MICROWAVE DRYING OF RESIN IMPREGNATED PAPER

by

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ABSTRACT

A pilot scale machine was designed and constructed to allow study of the continuous microwave drying at 2.45 GHz of paper impregnated with water or with phenol formaldehyde resin. This equipment could deliver microwave power at levels up to 2.90 KW.

Resin impregnated paper dried by microwaves showed better resin distribution, abrasion resistance, and internal bond strength when compared to similar papers dried in a hot air natural convection oven. No significant differences in tensile strength, stretch, Young's modulus, or bending strength were observed.

A quantitative method for the determination of resin distribution was devised.

Overall efficiencies for the microwave drying based on power input to the microwave power supply were of the order of 50 to 70%.

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I - INTRODUCTION

Recently the application of microwave power to industrial heating and drying processes has become economically feasible in certain industries and is approaching economic feasibility in others. This results from the development of high efficiency and high power microwave generators of improved stability. These generators are available at much lower unit costs relative to earlier designs.

The advantages that microwave heating and drying have over conventional heating and drying arise from the fact that microwaves penetrate instantly to a significant depth in the material being heated and generate heat in this material throughout the volume which has been penetrated. In conventional heating and drying methods heat is transferred into the material being dried from the surface into the bulk of the material. Heat is first transferred to the surface by conduction, convection or radiation. In such a process the highest temperatures are at the surface and a temperature gradient within the material is unavoidable. The conduction process which transfers heat into the material is relatively slow. To speed up this process more severe conditions may be applied to the surface, e.g. increased air temperatures in hot air drying, increased platen temperatures in conduction heating, or increased radiation intensity in radiant heating. These more severe conditions may damage the surface and cause product defects such as surface cracks. In microwave heating the heat is generated internally, thus the surface conditions are no more severe than those inside the bulk of the material. In fact the surface temperature

is usually the lowest. Depending on the absorptive characteristics of the material being heated a less steep temperature gradient may be established.

Another feature of microwave heating which is particularly important in drying is selective heating of water. Water molecules because of their highly polar structure are able to strongly absorb microwave energy. Thus in the drying of paper, water absorbs microwave energy and is heated but cellulose is more or less transparent to microwaves and thus does not absorb much energy from them. In an industrial laminating operation such as plywood manufacture the glue layers could be heated up without having to heat up the bulk of the wood because the wood can transmit much of the microwave radiation.

This selective heating effect also contributes to a sort of self regulation of heating which is especially important in achieving a uniform and level moisture profile. Thus microwaves act upon the wet areas and ignore the dry areas. This could be of great significance in paper manufacture where the level moisture profiles across paper machines, which are necessary to give uniform reels of paper, are achieved by overdrying most of the sheet to remove the wettest streaks.

This study is concerned with using microwave energy in an attempt to improve the properties of phenolic resin impregnated paper by microwave drying. At present this material is dried in a conventional, hot gas, forced convection oven. Conventionally dried resin impregnated paper has a tendency to be rather brittle. When these papers are used as overlays for plywood, particle board etc. excessive flexing of the underlay material may cause cracks in the overlay. This has been attributed to an

uneven resin distribution which is believed to be caused by resin migration during drying in the forced convection drying process. Heat is applied to the surface causing the water suspending the resin emulsion to evaporate. To leave the sheet this water migrates to the surface and carries with it resin molecules which polymerize faster at the surface than in the interior due to the higher temperature. This highly polymerized resin cannot diffuse back into the sheet and hence the interior of the sheet tends to have a lower resin content than the surface. In microwave dried paper the hottest location is at the centre of the sheet and thus polymerization would be most rapid there. This would counteract the tendency to move toward the surface with the evaporating water because the resin molecules would, on attaining a certain degree of polymerization, drop out of suspension. This analysis would seem to be valid during the constant rate period of drying and the first falling rate period.

There is also a certain advantage in microwave drying during the falling rate periods in that the cellulose does not have to be heated up in order to evaporate the water because the heat is selectively generated in the water.

In this study phenol-formaldehyde impregnated paper is dried using a 2.5 kw meanderline, microwave drier under various conditions. The quality of this product is compared with the quality of forced convection dried papers produced commercially and in the laboratory. Some useful data for the microwave drying process is also obtained.

II - REVIEW OF PREVIOUS WORK

1. Drying Mechanism

Early workers^(1,2) in the field of drying divided the drying process into two stages, the constant rate stage, wherein the rate of evaporation is constant, and the falling rate stage in which the rate of evaporation decreases with decreasing moisture content. The constant rate period was, and is still, believed to be evaporation from a continuous, unbroken film of water on the surface of the material being dried. When sufficient water has been evaporated dry solid breaks through this surface film; the rate of drying decreases; this is the falling rate period. In this early work it was proposed that water moves by diffusion from the interior of the solid to the surface and that as more and more water is evaporated this diffusion encounters more and more resistance.

In 1937 Ceaglske and Hougen⁽³⁾ found that the moisture profile which they measured did not fit the profile that they calculated on the basis of a diffusion mechanism when drying beds of sand. They explained these results by introducing a capillary flow mechanism as opposed to a diffusion mechanism for the movement of water. Thus water was assumed to move from the interior of the solid to the surface under the influence of surface tension forces in the capillaries.

Corben and Newitt⁽⁴⁾ proposed in 1955 a theory of drying based on a series of studies on porous and non-porous materials. Using the capillary theory, mechanisms were put forward for the constant rate period and the first and second falling rate periods. During the constant rate period surface water is evaporated;

this is the first water to be removed in most drying processes. Further drying exposes the pores in the material. These pores lead into the interior of the solid. At their mouths pendular rings of water are present. When all these external pores are exposed and only pendular water rings remain on the surface the rings start to contract causing more of the pores to be opened. As the pendular rings contract increasingly narrow pores are exposed leading to greater capillary suctions. Eventually a stage will be reached when the pendular rings are incapable of transferring sufficient water to the surface from the interior to replace that which has been evaporated. Here the constant rate period ends and the falling rate period begins.

When water can no longer be removed by the meniscus receding into smaller pores further evaporation occurs by diffusion of water out of the solid. This is the second falling rate period. Both capillary and diffusion mechanisms may occur simultaneously in some materials.

The kind of material determines whether capillary effects or diffusion control the rate of moisture evaporation. In porous materials capillary suction is most important (e.g. beds of sand), whereas in non-porous materials (e.g. gelatine and other foods) diffusion controls. In other situations the drying equipment has an influence on the mechanism by which water is moved from the interior of the solid to the surface. In the conventional paper drying process the wet sheet is pressed against steam heated cylinders. Dreshfield and Han⁽⁵⁾ have reported an evaporation-condensation mechanism for this kind of drying. In this mechanism water is believed to evaporate at

or near the surface where the heat is being supplied; that is at the sheet cylinder interface. However, this water cannot escape through this surface which is effectively sealed by the metal cylinder. The water vapour then moves to the opposite, cooler side of the sheet where it condenses. The energy released in condensation then contributes to the energy required to vapourize water at the surface away from the cylinder. The water is supposed to migrate either by diffusion or capillarity.

This evaporation-condensation mechanism is most probable when the system is subject to large temperature gradients such as occur in drying by contact with a hot surface. Applying this mechanism Harmathy⁽⁶⁾ theoretically simulated various drying processes and showed that the evaporation-condensation mechanism was the governing mechanism of drying during the falling rate period.

Harmathy's⁽⁶⁾ paper is one of a number of papers which have appeared recently and which are mainly concerned with computer simulation of drying processes. Kauh⁽⁷⁾ has used a numerical solution of the diffusion equation in an attempt to predict a drying curve using a diffusion moisture movement mechanism. Although a successful prediction was claimed and good agreement between experimental and calculated results reported, the applicability of this kind of solution will be limited since the diffusion mechanism is not always the governing one.

For hot surface drying, such as is used in the steam cylinder drying of paper, Nissan et al.^(8,9,10,11) have numerically solved the Fourier heat conduction equation to get the temperature profile in paper and its drying rate curve. They assumed conductive heat transfer through the sheet and evaporation

from the side of the paper opposite the cylinder. The temperature profile was calculated assuming a uniform moisture content profile. In Nissan's work the operation of the dryer was divided into four phases; 1) where the paper sheet first contacts the cylinder; 2) where the paper is contacting the cylinder and is covered by the felt; 3) where the sheet is again exposed on one side and 4) where the paper sheet is between cylinders.

The following equation was solved

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha} \frac{\partial T}{\partial \theta}$$

Different boundary conditions appropriate to the various regions were used. These were

Initial condition

$$T = f(x) \quad \text{for } \theta = 0$$

Phase 1 and 3

$$\left(\frac{\partial T}{\partial r} \right)_{r=0} = - \frac{H_1 X}{k} (T_c - T_{r=0})$$

$$\left(\frac{\partial T}{\partial r} \right)_{r=1} = - \frac{H_2 X}{k} (T_{r=1} - T_a) - \frac{4.65 H_2 X}{k} (y_1 - y_a) T_b$$

Phase 2

$$\left(\frac{\partial T}{\partial r} \right)_{r=0} = - \frac{H_1 X}{k} (T_c - T_{r=0})$$

$$\left(\frac{\partial T}{\partial r} \right)_{r=1} = - \frac{H_2 X}{k} (T_{r=1} - T_f) - \frac{4.65 H_2 X}{k} (y_1 - y_f) T_b$$

Phase 4

$$\left(\frac{\partial T}{\partial r}\right)_{r=0} = -\frac{H_1 X}{k} (T_a - T_{r=0}) - \frac{4.65 H_1 X}{k} (y_o - y_a) T_b$$

$$\left(\frac{\partial T}{\partial r}\right)_{r=1} = -\frac{H_2 X}{k} (T_{r=1} - T_a) - \frac{4.65 H_2 X}{k} (y_1 - y_a) T_b$$

Comparing their numerical solutions with experimental measurements they concluded that heat was indeed transferred through the sheet by conduction alone if the cylinder temperature was below the boiling point of water. They noted that convective heat transfer became of increasing importance as the temperature rose. This suggested the presence of an evaporation-condensation mechanism⁽¹¹⁾.

Snow⁽¹²⁾ improved upon this kind of analysis by numerically solving the heat and mass transfer equations simultaneously. In his work he added a term to the heat conduction equation to allow for the evaporation-condensation mechanism. He solved

$$\rho C_p \frac{\partial T}{\partial \theta} = \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial x} \left(\lambda K_r \frac{\partial P_w}{\partial x} \right)$$

The first term on the right hand side represents conductive heat transfer and the second represents evaporation-condensation heat transfer. The appropriate mass transfer equation used was

$$\frac{\partial M}{\partial \theta} = -\frac{\partial}{\partial x} \left(K_c(M) \frac{\partial P_s(M)}{\partial x} \right) + \frac{\partial}{\partial x} \left(K_r \frac{\partial P_w}{\partial x} \right)$$

In this equation the first term on the right hand side represents the rate of flow of liquid water by capillary action. $P_s(M)$ is the capillary suction exerted on liquid water by the

capillaries in the paper having moisture content M . $k_c(M)$ represents the conductance of the paper for liquid water. This term was determined empirically. The second term on the right hand side represents the rate of flow of water vapour which contributes to the evaporation-condensation heat and mass transfer. K_r is calculated from the theory of molecular diffusion of water in air. Although the solutions of these equations rely on empirically determined coefficients which no doubt vary from material to material, Snows' analysis seems to give good results and his method should be tested on a wider range of materials.

2. Basics of Microwave Drying

There have not been many papers published on the subject of microwave drying and even fewer on the microwave drying of paper. Most of the latter are concerned with the economic feasibility of introducing microwave drying into papermaking. A number of papers have appeared which are concerned with the experimental determination of the dielectric properties of the material to be dried.

Because of the internal heat generation in the material being dried by microwave techniques the drying mechanism may be different than that found in conventional drying. However, as far as is known no research has been done on the mechanism of moisture removal in microwave drying.

Goerz and Jolly⁽¹³⁾ have done an economic feasibility analysis on the use of a meanderline waveguide drier for installation on a conventional paper machine. They predicted significant savings but this conclusion has been criticized by Gardner⁽¹⁴⁾.

who questions the cost figures they assigned to conventional drying. The advantages cited by Goerz and Jolly include a more uniform moisture profile, a higher overall moisture content, and a substantially reduced drier length.

Damskey, Hankin and Stephansen⁽¹⁵⁾ have presented another economic analysis of microwave application to conventional papermaking by using computer simulation techniques. In their work they computed the relative profitability of using microwave equipment over conventional equipment in papermaking and paper coating. The following assumptions were made:- 1) microwave drying produces a level moisture profile with a higher average moisture content; 2) the increased drying capacity provided by microwave methods permits higher papermachine or coating machine speeds. Their economic model indicates a better return on invested capital for microwave drying over conventional drying.

More experimental data is necessary in an accessible form before one could competently design or select a microwave drier for paper manufacture.

Microwave driers or heaters employ high frequency energy in the range 300 MHz to 30GHz (300×10^6 cycles/sec. to 30×10^9 cycles/sec.). In order to prevent interference with microwave communications systems the following frequencies have been assigned for industrial, medical, and scientific use.

Frequency MHz	Wave Length inches
890 - 940	13.0
2400 - 2500	4.9
5725 - 5875	2.0
22,000 - 22,250	0.24

The choice of frequency depends on several factors. Industrial equipment for drying is only available for 915 MHz and 2450 MHz. High frequencies promote higher power dissipation but the depth of penetration into the material is greater for low frequencies. In the present work a 2450 MHz generator was used.

At microwave frequencies electromagnetic energy is absorbed by means of a relaxation phenomenon or dielectric after effect. This is caused by the motion of the dielectric molecules in response to an applied alternating field. The motion consists of a distortion of the molecular structure. Thus the bond angles and interatomic distances in the molecule are distorted from their equilibrium position by the field. The polar molecules also try to align themselves with the field. But as the field direction is continually changing the molecules are continually distorting and realigning resulting in energy dissipation and production of heat.

When a microwave is transmitted into a dielectric material the incident power density (P_i) carried by the wave is related to the electric field density by

$$P_i = \frac{E_i^2}{2\eta_0}$$

where η_0 is the intrinsic impedance of free space.

At the surface of a dielectric material in a microwave field some of the incident energy is reflected back towards the source and the remainder (P_t) is transmitted into the material. Attenuation theory describes how the electric field density is attenuated in the dielectric material. From this theory it can be shown that the power carried by the microwaves is decreased

Figure 1. Plane-wave Transmission into Lossy Material

to $\frac{1}{e}$ of its surface value P_t in a distance d where

$$d = \frac{1}{2\alpha} = 1.5 \times 10^{10} (\pi f \sqrt{\epsilon'} \tan \delta)^{-1} \quad (\text{cm})$$

α = attenuation constant of the material

ϵ' = dielectric constant

f = frequency

$\tan \delta$ = loss factor

$$\epsilon = \epsilon' - j\epsilon'' = \epsilon'(1 - j\tan \delta)$$

$$\tan \delta = \frac{\epsilon''}{\epsilon'}$$

ϵ = complex permittivity

ϵ'' = dielectric loss factor

The equations describing the amounts of power absorbed, reflected and transmitted for lossy dielectrics are generally complex and difficult to apply because the characteristic constants ϵ' and $\tan \delta$ are temperature dependent. For materials which are thin enough that the electric field density (E_t) can be assumed to be constant in them the absorbed power is obtained from

$$P_a = 55.6 \times 10^{-14} E_t^2 f \epsilon' \tan \delta \quad (\text{watts/cm}^2)$$

In order to evaluate the power dissipated in microwave heating or drying processes the dielectric constant ϵ' and the loss factor $\tan \delta$ of the particular material at the particular frequency being used must be known. These values as well as being temperature dependent are also composition dependent. In

drying one of the components is water which has a relatively large loss factor, thus the ϵ' and $\tan \delta$ factors of the wet material depend on the moisture content.

Some empirical relations for these parameters have been reported. Voss⁽¹⁶⁾ after processing the experimental data of several workers has suggested the following equations relating the dielectric constant and the loss factor for water to temperature and frequency

$$T \tan \delta_w = 1.82 \times 10^{-9} f - 1.2$$

$$\epsilon'_w = 55 \pm 10 \% \quad \text{at } 9 - 10 \text{ GHz}$$

$$\epsilon'_w = 87 - 0.36T \quad \text{at } 2 - 3 \text{ GHz} \quad (T = \text{temperature } ^\circ\text{K})$$

Lewin⁽¹⁷⁾ has presented the following equation to describe the dielectric behaviour of a compound material. This equation rests on a semi-theoretical basis

$$\epsilon = \epsilon' - j\epsilon'' = \epsilon_1 \left(1 + \frac{3F}{\frac{\epsilon_2 + 2\epsilon_1}{\epsilon_2 - \epsilon_1} - F} \right)$$

ϵ_1 = complex permittivity of component 1 (dry solid)

ϵ_2 = complex permittivity of component 2 (water)

$$F = \frac{W}{W + \frac{\rho_2}{\rho_1}}$$

ρ_2 = density of component 2

ρ_1 = density of component 1

W = mass ratio of component 2 to component 1

Substituting

$$\epsilon_1 = \epsilon_1' - j\epsilon_1''$$

and

$$\epsilon_2 = \epsilon_2' - j\epsilon_2''$$

rearranging and collecting real and imaginary parts gives the dielectric constant ϵ' and the loss factor ϵ'' of the wet material as

$$\epsilon' = \frac{(1-F)(1+2F)(\epsilon_2'^2 + \epsilon_2''^2) + (4+F+4F^2)\epsilon_2'\epsilon_1' + 2(1-F)(2+F)\epsilon_1'^2}{\{\epsilon_2'(1-F) + \epsilon_1'(2+F)\}^2 - (F-1)^2\epsilon_2''^2}$$

$$\epsilon'' = \frac{9F\epsilon_1'^2\epsilon_2''}{\{\epsilon_2'(1-F) + \epsilon_1'(2+F)\}^2 - (F-1)^2\epsilon_2''^2}$$

The application of Lewin's equations to mixtures has not been completely successful⁽¹⁸⁾. In Lewin's analysis it was assumed that the two components were simply mixed without interaction. But in many materials such as cellulose, water molecules are actually bonded to the solids by for example, hydrogen bonds. These binding forces affect the dielectric loss behaviour.

Asami⁽¹⁹⁾ has developed an empirical expression for the dielectric permittivity of mixtures when bonding affects are present. In his equations an empirical constant n is introduced which represents the mixing condition. His equation is

$$\frac{\epsilon-1}{\epsilon-n} = F\left(\frac{\epsilon_1-1}{\epsilon_1+n}\right) + (1-F)\left(\frac{\epsilon_2-1}{\epsilon_2+n}\right)$$

Voss⁽¹⁶⁾ tested this equation with some experimental data obtained for wet wood and found good agreement.

Although only certain frequencies are allowed for industrial microwave use by law these may not necessarily be the optimum frequencies for a particular drying or heating process since the dielectric behaviour of materials is frequency dependent.

De Loor⁽²⁰⁾ studied frequency effects on the dielectric behaviours of heterogeneous systems containing water and related the mechanism of microwave absorption to frequency.

It is only recently that experimental data for use in designing practical microwave drying and heating processes have become available. For the microwave drying of wood Voss⁽¹⁶⁾ measured the dielectric constant and loss factor at 9.21 GHz. Similar work at 2.45 GHz was done by Tinga⁽²¹⁾. In the latter work the dielectric constants of several kinds of wood were measured as functions of temperature at various moisture contents. Leidigh, Stephansen, and Stolte⁽²²⁾ investigated the microwave absorption properties of paper at 2.45 GHz. They presented values of the dielectric constant and loss factor as functions of temperature and moisture content. More data is necessary before confident design or assessment of large scale industrial systems is feasible for the non equipment manufacturer.

3. Resin Distribution Measurement

It has been postulated that non uniform resin distribution is a contributing factor to some of the defects found in resin impregnated papers. Thus some method of observing or, preferably, measuring the uniformity of resin distribution is necessary to confirm the postulate.

In order to study the resin distribution through the thickness of the sheet it is necessary to section the sheet somehow. After sectioning the resin distribution may be considered by one of four methods⁽²⁴⁾.

- 1) microscopy
- 2) extraction and analysis
- 3) auto radiographic analysis
- 4) direct chemical analysis

There are several possible ways of sectioning a sheet of paper into layers. These include using a microtome, scotch tape, a sheet splitter, sandpaper, or a lathe. The microtome gives too little sample; scotch tape will not work on resin impregnated paper, neither will the Beloit sheet splitter; sandpaper contains phenolic resin which might affect subsequent analysis so we chose to use a lathe.

So far the microscopic method for observing resin distribution has not been made quantitative. Crosby and Marton⁽²⁵⁾ have studied the mechanism of resin penetration into laminating papers. They dyed phenolic resins prior to impregnation and then observed the resin distribution after drying the sheet, under a light microscope; embedding it in a polyamide mounting medium and sectioning by microtome. Dyes should be chosen so that they exert minimal effects on the properties or behaviour of the resin. Takahashi, Vasisht, and Cote⁽²³⁾ have developed a method for observing the resin distribution in a sheet of resin impregnated paper. Their technique involves soaking the dried and cured paper in hydrofluoric acid which dissolves all the cellulose leaving

behind the resin skeleton. It also would leave behind lignin but as the base papers were made from bleached kraft pulp the amount of lignin would be small. This resin skeleton was then carefully washed, embedded in a mounting medium and sectioned on a microtome. Microphotographs showed the resin distribution and a more uniform distribution was observed with microwave dried papers.

Extraction of the resin followed by chemical or physical analysis of the residue or of the extract has been used as a method for determining the total resin content of paper sheets. These could be adapted to the determination of a resin distribution in a sheet after it has been sectioned but does not seem to have been so applied previously. For phenolic resins a variety of solvents have been proposed-cyclohexane, n-butanol, dimethyl-formamide, acetone, or molten naphthol⁽²⁶⁾. The samples are weighed before and after extraction and the resin content determined by difference gravimetrically. Colorimetric analysis of the extract could also be useful. However, one is not certain of the solubility of the resins after a variety of curing processes.

Another sort of extraction process is dissolution of the cellulose after hydrolysis with acid, filtering and weighing the residue. Seifert⁽²⁷⁾ used this approach, modifying the Klason lignin determination method⁽²⁸⁾. In his method the cellulose was dissolved in sulfuric acid, and the lignin removed with sodium chlorite. The resin is the residue which was weighed to give the resin content. This method was confirmed as being reasonably accurate in the present study.

Hydrolysis of cellulose in sulfuric acid is rather slow, the whole analysis required about two days. Ettling and Adams⁽²⁹⁾ reported that this kind of analysis could be speeded up using chlorosulfonic acid instead of sulfuric acid. They reported successful results in measuring the resin content of particle board. However, Berkeley⁽³⁰⁾ tried this method and found it impossible to use for resin impregnated papers as he could not filter, or centrifuge off the residue. In the present work chlorosulfonic acid was tried and abandoned because of its violent reaction with the resin.

In the present work acid hydrolysis of cellulose was brought about using hydrofluoric acid.

In the auto radiographic method radioactive labels are introduced into the resin before impregnation. After drying and curing the sheet is sectioned and the resin content determined by a Geiger counter or by auto radiography. The method requires some elaborate equipment.

The direct chemical method depends on the chemical analysis of a particular chemical component of the resin. For example Kjeldahl analysis to get the nitrogen content allows calculation of the urea formaldehyde or melamine formaldehyde resin content. However, as phenolic resins contain only carbon, hydrogen, and oxygen which are precisely the components of cellulose this method cannot be used for determining the distribution of this resin.

III - APPARATUS

For this work a 2.5 kw microwave drier-resin impregnator was constructed. A schematic diagram of the equipment is presented in figure 2; an assembly drawing is presented in figure 3. Figures 4a to 4d are photographs of the equipment.

1. Process

Figure 2 provides a flow sheet or outline of the process. Base paper is first dipped into the resin solution and then drawn through the squeeze rollers into the microwave applicator.

The paper passes through slots in the waveguide wall into the interior of the waveguide where the microwave energy is absorbed. It then passes out of the first waveguide and into the second one etc. After the final waveguide the paper passes through the drive rolls and either is ripped off or is wound on a winder. The waveguides are ventilated to facilitate the removal of water.

The microwave system consists of a microwave generator (magnetron), a meander line (series of U bends) waveguide, a power meter and a water load. The antenna of the magnetron is coupled to the waveguide at the dry paper end of the machine. The water load is coupled to the wet end. Thus the microwaves propagate from the dry end to the wet end. However, the microwave-paper flow is not truly counter current but is in a sort of counter current-cross flow combination.

2. Paper Driving System

As shown in the assembly drawing (figure 3) the paper driving system consists of a 1/4 HP electric motor driving a paper driving roller through a reduction gear and a chain drive. Guide rollers

Figure 2. Flow Sheet of Apparatus

Figure 3 Assembly Drawing of Apparatus

Figure 4a Front View of Apparatus

Figure 4b Back View of Apparatus

Figure 4c Shielding of Apparatus

Figure 4d
Control Panel

carry the paper from the feed roll through the resin pan and squeeze rolls to the waveguide.

There are three speeds at which the paper can pass through the machine. The speed can be varied by means of 3 speed pulleys on the motor and on the gear box. The available speeds are 0.354, 0.812, and 1.67 meters/min. In order to maintain a constant tension on the paper a simple slip type clutch is installed on the paper winding roll. There is also provision for a friction brake on the feed roll but in this work it was never necessary to use it.

All the guide rollers were constructed of chromium plated copper pipe (4" O.D. Standard Copper Pipe); the squeeze rollers were also constructed of chromium plated copper pipe (3" O.D. Standard Copper Pipe).

3. Resin Impregnator

The resin impregnation system consists of a resin pan, a dipping box and two squeeze rolls.

The resin pan is 22" x 15" x 10" high and is made of polyvinylchloride. It can hold up to 4 gallons of resin solution and has a drain in the bottom for removing the resin.

The dipping box is 21" x 13" x 6" high, again it is of polyvinylchloride. Two 2" polyvinylchloride pipes (cut in half) are welded to the bottom of this dipping box. Thus the paper is dragged under the surface of the resin in the resin pan, over the two pipes on the dipping box and out of the resin. The depth of immersion of the paper can be adjusted by long, threaded rods which are attached to the dipping box. The depth of penetration allows some variation of the impregnation time.

The impregnated paper then goes through the squeeze rolls.

These two squeeze rolls are constructed of 3" outside diameter, chrome plated, copper pipes. The pressure applied to the resin impregnated sheet can be varied by moving weights along lever arms attached to the movable roll.

Passage through the squeeze rolls makes the resin distribution more uniform and squeezes excess resin from the paper. The amount of resin pick up can be controlled by adjusting the pressure between the squeeze rolls.

4. Ventilation System

In order to transfer mass in the form of water from the paper being dried it is of course necessary to ventilate the waveguide. Also if the water content of the air in the waveguide is too high water condenses inside the waveguide and drips causing arcing which could lead to fires.

Air enters through the slots in the waveguides and is sucked out through the ventilation ports on the waveguide bends by a turbine type fan. The flow rate of air in the exhaust duct can be measured by an orifice plate installed in the duct on the delivery side of the fan. Wet and dry bulb temperatures of the air leaving the waveguide were also measured by a psychrometer mounted in the duct on the suction side of the fan.

5. Surface Thermocouples

A set of thermocouples was constructed to measure the surface temperature of the paper. For such surface temperature measurements the thermocouple should be in good contact with the surface and heat losses from the thermocouple junction should be minimized. Therefore the thermocouples (40 gauge copper-constantan) were embedded in $3/4"$ x $2"$ x $1/16"$ strips of polyethylene as shown in figure 5. Thus the thermocouple junction

Figure 5. Surface Thermocouple.

Figure 6. Assembling of Surface Thermocouples

is insulated and maintained in good contact with the sheet surface.

Five of these thermocouples were mounted on a bar which could be moved from one side of the paper web to the other giving temperature profiles across the sheet. The positions of the thermocouples were such that temperature measurements on each side of each waveguide could be obtained. Details of the thermocouple mounting are shown in figure 6.

6. Microwave Generator and Power Supply System

A wiring diagram of the power supply is provided in figure 7. Figure 4d is a photograph of the power supply control panel. The heart of the microwave generator is a 2.5 kw magnetron (Microtron L3858 manufactured by Litton Industries Ltd. Electron Tube Div. Williamsport Penna.). The power supply has two ranges, a low power one (0-1 kw) and a high power one (1-2.6 kw). Both ranges can be spanned continuously by adjusting the Variac transformer T2. To change from the low to high setting one must change the high voltage transformer tap, the filament voltage and the field current. These changes are accomplished by switch S2. The functions of individual components of the power supply are described below:-

- S1 - turns control circuit power on
- starts fan F1
- SF1 - temperature sensor for magnet cooling
- SF1 - flow sensor for magnetron coolant
- R1 - turns on filament time delay relay TDR(R1-1)
and field current circuits R1-2 and R1-3
- L1 - panel dial light indicating preheat cycle

Figure 7 Wiring Diagram of Power Supply System

- R7-1 in the field supply closes, indicating that the field is on. R6-1,2 closes when the time delay is over through R5 switching in R6 and the TDR out. L1 then goes off. The control power now reaches the selector switch S2 if the filament has been preheated and the field is on.

S2 - Selector switch

- should normally be left at low
- relay R2 selects the correct filament, voltage pre-heat (R2-1), field current range (R2-2) and power transformer tap R2-3
- panel lights L2 and L3 indicate low or high range respectively
- do not change from low to high or vice versa when S3 is on

S3 - Microwave on-off switch

- activates panel lights L4 or L5
- actuates magnetron

7. Microwave Applicator

The microwave applicator is a meanderline type having four passes through the slotted waveguides (EIMAC WR-340). The dimensions of the waveguides are 24" length, cross section 3" x 1.3/4". Each waveguide has slots 3/16" wide and 20" long on the 3" x 24" faces. These straight sections of waveguide are connected by 180° E bends (EIMAC EW3-EUA). Each waveguide bend has a 2" nozzle which is shielded with perforated plate. These nozzles can be open, plugged with rubber corks or con-

nected to the fan depending on the air flow pattern desired.

8. Directional Power Meter

A directional power meter (EIMAC EW3-DPH3), which indicates both forward and reverse power transmitted in the waveguide is coupled between the applicator and the water load. The power level is detected by one of two microwave sensitive crystals which are located so that one measures the forward power, that is the power transmitted away from the magnetron and the other measures the reverse power, i.e. the power reflected back towards the magnetron.

Perhaps the simplest and best way to measure the power absorbed by the dielectric material (in this case resin or water soaked paper) would be to put directional power meters between the generator and the applicator and between the applicator and the water load. The first meter would indicate power directed towards the load from the generator and power reflected back toward the generator from the load. The second meter would indicate the unabsorbed power moving from the applicator toward the water load and any power reflected back from the water load.

In this apparatus only one power meter was used. Thus only unabsorbed forward power is measured by the power meter. The total power generated was measured before the load (i.e. the paper) was in the waveguide. The procedures for evaluating the absorption of power and the calibration of the power meter are given in Appendix A.

9. Water Load

A water load (EIMAC EW3-WL) is installed at the end of the waveguide remote from the generator to absorb any excess power

not absorbed by the load or to absorb all the power when there is no other load. Thermocouples at the water inlet and outlet and a rotameter allow the use of the water load as a calorimeter. This requires that the water load be well insulated to diminish any heat losses.

10. Shielding and Radiation Leakage

It is known that microwave radiation is hazardous for humans. Recently Birenbaum et al.⁽³¹⁾ have shown how sufficiently high levels of microwave radiation can lead to lens injuries in the eye of a rabbit. Similar lens defects could be induced in the human eye because of a similarity in anatomy and function to that of the rabbit.

In order to guard against this hazard and any others which might result from microwave, radiation safety limits have been prescribed by various agencies. The U.S. Radiation Control for Health and Safety Act suggests a maximum permissible exposure of 10 milliwatts per cm^2 . However, there is considerable dissatisfaction with this level, and recent trends are towards adopting the U.S.S.R. standard of $.01 \text{ mw/cm}^2$ for all day exposure.

In this work the microwave applicator was almost completely surrounded by aluminium sheet shielding to minimize radiation leaks. Figure 4c shows the shielding in place over the applicator.

Checks for leaks were made with a neon bulb (Phillips 4662) which was supposed to turn blue if the radiation intensity is greater than 10 mw/cm^2 . Later in the work a Ramcor densiometer (model 1270) was purchased. This instrument reads radiation intensity quantitatively from 0 mw/cm^2 to

20mw/cm² to within 0.5 mw/cm². These instruments are calibrated in fields emanating from distant source so they may be inaccurate when readings are taken close to conductors⁽³²⁾ It should also be kept in mind that the radiation intensity decreases with the increase of the distance from the source squared. Thus a remote control panel was constructed so the operator did not have to stand close to the machine.

During the work the neon bulb was used around the apparatus to detect any leaks. From time to time a check with the densiometer was made.

IV - EXPERIMENTAL

1. Base Paper and Resin

The base paper used in these experiments was 130 lb. bleached kraft paper. This was supplied by Reichhold Chemicals (Canada) Limited in roll form. The long rolls were cut to give a roll width of 18".

The resin used was a phenol-formaldehyde type supplied by Reichhold Chemicals (Canada) Limited and called soluble, modified phenolic resin. The resin solution as supplied contains about 50% (by weight) of nonvolatile solids. This resin was slowly diluted with water to a final solids content of around 25%. This latter resin solution was used in the impregnating and drying experiments. Before each group of drying experiments 1-2 grams of resin solution were accurately weighed in a glass dish and dried at 120°C for 2 hours. After cooling, the residue (non volatile solids) was weighed. The resin content then is defined as the percentage of nonvolatile material in the resin solution.

2. Start-Up and Shut-Down of the Microwave Power Supply System

The microwave power supply system was turned on at least two hours before the drying experiment to ensure steady power generation. Details of the power measuring methods are given in Appendix A.

The start up and shut down procedures are as follows:-

Start up.

- 1) Connect the power meter leads to the waveguide outlets.

- 2) Turn on the cooling water and set the flow so that the water pressure is at least 30 psig.
- 3) Plug in the radiation detector lamp
- 4) Switch on the "main power" switch. The two field supply lights and the two high voltage supply lights should turn on
- 5) Turn on the "system" switch. The control pilot light, the filament light and the preheat light should turn on. After about 20 seconds the preheat light should go off and the high range light and the microwave light should go on
- 6) Set the range control switch
- 7) Turn on the "microwave" switch
- 8) Adjust the power level with the Variac
- 9) Turn on the ventilation fan
- 10) Check for radiation leaks with the neon lamp detector or with the Ramcor densiometer

Shut down

- 1) Turn the "microwave" switch off
- 2) Turn the "system" switch off
- 3) Turn the "main power" switch off
- 4) Turn off the water
- 5) Turn off the ventilation fan

3. Procedure for Drying Experiments

After the microwave power generation has reached steady state the power is adjusted to the level at which the experiment is to be performed. The power meter output, total

supply current, water flow rate and temperature are recorded. Following these measurements the "microwave" switch is turned off and the paper web threaded through the waveguide slots. The paper drive is turned on and shielding placed over the microwave applicator.

After the wet paper has reached the dry end waveguide the "microwave" switch is turned on and readings of the paper surface temperature at the dry end are begun. The surface temperature here rose rapidly and reached a steady state in a few minutes, however, at least 5 minutes was allowed to pass after the microwave application was started before readings were taken. The product paper was marked to distinguish the presteady state material from the steady state material. Steady state operation was normally continued for about 5 to 10 minutes in order to get enough product for quality analysis.

During the steady state operating period power meter readings, water flow rates, inlet and outlet temperatures of water load coolant, high voltage supply current, air temperature and humidity and paper surface temperatures were recorded.

After collecting enough product the "microwave" switch, the paper drive, and the ventilation fan were turned off at the same time. The shielding was quickly removed and paper samples taken. About 5 - 10 grams of paper were torn off from before the wet end waveguide, between each waveguide and after the dry end waveguide, giving 5 samples. These samples were immediately wrapped in preweighed polyethylene

sheets and weighed. After weighing the sheets were unwrapped and dried in an air oven at 120°C for 2 hours. The dried paper was then weighed and the moisture or resin content of the original sheets determined. Total resin pick up was obtained from these measurements on the sample taken from the wet end assuming no moisture was lost before entering the waveguide.

The paper was then removed from the waveguide and the microwave switch and ventilation air turned on again. After waiting about 5 minutes the operating conditions were recorded and compared with the data obtained prior to insertion of the paper. The microwave power system was then shut down or readjusted to another level for the next experiment.

4. Tensile Strength Measurement

The tensile strengths of the papers used in this study were tested by a standard method⁽³³⁾. Ten samples in the machine direction and ten samples in the cross machine direction were tested to get average values for each sample. The measurements were made on an Instron testing machine which produced load elongation curves for each sample tested. Thus in addition to the tensile breaking stress, the stretch to rupture, and Young's modulus could be determined from the load-elongation curve. Paper thickness was measured at three points along the tensile sample strip using a micrometer. These thickness measurements were averaged to give the paper thickness.

Figure 8 is a typical load elongation curve obtained with resin impregnated paper. As the lower clamp of the testing machine moves away from the fixed upper clamp the paper is extended at a constant rate. Up to point A the load is pro-

Figure 8. Load-Elongation Curve

portional to the elongation. Point A is called the proportional limit and beyond this the load developed per unit increase in extension is less and less: the paper sample broke at point B. The tensile strength is the stress at point B. This stress is the load at point B divided by the cross sectional area of the sheet and is reported in kg/cm^2 . The total elongation is the distance OS_1 , this is usually expressed as a percentage. Thus strain is the extension divided by the original sample length between the clamps. This is multiplied by a hundred and reported as stretch. Young's modulus is the ratio of stress to strain in the region OA.

The tensile samples were 4" long, 1.5 cm wide and were tested at a rate of extension of 0.05"/min. (recorder chart speed = 1"/min.) after conditioning at least 24 hours in a room maintained at 23°C and 50% relative humidity.

5. Paper Bending Test

Brittleness and flexibility are two important criteria used in assessing the quality of resin treated paper. However, these criteria are difficult to evaluate quantitatively. There do not seem to be any standard tests for these properties.

It was felt that some indication of brittleness and/or flexibility might be provided by a bending test. So an instrument was designed and built (see figure 9) to measure the angle at which a strip of paper breaks when bent as shown in the figure. This breaking angle is probably dependent on sample width, sample length, and the angular velocity of bending, therefore all these values were kept constant in the tests. The sample dimensions used were width 1.5 cm and length 10 cm. The

Figure 9. Paper Bending Tester

angular velocity was 180 degrees per minute. Ten samples were tested and averaged for each particular paper tested. Again this measurement was done under controlled environment conditions of 23°C and 50% relative humidity.

6. Internal Bond Test

The internal bond of a resin impregnated sheet is a measure of its resistance to being pulled apart by forces applied to its top and bottom surfaces. This would seem to be a property which should be quite sensitive to resin distribution. A CSA⁽³⁴⁾ standard test for internal bond was followed.

The test specimen was 2.1/2" square and was bonded between two loading blocks made of a steel alloy. These were 2" square and 1" thick as can be seen in figure 10. These blocks must be free of any surface contamination. The adhesive had to be selected carefully because we did not want the adhesive which bonds the sheet to the blocks to penetrate into the sheet. For this purpose a polyester adhesive was used which consisted of 100 parts of Epoxy Resin (Epotus 37-140) to 32 parts of Hardener (Epotus 37-605). The well mixed adhesive was applied as uniformly as possible to the surfaces of the blocks and the paper and then the paper was placed between the blocks. To ensure complete contact between the specimen and the blocks a circular rubbing technique was used. Keeping the steel blocks aligned vertically, 2 to 4 hours were allowed for the adhesive to set.

The internal bond was measured in a tensile type tester (National Forge Tester) at constant rate of extension. This measurement should be done in a controlled environment but because

Figure 10. Metal Blocks for Internal Bond Test

the tests were done in an industrial laboratory this was not possible. The test result is psi required to pull the blocks apart.

7. Surface Abrasion Test

The surface abrasion test is a measure of the ability of the surface of a resin impregnated paper to resist abrasion. The device used was a Taber Abraser Model 503 using abrasive wheels C5-17 and a load of 750 grams. Once again although standard temperature and humidity conditions would have been desirable, these were not available.

In the test abrasive wheels under load abrade the surface of the sheet. The number of revolutions is counted and the weight loss or sheet thickness is recorded after various numbers of revolutions. For these tests the resin treated paper was overlaid onto hardboard. The overlaying was done in a hot press at 300°F under 2000 psi load for 5 minutes. The overlaid board was cut into 4" squares and put in the tester. The thickness of the sample was measured at four points by micrometer and the average decrease in thickness with abrasion calculated. The thickness was recorded after every 500 cycles until the paper-hardboard interface was reached.

The wearing factor is defined as the thickness decrease in inches per 10^6 abrasion cycles. The wearing factor is plotted against the total number of abrasion cycles and the distance from the original surface^(35,36).

8. Quantitative Resin Distribution Measurement

As a part of this work two methods were tried for determining in a quantitative way the resin distribution across the sheet. These involved the removal of cellulose by hydrolysis with 1) sulfuric acid or 2) hydrofluoric acid after sectioning of the sheet (see Section II-3).

The sulfuric acid method is based on the Tappi standard method⁽²⁸⁾ for lignin determination. The hydrofluoric acid technique was suggested by Takahashi and Vasishth⁽²³⁾.

As outlined in Section II-3 the determination of a resin concentration profile through the thickness of a dried, and cured, resin impregnated sheet requires that the sheet be sectioned into thin layers. In order to achieve this sectioning the resin impregnated sheet was fixed to a circular aluminium disc and sections of the paper machined off from the surface using a machinist's lathe. The dust and shavings from each layer were collected and analyzed for resin content.

In detail then the paper sample was dried at 170°C for 5 minutes. A 6" diameter circle was cut from this cured sheet and glued onto the face of a 6" diameter aluminium disc with starch glue. Several kinds of glue were used in preliminary experiments, however, it was found that starch glue gave good adhesion with minimum penetration into the sheet. It was felt that although unlikely, penetration of the glue into the sheet might interfere with the resin distribution determination. To check the penetration the glue was dyed with ink. Sections were cut using the lathe until the ink was visible. By means of experiments such as this the penetration of starch glue into the sheet was found to be less than 0.1 mm in a sheet which was

Figure 11. Aluminium Disc for Sectioning

Figure 12. Experimental Set-up of Sectioning

around 0.45 mm in thickness.

The aluminium disc with the mounted paper sample was carefully aligned in the lathe so that the tip of the cutting tool was exactly parallel to the plane of the sheet. The cutter tip was adjusted to just touch the paper surface and the longitudinal carriage fixed. The top compound feed of the lathe was adjusted to remove the desired thickness of paper.

In the experiments a type 25-A South Bend lathe was used. This machine had a .001" top compound indicator and an adjustable cutting angle of from 0 to 90°. Each slice of paper was removed by moving the top compound indicator (and hence the cutting tool) in by .002". Six sections could be cut from a typical sample from the outside to the centre of the sheet. The resin distribution was assumed to be symmetrical about the centre of the sheet. Figure 11 shows the aluminium disc and figure 12 shows the experimental set up for sectioning.

a) Pretreatment of Samples

It was felt that to get uniform results the resin impregnated sheets should be fully cured before resin analysis was done as the recoverability of resin might be affected by the degree of cure. The paper samples used in sectioning were cured at 170°C for 5 mins. prior to sectioning which is equivalent to commercial practice.

In order to find out whether this represented a full cure some experiments were undertaken. Figure 13 is a plot of unimpregnated paper sample weight divided by the weight after a certain drying period weight. Three temperatures were used 120°, 150°, and 170°C. Only slight changes in moisture con-

Figure 13. Drying Curves for Base Paper

tent occurred after 1 hour. So 1 hour is sufficient to dry the unimpregnated paper.

In figure 14 are plotted the results of curing dried resin (no paper). The resin solution was dried for 2 hours at 120°C. This dried material was crushed and screened to pass a 60m screen. This screened material was then cured at 120°, 150°, and 170°C for various times. The ratio of weight to initial weight is plotted vs time. Significant weight losses were recorded up to 3 hours.

In figure 15 the equivalent curves for resin impregnated papers are presented. From these figures it can be concluded that the rate of curing of the resin is a much slower process than the rate of removal of moisture (or other volatile) from the paper itself. This rate is also temperature dependent.

b) Resin Content Analysis - Sulfuric Acid Method

About 0.5 gm of the lathe turnings of the resin impregnated paper was accurately weighed and dried for 2 hours at 120°C in a weighing bottle. 10 ml of 75% sulfuric acid were then added to the weighed material and agitated until the sample was completely dispersed. This mixture was maintained at 20°C for 2 hours, poured into a 500 ml flask and diluted with 250 ml of water. The diluted suspension was refluxed for 4 hours. This treatment is presumed to dissolve all of the cellulose. Then any remaining solids were removed in a tared, sintered glass crucible, washed with 200 ml of hot water, dried at 120°C for 2 hours and the weight of residue determined. The residue is assumed to be resin plus any lignin which could come from the base paper.

Figure 14. Drying Curves for Resin

Figure 15. Drying Curves for Resin Impregnated Paper

An identical treatment of the base paper allowed correction for the lignin content. Resin recoverability by this technique was checked by using known amounts of resin. Table I presents the lignin content of the base paper and resin recoverability figures. The lignin content of the base paper is negligible.

In the resin recoverability method dried resin was crushed and screened to -60 m. Samples of this material were dried for 2 hours at 120°C and analyzed for resin content as outlined above. About 80% of the resin was recovered after the analysis. It is known that sodium hydroxide is used as a catalyst in this resin formulation but how much is not known. This may account for the losses. To check to see if resin was being continually dissolved the residue from one analysis was reanalysed. The recovery of this pretreated resin was 100%. Thus if this sulfuric acid method is to be used the resin content must be determined as

$$\text{resin content (\%)} = \frac{\text{residue weight}}{\text{dry sample weight}} \times \frac{100}{0.8}$$

c) Resin Content Analysis - Hydrofluoric Acid Method

An accurately weighed sample of dried lathe shavings of the resin impregnated paper was transferred into a polypropylene bottle. About 10 gms of 80% hydrofluoric acid was then added to the material in the bottle. This mixture was kept at 20°C for 1 hour with shaking every 10 minutes. After this the mixture was diluted with 100 ml of water and neutralized with 10-20% ammonium hydroxide solution until just alkaline. Phenolphthalein was used as an indicator of alkalinity. The neutralized mixture was filtered through a tared, sintered glass crucible, and washed with water until no phenolphthalein

TABLE I SULFURIC ACID TREATMENT DATA FOR BASE PAPER, PURE RESIN, AND RESIN IMPREGNATED PAPER

		SAMPLE WT. (gr)	RESIDUE WT. (gr)	RESIDUE (%)
BASE PAPER	1	0.5186	0.0009	0.2
	2	0.5054	0.0003	0.1
	3	0.5415	0.0024	0.4
PURE RESIN	1	1.1096	0.8857	80.0
	2	1.0723	0.8506	79.5
	3	1.0341	0.8283	80.0
RESIN IMPREG- NATED PAPER	1	0.2117	0.0633	29.9
	2	0.2134	0.0681	31.9
	3	0.1980	0.0620	31.3

TABLE II HYDROFLUORIC ACID TREATMENT DATA FOR BASE PAPER, PURE RESIN, AND RESIN IMPREGNATED PAPER

SAMPLE	TREATING TIME (hr)	SAMPLE WT. (gr)	RESIDUE WT. (gr)	RESIDUE (%)
BASE PAPER	1	0.4207	0.0012	0.28
	2	0.7957	0.0042	0.53
	4	1.1708	0.0036	0.33
PURE RESIN	1	1.2166	1.0135	83.30
	2	1.6458	1.4124	85.82
	4	2.1084	1.8136	86.02
RESIN IMPREGNATED PAPER	1	0.6636	0.1690	25.47
	2	0.6503	0.1541	23.70
	4	0.6511	0.1576	24.41

could be seen in the filtrate (the wash water was made slightly alkaline by addition of ammonia). The washed residue was then dried and weighed.

The residue consisted of recovered resin and lignin and so corrections to get the resin content were necessary. Various times were tried for the hydrofluoric acid treatment. The results are given in Table II. From these results it seemed that 1 hour was sufficient. Lignin content again was low but was measured to be somewhat higher than in the sulfuric acid technique. The resin recoverability was higher at about 85%.

V - RESULTS AND DISCUSSION

1. Drying Experiments

The drying experiments were of three kinds. These were the drying of paper wetted with water, the drying of resin impregnated paper, and the drying of paper wetted with water by convection only. The last category was merely a check on any contribution which might be made to drying by the movement of air through the waveguide.

a) Drying of Paper Wetted with Water

In these experiments the base paper used for resin impregnation was wetted in water and dried using microwaves. These drying experiments were performed at five microwave power application levels, at constant paper feed rate and more or less constant initial moisture content.

The results are reported in Tables III and IV. In these tables the net power generated was determined from the difference between the forward and reverse power meter readings and the calibration curve for this meter (see Appendix A). The total supply current was measured and used in calculating the overall efficiency of the dryer (see Appendix E).

In order to study convective mass transfer rates from the wet sheet one would have to try to maintain a constant velocity of air over the sheet surface at the same moisture content. In these experiments this was practically impossible to do. The fan used to ventilate the waveguide sucked air through the slots in the waveguide and removed this air and any evaporated water which did not condense in the piping. What control there was was

TABLE III DRYING DATA FOR WET PAPER

OPERATING CONDITION		EXPERIMENT NUMBER (WATER)				
		1	2	3	4	5
FORWARD POWER	(kw)	0.50	1.00	1.60	2.10	2.50
REVERSE POWER	(kw)	0.0	0.03	0.05	0.07	0.06
POWER GENERATION	(kw)	0.70	1.36	2.25	2.70	2.95
SUPPLY CURRENT	(amp)	7.7	16.5	22.6	26.4	29.4
WATER FLOW RATE	(kg/hr)	36.0	39.5	36.5	37.5	36.0
INLET TEMP.	(°C)	11.5	11.5	11.5	11.2	11.2
OUTLET TEMP.	(°C)	27.5	38.0	61.5	74.0	75.0
WET AIR FLOW RATE	(kg/hr)	205.5	186.7	172.3	166.0	164.4
DRY AIR FLOW RATE	(kg/hr)	200.5	184.0	162.8	155.7	153.4
DRY BULB TEMP.	(°C)	30.9	37.2	43.0	46.3	47.0
WET BULB TEMP.	(°C)	28.7	34.3	42.2	44.6	46.1
HUMIDITY	(kg/kg)	0.0243	0.0339	0.0551	0.0682	0.0688
ROOM TEMPERATURE	(°C)	26.8	29.5	25.3	27.5	27.5
REL. HUMIDITY	(%)	77.9	78.3	62.1	62.6	61.8
ATM. PRESSURE	(mmHg)	754.6	754.6	756.3	756.3	756.3
SURFACE TEMP. OF PAPER (°C)	1	56.6	69.1	63.4	50.1	59.5
	2	39.6	57.6	85.2	51.2	39.8
	3	31.1	45.4	67.1	30.5	59.7
	4	27.4	31.4	31.8	30.5	52.4
	5	24.9	30.1	28.4	28.7	29.4
MOISTURE CONTENT OF PAPER (%)	1	136.8	98.0	51.9	20.0	12.0
	2	158.2	144.7	125.1	76.2	39.7
	3	171.5	168.8	176.6	140.3	119.8
	4	178.1	176.8	183.1	180.3	174.9
	5	181.9	183.1	189.6	190.1	189.7

TABLE IV APPLICATOR EFFICIENCY FOR WET PAPER DRYING

	EXPERIMENT NUMBER (WATER WETTED)				
	1	2	3	4	5
POWER INPUT (kcal/hr)	602	1170	1936	2323	2538
WATER PICK-UP (kg/hr)	6.19	3.20	3.32	3.33	3.31
TOTAL EVAPORATION (kg/hr)	0.79	1.49	2.40	2.97	3.10
ENERGY FOR EVAPORATION (kcal/hr)	429	832	1408	1773	1883
SENSIBLE HEAT OF PRODUCT (kcal/hr)	92	87	50	17	22
TOTAL ABSORBED ENERGY (kcal/hr)	521	919	1458	1790	1905
EFFICIENCY BASED ON EVAPORATION (%)	71.2	71.1	72.7	76.3	74.2
EFFICIENCY BASED ON ABSORBED ENERGY (%)	86.5	78.5	75.3	77.1	75.1

achieved by setting the valve in the exhaust air line so that the manometer reading across the orifice in the exit line from the fan was constant. However, because the temperature and moisture content of the exit air changed by different amounts depending on the energy level supplied by the magnetron and because the fan was drawing a more or less constant volume of exit air through itself, the mass flow rate of air decreased as the power level rose.

Relative humidities were measured in the outlet air pipe but because a lot of condensate was observed these were not used in the heat and mass balance calculations. In subsequent work, hot air should be used and the waveguides and air pipes insulated.

Surface temperatures were measured at five positions (before and after each waveguide) from the wet end to the dry end. Position 5 is before the first waveguide the wet paper enters and position 1 is after the last waveguide the dry paper leaves. It is possible that the surface thermocouples are affected by the presence of microwave leakage from the slots leading to a higher reading than the actual surface temperature. This was checked by reading the thermocouples with no paper in the slots and the microwaves off. Then the microwaves were turned on and the thermocouples read. This procedure resulted in as much as a 3°C increase in the thermocouple reading. The greatest effect was at the dry end waveguide which was nearest the microwave source.

With a dielectric in the waveguide, leakage of radiation would probably be greatest where the most energy was being absorbed. An attempt was made to observe thermocouple readings with paper in the slots but not moving but this started the paper on fire.

The moisture content of the sheet was measured before and after each waveguide of the system. These results are plotted in

Figure 16. Moisture Content versus Power Generation
(Drying of Water Wetted Paper)

Figure 17. Relative Moisture Content versus Power Generation
(Drying of Water Wetted Paper)

Figure 18. Absorbed Energy versus Position
(Drying of Water Wetted Paper)

Figure 16 against power level. However the original moisture contents were not the same in each of five experiments, so these curves were replotted in Figure 17 by dividing each moisture content by the original moisture content.

The energy absorbed in each waveguide is plotted in Figure 18 as a function of absorbed power level. This figure shows that at low power levels most of the energy is absorbed in the dry end waveguide (No 1 waveguide) which is the one coupled to the magnetron. However, beyond a certain power level more energy is consumed in waveguide No.2. If sufficient power were available presumably this progression would continue until the bulk of the energy absorbed would be absorbed in the wet waveguide. In the 2.95kw experiment more energy was absorbed in waveguide No.2 even though the power intensity would be higher in waveguide No. 1. However, since the microwave energy is selectively absorbed by the water and the water content of sheet was higher in waveguide No.2 than in No.1 and the absolute level of moisture in the sheet was low in waveguide No. 1 this is not surprising. Note also from Table III that the surface temperature at the dry end waveguide is relatively low. Thus heat damage to the sheet is minimized by this kind of drying.

b) Drying of Resin Impregnated Paper

Similar experiments were performed using resin impregnated paper. The results of these are given in Tables V and VI.

The base paper was impregnated with a 33.7% phenol-formaldehyde resin solution and dried at one of 5 microwave power levels. The paper feed rate was maintained constant at 21.2 meters per

TABLE V DRYING DATA FOR RESIN IMPREGNATED PAPER

OPERATING CONDITION		EXPERIMENT NUMBER (RESIN)				
		1	2	3	4	5
FORWARD POWER	(kw)	0.70	1.00	1.20	1.40	1.80
REVERSE POWER	(kw)	0.01	0.03	0.05	0.05	0.06
POWER GENERATION	(kw)	0.96	1.37	1.75	2.02	2.45
SUPPLY CURRENT	(amp)	10.5	14.0	19.6	21.2	24.0
WATER FLOW RATE	(kg/hr)	36.0	33.0	34.0	33.5	37.5
INLET TEMP.	(°C)	13.2	12.0	12.0	12.7	15.3
OUTLET TEMP.	(°C)	35.7	46.0	55.0	63.0	65.9
WET AIR FLOW RATE	(kg/hr)	189.6	185.5	175.4	168.4	156.5
DRY AIR FLOW RATE	(kg/hr)	183.8	179.0	167.9	159.4	145.5
DRY BULB TEMP.	(°C)	36.2	37.7	42.0	45.3	52.0
WET BULB TEMP.	(°C)	32.8	35.0	38.4	41.8	47.0
HUMIDITY	(kg/kg)	0.0307	0.0354	0.0431	0.0528	0.0708
ROOM TEMPERATURE	(°C)	29.2	29.2	28.4	31.6	31.8
REL. HUMIDITY	(%)	61.5	61.5	61.6	58.7	56.3
ATM. PRESSURE	(mmHg)	756.8	756.7	754.0	754.0	754.0
SURFACE TEMP. OF PAPER (°C)	1	69.3	72.7	72.3	81.5	152.7
	2	32.6	35.0	57.4	58.5	63.4
	3	26.7	27.7	30.9	33.3	69.6
	4	24.5	26.2	25.0	27.7	29.9
	5	23.5	26.0	23.0	26.9	27.2
MOISTURE CONTENT OF PAPER (%)	1	91.5	71.0	19.6	7.8	2.0
	2	140.1	131.5	80.8	78.4	11.9
	3	137.5	146.4	135.2	141.5	96.3
	4	138.7	139.3	138.4	154.3	139.5
	5	142.5	150.5	146.0	152.4	149.6

TABLE VI APPLICATOR EFFICIENCY FOR RESIN IMPREGNATED PAPER DRYING

	EXPERIMENT NUMBER (RESIN)				
	1	2	3	4	5
POWER INPUT (kcal/hr)	825	1178	1505	1738	2107
RESIN PICK-UP (kg/hr)	0.70	0.76	0.74	0.77	0.76
WATER PICK-UP (kg/hr)	2.49	2.82	2.55	2.67	2.57
TOTAL EVAPORATION (kg/hr)	0.73	1.40	2.38	2.53	2.56
ENERGY FOR EVAPORATION (kcal/hr)	516	787	1261	1471	1566
SENSIBLE HEAT OF PRODUCT (kcal/hr)	92	115	59	65	133
TOTAL ABSORBED ENERGY (kcal/hr)	608	902	1326	1542	1699
EFFICIENCY BASED ON EVAPORATION (%)	62.5	66.8	83.8	84.9	74.3
EFFICIENCY BASED ON ABSORBED ENERGY (%)	73.7	76.5	88.1	88.7	80.6

Figure 19. Relative Moisture Content versus Power Generation
(Drying of Resin Impregnated Paper)

Figure 20. Absorbed Energy versus Position
(Drying of Resin Impregnated Paper)

hour for all experiments. The resin pick up of the paper remained more or less constant. The resin content was measured as outlined in Section IV-3 The moisture content was determined at each sampling position and was used in the energy balances. Figure 19 is a plot of the relative moisture content in each waveguide at various applied power levels.

Over heating of the paper was observed at the highest power level applied. This resulted in a discoloured and weakened sheet; this will be commented on in later sections. This was not observed when drying paper wetted only with water at even higher power levels. This may mean that there is considerable absorption of microwave energy not only by the water but also by the phenol-formaldehyde resin itself. Note that when drying the water impregnated sheet the dry end sheet temperature was around 60°C at an applied power level of 2.95 KW but when drying the resin impregnated sheet the dry end temperature was 153°C at a power level of only 2.45 KW. In this particular run, discoloured (presumably over heated) zones appeared every half wavelength across the width of the sheet. This suggested the presence of a standing wave in the waveguide with the points of highest intensity causing the over heating. Elimination of this standing wave would require staggered waveguides, angled waveguides, or some type of mechanical mode mixer.

Figure 20 is a plot of the energy absorbed in each waveguide which shows similar trends to those shown by figure 18. However, in the 1.37 KW experiment an apparently faulty moisture content measurement between waveguides No.3 and No.2 has resulted in erroneous absorbed energy levels in these waveguides.

So the 1.37 KW curve is probably not very reliable.

c) Convective Drying Effect

To check the effects of air flow in the absence of microwaves several runs were made with water saturated paper passing through the waveguides at 21.2 meter/hr. and a variety of air flow rates. Table VII shows as might be expected, a slight tendency to increased drying as the paper passed from the wet to the dry end of the apparatus but no significant effect of air flow rate was noted over the range 0 Kg/hr to 300 Kg/hr.

In industrial systems hot air, and higher flow rates would probably be used. Thus it would be useful to study mass transfer rates as a function of air flow rates in the presence of microwaves. However, this would require a different design of apparatus in which temperature, air velocity, and humidity measurements could be made. This was not possible in the present equipment. In fact it is a problem to make measurements in microwave fields with metallic devices and with devices constructed of materials which conduct microwaves because of the field distortions they cause.

2. Product Quality Tests

a) Tension Tests

The tension or tensile strength test procedures were outlined in Section IV-4. The results of the tensile breaking stress tests are presented in Table VIII; the results of the stretch at breaking appear in Table IX; and the results of the measurement of Young's modulus are given in Table X.

Not surprisingly the tensile breaking strength of the resin

TABLE VII CONVECTIVE EFFECT OF VENTILATION AIR

		EXPERIMENT NUMBER (CONVECTION)				
		1	2	3	4	5
PAPER FEED RATE	(m/hr)	21.2	21.2	21.2	21.2	21.2
AIR FLOW RATE	(kg/hr)	0	190	242	256	303
AIR TEMPERATURE	(°C)	22.7	21.0	21.8	22.3	22.3
REL. HUMIDITY	(%)	82.2	76.9	73.3	72.0	74.3
ATM. PRESSURE	(mmHg)	756.8	754.0	754.0	756.8	756.8
SURFACE TEMP. OF PAPER	1	21.0	18.5	20.0	19.5	20.0
	2	21.0	19.0	20.0	20.5	20.5
	3	21.0	19.0	20.0	20.0	20.5
	4	21.0	19.0	20.0	20.0	20.0
	5	21.0	19.5	20.0	20.0	20.0
MOISTURE CONTENT OF PAPER (%)	1	1.86	1.87	1.81	1.80	1.80
	2	1.96	1.94	2.09	1.73	1.87
	3	1.93	1.86	1.85	1.88	2.00
	4	1.89	1.84	1.85	2.00	2.03

impregnated paper is greater than that of the base paper. Also as is well known, the machine direction strips are stronger than the cross machine direction strips.

Statistically about all one can say is that the best microwave dried group (2.02 KW) is stronger than the best oven dried group (120°C) in the machine direction. But this is not seen in the cross machine direction strips. So in general one can conclude that microwave drying has no advantage over conventional drying as far as tensile strength is concerned. It should be noted however that both excessive microwave drying (2.45 KW) and excessive oven drying (170°C) degrade the strength of the paper.

The stretch at breaking tests present no significant evidence that microwave drying is better or worse than conventional drying. The cross machine stretch seems to be reduced by the presence of resin and as would be anticipated for conventional papers the cross machine direction stretch is higher than the machine direction stretch.

The Young's modulus results parallel those of the tensile breaking strength and stretch.

b) Internal Bond Test

The internal bond test(see Section IV-6) results are presented in Table XI. In these tests 5 replicate samples were tested in each group. However, because of the capacity limit of the testing machine available (equivalent to 70 Kg/cm²) many of the samples could not be broken. So the number of samples broken and the average breaking stress are reported. In future work smaller samples or a testing machine of greater capacity should be used.

The results of Table XI do suggest that the microwave dried

TABLE VIII TENSION TEST DATA (TENSILE BREAKING STRENGTH)

DRYING CONDITION		TENSILE BREAKING STRENGTH (kg/cm ²)			
		MACHINE DIRECTION		C-MACHINE DIRECTION	
		AVERAGE	STD.DEV.	AVERAGE	STD.DEV.
M.W. POWER LEVEL (kw)	0.96	290.3	13.4	224.6	6.2
	1.37	318.5	12.1	200.0	7.0
	1.75	313.3	15.7	210.7	7.4
	2.02	352.0	12.1	207.1	5.7
	2.45	266.3	21.2	194.2	18.7
OVEN DRYING TEMP. (°C)	120	302.5	8.1	231.1	5.7
	170	281.6	15.3	213.7	9.9
BASE PAPER		198.2	5.6	113.4	3.3

TABLE IX TENSION TEST DATA (STRETCH)

DRYING CONDITION		STRETCH (%)			
		MACHINE DIRECTION		C-MACHINE DIRECTION	
		AVERAGE	STD.DEV.	AVERAGE	STD.DEV.
M.W. POWER LEVEL (kw)	0.96	1.45	0.14	1.87	0.09
	1.37	1.78	0.11	2.20	0.12
	1.75	1.49	0.11	2.00	0.13
	2.02	1.87	0.08	1.81	0.09
	2.45	1.41	0.05	1.08	0.13
OVEN DRYING TEMP. (°C)	120	1.92	0.09	2.07	0.11
	170	1.39	0.11	1.18	0.08
Base Paper		1.78	0.05	4.69	0.33

TABLE X TENSION TEST DATA (YOUNG'S MODULUS)

DRYING CONDITION		YOUNG'S MODULUS $\times 10^4$ (kg/cm ²)			
		MACHINE DIRECTION		C-MACHINE DIRECTION	
		AVERAGE	STD.DEV.	AVERAGE	STD.DEV.
M.W. POWER LEVEL (kw)	0.96	1.150	0.314	0.743	0.019
	1.37	0.937	0.024	0.678	0.027
	1.75	1.049	0.024	0.682	0.017
	2.02	0.902	0.031	0.707	0.023
	2.45	0.909	0.078	0.781	0.013
OVEN DRYING TEMP. (°C)	120	0.749	0.022	0.653	0.017
	170	0.949	0.029	0.800	0.014
BASE PAPER		0.775	0.022	0.424	0.029

sheets have better internal bond than do the sheets dried conventionally at 170°C. Note that 170°C is typical of industrial practice. If one had a more uniform resin distribution one would expect a higher internal bond because the non uniform resin distribution would leave a weak plane in the centre of the sheet. This test is one piece of evidence then that the resin impregnated paper dried by microwaves has a more uniform resin distribution.

c) Surface Abrasion Test

The surface abrasion test (see Section IV-7) results are presented in Table XII and figure 21. The data in Table XII are the averages of duplicate samples. The results indicate that the microwave dried sheets have greater abrasion resistance than the conventionally dried at 170°C sheets. Not only is the overall resistance better but it is more uniform; that is the slope of the curves is less steep for the microwave dried papers suggesting that they have a more uniform resin distribution. The 2.45 KW samples are not as good as the others probably because of over heating. The appearance of this sample suggested over heating. However, the oven dried sample had a normal appearance.

These results are another piece of evidence that microwave dried papers have a more uniform resin distribution. They are in agreement with those of Takahashi et al.⁽²³⁾ in that the microwave dried sheets show a flat abrasion rate vs number of abrasion cycles plot. However, our results have a generally higher wear rate and do not show a maximum in the oven dried samples.

TABLE XI INTERNAL BOND TEST DATA

DRYING CONDITION	INTERNAL BOND STRENGTH (kg/cm ²)		NUMBER OF FAILED SAMPLES
M.W. POWER LEVEL (kw)	0.96	45.9	5/5
	0.96	70.0	1/5
	2.02	57.3	1/5
	2.45	57.7	3/5
OVEN DRYING TEMP. (°C)	170	33.2	5/5

TABLE XII SURFACE ABRASION TEST DATA

ABRASION CYCLES	ABRASION RATE (inches/10 ⁶ cycles)				
	M.W. POWER LEVEL (kw)				OVEN DRYING 170 °C
	0.96	1.75	2.02	2.45	
500	1.3	1.2	1.2	1.3	2.9
1000	1.2	1.5	1.2	1.7	2.3
1500	1.5	1.4	1.6	2.0	2.5
2000	1.3	1.6	1.5	2.6	3.4
2500	1.8	1.6	1.7	2.6	3.7
3000	1.9	1.8	1.7	3.2	4.4
3500	2.1	1.8	2.0	3.4	4.4
4000	1.9	1.6	1.7	2.8	-
4500	2.1	1.7	2.3	3.8	-
5000	1.9	1.8	1.7	-	-
5500	-	1.4	2.0	-	-

Figure 21. Surface Abrasion Rate versus Abrasion Cycles

d) Paper Bending Test

The results of the paper bending test which was performed as described in Section IV-5 are recorded in Table XIII. These measurements were done on machine direction strips only because of buckling which seemed to occur with cross machine direction strips.

Data comparisons using the student t test showed no advantage of microwave dried paper over conventionally dried paper. The 170°C conventionally dried paper and the 2.45 KW microwave dried papers were significantly weaker in bending than the other papers implying that they were more brittle.

3. Resin Distribution

The resin distribution was determined by sectioning the sheet and removing the cellulose in hydrofluoric acid. About six slices were shaved from each sample which amounted to about half the sheet. The shavings were analyzed for resin content and the results appear in Table XIV. Lignin content was neglected (see Section IV-8). In Table XIV the results of one commercial product analysis are also reported. This one was done using sulfuric acid instead of hydrofluoric acid. All the resin distribution data are plotted in figure 22 where resin content is plotted against distance from the sheet surface. The sheets were around 0.4 mm in thickness. It was assumed that the resin distribution was symmetrical about the centre of the sheet.

It is apparent from figure 22 that the resin concentration profiles are flatter for the microwave dried sheets than for the oven dried sheets. The 2.45 KW curve is not as flat as the

TABLE XIII PAPER BENDING TEST DATA

DRYING CONDITION		BREAKING ANGLE (degree)	
		AVERAGE	STD.DEV.
M.W. POWER LEVEL (kw)	0.96	193	4.27
	1.37	188	6.99
	1.75	181	3.45
	2.02	187	2.05
	2.45	146	6.01
OVEN DRYING TEMP. (°C)	120	187	3.90
	170	148	5.29

TABLE XIV RESIN CONTENT DISTRIBUTION

(RESIN CONTENT %)

DRYING CONDITION		AVERAGE DISTANCE FROM THE SURFACE (mm)					
		0.017	0.051	0.085	0.119	0.153	1.187
M.W. POWER LEVEL (kw)	0.96	34.9	33.8	33.5	33.9	35.4	36.3
	1.37	45.3	41.7	45.5	44.1	39.1	38.2
	1.75	45.4	45.7	45.8	42.2	42.9	39.9
	2.02	46.8	50.0	45.8	45.1	45.5	39.3
	2.45	51.6	48.8	-	46.7	43.8	39.9
OVEN DRYING TEMP. (°C)	120	43.1	44.9	42.9	38.3	32.5	28.4
	170	45.3	37.0	38.2	31.9	24.6	17.8
COMMERCIAL PRODUCT (REICHOLD CHEMICALS)		33.4	32.9	25.3	21.4	22.7]	18.7

TABLE XV RESIN PICK UP OF MICROWAVE DRIED PRODUCTS

M.W. POWER LEVEL (kw)	RESIN ANALYSIS (SECTIONING EXPT.)		RESIN PICK UP (DRYING EXPT.)
	RESIN CONTENT (%)	RESIN PICK UP kg/kg paper	kg/kg paper
0.96	34.6	0.529	0.721
1.37	42.3	0.529	0.721
1.75	43.7	0.775	0.740
2.02	45.4	0.831	0.775
2.45	46.1	0.856	0.764

Figure 22. Resin Content Distribution

other microwave dried sheets. These results support those obtained in the abrasion resistance and internal bond tests (see Sections V-2c and V-2d. They are also in agreement with the photographs presented by Takahashi et al (23).

Table XV compares the total sheet resin content measured as outlined in Section V-1 with the total sheet resin content measured in the sectioning experiment. In 3 out of 5 of these the agreement between the two methods is reasonable but at the lowest (0.96 KW) and highest (2.45 KW) levels there is sufficient disagreement for concern. In the low power level sample the sectioning analysis gives a lower resin content than the total analysis. However, at the high power level the opposite is true. One would think that losses in the sectioning experiment might lead to lower values of total resin content but higher results cannot be immediately explained.

Table XIV shows that the resin content of the sheet increases as the applied microwave power level increases but the total sheet resin content measured at the wet end stays more or less the same. This may indicate that the microwave radiation or perhaps merely the higher temperature has something to do with the polymerisation process. More fundamental work should be done in this area.

4. Product Appearance

Resin impregnated papers must be acceptable to the consumers of these products and in certain uses (e.g. printed wood grain overlays for furniture manufacture) visual appearance is important. In this work no systematic statistical comparisons of product

appearance were made but some noteworthy effects were observed.

When paper is impregnated with resin it looks rather patchy. That is there are areas which are discernably more translucent than others. This is probably due to non uniform impregnation with resin. When such a sheet is dried in a conventional drying process this patchiness can still be observed. But when such a sheet was microwave dried it appeared to be much more uniform. This tendency is shown in figures 23c and 23d. Figures 23a, b, and d are of microwave dried products, photograph c is an oven dried paper (170°C).

One could speculate that in the microwave dried paper, due to the volume heating (internal heat generation) effect, that the temperature rises rapidly throughout the sheet lowering the viscosity of the resin emulsion and producing a faster and more uniform penetration of the sheet. In convective drying the heating up process is slower and material at the surface may be polymerised before uniform penetration is achieved.

In a waveguide it is possible to establish a standing wave pattern. If the material being dried is completely transparent to microwaves this need not be a problem provided sufficient energy is available. However, this is an idealization. Resin impregnated papers contain non volatile resin and some bound water difficult to remove. In removing these last traces of water the temperature will rise more at those parts of the wave where the energy applied is most intense. This tends to heat up the paper excessively at these points. The same applies apparently to the phenolic resin which heats up considerably.

PHENOL-FORMALDEHYDE RESIN IMPREGNATED PAPER

a

MICROWAVE DRIED
2.45 KW, 34 SEC.
RESIN PICK UP 0.764

b

MICROWAVE DRIED
270 KW, 17 SEC.
RESIN PICK UP 0.721

c

ELEC. OVEN DRIED
170°C, 5 SEC.
RESIN PICK UP 0.684

d

MICROWAVE DRIED
2.02 KW, 34 SEC.
RESIN PICK UP 0.775

Figure 23 Photographs of Resin Impregnated Papers

Figure 23a shows a resin impregnated paper dried at the 2.45 KW power level. The residence time of this paper in the waveguide was 34 sec. Its final moisture content was 2.0%. The over heated zones are obvious. These zones appear every half wavelength suggesting that a standing wave is the cause. These effects were not observed visually in drying paper wetted with water or for resin impregnated papers at lower power levels but equal residence times (figure 23d). The sheet shown in figure 23d had a final moisture content of 7.8%. These effects were also not observed at higher power levels (2.70 KW) but lower retention time (16 sec) as evidenced by figure 23b. One explanation is that at high enough temperatures the resin is oxidized. These sheets (2.45 KW) were weaker than the others dried at lower power levels (see Section V).

In commercial units mode mixing devices could be tried to eliminate this problem or the sheet could be dried to a higher moisture content.

When this equipment was designed it was assumed that all evaporated water would be carried away as vapor by the ventilation air. However, during the experiments condensate was observed in the waveguides. Some of this water dripped onto the surface of the paper causing a stain. It was felt that arcing could be caused by these drops and this could cause a burn or scorch mark on the paper. This problem could be eliminated by using higher air flow rates or by using heated ventilation air.

At high power intensities spotting of the paper surface was evident (Figure 23b). These spots were lustrous and resin rich. They only occurred at power levels of over 2.5 KW and

only for a few inches from the side of the waveguide nearest the power source. No reason for this can be advanced. Further study with high speed photographs during drying might shed some light on this. The problem could probably be eliminated by using several low power applicators instead of one high power applicator.

VI - CONCLUSIONS

- 1) Resin impregnated papers can be dried by microwave absorption.
- 2) Over the range of variables studied the average applicator efficiency was around 74%. The efficiency of the microwave power generator ranged from 70 to 90% giving overall efficiencies of 50 to 70%.
- 3) Certain product appearance defects were noted with resin impregnated papers dried with microwaves. The sheets with the worst appearance were considerably weakened by the drying process. This was attributed to over drying. However, under less severe drying conditions the microwave papers appeared to be more uniform.
- 4) No significant differences were observed in the tensile and bending behaviour of resin impregnated papers when compared to similar papers dried in a natural convection oven. The microwave dried papers were better in terms of abrasion resistance and internal bond strength.
- 5) A resin content distribution analysis was performed by extracting the cellulose from the residual resin by hydrofluoric acid after sectioning the sheets on a lathe. The microwave dried sheets gave a more uniform resin distribution profile than the conventionally dried papers.

VII - REFERENCES

1. McAdams, W.H., Lewis, W. K., and Adams, F. W., Paper Trade Journal 84(18), 61 (1927)
2. Sherwood, T. K., Ind. Eng. Chem. 21, 976 (1929)
3. Ceaglske, N. H., and Hougen, O. A., Ind. Eng. Chem. 29, 805 (1937)
4. Corben, R. W., and Newitt, D. M., Trans. Instn. Chem. Engrs. 33, 52 (1955)
5. Dreshfield, A. C., and Han, S. T., Tappi 39(7), 499 (1956)
6. Harmathy, T. Z., Ind. Eng. Chem. Fundamentals 8, 92 (1969)
7. Kauh, J. Y., Ph.D. Thesis, Illinois Institute of Technology, (1966)
8. Nissan, A. H., and Hansen, D., Tappi 43(9), 753 (1960)
9. Nissan, A. H., and Hansen, D., A.I.Ch.E. Journal 6(4), 606 (1960)
10. Nissan, A. H., and Hansen, D., Tappi 44(8), 529 (1961)
11. Nissan, A. H., George, H. H., and Hansen, D., Tappi 45(3), 213 (1962)
12. Snow, R. H., IITRI Report NO. C8081-4, IIT Research Institute (1966)
13. Goerz, D. J., and Jolly, J. A., The Journal of Microwave Power 2, 87 (1967)
14. Gardner, T. A., Preprint, Symposium on Water Removal, Canadian Pulp and Paper Association (1968)
15. Damskey, L. R., Hankin, J. W., and Stephansen, E. W., The Journal of Microwave Power 4, 294 (1969)
16. Voss, W. A. G., IEEE Transactions on Industry and General Application 2(3), 234 (1966)
17. Lewin, L., "Advanced Theory of Waveguides", Ilife and Sons, London, (1951)
18. Allan, G. B., M.Sc. Thesis, The University of Alberta, (1967)

19. Asami, Y., Research Institute of Applied Electricity Report, Hokkaido University, Japan, (1958)
20. de Loor, G. P., The Journal of Microwave Power 3, 67 (1968)
21. Tinga, W. R., The Journal of Microwave Power 4, 162 (1969)
22. Leidigh, W. J., Stephansen, E. W., and Stolte, W. J., International Microwave Power Institute Fourth Symposium, Edmonton, (1969)
23. Takahashi, K., Vasishth, R. C., and Cote', W. A., The Journal of Microwave Power 4, 64 (1969)
24. Seiler, C. J., Tappi 44(10), 172A (1961)
25. Marton, R., and Crosby, C. M., Tappi 52(4), 681 (1969)
26. Siconolfi, C. A., Tappi 43(3), 152A (1960)
27. Seifert, K., Holz als Roh und Werkstoff 16, 335 (1958)
28. Tappi Standards and Suggested Methods, T 222 os-54
Acid-insoluble Lignin in Wood Pulp
29. Ettling, B. F., and Adams, M. F., Forest Products Journal 16(6), 26 (1966)
30. Berkeley, D. E., B.A.Sc. Thesis, The University of British Columbia, (1968)
31. Birenbaum, L., Kaplan, I. T., Metlay, W., Rosenthal, S. W., Schmidt, H., and Zaret, M. M., The Journal of Microwave Power 4, 232 (1969)
32. Crapuchettes, P. W., The Journal of Microwave Power 4, 137 (1969)
33. Tappi Standards and Suggested Methods, T 404 ts-66
"Tensile Breaking Strength of Paper and Paperboard"
34. Canadian Standard Association, CSA-0188-6'7
"Measurment of Internal Bond Strength"
35. TICO Bulletin NO. 6504-1M
"TABER Model 503 Abraser Instruction Manual"

36. NEMA Standard, NO. 8-20-1962
"Method of Test for Resistance of Surface to Wear"
37. Galloway, L. R., Ph.D. Thesis, The University of British Columbia, (1963)

VIII - NOMENCLATURE

1. Drying Theory

C_p	specific heat	kcal/(kg)(°C)
H_1	heat transfer coefficient (cylinder - sheet interface)	kcal/(m ²)(hr)(°C)
H_2	heat transfer coefficient (sheet - felt interface)	kcal/(m ²)(hr)(°C)
K_c	conductance of pulp for liquid water	kg/(m)(hr)(atm)
K_r	coefficient of evaporation-condensation mechanism	kg/(m)(hr)(atm)
k	thermal conductivity	kcal/(m)(hr)(°C)
M	moisture content	kg/m ³
P_s	capillary pressure	atm
P_w	vapor pressure of water	atm
r	dimensionless distance	
T	temperature	°C
T_a	air temperature	°C
T_c	cylinder temperature	°C
T_f	felt temperature	°C
X	sheet thickness	m
x	distance through thickness	m
y_a	mole fraction of water in bulk air	
y_f	mole fraction of water in felt	
y_o	mole fraction of water at sheet surface ($r=0$)	
y_1	mole fraction of water at sheet surface ($r=1$)	
α	thermal diffusivity	m ² /hr
θ	time	hr
λ	heat of evaporation	kcal/kg-mole

ρ	density	kg/m^3
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2. Microwave Theory

d	penetration depth	cm
E_i	incident electric field density	volts/m
E_t	transmitted electric field density	volts/m
f	frequency	Hz
n	mixing condition	(-)
P_a	absorbed power density	watts/cm^3
P_i	incident power density	watts/cm^3
P_t	transmitted power density	watts/cm^3
W	weight ratio of component 2 to component 1	
α	attenuation constant	m^{-1}
ϵ	complex permittivity	farads/m
ϵ_1	complex permittivity of component 1	farads/m
ϵ_2	complex permittivity of component 2	farads/m
ϵ'	dielectric constant	farads/m
ϵ'_w	dielectric constant of water	farads/m
ϵ''	dielectric loss factor	farads/m
η_0	intrinsic wave impedance of free space	377 ohms
ρ_1	density of component 1	gr/cm^3
ρ_2	density of component 2	gr/cm^3

APPENDIX A

Power Meter Calibration

The crystal type forward and reverse power meter (EIMAC EW3-DPM3) was calibrated using the water load as a calorimeter. This power meter was mounted in the waveguide between the microwave applicator and the water load.

To calibrate the power meter the microwave power level was set at some value and the cooling water flow rate through the water load and its inlet and outlet temperatures were recorded. The power consumed was calculated from the temperature rise and correlated with the difference between the forward and reverse power meter readings. Total supply current and Variac setting were also recorded for correlation with the energy absorbed in the water load. The data obtained are recorded in Table A-I. In figure A-1 the net power absorbed is plotted against the difference between forward and reverse power meter reading. Two different curves resulted one for each range of the power supply. Since the behaviour of the water load and the power meter should not depend on the power supply circuit to the magnetron this was unexpected. The only explanation that comes to mind is that some mismatching between the magnetron and the waveguide occurs when the range switch is changed or that the power meter is somehow affected by this change.

The net power absorbed is plotted against total supply current in figure A-2 and against Variac setting in figure A-3. Thus these parameters can also be used as power generation indicators as well as the power meter.

Total power supplied was calculated from the total supply

current and supply voltage assuming the supply voltage was 115 v. The efficiency of the microwave power generator was then calculated and plotted in figure A-4. The overall efficiency of the complete drying process is the product of power supply efficiency and drying efficiency.

Figure A-5 shows the time required for the microwave generator system to achieve steady state. In collecting the data for these curves the Variac setting and the cooling water flow rate were maintained constant. The figure shows that about 2 hours are required to reach steady state after switching on the magnetron. Curves a and c were obtained when the magnetron was on continuously and curve b was obtained when the magnetron was switched on, a reading taken, and then turned off until the next reading was made. Data for the curves of figure A-5 are given in Table A-II.

Figure A-1. Power Generation versus Power Meter Reading

Figure A-2. Power Generation versus Supply Current

Figure A-3. Power Generation versus Variac Setting

Figure A-4. Power Supply Efficiency versus Power Generation

Figure A-5. Start-up Time for Microwave Generator

TABLE A-1a POWER METER CALIBRATION DATA (LOW RANGE)

POWER METER READING (kw)		WATER FLOW RATE (kg/hr)	WATER TEMPERATURE (°C)		POWER GENERATION (kw)	VARIAC SETTING (-)	SUPPLY CURRENT (amp)	SUPPLY POWER (kw)	EFFICI- ENCY (%)
FORWARD	REVERSE		INLET	OUTLET					
0.100	0.000	41.0	12.2	15.0	0.13	99	-	-	-
0.200	0.002	41.0	12.2	18.3	0.26	90	3.0	0.35	75.4
0.300	0.003	41.7	12.2	20.8	0.41	80	5.0	0.58	70.7
0.400	0.005	41.7	12.2	23.5	0.55	72	6.5	0.75	73.5
0.500	0.010	41.2	12.2	26.6	0.71	62	7.8	0.90	78.9
0.600	0.010	41.7	12.2	29.9	0.86	54	9.1	1.05	81.9
0.700	0.015	42.0	12.2	32.3	0.98	46	10.4	1.20	81.7
0.800	0.020	41.7	12.0	34.5	1.09	38	11.5	1.32	82.6
0.900	0.020	42.0	12.0	37.2	1.23	31	12.6	1.45	84.8
1.000	0.025	43.0	12.0	39.1	1.35	20	13.8	1.59	84.9

TABLE A-1b POWER METER CALIBRATION (HIGH RANGE)

POWER METER READING (kw)		WATER FLOW RATE (kg/hr)	WATER TEMPERATURE (°C)		POWER GENERATION (kw)	VARIAC SETTING (-)	SUPPLY CURRENT (amp)	SUPPLY POWER (kw)	EFFICI- ENCY (%)
FORWARD	REVERSE		INLET	OUTLET					
1.000	0.030	40.2	12.2	44.2	1.50	123	16.5	1.90	78.9
1.100	0.040	39.5	12.2	47.0	1.61	118	17.5	2.01	80.1
1.200	0.45	39.5	12.2	49.9	1.76	113	18.6	2.14	82.2
1.300	0.050	39.2	12.2	52.9	1.87	108	19.5	2.24	83.5
1.400	0.055	39.2	12.2	56.2	2.02	101	20.5	2.36	85.6
1.500	0.060	39.5	12.2	58.5	2.14	95	21.5	2.47	86.6
1.600	0.065	40.8	12.2	59.7	2.26	90	22.5	2.59	87.3
1.700	0.070	40.4	12.2	62.2	2.36	85	23.2	2.67	88.4
1.800	0.070	39.5	12.2	64.5	2.44	80	24.0	2.76	88.4
1.900	0.070	39.5	12.2	67.7	2.59	75	25.0	2.88	89.9
2.100	0.065	40.2	12.2	70.9	2.69	68	26.6	3.06	87.9
2.200	0.065	41.5	12.5	72.5	2.77	64	27.2	3.12	88.8
2.300	0.075	40.2	13.2	74.6	2.90	57	27.6	3.17	91.8
2.400	0.075	40.2	13.2	76.4	2.98	53	28.2	3.24	92.0

TABLE A-2a START-UP TIME FOR MICROWAVE GENERATOR
(VARIAC SETTING IN HIGH RANGE 75)

TIME (min)	POWER METER READING (kw)			SUPPLY CURRENT (amp)
	FORWARD	REVERSE	DIFFERENCE	
0	1.13	0.03	1.10	18.1
10	1.26	0.04	1.22	19.3
20	1.35	0.04	1.31	20.1
30	1.40	0.04	1.36	20.6
50	1.49	0.05	1.44	21.7
70	1.52	0.05	1.47	22.3
100	1.52	0.05	1.47	22.5
120	1.52	0.05	1.47	22.5

TABLE A-2b START-UP TIME FOR MICROWAVE GENERATOR
(VARIAC SETTING IN HIGH RANGE 130)

TIME (min)	POWER METER READING (kw)			SUPPLY CURRENT (amp)
	FORWARD	REVERSE	DIFFERENCE	
0	0.20	0.0	0.20	5.1
5	0.32	0.0	0.32	6.4
10	0.43	0.01	0.42	7.8
20	0.53	0.01	0.52	9.7
30	0.65	0.02	0.63	11.4
40	0.75	0.02	0.73	12.8
50	0.85	0.02	0.83	14.8
60	0.90	0.03	0.87	14.8
70	0.93	0.03	0.90	15.0
80	0.96	0.03	0.93	15.5
90	0.98	0.03	0.95	15.9
100	0.99	0.03	0.96	15.9
110	1.02	0.03	0.99	16.5

TABLE A-2c START-UP TIME FOR MICROWAVE GENERATOR
(VARIAC SETTING IN LOW RANGE 70)

TIME (min)	POWER METER READING (kw)			SUPPLY CURRENT (amp)
	FORWARD	REVERSE	DIFFERENCE	
0	0.10	0.0	0.10	3.0
10	0.13	0.0	0.13	3.5
20	0.24	0.0	0.24	4.5
30	0.26	0.0	0.26	4.5
40	0.30	0.0	0.30	5.0
60	0.32	0.01	0.31	5.5
70	0.34	0.01	0.33	5.5
80	0.35	0.01	0.34	5.7
90	0.35	0.01	0.34	5.8
110	0.37	0.02	0.35	6.1
130	0.37	0.02	0.35	6.0

APPENDIX B

Rotameter Calibration

Figure B-1 and Table B-I are the data collected for calibrating the Brooks Rotameter R-6-15A used in controlling the cooling water flow rate. This was done for two water temperatures 12°C and 17°C. No temperature effect was observed.

TABLE B-1 ROTAMETER CALIBRATION DATA

ROTAMETER SETTING	WATER FLOW RATE (kg/hr)	WATER TEMP. (°C)
25.2	3.4	17.0
31.5	5.3	17.0
42.0	8.6	17.0
54.0	12.1	17.0
61.5	14.4	17.0
72.0	17.8	17.0
84.0	22.0	17.0
96.0	25.7	17.0
102.0	28.0	17.0
113.5	32.6	17.0
124.5	36.2	17.0
134.0	39.6	17.0
22.0	2.5	12.0
37.0	7.0	12.0
54.2	12.0	12.0
69.7	16.9	12.0
88.5	23.0	12.0
103.0	28.2	12.0
115.0	33.1	12.0
125.0	35.4	12.0
137.0	40.2	12.0

Figure B-1. Rotameter Calibration Curve

APPENDIX C

Thermocouple Calibration

The copper constantan thermocouples were calibrated using a quartz thermometer. The calibration data is presented in Tables C-I and C-II.

The maximum error due to reading of the recorder chart was estimated to be $\pm 0.2^{\circ}\text{C}$.

TABLE C-1 SURFACE THERMOCOUPLE CALIBRATION DATA
(THERMOCOUPLE NO.1 TO NO.5)

TEMPERATURE (°C)	POTENTIAL DIFFERENCE (mV)				
	NO.1	NO.2	NO.3	NO.4	NO.5
11.1	0.44	0.44	0.44	0.44	0.44
19.9	0.78	0.78	0.78	0.78	0.78
29.8	1.18	1.18	1.18	1.18	1.18
40.5	1.63	1.63	1.63	1.63	1.63
50.7	2.06	2.06	2.06	2.06	2.06
60.6	2.49	2.49	2.48	2.49	2.49
70.4	2.90	2.90	2.90	2.90	2.90
81.2	2.39	2.39	2.38	2.39	2.38
91.1	3.85	3.85	3.83	3.85	3.85
96.0	4.07	4.07	4.07	4.07	4.05

TABLE C-2 THERMOCOUPLE CALIBRATION DATA
(THERMOCOUPLE NO.6 TO NO.9)

TEMPERATURE (°C)	POTENTIAL DIFFERENCE (mV)			
	NO.6	NO.7	NO.8	NO.9
21.2	0.87	0.86	0.86	0.86
30.0	1.24	1.23	1.23	1.23
40.1	1.67	1.65	1.65	1.65
50.1	2.11	2.10	2.09	2.09
60.0	2.55	2.55	2.54	2.53
70.1	2.99	2.99	2.97	2.97
80.0	3.48	3.46	3.45	3.43
90.0	3.95	3.93	3.91	3.88

APPENDIX D

Orifice Meter

A three inch standard orifice meter was installed in the exit line from the fan which ventilated the waveguide. This was used to set the air flow rate. The air flow rates were calculated from

$$W = KA_o \sqrt{2g_c (P_1 - P_2) \rho_o}$$

where K = discharge coefficient (-)

A_o = cross sectional area of the orifice (ft²)

ρ_o = density of the fluid at the orifice (gm/cm³)

W = mass flow rate (lb/sec)

$P_1 - P_2$ = pressure drop across the orifice

$$= 2.048 \Delta h_o \rho_{bo} \quad (\text{lbf/ft}^2)$$

Δh_o = manometer level difference (cm)

ρ_{bo} = manometer fluid density (gm/cm³)

The orifice discharge coefficients were taken from the thesis of Galloway⁽³⁴⁾ who used and calibrated this particular orifice.

APPENDIX E

Sample Calculation for Heat Balance

Sample calculation was done for experiment No.3 of resin impregnated paper drying test.

(1) Power Input Calculation

forward power from power meter = 1.20 kw

reverse power from power meter = 0.05 kw

difference of forward-reverse power = 1.15 kw

power generation = 1.75 kw

(from figure A-1)

(2) Moisture Content and Resin Pick up Calculation

paper feed speed = 21.24 m/hr

width of paper web = 0.41 m

density of paper = 0.201 kg/m²

paper feed rate = (21.24)(0.41)(0.201)=1.75 kg/hr

moisture content and resin pick up at position 5

(wet end)

concentration of resin solution = 33.67%

weight of wet sample = 11.20 gr

weight of oven dried sample = 6.09 gr

evaporated water = 11.20 - 6.09 = 5.11 gr

weight of resin = $\frac{(0.3367)(5.11)}{1 - 0.3367}$ = 2.59 gr

weight of paper = 11.20 - (5.11+2.59)

= 3.50 gr

$$\text{resin pick-up} = \frac{2.59}{3.50} = 0.74 \text{ gr/gr-paper}$$

$$\text{moisture content} = \frac{5.11}{3.50} \times 100 = 146.0 \%$$

moisture content and resin pick up at position 4

$$\text{weight of sample} = 4.46 \text{ gr}$$

$$\text{weight of oven dried sample} = 2.48 \text{ gr}$$

$$\text{weight of water} = 4.46 - 2.48 = 1.98 \text{ gr}$$

$$\text{resin pick-up} = 0.74 \quad (\text{from wet end data})$$

$$\text{weight of paper} = \frac{2.48}{1 + 0.74} = 1.43 \text{ gr}$$

$$\text{moisture content} = \frac{1.98}{1.43} \times 100 = 138.4 \%$$

Similar calculation was done for each position. Results were given as follows:-

	Position				
	1	2	3	4	5
sample weight	6.11	5.73	7.54	4.46	11.20
oven dried weight	5.49	3.91	4.24	2.48	6.09
weight of water	0.62	1.82	3.30	1.98	5.11
weight of resin	2.33	1.66	1.80	1.05	2.59
weight of paper	3.16	2.25	2.44	1.43	3.50
resin pick-up	-	-	-	-	0.74
moisture content	19.6	80.8	135.2	138.4	146.0

(3) Energy Calculation for Evaporation

evaporation at position 1 (dry end waveguide)

$$\text{moisture content difference} = 0.808 - 0.196$$

$$= 0.612 \text{ kg-water/kg-paper}$$

$$\text{water evaporation} = (0.612)(1.75) = 1.07 \text{ kg/hr}$$

$$\text{paper temperature at position 5} = 23.0^{\circ}\text{C}$$

$$\text{paper temperature at position 1} = 72.3^{\circ}\text{C}$$

$$\text{specific heat of water} = 1.0 \text{ kcal/(kg)}(^{\circ}\text{C})$$

$$\text{heat of vaporization of water} = 555 \text{ kcal/kg}$$

$$(\text{at } 72.3^{\circ}\text{C})$$

energy for evaporation

$$= (1.07) \{ (1.0)(72.3 - 59.4) + 555 \}$$

$$= 609 \text{ kcal/hr}$$

Similar calculation was done for each position. Results were given as following:-

Waveguide No.	Water Evaporation (kg/hr)	Energy for Evaporation (kcal/hr)
1 dry	1.071	609
2	0.952	505
3	0.056	53
4 wet	0.133	97
total	2.212	1261

(4) Energy Calculation for Sensible Heat

$$\text{specific heat of paper} = 0.30 \text{ kcal/(kg)}(^{\circ}\text{C})$$

$$\text{specific heat of resin} = 0.40 \text{ kcal/(kg)}(^{\circ}\text{C})$$

(assumed)

paper temperature at position 5 = 23.0 °C

paper temperature at position 1 = 72.3 °C

$$\begin{aligned}\text{sensible heat of paper} &= (1.75)(0.30)(72.3 - 23.0) \\ &= 25.9 \text{ kcal/hr}\end{aligned}$$

$$\begin{aligned}\text{sensible heat of resin} &= (1.75)(0.74)(0.40)(72.3 - 23.0) \\ &= 25.5 \text{ kcal/hr}\end{aligned}$$

sensible heat of water

$$\begin{aligned}\text{in product} &= (1.75)(0.196)(1.0)(72.3 - 23.0) \\ &= 13.5 \text{ kcal/hr}\end{aligned}$$

$$\begin{aligned}\text{total sensible heat} &= 25.9 + 25.5 + 13.5 \\ &= 64.9 \text{ kcal/hr}\end{aligned}$$

(5) Efficiency of Applicator

$$\text{energy input} = (1.75)(860.5) = 1.505 \text{ kcal/hr}$$

$$(1 \text{ kw} = 860.5 \text{ kcal/hr})$$

efficiency based on

$$\text{evaporation} = \frac{1,261}{1,505} \times 100 = 83.8 \%$$

efficiency based on total

$$\begin{aligned}\text{energy absorption} &= \frac{1,261 + 64.9}{1,505} \times 100 \\ &= 88.0 \%\end{aligned}$$