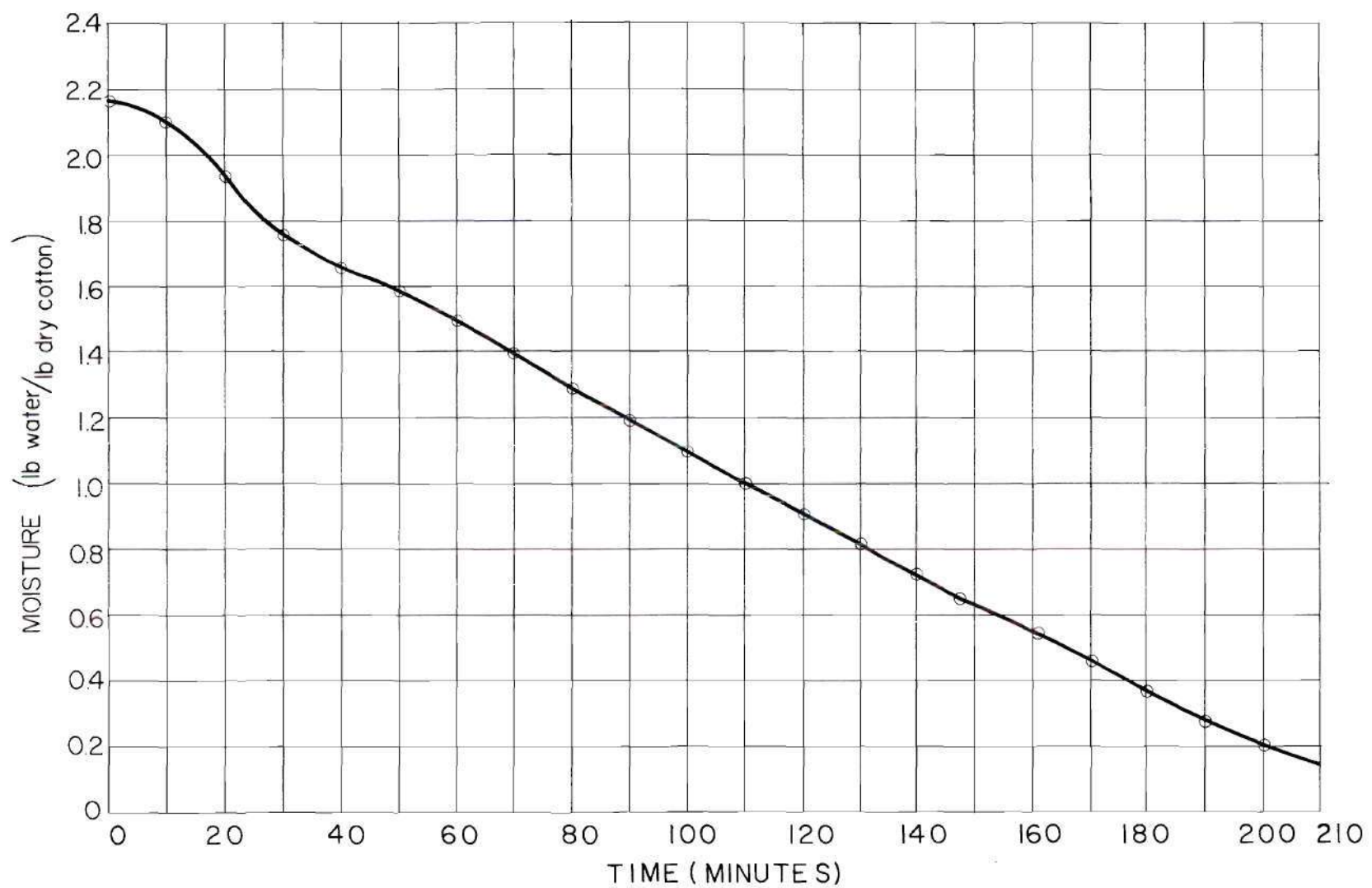
Figure 20. Typical Total Moisture Content Variation During Drying Using Microwave Heating, Ends Sealed--Run 32.
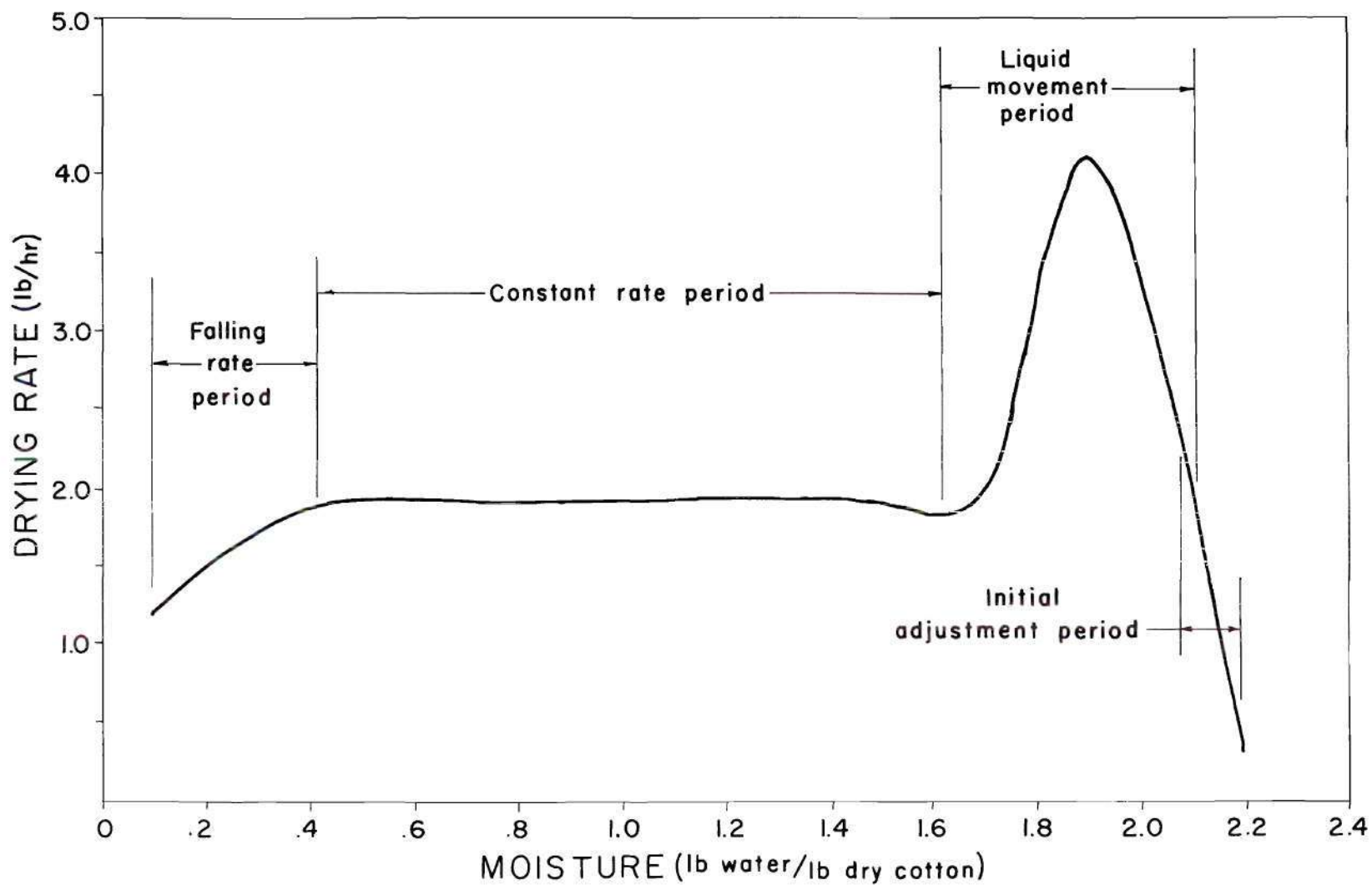
Figure 21. Typical Drying Rate Curve for Drying Using Microwave Heating, Ends Sealed--Run 32.
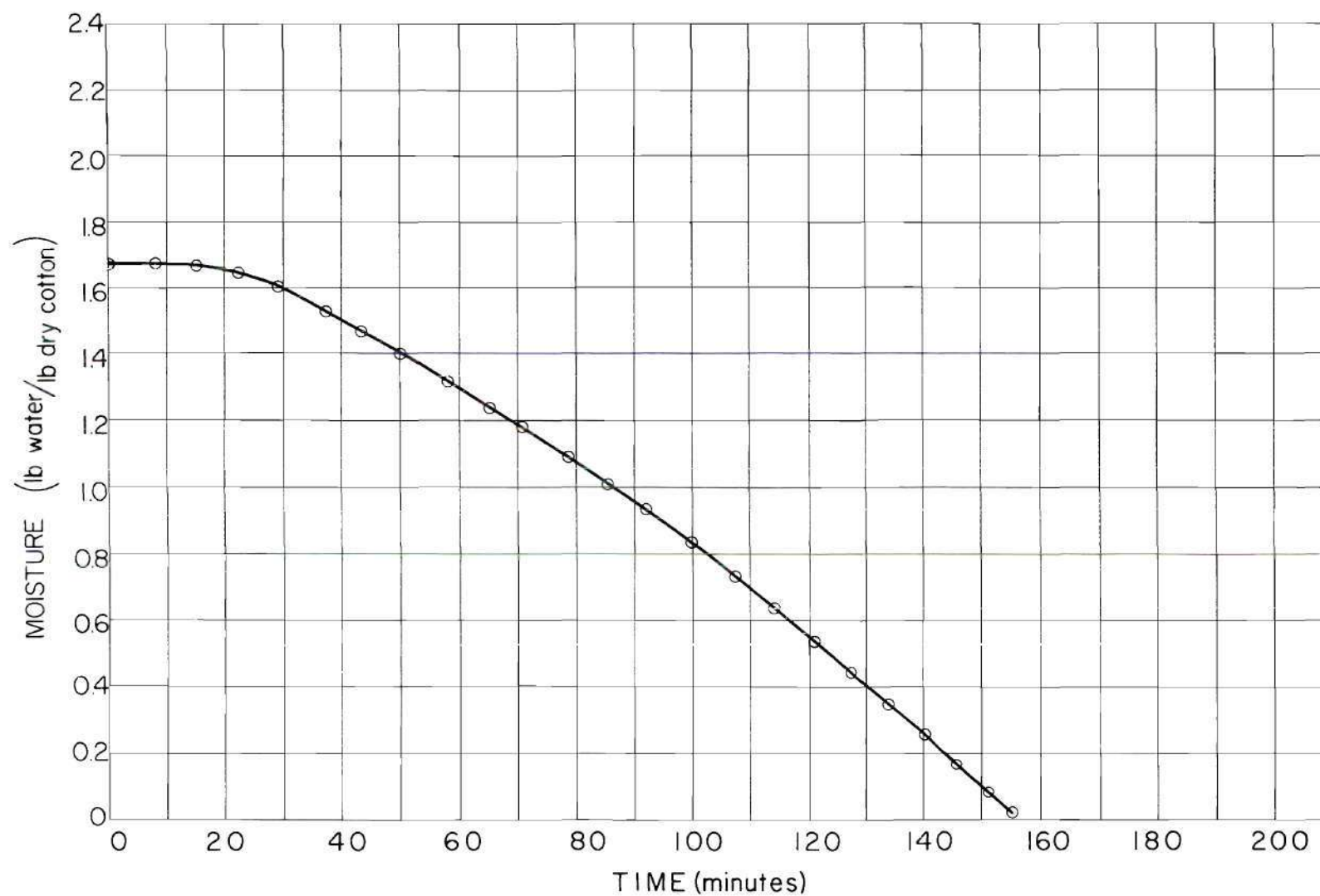
Figure 22. Total Moisture Content Variation During Drying Using Microwave Heating of a Sample with Low Initial Mositure Content, Unsealed--Run 49.

The temperature variation as a function of time at several locations along the axial direction is shown in Figure 23. These measurements were taken by thermometers inserted into the sample to a radius of 2-1/4 inches. The temperature variation at locations along the radial direction for the same sample whose moisture content variation is shown in Figures 20 and 21 is shown in Figure 24. These measurements were taken spaced along a diameter, located axially 2-1/2 inches from the end of the sample. It can be seen from these figures that the temperature throughout the sample rises rapidly and steadily during approximately the first thirty minutes of drying.

At the end of this initial adjustment period, the temperatures throughout the sample approach 210°F (the local boiling point of Atlanta tap water). As the temperatures approach 210°F, a rapid increase in the drying rate is sometimes observed for samples with a very high initial moisture content. The drying rate may become the largest rate occurring during the entire drying process. Liquid moisture is sometimes observed oozing from the sample. As the temperature of the sample approaches 210°F, the vapor generation becomes so rapid that an internal pressure gradient is established within the sample. Liquid moisture may be blown from the sample by this pressure gradient. This liquid moisture is removed hydro-dynamically rather than thermally. This writer has designated this period of drying as the "liquid movement period." Such a period was observed only when the samples had a high initial moisture content, over 200 per-cent. Drier samples, as demonstrated by Figure 22, do not exhibit a liquid movement period.

As drying proceeds, the amount of liquid water within the sample decreases. The observable movement of liquid water ceases and the total
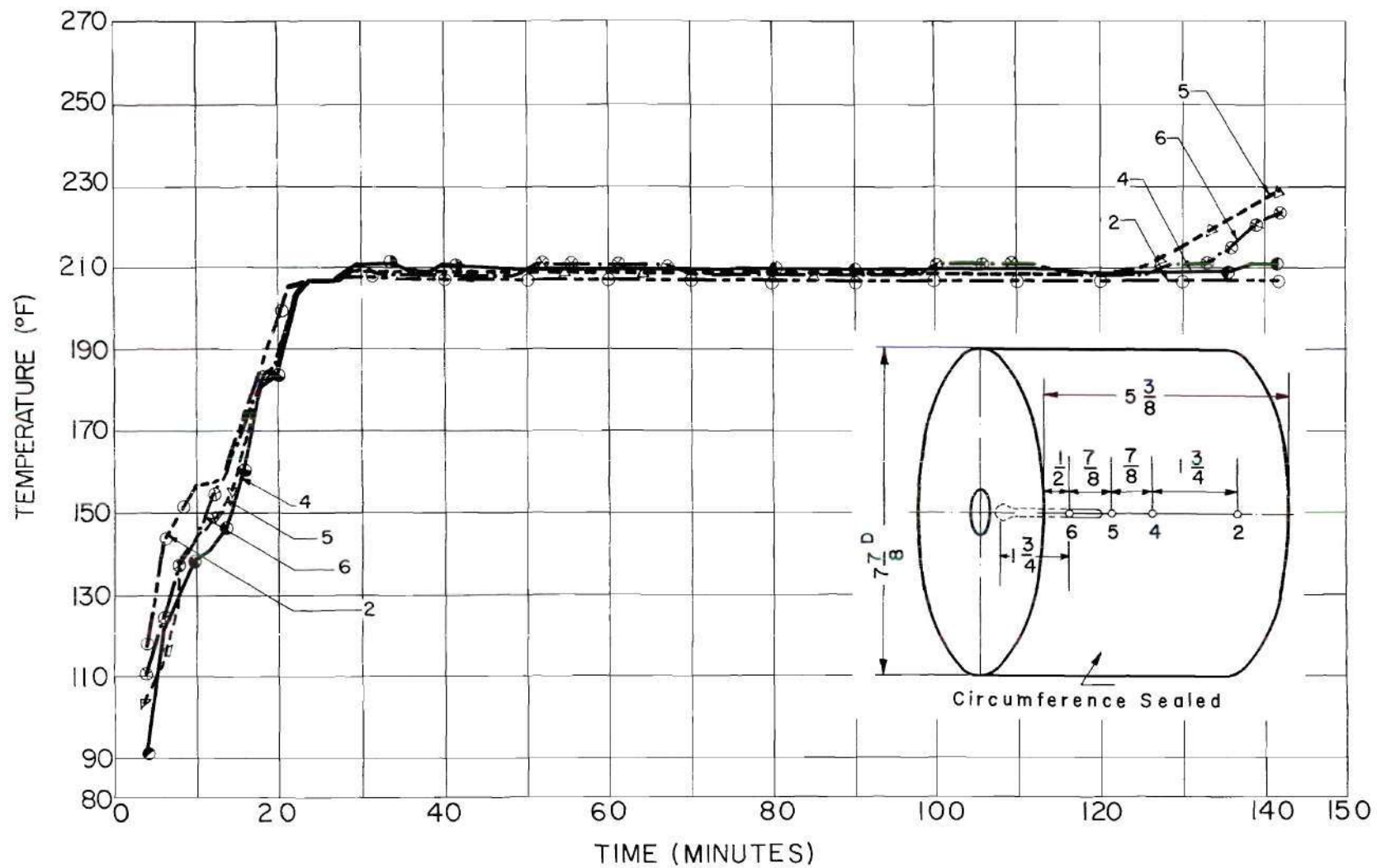
Figure 23.   Temperature Variation at Several Locations of 2-1/4 Inches
Radius, Spaced Along the Axial Dimension, Circumference
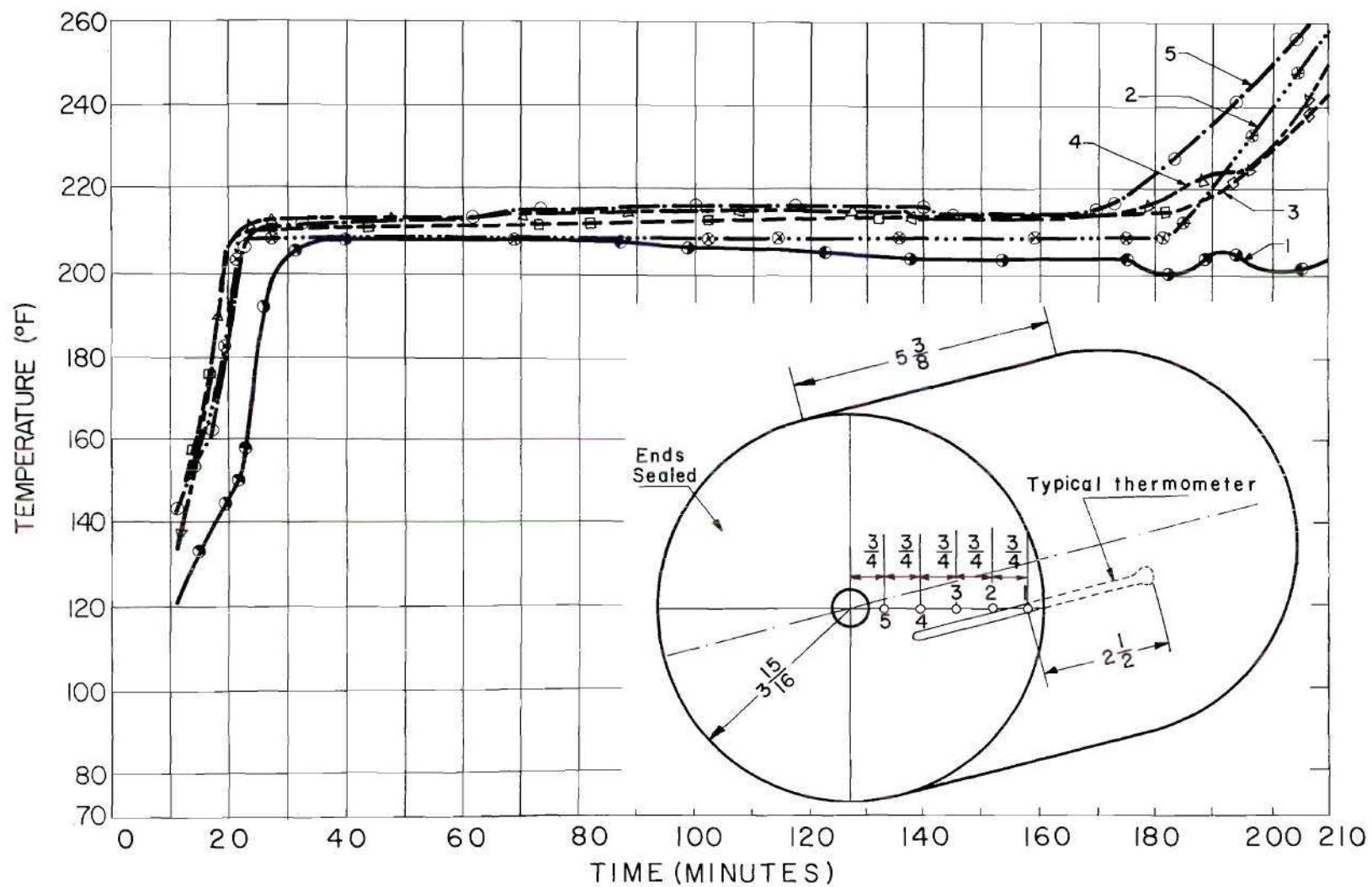Sealed--Run 33.

Figure 24. Temperature Variation at Several Locations Along a Sample
Diameter Located Axially 2-1/2 Inches from the End of the
Sample, Ends Sealed--Run 32.

moisture movement becomes primarily a movement of water vapor. The temperature throughout the sample becomes and remains at the local water boiling temperature. Since the moisture is vaporized before leaving the sample, the drying rate is proportional to the vaporization rate and is, therefore, proportional to the energy input to the sample. The microwave energy output of the oven remains relatively constant throughout the drying process and, therefore, the drying rate during this period remains constant. This period of drying has been designated as the "constant rate period." For samples dried in the 2450 megacycles per second oven, the drying rate was between 1.75 and 2.0 pounds of water per hour, regardless of sample size or type. If all of the moisture is vaporized before leaving the product, the required energy rate to vaporize this moisture is between 0.50 and 0.57 kilowatts.

Near the end of the drying process some portions of the sample become dry, while others remain slightly wet. The drying rate tends to fall off. If microwave energy is added to the sample at a rapid rate, the temperature of the dry portions of the sample may rise. This period of drying has been designated as the "falling rate period."

A comparison can be made between the drying rate curve, using conventional heating, Figure 18, and the drying rate curve using microwave heating, Figure 21. An initial adjustment period is common to drying with either type of heating. At the end of the initial adjustment period, the drying process using microwave heating may exhibit a "liquid movement period." No corresponding period exists when using conventional heating. Drying processes with either type of heating exhibit a constant rate period. With microwave heating, the constant rate period comprises the

majority of the drying process. The critical moisture content (i.e., mois-
ture content at the end of the constant rate period) is much lower than it
is when conventional heating is used. Consequently, with microwave heat-
ing, the falling rate period is much shorter than the falling rate period
with conventional heating.

Typical temperature profiles within the drying samples at selected
times are shown in Figures 25 and 26. Figure 25 shows the temperature
variation along the axial direction. The temperature was measured by
several thermometers spaced along the axial direction each inserted to a
radius of approximately 2-1/4 inches. Figure 26 shows the temperature
profiles in the radial direction. The thermometer bulbs were spaced along
a sample diameter, positioned axially at 2-1/2 inches from one end of the
sample. The figures demonstrate the uniformity of the temperature through-
out the sample during the majority of the drying process. During the ini-
tial warm up period, some temperature variation exists throughout the
sample but once the sample reaches 210°F, the temperature distribution
throughout the sample remains uniform.

It is significant to note that there is no large temperature gradient
throughout the sample. The heat conduction that does occur takes place
from the inner portions of the sample to the surface, which is cooled by the
cool atmosphere in the oven. Measurements of the sample surface tempera-
ture showed that there was a considerable temperature gradient near the
surface. The depth beneath the surface at which the temperature remained
substantially less than the sample center temperature (210°F) varied quite
arbitrarily during drying and was strongly affected by movements of the
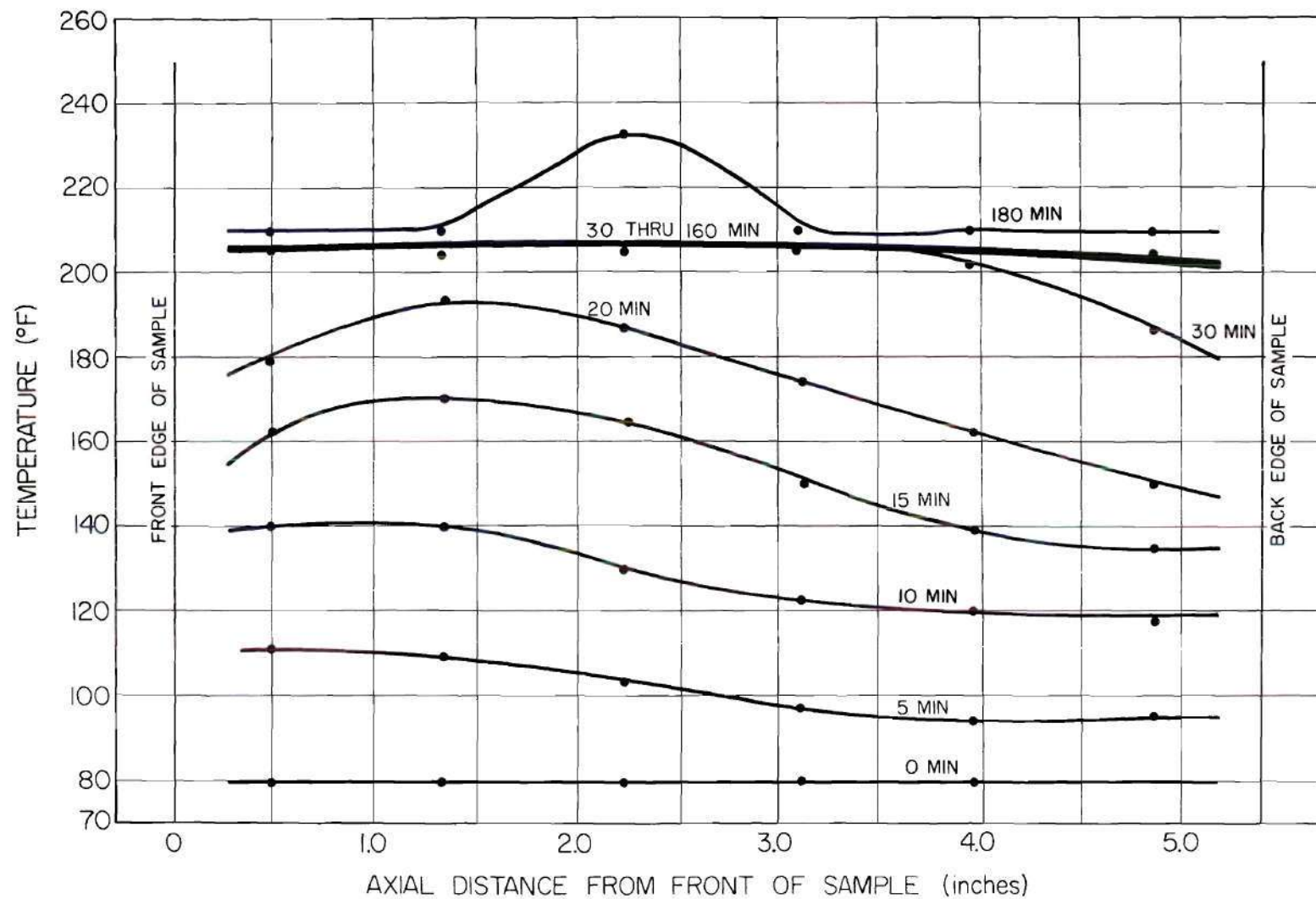air surrounding the sample. In all cases the cooler surface layer seldom

Figure 25. Temperature Profiles Along the Axial Direction at a Radius of 2-1/4 Inches, Unsealed Sample--Run 34.
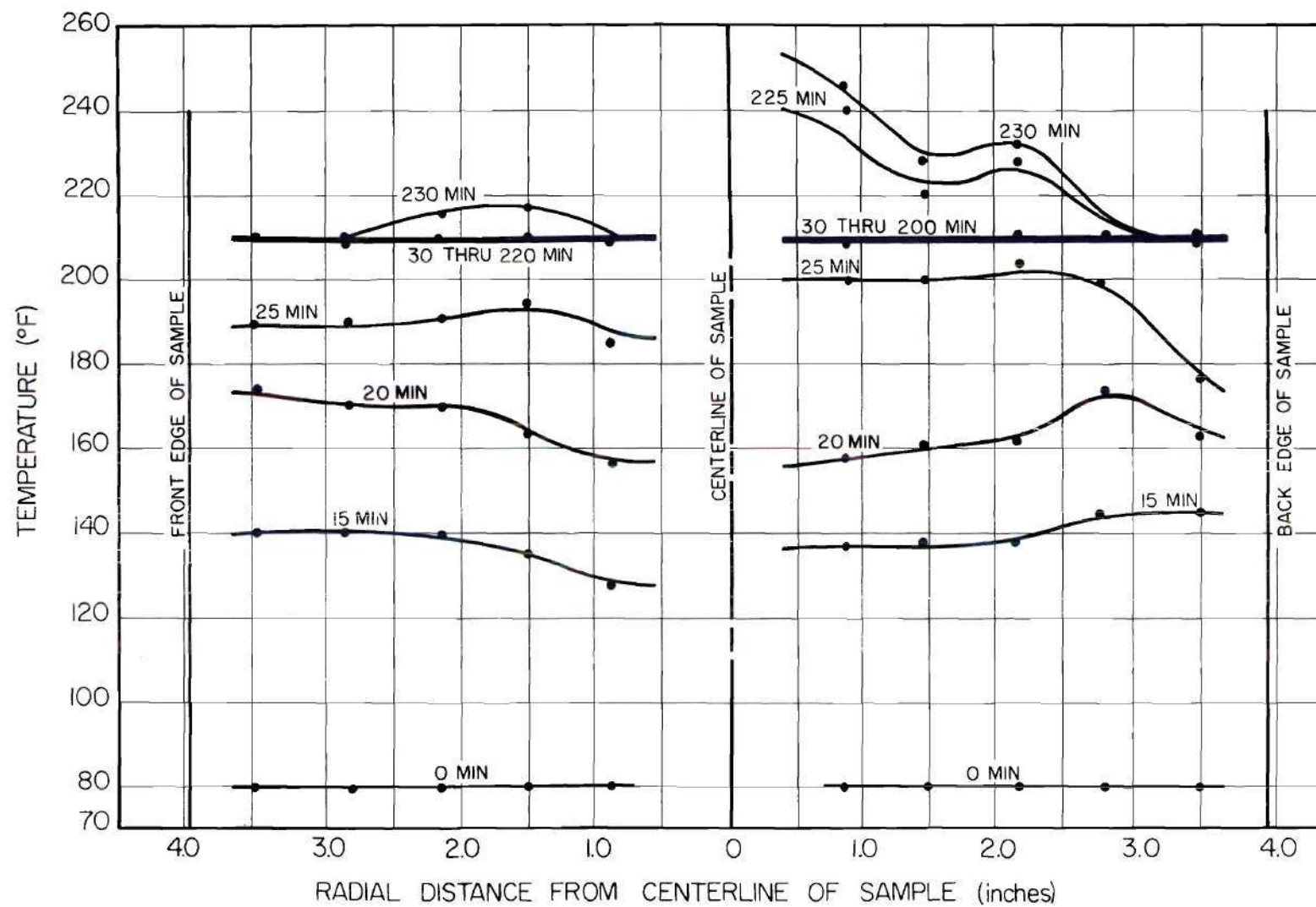
Figure 26. Temperature Profiles Along a Diameter of the Sample at an Axial Distance of 2-1/2 Inches from One End, Circumference Sealed--Run 29.

extended beyond 1/4 inch below the surface. Measurements of the surface temperature showed that the surface heated at a rate similar to the inner portions until a surface temperature of approximately 140°F was reached. The surface temperature then remained in the neighborhood of 155°F throughout the remainder of the drying process. A variation of 10°F was found in measurements at different locations along the surface. A 10°F variation was also observed at the same location at different times.

The pressure variation inside the sample as a function of time is shown in Figure 27. This particular graph presents the pressure variation at several different radial locations for a sample with the ends sealed (i.e., radial moisture flow). The pressure throughout the sample remains nearly atmospheric throughout the initial adjustment period. At the end of the initial adjustment period, as the temperature of portions of the sample approaches 210°F, a sharp rise in the pressure is observed. This period where the pressure rises very rapidly corresponds in time to the start of the liquid movement period. The pressure throughout the sample reaches a peak, and then starts to decrease as drying continues. The positions of highest pressure occur at the center of the sample. As the sample dries and the permeability increases, the pressure at all locations within the sample continuously decreases.

A plot of the pressure profiles in the radial direction, shown in Figure 28, demonstrates that the highest pressure within the sample at any time occurs at the center of the sample. The pressure profile along the direction of moisture flow tends to be parabolic throughout the drying process.

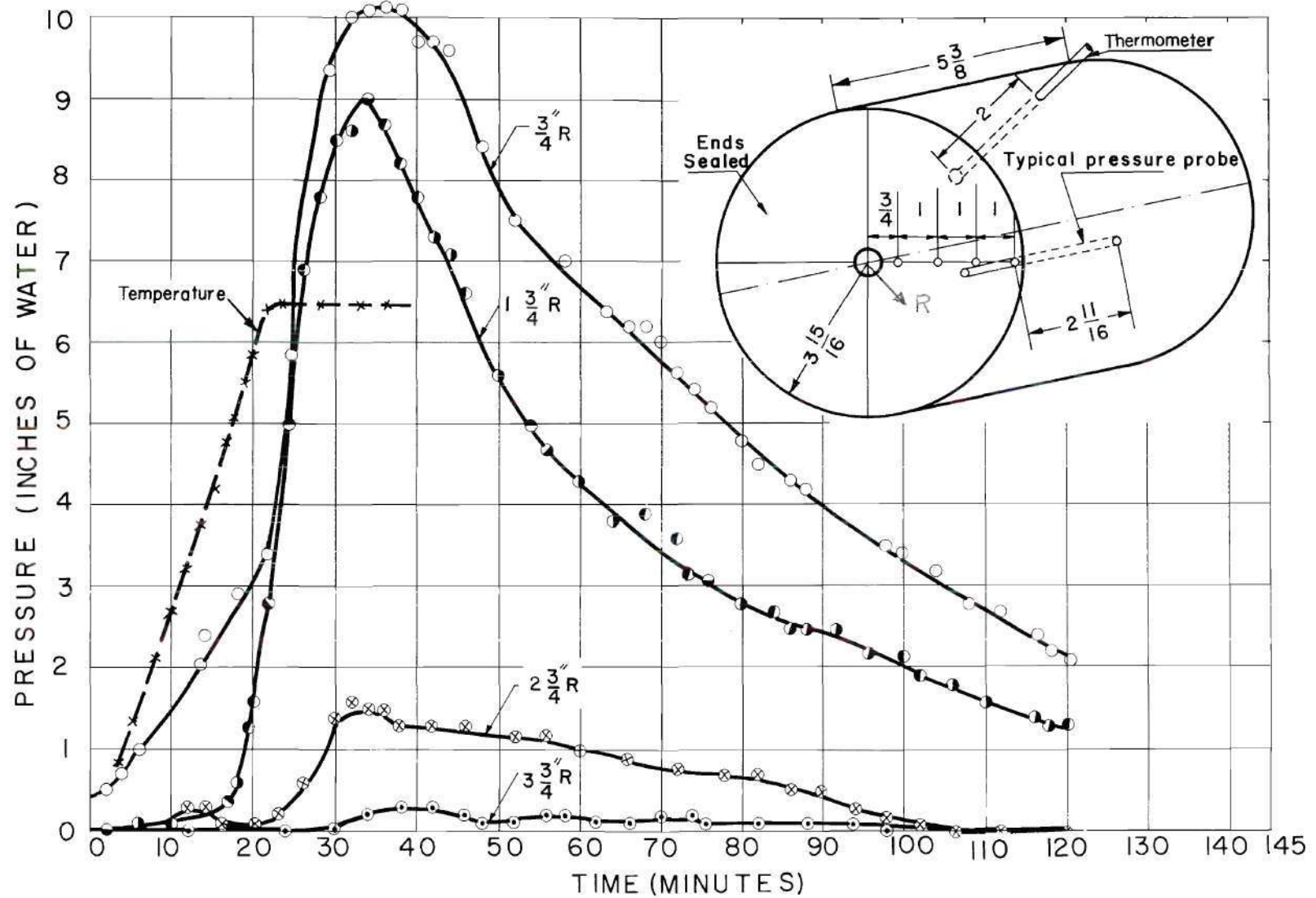The local moisture variation within the sample at selected loca-

Figure 27. Pressure Variation at Several Radial Locations for Radial
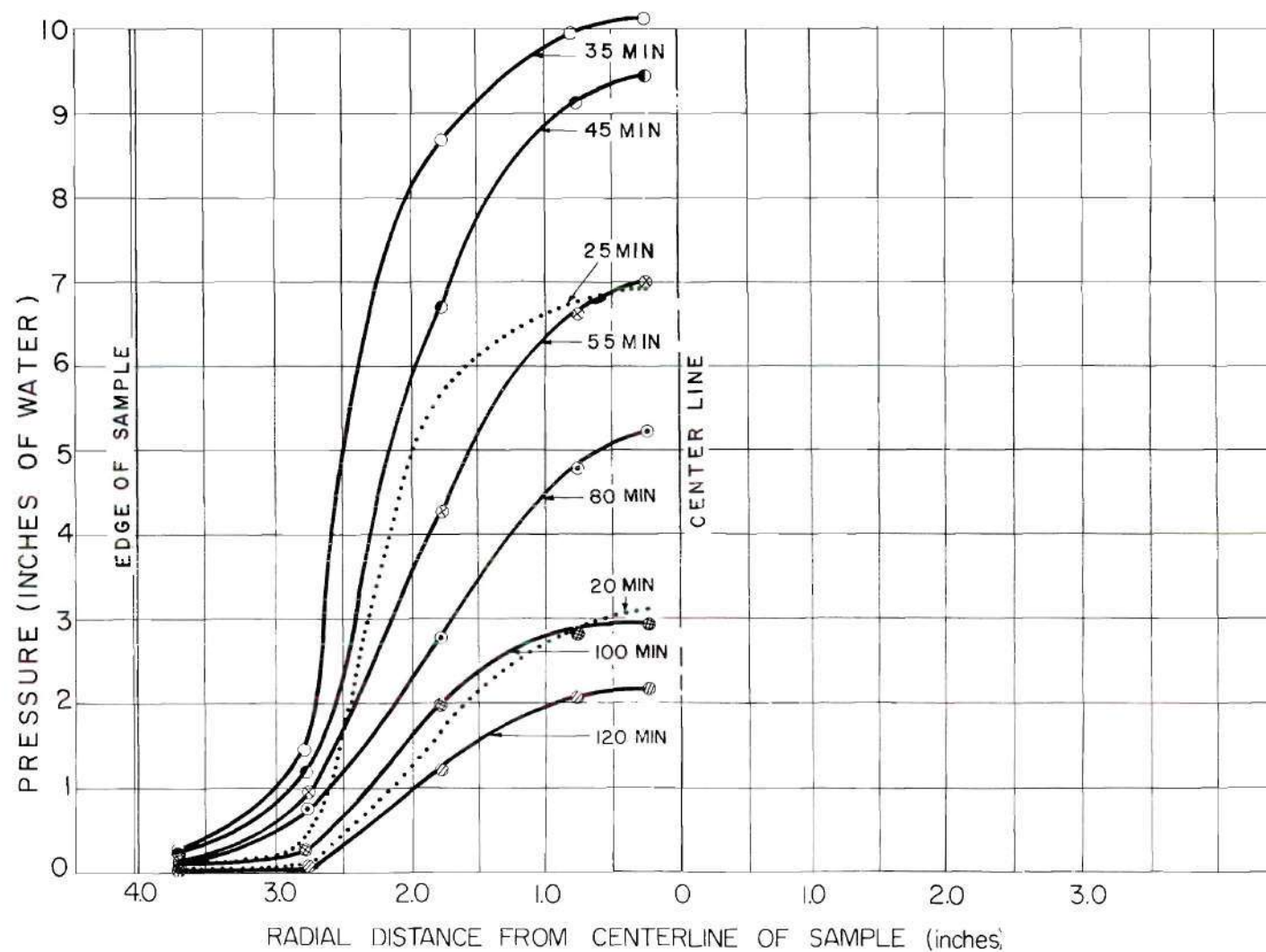Moisture Flow, Ends Sealed--Run 52.

Figure 28   Pressure Profiles in the Radial (Flow) Direction at Fixed Times, Ends Sealed--Run 52.

tions is shown in Figure 29. The local moisture content curves demonstrate the same periods of drying, initial adjustment, constant rate, etc. as does the total moisture content curve (Figure 20).

It is significant that the sample dries uniformly, i.e., the center dries as rapidly as does the surface. The moisture content remains uniform throughout the drying process. Figure 30 shows the moisture content variation along the axial dimension of an unsealed sample at selected times. To obtain these measurements the gamma ray beam was made to shine through the sample along a diameter line. Each measurement represents the average moisture content along the line. Measurements taken in the opposite direction, demonstrating the moisture uniformity in the radial direction, are plotted in Figure 31. Both of the test samples whose moisture content are described in Figures 30 and 31 are unsealed samples, thus the moisture diffusion could occur in both the axial and radial directions. It can be seen from these figures that throughout the drying process negligible moisture content gradients exist in either direction.

Although all samples, sealed, unsealed, large, small, absorbent, nonabsorbent, etc. had similar drying characteristics, each of these type samples was examined individually. The next sections of this chapter are devoted to presenting the results of each of these special situations.

Sealed Circumference, Axial Flow

The circumference of cylindrical packages of yarn, 8 inches in diameter and 5-3/8 inches long, was sealed with plastic so that the moisture movement was restricted to axial flow. Such a moisture flow pattern would be typical of a cylinder with a large diameter-to-length ratio or
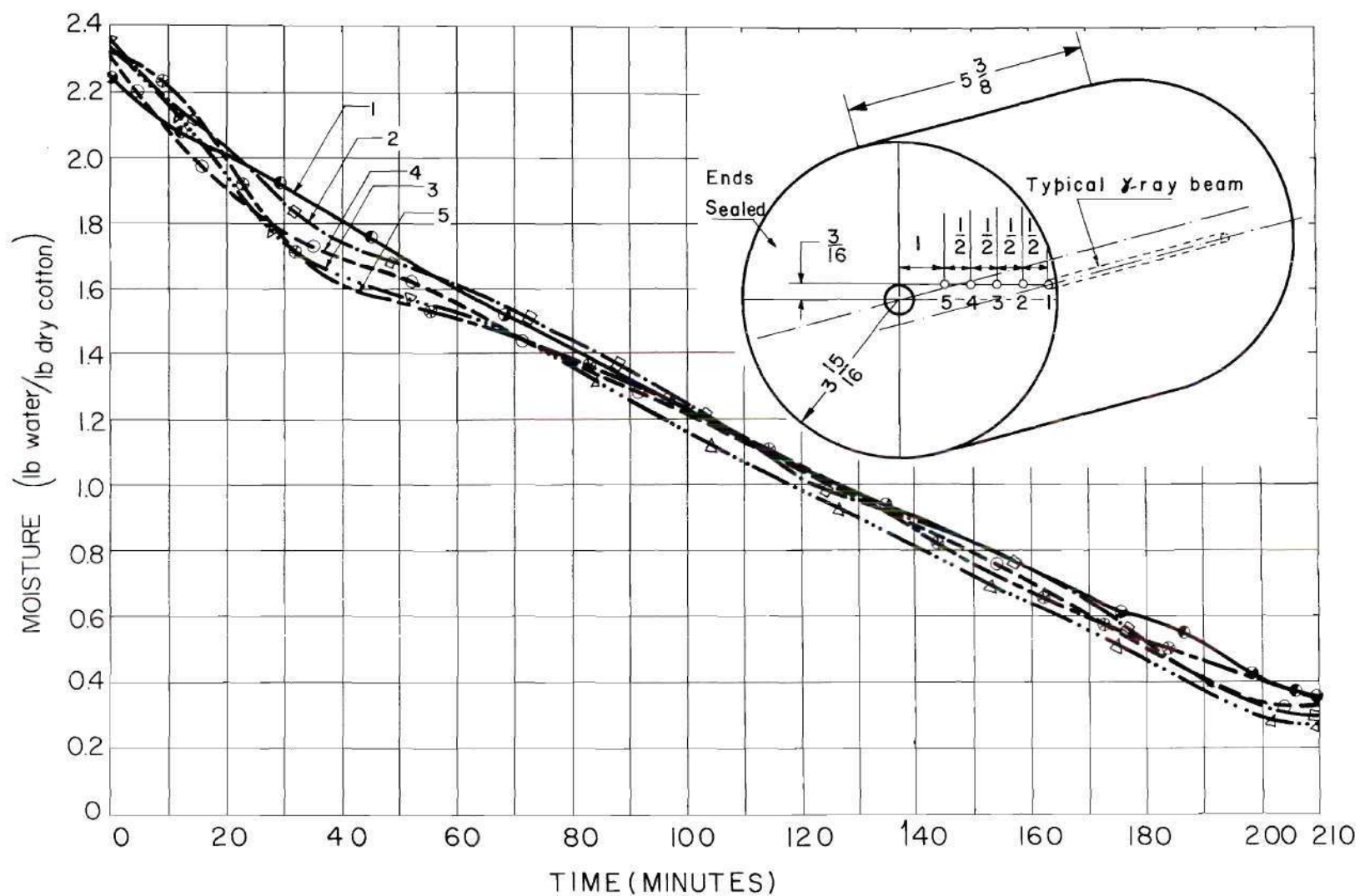
Figure 29. Moisture Content Variation at Several Locations Along the
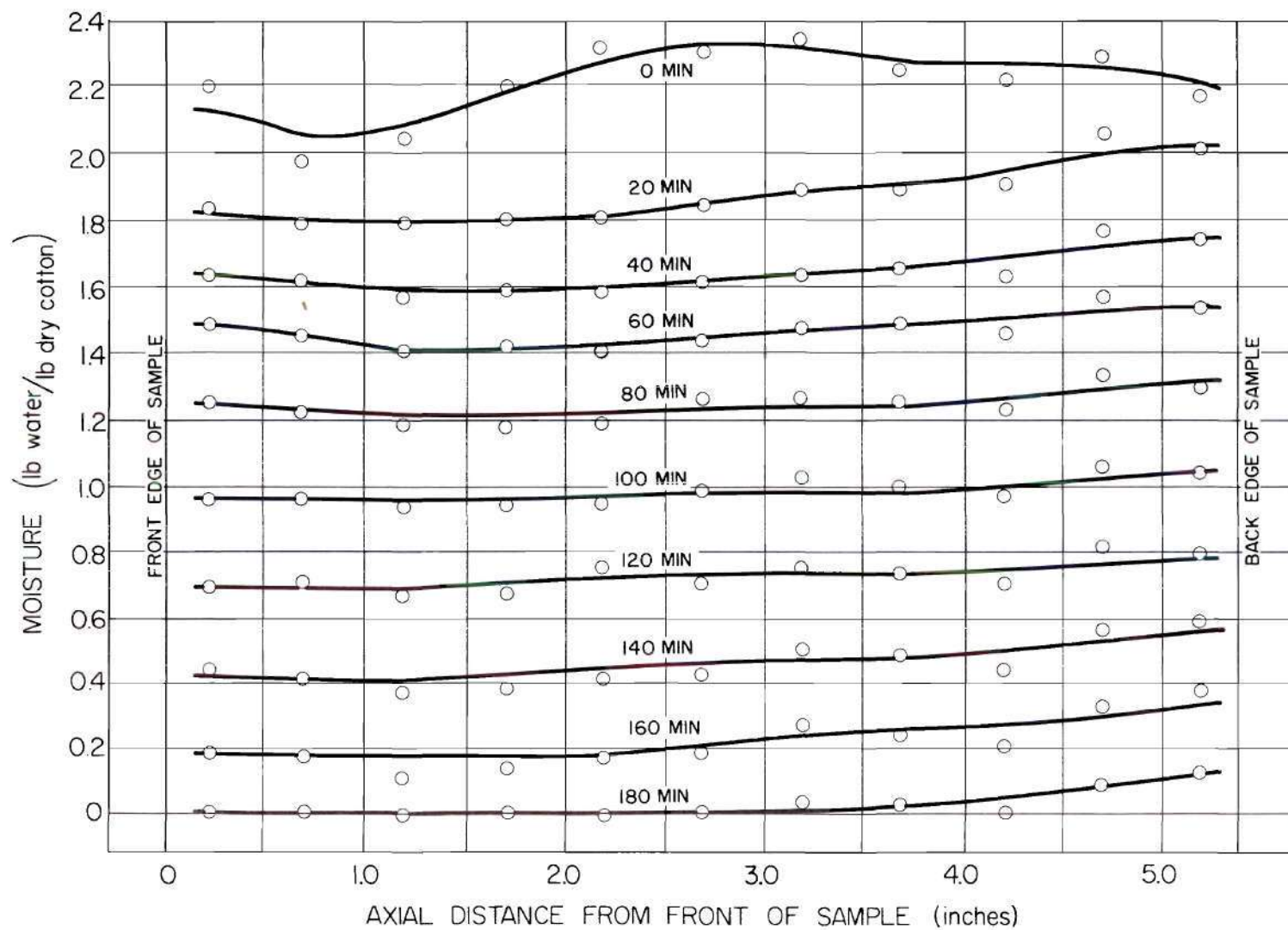Radial (Flow) Direction, Ends Sealed--Run 32.

Figure 30. Moisture Content Profiles Along the Axial Dimension at Fixed Times, Unsealed--Run 34.
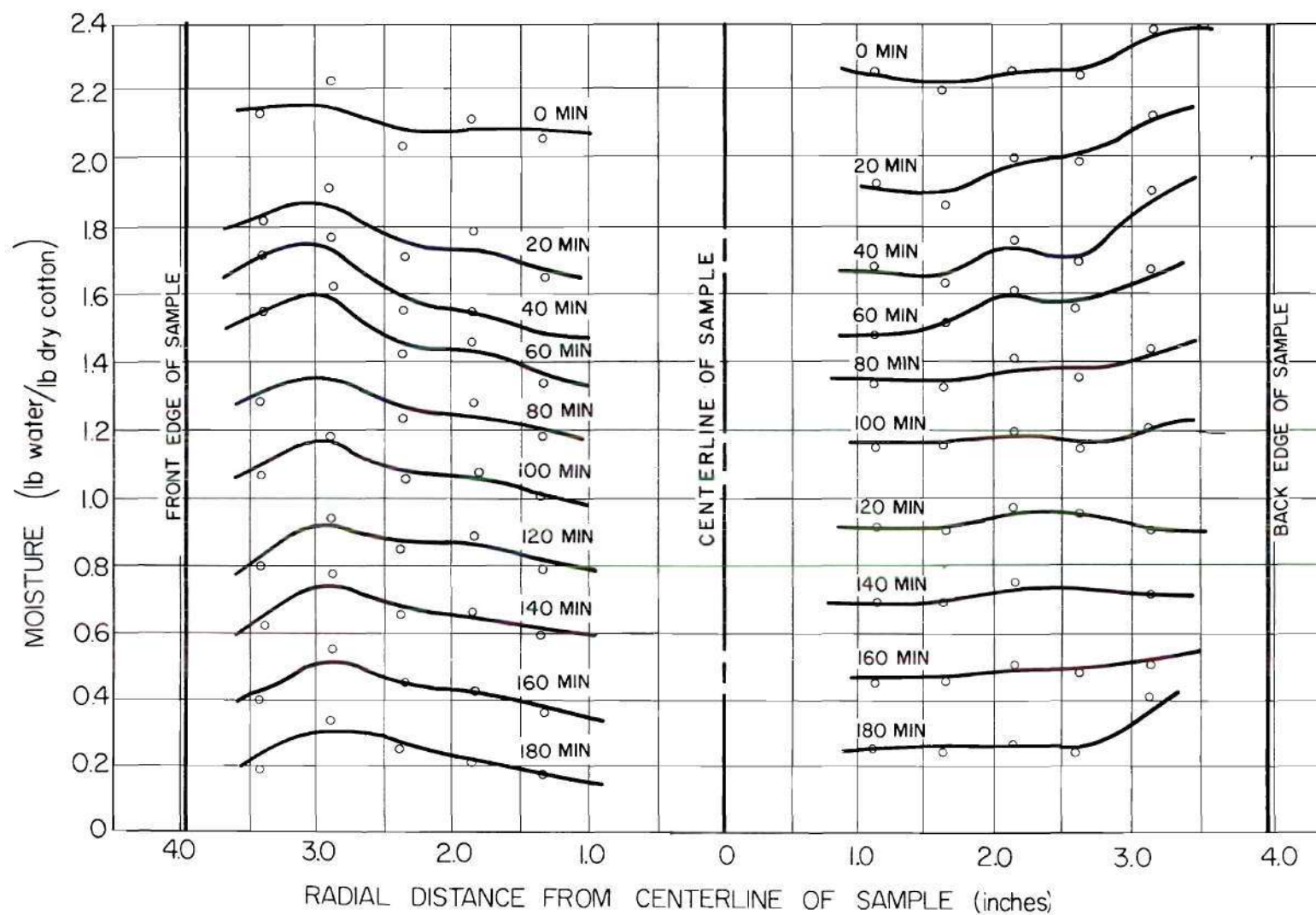
Figure 31. Moisture Content Profiles Along a Diameter at Fixed Times, Unsealed--Run 38.

a semi-infinite slab of material. The samples were soaked in water and dried in the 2450 megacycles per second oven. The typical variation of the total moisture content during drying is shown in Figure 32. It was found that the drying rate during liquid movement period of drying tended to be larger for circumference-sealed samples than for ends sealed or unsealed samples. Because of the large amount of moisture removed in liquid form during this period, the total drying time for this type of sample tended to be less than that for a similar size but unsealed sample. As was pointed out previously, the liquid movement period exists only for very wet samples. Circumference-sealed samples that had a low initial moisture content did not exhibit a liquid movement period.

A typical plot of the temperature at various locations along the axial flow direction is shown in Figure 23. The temperature of the sample was found to rise rather uniformly until it reached approximately 210°F. The temperature at all points within the sample remained at or near 210°F during most of the drying process. Near the end of drying, the temperature of some parts of the sample rose rapidly.

The moisture content variation at specified locations along the flow axis is shown in Figure 33. After an initial adjustment period at the beginning of the drying process, the moisture content of all portions of the sample decreases at a nearly constant rate until near the end of the drying process.

The temperature and moisture content variations between locations within the sample can be shown by plotting profile curves. Figure 34 is a plot of the temperature profile along the axial direction at a radius of 2-1/4 inches. Figure 26 is a plot of the temperature profile along a
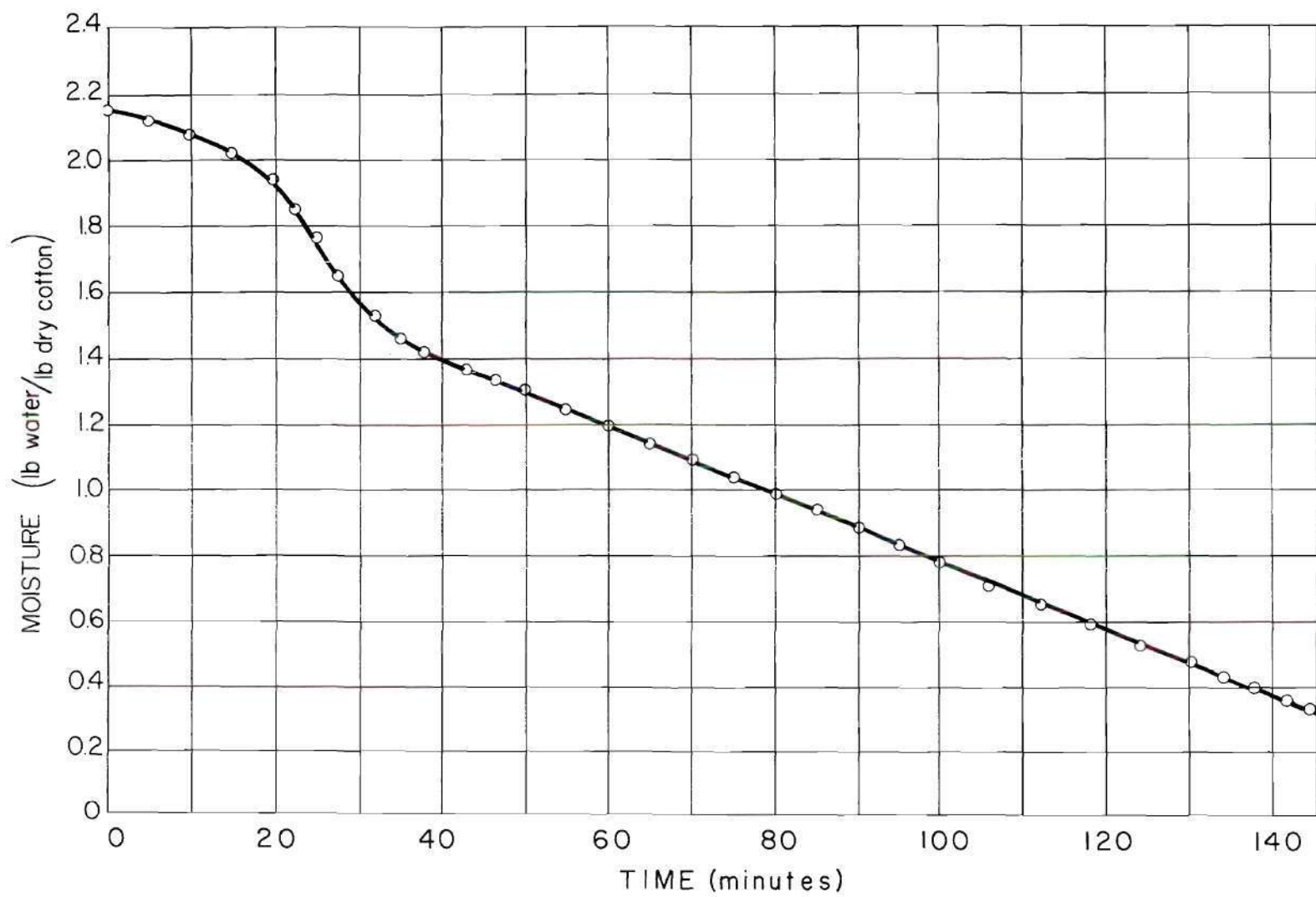
Figure 32. Total Moisture Content Variation During Microwave Drying,
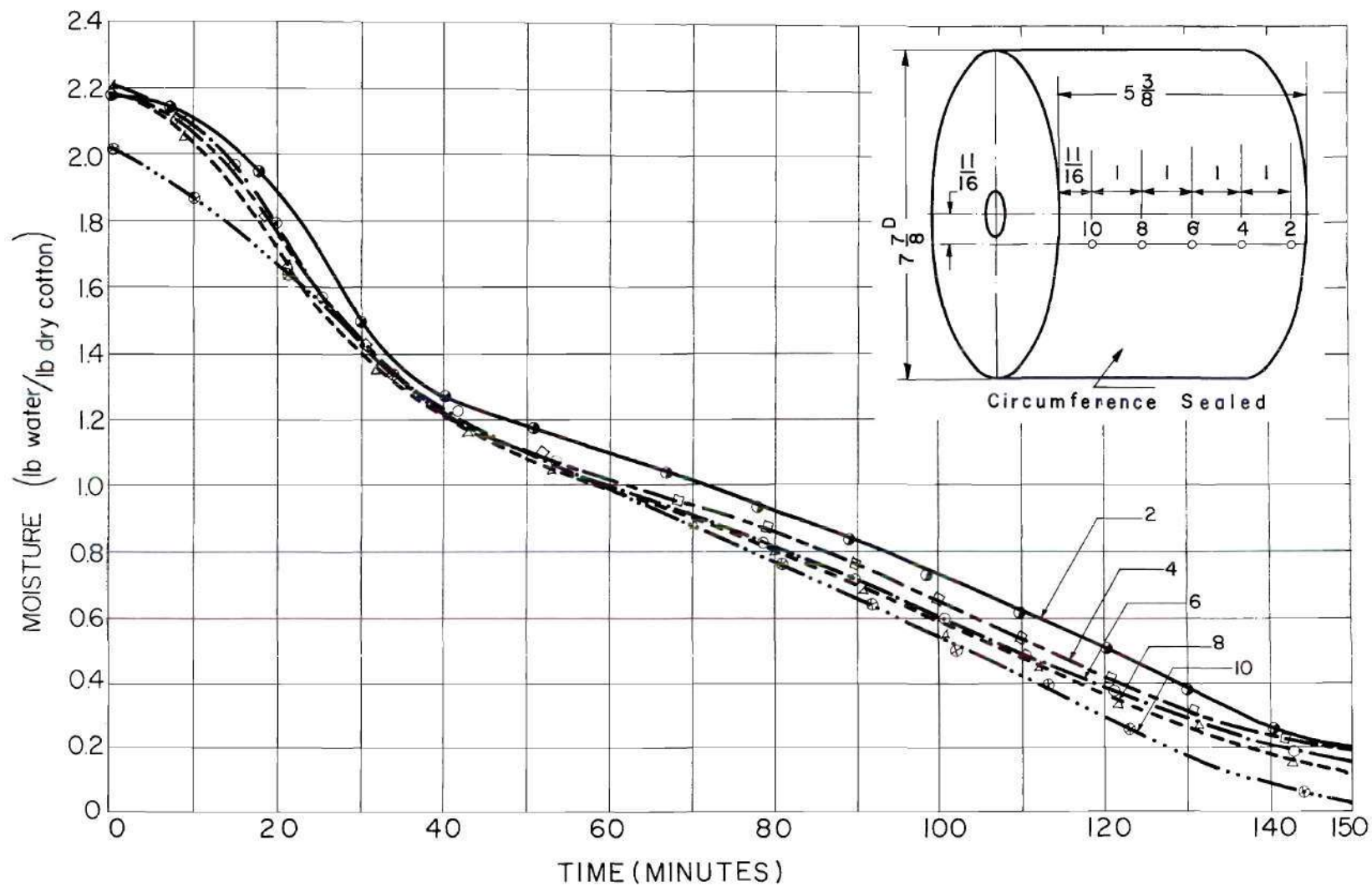Circumference Sealed--Run 33.

Figure 33.   Moisture Content Variation at Selected Locations Along the
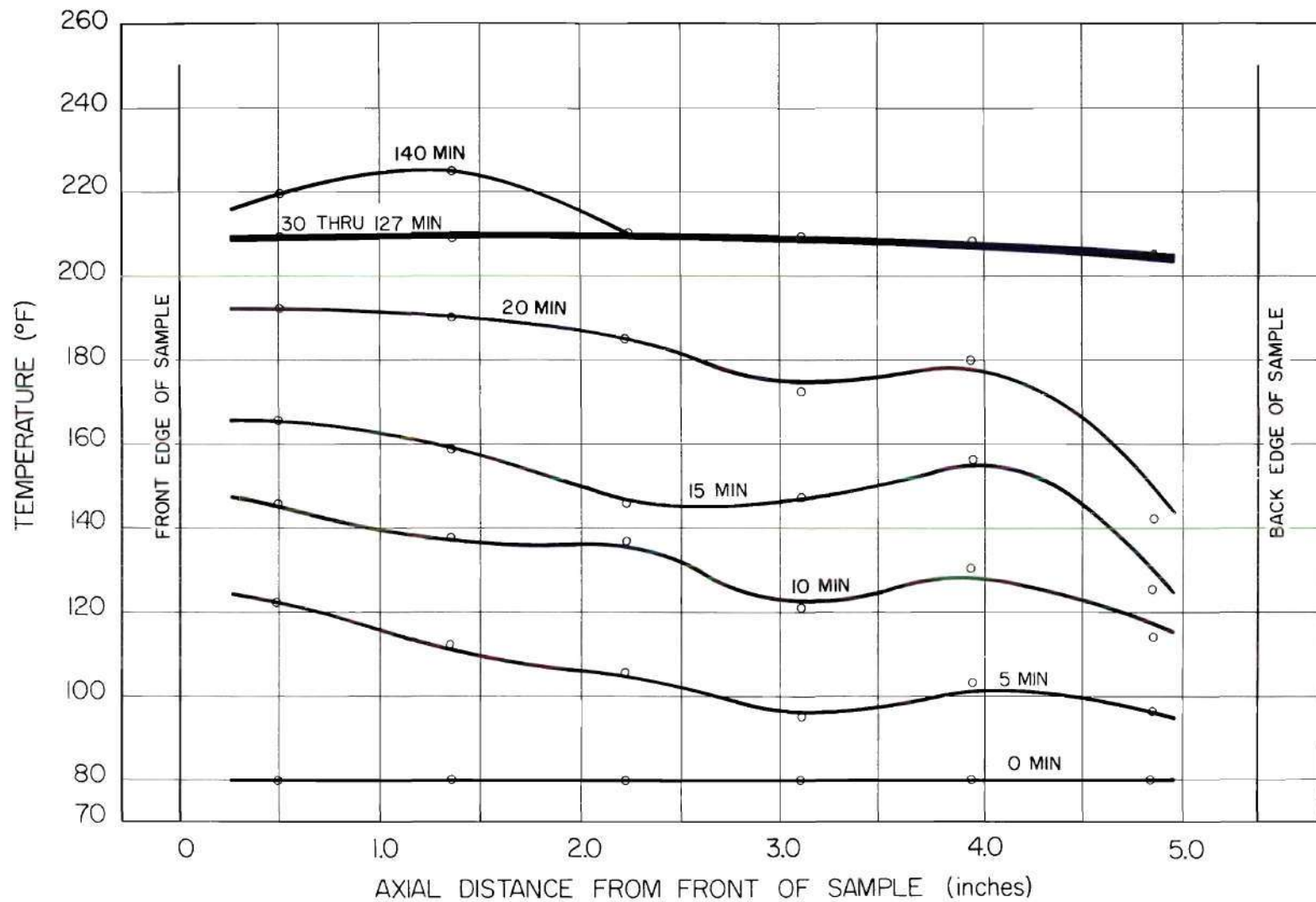Axial (Flow) Direction, Circumference Sealed--Run 33.

Figure 34. Temperature Profiles Along the Axial (Flow) Direction at Fixed Times, Circumference Sealed--Run 33.

diameter of the sample 2-1/2 inches from the end of the sample. It is observed that the temperature profiles are flat during the majority of the drying process. Towards the end of drying, during the falling rate period, the temperature at positions along the axial core tends to rise above the temperature of the surface.

Moisture content profiles along the axial (moisture flow) direction are shown in Figure 35. This figure demonstrates that there is no significant moisture gradient in the flow direction. The uniformity of the moisture content in a direction perpendicular to the flow (radial direction) is demonstrated by Figure 36 which is a plot of moisture profiles along a sample diameter. Figures 35 and 36 demonstrate that, for circumferencially sealed samples, the moisture content is relatively uniform throughout the entire sample during the majority of the drying process. However, toward the end of drying, the circumferential layer near the sealed surface tends to dry slightly slower than the center of the sample. As mentioned previously, the axial center temperatures become higher than the surface temperatures and the drying rate falls off.

During the first 15 to 20 minutes of heating, the pressure inside the sample remains essentially equal to the surrounding atmospheric pressure. After approximately 20 to 30 minutes of heating the pressure throughout the sample rises rapidly. The pressure at various positions along the flow axis is plotted in Figure 37. The sudden rise in pressure occurs at the time when the temperatures within the sample reach 210°F (the local boiling temperature).

Figure 38 shows the pressure profile along the direction of flow at selected times. Throughout the drying process the pressure profile
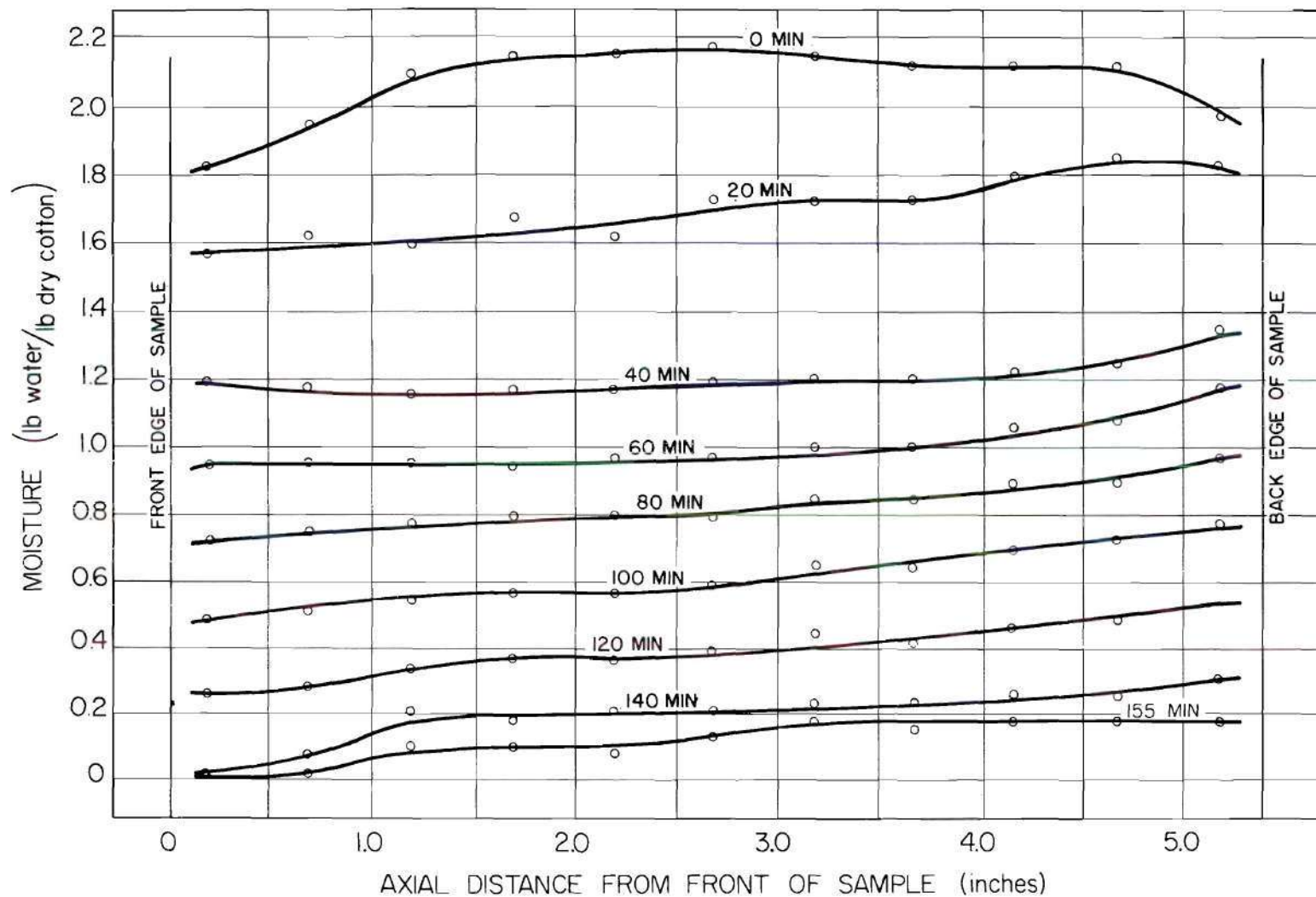
Figure 35. Moisture Content Profiles Along the Axial (Flow) Direction at Fixed Times, Circumference Sealed--Run 33.

Figure 36. Moisture Content Profiles Along a Diameter Perpendicular to the Direction of Moisture Flow, Circumference Sealed--Run 29.

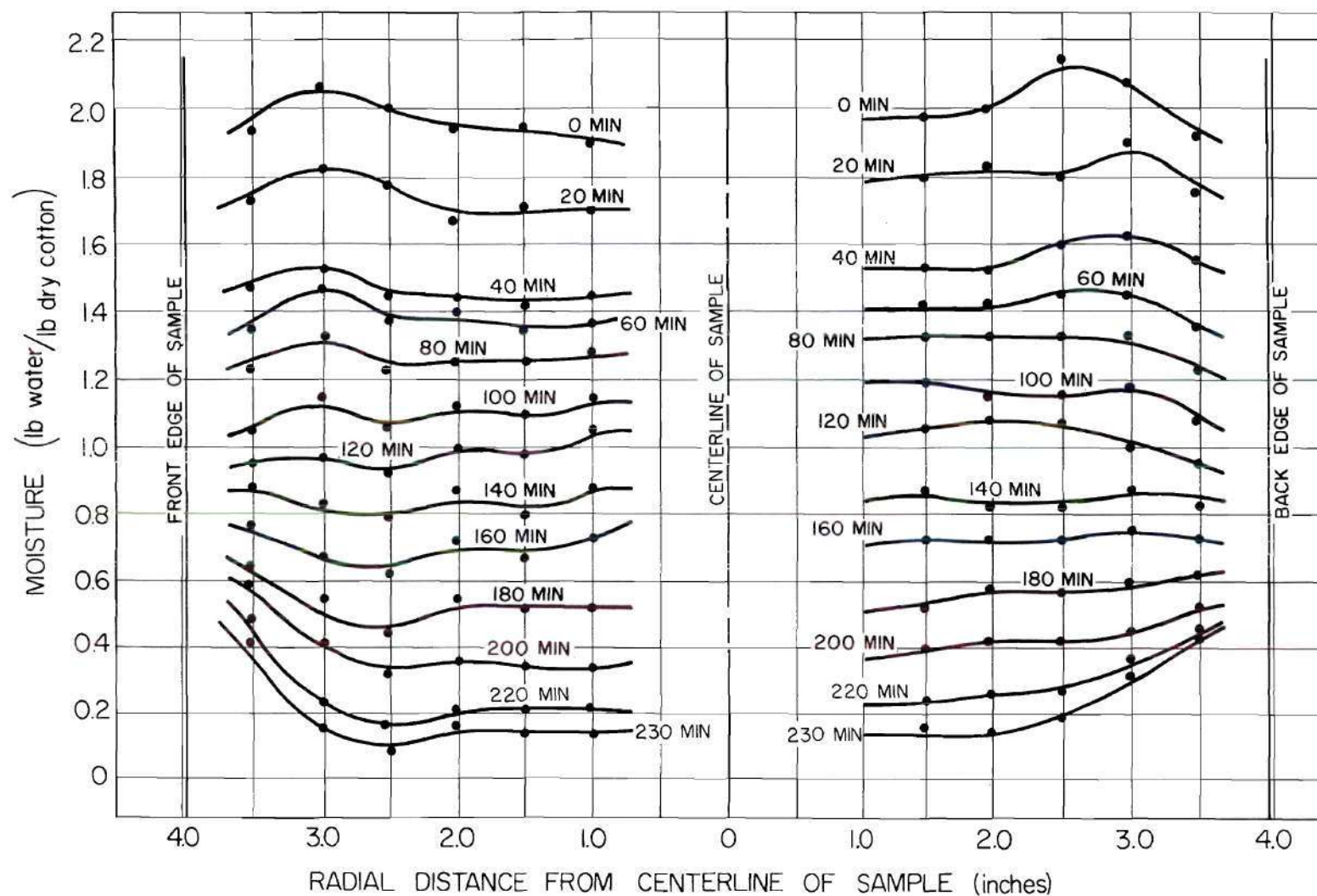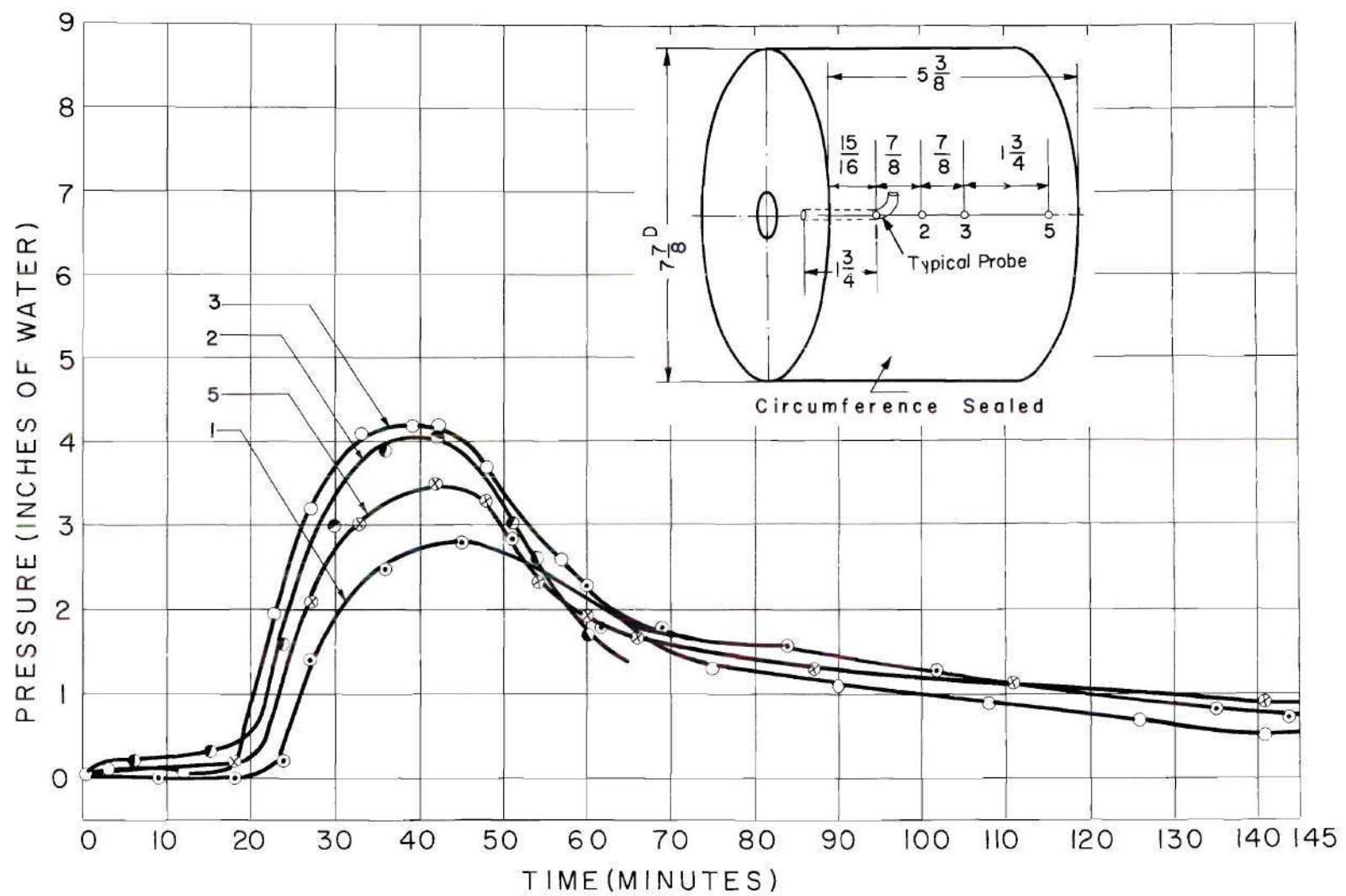Figure 37. Pressure Variations at Several Locations Along the Axial (Flow) Direction, Circumference Sealed--Run 47.
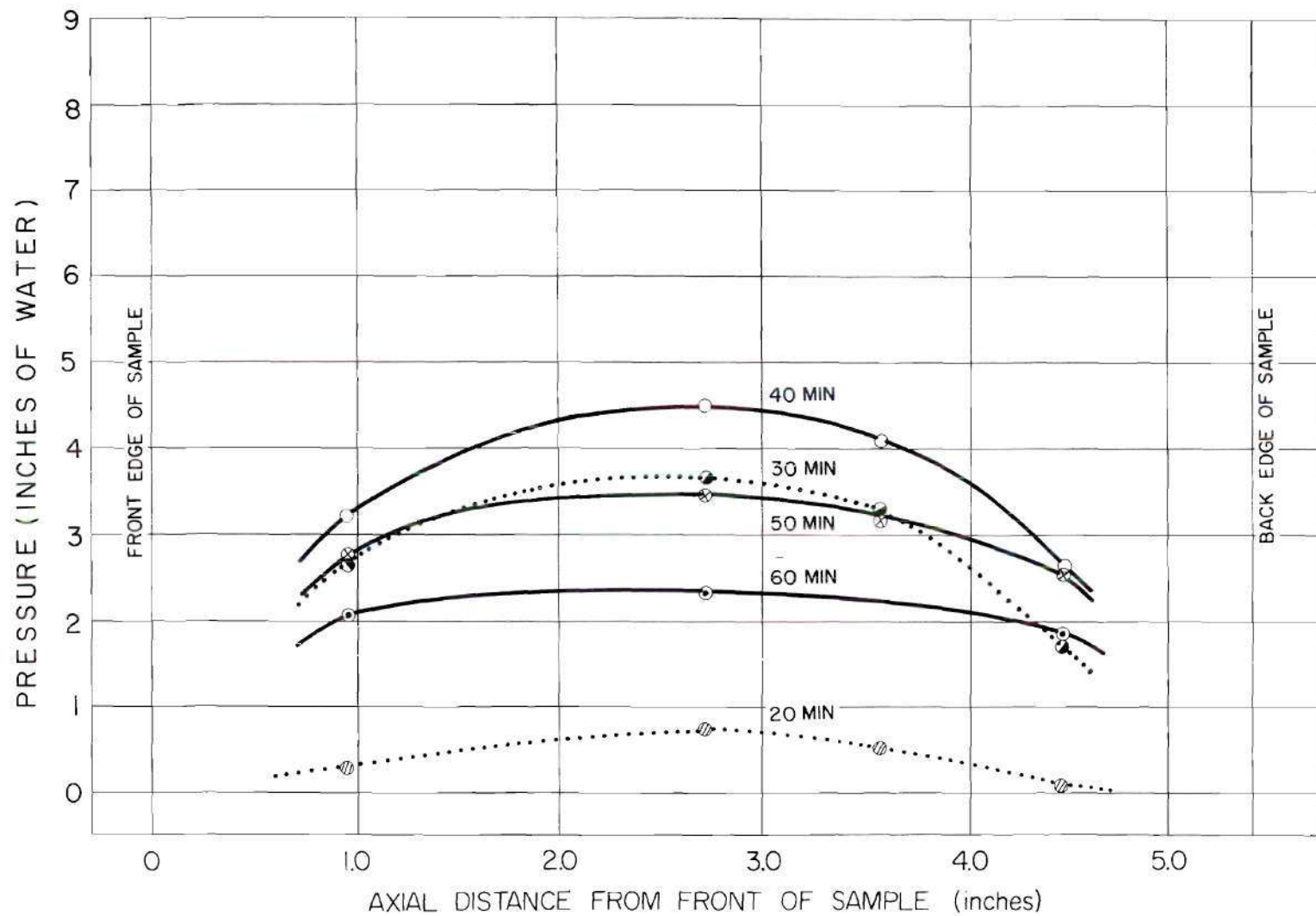
Figure 38. Pressure Profile Along the Axial (Flow) Direction at Fixed
Times, Circumference Sealed--Run 47.

remains parabolic in shape with the highest pressure at the axial center
of the sample. During the constant drying rate period, the overall magni-
tude of the pressure profile shifts downward as drying proceeds and the
permeability of the sample increases.

Ends Sealed, Radial Flow

The ends of 8 inch diameter, 5-3/8 inches long cylindrical packages
of absorbent cotton yarn were sealed with plastic. The moisture flow was
thus restricted to the radial direction only. The samples were wetted
and placed in the 2450 megacycles per second oven and dried. A typical
plot of the total moisture content variation is shown in Figure 20 and
the corresponding drying rate curve in Figure 21. The temperature varia-
tion with drying time at several locations along the direction of moisture
flow (radial direction) and 2-1/2 inches from the end of the sample is
shown in Figure 24. The temperature profiles along the flow direction at
selected times can be observed from Figure 39, which presents temperature
versus radial position. The temperature profiles in the axial direction
are shown in Figure 40. During the majority of the drying process, the
temperature throughout the sample is nearly uniform at 210°F. Near the
end of the drying, the portion of the sample along the center core tends
to dry first and the center core temperature becomes higher than the sur-
face temperature.

The variation of the pressure at different radial locations is
shown in Figure 27. A cross plot showing the typical pressure profiles
in the direction of moisture flow is presented in Figure 28. The pressure
profiles are parabolic with the highest pressure at the center of the
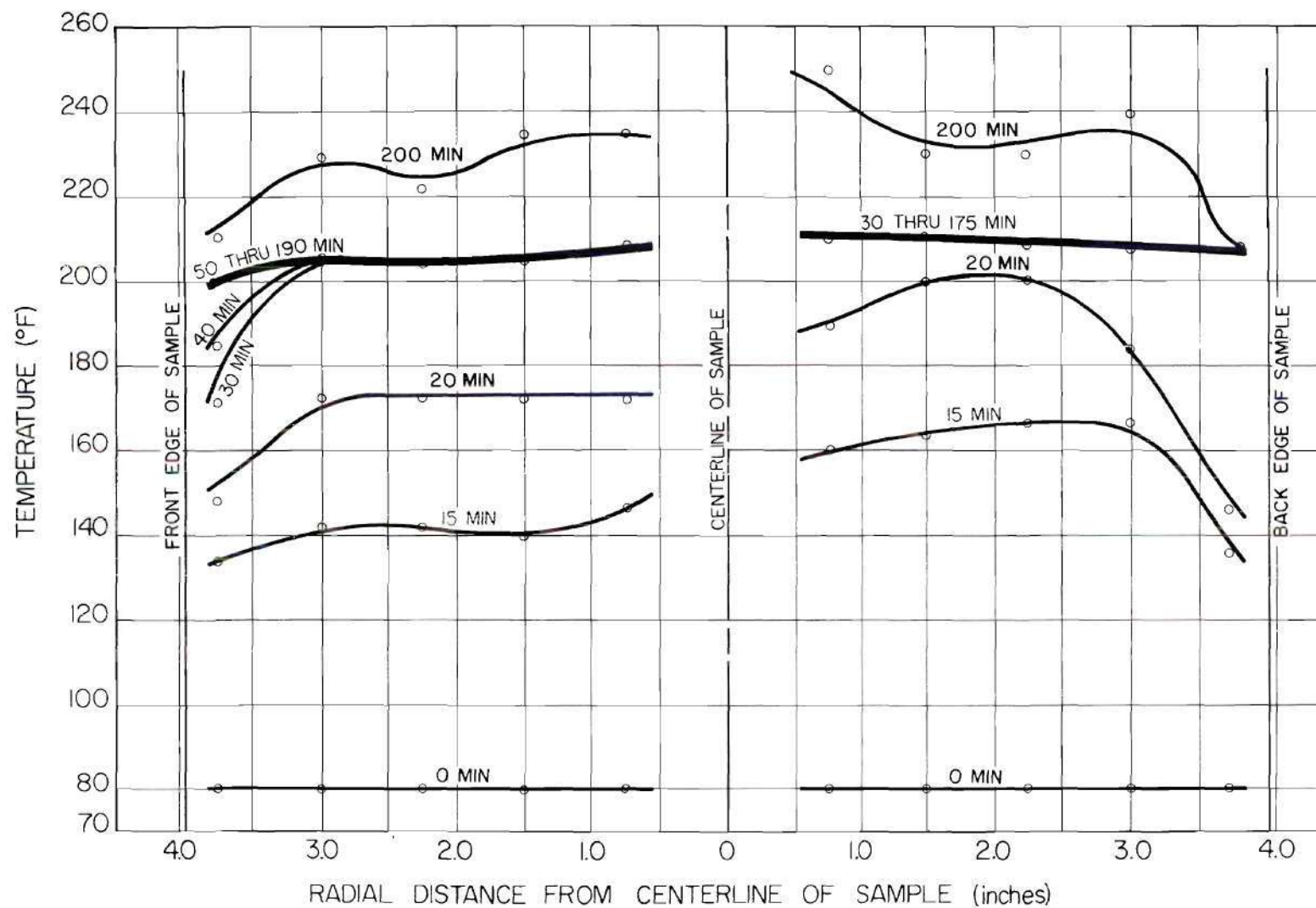
Figure 39.   Temperature Profiles Along the Radial (Flow) Direction 2-1/2
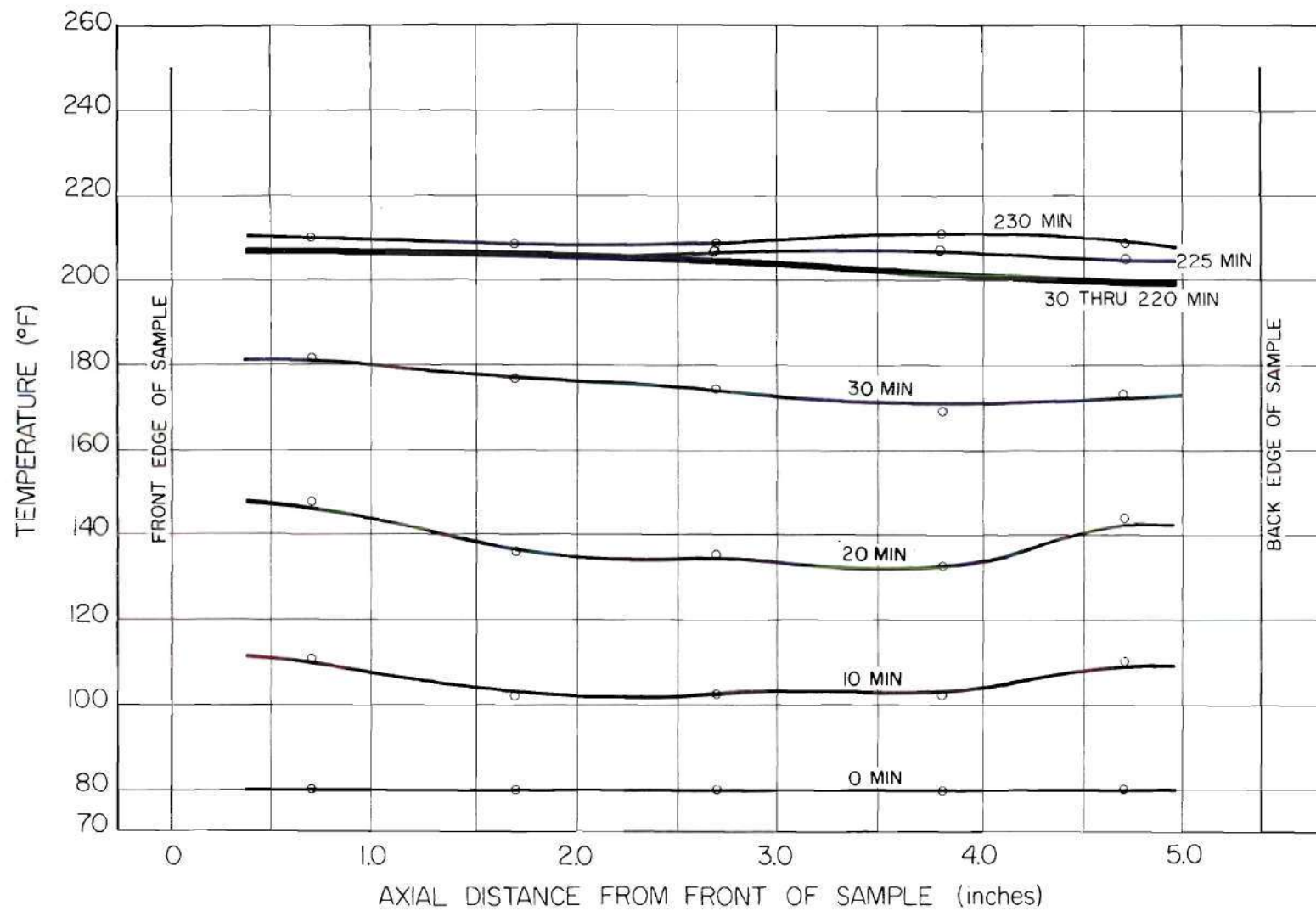Inches from One End of the Sample, Ends Sealed--Run 32.

Figure 40. Temperature Profiles in the Axial (Opposite Flow) Direction at 2-1/4 Inches Radius, Ends Sealed--Run 28.

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sample. A larger pressure gradient is observed for samples with the ends sealed than for circumferentially sealed samples. This is reasonable as the maximum distance of moisture flow in the radial direction is 3-1/2 inches while the maximum distance of moisture flow in the axial direction is 2-5/8 inches. Considering similar vapor generation rates and similar permeabilities, the radial flow situation would thus require a larger pressure drop to maintain the same flow rate.

The variation of moisture content at several radial positions is shown in Figure 29. A cross plot showing the moisture profiles along the radial flow direction is shown in Figure 41. There is no significant moisture gradient along the radial flow direction. The moisture profile in the axial direction is shown in Figure 42. This graph demonstrates that the moisture is also uniform in the direction perpendicular to moisture flow.

Unsealed Samples, Axial and Radial Flow

Samples 8 inches in diameter and 5-3/8 inches long of absorbent cotton yarn were wetted and dried in the 2450 megacycles per second oven. None of the samples' surfaces was sealed with plastic. The typical variation of the total moisture content during drying is shown in Figure 42. When the initial moisture content of the sample is very high (over 200 percent), the initial adjustment period in the drying rate is quite short. It seems possible that much of the moisture loss during the initial adjustment period is primarily liquid water draining from the sample. When the sample has a lower initial moisture content, a more pronounced initial adjustment period is observed.
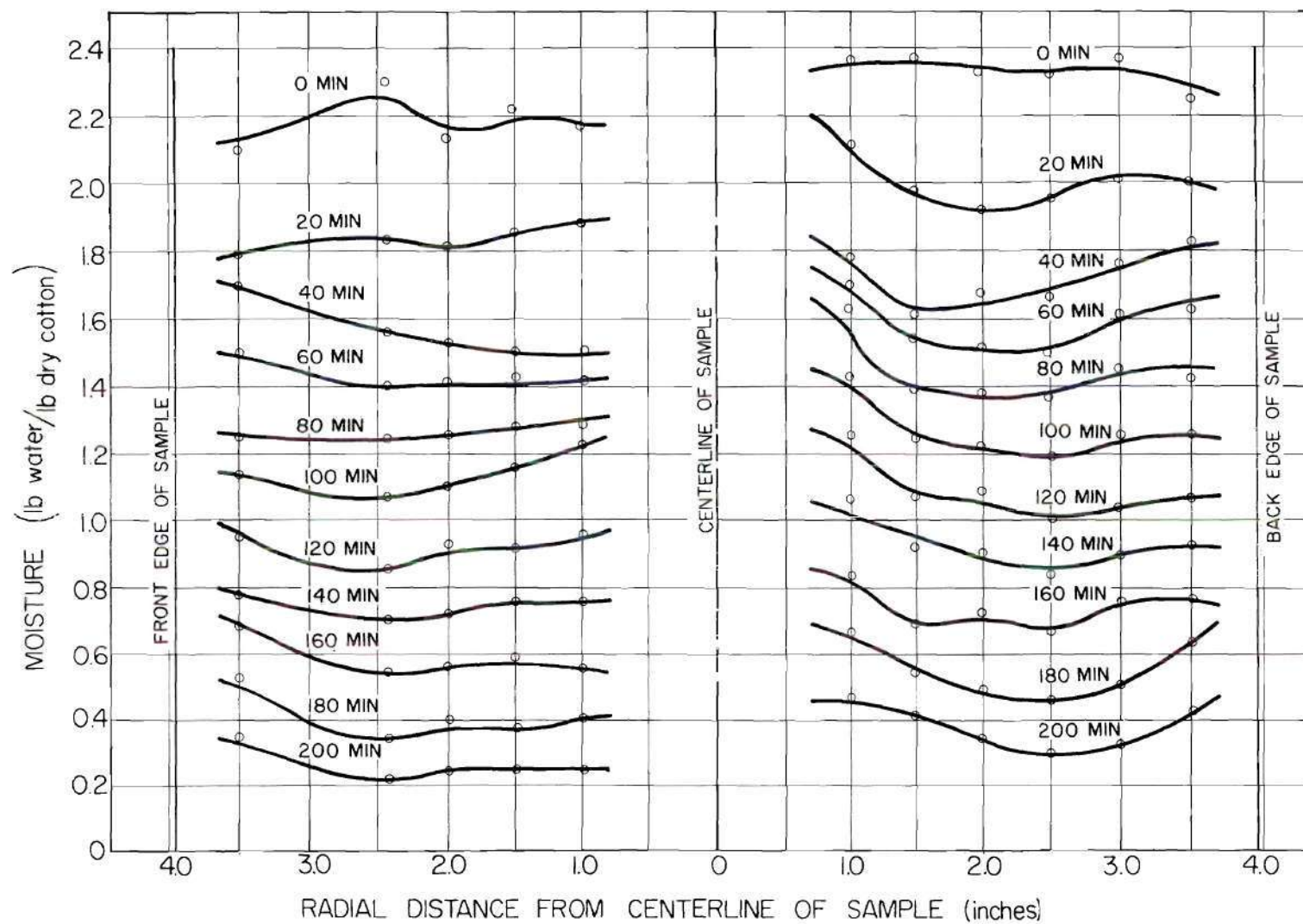
Figure 41. Moisture Content Profiles Along the Radial (Flow) Direction at Fixed Times, Ends Sealed--Run 32.
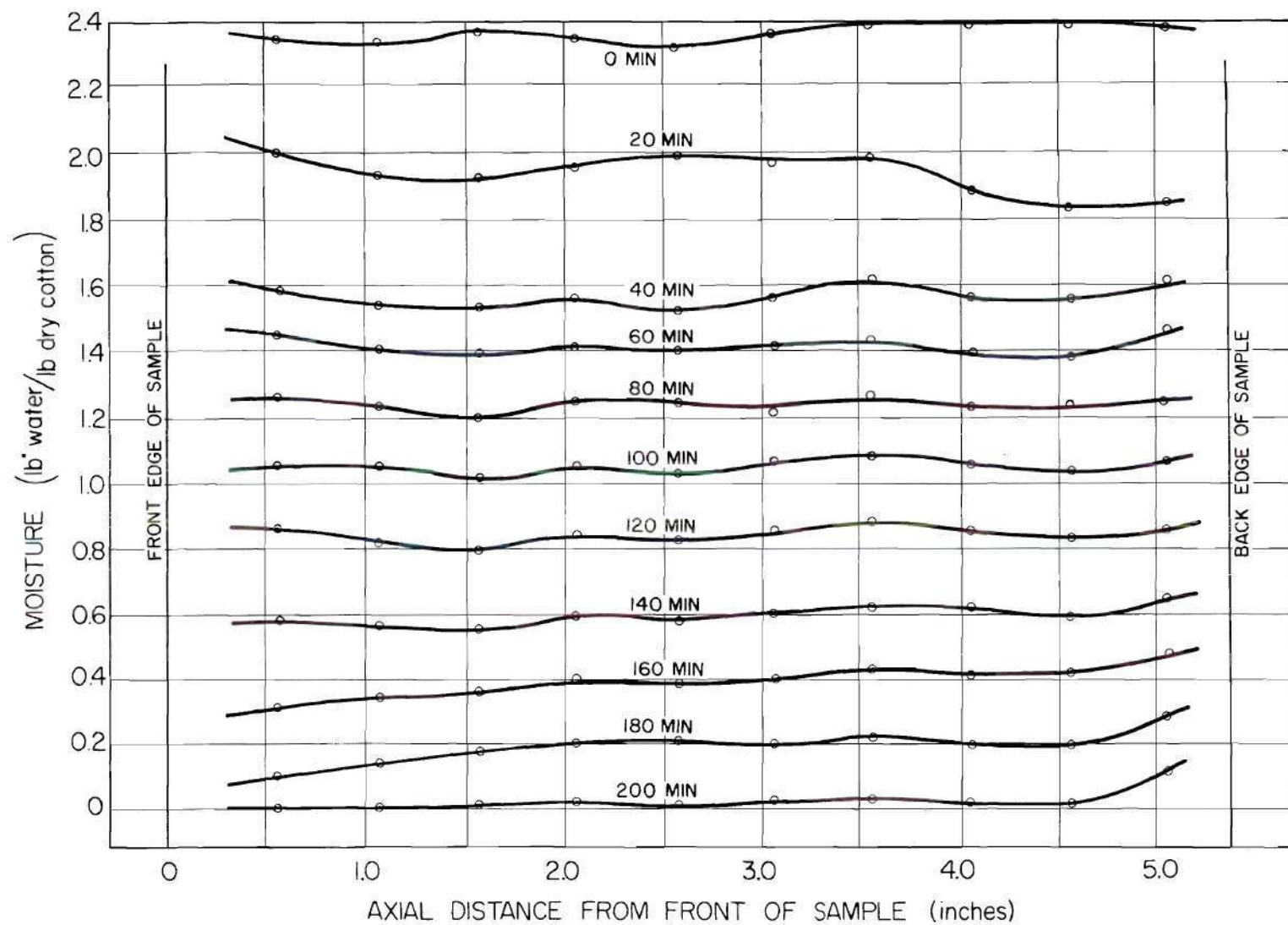
Figure 42. Moisture Profiles Perpendicular to the Direction of Moisture Flow at Fixed Times, Ends Sealed--Run 28.

Generally, for unsealed samples, either a short liquid movement period or no liquid movement period is observed, regardless of initial moisture content. It is felt that the pressure buildup inside the sample is not sufficient to "blow" an appreciable amount of water from the sample. During this research, the rate of vapor generation was limited by the fixed energy output of the microwave ovens. It is possible that a more predominant liquid movement period would be observed if the sample were heated more rapidly.

Although a larger output microwave oven might have allowed even more rapid drying of the sample, it is interesting to compare the drying time between microwave and conventional heating. Figures 17 and 43 represent the total moisture content variation for identical samples, one using conventional heating and one using microwave heating. The drying time with conventional heating was over 24 hours, while the drying time with microwave heating was less than 3-1/2 hours.

The temperature profiles in the axial and radial direction are shown in Figures 25 and 44. It is observed that the temperature is generally uniform throughout the sample during the majority of the drying process. The moisture profiles within the sample are presented in Figures 30 and 31. The curves demonstrate that the moisture content throughout the sample is also generally uniform, i.e., no moisture gradients.

Nonabsorbent Sample

The majority of the samples dried were absorbent cotton yarn. In order to examine the effect absorbency has upon the drying characteristics,

Figure 43.   Variation of Total Moisture Content During Microwave Drying, Unsealed Sample--Run 38.
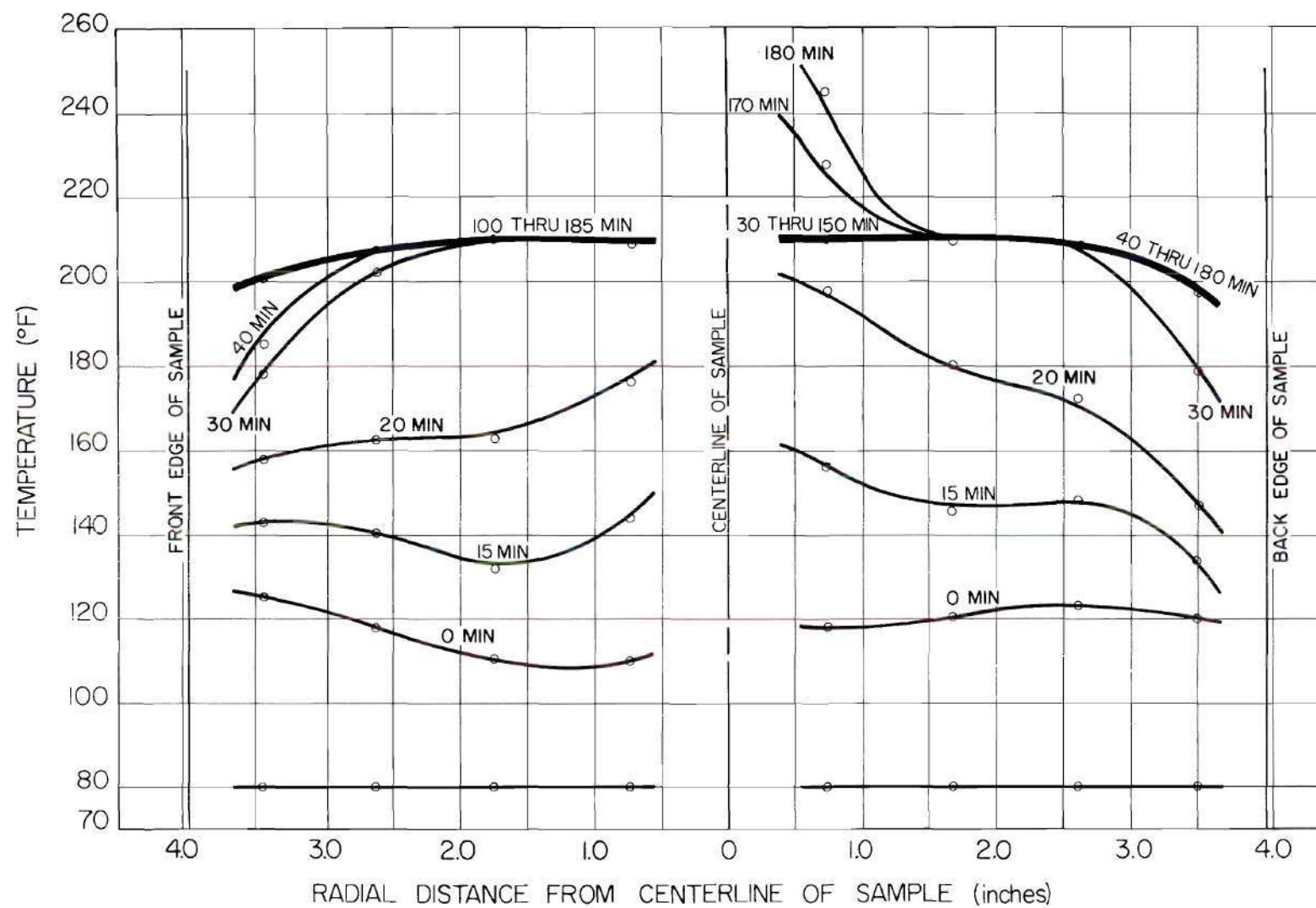
Figure 44. Temperature Profiles Along Diameter at 2-1/2 Inches from One End, Unsealed Sample--Run 38.

some samples of nonabsorbent yarn were dried. Samples 8 inches in diameter
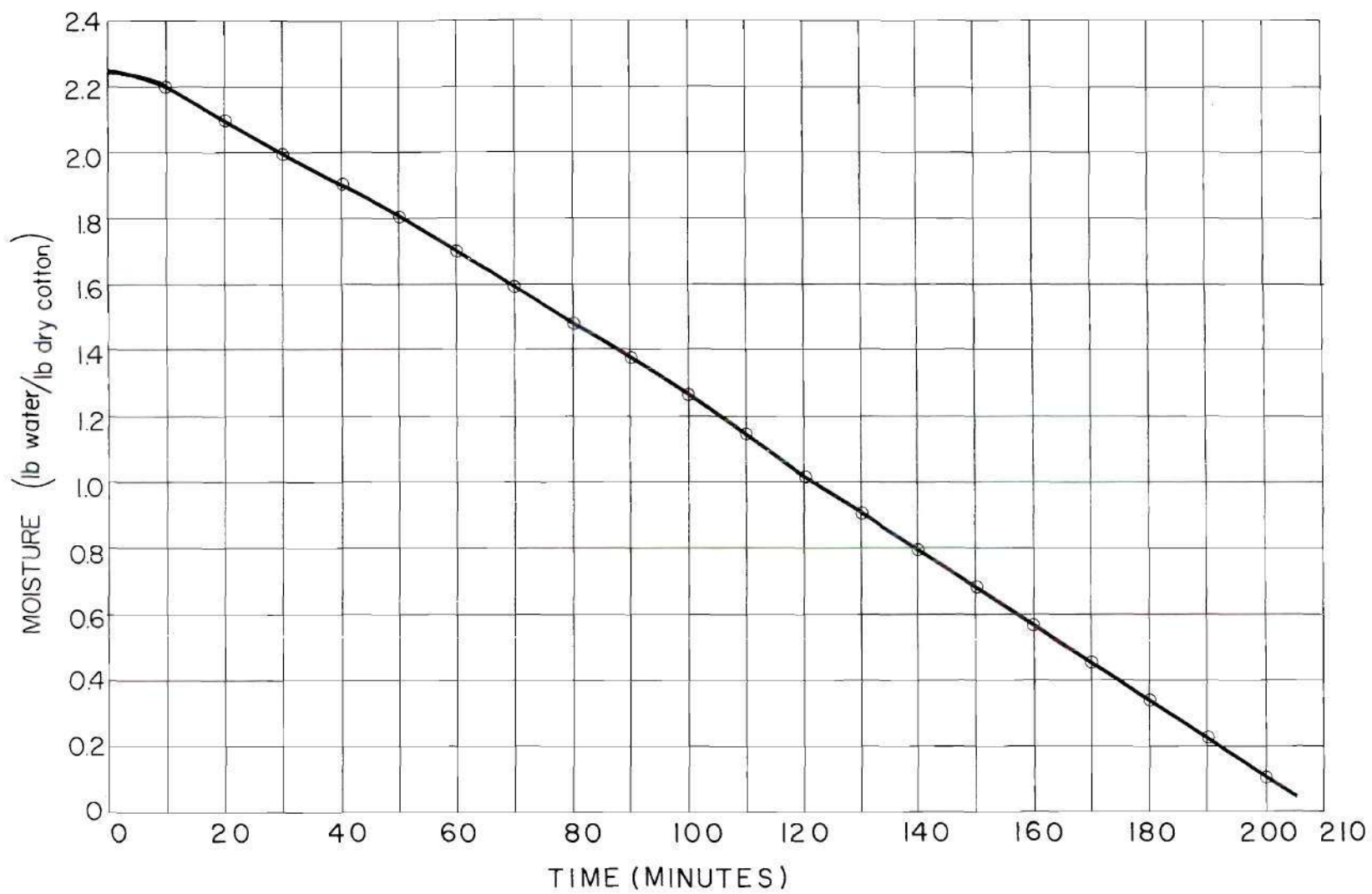and 5-3/8 inches long, were wound from unbleached, nonabsorbent yarn. The
samples were submerged in water and soaked for several days and then dried
in the 2450 megacycles per second oven. Since the yarn was nonabsorbent,
it was difficult to wet the sample uniformly throughout. Complete uni-
formity could not be obtained even after seven days of soaking.

A typical variation of the total moisture content throughout the
drying process is shown in Figure 45. A comparison shows that this is
quite similar to the moisture content variation for a partially wet absor-
bent cotton sample (Figure 22). Typical temperature profiles throughout
a nonabsorbent sample are shown in Figure 46. It is seen that like absor-
bent cotton samples, the temperature throughout the nonabsorbent sample
was relatively constant and uniform during most of the drying process.
The moisture content profiles measured along the radial direction are
shown in Figure 47. The difficulty in obtaining initial moisture uni-
formity is demonstrated by the profile at zero drying time. The outer
layers of the sample were substantially wetter than the center. As the
sample was heated however, the moisture content became more uniform. After
about 30 minutes of drying (after the sample reached a uniform 210°F), the
moisture content profile became relatively flat. It is interesting to ob-
serve that some portions of the sample got wetter during the initial ad-
justment period. It can be observed from the temperature profile graph,
Figure 46, that the layers of the sample at approximately 2-1/2 inches
radius were the first to heat to 210°F. Evidently the pressure buildup
due to rapid vaporization in these layers forced some moisture toward the
center of the sample. Once the moisture content became uniform, it re-
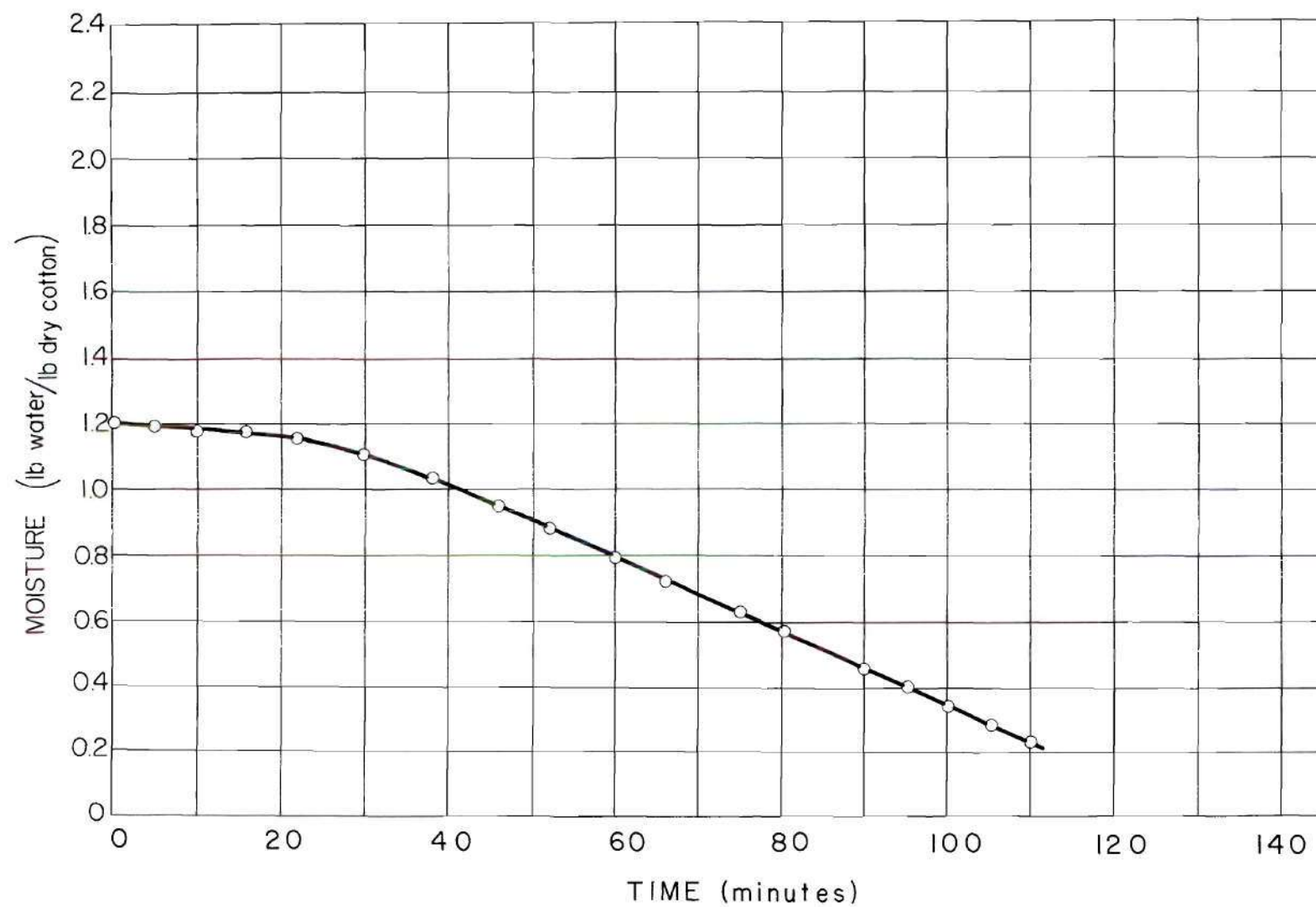
Figure 45. Total Moisture Content Variation During the Drying of a Non-absorbent Sample, Unsealed--Run 48.
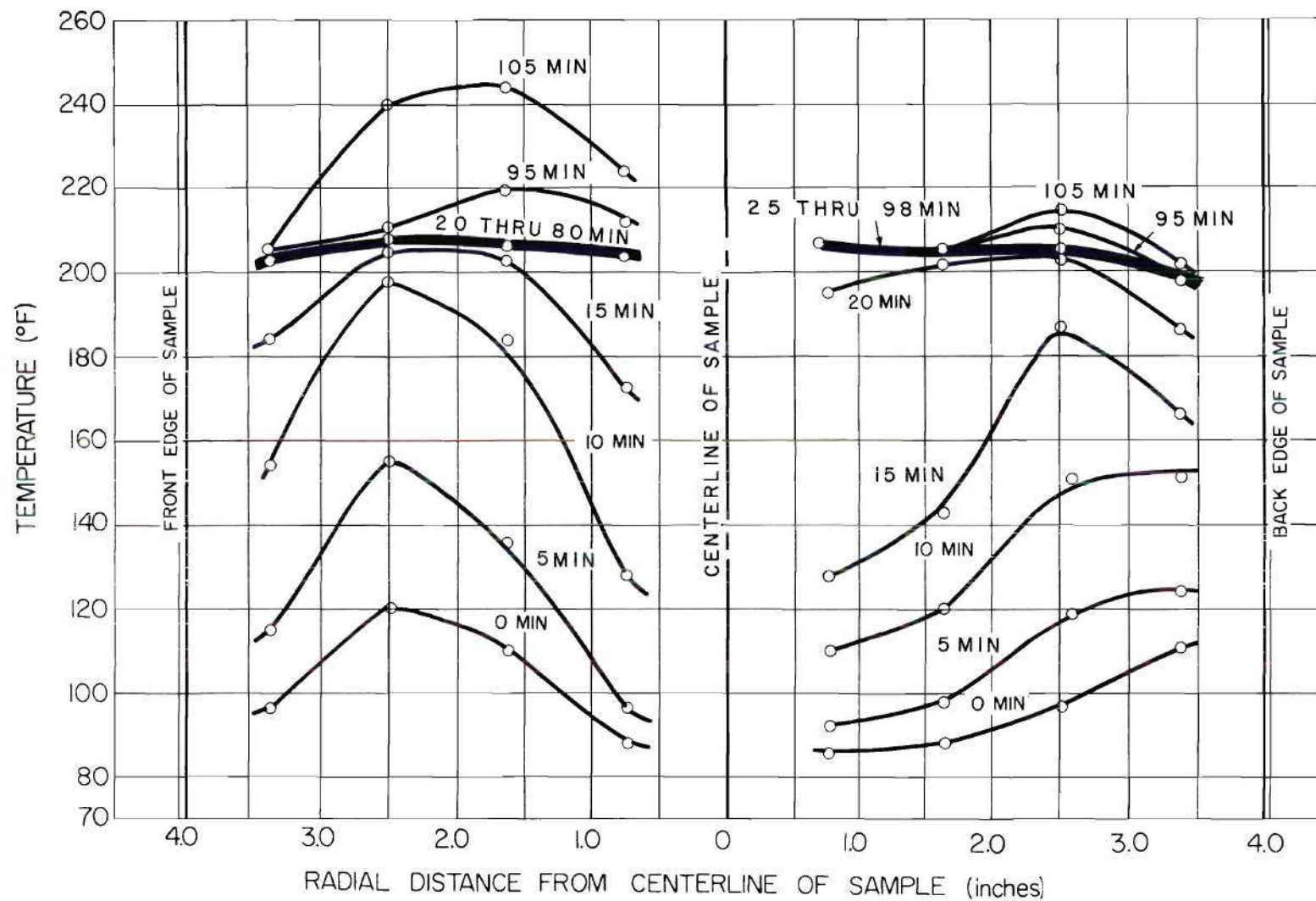
Figure 46. Temperature Profiles Along a Diameter at 2-1/2 Inches from One
End of a Nonabsorbent Cotton Sample, Unsealed--Run 48.
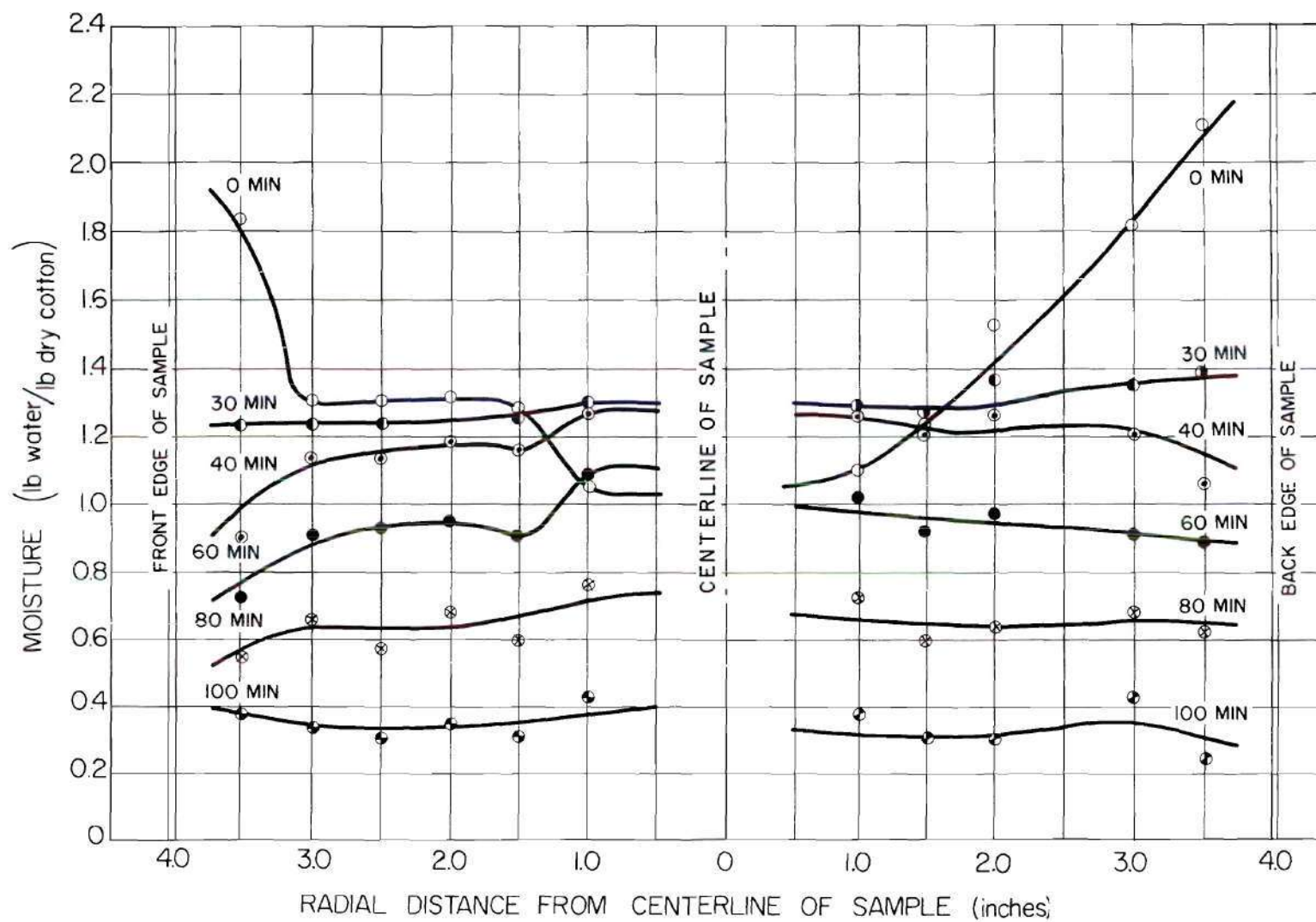
Figure 47. Moisture Content Profiles Along a Diameter of a Nonabsorbent Cotton Sample, Unsealed--Run 48.

mained uniform throughout the remainder of the drying process.

915 Megacycles per Second Oven

Samples of absorbent and nonabsorbent cotton yarn were wound in cylindrical shape, 8 inches in diameter and 2-1/2 inches long. Some samples were sealed on the ends and some were left unsealed. The samples were wetted and dried in the 915 megacycles per second oven. The variation of total moisture content, temperature, and pressure was found to be similar to variation in the same properties observed during drying with the 2450 megacycles per second oven. When a wet sample was placed in the oven, the temperature throughout the sample would rise rather uniformly until reaching 210°F. The temperature throughout the sample would then remain at this temperature for some portion of the drying process. After some period of drying, hot spots began to occur throughout the sample. The average moisture content when the hot spots first occurred was higher when the sample was heated in the 915 megacycles per second oven than when heated in the 2450 megacycles per second oven. Because of the occurrence of these hot spots, it was difficult to dry the sample to as low an average moisture content without causing product damage.

The microwave field in the 915 megacycles per second oven was quite nonuniform. When beakers of water were dispersed about the oven, some absorbed considerably more energy than others. It is felt that this field nonuniformity might account for the heating nonuniformity.

Because of the geometry of the 915 megacycles per second oven, it was not possible to measure the local moisture within the sample while the sample was in the oven. It was possible to get some information con-

cerning the moisture distribution by removing the sample from the oven and quickly placing it in the path of the gamma ray beam and measuring the moisture content. Such measurements showed that the moisture content of the sample remained quite uniform until hot spots began to occur. In the neighborhood of the hot spots, the local moisture content approached zero.

Effect of Sample Size

The effect of sample size on the drying characteristics was examined by drying several different size samples. The majority of the tests were conducted using a sample size of 8 inches in diameter and 5-3/8 inches long. Some tests were conducted with a similar diameter sample but 2-1/2 inches long, and others with a sample 6-3/8 inches in diameter and 4-1/4 inches long. No variation in the drying characteristics between large and small samples was found. The measured parameters such as temperature, pressure, and moisture content all varied in a similar manner. As an example of this, observe Figure 48 which plots the variation in total moisture content and Figure 49 which shows the temperature variation for a 6-3/8 inches diameter sample. The shape of both of these curves is the same as those observed for larger samples, Figures 43 and 23. The drying time for smaller samples was less than the drying time for larger samples because there was less moisture to be removed. The drying rate during the constant rate period was nearly the same for all sample sizes.

The ends of some of the 8 inches diameter and 2-1/2 inches long samples were coated with plastic, restricting the moisture to radial flow. The pressure distribution in the direction of moisture flow was found to vary parabolically in a similar manner to the pressure profile observed
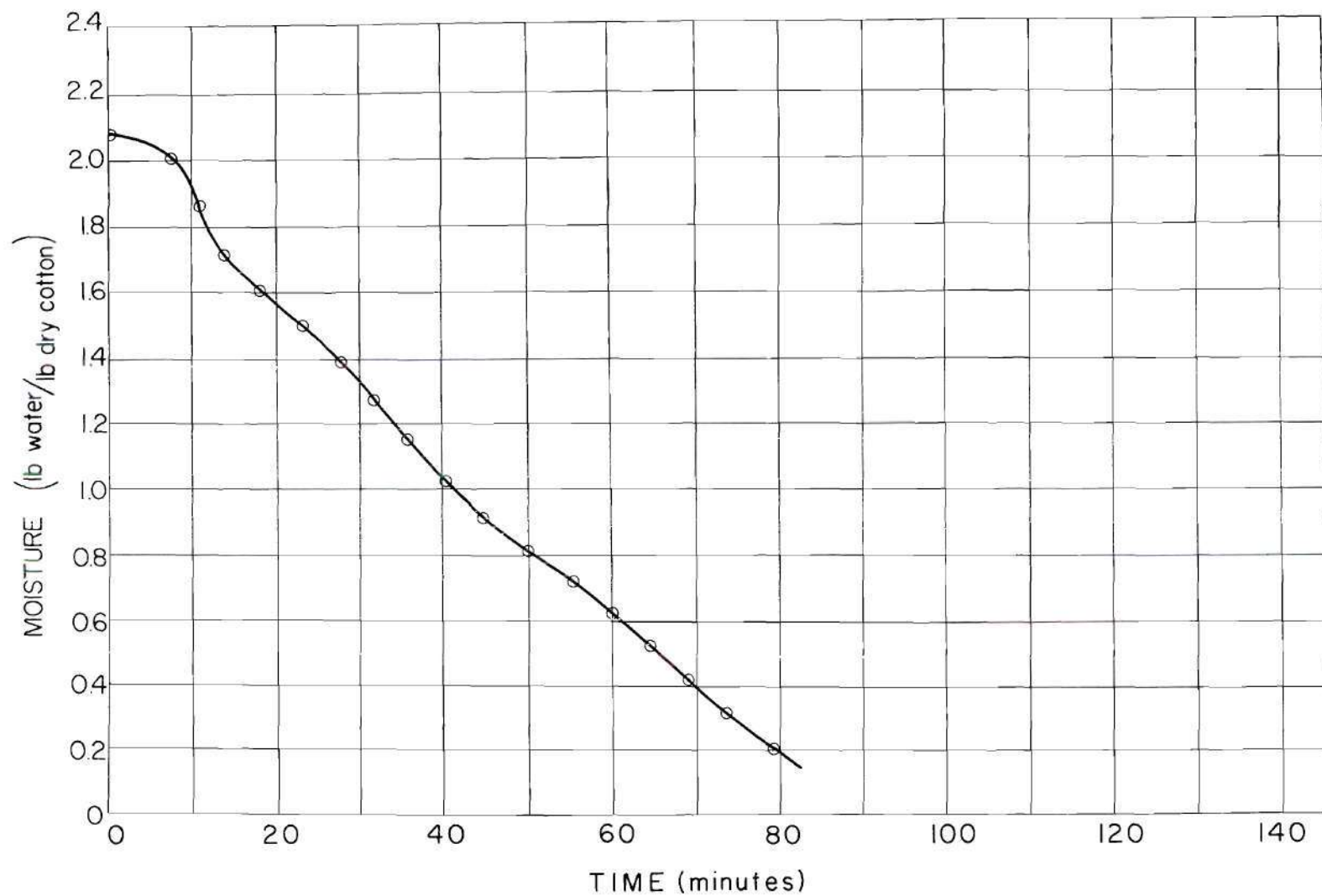
Figure 48. Total Moisture Content Variation for a 6-3/8 Inches Diameter, 4-1/2 Inches Long Sample, Unsealed--Run 32.
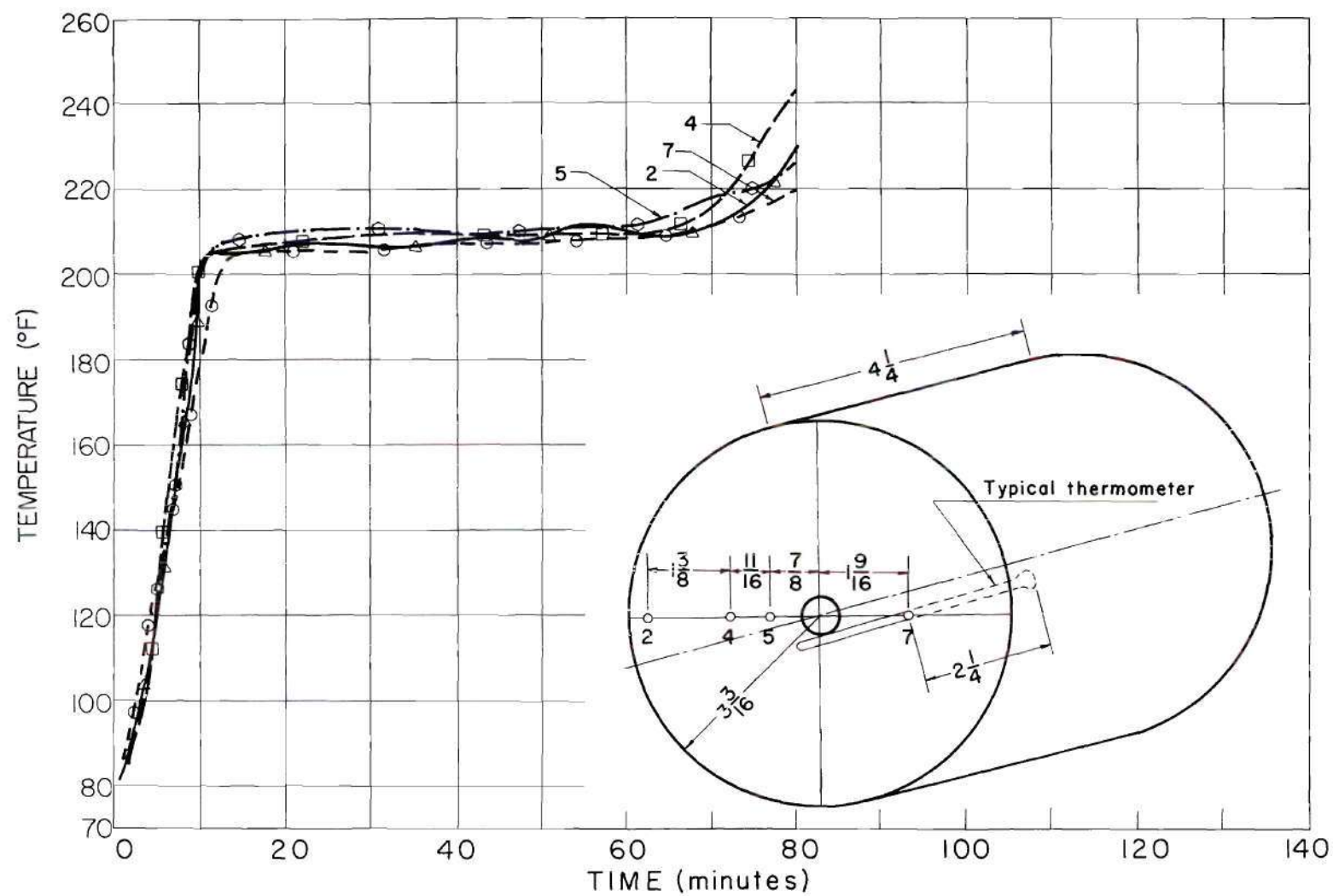
Figure 49. Temperature Variation at Several Locations in a 6-3/8 Inches
Diameter and 4-1/2 Inches Long Sample, Unsealed--Run 37.

when drying longer length samples. However, the pressure at the center
of the shorter sample was higher than that typical of longer samples, i.e.,
the pressure gradient was steeper. This is reasonable since the vapor
generation rate is the same for both size samples. The vapor flow area
is greater in the larger sample and, therefore, a lesser pressure gradient
is required to maintain the same flow rate.

Damage Due to Overheating

Near the end of the drying process, the temperature of some portions
of the product rises above 210°F. The hot spots are often quite localized
and the position of these hot spots varies from sample to sample. Gener-
ally, the hottest points within the sample are located 1-1/2 to 2-1/2
inches beneath the sample surface.

If the heating is continued after the hot spots appear, the tempera-
ture at some locations will pass the combustion temperature for the tex-
tile. Internal burning then occurs. A photograph showing the effect of
continued heating of the sample after it has become dry is shown in Fig-
ure 50. When the sample was removed from the oven and cut apart, the
burned spot shown in the photograph was found to be 1-1/2 inches from
the circumferential surface and 2 inches from the end of the sample. This
was the only burned spot found in this sample. Many of the samples dried
in the microwave ovens were cut apart to check for internal product dam-
age. No product damage was observed unless an attempt was made to con-
tinue to heat samples after hot spots had occurred. In the 2450 mega-
cycles per second oven, hot spots never occurred unless the average moisture
content of the sample was less than 15 percent. Sometimes the samples would
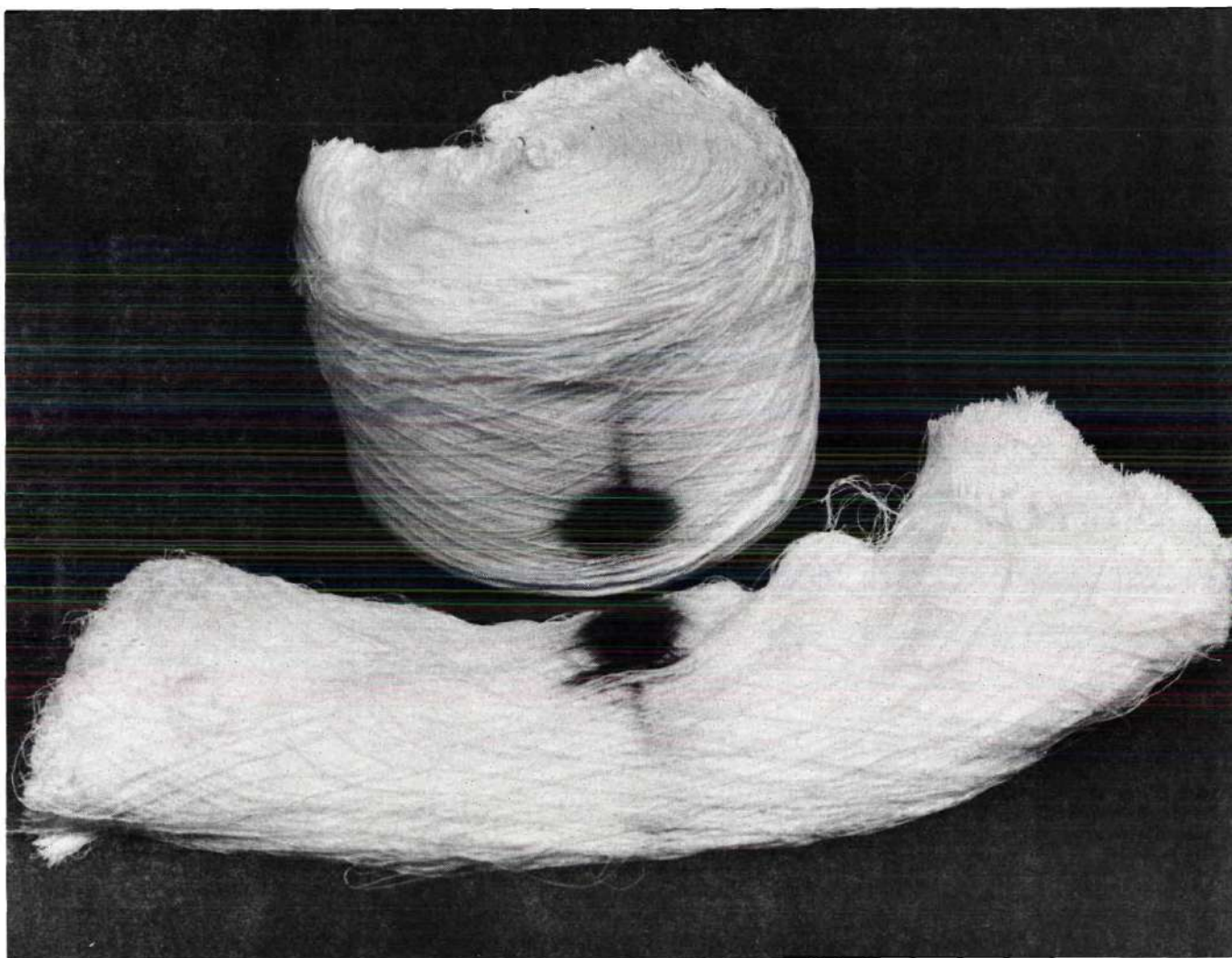
Figure 50. Burned Spot Found Inside the Sample. Microwave Heating was
Continued after Sample became Dry.   2450 mc/s Oven.

dry to nearly zero moisture content without the appearance of hot spots. After slight hot spots did occur, it was found that drying could safely be continued without product damage if the average energy input to the oven was reduced. The reduction in the average energy input can be accomplished by turning off the microwave generator for short periods.

It is believed that the hot spots represent portions of the sample which become dry before the entire sample dries. Recall from Chapter III, however, that dry cotton will generally absorb less microwave energy than will wet cotton because of the lower loss factor of dry cotton. In spite of the tendency to absorb less energy, the dry cotton overheats. It is possible to make a rough comparison of the tendency of the dry cotton to increase in temperature by comparing the amount of energy required to vaporize a pound of water from a wet portion of the sample with the amount of energy required to increase the temperature of a one pound dry portion 100°F. To vaporize the water would require an energy absorption of nearly 1,000 Btu but to heat the cotton would require only 10 Btu. The dry cotton does absorb some energy, even though it absorbs less than the wet portions of the sample. The slight energy absorption of the dry cotton causes an appreciable increase in temperature.

Internal Microwave Attenuation

Except for extremely wet samples during the initial warm-up period, no effect was observed due to attenuation of the microwave field as the field penetrates the sample. The calculations of penetration depth presented in Chapter III suggest that the microwave field at the center of a very wet sample would be substantially attenuated by the wet outer layer. For an 8 inch diameter, 5 inch long sample, some portions of the sample

are 2-1/2 inches from the nearest surface. The attenuation effect should
be more predominant in the 2450 megacycles per second oven than in the
longer wavelength 915 megacycles per second oven. One possible reason
that no nonuniform heating due to attenuation was observed in either oven
is because heat conduction tended to cancel the effect of nonuniform heat-
ing. The steady state temperature distribution in a sample cooled at the
surface with internal heat generation (uniform or nonuniform) would be
highest at the center of the sample. Another factor which might account
for some of the discrepancy between calculated and measured penetration
depths is that in making the calculations for a wet sample, the sample was
assumed to be a continuous uniform media with a microwave attenuation
factor similar to that of liquid water except reduced by the fact that
the product is only partially water. In actuality the water, which comprises
most of the load, is not continuous but is dispersed with different drop-
lets separated by cotton fibers. Little information has been published
concerning the electromagnetic properties of such a dispersed liquid water
load and the possibility exists that the dispersed water has electromag-
netic properties considerably different from those of a liquid water con-
tinuum. Also it should be kept in mind that because of limitations in
the available oven sizes, the largest sample that could be examined in
this research was 8 inches in diameter and 5-3/8 inches long. Larger
samples might exhibit an attenuation effect. Although the reasons are not
clear, it is significant to note that samples at least 8 inches in diameter
and 5-3/8 inches long can be dried uniformly with frequencies as high as
2450 mc/s.

CHAPTER VIII

DISCUSSION OF RESULTS AND CONCLUSIONS

Comparison of Analytical and Experimental Results

A set of partial differential equations which describe the temperature, pressure, and moisture variation throughout the sample is derived in Chapter IV. If these equations could be solved taking into account the time variation and spatial variation of the sample's properties, which are contained in the coefficients of the equations, and also the variation in the boundary conditions, the obtained solutions will predict the temperature, pressure, and moisture variation throughout the sample during the entire drying process. Because of the mathematical elaborateness of the partial differential equations and because of the lack of information concerning sample properties, these equations, in complete form, have not been solved. However, during drying with microwave heating, the constant rate period comprises the majority of the drying process. The results of the experimental investigation, discussed in Chapter VII, suggest that during this period of drying it is reasonable to make several assumptions which greatly simplify the set of partial differential equations. In particular it was found experimentally that during the constant rate period of drying the temperature remains constant with respect to time and space and the moisture content remains uniform throughout the sample. Also, as is indicated by the name of this drying period, the drying rate is constant.

The application of these assumptions to the equations is discussed in Chapter IV. The simplified equations resulting are solved. The solutions prescribe that the pressure profile in the moisture flow direction should be parabolic, with the highest pressure at the center of the sample. Also the magnitude of the pressure is an inverse function of the permeability of the sample which increases as drying proceeds. Therefore the solutions predict a pressure profile which remains parabolic but continually reduces (flattens out) as the drying time increases. Experiments measuring the pressure profile for both axial flow (Figure 38) and radial flow (Figure 28) showed that this prediction corresponds with the physical situation.

A valuable prediction of the analytical investigation is that the constant drying rate is proportional to the energy output of the microwave oven, which was relatively constant during this research. The analytical solutions suggest that the constant of proportionality is the latent heat of vaporization of the water and that all the moisture movement during the constant rate period is the movement of moisture in the vapor state. Because of the lack of available instrumentation it was not possible to measure the microwave energy output of the oven during each of the drying runs. However the typical energy output could be determined by heating a known amount of water in a beaker and observing the amount of energy absorbed by this water. Such experiments indicated that in the 2450 mc/s oven the water in the beaker would absorb energy at between 0.52 and 0.56 kilowatts, depending upon the amount of water in the beakers and the beakers' positions in the oven. Such an energy rate could vaporize 1.8 to 1.9 pounds of water per hour. As pointed out in Chapter VII, the drying rate

during the constant rate period for all types of samples was between 1.75 and 2.0 pounds of water per hour. The correspondence between predicted and measured drying rate is quite good. The variation in the measured drying rate between different samples could be due to a variation in the energy output of the microwave generating tube, since the output of the microwave generator is somewhat a function of the electromagnetic coupling between the load (drying sample) and the generator and different samples present slightly different load characteristics.

Summary of External Characteristics

The characteristics of drying using microwave heating are considerably different from the characteristics of using conventional heating. The atmosphere surrounding the sample during drying using microwave heating need not be heated or conditioned. The oven walls do not heat and radiate energy to the surroundings. However, special precautions must be taken to contain the microwave energy to insure that leakage causes no danger to either personnel or communications facilities.

The drying rate can be much faster using microwave heating than is possible using conventional heating. This is perhaps the most significant advantage of using microwave heating. During this research, samples were dried in minutes which, if dried using convective hot air heating, would have taken over 100 hours to dry. The drying rate using conventional heating is limited by the maximum surface temperature the product can withstand before product damage occurs. During drying using microwave heating, the drying rate is dependent upon the energy input to the sample. Theoretically, the sample could be dried extremely fast by increasing the micro-

wave energy output of the oven. This writer feels that the drying rate could be increased by several orders of magnitude over the drying rate used in this research. Because of limitations in available microwave ovens no attempt was made during this research to investigate the maximum drying rate or the factors establishing such a maximum. Such an investigation would make an interesting continuation of this research.

The drying rate curve for drying using microwave heating is substantially different from that using conventional heating. The drying rate during the initial adjustment period is less than the constant rate period while it is generally greater when using conventional heating. The liquid movement period is unique to drying using microwave heating. No corresponding period exists during drying using conventional heating. The constant rate period extends to a much lower average moisture content and the falling rate period is thus quite short.

Summary of Internal Characteristics

A unique characteristic of drying using microwave heating is that the moisture content tends to remain uniform throughout the drying process, i.e., the center of the sample dries as rapidly as the surface. As discussed in Chapter VII, when a nonabsorbent sample with a nonuniform initial moisture profile was heated in the oven, the moisture content became uniform and remained uniform throughout the majority of the drying process. Similarly, no large temperature gradients exist within the sample except for the gradient in the thin surface layer. During drying using conventional heating, the potential of energy transfer is the large temperature gradient which causes heat conduction from the hot surface to the cooler inner por-

tions. Similarly, the potential of moisture flow is the moisture gradient which exists between the wet inner portions and the drier surface. During drying using microwave heating, the mechanism of energy transfer is primarily internal heat generation. The potential of moisture flow is primarily the total pressure gradient which is established due to the rapid vapor generation inside the sample. The drying rate can be increased by increasing the vaporization rate and the pressure gradient will increase correspondingly, adjusting for a higher moisture flow rate. Theoretically it is possible to increase the vaporization rate until the pressure forces inside the sample become so large that they exceed the strength of the sample.

During drying with microwave heating the majority of the moisture is vaporized before leaving the sample. However, when the sample is initially very wet and the pressure inside the sample rises rapidly, liquid moisture may be "blown" from the sample. The more moisture removed in liquid form, the less energy which is required to dry the sample. A more detailed study of the liquid movement period of drying is suggested as an interesting extension of this research.

Future of Microwave Heating

The use of microwave heating for drying processes has the great advantage of potentially increasing the drying rate. The concept of being able to dry materials at a rapid rate allows the visualization of many innovations in many fields of manufacturing and processing. As an example, consider the potential advantage of: the drying of lumber as it is sawed rather than in a drying shed; the drying of grains such as corn or peanuts as they are picked; the rapid drying of household laundry; the rapid freeze

drying and dehydration of food products; the rapid drying of textiles or paper during processing. There are a tremendous number of situations where the delay in drying causes considerable delay in the processing of the product and consequently greatly increases the handling and storage problems. However, it is not likely that in the near future microwave heating will be used for all of these drying applications. As pointed out in Chapter III, microwave heating is expensive. Both equipment costs and fuel costs are high. Also as indicated by the sample with the internal burned area shown in Figure 50, microwave heating must be applied with caution. There are special design considerations which make the application of microwave heating difficult. However for certain applications, the economic or convenience advantages accompanying an increased drying rate may justify the development and operating costs of microwave heating. As the electronic technology grows, the microwave generating equipment is becoming less expensive and more efficient to operate. As more is learned about the drying processes, dryers can be constructed which operate at the most efficient energy level. Each of these advances reduces the overall cost of microwave heating. This writer believes that within the next few years microwave heating will be used for an ever increasing number of drying applications.

APPENDICES

APPENDIX A

TABLE OF RUNS

Table 3. Table of Runs

Run Number	Type of Cotton	Surfaces Sealed	Oven Used	Sample Size, diameter by length, in.	Dry Weight of Cotton, lbs.	Initial Moisture Content**	Measurements Taken*
1	absorb.	none	none	8-3/4 × 4	2.80	0.0	Wicking
2	nonabs.	ends	915	6 × 2-1/2	0.96	0.34	T
3	nonabs.	ends	915	8 × 2-1/2	1.85	0.48	T W
4	nonabs.	none	none	8 × 2-1/2	1.75	0.0	Wicking
5	absorb.	none	none	8-1/2 × 4	2.8	0.0	Wicking
6	nonabs.	none	915	8 × 2-1/2	1.72	0.31	T M
7	nonab.	ends	915	8 × 2-1/2	2.0	0.20	P
8	absorb.	none	2450	8 × 2-1/2	1.70	2.05	T W
9	absorb.	none	2450	8 × 2-1/2	1.75	1.90	T
10	absorb.	ends	2450	8 × 2-1/2	1.71	1.84	T
11	absorb.	none	2450	8 × 2-1/2	2.09	1.62	T W
12	absorb.	none	2450	8 × 2-1/2	1.71	1.87	T W M
13	absorb.	ends	2450	8 × 2-1/2	2.09	1.65	T W M
14	absorb.	ends	2450	8 × 2-1/2	2.10	1.62	T M
15	absorb.	ends	2450	8 × 2-1/2	1.97	1.42	T
16	absorb.	ends	2450	8 × 2-1/2	1.97	1.32	T M
17	absorb.	ends	2450	8 × 2-1/2	2.1	1.19	M
18	absorb.	circum.	2450	7-7/8 × 5-3/8	3.46	1.91	T M
19	absorb.	ends	2450	9 × 2-1/2	2.10	1.91	M P
20	absorb.	circum.	2450	7-7/8 × 5-3/8	3.79	1.30	T W M
21	absorb.	ends	2450	9 × 2-1/2	2.56	1.45	W M P
22	absorb.	circum.	2450	7-7/8 × 5-3/8	3.06	1.93	T W M

*T = Temperature; W = Weight; M = Local Moisture Content; P = Pressure
**Moisture content measured as lb water per lb dry cotton

Table 3.   Table of Runs
(Concluded)

Run Number	Type of Cotton	Surfaces Sealed	Oven Used	Sample Size, diameter by length, in.	Dry Weight of Cotton, lbs.	Initial Moisture Content	Measurements Taken
23	absorb.	circum.	2450	7-7/8 × 5-3/8	3.32	2.01	T W M
24	absorb.	ends	2450	9 × 2-1/2	2.10	1.91	W P
25	absorb.	ends	2450	7-7/8 × 5-3/8	3.21	2.36	T M
27	absorb.	ends	2450	8 × 2-1/2	2.10	1.80	P
28	absorb.	ends	2450	7-7/8 × 5-3/8	3.22	2.34	T W
29	absorb.	circum.	2450	7-7/8 × 5-3/8	3.32	1.99	T W M
31	absorb.	circum.	2450	7-7/8 × 5-3/8	3.06	1.97	T W M
32	absorb.	ends	2450	7-7/8 × 5-3/8	3.24	2.18	T W M
33	absorb.	circum.	2450	7-7/8 × 5-3/8	3.25	2.12	T W M
34	absorb.	none	2450	7-7/8 × 5-3/8	3.24	2.24	T W M
35	absorb.	circum.	2450	7-7/8 × 5-3/8	3.25	2.14	T W M
36	absorb.	none	2450	7-7/8 × 5-3/8	3.20	2.30	T W M
37	absorb.	none	2450	6-3/8 × 4-1/4	1.63	2.14	T W M
38	absorb.	none	2450	7-7/8 × 5-3/8	3.20	2.23	T W M
39	absorb.	none	2450	6-3/8 × 4-1/4	1.72	2.11	T W M
40	absorb.	none	conven.	7-7/8 × 5-3/8	3.38	2.10	T W
41	absorb.	ends	2450	7-7/8 × 5-3/8	3.10	2.15	W P
42	absorb.	none	conven.	7-7/8 × 5-3/8	3.15	2.35	T W
46	absorb.	circum.	2450	7-7/8 × 5-3/8	3.32	2.49	W P
47	absorb.	circum.	2450	7-7/8 × 5-3/8	3.32	2.46	W P
48	nonabs.	none	2450	7-7/8 × 5-3/8	3.47	1.21	T W M
49	absorb.	none	2450	7-7/8 × 5-3/8	3.24	1.67	T W
50	absorb.	ends	2450	7-7/8 × 5-3/8	3.42	2.00	W P
51	absorb.	ends	2450	7-7/8 × 5-3/8	3.42	1.98	T WP
52	absorb.	ends	2450	7-7/8 × 5-3/8	3.42	2.00	T W P
53	absorb.	ends	2450	7-7/8 × 5-3/8	3.42	2.00	T W P
54	absorb.	circum.	2450	7-7/8 × 5-3/8	3.37	2.10	T W P

APPENDIX B

MEASUREMENT ACCURACY

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MEASUREMENT ACCURACY

Temperature

The majority of the temperature measurements made inside the drying sample were made using alcohol-in-glass thermometers. The thermometers have a scale range of 0 to 220°F with 2°F divisions. Through individual calibration, the temperature scale can be extended to 250°F. After calibration, an accuracy of one-half of a division or ± 1°F can be expected. While thermometers are in the oven, they are difficult to read. The maximum expected readout error is one division or ± 2°F. An overall thermometer and readout accuracy was ± 3°F.

The thermometers are designed for full immersion. They were generally inserted between 1-3/4 and 2-1/2 inches. During the majority of the drying process, the temperature of the sample was in the neighborhood of 210°F, while the oven atmosphere surrounding the thermometer stem could vary from 210°F to as low as 80°F. In order to make a correction for immersion depth, it is necessary to know the temperature of the atmosphere surrounding the stem. The temperature of this surrounding atmosphere varied considerably depending upon the thermometer's position with respect to the scavenging air flow. It is believed that the temperature on the down-wind side of the sample (which was the front side of the oven) would approach 200°F, while the temperature of the oven atmosphere, directly in line with the inlet flow stream (which entered the back of the

oven), would approach the inlet air temperature, 80°F. Because of the randomness of the air flow pattern, it was not possible to develop a reasonable stem correction procedure. In order to obtain an estimate of how significant stem errors could be, two adjacent thermometers were inserted into the sample. One thermometer stem was wrapped with wet textile which heated similarly to the sample. A maximum temperature variation of 5°F was found between the wrapped and unwrapped thermometers. This was the maximum observed variation with the typical variation less than this. The amount of variation was dependent not only upon the location of the stems with respect to scavenging air flow but also was affected by how rapidly the sample was drying. During the liquid movement period when much liquid and vapor are oozing from the sample, the stem was apparently heated by this exiting moisture.

Because of the random nature of the effect of the exposed stem, no correction was made for insertion depth in any of the data reported. In all instances, the scavenging air flow rate was from the back of the sample towards the front of the sample. The error due to stem cooling might account for the slightly lower temperatures sometimes recorded near the back of the sample.

In order to understand the drying process, it is important to know the exact temperature of the sample during the constant rate period. This temperature was checked in two ways. Large, expanded scale, alcohol thermometers were calibrated and inserted into the sample such that they were properly immersed according to their calibration. Care was taken to insure that the maximum error in these thermometers, including readout error was less than 0.5°F. As an additional check on the thermometer

readings, the sample was quickly removed from the oven and probed with a hypodermic-needle-type probe with a thermocouple on the end. All of these measurements substantiated that the temperature throughout the sample during the constant rate period was between the limits of 210°F and 210.5°F.

Moisture

The local moisture measurements were made by shining a gamma ray beam through the sample and measuring the amount of attenuation of the beam due to the moisture in the beam's path. The amount of attenuation due to the water was determined by comparing the beam intensity through the sample at unknown moisture content with the intensity of the beam when it is shone through the same line through the sample at two known moisture contents. One of these known moisture contents or calibration points, was zero moisture. (The beam was shone through the sample before it was wetted. By separate experiment, the equilibrium moisture content of the dry cotton in the laboratory atmosphere was determined to be less than 0.06 pounds of water per pound of dry cotton.)

The other calibration point was obtained after the sample was wetted but before the microwave field was turned on. The total average moisture content of the sample could be obtained by weighing the sample. The beam was then shone through the sample at several measurement locations spaced along either a diameter or the cylindrical axis of the sample, and the intensity at each location recorded. The average of all of these beam intensities was assumed to correspond to the total average moisture content. The intensity reading through each location could then be equated to a moisture content which was above or below the total average moisture

content, an amount corresponding to the amount the intensity was above or below the average intensity. In general, the initial moisture content throughout the sample was quite uniform, and the deviation in intensity readings from point to point was slight, making the averaging procedure both simple and reliable.

The intensity readings taken both to determine the calibration points and also to determine the moisture content during the drying process are all subject to statistical errors as well as errors due to drift in equipment. Since the beam intensity was nearly always high enough such that the count rate was over one million counts per counting period, the error in the moisture content due to statistical variations was less than one percent moisture content. The error due to drift in equipment can be judged by the reproducibility and consistency of the readings and is believed to have been less than three percent moisture content.

The overall reliability of any one reading including the individual errors and the error in establishing the upper calibration point is believed to be less than ten percent moisture content (0.10 pounds water per dry product).

Pressure

As was pointed out in Chapter V, one difficulty in measuring the pressure inside the sample was that the water vapor from inside the sample would flow into the leadout Teflon tubes and condense back into liquid water. These droplets could cause a pressure variation along the leadout tubes due to surface tension effects. The effect could be minimized by using large tubes so that the droplets tended not to fill the whole tube

and by vibrating the leadout tubes to disperse droplets which did form or to equalize the pressure on each side of the slug of water. It is felt that the maximum error in the pressure readings due to this effect and other more minor inaccuracies was one-half inch of water.

Weight

The weight of the sample was continuously monitored by measuring the strain at the root of a cantilevered metal beam which supported the weight of the sample. The sensitivity of the device was 0.01 pounds. It is felt that, including calibration errors and drift errors in the strain measurement equipment, the maximum error in the weight measurement was 0.10 pounds.

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