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Construction and Commissioning of a High Intensity Through Air Dryer for Paper

by

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Construction and commissioning of a
high intensity through air dryer

Abstract

A new experimental apparatus for high intensity through drying of paper was constructed and commissioned. The principal direct measurements with this facility are the air flow rate, and on-line measurements from beginning to end of the drying of the air temperature and pressure above and below the sheet, the sheet surface temperature on the flow inlet side and the local moisture content of a 2.5 mm diameter spot of the sheet. The equipment, constructed for the use of either air or superheated steam as the drying fluid, was commissioned with air as the drying medium. This facility was tested using three levels of drying air temperature, 90°, 200°, and 300°C, for through-flow rates up to those for which pressure drop across the sheet did not exceed 40 kPa. Papers from kraft, TMP and blended furnishes of grammage between 44 and 100 g/m^2, were dried from a range of initial moisture contents.

Sheet moisture content was measured on-line with a custom made, 3-wavelength transmission-type infra-red moisture sensor with optical fibre leads permitting installation inside the dryer. As this moisture sensor is sensitive to paper grammage as well as to moisture content, the local grammage of the precise sensing area was determined using light transmission image analysis. For papers made from several commercially important furnishes the sensor is very sensitive to moisture content below the fibre saturation point value, becoming increasingly less sensitive above this level of moisture content. For paper from one furnish a satisfactory calibration could not be obtained.

For the kraft and TMP papers for which satisfactory moisture sensor calibrations were obtained, the moisture content-time drying history curves were processed to yield drying rate curves with the instantaneous drying rate as a function of local sheet moisture content. For through-air drying with 300°C air, where the drying time can be less than a second, extreme care with the data processing is required. As drying rate curves for such high intensity drying conditions have not previously been reported, these results are unique to this equipment. The apparatus is now ready for operation as an experimental high intensity through drying facility, including for characterizing the local non-uniformity of drying.

Résumé

Un nouvel appareillage expérimental destiné au séchage du papier par air traversant à haute intensité a été construit et mis en service. Les mesures directes permises par l'équipement sont le flux d'air, ainsi que le suivi en temps réel, du début du séchage jusqu'à la fin, de la température de l'air, de la pression au-dessus et au-dessous de la feuille, de la température de surface de la feuille du côté du flux entrant et de la teneur en eau locale d'un disque de diamètre 2,5 mm. L'équipement, conçu pour être utilisé soit avec de l'air, soit avec de la vapeur surchauffée comme fluide de séchage, a été mis en service avec de l'air. Trois valeurs de température ont été utilisées : 90°, 200° et 300° C, pour des valeurs du flux d'air traversant aussi élevées que possible sans que la chute de pression au travers de la feuille ne dépasse 40 kPa. Les feuilles de papier, de types kraft et pulpe thermo-mécanique, et de grammage compris entre 44 et 100 g/m^2, ont été séchées pour différentes valeurs de la teneur en eau initiale.

La teneur en eau est mesurée avec un capteur infra-rouge construit dans ce but spécifique, fonctionnant en mode transmission, comportant trois longueurs d'onde différentes transmises par fibre optique, installé à l'intérieur de la chambre de séchage. Ce capteur étant sensible aux variations du grammage aussi bien qu'aux variations de la teneur en eau, nous avons mesuré le grammage local du disque dont nous suivons la teneur en eau au moyen d'un système d'analyse d'image basé sur la transmission de lumière. Pour la majorité des papiers testés, la cellule est très sensible aux changements d'humidité en dessous du point de saturation des fibres, et le devient de moins en moins lorsque la teneur en eau dépasse cette valeur. Dans un cas, il n'a pas été possible d'obtenir un étalonnage satisfaisant.

Dans le cas des papiers kraft et thermo-mécaniques pour lesquels l'étalonnage de la cellule était satisfaisant, les données fournissant l'humidité en fonction du temps ont été traitées afin d'obtenir le taux de séchage instantané en fonction de l'humidité locale. Dans le cas du séchage par air traversant avec de l'air à 300° C, où le temps de séchage peut être inférieur à une seconde, il est nécessaire de procéder avec de nombreuses précautions. Les courbes du taux de séchage pour des intensités de séchage aussi élevées n'ayant jamais été publiées, ces résultats sont uniques. L'équipement qui les a permis est maintenant prêt pour opérer en tant qu'installation expérimentale de séchage par air traversant à haute intensité, y compris pour étudier les irrégularités locales de l'humidité au cours du séchage.

Acknowledgments

I would like to express my sincere gratitude to all the people who have contributed towards the completion of this thesis. First I thank my supervisor, Prof. W.J.M. Douglas, for his technical and financial support through-out this work. I owe particular thanks to Dr. J.-F. Bond and S.J. Hashemi, who worked on high intensity through air drying before me and provided much advice and assistance. Dr. V. G. Gomes also provided much useful insight at the beginning of the project.

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Nomenclature

B	grammage, g/m^2
D	characteristic diameter, m
f	Fanning friction factor
FSP	see X_{fsp}
G	through flow air mass flow rate, kg/m^2s
G_{max}	mass flow at maximum pressure drop, kg/m^2s
L	characteristic length, m
P_1	pressure entering the critical flow valve, Pa
P_2	pressure exiting the critical flow valve, Pa
ΔP	pressure drop, kPa
R	drying rate, kg water/m^2s
t	time, s
T_i	inlet drying fluid temperature, °C
$V_{2,max}$	maximum exit velocity from critical flow valve, m/s
w	mass flow rate, kg/s
X_{fsp}	fibre saturation point moisture content, kg H_2O/kg dry fibre
X_o	initial moisture content, kg H_2O/kg dry fibre
ρ_1	density of gas entering critical flow valve
ρ_2	density of gas exiting critical flow valve

1 Introduction

1.1 Background

Paper, a network of fibres and filler material bound together in a sheet, is formed by removing the water from a suspension of pulp fibres spread on a moving screen. The remainder of the paper machine is dedicated to removing water from this wet web, first by drainage through the forming wire mesh, then by pressing and finally by drying. As the dominant process for drying paper industrial requires large, capital intensive dryers, in which approximately 75% of the energy used to make paper is consumed, there is strong economic incentive for improving conventional paper drying techniques.

1.2 Literature Review

In a conventional paper machine, drying is accomplished by the mechanism of direct contact heat transfer in passing the paper over a series of steam heated rolls. Due to the inherently low heat transfer rates of hot surface contact drying, giving overall drying rates from wet to dry in the order of 15 kg/m^2h, 40 to 60 cylinders are generally required. Despite its drawbacks, this system is still the dominant process, as can be seen in Table 1.1, from *McConnell, 1980.* The use of through-air drying of tissue has increased substantially, and most major producers now use this technology in the drying of their tissue production.

Table 1.1

U.S. paper industry dryer distribution

Dryer Type	Drying Application					Total
	Pulp	Tissue	Paper	Board	Coating	
	1980 Dryer Distribution (%)					
Cylinder	-	15	95	95	35	82.3
Impingement	70	-	2	2	50	7.6
Yankee	-	70	-	-	-	4.2
Infra-red	-	-	3	3	15	2.8
Through	-	15	-	-	-	0.9
Flash	15	-	-	-	-	1.1
Vacuum	15	-	-	-	-	1.1

In through-air drying the paper is passed over cylinders of a very open, honeycomb construction, wrapped with wire mesh. High temperature air is drawn from a hood surrounding the cylinder, through the paper, and is exhausted from the cylinder. Due to the high heat and mass transfer rates from the air passing directly through the paper, the drying rate is very high, with values higher than 120 kg/m²h reported by *Chen, 1994*, for 50 g/m² paper with an air through flow rate of 1.5 kg/m²s, even at the very low drying temperature of 90°C. Tissue is commonly dried in air of 300-400°C. Although through-air drying is widely used for the production of tissue and towelling, it has not been used for printing grades of paper because of the cost of providing the high pressure drop required and because of the perception that through-drying degrades the surface properties of the paper for printing because of locally non-uniform drying. At one point the interest in expanding the use of through-drying to printing grades of paper reached the extent of *Burgess et al.,1972 b*, installing a combined impingement and through-air dryer in the Trois Rivières newsprint mill of the Canadian International Paper Company for mill-scale tests. Although the results of this experiment appeared promising, a combination of factors led to it not being followed up by industrial application.

This reluctance to commit significant capital investment to a process which is not understood is hardly surprising. There is a significant lack of knowledge about the actual mechanism of through-drying, including the aspect of local non-uniformities. As detailed by *Polat, 1989*, much of the previous work done in this field had suffered from various problems with experimental design leading to uninformative results. Recently, however, new work has utilised improved experimental techniques. Begun by *Polat, 1989*, this work has been aimed at gaining a complete understanding of the mechanisms of through-air drying. In his pioneering work, Polat made a number of important discoveries. He was the first to appreciate the fact that there can be not two but three separate periods of importance during through-drying of paper. Thus, in addition to the constant rate and falling rate periods Polat showed that the increasing rate period, between the start of drying and the constant rate period, can account for a significant portion of the drying time.

This improved understanding of the drying process allowed *Polat et al. ,1991a,* to formulate a comprehensive model of through drying. This model, based on a general correlation of mass and momentum transfer (*Polat et al., 1992*), was the first to take into account all three drying rate periods. *Polat et al., 1991b* also showed that under higher intensity drying conditions there is no constant rate period, with the drying rate going directly from the increasing rate to the falling rate period. This work was followed by *Chen, 1994*, who carried out a further experimental and modelling investigation of through-drying as a part of his research on combined impingement and through-drying of paper. He showed that under certain conditions the period of increasing rate may account for nearly half of the drying. Chen was able to provide a model of the through-drying process improved over that of Polat. Chen also showed that through-drying rates are not affected by providing the drying air as impinging jets. Chen's modelling accurately predicted the results of the Papridryer pilot plant study of *Burgess et al.,1972 a.*

A limitation of the studies of Polat and Chen is that industrially relevant temperatures were not used, and that papermachine formed sheets were not used. The latter aspect has been investigated in this laboratory by *Hashemi, 1994*, while the first is the focus of the current study. Although the local non-uniformity of through drying was not a part of the research of Polat or Chen, an important start has been made by *Thompson et al.,1995* in very recent work in this laboratory.

With respect to the effect of sheet formation, the prime difference between laboratory handsheets and machine produced paper is the degree of local non-uniformity of fibre distribution. The quite variable types of distribution of local grammage have been shown by many investigators, for example by *Cresson and Luner, 1991*, and more recently by *Bernié and Douglas, 1994.* Substantial local variation in grammage is a factor in all drying processes, but is particularly relevant for the technique of through-air drying. There are a number of compounding reasons for this importance.

In regions of locally higher paper grammage, caused by the presence of flocs, the sheet permeability to air through-flow is lower, which results in locally lower values of through-flow rate and drying rate, so that the increase of local permeability to through flow as the sheet dries is likewise retarded. By contrast, the inter-floc regions of lower grammage initially have a higher local through-flow rate and therefore dry faster, causing a more rapid increase of local permeability to through flow, leading to yet higher local through-flow and drying rates. Thus the coupling of local grammage, local permeability, local flow rate and local drying rate has the effect of progressively exaggerating the differences in local drying rate that exist at the start of drying because of locally non-uniform grammage.

A new method for determining the distribution of local grammage has been developed by *Bernié and Douglas, 1994.* Using an improved version of light transmission, a better quality map of local grammage is produced. This data is then subjected to a type of Fast Fourier Transform treatment to produce a floc contour map and finally a Floc Formation Index (FFI). This FFI criterion has been shown to be a more sensitive measurement of local non-uniformity of grammage than is the commonly used formation number, the normalized standard deviation of the distribution of local grammage.

As the much higher drying rates of through-drying relative to the hot surface contact drying of conventional cylinder dryers in paper mills are achieved at the cost of the blower power required for the pressure drop across the sheet, non-uniform sheet formation is of fundamental importance. *Hashemi, 1994*, has shown that during drying, once the moisture content of paper has been brought down to the fibre saturation point, X_{fsp} (0.6-0.8 kg H_2O/kg fibre, depending on pulp type), the permeability is only moderately less than that for the dried sheet. By contrast, at moisture contents above the fibre saturation point the sheet permeability is markedly lower. Moreover the recent work done by *Thompson et al., 1995*, has shown that if through drying is started at moisture contents above that of the fibre saturation point, the presence of water in the pores of the wet sheet further magnifies the local non-uniformity of through drying. For tissue and towelling, through-air drying must be started at very high moisture contents, 3 to 4 kg/kg dry fibre, in order to obtain a dry paper with as high bulk as possible. For printing grades of paper the moisture content for the sheet entering the dryer section from the wet press is typically about 1.5 kg water/kg fibre, so that removal of moisture from the fibre saturation point to dryness would still correspond to about half of the total drying.

Although the work noted above has provided an improved understanding of the through-drying of machine formed paper under low intensity drying conditions, investigation at the high drying intensities which can be achieved industrially has not been done. The highest air temperatures used by any of the above researchers are in the range of 90°C. As industrial conditions for through-drying the light weight grades of tissue and towelling involve air temperatures of 300°C and higher, work is needed both with heavier grades of paper, including machine-formed sheets, and under more industrially realistic conditions of high intensity through-drying.

2 Objectives

The objectives of this project are divided into two categories: equipment related and experimental. The overall equipment related objective is as follows:

To build an experimental facility in which paper of grammage in the range of $40g/m^2$ to $100\ g/m^2$ can be through-air dried with air of inlet temperature to at least 300°C, at air through flow rates up to those giving a pressure drop across the sheet of not more than 40 kPa, with the ability to follow on-line the local and average sheet temperature and sheet moisture content. Key aspects of this general objective are:

1) Design a sheet support device of high open area, that will not be subject to excessive sagging, which will not wire mark the sheet during drying, while allowing accurate measurement of local moisture content of the paper by the moisture sensor.

2) Install, calibrate, and render operational a Fujitechnica IR moisture sensor in the high intensity through (HIT) dryer.

3) Render the HIT dryer facility operational, ensuring that all parts of the apparatus function properly, to achieve the equipment objectives.

The second category of objectives is to test the capability of the apparatus to investigate high intensity through-air drying of paper and to develop the techniques necessary to analyze the results. The specific experimental objectives are to determine:

1) Can this facility be used at high intensity drying conditions for reliable documentation of the drying history of the sheet, in the form of the evolution with drying time of moisture content and temperature of the sheet, pressure drop-through flow relations, and through flow exhaust air temperature out of the sheet?

2) To what extent is the sheet moisture sensor sensitive to local grammage as determined by light transmission image analysis?

3) What is the extent of local non-uniformity of sheet moisture content under these high intensity drying conditions?

3 Description of Apparatus

The design and construction of an experimental facility was completed to allow the study of through-drying of paper at industrially relevant conditions. The facility was designed such that either air or superheated steam could eventually be used as the drying fluid.

3.1 Overall Design Concept

The heart of the experimental apparatus is the chamber in which the paper is dried. A key consideration is the design of a sheet holder of high open area to accommodate through flow and to ensure that there is no leakage of the drying fluid around the sheet. The paper is held totally restrained in a circular support which is mounted in a sliding tray which is inserted and retracted through a narrow slot in the side of the drying chamber. The end plate of this tray is fitted with an O-ring which seals it against the outside of the chamber when the tray is in the inserted position, preventing leakage of drying fluid into the surroundings. Another O-ring on the bottom of the sheet holder seals against a plate inside the chamber to ensure that no air bypasses the sheet. The drying fluid enters through a flow distribution cylinder extending from just above the sheet to the top of the chamber, thereby providing the desired uniform air flow to the surface of the paper. This cylinder is drilled with a regular pattern of small holes providing a pressure drop sufficiently high to ensure a uniform air distribution. The drying fluid enters the drying chamber enclosure through a single pipe, set in one corner outside this flow distribution cylinder.

Numerous measurements are made in the drying chamber. There are two thermocouples on the in-flow side of the paper and one on the through flow exhaust side to measure the fluid temperature. The two adjacent thermocouples on the flow inlet side of the sheet are to detect any temperature non-uniformity.

Two IR pyrometers are mounted outside the chamber to monitor, through germanium windows in the chamber, the temperatures of both surfaces of the sheet. An important consideration when dealing with IR pyrometry is emissivity. In this case the measurement is complicated because the emissivity of paper varies with both sheet temperature and moisture content.

The most important and difficult measurement is the local moisture content of the paper. This measurement is performed by a custom-made three wavelength forward scatter IR sensor, developed collaboratively between this laboratory and the Fujitechnica Company. This sensor is operated in the present study in transmission mode with the transmitter and receiver on opposite sides of the sheet, although it can also be used in reflectance mode.

The sheet holder is a circular ring of titanium and steel. A honeycomb grid inside the ring provides good sheet support with a high open area. This grid is in turn supported by a titanium plate, drilled to provide maximum open area and hence minimum interference with the air flow pattern and to facilitate viewing the sheet by the moisture sensor. To minimize marking of the paper by the honeycomb a wire mesh is placed over the honeycomb.

Although the current research investigated air drying only, the apparatus is designed to use either air or superheated steam as the drying medium. The air and steam mains, with check valves to prevent back-flow, are connected via ball valves to a tee. The selected drying fluid passes through a pressure regulator to the heater. The combination of a pressure regulator followed by a critical flow valve in series ensures a constant mass flow rate of drying fluid into the chamber, from start to finish of drying, in spite of the significant increase in sheet permeability and decrease in ΔP across the sheet during drying. Detailed calculations of the critical flow relations are given in Appendix A-1. The volumetric flow rate of drying fluid into the drying chamber is measured by a turbine flowmeter. Due to the delicate nature of the turbine, any particulates in the flow could damage the blades. Although the system is protected against particulate matter by an air filter, any work on the piping before the flowmeter could knock particles loose. For this reason a dummy section of pipe was cut to replace the flowmeter after any piping work to allow the particulate matter to be blown through the system.

A direct contact condenser cools the drying fluid with a cold water spray after it leaves the drying chamber. The cooled air is vented to the atmosphere and the water drained to the sewer.

3.2 Equipment Description

3.2.1 General Description

A schematic diagram and a photograph of the apparatus can be seen in Figures 3.1 and 3.2, respectively. Black iron pipes, 1" (2.5cm) diameter, are used throughout, with the exception of the water line which is 3/4" (1.9cm) galvanized pipe, and the pipe between the heater and the drying chamber which is 1" (2.5cm) stainless steel. At the entry to the apparatus the air is cleaned by a filter, 1 (Wilkerson F30-08-G00), to ensure that no particles enter the system. The air and the steam each pass through a ball valve, 2a,b (Watts) and a check valve, 3a,b (Jenkins) before being joined together at a "T" joint. The selected fluid then passes through a pressure regulator, 4 (Spirax/Sarco 3/4"), and a safety valve, 5 (Lonergan Valve L14C 2250120), before entering the heater, 6 (Caloritech EXI11743-01). The heater is a 600 volt, 30 kW vertical heating element which can bring the fluid to temperatures of over 500°C. At the exit of the heater the temperature of the drying fluid is measured by a K-type thermocouple (Omega) before passing through a turbine flowmeter, 7 (Sponsler SP1¼-M8-PH7-A-4X-HT) to determine the mass flow-rate through the chamber. Just after the flowmeter is the critical flow valve, 8 (Conbraco Industries 1" s.s.), which ensures a constant mass flow rate as the fluid enters the drying chamber, 9.

In the drying chamber the fluid temperature is measured above and below the sheet by three more K-type thermocouples (Omega), while two IR pyrometers, 10a,b (Williamson 1900-B-C-SB) are provided to measure the top and bottom sheet temperature, mounted at an angle of 30° from vertical on the outside of the drying chamber. They operate with a spectral response range from 8 to 14 microns. This range is chosen because the smaller the wavelength the greater the accuracy, but below 8 microns water vapour in the air begins to interfere with the measurement. Their field of view is a 2.5cm diameter circle at the centre of the sheet.

Figure 3.1 Schematic diagram of hit drying apparatus

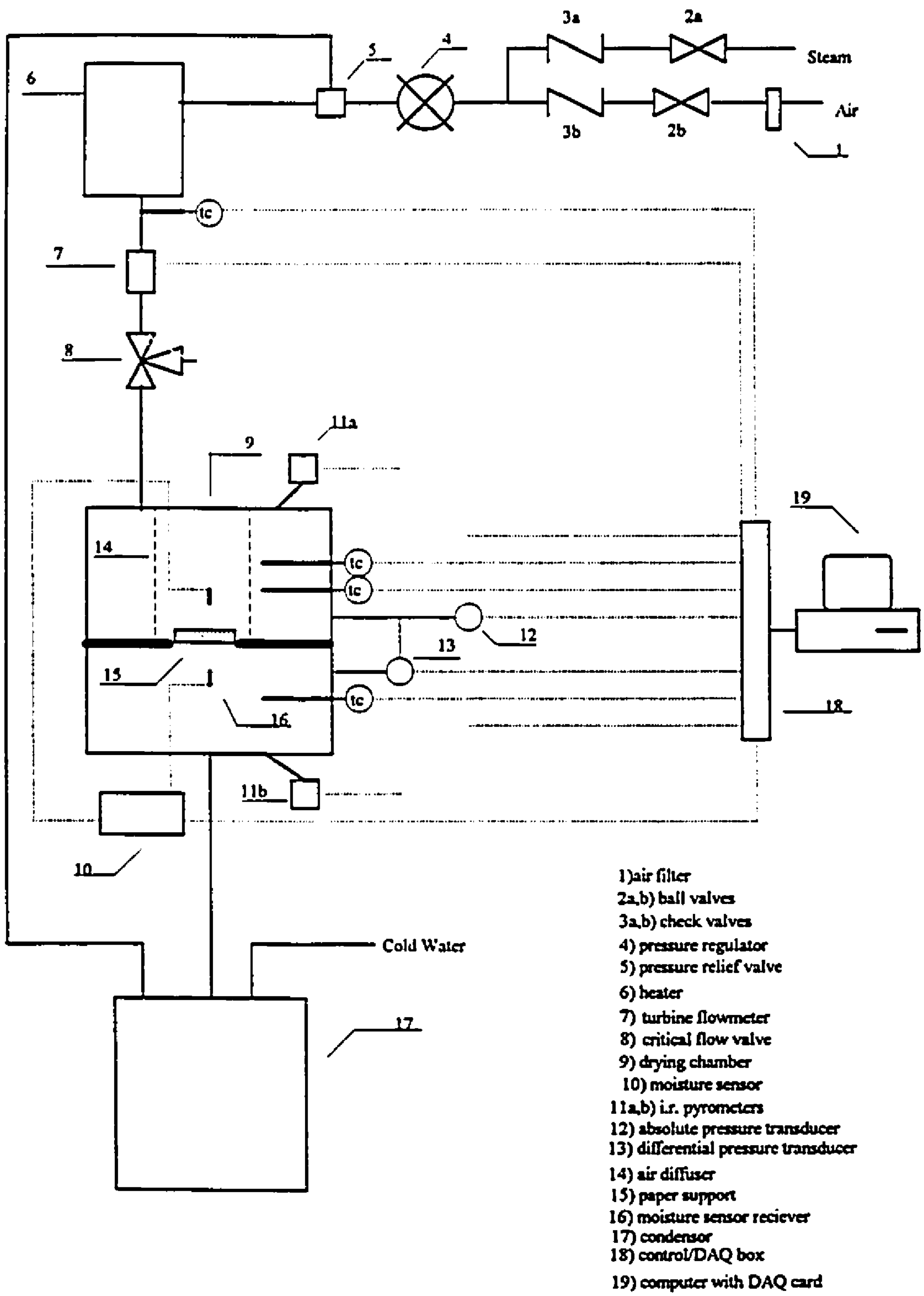


Figure 3.2 HIT drying apparatus (photo)

The pressure above the sheet is measured by an absolute pressure transducer, 11 (Haenni EDA 430/312.215/A15), and the pressure across the sheet is measured by a differential pressure transducer, 12 (Sensotron SEN-505A-15D-250-11-A) which is connected to the data acquisition card, 18 (Data Translation DT-2801A), along with all of the other measurement devices.

The moisture content of the sheet is measured by the IR transmitter and receiver, 15, which are connected via fibre-optic cable to the moisture sensor, 9 (Fujitechnica IM-3SCV model 1900). These sensor heads are attached to arms which can be swept in an arc over the paper by a stepping motor. In order to maintain the required perfect alignment between the emitting and receiving IR heads, the arms are connected rigidly by a large U-shaped arm which passes externally around the drying chamber. The top shaft is driven directly by the stepping-motor, while the lower shaft is driven by the connecting arm. The exit of the drying chamber leads to the condenser, 17, which uses a cold water spray to condense the steam and cool the air. The water is then drained to the sewer while the air is vented to the atmosphere.

3.2.2 Drying Chamber

The drying chamber is constructed of ½" (1.3cm) thick 316 stainless steel. The top and bottom have 1½" (3.8cm) flanges to which covers are bolted. The inside dimensions are 9" (23cm) square by 12½" (32cm) high. On one side of the drying chamber, 5" (13cm) below the top, is a ½" (1.3cm) wide slot for the insertion-retraction tray carrying the sheet holder. Two horizontal plates, ½" (1.3cm) thick with 6" (15cm) diameter circles cut in the centre of each are located immediately above and below this slot so that none of the drying fluid bypasses the paper. A block is screwed to the outside of this slot to help support the insertion-retraction tray. Both the top of this block and the bottom of the upper plate are machined with three grooves to guide the sheet holder into the chamber.

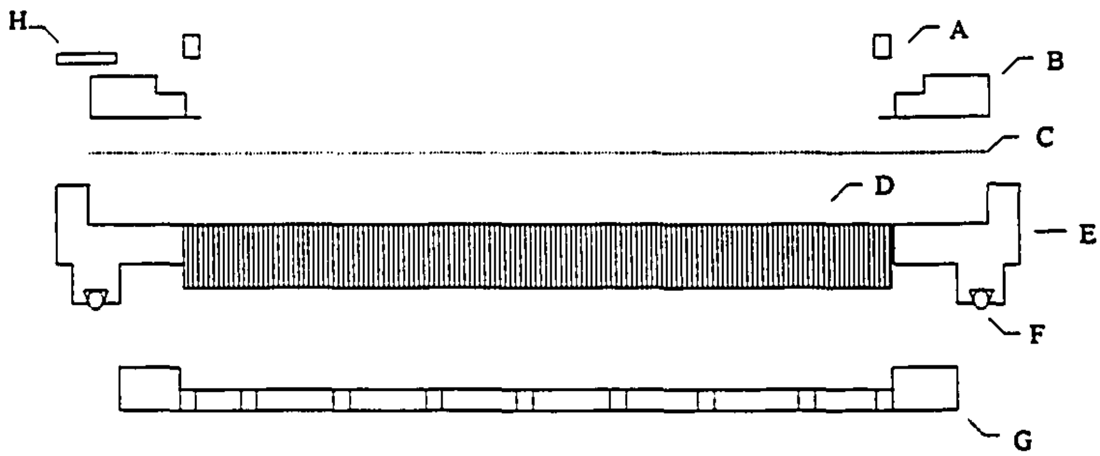
3.2.3 Paper Support

During drying the paper is held in a sheet holder composed of three rings, a drilled disk, a honeycomb grid, and four guides, as seen in Figures 3.3 and 3.4. All other components are attached to the main sheet holder ring, E. Screwed to the bottom is the titanium support disk for the honeycomb, G, providing rigidity for the paper. The disk can be seen on the bottom of the holder in the photograph in Figure 3.5. Titanium was chosen for this support disk for lightness, desired to allow greater accuracy in determining sheet moisture content by weighing the paper while held by the support, and to facilitate fast insertion and retraction with the pneumatic cylinder. On top of this support disk, and inside the main sheet holder ring, is a ¼" (0.6cm) thick honeycomb grid, D, on which rests a wire screen, C, which is in direct contact with the paper. The wire screen and honeycomb are both held in place by a second ring, B, screwed inside the top of the main ring. A third ring, A, holds the sheet into ring B by a friction fit, Figures 3.6a,b. The entire assembly is set into the insertion-retraction tray, with one of the guides, H, ensuring correct alignment, Figure 3.7. When the tray is inserted into the drying chamber the other three guides act to push the sheet holder down onto the sealing plate inside the chamber. The seal is made by the O-ring on the bottom of the main sheet holder ring, thus ensuring that no air by-passes the sheet.

3.2.4 Data Acquisition and Control System

The data acquisition and control system and its accompanying software were designed to perform two general functions. First, they run the experiment by controlling the set temperature of the drying fluid, positioning the moisture sensor heads, and actuating the sheet insertion-retraction tray. Secondly, this system reads and interprets all signals from the instruments and records them when desired. All signals from the thermocouples, pyrometers, pressure transducers, flowmeter, and moisture sensor are collected by the data acquisition system. The signals from the four thermocouples go first to amplification chips with built-in cold junction compensation before going to a screw terminal card which is connected via a 50 wire ribbon to the Data Translation DT2801-A data acquisition card in the computer. The other instrument signals, which go directly to the screw terminal card, can be divided into two categories: variable voltage and variable current. The two pyrometers and the absolute pressure gauge give

Figure 3.3 Sheet holder



A: Friction fit ring to hold paper in place

B: Ring to hold wire screen and honeycomb

C: Wire screen

D: Honeycomb

E: Main sheet holder ring

F: O-ring

G: Titanium support disk for honeycomb

H: Guide

Figure 3.4 Sheet holder (photo)

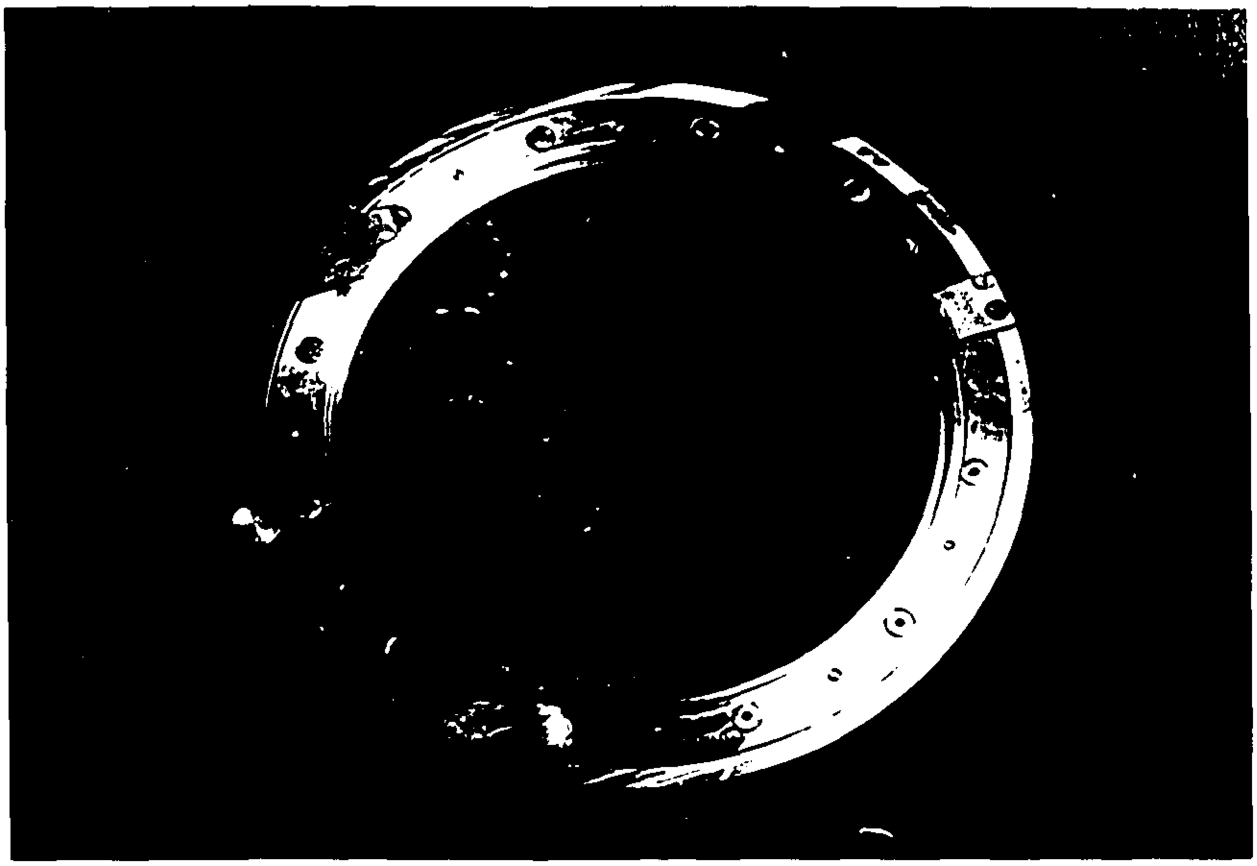


Figure 3.5 Honeycomb support disk

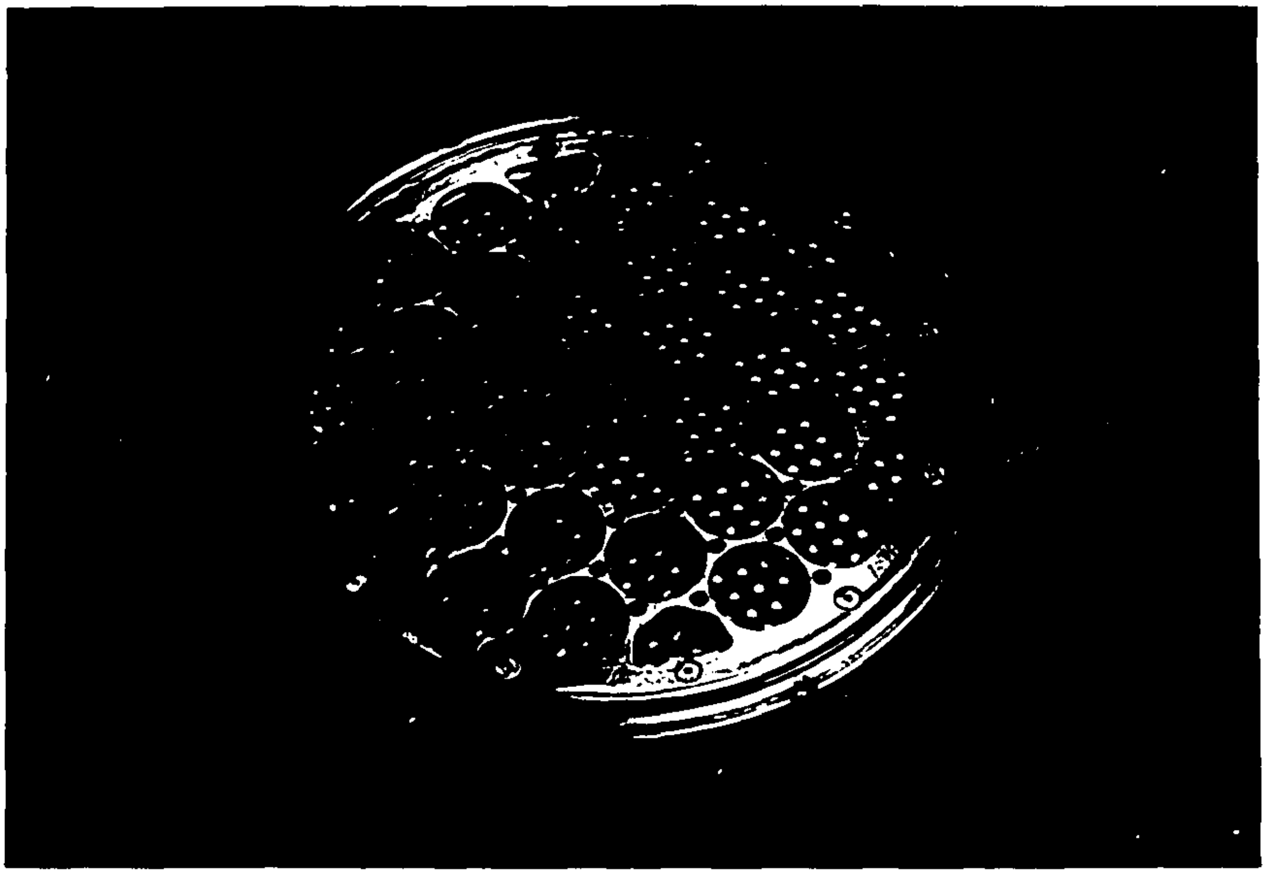


Figure 3.6a Clamping of sheet

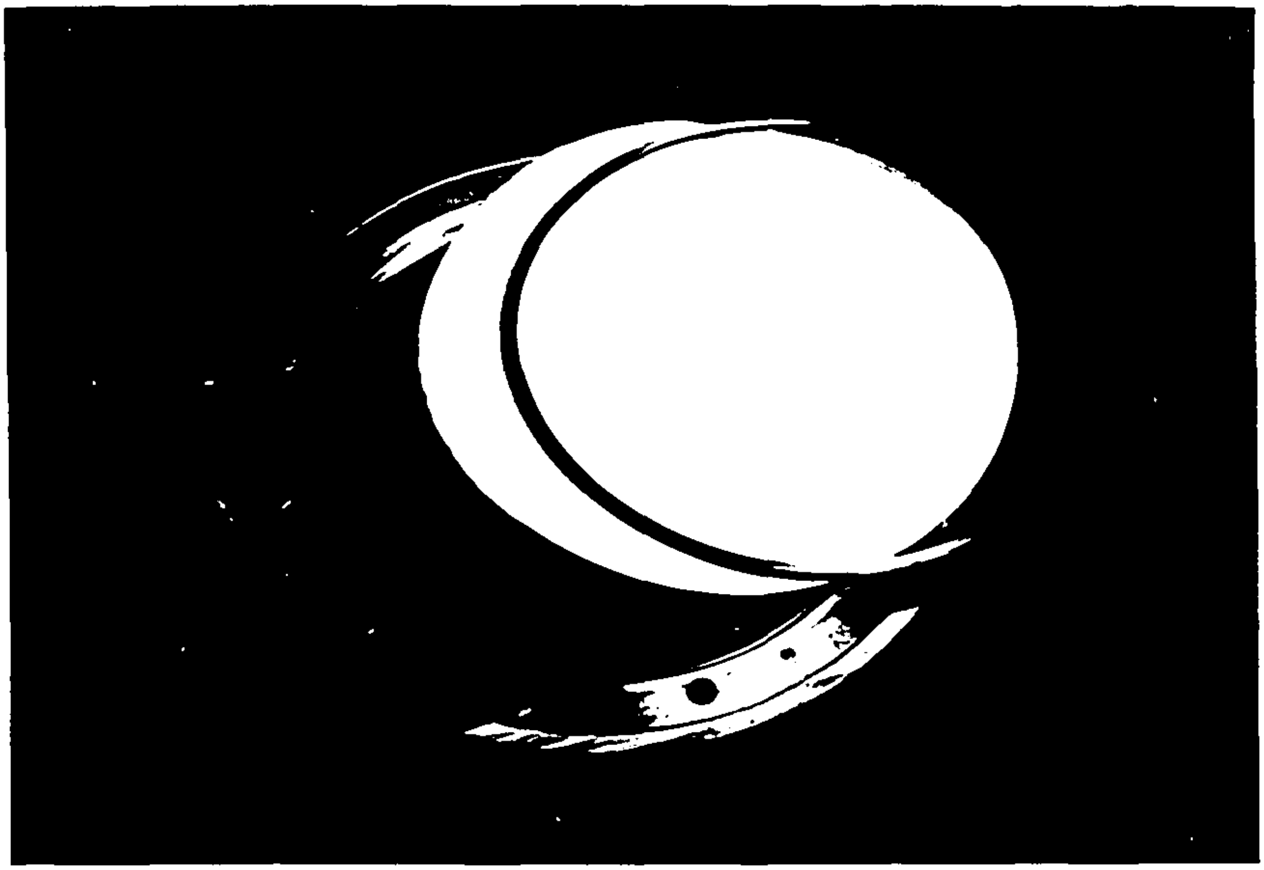


Figure 3.6b Clamping of sheet

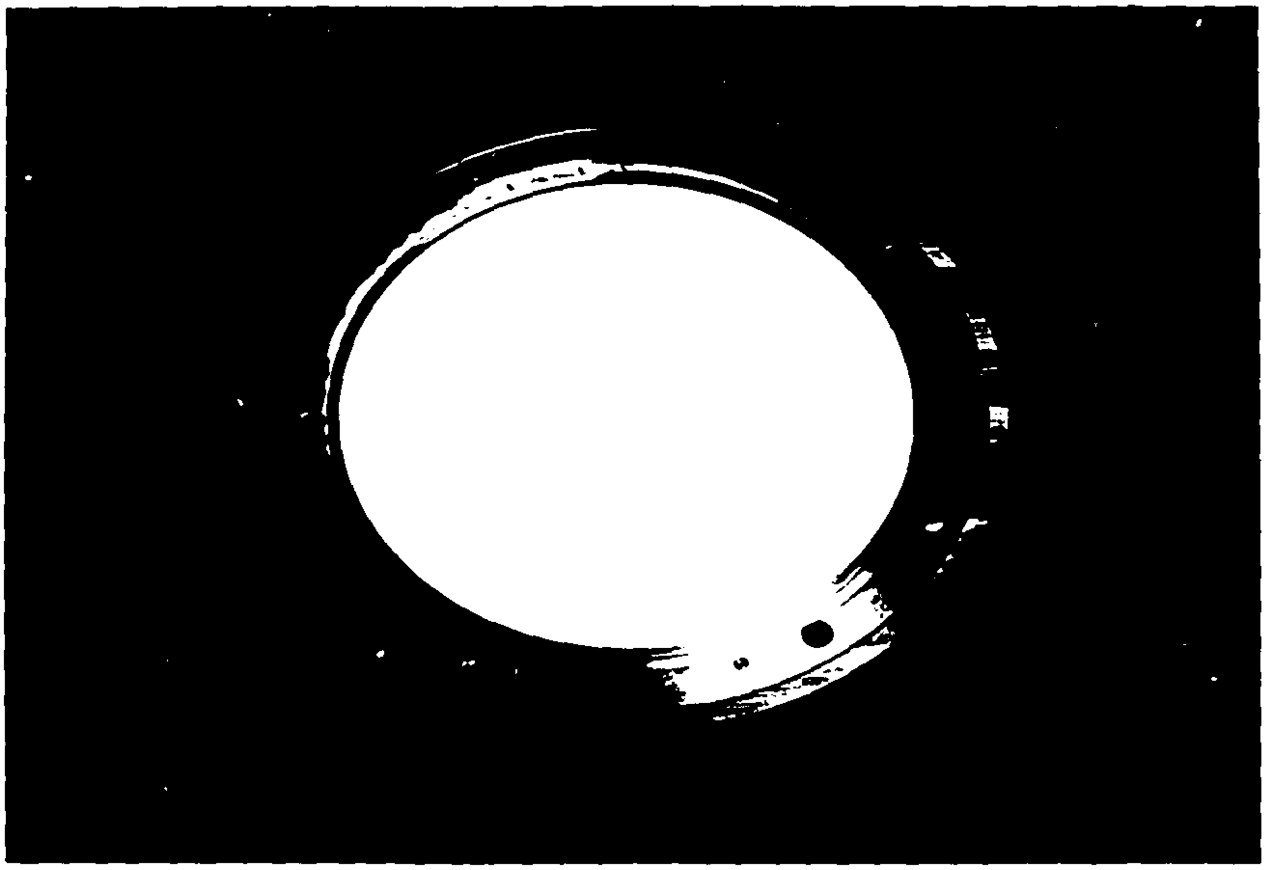


Figure 3.7 Insertion-retraction tray with sheet holder

the variable current signals. As the data acquisition system is designed for variable voltage signals, 250 ohm resistors are placed across the positive (signal) and negative (ground) to convert the 4-20 milli-amp variable current to 0-5 volt variable voltage. The remaining, variable voltage, signals are unmodified before they enter the computer, with the exception of that from the moisture sensor. The moisture sensor was found to exhibit background noise of frequency 250 kHz, amplitude 0.15 volts. This noise is removed by a passive low-pass filter comprising a 390 ohm resister and a 4.7 micro-farad capacitor, providing a cut-off frequency of 87 Hz with a time constant of 1.8 ms. The computer is a 25 MHz 486DX with an Omega DIO-PC-48 timer card. A sampling frequency of 5 Hz was used for experiments longer than 20 s, while shorter experiments were sampled at 10 Hz.

The data acquisition program, written in QuickBasic 3.0 with PCLab subroutines, is given in Appendix B. All data is displayed on the screen for quick reference during warm-up as well as during experiments. The data can be also be saved to disk both during the experiment and during warm-up to allow for future analysis. In addition to handling data, the program and D/A board also control the apparatus. This is done through the use of five relays situated in the DAQ-Control box. Of these relays, one controls the heater, two operate the cylinder solenoid valves for the insertion and retraction of the tray and two relays operate the stepper motor which positions the moisture sensor. The control of the heater relay is done automatically by the program. The user enters the target temperature and an acceptable deviation, typically 1°C. Using both the heater exit thermocouple and one of the thermocouples inside the drying chamber as references, the heater is switched on or off to maintain the correct temperature. Simple on/off control is satisfactory because of the very large thermal inertia of the heater. The data acquisition and control box both receives data from and supplies 15 volt DC power to the pressure transducers and IR pyrometers.

3.2.5 Infra-Red Moisture Sensor

The infra-red moisture sensor is based on the principle that light absorption varies with wave-length. In this case, light of 1.94 μm wave-length is transmitted through the sheet and the difference in intensity between the incident and transmitted beams is measured. Since the amount absorbed is proportional not only to the moisture but also to the polymeric composition and physical state of the paper, its colour, and surface conditions, two other wave-lengths, 1.8μm and 2.1μm, are also transmitted and measured. These wavelengths are little absorbed by water and so are proportional to the degree of interference by other than water molecules between the transmitter and receiver. In order to measure the three wave-lengths a wheel with three different filter elements is rotated in front of a tungsten lamp. The sampling circuit is synchronized with the wheel so that the three values are measured at the correct time. The moisture sensor does the correction calculation by averaging the amount of light transmitted by the two reference wave-lengths, dividing them by the measuring wave-length, then providing the logarithm of this ratio. The resultant value is multiplied by a constant gain to give the output as a ± 10 volt signal which is sent to the data acquisition system as well as being displayed in millivolts on the front of the sensor box. Due to the sensitivity to vibrations of the tungsten lamp which generates the light, the moisture sensor must rest on a completely independent table.

4 Commissioning of the Apparatus

Before the final alterations could be made to the apparatus, it had to be moved from its initial location in a different laboratory. During this re-location some changes were made. The orientation of the heater was reversed, placing the electrical connections at the bottom instead of the top, with the drying fluid flowing from the bottom to the top. This change was recommended by the supplier for several reasons. First, if flow into the heater were to be cut off during operation, natural convection would carry the hot air away from, not towards the electrical connections. Secondly, if condensate were to collect in the heater while cool, then when the power is turned on the heating element nearest the connections would be submerged, as submersion of the opposite end might cause a burn out. In addition to the suppliers recommendations, it was found that inverting the heater shortened the length of pipe between the heater and the chamber by approximately 20%, thus reducing heat losses. Other changes made included addition of the filter on the air main and insulation of the steam main before the heater.

4.1 Calibration

Before the apparatus could be used, each instrument was calibrated and the validity of such results checked. In some cases the instruments came with calibrations from the suppliers which were tested and confirmed, while in other cases an original calibration was done.

4.1.1 Pyrometers

Because infra-red emissivities vary with the surface measured an IR pyrometer must be calibrated for the specific viewing surface. As the infra-red emissivity of moist paper varies with both moisture content and temperature, two types of calibration experiments were performed, one holding the temperature constant while varying moisture content and the second varying the temperature with dry paper. Quantification of the effect of moisture content required a number of experiments. Each test was performed with no air flow, and recorded the thermocouple temperatures above and below the sheet as well as the top and bottom pyrometer outputs. All experiments were performed within two hours with the same kraft handsheet, starting with the highest moisture content and allowing the paper to dry by natural convection between each experiment. As there was some convection drying during the three-second duration experiments, the average of the mass before and after each test was used. Between 27 and 29 pyrometer readings were taken for each experiment, from which the mean and standard deviation at each moisture content were computed. On the graph of results, Figures 4.1a,b, each line represents +/- one standard deviation from the mean. The bottom pyrometer readings, 19.4 to 21.6, are higher than those of the top, 18.2 to 21.3, because the bottom pyrometer 'sees' not only the sheet but also some of the metal, which has an emissivity different from the paper.

More important, however, is the finding that the change in pyrometer output due to this large change in paper moisture content is significantly less than the inherent error in the output. For this reason the pyrometer output may be considered independent of the paper moisture content and was not studied for other types of paper.

The second calibration performed was to determine the effect of paper temperature on pyrometer output. A sheet of the type of paper to be tested was inserted into the chamber and fully through-dried with room temperature air. The heater was then turned on and the thermocouple and pyrometer readings recorded every two minutes until the air leaving the sheet had reached 120°C, taking about one hour. Figure 4.2 again shows that the bottom pyrometer indicates an erroneously high temperature because of the partial viewing of metal. Thus it is confirmed that the bottom surface temperature of the sheet cannot be measured with this configuration. For temperatures up to about 70°C, Figure 4.2 also shows that the top reading agrees closely with the true temperature while in the range of 70° to 125°C the calibration defines the correction factor to be applied to the pyrometer reading.

Figure 4.1a Moisture sensitivity of top pyrometer

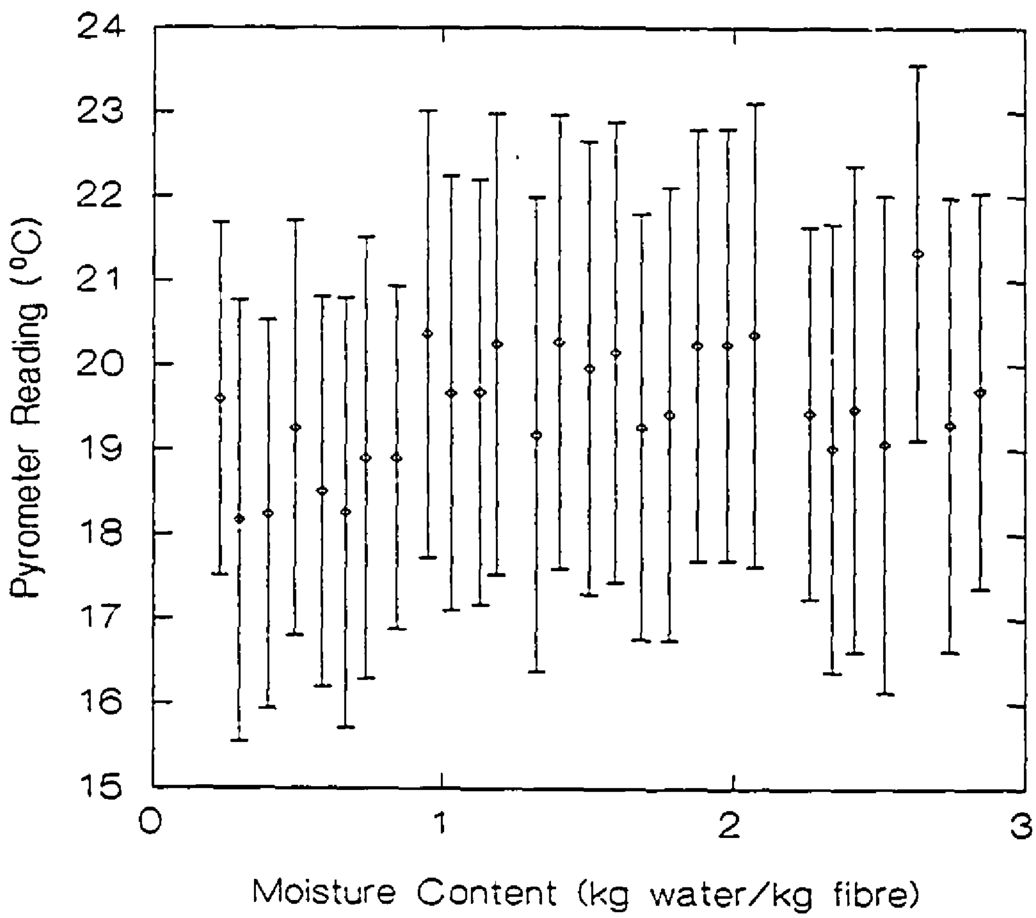


Figure 4.1b Moisture sensitivity of bottom pyrometer

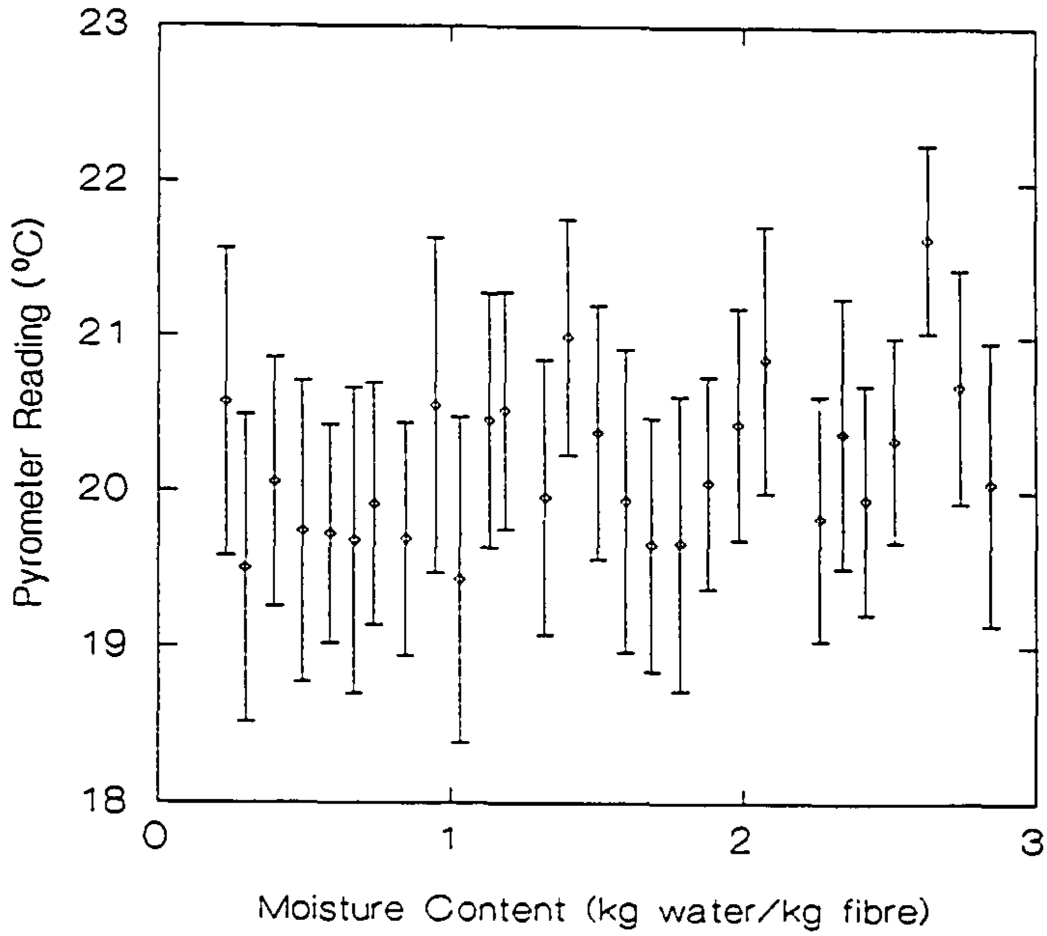
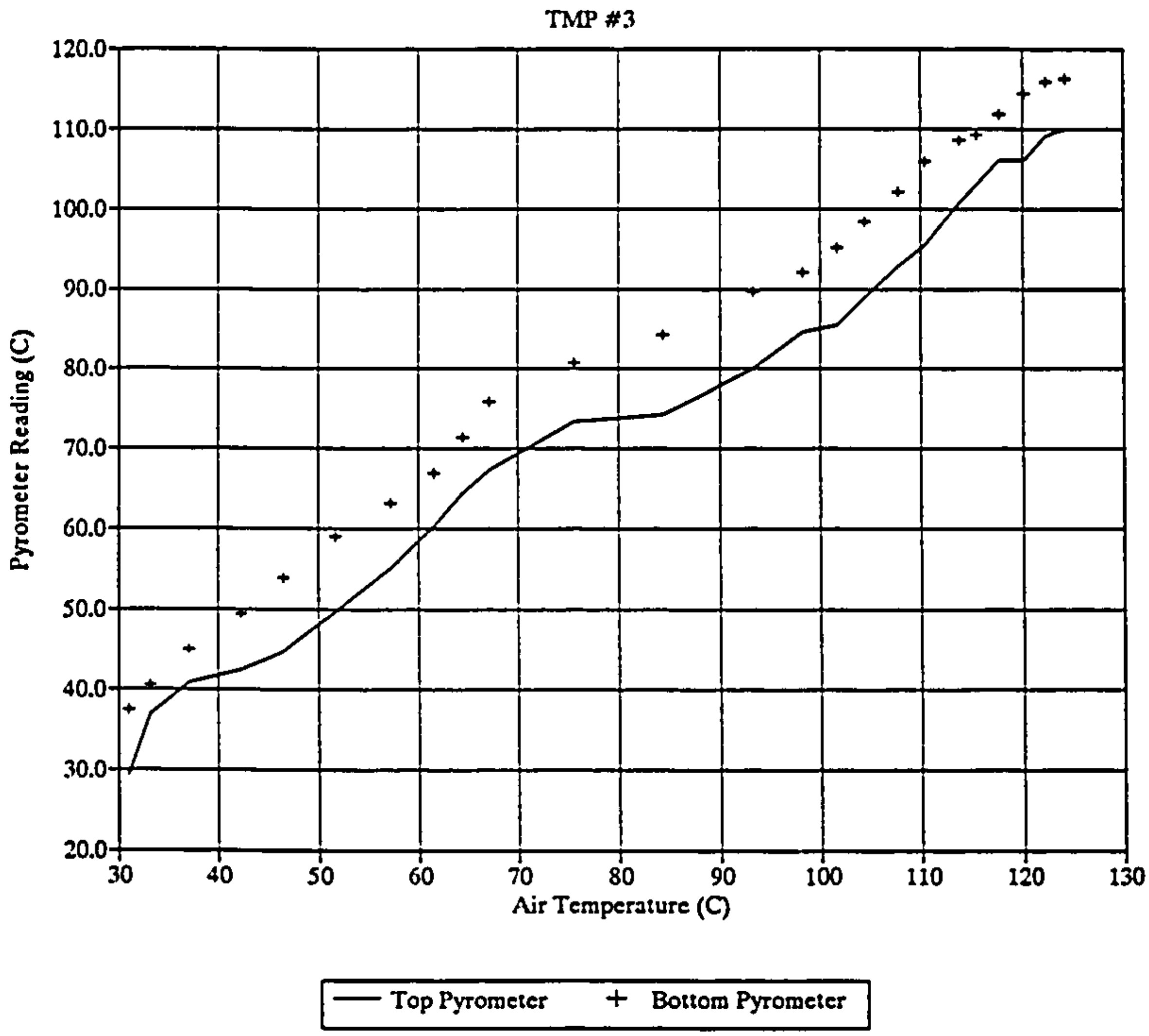


Figure 4.2 Pyrometer calibration with dry sheet



4.1.2 Turbine Flowmeter

The turbine flowmeter is composed of an assembly of blades mounted axially inside the pipe and turning on low friction bearings, and a magnetic pick-up coil mounted on the exterior of the pipe. The rotation of the turbine blades generates a pulsed signal in the magnetic coil, of frequency proportional to the volumetric flow rate. This signal is converted to a variable voltage which is read by the data acquisition board.

In keeping with its nature as an accurate but extremely sensitive instrument, calibration of the turbine flowmeter requires two steps. The first is a bench-top calibration of the electronics used to convert the pulsed signal of the turbine into a variable voltage. This calibration was performed with a Racal Dana function generator (F64) and a Scope digital voltmeter (DVM-630). The second, and more involved, calibration is to determine the turbine revolutions per unit volume of gas flow. This calibration was supplied with the meter but was verified for accuracy. For this purpose the flowmeter was connected in series with a Canadian Meter Co. diaphragm gas meter (AL M1400) and the time measured for a set volume to pass through both meters at a constant flow rate. As it was found that the manufacturer's supplied calibration was accurate a complete re-calibration was not performed.

4.1.3 Thermocouples

The four alumel/chromel type K thermocouples used were calibrated using boiling water and ice water baths, with temperature from a precision mercury thermometer.

4.1.4 Pressure Transducers

Two pressure transducers are used, one for the absolute pressure in the drying chamber above the sheet, and the other for the differential pressure across the sheet. Both were found to have linear response when calibrated with a dead weight tester.

4.1.5 Moisture Sensor

The IR moisture sensor was the most complex instrument to calibrate. This complexity was due in part to the nature of IR moisture measurement and in part to the specific use of the instrument. The instrument is intrinsically sensitive to the amount of water, the amount of fibre, and the type of fibre that the beam passes through, i.e. to the moisture content, grammage, and furnish of the paper. In the specific use of the instrument, a spot of only 2.5mm diameter is sensed, so the instrument sees the local values of grammage and moisture content, not the sheet average value. As the instrument voltage output derives from the difference between the intensity of the incident and transmitted beams, an increase in instrument voltage output results from an increase in absorption, i.e. a decrease in transmittance of IR light of the measuring wavelength with respect to the reference wavelengths.

The moisture sensor was calibrated gravimetrically. First, a sheet of the desired furnish and grammage was wetted, placed between sheets of plastic, and left in the refrigerator overnight to achieve complete uniformity of moisture content. This paper was then placed in the same sheet holder used in the dryer, with the holder placed on a stand resting on a balance. The balance and moisture sensor were connected to a computer data acquisition card such that the readings were recorded simultaneously. After approaching dryness for ambient conditions, the sheet was oven-dried to determine the bone-dry mass, thus providing accurate values of the water to fibre moisture ratio. Subsequently the grammage of the precise spot where the moisture sensor was focused was determined using light transmission image analysis. In order to ensure that a wide range of local grammages were calibrated, the experiments were repeated nine or more times per paper type.

The moisture sensor calibration was determined with the seven types of paper used in the present study. The test papers used differed in formation, as five were machine formed and two were handsheets, and differed also through the use of varied furnishes and grammages. The complete specifications are given subsequently in Table 5.1, which should be consulted for the designations used in the present section.

The resultant calibration curves can be seen in Figures 4.3a..g. An examination of the curves in Figure 4.3a for the eight kraft handsheets tested shows the characteristic response of the IR moisture sensor. As the sensor is used in drying experiments, the calibration curves are analyzed from high to low moisture content.

Figure 4.3a Moisture sensor calibration, kraft handsheets

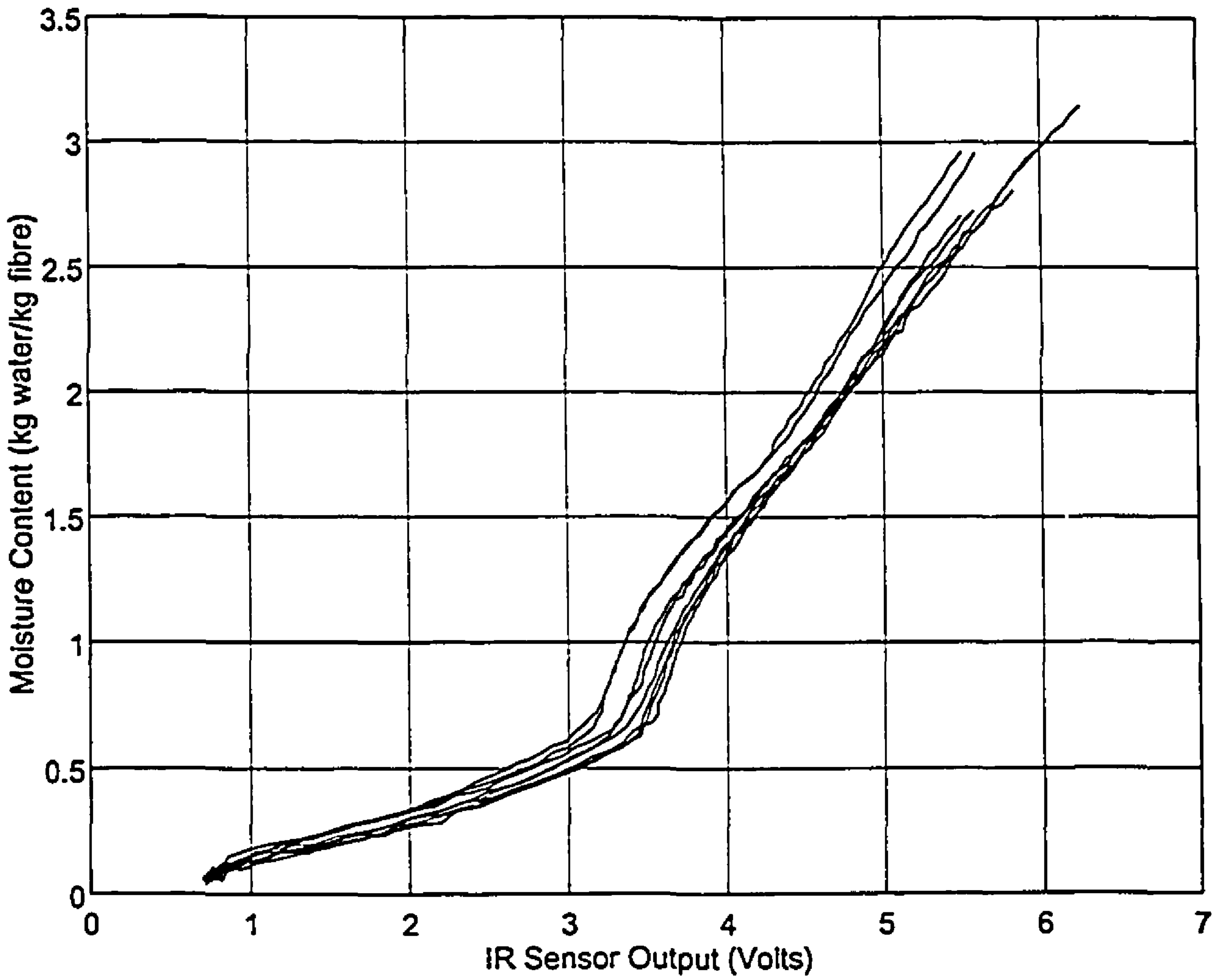


Figure 4.3b Moisture sensor calibration, TMP handsheets

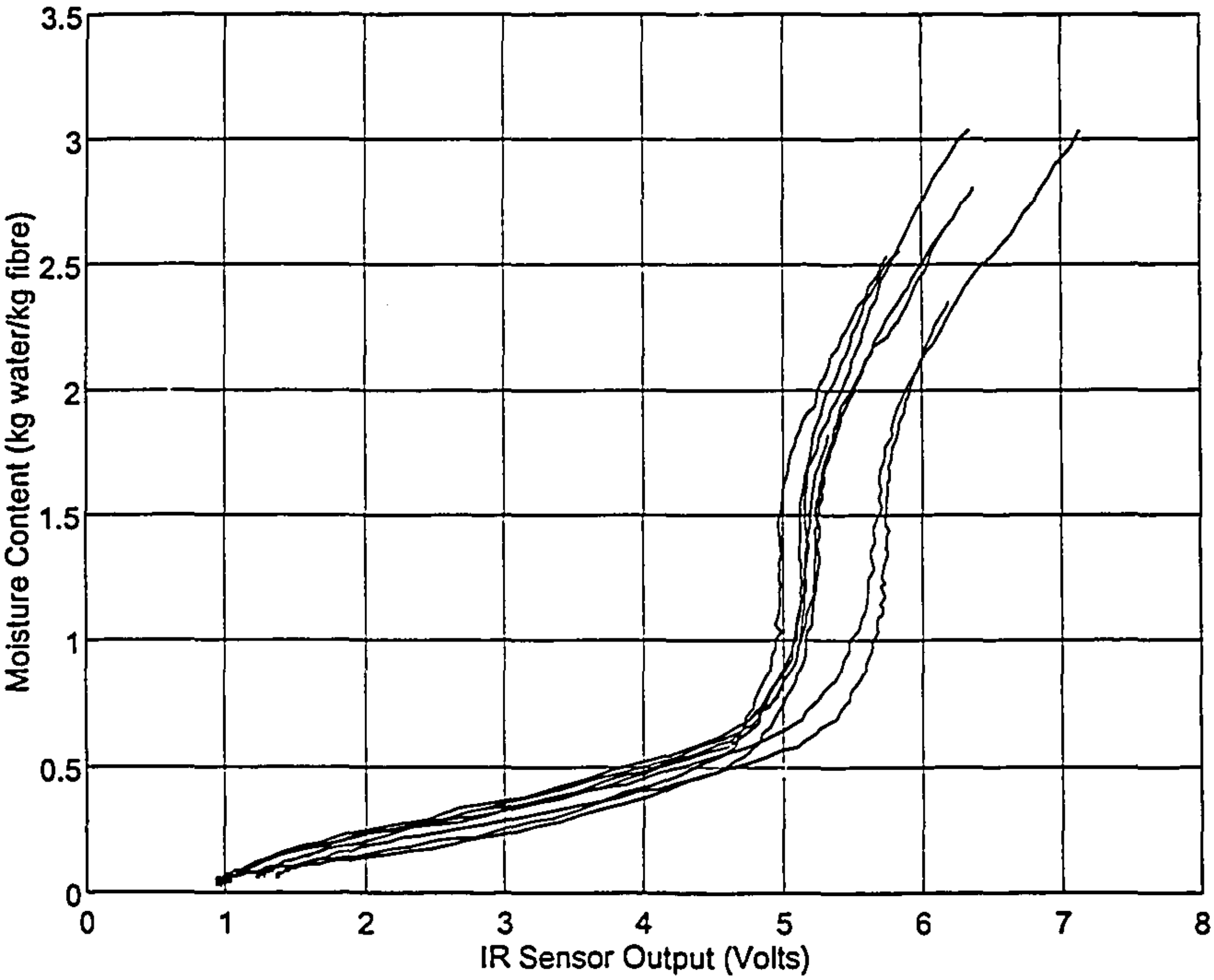


Figure 4.3c Moisture sensor calibration, machine formed paper: TMP #3

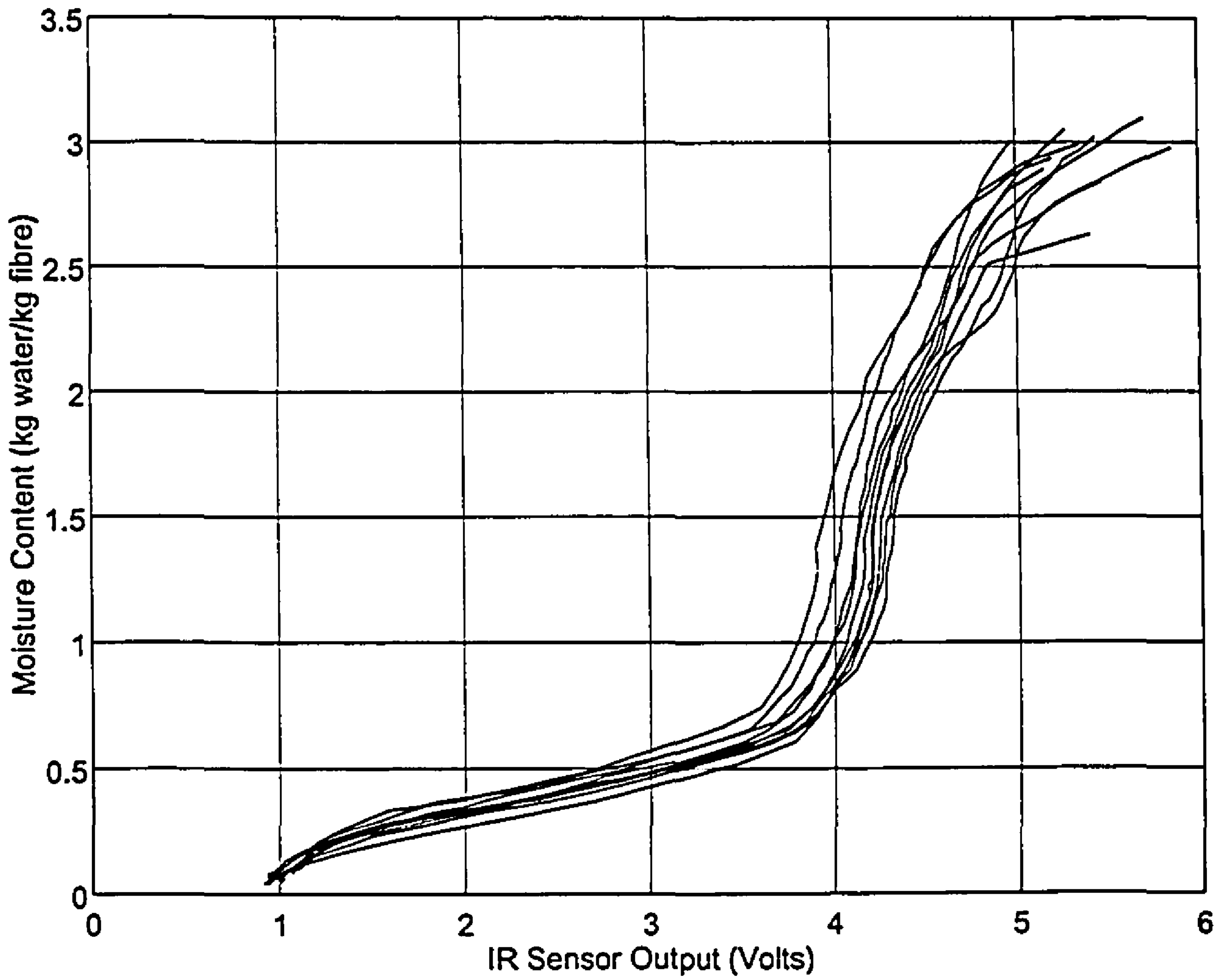


Figure 4.3d Moisture sensor calibration, machine formed paper: BF #1

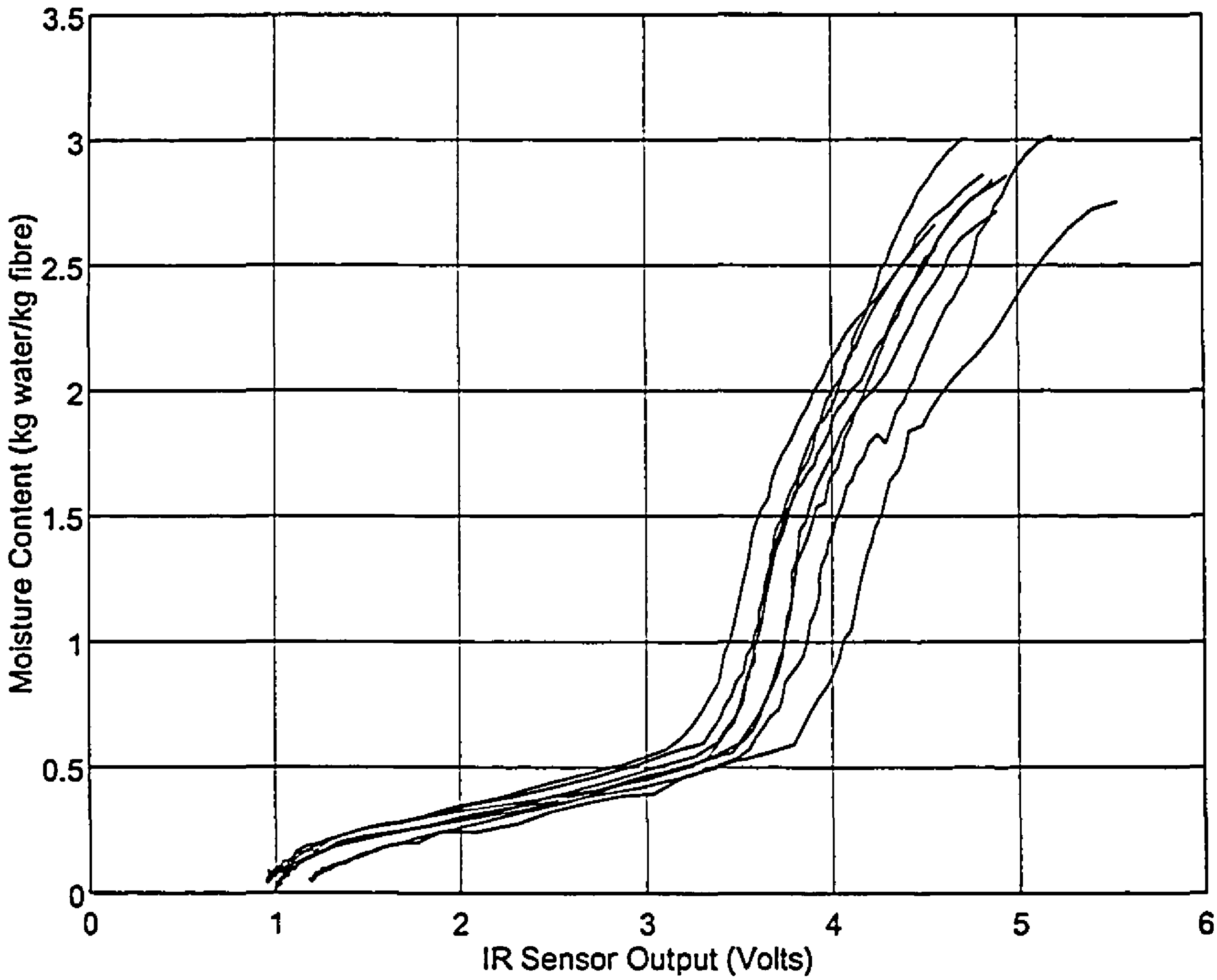


Figure 4.3e Moisture sensor calibration, machine formed paper: sack #7

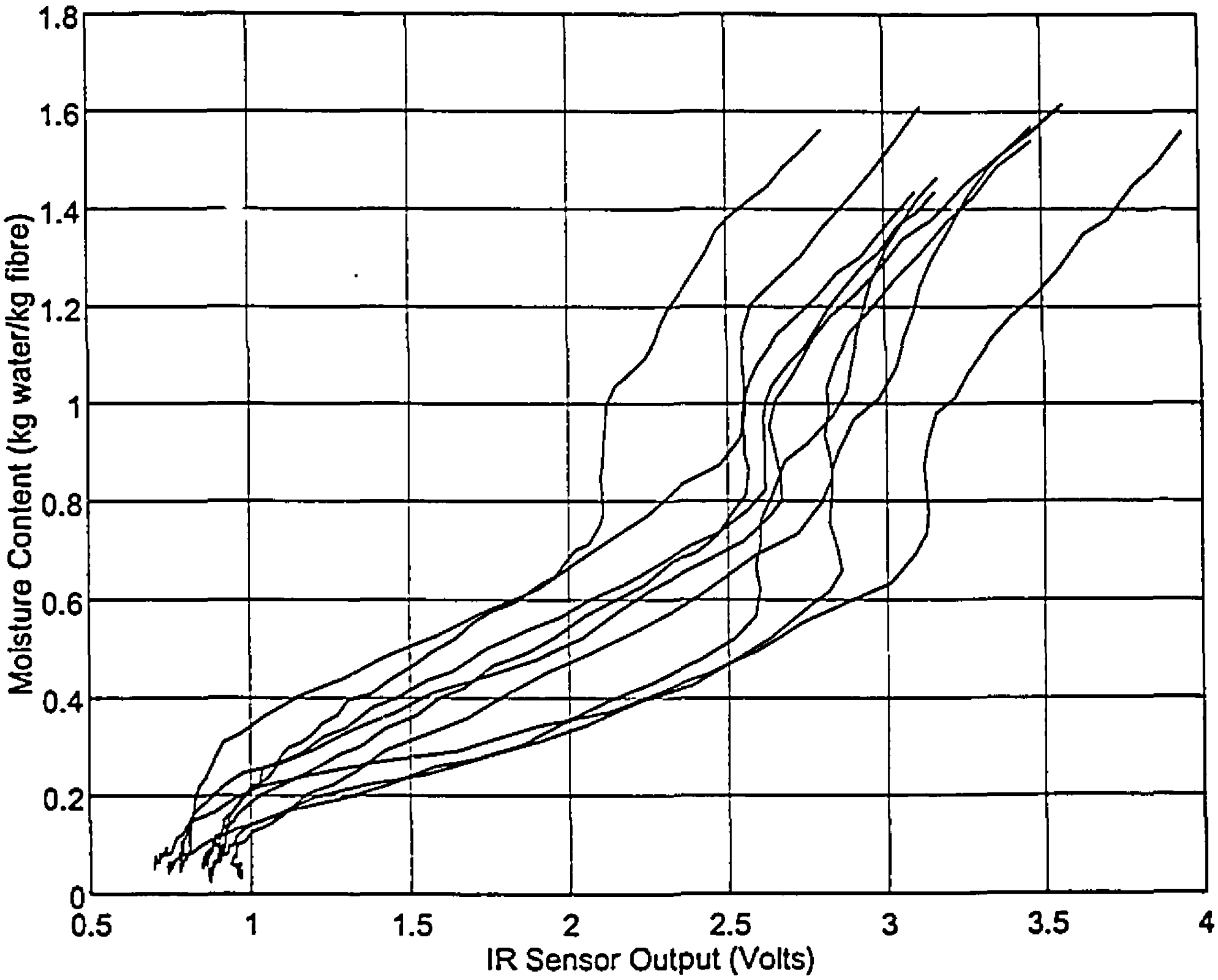


Figure 4.3f Moisture sensor calibration, machine formed paper: sack #11

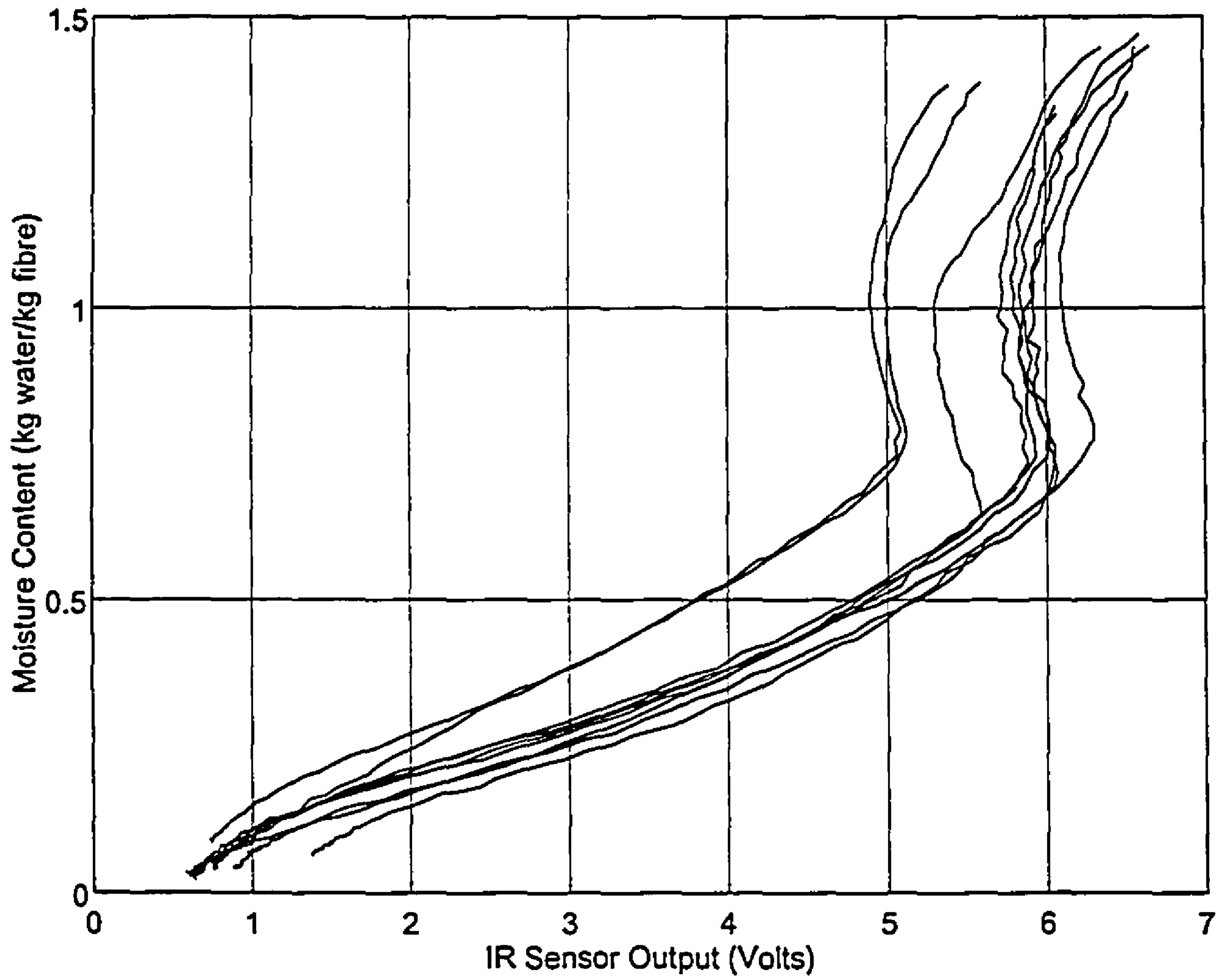
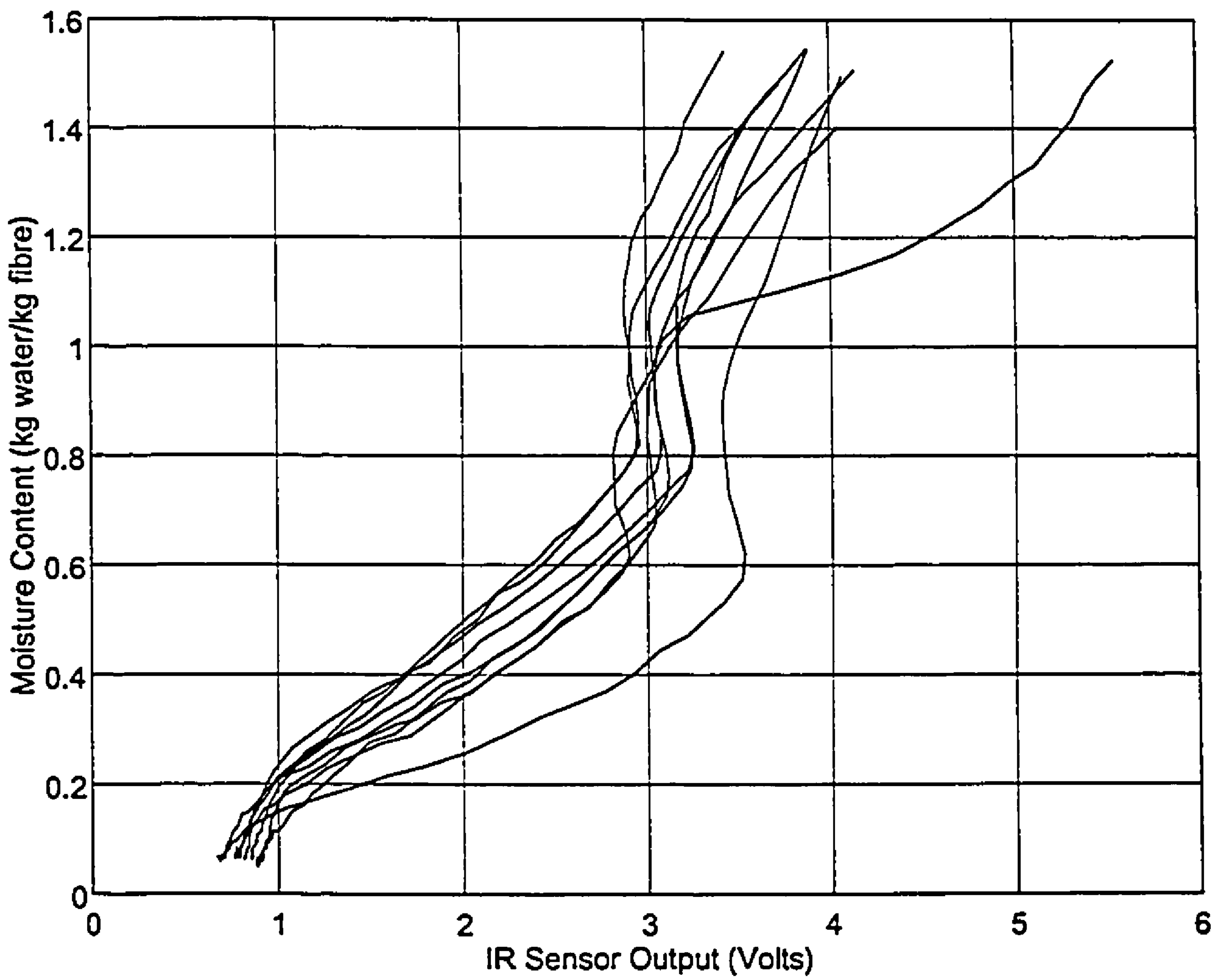


Figure 4.3g Moisture sensor calibration, machine formed paper: sack #13



A general observation is that as moisture content decreases, the IR sensor voltage output decreases, indicating a decrease in IR absorption, i.e. an increase in IR transmittance. This effect is just the opposite of the behaviour with visible light, where as paper drys it becomes more opaque, i.e. a decrease in visible light transmittance. At the highest moisture contents measured the sensor generally displays an almost linear trend with moderate sensitivity. As moisture content decreases to a level of about 1 kg moisture per kg fibre a near vertical section of very low sensitivity begins. At moisture contents below the fibre saturation point the calibration curves level off to give a region of very high sensitivity for the region from the fibre saturation point to dryness.

The basic shape of the curve for TMP handsheets is the same as for kraft handsheets. As can be seen in Figure 4.3b, the minimum sensitivity region starts at a higher moisture content, between 2 and 1.5 kg/kg, and is almost vertical until the moisture content drops to about 1 kg/kg. For moisture contents below about 0.7 kg/kg, the same high sensitivity seen in kraft handsheets applies also for TMP handsheets. The curves for the machine-made papers from pure TMP and from a blended furnish of groundwood/TMP/kraft pulp (TMP #3, BF #1, Figures 4.3c,d) are very similar to those for TMP handsheets. The three sack papers tested also showed similar tendencies, Figures 4.3e..g, but with the intermediate region of minimum sensitivity being even more extreme, sometimes actually with a negative slope. Compared to the other papers, there was significantly less reproducibility between tests on sheets taken from the same paper roll, for example sack #7, Figure 4.3f.

The reason for the insensitivity of the moisture sensor in the intermediate moisture content range is believed due to two related factors, *Fujitechnica, 1994*. The first of these relates to the paper transparency-moisture content dependence. As moisture content decreases below about 2 kg H_2O/kg fibre the transparency of the sheet to wave lengths not absorbed by water begins to decrease substantially until a moisture content in the range of about 0.65 kg/kg (the exact values depends on the paper type). This effect allows less transmittance of the beam as moisture content decreases. The second factor is that the reference wavelengths, which have a low absorbance of IR light by water, react differently to the level of transparency than does the measuring wavelength. As a result, the log ratio of the two does not decrease as much as would be expected for this moisture range, and in some cases, over a narrow range of moisture content, actually increases.

A possible explanation for the fact that the calibration curves for the sack papers are less reproducible relates to the beating of kraft pulps. A pulp becomes fibrillated to a degree proportional to the amount of beating. When the paper is wet the fibrils relax away from the fibres, but when the paper dries the fibrils collapse on the fibres. This effect changes the paper structure, which could affect the passage of the IR beam. The extent of beating is indicated by the freeness of the pulp, with a lower freeness value indicating more beating. The freeness values for S7, S11, and S13 are 357ml, 603ml, and 406ml respectively. Upon inspection one sees that the sack paper with the lowest freeness and hence the greatest degree of beating is S7, the paper which also showed the poorest reproducibility (greatest difference between curves). The next lowest freeness corresponds to S13, which follows after S7 as the least reproducible. Sack paper S11 is from the furnish of minimal beating and has a comparatively high degree of reproducibility.

Besides varying with moisture content, grammage, and furnish, it was found during the preliminary experimental program that the IR sensor output also varied with the temperature of the sheet. It is important to note that the temperature of the IR transmitter and receiver did not effect the reading, as was shown by the fact that the moisture sensor output with no paper inserted did not vary with temperature. For this reason experiments of the type done to calibrate the IR pyrometers were also used to obtain data for the effect of dry paper temperature on the IR moisture sensor output. A further discussion of these experiments is found in the section on experimentation.

For each type of paper, the different calibration curves were compared to their respective local grammages, determined by light transmission image analysis as mentioned earlier. These results showed a consistent trend. For the 6 tests with BF #1 paper for example, in Figure 4.3d, the variation in the voltage output for the same sheet average moisture content is apparent. When this variation is compared with the local grammage values as determined by light transmission image analysis, the curves with lower voltage are seen to correspond exactly with the spots of low local grammage. The consistency between the ranking from low to high local grammage and from low to high moisture sensor voltage is seen for all of the paper types in tables 4.1a..g. There are at least two possible causes for this correlation between the sensor output and local grammage, the first being that the extra fibre in the sensor path is absorbing more of the beam and hence causing a higher voltage. If this were the sole reason, then the difference between the curves would remain constant for all moisture contents, which is not the case. A second possible cause is that the local grammage of water, g/m^2,is proportional to the local grammage of fibre and therefore a region of higher local grammage is also a region of higher local grammage of water which is indicated by the moisture sensor. If this second cause were solely responsible for the effect then for dry paper the sensor would have the same output for all sheets in spite of the variation in local grammage of fibre, which is also not entirely the case. It can therefore be argued that both possible causes contribute to the noted effect.

4.2 Sealing

The test of the apparatus for leakage was of particular significance because all air passing through the critical flow valve and flow meter is assumed to pass through the paper. Any leakage would cause errors in the indicated flow rate and pressure drop, and therefore in the mass balance calculations used for the flow rate through the sheet. In order to test the chamber for leakage, a disk with the thickness and outside diameter of the clamping ring was used to hold a sheet in the paper support. The pressure regulator was set at 40 kPa (the maximum pressure drop across the sheet in any part of the experimental program) and the tray was inserted into the chamber. All joints were tested with soap solution for leaks. All threaded joints, both between pipes and in the drying chamber, were sealed with high temperature pipe thread sealant while all other joints were sealed with high temperature silicone sealant. When all exterior leaks were eliminated it was shown that there was no air leaking around the sheet holder as the flowmeter recorded zero flow.

Table 4.1

Relation between local grammage
and calibration moisture sensor voltage output

a (K1)

B	Volts
10	10,8
8	79
6,11	6,11,13,15
9	
15	
13,7	

b (T1)

B	Volts
3,4	6
6	8
8	3,4
2	5
5	2

c (T3)

B	Volts
4,3	7
7,1,5	3
2,10	1,4
6,8,9	5,2,6,8,10
	9

d (BF1)

B	Volts
6	6
1,9	1,9
2	2,4
4	5
5	

Note:

"B" signifies the order between repeated experiments according to increasing order of the local grammage of the measured spot.

"Volts" signifies the order between repeated experiments according to increasing order of the voltage output of the IR moisture sensor at the same spot.

e (S7)

B	Volts
7	7
10,12	13
13,8,6	5
5	6,8
9	12
	10
	9

f(S11)

B	Volts
1	1
3	3
2	2
5,4	6
6,9	7,5,10,4
7	9
10	

g (S13)

B	Volts
1	8,5
7,8	6
6	7
4	1?
5,2	4
3	2,9
9	3

Note:

"B" signifies the order between repeated experiments according to increasing order of the local grammage of the measured spot.

"Volts" signifies the order between repeated experiments according to increasing order of the voltage output of the IR moisture sensor at the same spot.

4.3 Experimentation

4.3.1 IR Spot Location

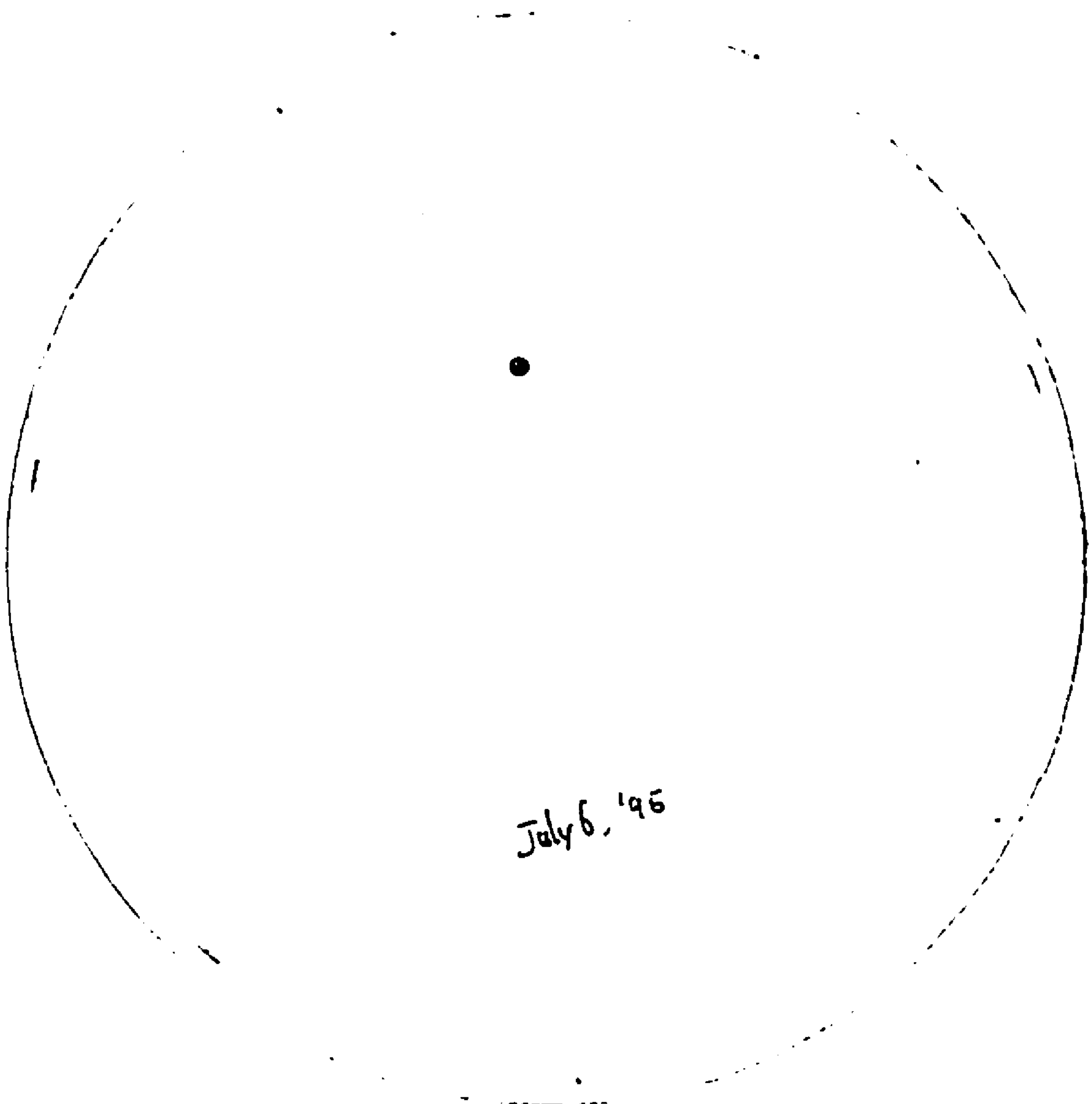
In order to determine the local grammage of the 2.5 mm diameter spot where the IR moisture sensor was focused the precise location of the spot must be known. The sensitivity of standard photographic paper to the moisture sensor IR beam enabled a simple and precise location of this spot. Thus, a black-out hood was sewn to cover the insertion-retraction tray and the side of the drying chamber with the slot for this tray (see Figure 4.4). Photographic paper placed in the sheet holder provided an image of the exact spot position. The use of three guide lines on the sheet holder enabled fixing the radial orientation of the photographic paper during its exposure to the IR beam and to mark the position of each sheet of paper tested, as shown in Figure 4.5.

4.3.2 Experimental Technique

At the start of every experimental session the electronics were allowed to warm up and the apparatus was brought up to temperature. Especially at higher temperature conditions, air flows of 1.2 kg/m^{2}s, up to six times those used during the experiments, were used in order to reach and maintain the desired temperature against heat losses to the surroundings. For operation at 300°C approximately one hour was required to achieve a steady operating temperature. The sheet to be dried was wetted as described for the calibration runs. After being placed in the sheet holder while resting on a balance, this sheet was allowed to dry until the mass indicated that the desired initial moisture content had been reached. The critical valve was adjusted for the desired mass flow rate of air, the sheet holder placed in the insertion-retraction tray, the relay to insert the tray was activated, the time was set to zero and the experiment began. The data acquisition system sampled at the set frequency until the time elapsed was the pre-set experiment length. The relay to retract the sheet holder tray then activated automatically and the data was saved to a file. The sheet holder was removed from the tray immediately upon retraction and the final mass determined before the paper absorbed any measurable moisture from the air. The paper was marked to show its radial orientation in the sheet holder before being removed to an oven at 105°C for eight hours for

Figure 4.4 Black-out hood

Figure 4.5 Location of IR moisture sensing spot on photographic paper



determination of the mass of dry fibre. The sheet holder, heated while in the drying chamber, was placed in a freezer for a short time to return it quickly to room temperature so it was not a heat source to dry the paper. Between drying experiments the air flow to the drying chamber was returned to the high level noted above by re-opening the valve, thus maintaining the apparatus at the desired temperature. After being oven dried and weighed the sheets were transferred to our light transmission image analysis laboratory for determination of the local grammage of the specific 2.5mm diameter area that had been monitored by the IR moisture sensor.

5 Results

5.1 Experimental Plan

The seven diverse types of paper studied were selected to give a range of papers which would test the capabilities of the apparatus. For the initial study it was decided not to include grades for which through-drying is currently used in industry but instead to study those which may have the potential to be so dried in future. Accordingly, two printing papers were selected, one made from pure TMP, the other a blended furnish of groundwood-TMP-semi-bleached kraft pulps. Sack paper, a grade made largely or entirely from kraft pulp without filler and therefore of high permeability, was included as a grade for which through drying might be applicable. Thus three kraft sack papers were chosen, covering a range of grammage, B, from 47 to 100 g/m^2, with a range of permeabilities. In order to compare this work with that of previous researchers, handsheets from two furnishes were also used, one from pure unbeaten kraft and the other from re-slushed TMP newsprint. The relevant properties, including the fibre saturation point moisture content, FSP, kg water/kg fibre, and the designations used for these papers can be found in Table 5.1.

Table 5.1

Specifications of the types of test papers

Paper	B g/m²	FSP kg/kg	Freeness ml	Furnish
Kraft Handsheet (K1)	60	0.8	685	100% kraft
TMP Handsheet (T1)	60	0.72		100% TMP
Papermachine TMP Paper #3 (T3)	47.5	0.64	188	100% TMP
Papermachine Blended Furnish Paper #1 (BF1)	44.2	0.65	272	35% TMP,59% GWD,8% SBK
Papermachine Sack Paper #7 (S7)	47	0.88	357	kraft
Papermachine Sack Paper #11 (S11)	100	0.99	603	kraft
Papermachine Sack Paper #13 (S13)	55	0.87	406	kraft

During the experimental program the seven types of paper were dried in air of three temperature levels. Seventeen combinations of paper type and drying air temperature were tested. For each of these 17 combinations, paper was dried from three initial moisture contents, i.e. the fibre saturation point, FSP, and 25% above and below this value, 0.75 FSP and 1.25 FSP. For each of the experimental conditions, the through flow rate was set so the pressure drop across the wet sheet at its initial moisture content was no greater than 40kPa, a value above which it would not be economic to operate in industry. The conditions used for the 125 successful through drying experiments are given in Table 5.2. Information on the local non-uniformity of drying was provided by multiple experiments under the same conditions, as the IR sensing spot for each experiment provides an independent record of the drying history for a small element of that type of sheet dried under the specific conditions.

Table 5.2

Number of experiments performed

Air Temp. °C	Initial Moisture Content	Paper Type						
		K1	T1	T3	BF1	S7	S11	S13
90	0.75 FSP	2	1	1	1	2	2	-
90	FSP	4	1	2	3	2	2	-
90	1.25 FSP	4	1	1	2	2	2	-
200	0.75 FSP	-	3	3	2	2	-	3
200	FSP	-	3	3	2	3	-	3
200	1.25 FSP	-	2	3	2	2	-	2
300	0.75 FSP	1	-	1	1	1	1	1
300	FSP	7	-	6	7	6	7	7
300	1.25 FSP	1	-	1	1	1	1	1

5.2 Observations

5.2.1 Local Grammage

Light transmission image analysis was used with the dried paper to determine the local grammage at the precise location of the 2.5 mm diameter area that had been monitored by the IR moisture sensor. For each of the seven types of paper used, the correlation between these values of local grammage of fibres and the voltage-drying time curves of the IR moisture sensor were examined, as was done for the sensor calibration runs. As the drying runs were started at different moisture contents and air temperatures, the only runs which had sufficient curves for such a comparison were for the six types of paper dried in 300°C air from the FSP initial moisture content, each of which are documented by six or seven replicate drying experiments.

Due to variability in sheet formation between the kraft handsheets, this type of paper had to be excluded from this aspect of the study, leaving five types of paper for comparison, as seen in Tables 5.3a..e. It was found that sack paper #7 did not show a correlation between sensor output and grammage of the sensing area, as was likewise the case for this type of paper for the IR moisture sensor calibrations. Therefore sack paper #7 was not studied further. TMP paper #3 also did not show a sensor output-grammage correlation, contrary to the very good correlation shown during the calibration runs. This single inconsistency between the results during sensor calibration and those during a drying experiment is probably because for drying in 300°C air the control of drying time was very difficult. Drying the paper a fraction of a second too long caused slight scorching on the sheet top surface, in some cases even when the paper was removed before drying was complete. The change in colour associated with such scorching caused errors in determining the local grammage by the light transmission analysis technique. Even with this problem, however, conclusions may be drawn from experiments with this paper type because in the original IR sensor calibration all curves at various local grammages were very close, i.e. the sensor sensitivity to local grammage was small for this type of paper. Thus, even if the moisture content is displaced somewhat from the true value the calibration curves are still accurate qualitatively. Slight scorching of the paper did not appear to affect the output of the moisture sensor in any way, as indicated by curves 2, 3, and 4 in Figure 5.1 which all show the same value for the dry paper although different extents of scorching occurred. This very good characteristic of the moisture sensor might derive from its use of three wavelengths. In spite of the various difficulties noted above, the remaining three types, TMP 6 paper and sack papers 11 and 13, all showed an excellent correlation between local grammage and moisture sensor output. This finding, involving 21 IR sensor output curves, establishes that for these three papers at least, it is possible to use light transmission image analysis to relate IR moisture sensor data from a drying experiment to the calibration curve for the appropriate value of local grammage of the spot used for moisture sensing during drying.

An even more significant observation can be made by comparing the results for sack paper #11 in Table 5.3b with the moisture sensor output-time graph for those drying experiments, shown in Figure 5.2. The correlation in Table 5.3 shows that what might

Figure 5.1 Drying of TMP #3 paper: six experiments

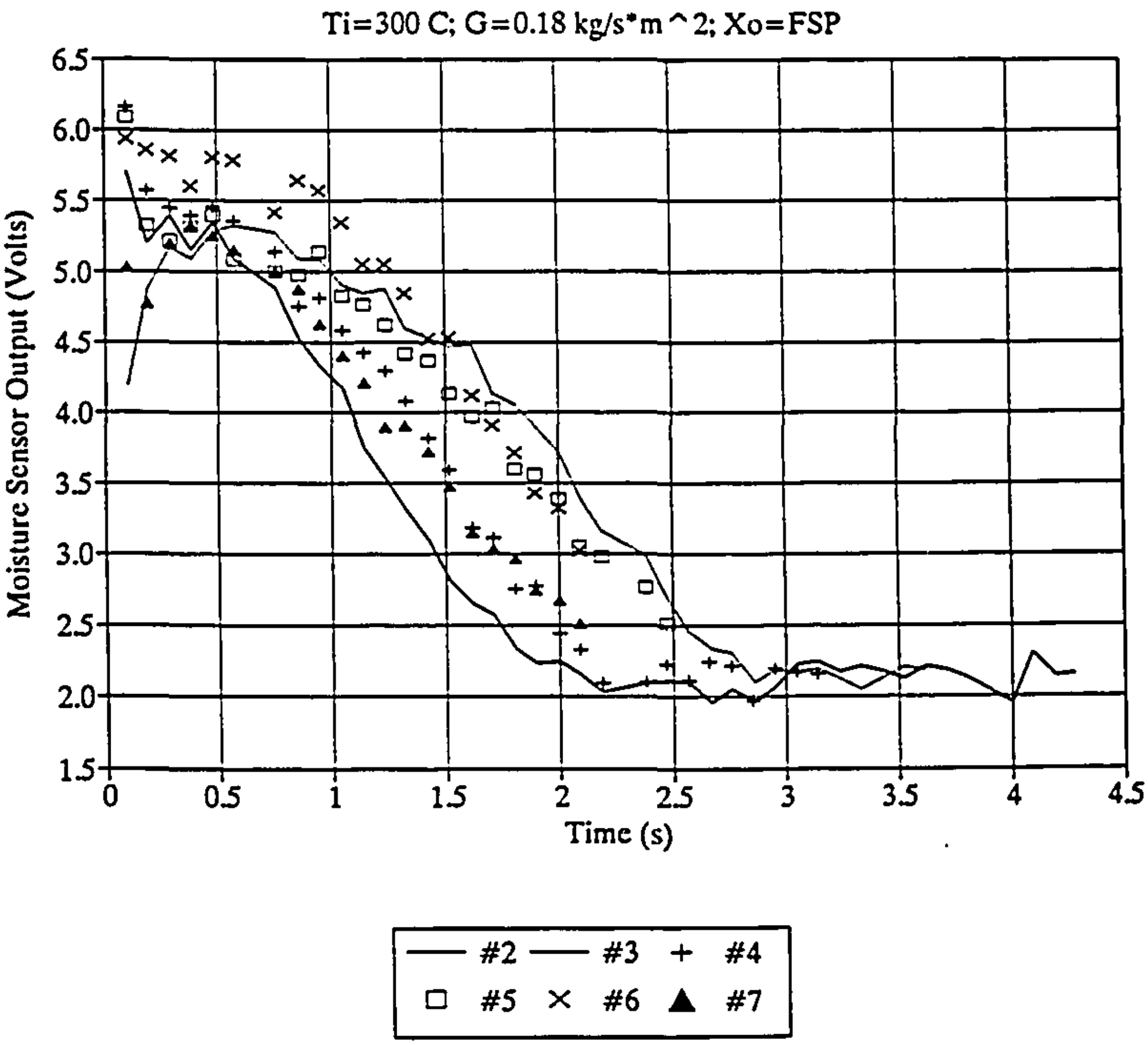


Table 5.3

Relation between local grammage and moisture sensor voltage output

a (Paper S7)

B	Volts
4	3
5	1
3	7
1,7	6
6	5
	4

b (Paper S11)

B	Volts
3	3
7	7
4	2
2	4
8	6
6	8

c (Paper S13)

B	Volts
7	1
4	7
5	4
1	5
3	2
2	3

d (Paper T3)

B	Volts
3	2
5	7
7	4
6	5
4	6
2	3

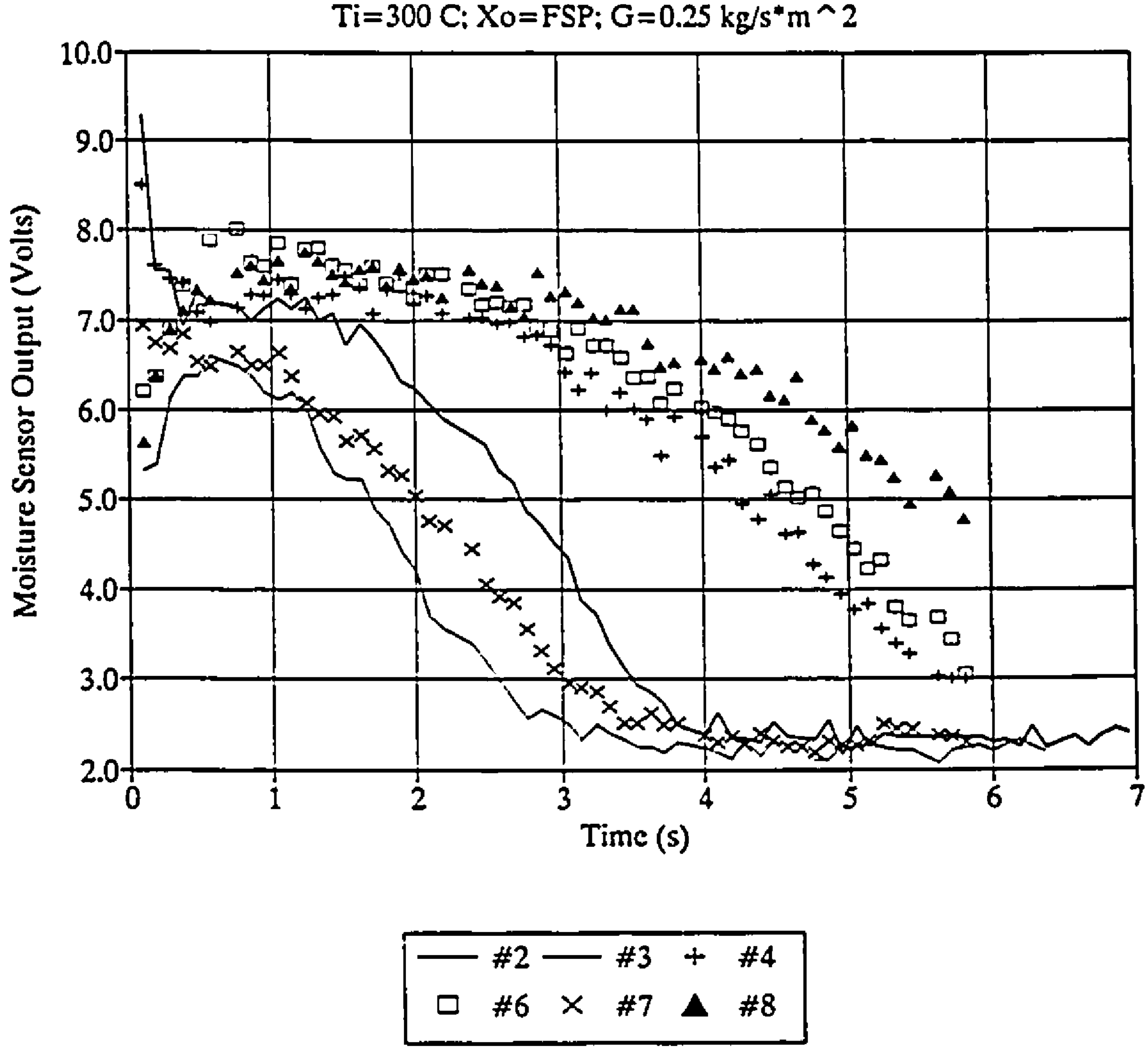
e (Paper BF1)

B	Volts
1,6	1
7	7
5,2	2
8	5,8,6

Note: "B" signifies the order between repeated experiments according to increasing order of the local grammage of the measured spot.

"Volts" signifies the order between repeated experiments according to increasing order of the voltage output of the IR moisture sensor at the same spot.

Figure 5.2 Drying of sack paper #11: six experiments



have appeared to be massive scatter in the curves in Figure 5.2 is in fact unique and striking experimental evidence of the non-uniformity of the high intensity through drying under these conditions and for this machine-formed paper! This documentation of the fact that areas of locally high grammage take significantly longer to dry than areas of locally low grammage, in this case over 6s versus 3s, demonstrates the experimental facility's impressive capability to document local non-uniformity in through drying.

5.2.2 Wire Marking

Wire marking was evident in these laboratory through drying experiments. The most noticeable wire marking was due not to the wire mesh in contact with the sheet but to the honeycomb beneath the wire. The wire mesh evidently deformed to match the shape of the honeycomb, and the paper was marked by these honeycomb-shaped ridges. The extent of wire marking was affected by four factors, the most significant being initial moisture content. When the sheet was put into the chamber dry for the temperature calibration runs, there was no wire marking for any of the types except paper T1. The next most significant factor was drying air temperature. In all of the papers dried, the amount of wire marking increased significantly with temperature, even when the flow rate was lowered in an attempt to prevent the marking. Other factors which appeared to have an effect are grammage and furnish. For sheets of different grammage but similar furnish dried in the same temperature of air, sheets of higher grammage showed less wire marking. This effect was most noticeable for paper S11, the 100g/m^2 sack paper, where even at 300°C there was little wire marking. The last factor observed is furnish, most evident when comparing the 60 g/m^2 kraft and TMP handsheets, where wire marking was minimal with the kraft paper but was significant for the TMP paper. This observation must be offset, however, by comparing the 47.5 g/m^2 pure TMP T3 paper with the 47 g/m^2 S7 sack paper, where the wire marking was similar for sheets dried from the same initial moisture content in the same temperature of air. An obvious factor affecting wire marking that is not studied here is the pressure drop across the sheet. This factor was not investigated because the flow rate, which determines the pressure drop, was not used as an independent variable. It should be recognized, however, that the pressure drop is the driving force causing the wire marking, and the other factors simply serve to modify the effect.

Most of these observations can be explained by one physical phenomenon: softening of lignin at temperatures above its glass transition point. This paper characteristic explains the increased marking with increased temperature, since for the dry (0.001 kg H_2O / kg air) air used the adiabatic saturation temperature for 90°C is 30.8°C while it is 50.2°C and 62.6°C for dry air temperatures of 200°C and 300°C. Since the glass transition temperature for wet cellulose is higher than that of wet lignin this also explains the difference between the kraft and TMP handsheets, as kraft paper lacks the lignin that is present in the TMP. The lack of difference between the machine-formed TMP and sack papers may be explained by the fact that although the exact furnish of the sack paper is unknown, it has a certain recycled content, which may include some lignin containing pulp. The final factor that appears to affect wire marking is grammage. A simple and plausible explanation for this is that for the same pressure drop across the sheet, the heavy paper has more mechanical strength to withstand the forces placed upon it. It is important to note that no wire marking from the mesh was observed. Thus, if the wire mesh were simply held under sufficient tension in a paper machine to minimize flexing wire marking should be eliminated even under the very high level of pressure drop tested, 40kPa. In the test equipment the wire mesh was under no tension.

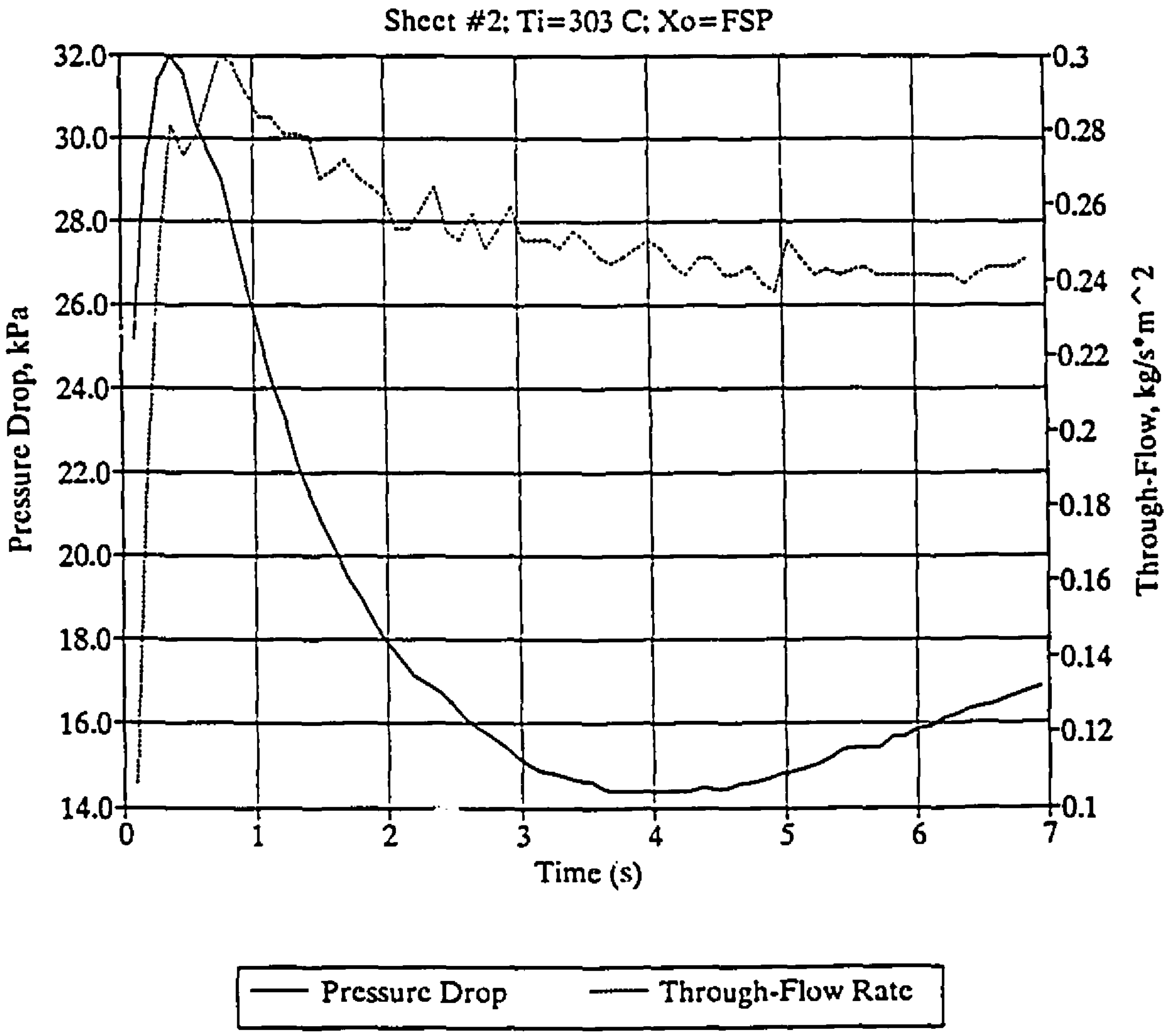
5.2.3 Through-Flow Rate

A fundamental problem in any study of through drying of paper is how the experimental design accommodates to the substantial increase in sheet permeability, and hence in the through flow rate-pressure drop relationship as the sheet goes from wet to dry. Some studies did not hold either variable completely constant during drying, while most of the early studies used equipment giving constant pressure drop and hence variable through-flow rate, which provides results which are difficult to interpret because all transport phenomena involved vary with the through flow. This apparatus uses the same design principle as that of Polat, 1989, to maintain constant flow through the sheet from wet to dry. As detailed in Appendix A-1, this is accomplished by having a critical flow valve in the air supply line to the drying chamber, and supplying the air upstream of this valve at a constant pressure at least double that downstream of the critical flow valve.

Although the use of critical flow across a restriction achieves a constant mass flow rate through the valve and into the drying chamber, the flow rate of interest is that through the sheet. At steady state these two flow rates are equal, but during the transient conditions experienced upon insertion of the sheet this is not the case. At the instant the sheet is inserted through the slot in the side of the drying chamber, the pressure in the chamber and the piping downstream of the critical valve is atmospheric. With the sheet inserted this system pressure then increases until a constant value is reached, at which point the flow rate through the sheet equals that through the critical flow valve. For past researchers investigating through air drying under low intensity conditions this transient time, which is a function of system volume, sheet permeability and air temperature, has not been a significant fraction of the total drying time. In the present high intensity through drying apparatus, however, with the very low drying times and an increased chamber volume to incorporate the moisture sensor, the period of transient flow becomes a substantial portion of the total drying time. Moreover, previous researchers, *Polat, 1989*, and *Chen, 1994*, could calculate the transient time assuming a constant value of paper permeability because paper moisture content did not change significantly during the transient period. For the present study one should use transient permeability values, which can only be calculated from the experimental data.

As both the drying chamber pressure and the flow through the sheet are required to calculate permeability, and the flow itself yields the actual transient time, it proves unnecessary to calculate the theoretical transient time. Thus, the actual transient time can be determined by calculating the true flow through the sheet and noting when it reaches a satisfactory approach to steady state. The flow is calculated by using the absolute pressure and temperature of the air in the drying chamber, which are measured, the volume between the critical valve and the sheet, which is known, and the law of conservation of mass. For the case of sack paper #11 dried in 300°C air, Figure 5.3

Figure 5.3 Drying of sack paper #11: pressure drop and flow rate



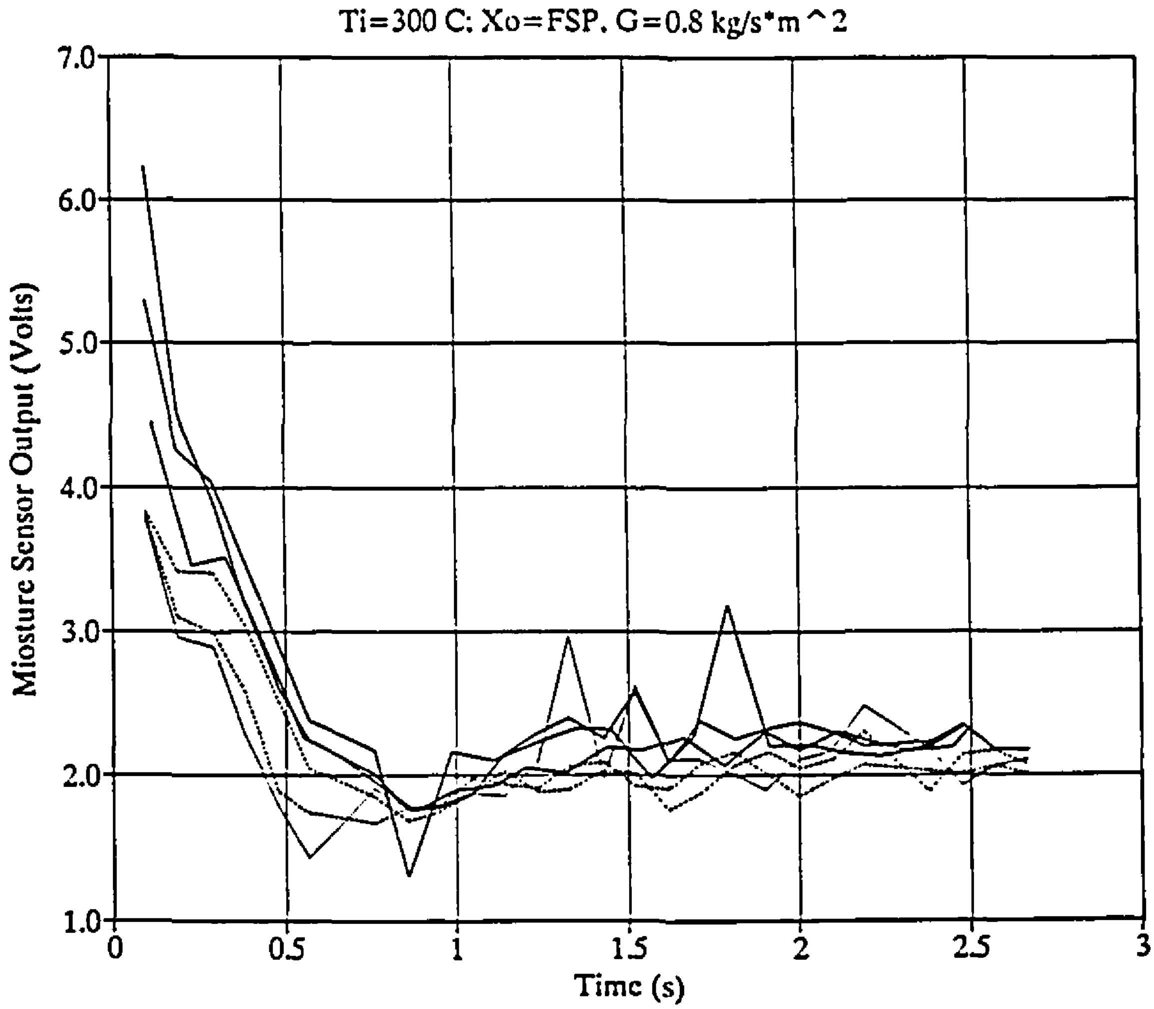
shows the results of such a through flow rate calculation. In the case of kraft handsheets dried in 300°C the entire drying is completed while the pressure is building up in the drying chamber, because at the higher through flow rate used for this very permeable paper, drying is complete in less than 1s, as shown in Figure 5.4 by the moisture sensor voltage output for six runs.

5.3 On-line Determination of Local Moisture Content

The most significant parameter in drying, sheet moisture content, must be determined with particular care. As noted earlier, the IR moisture sensor is sensitive to temperature and local grammage as well as to moisture content. The problem of sensitivity to local grammage of the sensing area is addressed by measuring, after the experiment, the grammage of the exact 2.5mm diameter sensing spot and using the calibration curve for the most similar grammage. The problem of temperature sensitivity, however, provides a greater challenge. The problem stems from the fact that for the same paper dry, the moisture sensor reading varies with paper temperature. Although the sensor output varies with paper type, the trend is always the same. As the temperature of the dry paper increases, the sensor output drops, sometimes below zero, then levels off. For the specific case of TMP #3 paper, Figure 5.5 shows that the sensor output levels out when paper temperature reaches about 65°C. Paper temperature measurements taken during drying experiments indicate that the sensor voltage begins to increase again by 200°C, and by 300°C it is generally over twice the output at room temperature.

Two methods of eliminating this temperature effect were tried. The first method, referred to as the voltage difference method, is based upon the observation that the difference between voltage output for the initial moisture content and the dry sheet is very similar for tests at different temperatures but the same initial moisture content. It could be hypothesized that the temperature effect on the IR sensor voltage output during the drying of a sheet is simply an offset from the voltages obtained during the room temperature calibration of the sensor. Using this reasoning, a voltage value equivalent to zero moisture content was assigned for the experimental run and for the calibration

Figure 5.4 Drying of kraft handsheets: six experiments



curve whose grammage was closest to that of the sensing area during the drying experiment. These values were subtracted from their respective curves to give differenced voltage curves. The values of moisture content during the drying run were determined by table look-up from the calibration with the corresponding value of local grammage. Linear interpolation was used between points. These values of moisture content were then plotted versus time to give X-t curves.

The second method of removing the effect of temperature is based on the pyrometer calibration experiments where the temperature of a dry sheet was varied, and is referred to as the dry temperature method. As the moisture sensor voltage became negative for many experiments when the pyrometer indicated paper temperature to be in the range of 50 to 100°C, and the data acquisition card is limited to positive voltages, only a limited number of these experiments are useful. The best of these tests with dry paper is the one performed on paper T3, where the air temperature leaving the sheet reaches 125°C and the moisture sensor voltage varies from 0.8 to 0.2 volts, as seen in Figure 5.5. In this case, the difference between the voltage for the dry sheet at room temperature and the dry sheet at the actual temperature (eg. 0.8-0.5 = 0.3 volts at 40°C) is added to each value of the moisture sensor voltage during the drying experiment. Once again the moisture content as determined by this method provides the X-t history for drying experiments. The X-t curves of the two methods are plotted in Figure 5.6.

It is particularly reassuring that there is no significant difference between the two curves. This good agreement suggests that there is justification to both methods. As the dry temperature based method cannot be used for cases where the temperature is above that at which the paper would burn in the dry paper test, nor for cases when the moisture sensor output voltage is negative, the voltage difference method was adopted for all further investigation.

It is apparent from the X-t curves of Figure 5.6 that the first few values of moisture content are significantly higher than the initial moisture content as determined gravimetrically for the paper when the sheet holder is placed in the insertion-retraction tray. In other drying experiments the first few values of moisture content were significantly lower than the correct value. However, as these early values of moisture

Figure 5.5 Dry sheet temperature calibration

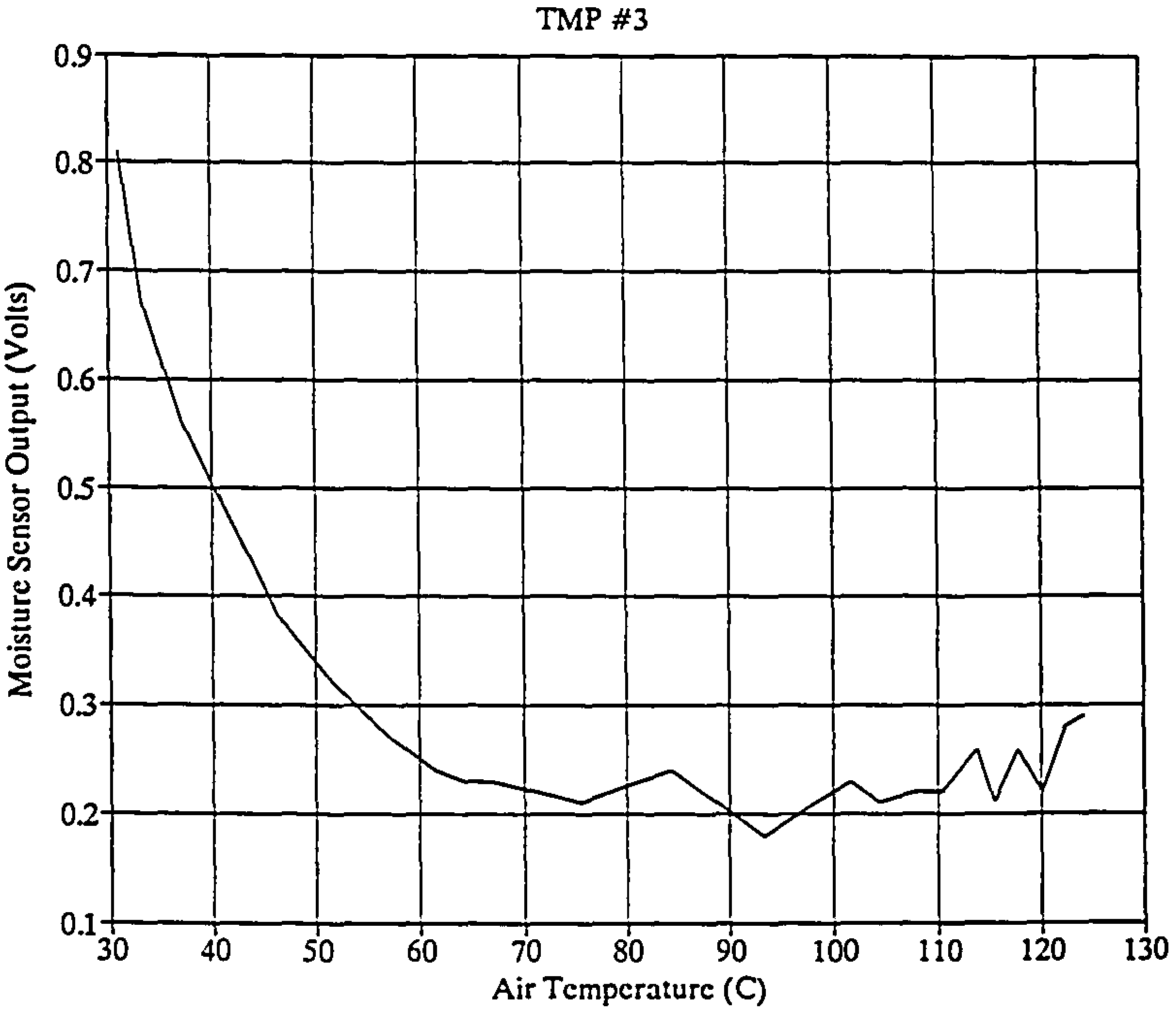
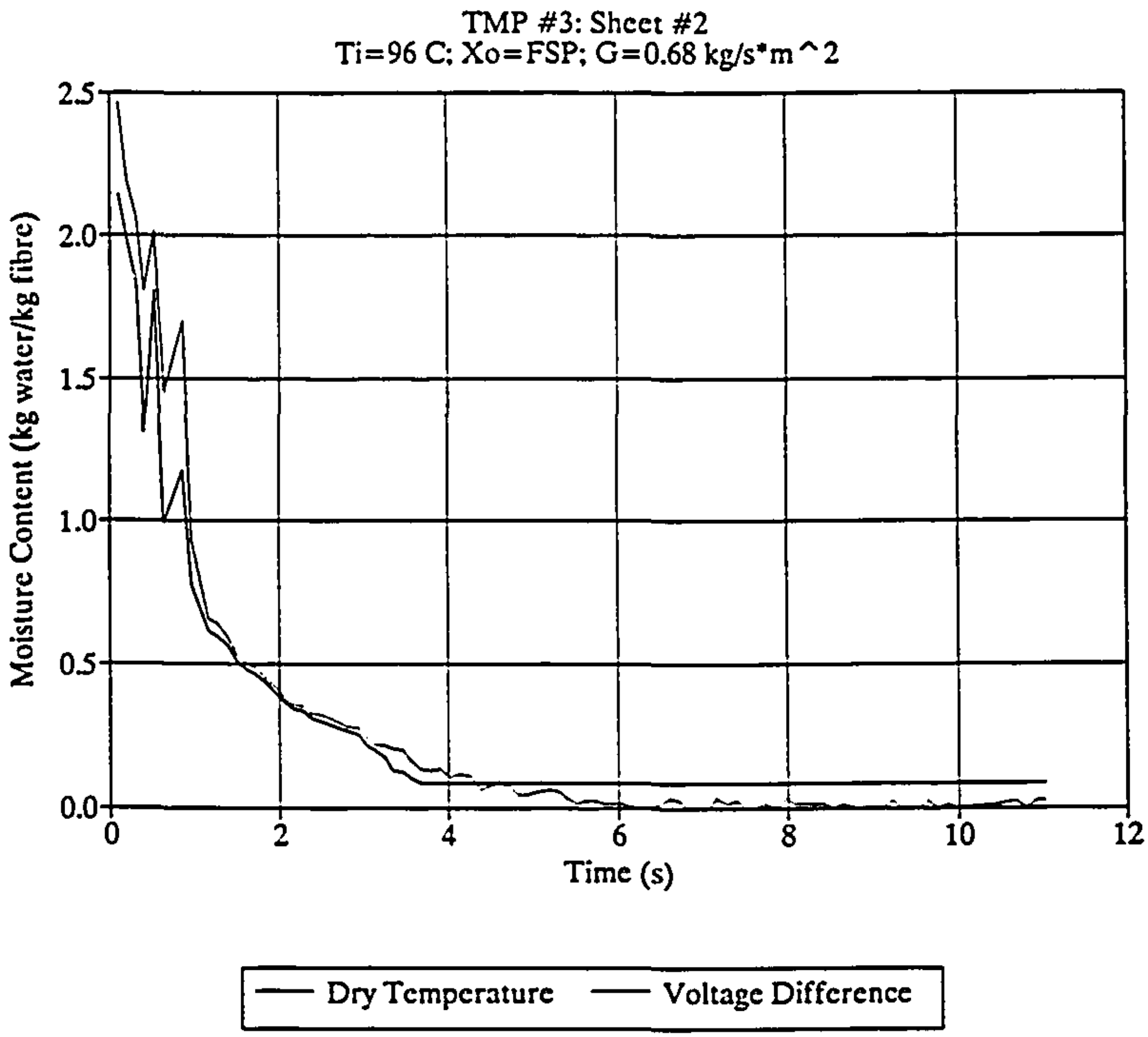


Figure 5.6 Comparison of calculation methods for moisture content



content are in the insensitive range of the moisture sensor calibration curves, Figures 4.3a to 4.3g, these values are not reliable. With these points removed, another problem is that it appears to take some short period after the experiment starts before the paper begins to dry. This effect is due to time zero being established when the key on the computer is struck. Subsequent to that moment the paper is not inserted into the chamber until the solenoid valve on the compressed air supply has been activated, the compressed air entered the cylinder, and this pressure is built up sufficiently that the insertion-retraction tray is moved into the chamber. This entire procedure is estimated to take approximately 0.25s.

One of the most informative curves to describe drying history is that of drying rate vs. paper moisture content. Thus the drying rate, R, was calculated from the moisture content-time data. Drying rate, kg water/m^{2}s, is the absolute value of the time derivative of sheet moisture content, kg water/kg fibre, multiplied by the grammage, kg fibre/m^2, i.e.

$$R=-B\frac{\partial X}{\partial t}$$

Although this derivative might be approximated by using differences from the raw data, the noise in the moisture sensor output makes this an unsatisfactory option. Two other methods are considered, statistical modelling of the X-t data followed by calculation of the exact derivative, and smoothing of the X-t data followed by numerical differentiation. As a test both methods were performed for an experiment on sack paper #11 with X_o = FSP, T_i = 303°C, and G = 0.25kg/m^{2}s. It is important to note that both the statistical and numerical methods were performed without using the first few X-t data points as these fall in the insensitive range of the moisture sensor, as noted above.

For the modelling of the X-t data a power law function was fitted:

$$X= 1.174 * 0.414^{t}$$

The experimental and the modeled moisture content-time curves are shown in Figure 5.7, while the resultant drying rate curve is shown in Figure 5.8a. When the model is evaluated at t=0.1s, it gives an initial moisture content of X_o = 1.07 kg/kg, exactly the

Figure 5.7 Two methods of treating experimental X-t data

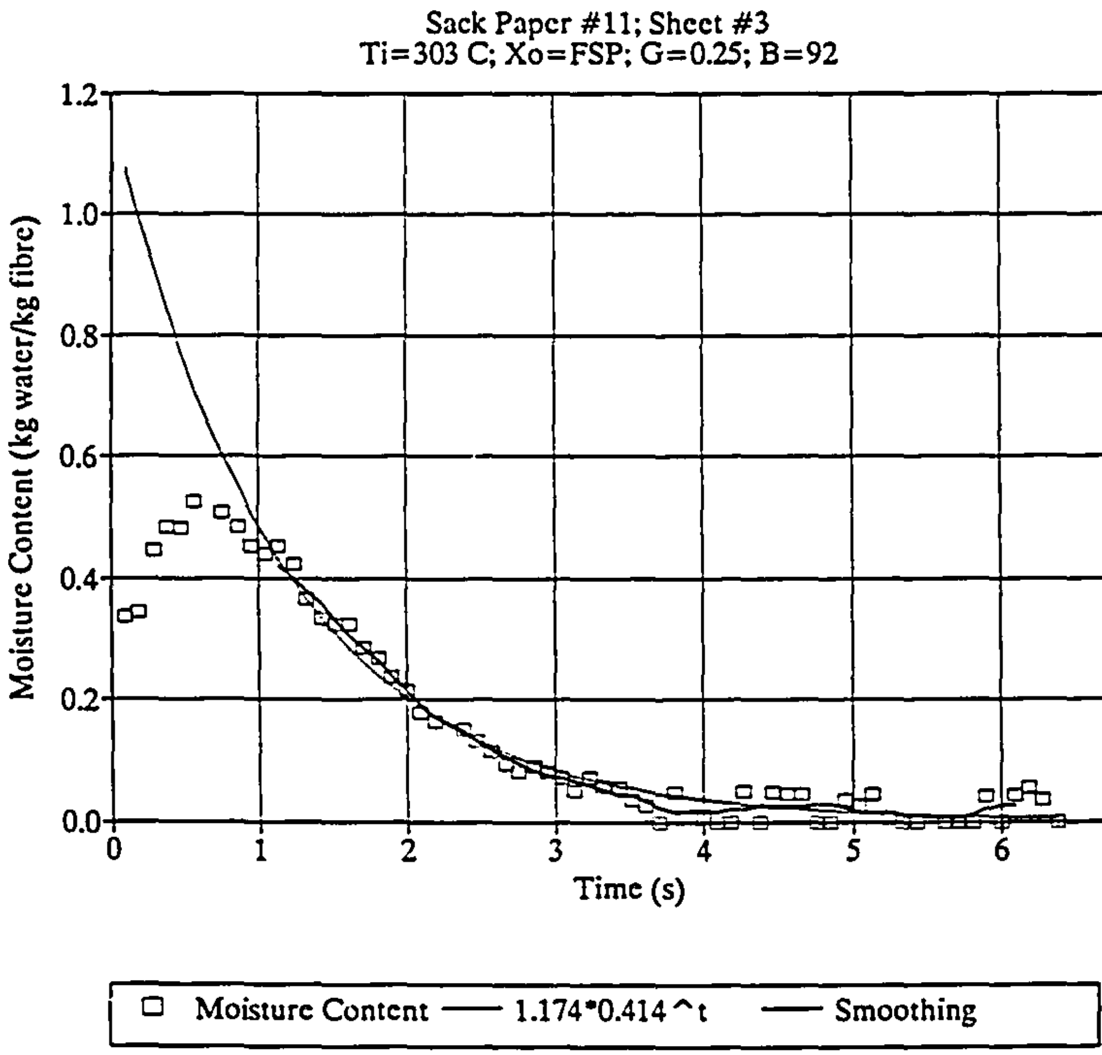
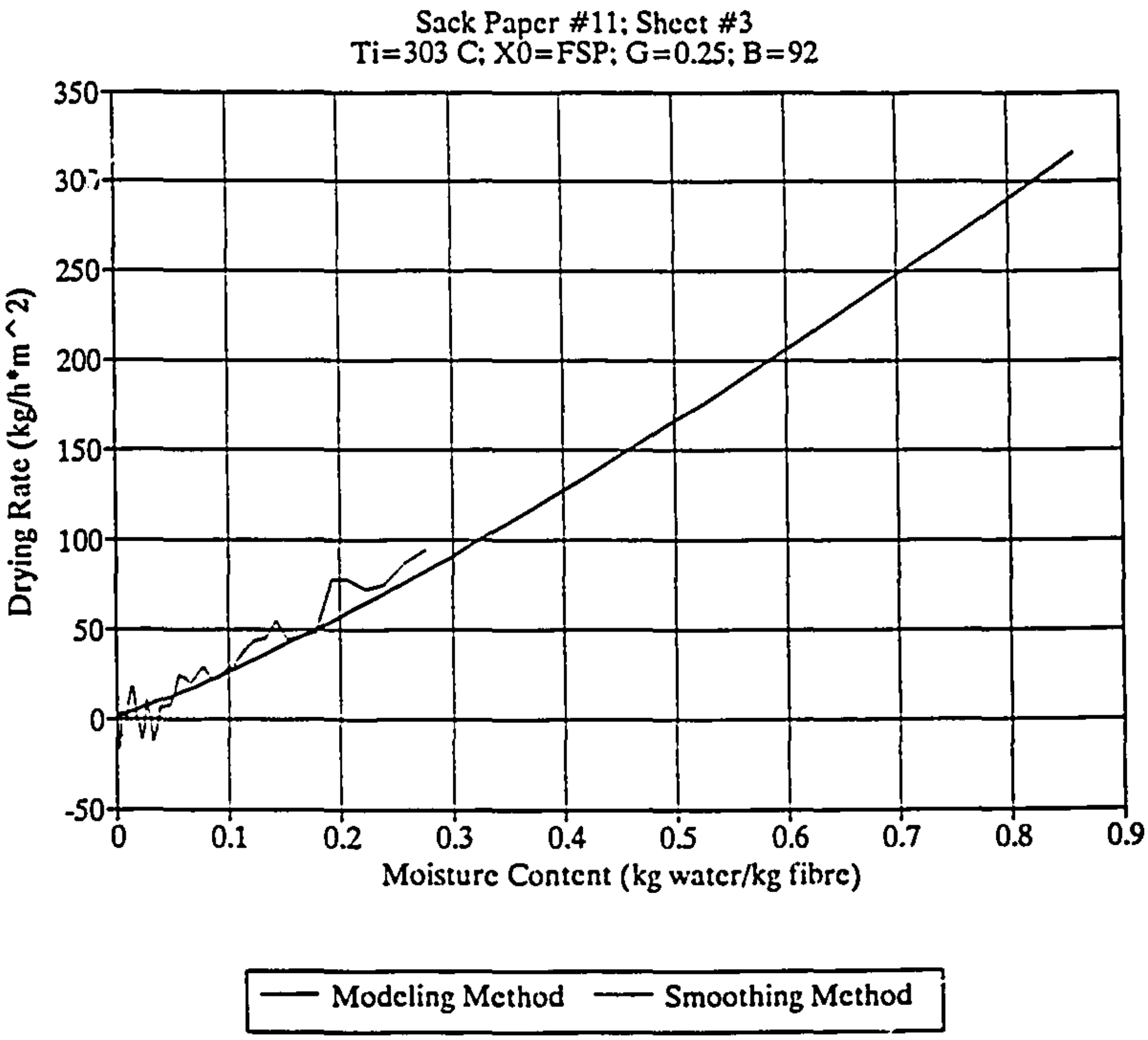


Figure 5.8a Comparison of drying rate calculation methods



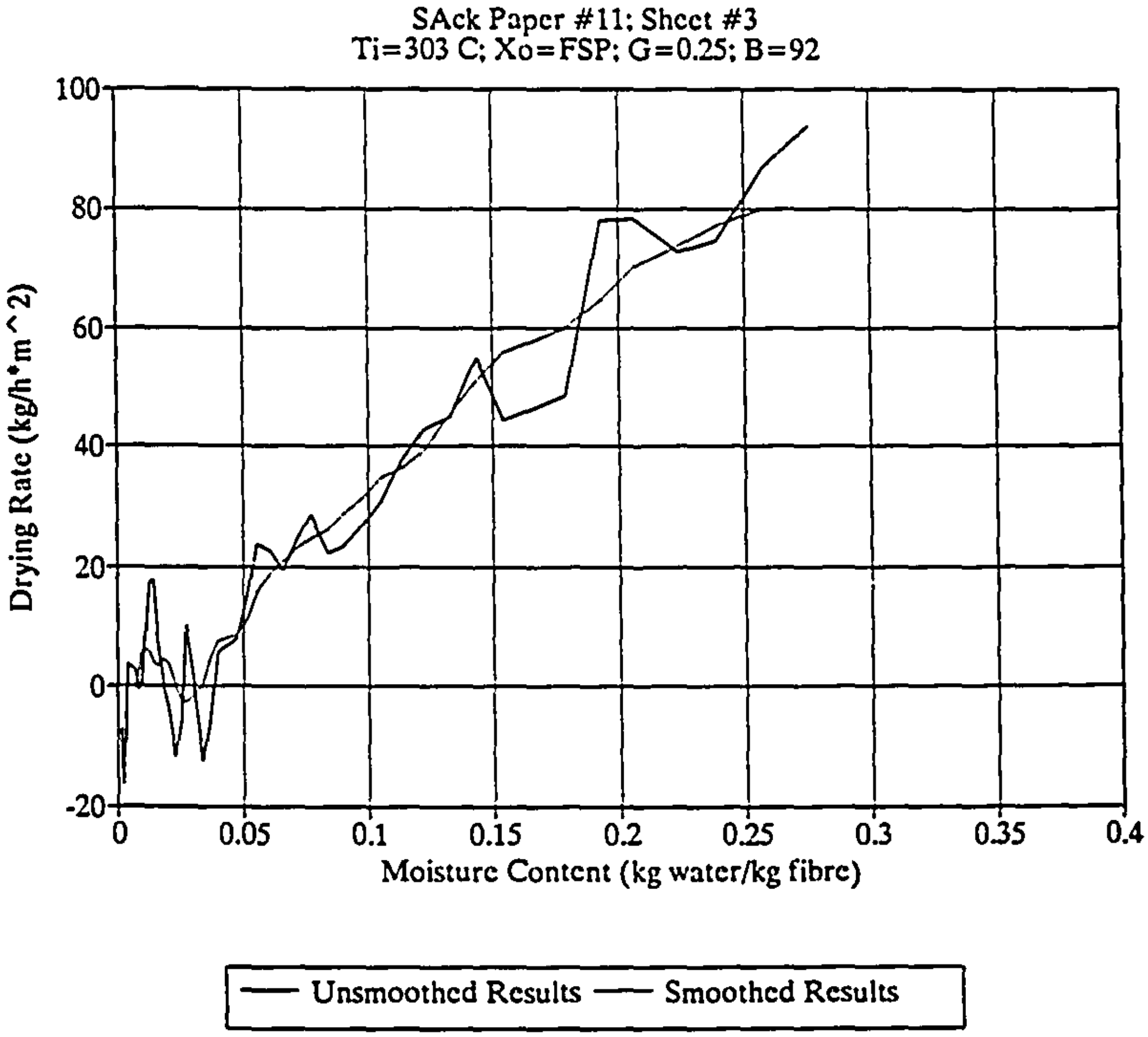
same as the value determined gravimetrically.

The R-X drying rate curve shows that, as expected for these conditions of high intensity drying, the entire drying history is during the falling rate period of drying. The drying rate begins at 320 kg/m^{2}h and falls almost linearly with sheet moisture content until the paper is dry.

To calculate the drying rate using numerical differentiation in the second method, the X-t data were first smoothed using a seven point moving average algorithm, which necessarily eliminates data points from the end of the curve. This can be seen in Figure 5.7, and in the resulting drying rate curve of Figure 5.8a, where the curve shows the same shape as the previous method.

The differences between these two curves are now discussed. The jagged nature of the curve produced by the numerical differentiation, the result of the noise in the original data, can be removed by smoothing the drying rate values, as seen in Figure 5.8b. Once again the removal of data points from the end of the curve, a draw-back of this method, eliminates having a drying rate for the higher moisture content region. Conversely, by modelling the X-t data and then differentiating the model, the drying rate may be estimated for those moisture contents which fall in the insensitive range of the IR moisture sensor. The obvious disadvantage of the X-t modelling method is that there can be no assurance that the model accurately describes the X-t curve in the low time, high moisture content region where reliable experimental data cannot be obtained. Since small changes in the slope have a large effect on the rate, the final rate curve will not necessarily display the correct shape. However because the R-X curve is derived from the X-t curve the R-X curve therefore automatically satisfies the constraint that a drying time calculated from the R-X curve will correspond to the actual measured X-t curve to within the accuracy of the original measurements.

Figure 5.8b Smoothing of drying rate from numerical differentiation

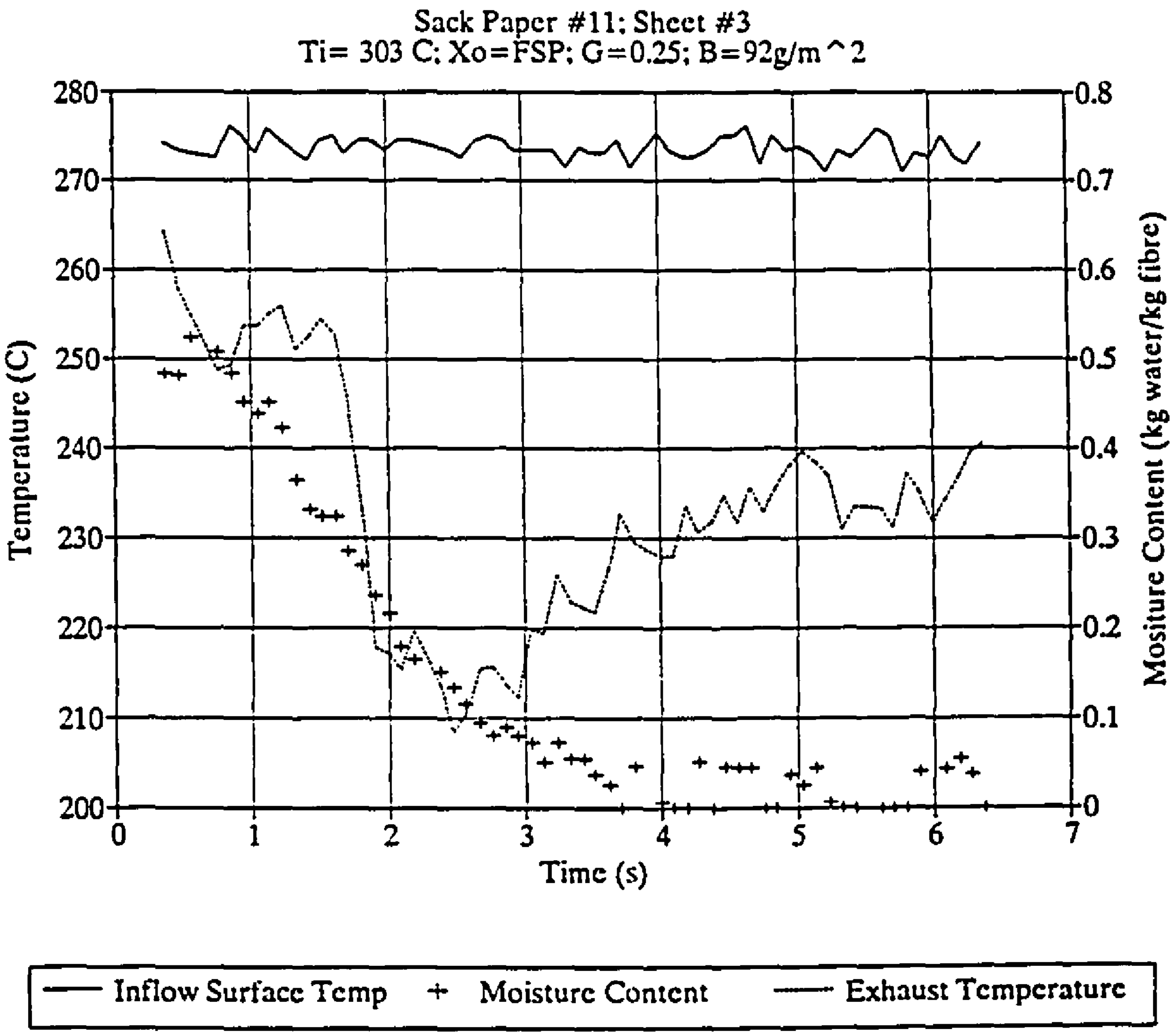


5.4 Temperature

A total of six temperatures were measured, two by IR pyrometry and four by thermocouples. The first thermocouple controls the drying fluid heater, and is located at the heater exit. The two thermocouples which record the temperature of the air above the surface of the sheet ensure both that this temperature is the target value and that it is uniform. The check for uniformity was successful because the two temperatures converge to within their ±2°C accuracy range once the apparatus has reached steady state. Although the two pyrometers were designed to measure the top and bottom surface temperatures of the paper, the design of the sheet holder is such that the bottom side of the sheet was partially obscured from view by the steel honeycomb. As detailed in section 4.1.1, with the difference in emissivity between paper and steel, the bottom pyrometer readings are meaningless. As the top pyrometer has an unobstructed view of the centre of the sheet the temperature of the through-flow inlet surface of the paper was obtained on-line during each drying experiment. A comparison of this temperature and the temperature of the exhaust air at the through-flow outlet side of the sheet, obtained by a thermocouple, is considered next.

A record of the air exhaust temperature out of the sheet and the surface temperature on the through-flow inlet side of the sheet during a drying experiment (Sack paper #11 dried in 300°C air) is given in Figure 5.9. The through-flow inlet surface temperature is effectively constant after the approximately half a second required to start acquiring this temperature. This is in agreement with the recent findings of *Hashemi et al., 1995*, who showed that through air drying occurs as a front which passes through the sheet. Thus it is believed that after the sheet enters the drying chamber a very thin layer of fibres at the through-flow inlet surface of the sheet is dried faster than this temperature can be acquired, the temperature of this thin layer of fibres adjusting to the temperature of the drying air. The fact that a transient heating-up period is not observed can be explained by two reasons linked to the procedure for starting the experiment. Before insertion, a small leakage flow of hot air from the drying chamber blows over the top of the sheet due to the three guide slots in the block at the upper side of the chamber

Figure 5.9 Sheet inflow surface and air exhaust temperatures



slot opening. Moreover, during sheet insertion air begins flowing through the leading edge of the sheet and drying the top layer before any element of the sheet passes under the pyrometer. Observation indicates that even with the minimum possible starting delay, sufficient leakage air passes over the top of sheet from the opening for the sheet holder tray to start the drying of the top layer of fibres of the sheet.

The bottom thermocouple is at the temperature of the drying air, 303°C in this case, when the sheet is inserted, which is why this temperature at first drops. Assuming that the flow is perfectly mixed in the through-flow exhaust side of the chamber, with a volume of $0.0086m^3$ and a flow rate of $0.0058m^3/s$ the chamber has a mean residence time of 1.5s, long enough to explain the observed delay. Only after this temperature starts to rise from its minimum near 210°C, after about 2.5s, can it be taken as indicating the air exhaust temperature. Thereafter this temperature rises as the paper approaches dryness. The fact that the adiabatic saturation temperature, about 53°C in this case, is not reached indicates that the air is not saturated as it leaves the sheet. As Chen, 1994, observed significant departures from the adiabatic saturation temperature limit for the sheet exhaust air temperature for cases of much lower drying intensity than that of the present study, it would be expected that the exhaust air here would be well below saturation.

6 Summary and Conclusions

6.1 Capabilities of the Facility

The equipment was shown to have the capabilities required for investigating the through drying of paper under high intensity conditions, including the local non-uniformity of such drying. Although designed for operation with either air or superheated steam as the drying fluid, the facility was commissioned using only air. However there is no reason to expect any operating difficulties for superheated steam drying that are not noted below for air. Air of up to 300°C was used, and flow rates greater than that required to produce a 40 kPa pressure drop across any sheet used were shown to be possible. The facility measures the air temperature for both the inlet and exhaust sides of the sheet, and measures the sheet surface temperature of the inlet side of the sheet. The pressure drop across the sheet is also measured, along with the absolute pressure above the sheet and the mass flow rate into the drying chamber, thus allowing for calculation of the mass flow rate through the paper and thereby the sheet permeability from wet to dry. All of these measurements can be taken at rates of up to 10Hz, allowing for accurate characterization of this high speed drying process.

The sheets tested were made from a range of furnishes, from TMP to kraft pulp. Although the special model of IR paper moisture sensor used has three IR wavelengths for better compensation, it retains significant sensitivity to the paper. The calibration between local moisture content and the IR moisture sensor signal was obtained using the local grammage of the 2.5mm diameter sensing spot as determined by light transmission image analysis. Of the papers tested, good IR moisture sensor calibrations were obtained for those made from TMP and blended furnishes and high-freeness kraft pulps. When used during drying experiments it was found that the IR moisture sensor output is sensitive also to the high temperatures reached briefly by the entire sheet at the end of through drying. Because of this characteristic two methods were examined for calculating the moisture content from the IR moisture sensor voltage signal, and were found to give comparable results. In this way sheet moisture content-time curves were produced. For the 125 drying experiments carried out, drying time ranged down to ca. 0.75s. Drying rates were calculated from these X-t curves in two ways. Over the range of moisture content common to the two methods, the drying rate curves by these methods were consistent. The method of modelling the X-t curve and differentiating the model equation has the benefit of providing a drying rate curve over the entire range of moisture content from start to finish of drying.

6.2 Identification of Limitations

The most significant of the problems discovered during commissioning is the fact that the IR moisture sensor is insensitive to moisture contents over a range of moisture content above the fibre saturation point, thus limiting the range of drying which can be studied. Also, the moisture sensor could not be satisfactorily calibrated for certain types of paper, specifically kraft paper made from pulps that have a low freeness. Another desired measurement which proved unobtainable was the surface temperature of the through flow exhaust side of the sheet.

Some problems affected the precision of the results. As currently instrumented the exact instant at which the sheet is fully inserted in the drying chamber is not known, thus making unknown the precise starting time of drying. Also, the exact moisture content of the paper at the start of drying is unknown because of some drying by air blowing across the sheet just before its insertion into the chamber.

Some problems occurred during the drying of the paper. The sheet holder left wire markings on the sheet at certain conditions. In a few cases of the highest intensity drying conditions the paper was scorched on the through flow inlet side of the sheet even if the other side of the sheet was not yet dry.

6.3 Improvements in Equipment and Procedures

In order to determine the exact time at which the sheet enters the chamber, light and dark spots could be placed on the side of the tray and a light sensor located such that it would determine the exact time history of insertion and retraction of the sheet holder.

The other problem concerning the start of drying occurs during the short time between placing the sheet holder in the insertion-retraction tray and its insertion into the dryer. Due to grooves machined in the entrance slot of the drying chamber, accommodating the guides on the top of the sheet holder, some escaping drying fluid flows across the top of the paper before insertion. Although this time was minimized, drying prior to sheet insertion could be further reduced by placing a flow deflector on this tray in front of the grooves until insertion.

Two techniques could be tried in order to improve the moisture sensor calibration. First, the upper limit of the temperature over which the dry temperature method can be applied might be extended by inserting dry sheets for short times into the drying chamber already at its target high temperature. By keeping the time in the dryer less than that for which the paper would ignite, there should be a short period during which a useful calibration could be acquired. Another method would be to calibrate at the desired high temperature of the drying fluid using the technique of interrupted drying. In this method the paper would be removed from the chamber when partially dry, capped quickly to prevent evaporation, then weighed to determine the moisture content. In this way, gravimetrically determined values of sheet moisture content at various points from wet to dry could be obtained to provide a more precise calibration of the IR moisture sensor. Finally, it should be recalled that this is a new and unique paper moisture sensor, being used for the first time inside a dryer for on-line monitoring of sheet moisture content. As this instrument evolved through collaboration between this laboratory and its manufacturer, the Fujitechnica Company, it is possible that its designers may identify modifications to improve the instrument characteristics now that the first test data with the sensor installed in the dryer are available.

Another problem experienced was deformation of the drilled titanium disk that supports the honeycomb in the sheet holder. Deformation occurred gradually, so that by the end of the experimental program the centre of this disk was permanently deflected by 1 mm. The sheet of course conforms to this shape. Although such a deflection should not cause a significant error in the IR moisture sensor operated in transmission mode, it is preferable to remove all possible sources of error. The material of construction could be changed to one which is more resistant, the drilled hole pattern could be changed to a lower open area to provide greater strength, or the disk thickness could be increased.

6.4 Improvements in Analysis

Analysis of the data may be improved in several ways. The table look-up algorithm relating the IR sensor output and grammage to the sheet moisture content should be replaced by modelling the moisture sensor calibration curves. Due to the nature of the insensitive region in those calibration curves, it should be necessary to model only to about the inflection point in the curve for TMP and blended papers and to below the inflection point for sack paper. The most difficult challenge in modelling these calibration curves is to include the effect of grammage. Of the seven types of paper tested to date it appears possible to obtain a model with the grammage parameter for six of these types. It should be helpful also to analyze the data as a function of grammage of water and grammage of fibre, the actual variables to which the IR beam is responding.

An area which has not been touched at all to date but should be the subject of further studies is that of paper properties. If through drying is to be used industrially an essential feature will be to determine the relation between drying conditions and the properties of the dry paper thereby produced. The process of through drying is inherently coupled with the possibility of local non-uniformity in drying and the resultant presence of local non-uniformity in some paper properties. The present equipment is uniquely designed for such investigations through its ability for on-line monitoring of the drying history locally on the sheet. That aspect of the follow-up study will be further aided by state-of-the-art techniques in this laboratory for the use of light transmission image analysis to characterise the local non-uniformity of sheet formation, which is fundamental to characterizing through drying on a local scale.

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Appendix A

Critical Flow Valve

A critical flow valve is used to ensure a constant mass flow rate into the drying chamber, irrelevant of the varying pressure downstream of the valve. An analysis of the phenomenon of critical flow of a gas through a constriction is found in Denn (1980). Starting with the Bernoulli equation and that for Reynold's number he shows that the mass flow through a nozzle is:

$$w^2 = \frac{\pi^2 D^4 \rho_1 p_1}{16}\left[\frac{1-(p_2/p_1)^2}{(4fL/D)-\ln(p_2/p_1)^2}\right]$$

This relation indicates that the mass flow w goes to zero not only as p_2/p_1 approaches 1, but also a p_2/p_1 approaches zero! This implies, therefore, that there is a maximum value of w which can be found by differentiating with respect to $(p_2/p_1)^2$ and setting the derivative equal to zero:

$$\frac{dw^2}{d(p_2/p_1)^2} = \frac{\pi^2 D^4 \rho_1 p_1}{16}\left\{-\frac{1}{\frac{4fL}{D}-\ln\left(\frac{p_2}{p_1}\right)^2} + \frac{1-(p_2/p_1)^2}{\left(\frac{p_2}{p_1}\right)\left[\frac{4fL}{D}-\ln\left(\frac{p_2}{p_1}\right)^2\right]^2}\right\} = 0$$

Combining these two equations to eliminate the term involving fL/D and the logarithm, gives

$$w_{max}{}^2 = \left(\rho_2 \frac{\pi D^2}{4} V_{2,max}\right)^2 = \left(\frac{\pi D^2}{4}\right)^2 p_2{}^2 \frac{\rho_1}{p_1}$$

Assuming the system is adiabatic and behaves as an ideal gas gives $p_1/\rho_1 = p_2/\rho_2$ and therefore, solving for the velocity at the maximum throughput:

$$V_{2,max} = \sqrt{\frac{p_2}{\rho_2}}$$

This velocity is also the speed of sound in an isothermal ideal gas, so it can be seen that the exit velocity through the valve cannot exceed the speed of sound.

From Perry, Chemical Engineers Handbook the critical pressure ratio necessary for this condition is given as:

$$r_c=\left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}$$

for air k = 1.4 and therefore r_c = 0.528. Thus, as long as the pressure in the drying chamber, in the present case the pressure downstream of the critical flow valve, is less than 0.528 times the pressure above the critical flow valve there will be a constant volumetric flow rate through that valve. If in addition the air is supplied to the upstream side of the critical flow valve at a constant pressure, which is the case in the present equipment, the constant volumetric flow rate through this valve becomes a constant mass flow rate of air into the drying chamber.

Appendix B

Data Acquisition and Process Control Program

```
'
'     HITD.BAS - DATA ACQUISITION AND PROCESS CONTROL PROGRAM FOR
'                HIGH INTENSITY THROUGH-DRYER
'
'              Tong Chen and Jean-Francois Bond
'
'              Revised by David Sanguinetti
'
'*************************************************************************
' LAYOUT OF EXPERIMENTAL DATA FILE AND DT 2801-A ANALOG PORT ASSIGNMENTS
'*************************************************************************
'
' READING | DT-2801A |        MEASUREMENT                 | UNITS
'   #     | CHANNEL  |                                    |
'         |          |                                    |
'   0     |    -     | TIME                               | S
'   1     |    0     | SUPERHEATER EXHAUST TC.    (CHIP #1) | DEG. C
'   2     |    1     | DRYING CHAMBER INLET TC. #1 (CHIP #2) | DEG. C
'   3     |    2     | UNUSED THERMOCOUPLE        (CHIP #3) |
'   4     |    3     | UNUSED THERMOCOUPLE        (CHIP #4) |
'   5     |    4     | DRYING CHAMBER INLET TC. #2 (CHIP #5) | DEG. C
'   6     |    5     | DRYING CHAMBER EXHAUST TC.  (CHIP #6) | DEG. C
'   7     |    6     | UNUSED THERMOCOUPLE        (CHIP #7) |
'   8     |    7     | UNUSED THERMOCOUPLE        (CHIP #8) |
'   9     |    8     | SHEET TOP PYROMETER                | DEG. C
'         |          |                                    |
'  10     |    9     | SHEET BOTTOM PYROMETER             | DEG. C
'  11     |   10     | PLENUM ABSOLUTE PRESSURE GAUGE     | KPAA
'  12     |   11     | SHEET DIFFERENTIAL PRESSURE GAUGE  | KPAD
'  13     |   12     | TURBINE FLOWMETER                  | L/S
'  14     |   13     | unused                             |
'  15     |   14     | moisture sensor                    | Volts
'  16     |   15     | UNUSED                             |
'  17     |    -     | IR POSITION                        | DEG.
'  18     |    -     | MASS FLUX                          | KG/M^2-S
'  19     |    -     | DRYING RATE                        | KG/M^2-H
'
'
' FILE # ASSIGNMENTS:
' #1 = flnam$  (WARM-UP DATA FILE)
' #2 = PARMS.DAT
' #3 = FILENAME$  (EXPERIMENTAL DATA FILE)
' #4 = ZEROS.NUM
'
'*************************************************************************
' 1-              HARDWARE INITIALIZATION
'*************************************************************************

'INCLUDE SUBROUTINE FILES

REM $INCLUDE: 'PCLAB.INC'       ' DATA TRANSLATION BOARD SUBROUTINES
REM $INCLUDE: 'CONSTANT.INC'    ' INSTRUMENT CALIBRATION CONSTANTS
```

```
' INITIALIZING ARRAYS AND VARIABLES

DEFINT A-Z

DIM CHAN%(16)
DIM RDGS!(20)
DIM BITS%(16)
DIM EXPT.VALS%(9000)
DIM COMMENT$(20)
DIM NEWTEMP(16)
DIM TIME.EL#(1000)
DIM POSITION (1000)
DIM TEST(5)
DIM maxvalue!(6)
DIM BP!(20)

REM $DYNAMIC
DIM RAWDATA!(520, 20)
DIM AVDATA!(260, 20)
DIM REDDATA!(260, 25)

NUM.OF.CHANS = 16
IRANGLE = 0
STEP.DEL# = 0.1#          'PAUSE AFTER COMMAND TO STEPPER MOTOR, S
H.VOLTS! = 9.998999
L.VOLTS! = -.001
RANGE! = H.VOLTS! - L.VOLTS!
NOC! = 4096          ' NOC! = 2^12 = 4096
LSB! = RANGE! / NOC!   ' LSB! = 2.44 mV/bit

FOR I = 0 TO 15
CHAN%(I) = I
BITS%(I) = 0
NEXT

SV% = 0
MFAVG! = 0!


P.DANGER.BIT = (155.132 - BP!(4)) / mp!(4)  'Pdiff proof=1.5 FSPR,FSPR=15psi
IF P.DANGER.BIT > 4092 THEN P.DANGER.BIT = 4092


DIA! = .1525                         ' SHEET DIAMETER, M
RU! = 8.31441                        ' UNIVERSAL GAS CONSTANT
PI! = 3.14159
AREA! = PI! * (DIA! ^ 2) / 4           ' SHEET AREA, M^2

KEY OFF
SCREEN 0

'GET INSTRUMENT ZERO OFFSETS
```

```
OPEN "ZEROS.NUM" FOR INPUT AS #4
FOR I = 1 TO 7
INPUT #4, BP!(I)
NEXT I
CLOSE #4

'GET CURRENT EXPERIMENTAL SETTINGS

OPEN "PARMS.DTA" FOR INPUT AS #2
 INPUT #2, FL$, PP$, THERM!, DELTAT!, PREG!, TIME#, BW!, G!, STEPS, DELSTEP!,
FILENUM
CLOSE #2

'INITIALIZING OF A/D BOARD

CALL XINIT
CALL XEFO(0)
CALL XODV(0, 255, 0)
CALL XST(500)

PORT1 = 0
PORT2 = 1


AWO = 1
CCW = 2
SM.IN = 4
SM.OU = 5
HEATR = 6

AWO.MASK = 2 ^ AWO              'ALL WINDINGS OFF MASK (BIT 1, RELAY 6)
CCW.MASK = 2 ^ CCW              'COUNTER-CLOCKWISE MASK (BIT 2,RELAY 5)
SM.IN.MASK = 2 ^ SM.IN          'SAMPLE IN MASK (BIT 4,RELAY 3)
SM.OU.MASK = 2 ^ SM.OU          'SAMPLE OUT MASK (BIT 5,RELAY 2)
HEATR.MASK = 2 ^ HEATR          'HEATER MASK (BIT 6, RELAY1)
ALL.MASK = &HFF

OUTP.HI = 127
OUTP.LO = 0
TIMING.SOURCE = 0
GAIN = 1

'
'COUNTER/TIMER CHIP INITIALIZATION (8253 #1)
'SEE THE DEVELOPMENT FILE CASCADE.BAS FOR DESCRIPTION OF TIMEMEASUREMENT
'
DIO48 = &H280                   'BOARD HOME ADDRESS

OUT DIO48 + &H0B, &H30          'INITIALIZE COUNTER 0 FOR MODE 0
OUT DIO48 + &H0B, &H74          'INITIALIZE CCUNTER 1 FOR MODE 1
OUT DIO48 + &H0B, &HB4          'INITIALIZE COUNTER 2 FOR MODE 1
```

```
'LOADING CTC REGISTERS

OUT DIO48 +&H08, &HFF          'DATA WRITE TO COUNTER 0, L. S.BYTE
OUT DIO48 +&H08, &HFF          'DATA WRITE TO COUNTER 0,M. S. BYTE
OUT DIO48 +&H09, &HFF          'DATA WRITE TO COUNTER 1, L. S. BYTE
OUT DIO48 +&H09, &HFF          'DATA WRITE TO COUNTER 1, M. S. BYTE
OUT DIO48 +&H0A, &HFF          'DATA WRITE TO COUNTER 2, L. S. BYTE
OUT DIO48 +&H0A, &HFF          'DATA WRITE TO COUNTER 2, M. S. BYTE

'ARTIFICIAL DELAY (NECESSARY TO STABILIZE COUNTER 0 OUTPUT).

FOR AD# = 1 TO 20000
NEXT AD#


'STEPPER MOTOR INITIALIZATION


'TURN MOTOR WINDINGS OFF          'SEE SUBROUTINE SCANNER FOR A
CALL XODV (0, AWO.MASK, OUTP.HI)  'DESCRIPTION OF STEPPER MOTOR CONTROL.
CALL XDV (1, 4095)
DELTIME# = STEP.DEL#: GOSUB DELAY
CALL XDV (1, 0)
DELTIME# = STEP.DEL# : GOSUB DELAY



'*******************************************************************************
' 2-                  EXPERIMENTAL SETTINGS
'*******************************************************************************

'TITLE SCREEN

TITLE:
  COLOR 11, 0
  CLS
 TOPROW = 1: BOTROW = 5: LEFTCOL = 1: RIGHTCOL = 80
  GOSUB BOX
  LOCATE 2, 12
  PRINT " DATA ACQUISITION PROGRAM FOR HIGH INTENSITY THROUGH-DRYER";
  LOCATE 3, 23
  PRINT "WRITTEN BY TONG CHEN AND J. F. BOND, 1993";
  LOCATE 4, 26
  PRINT "Modified by DAVID SANGUINETTI, 1994, 1995";

 'DISPLAY AND MODIFICATION OF EXPERIMENTAL SETTINGS

 NEWPROPS:
  COLOR 11, 4
  TOPROW = 5: BOTROW = 24: LEFTCOL = 1: RIGHTCOL = 80
  GOSUB BOX
```

```
LOCATE 6, 26
PRINT "CURRENT EXPERIMENTAL SETTINGS";
LOCATE 8, 3
PRINT "PAPER:"
LOCATE 8, 23
PRINT "Pulp type :   "; PP$; "";
LOCATE 9, 23
PRINT "Basis weight (g/m^2) :  "; BW!; "";
LOCATE 10, 23
PRINT "Sheet residence time = "; TIME#; " seconds";
LOCATE 12, 3
PRINT "DRYING FLUID:"
LOCATE 12, 23
PRINT "Drying fluid : "; FL$; "";
LOCATE 13, 23
PRINT "Mass Flux (kg/m^2-s) : "; G!; "";
LOCATE 14, 23
PRINT "Plenum chamber target temperature = "; THERM!; "deg. C";
LOCATE 15, 23
PRINT "Acceptable temperature deviation = +/-  "; DELTAT!; " deg.C";
LOCATE 16, 23
PRINT "Pressure regulator setting = "; PREG!; " kPag";
LOCATE 18, 3
PRINT "MOISTURE SENSOR"
LOCATE 19, 3
PRINT "SCANNING:"
LOCATE 18, 23
PRINT "Number of scan steps = "; STEPS
LOCATE 19, 23
PRINT "Delay between scan steps = "; DELSTEP!; "seconds";

LOCATE 23, 3
 COLOR 15, 0
 PRINT "Do you wish to change any of these settings? (Y/N) ";
 COL.. . 11,0
 GOSUB YN
 IF YES = 1 THEN
 GOSUB PARMS
 GOTO NEWPROPS
 END IF

LOCATE 23, 3
COLOR 15, 0
PRINT "Do you want to save the current parameters as the default? (Y/N) ";
COLOR 11, 0
GOSUB YN
   IF YES = 0 GOTO NOPARMSAVE
  OPEN "PARMS.DTA" FOR OUTPUT AS #2
  WRITE #2, FL$, PP$, THERM!, DELTAT!, PREG!, TIME#, BW!, G!, STEPS, DELSTEP!,
FILENUM
  CLOSE #2
```

```
NOPARMSAVE:

LOCATE 23, 3
COLOR 15, 0
PRINT "Do you want to save the data to a file during warmup? (Y/N)      ";
COLOR 11, 0
GOSUB YN
    IF YES = 1 THEN
    LOCATE 23,3
PRINT "                                                              ";
    LOCATE 23, 3
    INPUT "DATA FILE NAME:      ", flnam$
    SV% = 1
    LOCATE 23,3
PRINT "                                                              ";
    LOCATE 23, 3
    INPUT "ENTER INTERVAL BETWEEN DISK WRITE OPERATIONS (s):              ",
INCREMENT#

OPEN flnam$ FOR OUTPUT AS #1
        WRITE #1, " Time ", " S/H  ", "DCIN (#1) ", " ---- ", " ---- ", "DCIN (#2)", "  DCOUT
", " ---- ", " ---- ", "PYRO(T)", "PYRO(B)", "Pabs", "Pdiff ", "FLOW ", "  IR  ", " ---- ", " ---- ",
"IRPOS ", " FLUX ", "DRATE "
        WRITE #1, "   S  ", "DEG. C", "  DEG.C   ", "      ", "      ", " DEG. C  ", "  DEG. C
", "      ", "      ", " DEG. C", " DEG. C", " kPa ", " kPa ", " L/S ", "KG/KG ", "      ", "      ",
" DEG. ", "KG/M2S", "KG/M2H"
   WRITE #1,
 END IF


'INITIAL SETTING OF DRYING CHAMBER AND SUPERHEATER TEMPERATURE SET POINTS

 TEMP! = THERM! + DELTAT!
     PLENUMHI! = TEMP!
     CHIP% = 2
     GOSUB BITS
     PLENUM.HI = TEMP!
   TEMP! = THERM! - DELTAT!
     PLENUMLO! = TEMP!
     GOSUB BITS
     PLENUM.LO = TEMP!
   TEMP! = THERM! + 160
     SHSHI! = TEMP!
     CHIP% = 1
     GOSUB BITS
     SHS.HI = TEMP!
   TEMP! = THERM! + 100
     SHSLO! = TEMP!
     GOSUB BITS
     SHS.LO = TEMP!

'ABSOLUTE PRESSURE AND SPECIFIC GAS CONSTANT
```

```
IF LEFT$(FL$, 1) = "S" OR LEFT$(FL$, 1) = "s" THEN
 MW! = .0180152
     fluid$ = "Steam"
ELSEIF LEFT$(FL$, 1) = "A" OR LEFT$(FL$, 1) = "a" THEN
     MW! = .028964
     fluid$ = "Air"
 END IF

  PREGA! = PREG! + 101.325
  RS! = RU! / MW!  ' SPECIFIC GAS CONSTANT


'SETTING OF ANALOG DATA CHANNEL SWEEP RATE



  IF TIME# > 100 THEN
     RATE# = 1
  ELSEIF TIME# > 50 THEN
     RATE# = 2
  ELSEIF TIME# > 20 THEN
     RATE# = 5
  ELSE
  RATE# = 10
  END IF

' LAR.INCR is inputs per second:
'  4 if RATE# = 0.25 Hz, 16 if RATE# =  1 Hz, 32 if RATE# = 2 Hz
'  40 if RATE# = 4 Hz
' SM.INCR# is the length in 1/100 sec. of the main experiment loop

  LAR.INCR = NUM.OF.CHANS*RATE#
  SM.INCR# = 100/RATE#
  PERIOD# = SM.INCR#/100#          ' set clock increment period
  TIME.BIT = LAR.INCR*TIME#


' TOTAL.READS = TIME# * RATE# * NUM.OF.CHANS
'  IF RATE# = .25 THEN
'  CLOCK.UNIT = 1200
'  ELSE
'  CLOCK.UNIT = INT(1000! / RATE# / 1.25 / num.of.chans * 1000!)
'  END IF

'************************************************************************
' 3-          INSTRUMENT AND CONTROL PANEL DISPLAY
'************************************************************************

 DRAWSCREEN:
 COLOR 7, 1
 CLS
```

```
LOCATE 1, 1
COLOR 0, 7
PRINT ; "                    ***** HIGH INTENSITY THROUGH-DRYER *****                    ";
COLOR 7, 1

XANCHOR = 2: YANCHOR = 4: GOSUB SUPERHEATER
XANCHOR = 17: YANCHOR = 4: GOSUB FLOWMETER
XANCHOR = 17: YANCHOR = 9: GOSUB IRSENSOR
XANCHOR = 35: YANCHOR = 4: GOSUB CHAMBER
XANCHOR = 65: YANCHOR = 2: GOSUB PYROUP
XANCHOR = 65: YANCHOR = 6: GOSUB TCBOX
XANCHOR = 65: YANCHOR = 9: GOSUB PTABS
XANCHOR = 65: YANCHOR = 13: GOSUB PTDIFF
XANCHOR = 65: YANCHOR = 16: GOSUB TCBOX
XANCHOR = 65: YANCHOR = 20: GOSUB PYRODOWN
XANCHOR = 17: YANCHOR = 20: GOSUB SHTCBOX
LOCATE 23, 1: GOSUB ACTIONPROMPT


'INITIALIZATION OF INSTRUMENT MEASUREMENT LOOP

GOSUB NOW

STARTTIME# = SHSTIME#
RESETTIME# = SHSTIME#
ELTIME# = 0
FOR I = 0 TO 15                'FIRST INSTRUMENT READING
CALL XAV(CHAN%(I), GAIN, BITS%(I))
NEXT I


'INSTRUMENT MEASUREMENT LOOP BEGINS HERE


MEASURE:

'DISPLAY STATUS OF SLIDE AND DRYING FLUID

COLOR 15, 4
LOCATE 7, 22
PRINT FL$'

IF (SLIDE$ <> " ") THEN
LOCATE 12, 50
PRINT SLIDE$;
END IF

LOCATE 11, 5
PRINT USING "###"; SHSHI!
LOCATE 18, 5
PRINT USING "###"; SHSLO!
```

```
GOSUB NOW
RDGS!(0) = SHSTIME# - STARTTIME#
ELTIME#  = SHSTIME# - RESETTIME#

'READ AND AVERAGE INSTRUMENT DIGITAL VALUES

FOR I = 0 TO 15
CALL XAV(CHAN%(I), GAIN, BITS%(I))
NEXT I

GOSUB CONVERSION        'CONVERT DIGITAL VALUES TO PHYSICAL QUANTITIES


'DISPLAY 4 THERMOCOUPLE TEMPERATURES

LOCATE 21, 18
PRINT USING "###.#  "; RDGS!(1);
LOCATE 5, 66
PRINT USING "###.# "; RDGS!(5);
LOCATE 7, 66
PRINT USING "###.#  "; RDGS!(2);
GOSUB TEMP
LOCATE 17, 66
PRINT USING "###.#  "; RDGS!(6);


LOCATE 3, 66
PRINT USING "###.# "; RDGS!(9);       'UPSTREAM PYROMETER

LOCATE 10, 66
PRINT USING "###.# "; RDGS!(11);      'ABSOLUTE PRESSURE

LOCATE 14, 66
PRINT USING "###.# "; RDGS!(12);      'DIFFERENTIAL PRESSURE

LOCATE 21, 66
PRINT USING "###.# "; RDGS!(10);      'DOWNSTREAM PYROMETER

LOCATE 12, 22
PRINT USING "##.## "; RDGS!(15);      'MOISTURE CONTENT

LOCATE 18, 22
PRINT USING " ###"; RDGS!(17);        'IR SENSOR POSITION

LOCATE 6, 19
PRINT USING "#.##"; RDGS!(18);        'MASS FLUX


COLOR 7, 1   'THIS LINE CHANGED 15 SEPTEMBER 1993

'SUPERHEATER CONTROL
```

```
IF (BITS%(4) > PLENUM.HI) OR (BITS%(0) > SHS.HI) THEN
CALL XODV(PORT1, HEATR.MASK, OUTP.LO)
COLOR 15, 4
LOCATE 7, 5
PRINT "OFF";
COLOR 7, 1
ELSEIF (BITS%(4) < PLENUM.LO) AND (BITS%(0) < SHS.LO) THEN
CALL XODV(PORT1, HEATR.MASK, OUTP.HI)
COLOR 15, 4
LOCATE 7, 5
PRINT "ON ";
COLOR 7, 1

END IF


'WRITING INSTRUMENT READINGS TO A DISK FILE

    IF SV% = 1 THEN
    IF ELTIME# > INCREMENT# THEN
    FOR I = 0 TO 18
    PRINT #1, USING "###.## "; RDGS!(I);
    NEXT I
    PRINT #1, " "
    GOSUB NOW
    RESETTIME# = SHSTIME#
    END IF
  END IF

'BRANCHING ON USER INPUT

  ret$ = INKEY$
  IF ret$ = "" GOTO MEASURE
   IF (ret$ = "h") OR (ret$ = "H") THEN GOSUB INCREASE
   IF (ret$ = "c") OR (ret$ = "C") THEN GOSUB DECREASE
   IF (ASC(ret$) = 26) THEN GOSUB ZERO
   IF (ASC(ret$) = 5) THEN GOTO BEGINEXPT
   IF (ASC(ret$) = 9) THEN GOSUB SAMPLEIN        'MANUAL SHEET INSERTION
   IF (ASC(ret$) = 19) THEN GOSUB SAMPLEOUT      'MANUAL SHEET REMOVAL
   IF (ret$ = "m") OR (ret$ = "M") THEN GOTO TITLE
   IF (ASC(ret$) = 17) THEN GOTO ENDEXPT
   IF (RET$ = "a") OR (RET$ = "A") THEN GOSUB SCANMAN
   IF (RET$ = "+") THEN GOSUB CWSTEP
   IF (RET$ = "-") THEN GOSUB CCWSTEP

GO TO MEASURE

'************************************************************************
' 4-              THROUGH DRYING EXPERIMENT
'************************************************************************

'INITIALIZATION OF INSTRUMENT MEASUREMENT LOOP
```

```
BEGINEXPT:

LOCATE 3, 10
COLOR 0, 10
PRINT "IS THE PAPER SLIDE CLEAR AND SAFE? (Y/N)";
COLOR 7,1
GOSUB YN
 IF YES=0 THEN GOTO DRAWSCREEN

LOCATE 21, 35
PRINT "                                   ";

HOT = 0
YES = 0
STOP.VAL = 0

CLOCK.UNIT = 30
CALL XSCD(CLOCK.UNIT)
CALL XSA(TIMING.SOURCE, CHAN%(0), CHAN%(15), GAIN)
CALL XODV(PORT1, ALL.MASK, OUTP.LO)             'RESET ALL RELAYS

TEST1! = RDGS!(1)
TEST2! = RDGS!(2)
TEST3! = RDGS!(18)


'STEPPER MOTOR INITIALIZATION

CALL XODV (0, AWO.MASK, OUTP.LO)       'SUPPLY CURRENT TO MOTOR WINDINGS
CALL XDV (1, 4095)
DELTIME# = STEP.DEL#: GOSUB DELAY
CALL XDV (1, 0)
DELTIME# = STEP.DEL#: GOSUB DELAY


COLOR 0, 15
LOCATE 9, 37
PRINT "EXPERIMENT IN PROGRESS";
LOCATE 15, 43:
PRINT "ESC TO QUIT";
LOCATE 16, 38:
PRINT "ELAPSED TIME:       S";
COLOR 7, 1

GOSUB SAMPLEIN                         'INSERT SHEET

GOSUB NOW
TIME.ORG# = SHSTIME#
TIME.END# = TIME.ORG#
TIME.REC# = PERIOD#                    'TIME OF FIRST RECORD
```

```
DRYPAPER:

TIME.BEG# = TIME.END#

IF STEPS < > 0 THEN GOSUB SCANNER

CALL XBAD(NUM.OF.CHANS, EXPT.VALS%(STOP.VAL))
CALL XWAD(EXPT.VALS%(STOP.VAL + NUM.OF.CHANS - 1))

TEST(1) = EXPT.VALS%(STOP.VAL - NUM.OF.CHANS )
TEST(2) = EXPT.VALS%(STOP.VAL - NUM.OF.CHANS + 1)
TEST(3) = EXPT.VALS%(STOP.VAL - NUM.OF.CHANS + 12)
TEST(4) = EXPT.VALS%(STOP.VAL - NUM.OF.CHANS + 11)


    TEMP! = TEST(1)
    CHIP% = 1
    GOSUB TEMP
              TEST1! = 0.90 * TEST1! + 0.10 * TEMP!
    LOCATE 21, 18
    PRINT USING "###.#  "; TEST1!;


    TEMP! = TEST(2)
    CHIP% = 2
    GOSUB TEMP
              TEST2! = 0.90 * TEST2! + 0.10 * TEMP!
    LOCATE 7, 66
    PRINT USING "###.#  "; TEST2!;

    SUM! = TEST1! + TEST2!



VFR! = MP!(5) * TEST(3) + BP!(5)
RHO! = 1000 * PREGA! / (RS! * (.5 * SUM! + 273.2 ))  'DENSITY, KG/M^3
MFLUX! = (VFR! * RHO!/ AREA!)/1000
TEST3! = 0.90 * TEST3! + 0.10 * MFLUX!          'MASS FLUX, KG/M^2-S

LOCATE 6, 19
PRINT USING "#.##"; TEST3!


'IF TEST(4) > P.DANGER.BIT THEN CALL xsad: GOTO EMER
 ret$ = INKEY$
 IF ret$ < > "" THEN IF ASC(ret$) = 27 THEN CALL xsad: GOTO EMER

'SUPERHEATER CONTROL

IF (TEST(2) > PLENUM.HI) OR (TEST(1) > SHS.HI) THEN
CALL XODV(PORT1, HEATR.MASK, OUTP.LO)
COLOR 15, 4
```

```
LOCATE 7, 5
PRINT "OFF";
COLOR 7, 1

ELSEIF (TEST(2) < PLENUM.LO) AND (TEST(1) < SHS.LO) THEN
CALL XODV(PORT1, HEATR.MASK, OUTP.HI)
COLOR 15, 4
LOCATE 7, 5
PRINT "ON ";
COLOR 7, 1
END IF


IF RATE# = .25 THEN DELTIME# = 4: GOSUB DELAY


STOP.VAL = STOP.VAL + NUM.OF.CHANS

DELAY001:
GOSUB NOW
TIME.END# = SHSTIME#
IF CINT((TIME.END# - TIME.BEG#)*100#) < SM.INCR# GOTO DELAY001


TIME.EL#(STOP.VAL/(NUM.OF.CHANS + 1)) = TIME.REC#
POSITION(STOP.VAL/(NUM.OF.CHANS + 1)) = IRANGLE
TIME.REC# = TIME.END# - TIME.ORG#

COLOR 15, 4
LOCATE 16, 52
PRINT USING "###.#";TIME.REC#;

IF TIME.REC# <= TIME# THEN GOTO DRYPAPER


' MAIN EXPERIMENT LOOP ENDS here

FINISHED:

GOSUB SAMPLEOUT                    'REMOVE THE SHEET

DELTIME# = 1: GOSUB DELAY

COLOR 0, 15
LOCATE 9, 37
PRINT "  EXPERIMENT OVER   ";
COLOR 7, 1


'TURN MOTOR WINDINGS OFF

CALL XODV (0, AWO.MASK, OUTP.HI)    'ALL WINDINGS
```

```
CALL XDV (1, 4095)              'CLEAR/LOAD
DELTIME# = STEP.DEL#: GOSUB DELAY
CALL XDV (1, 0)
DELTIME# = STEP.DEL#: GOSUB DELAY




'*********************************************************************************
' 5-              DATA CONVERSION AND STORAGE
'*********************************************************************************

COLOR 7, 0
CLS
LOCATE 4, 3
 PRINT "Do you want to save your data to disk? (Y/N) ";
  GOSUB YN
   IF YES = 1 GOTO SAVEDATA
  LOCATE 6, 3
  PRINT "Are you sure? (Y/N) "
  GOSUB YN
    IF YES = 1 GOTO DRAWSCREEN

SAVEDATA:

CLS
  LOCATE 8, 3
  INPUT "Enter the initial sample weight (G):", WI!
  LOCATE 10, 3
  INPUT "Enter the final sample weight (G):", WF!


  LOCATE 12, 3
  PRINT "Automatic File Naming? (Y/N) ";
  GOSUB YN
    IF YES = 1 THEN GOTO AUTOFILE
  LOCATE 14, 3
  PRINT "Enter name of Data File";
  INPUT " ", FILENAMES
  FILENAMES = "C:\RUNDISK\DATA\" + LEFTS(FILENAMES, 8) + ".PRN"
GOTO DATASAVE

AUTOFILE:
  IF LEFTS(FLS, 1) = "A" OR LEFTS(FLS, 1) = "a" THEN CHAR1S = "A" ELSE CHAR1S = "S"
  CHAR2S = STRS(CINT(THERM!))
  LENGTH% = LEN(CHAR2S) - 1
  CHAR2S = RIGHTS(CHAR2S, LENGTH%)
  CHAR3S = "T"
  FILENUM = FILENUM + 1
  IF FILENUM > 999 THEN FILENUM = 1
```

```
CHAR4$ = STR$(FILENUM)
LENGTH% = LEN(CHAR4$) - 1
CHAR4$ = RIGHT$(CHAR4$, LENGTH%)
FILENAME$ = "C:\RUNDISK\DATA\" + CHAR1$ + CHAR2$ + CHAR3$ + CHAR4$ + ".PRN"


DATASAVE:


'TRANSFER OF RAW DATA FROM 1-D TO 2-D ARRAY

COUNT = 0

FOR ROW = 1 TO 500

RAWDATA!(ROW, O) = TIME.EL#(ROW)
RAWDATA!(ROW, 17) = POSITION(ROW)
FOR COLUMN = 1 TO 16
RAWDATA!(ROW, COLUMN) = EXPT.VALS%(COUNT)
COUNT = COUNT + 1

IF COUNT > STOP.VAL THEN
NUM.ROWS = ROW
GOTO AVERAGE
END IF

NEXT COLUMN

NEXT ROW


'RAW DATA AVERAGING
'ALL MEASUREMENTS EXCEPT TIME AND IR SENSOR POSITION ARE AVERAGED
AVERAGE:

AVGPARAM = 2        'AVERAGING PARAMETER MUST BE RESET HERE IF REQUIRED

'FOR ROW = 1 TO NUM.ROWS STEP 2
'ROW.RED = (ROW + 1) / 2
'AVDATA!(ROW.RED, 0) = RAWDATA!(ROW, 0)
'REDDATA!(ROW.RED, 0) = RAWDATA!(ROW, 0)

'FOR COLUMN = 1 TO 16

'SUM.POINTS! = 0
'NUM.POINTS = 0

'FOR K = ROW - AVGPARAM TO ROW + AVGPARAM

'IF (K > 0 AND K <= NUM.ROWS) THEN
'SUM.POINTS! = SUM.POINTS! + RAWDATA!(K, COLUMN)
'NUM.POINTS = NUM.POINTS + 1
```

```
'END IF

'NEXT K

'AVDATA!(ROW.RED, COLUMN) = SUM.POINTS! / NUM.POINTS

'NEXT COLUMN

'AVDATA!(ROW.RED, 17) = RAWDATA!(ROW, 17)
'REDDATA!(ROW.RED, 17) = RAWDATA!(ROW, 17)

'NEXT ROW
'RED.ROWS = ROW.RED


' DATA CONVERSION

FOR ROW = 1 TO NUM.ROWS

FOR J = 0 TO 15
BITS%(J) = RAWDATA! (ROW, J+1)
NEXT J

GOSUB CONVERSION
FOR COLUMN = 1 TO 16
RAWDATA!(ROW,COLUMN) = RDGS!(COLUMN)
NEXT COLUMN

FOR COLUMN = 18 TO 19
RAWDATA!(ROW,COLUMN) = RDGS!(COLUMN)
NEXT COLUMN

NEXT ROW


'STORAGE TO DISK

LOCATE 16, 3
  PRINT "Saving data to file "; FILENAME$; "
  GOSUB NOW2
  OPEN FILENAME$ FOR OUTPUT AS #3

  LABEL1$ = "DATA FILE NAME:  "
  LABEL2$ = "DATE OF EXPERIMENT:  "
  LABEL3$ = "TIME OF EXPERIMENT:  "
  LABEL4$ = "AVERAGING PARAMETER: "
  LABEL5$ = "PULP TYPE:  "
  LABEL6$ = "BASIS WEIGHT (GM/M^2):  "
  LABEL7$ = "DRYING FLUID:  "
  LABEL8$ = "MASS FLUX (KG/M^2-S):  "
  LABEL9$ = "DRYING FLUID TEMPERATURE (DEG. C):  "
  LABEL10$ = "SHEET RESIDENCE TIME (S):  "
```

```
LABEL11$ = "INITIAL WEIGHT OF SAMPLE AND HOLDER (G): "
LABEL12$ = "FINAL WEIGHT OF SAMPLE AND HOLDER (G): "
LABEL13$ = "MOISTURE LOSS (GM.): "


WRITE #3, LABEL1$, FILENAME$, GRAPHTITLE$
WRITE #3, LABEL2$, DATE$
WRITE #3, LABEL3$, SHSCLOCK$
WRITE #3, LABEL4$, AVGPARAM
WRITE #3, LABEL5$, PP$
WRITE #3, LABEL6$, BW!
WRITE #3, LABEL7$, FL$
WRITE #3, LABEL8$, G!
WRITE #3, " "
WRITE #3, " "
WRITE #3, LABEL9$, THERM!
WRITE #3, LABEL10$, TIME#
WRITE #3, " "
WRITE #3, LABEL11$, WI!
WRITE #3, LABEL12$, WF!
WRITE #3, LABEL13$, WI! - WF!
WRITE #3, " "

WRITE #3, " Time ", " S/H ", "DCIN (#1) ", " ---- ", " ---- ", "DCIN (#2)", " DCOUT ", " ----
", " ---- ", "PYRO(T)", "PYRO(B)", "Pabs ", "Pdiff ", "FLOW ", " IR ", " ---- ", " ---- ", "IRPOS
", " FLUX ", "DRATE "
WRITE #3, "  S ", "DEG. C", " DEG.C  ", "      ", "      ", " DEG. C ", " DEG. C ", "
", "      ", " DEG. C", " DEG. C", " kPa ", " kPa ", " L/S ", "KG/KG ", "      ", "      ", " DEG.
", "KG/M2S", "KG/M2H"
WRITE #3, " "


FOR ROW = 1 TO NUM.ROWS
FOR COLUMN = 0 TO 19
PRINT #3, USING "####.##"; RAWDATA!(ROW, COLUMN);
NEXT COLUMN
WRITE #3, " "
NEXT ROW
WRITE #3,

LOCATE 18, 3
PRINT "Do you want to add any comments? (Y/N) ";
GOSUB YN
IF YES = 1 THEN GOSUB COMMENTS
CLOSE #3


LOCATE 24, 3
PRINT "Data reduced succesfully and saved to file "; FILENAME$;

DELTIME# = 2: GOSUB DELAY
```

```
' FILE NUMBER IS UPDATED IN PARMS.DTA

  OPEN "PARMS.DTA" FOR INPUT AS #2
  INPUT #2, FL$, PP$, THERM!, DELTAT!, PREG!, TIME#, BW!, G!, STEPS, DELSTEP!
  CLOSE #2
  OPEN "PARMS.DTA" FOR OUTPUT AS #2
  WRITE #2, FL$, PP$, THERM!, DELTAT!, PREG!, TIME#, BW!, G!, STEPS, DELSTEP!,
FILENUM
  CLOSE #2

GOTO DRAWSCREEN

ENDEXPT:

CALL XODV(PORT1, ALL.MASK, OUTP.LO)      ' CUT ALL POWER
IF SV% = 1 THEN CLOSE #1
COLOR 7, 0
CLS

CALL XTERM
CALL XFDL(expt.vals%(0), usable)
PRINT "DMA space available: "; usable

END

'****************************END OF PROGRAM*********************************

'***************************************************************************
' A-1-                    SUBROUTINES
'***************************************************************************


' THIS SUBROUTINE CONVERTS TEMP! FROM A TEMPERATURE TO BIT

BITS:
  F! = 0
  FOR JJ = 8 TO 1 STEP -1
    F! = TEMP! * (B!(JJ) + F!)
  NEXT JJ
  TEMP! = F! + B!(0)
  TEMP! = (MT!(CHIP%) * TEMP! + BT!(CHIP%)) * 409.6' convert voltage to 0-4096
  IF TEMP! > 4095 THEN TEMP! = 4096
RETURN

' THIS SUBROUTINE DRAWS A BOX ON THE SCREEN
BOX:
  LOCATE TOPROW, LEFTCOL: PRINT CHR$(201);
  LOCATE TOPROW, RIGHTCOL: PRINT CHR$(187);
  LOCATE BOTROW, LEFTCOL: PRINT CHR$(200);
  LOCATE BOTROW, RIGHTCOL: PRINT CHR$(188);
  FOR I = TOPROW + 1 TO BOTROW - 1
```

```
  LOCATE I, LEFTCOL: PRINT CHR$(186);
  LOCATE I, RIGHTCOL: PRINT CHR$(186);
 NEXT
 FOR I = LEFTCOL + 1 TO RIGHTCOL - 1
  LOCATE TOPROW, I: PRINT CHR$(205);
  LOCATE BOTROW, I: PRINT CHR$(205);
 NEXT

FOR I = LEFTCOL + 1 TO RIGHTCOL - 1
FOR J = TOPROW + 1 TO BOTROW - 1
LOCATE J, I: PRINT " ";
NEXT J
NEXT I

LOCATE TOPROW + 1, LEFTCOL + 2
 RETURN


' THESE 3 SUBROUTINES VARY THE SHS TEMPERATURE BY 5% WHEN CTRL H (INCREASE)
' OR CTRL C (DECREASE) HAS BEEN PRESSED DURING THE MEASUREMENT LOOP
ALTER:
 CHIP% = 1
 SHSHI! = SHSHI! * FACTOR!
 TEMP! = SHSHI!
 GOSUB BITS
 SHS.HI = TEMP!
 SHSLO! = SHSLO! * FACTOR!
 TEMP! = SHSLO!
 GOSUB BITS
 SHS.LO = TEMP!
RETURN

DECREASE:
 FACTOR! = 1 / 1.05
 GOSUB ALTER
RETURN

INCREASE:
  FACTOR! = 1.05
  GOSUB ALTER
RETURN

'
' THIS SUBROUTINE RETURNS THE NUMBER OF SECONDS ELAPSED SINCE
' PROGRAM INITIALIZATION. SEE THE DEVELOPMENT FILE CASCADE2.BAS
' FOR DETAILS OF TIME MEASUREMENT.
' SINCE LATCHING THE COUNTERS WAS DISCOVERED TO INTERFERE WITH OPERATION
' OF THE DT-2801A BOARD, COUNTER LATCHING WAS DISABLED ON 11-29-93


NOW:
```

```
'OUT (DIO48 + &H0B), &H00    'LATCH COUNTER 0, CHIP 1 DATA
J2A1# = INP (DIO48 + &H8)    'READ COUNTER 0, L. S. BYTE
J2A2# = INP (DIO48 + &H8)    'READ COUNTER 0, M. S. BYTE
'OUT (DIO48 + &H0B), &H40    'LATCH COUNTER 1, CHIP 1 DATA
J2B1# = INP (DIO48 + &H9)    'READ COUNTER 1, L. S. BYTE
J2B2# = INP (DIO48 + &H9)    'READ COUNTER 1, M. S. BYTE
'OUT (DIO48 + &H0B), &H80    'LATCH COUNTER 2, CHIP 1 DATA
J2C1# = INP (DIO48 + &H0A)   'READ COUNTER 2, L. S. BYTE
J2C2# = INP (DIO48 + &H0A)   'READ COUNTER 2, M. S. BYTE

COUNT0# = 65536# -(J2A1# + 256# * J2A2#)
COUNT1# = 65536# -(J2B1# + 256# * J2B2#)
COUNT2# = 65536# -(J2C1# + 256# * J2C2#)
SHSTIME# = COUNT0# * 4294.956296# + COUNT1# * 0.065536# + COUNT2# * 0.000001# -
200000#

RETURN



' THIS SUBROUTINE CONVERTS TEMP! FROM BIT FORM TO A TEMPERATURE

TEMP:
 TEMP! = (TEMP! / 409.6 - BT!(CHIP%)) / MT!(CHIP%)' convert 0-4096 to volts
 F! = 0
 FOR JJ = 8 TO 1 STEP -1
 F! = TEMP! * (A!(JJ) + F!)
 NEXT JJ
 TEMP! = F! + A!(0)
RETURN


' THIS SUBROUTINE SHUTS EVERYTHING OFF IN AN EMERGENCY AND RESTARTS IF REQD

EMER:
COLOR 7,0
 CALL XODV(PORT1, all.mask, OUTP.lo)     ' CUT ALL POWER
 CALL XTERM
 CLS
 PRINT
 PRINT "** EMERGENCY SHUT-DOWN **"
 PRINT
 PRINT "Current pressure is"; TEST(4); "bits; maximum allowable is"; P.DANGER.BIT
 PRINT
 PRINT "Press CTRL P to PRINT data acquired so far to a diskette,"
 PRINT "      CTRL Q to QUIT."
 PRINT "      CTRL R to RESTART the experiment,"
 PRINT "   or CTRL S to remove the sheet."
WAITFORCHOICE:
 ret$ = INKEY$
 IF ret$ = "" THEN
```

```
  GOTO WAITFORCHOICE
 ELSEIF ASC(ret$) = 16 THEN
  GOTO SAVEDATA
 ELSEIF ASC(ret$) = 17 THEN
  GOTO ENDEXPT
 ELSEIF ASC(ret$) = 18 THEN
   GOTO TITLE
 ELSEIF ASC(ret$) = 19 THEN
   GOSUB SAMPLEOUT
 END IF
GOTO WAITFORCHOICE


' THIS SUBROUTINE TESTS THE KBD FOR A YES OR A NO

YN:
 ret$ = INKEY$
  IF ret$ = "" GOTO YN
 IF (ret$ = "Y") OR (ret$ = "y") THEN
  YES = 1
 ELSEIF (ret$ = "N") OR (ret$ = "n") THEN
  YES = 0
 ELSE GOTO YN
 END IF
 RETURN

' THIS SUBROUTINE RETURNS THE TIME OF DAY, READ FROM THE EXTERNAL CLOCK

NOW2:
 SHSCLOCK$ = TIME$
 RETURN

' THIS SUBROUTINE GETS CHANGES IN EXPERIMENTAL SETTINGS

PARMS:
 TOPROW = 5: BOTROW = 24: LEFTCOL = 1: RIGHTCOL = 80
 GOSUB BOX
 LOCATE 8, 3
 PRINT "Enter type of Pulp ("; PP$; "):";
 INPUT " ", TEMP$
 IF TEMP$ <> "" THEN PP$ = TEMP$
 LOCATE 9, 3
 PRINT "Enter basis weight (gm/m^2) ("; BW!; "):";
 INPUT " ", TEMP$
 IF TEMP$ <> "" THEN BW! = VAL(TEMP$)
UNACCEPT2:
   LOCATE 10, 3
PRINT "Enter sheet residence time (secs.) ("; TIME#; "): ";
INPUT " ", TEMP$
    IF TEMP$ <> "" THEN TIME# = VAL(TEMP$)
```

```
IF TIME# <= 1 OR TIME# >= 2000 THEN
PRINT "Residence time must >= 1 and <= 2000 seconds; please enter a new time."
GOTO UNACCEPT2
END IF


  LOCATE 12, 3
  PRINT "Enter drying fluid ("; FL$; "):";
  INPUT " ", TEMP$
  IF TEMP$ <> "" THEN FL$ = TEMP$
  LOCATE 13, 3
  PRINT "Enter mass flux (kg/m^2-s) ("; G!; "):";
  INPUT " ", TEMP$
  IF TEMP$ <> "" THEN G! = VAL(TEMP$)

      LOCATE 14, 3
    PRINT "Enter plenum chamber target temperature (deg. C) ("; THERM!; ") :";
    INPUT " ", TEMP$
    IF TEMP$ <> "" THEN THERM! = VAL(TEMP$)
      LOCATE 15, 3
    PRINT "Enter acceptable deviation about target (deg. C) ("; DELTAT!; ") :";
    INPUT " ", TEMP$
    IF TEMP$ <> "" THEN DELTAT! = VAL(TEMP$)


LOCATE 16, 3
      PRINT "Enter pressure regulator setting (kPag) ("; PREG!; "):";
      INPUT " ", TEMP$
      IF TEMP$ <> "" THEN PREG! = VAL(TEMP$)

  LOCATE 18, 3
  PRINT "Enter number of scan steps (";STEPS; "):";
  INPUT " ", TEMP$
  IF TEMP$ <> "" THEN STEPS = VAL(TEMP$)
  LOCATE 19, 3
  PRINT "Enter delay between scan steps (seconds) (";DELSTEP!; "):";
  INPUT " ", TEMP$
  IF TEMP$ <> "" THEN DELSTEP! = VAL(TEMP$)


RETURN

' THIS SECTION READS UP TO 20 LINES OF COMMENTS AND STORES THEM
' AT THE END OF THE PRN FILE

COMMENTS:
  CLS
  PRINT "Enter up to 20 lines of comments here; lines are delimited by"
  PRINT "a carriage return. Press F10 followed by ENTER to end input."
  PRINT
  WRITE #3,
  KEY(10) ON
```

```
 ON KEY(10) GOSUB NOMORE
 LINENUM2 = 1
MORECOMMENTS:
 LINE INPUT COMMENT$(LINENUM2)
 LINENUM2 = LINENUM2 + 1
 IF LINENUM2 < 20 THEN GOTO MORECOMMENTS
NOMORECOMMENTS:
 KEY OFF
 FOR I = 1 TO LINENUM2
        WRITE #3, COMMENT$(I)
 NEXT I
RETURN
NOMORE:
 RETURN NOMORECOMMENTS


'THIS SUBROUTINE GENERATES A DELAY OF DELTIME# SECONDS
DELAY:
 GOSUB NOW
 TIME.OLD# = SHSTIME#
WAITHERE:
 GOSUB NOW
 TIME.NEW# = SHSTIME#
 IF (TIME.NEW# - TIME.OLD# < DELTIME#) GOTO WAITHERE
RETURN


'THIS SUBROUTINE DRAWS THE SUPERHEATER ON THE SCREEN
SUPERHEATER:
TOPROW = YANCHOR: BOTROW = YANCHOR + 16: LEFTCOL = XANCHOR: RIGHTCOL =
XANCHOR + 9

  LOCATE TOPROW, LEFTCOL: PRINT CHR$(201);
  LOCATE TOPROW, RIGHTCOL: PRINT CHR$(187);
  LOCATE BOTROW, LEFTCOL: PRINT CHR$(200);
  LOCATE BOTROW, RIGHTCOL: PRINT CHR$(188);
  FOR I = TOPROW + 1 TO BOTROW - 1
    LOCATE I, LEFTCOL: PRINT CHR$(186);
    LOCATE I, RIGHTCOL: PRINT CHR$(186);
    LOCATE I + 1, RIGHTCOL + 3: PRINT CHR$(179);
 NEXT
  FOR I = LEFTCOL + 1 TO RIGHTCOL - 1
    LOCATE TOPROW, I: PRINT CHR$(205);
    LOCATE BOTROW, I: PRINT CHR$(205);
  NEXT
  LOCATE TOPROW + 1, LEFTCOL + 2

 PRINT "SUPER";
  LOCATE TOPROW + 2, LEFTCOL + 2
  PRINT "HEATER";
  LOCATE TOPROW + 5, LEFTCOL + 2
```

```
 PRINT "HI SET ";
 LOCATE TOPROW + 6, LEFTCOL + 2
PRINT "POINT:";
 LOCATE TOPROW + 8, LEFTCOL + 2
PRINT "DEG. C";


LOCATE TOPROW + 12, LEFTCOL + 2
 PRINT "LO SET";
 LOCATE TOPROW + 13, LEFTCOL + 2
PRINT "POINT:";
 LOCATE TOPROW + 15, LEFTCOL + 2
PRINT "DEG. C";

 LOCATE BOTROW, (RIGHTCOL + LEFTCOL) / 2
 PRINT CHR$(209);
 LOCATE BOTROW + 1, (RIGHTCOL + LEFTCOL) / 2
 PRINT CHR$(192);
 LOCATE BOTROW + 1, ((RIGHTCOL + LEFTCOL) / 2) + 1
 PRINT CHR$(196);
 LOCATE BOTROW + 1, ((RIGHTCOL + LEFTCOL) / 2) + 2
 PRINT CHR$(196);
 LOCATE BOTROW + 1, ((RIGHTCOL + LEFTCOL) / 2) + 3
 PRINT CHR$(196);
 LOCATE BOTROW + 1, ((RIGHTCOL + LEFTCOL) / 2) + 4
 PRINT CHR$(196);
 LOCATE BOTROW + 1, ((RIGHTCOL + LEFTCOL) / 2) + 5
 PRINT CHR$(196);
 LOCATE BOTROW + 1, ((RIGHTCOL + LEFTCOL) / 2) + 6
 PRINT CHR$(196);
 LOCATE BOTROW + 1, ((RIGHTCOL + LEFTCOL) / 2) + 7
 PRINT CHR$(217);
 RETURN

' THIS SUBROUTINE DRAWS THE FLOWMETER

FLOWMETER:

TOPROW = YANCHOR: BOTROW = YANCHOR + 4: LEFTCOL = XANCHOR: RIGHTCOL =
XANCHOR + 14

 LOCATE TOPROW, LEFTCOL: PRINT CHR$(201);
 LOCATE TOPROW, RIGHTCOL: PRINT CHR$(187);
 LOCATE BOTROW, LEFTCOL: PRINT CHR$(200);
 LOCATE BOTROW, RIGHTCOL: PRINT CHR$(188);


 FOR I = TOPROW + 1 TO BOTROW - 1
  LOCATE I, LEFTCOL: PRINT CHR$(186);
  LOCATE I, RIGHTCOL: PRINT CHR$(186);
 NEXT
 FOR I = LEFTCOL + 1 TO RIGHTCOL - 1
```

```
   LOCATE TOPROW, I: PRINT CHR$(205);
   LOCATE BOTROW, I: PRINT CHR$(205);
 NEXT
 LOCATE TOPROW + 1, LEFTCOL + 3

PRINT "FLOWMETER";
 LOCATE TOPROW + 2, LEFTCOL + 3

PRINT "    KG/M^2S";



LOCATE ((TOPROW + BOTROW) / 2), LEFTCOL - 3

PRINT CHR$(218);
PRINT CHR$(196);
PRINT CHR$(196);
PRINT CHR$(182);

LOCATE ((TOPROW + BOTROW) / 2), RIGHTCOL
PRINT CHR$(199);
PRINT CHR$(196);
PRINT CHR$(196);
PRINT CHR$(196);
PRINT CHR$(182);



LOCATE TOPROW + 1, LEFTCOL + 2
 RETURN

' THIS SUBROUTINE DRAWS THE IR MOISTURE SENSOR

IRSENSOR:

TOPROW = YANCHOR: BOTROW = YANCHOR + 6: LEFTCOL = XANCHOR: RIGHTCOL =
XANCHOR + 14

 LOCATE TOPROW, LEFTCOL: PRINT CHR$(201);
 LOCATE TOPROW, RIGHTCOL: PRINT CHR$(187);
 LOCATE BOTROW, LEFTCOL: PRINT CHR$(200);
 LOCATE BOTROW, RIGHTCOL: PRINT CHR$(188);


 FOR I = TOPROW + 1 TO BOTROW - 1
    LOCATE I, LEFTCOL: PRINT CHR$(186);
    LOCATE I, RIGHTCOL: PRINT CHR$(186);
 NEXT
 FOR I = LEFTCOL + 1 TO RIGHTCOL - 1
    LOCATE TOPROW, I: PRINT CHR$(205);
    LOCATE BOTROW, I: PRINT CHR$(205);
```

```
 NEXT
 LOCATE TOPROW + 1, LEFTCOL + 3

PRINT "IR SENSOR";

LOCATE TOPROW + 3, LEFTCOL + 2
 PRINT "V:  ";



LOCATE TOPROW + 1, RIGHTCOL
PRINT CHR$(199); CHR$(196); CHR$(196); CHR$(196); CHR$(196); CHR$(196); CHR$(196);
PRINT CHR$(196); CHR$(196); CHR$(196); CHR$(196); CHR$(196); CHR$(196); CHR$(196);
CHR$(196); CHR$(196); CHR$(196); CHR$(191);

LOCATE BOTROW - 1, RIGHTCOL
PRINT CHR$(199); CHR$(196); CHR$(196); CHR$(196); CHR$(196); CHR$(196); CHR$(196);
PRINT CHR$(196); CHR$(196); CHR$(196); CHR$(196); CHR$(196); CHR$(196); CHR$(196);
CHR$(196); CHR$(196); CHR$(196); CHR$(217);

'DRAW SCANNER

TOPROW = YANCHOR + 7: BOTROW = YANCHOR + 10: LEFTCOL = XANCHOR: RIGHTCOL
= XANCHOR + 14

LOCATE TOPROW, LEFTCOL: PRINT CHR$(201);
 LOCATE TOPROW, RIGHTCOL: PRINT CHR$(187);
 LOCATE BOTROW, LEFTCOL: PRINT CHR$(200);
 LOCATE BOTROW, RIGHTCOL: PRINT CHR$(188);


 FOR I = TOPROW + 1 TO BOTROW - 1
    LOCATE I, LEFTCOL: PRINT CHR$(186);
    LOCATE I, RIGHTCOL: PRINT CHR$(186);
 NEXT
 FOR I = LEFTCOL + 1 TO RIGHTCOL - 1
    LOCATE TOPROW, I: PRINT CHR$(205);
    LOCATE BOTROW, I: PRINT CHR$(205);
 NEXT

LOCATE TOPROW - 1, LEFTCOL + 7
PRINT CHR$(209);
LOCATE TOPROW, LEFTCOL + 7
PRINT CHR$(207);



LOCATE TOPROW + 1, LEFTCOL + 4
PRINT "SCANNER";
```

```
LOCATE TOPROW + 2, LEFTCOL + 2
 PRINT "Θ:      DEG.";

RETURN


' THIS SUBROUTINE DRAWS THE DRYING CHAMBER
CHAMBER:
COLOR 7, 1

TOPROW = YANCHOR: BOTROW = YANCHOR + 16: LEFTCOL = XANCHOR: RIGHTCOL =
XANCHOR + 25

  LOCATE TOPROW, LEFTCOL: PRINT CHR$(201);
  LOCATE TOPROW, RIGHTCOL: PRINT CHR$(187);
  LOCATE BOTROW, LEFTCOL: PRINT CHR$(200);
  LOCATE BOTROW, RIGHTCOL: PRINT CHR$(188);


LOCATE ((TOPROW + BOTROW) / 2), LEFTCOL
PRINT CHR$(178);
PRINT CHR$(178);
PRINT CHR$(178);
PRINT CHR$(178);
PRINT CHR$(178);
PRINT CHR$(178);
PRINT CHR$(178);
PRINT CHR$(178);

PRINT " SLIDE     ";

PRINT CHR$(178);
PRINT CHR$(178);
PRINT CHR$(178);
PRINT CHR$(178);
PRINT CHR$(178);
PRINT CHR$(178);
PRINT CHR$(178);
PRINT CHR$(178);

 FOR I = TOPROW + 1 TO BOTROW - 1
    LOCATE I, LEFTCOL: PRINT CHR$(186);
    LOCATE I, RIGHTCOL: PRINT CHR$(186);
  NEXT
  FOR I = LEFTCOL + 1 TO RIGHTCOL - 1
    LOCATE TOPROW, I: PRINT CHR$(205);
    LOCATE BOTROW, I: PRINT CHR$(205);

 NEXT
  LOCATE TOPROW + 1, LEFTCOL + 2
 PRINT "   DRYING CHAMBER";
 LOCATE TOPROW + 2, LEFTCOL
```

```
PRINT CHR$(182);
LOCATE TOPROW + 6, LEFTCOL
PRINT CHR$(215);
LOCATE TOPROW + 10, LEFTCOL
PRINT CHR$(215);

COLOR 7, 1

 RETURN

' THIS SUBROUTINE DRAWS A THERMOCOUPLE BOX
TCBOX:

TOPROW = YANCHOR: BOTROW = YANCHOR + 2: LEFTCOL = XANCHOR: RIGHTCOL=
XANCHOR + 14

 LOCATE TOPROW, LEFTCOL: PRINT CHR$(218);
 LOCATE TOPROW, RIGHTCOL: PRINT CHR$(191);
 LOCATE BOTROW, LEFTCOL: PRINT CHR$(192);
 LOCATE BOTROW, RIGHTCOL: PRINT CHR$(217);


 FOR I = TOPROW + 1 TO BOTROW - 1
   LOCATE I, LEFTCOL: PRINT CHR$(179);
   LOCATE I, RIGHTCOL: PRINT CHR$(179);
 NEXT
 FOR I = LEFTCOL + 1 TO RIGHTCOL - 1
   LOCATE TOPROW, I: PRINT CHR$(196);
   LOCATE BOTROW, I: PRINT CHR$(196);
 NEXT

LOCATE (TOPROW + BOTROW) / 2, LEFTCOL - 15
PRINT CHR$(196);
PRINT CHR$(196);
PRINT CHR$(196);
PRINT CHR$(196);
PRINT CHR$(196);
PRINT CHR$(196);
PRINT CHR$(196);
PRINT CHR$(196);
PRINT CHR$(196);
PRINT CHR$(196);
PRINT CHR$(196);
COLOR 7, 1
PRINT CHR$(215);
COLOR 7, 1
PRINT CHR$(196);
PRINT CHR$(196);
PRINT CHR$(196);
PRINT CHR$(180);
PRINT "      DEG. C"
RETURN
```

```
' THIS SUBROUTINE DRAWS A THERMOCOUPLE BOX FOR THE SUPERHEATER

SHTCBOX:

TOPROW = YANCHOR: BOTROW = YANCHOR + 2: LEFTCOL = XANCHOR: RIGHTCOL =
XANCHOR + 14

 LOCATE TOPROW, LEFTCOL: PRINT CHR$(218);
 LOCATE TOPROW, RIGHTCOL: PRINT CHR$(191);
 LOCATE BOTROW, LEFTCOL: PRINT CHR$(192);
 LOCATE BOTROW, RIGHTCOL: PRINT CHR$(217);

FOR I = TOPROW + 1 TO BOTROW - 1
   LOCATE I, LEFTCOL: PRINT CHR$(179);
   LOCATE I, RIGHTCOL: PRINT CHR$(179);
 NEXT
 FOR I = LEFTCOL + 1 TO RIGHTCOL - 1
   LOCATE TOPROW, I: PRINT CHR$(196);
   LOCATE BOTROW, I: PRINT CHR$(196);
 NEXT

LOCATE (TOPROW + BOTROW) / 2, LEFTCOL - 3
PRINT CHR$(193);
PRINT CHR$(196);
PRINT CHR$(196);
PRINT CHR$(180);
PRINT "      DEG. C"

  RETURN



' THIS SUBROUTINE DRAWS THE ABSOLUTE PRESSURE TRANSDUCER
PTABS:

TOPROW = YANCHOR: BOTROW = YANCHOR + 2: LEFTCOL = XANCHOR: RIGHTCOL =
XANCHOR + 14

  LOCATE TOPROW, LEFTCOL: PRINT CHR$(218);
  LOCATE TOPROW, RIGHTCOL: PRINT CHR$(191);
  LOCATE BOTROW, LEFTCOL: PRINT CHR$(192);
  LOCATE BOTROW, RIGHTCOL: PRINT CHR$(217);


 FOR I = TOPROW + 1 TO BOTROW - 1
   LOCATE I, LEFTCOL: PRINT CHR$(179);
   LOCATE I, RIGHTCOL: PRINT CHR$(179);
  NEXT
  FOR I = LEFTCOL + 1 TO RIGHTCOL - 1
   LOCATE TOPROW, I: PRINT CHR$(196);
```

```
  LOCATE BOTROW, I: PRINT CHR$(196);
 NEXT

LOCATE (TOPROW + BOTROW) / 2, LEFTCOL - 7
PRINT CHR$(205);
PRINT CHR$(205);
PRINT CHR$(205);
COLOR 7, 1
PRINT CHR$(206);
COLOR 7, 1
PRINT CHR$(205);
PRINT CHR$(205);
PRINT CHR$(205);
PRINT CHR$(181);
PRINT "      KPAA";
LOCATE TOPROW + 1, LEFTCOL + 2
 RETURN

' THIS SUBROUTINE DRAWS THE DIFFERENTIAL PRESSURE TRANSDUCER
PTDIFF:

TOPROW = YANCHOR: BOTROW = YANCHOR + 2: LEFTCOL = XANCHOR: RIGHTCOL =
XANCHOR + 14

 LOCATE TOPROW, LEFTCOL: PRINT CHR$(218);
 LOCATE TOPROW, RIGHTCOL: PRINT CHR$(191);
 LOCATE BOTROW, LEFTCOL: PRINT CHR$(192);
 LOCATE BOTROW, RIGHTCOL: PRINT CHR$(217);


 FOR I = TOPROW + 1 TO BOTROW - 1
    LOCATE I, LEFTCOL: PRINT CHR$(179);
    LOCATE I, RIGHTCOL: PRINT CHR$(179);
 NEXT
 FOR I = LEFTCOL + 1 TO RIGHTCOL - 1
    LOCATE TOPROW, I: PRINT CHR$(196);
    LOCATE BOTROW, I: PRINT CHR$(196);
 NEXT

LOCATE (TOPROW + BOTROW) / 2, LEFTCOL - 7
PRINT CHR$(205);
PRINT CHR$(205);
PRINT CHR$(205);
COLOR 7, 1
PRINT CHR$(206);
COLOR 7, 1
PRINT CHR$(205);
PRINT CHR$(205);
PRINT CHR$(205);
PRINT CHR$(181);
PRINT "      KPAD";
```

```
LOCATE TOPROW - 3, LEFTCOL - 2
PRINT CHR$(203);
LOCATE TOPROW - 2, LEFTCOL - 2
PRINT CHR$(186);
LOCATE TOPROW - 1, LEFTCOL - 2
PRINT CHR$(200);
LOCATE TOPROW - 1, LEFTCOL - 1
PRINT CHR$(205);
LOCATE TOPROW - 1, LEFTCOL
PRINT CHR$(205);
LOCATE TOPROW - 1, LEFTCOL + 1
PRINT CHR$(205);
LOCATE TOPROW - 1, LEFTCOL + 2
PRINT CHR$(205);
LOCATE TOPROW - 1, LEFTCOL + 3
PRINT CHR$(205);
LOCATE TOPROW - 1, LEFTCOL + 4
PRINT CHR$(205);
LOCATE TOPROW - 1, LEFTCOL + 5
PRINT CHR$(205);
LOCATE TOPROW - 1, LEFTCOL + 6
PRINT CHR$(205);
LOCATE TOPROW - 1, LEFTCOL + 7
PRINT CHR$(187);
LOCATE TOPROW, LEFTCOL + 7
PRINT CHR$(208);
RETURN

' THIS SUBROUTINE DRAWS A BOX FOR THE UPSTREAM PYROMETER
PYROUP:

TOPROW = YANCHOR: BOTROW = YANCHOR + 2: LEFTCOL = XANCHOR: RIGHTCOL =
XANCHOR + 14

 LOCATE TOPROW, LEFTCOL: PRINT CHR$(218);
 LOCATE TOPROW, RIGHTCOL: PRINT CHR$(191);
 LOCATE BOTROW, LEFTCOL: PRINT CHR$(192);
 LOCATE BOTROW, RIGHTCOL: PRINT CHR$(217);

LOCATE (TOPROW + BOTROW) / 2, LEFTCOL - 1: PRINT "/";
LOCATE ((TOPROW + BOTROW) / 2), LEFTCOL + 8: PRINT "DEG. C";
LOCATE ((TOPROW + BOTROW) / 2) + 1, LEFTCOL - 2: PRINT "/";
LOCATE ((TOPROW + BOTROW) / 2) + 2, LEFTCOL - 3: PRINT "/";

  FOR I = TOPROW + 1 TO BOTROW - 1
   LOCATE I, LEFTCOL: PRINT CHR$(179);
   LOCATE I, RIGHTCOL: PRINT CHR$(179);
  NEXT
  FOR I = LEFTCOL + 1 TO RIGHTCOL - 1
   LOCATE TOPROW, I: PRINT CHR$(196);
   LOCATE BOTROW, I: PRINT CHR$(196);
```

```
 NEXT

 RETURN


' THIS SUBROUTINE DRAWS A BOX FOR THE DOWNSTREAM PYROMETER

PYRODOWN:

TOPROW = YANCHOR: BOTROW = YANCHOR + 2: LEFTCOL = XANCHOR: RIGHTCOL =
XANCHOR + 14

 LOCATE TOPROW, LEFTCOL: PRINT CHR$(218);
 LOCATE TOPROW, RIGHTCOL: PRINT CHR$(191);
 LOCATE BOTROW, LEFTCOL: PRINT CHR$(192);
 LOCATE BOTROW, RIGHTCOL: PRINT CHR$(217);

LOCATE ((TOPROW + BOTROW) / 2) - 2, LEFTCOL - 3: PRINT "\";
LOCATE ((TOPROW + BOTROW) / 2) - 1, LEFTCOL - 2: PRINT "\";
LOCATE (TOPROW + BOTROW) / 2, LEFTCOL - 1: PRINT "\";
LOCATE ((TOPROW + BOTROW) / 2), LEFTCOL + 8: PRINT "DEG. C";

FOR I = TOPROW + 1 TO BOTROW - 1
  LOCATE I, LEFTCOL: PRINT CHR$(179);
  LOCATE I, RIGHTCOL: PRINT CHR$(179);
 NEXT
 FOR I = LEFTCOL + 1 TO RIGHTCOL - 1
  LOCATE TOPROW, I: PRINT CHR$(196);
  LOCATE BOTROW, I: PRINT CHR$(196);
 NEXT
 LOCATE TOPROW + 1, LEFTCOL + 2
 RETURN


'THIS SUBROUTINE DISPLAYS EXPERIMENTAL SETTINGS AND
'PROMPTS THE USER FOR ACTION

ACTIONPROMPT:
COLOR 0, 7
FOR I = 1 TO 80
PRINT " ";
NEXT I
LOCATE 23, 1
PRINT " Mass Flux (KG/M^2-S):"; G!; "  Temperature (DEG. C):"; THERM!; "  Residence time (S):";
TIME#;
LOCATE 24, 1
COLOR 7, 1
FOR I = 1 TO 1
PRINT CHR$(196);
NEXT I
```

```
PRINT " :Cool SH; :Heat SH; :Settings Menu; :Agitate Sensor; :CW Step; :CCW Step";
FOR I = 1 TO 1
PRINT CHR$(196);
NEXT I
COLOR 0, 7
LOCATE 24, 2: PRINT "C"; : LOCATE 24, 13: PRINT "H"; : LOCATE 24, 24: PRINT "M"; :
LOCATE 24, 41: PRINT "A"; : LOCATE 24, 59: PRINT "+"; : LOCATE 24, 70: PRINT "-";
COLOR 7, 1
LOCATE 25, 1
PRINT "       : Insert; : Remove; : Quit; : Start experiment; : Zero instruments ";
COLOR 0, 7
LOCATE 25, 1: PRINT "CTRL+"; : LOCATE 25, 8: PRINT "I"; : LOCATE 25, 19: PRINT "S"; :
LOCATE 25, 30: PRINT "Q"; : LOCATE 25, 39: PRINT "E"; : LOCATE 25, 60: PRINT "Z";
COLOR 7, 0

RETURN




'SUBROUTINE ZERO FOR ADJUSTING THE ZERO OF PRESSURE TRANSDUCERS and
PYROMETERS.

ZERO:
    CLS
    PRINT "                ZERO ADJUST PROCEDURE       "
    PRINT
    PRINT " THIS PROCEDURE AUTOMATICALLY ADJUSTS THE PRESSURE TRANSDUCER"
    PRINT " AND PYROMETER ZERO OFFSETS AND UPDATES THEIR VALUE IN THE FILE"
    PRINT " ZEROS.NUM. THIS PROCEDURE CAN BE DONE ONLY BEFORE HEATING UP"
    PRINT " THE SYSTEM, I.E., IT ASSUMES A ROOM TEMPERATURE 20 DEGREE CELSIUS."
    PRINT " ALL AIR, STEAM AND WATER FLOWS MUST BE OFF. THE DRY PAPER SHEET"
    PRINT " MUST BE INSERTED FOR PYROMETER CALIBRATION."
    PRINT
    PRINT
    INPUT " IS THE PAPER SHEET INSERTED? (Y/N)", ret$
    IF (ret$ = "n") OR (ret$ = "N") THEN GOTO pzero
          BP!(1) = BP!(1) - (RDGS!(9) - RDGS!(2))
          BP!(2) = BP!(2) - (RDGS!(10) - RDGS!(2))
pzero:
    PRINT
    INPUT "ENTER VALUE OF ATMOSPHERIC PRESSURE (MM. HG): ", P.ATM!
    ATM! = P.ATM! * 101.325 / 760
    BP!(3) = BP!(3) - (RDGS!(11) - ATM!)
    BP!(4) = BP!(4) - RDGS!(12)
    BP!(5) = BP!(5) - RDGS!(13)
    BP!(6) = 0
    BP!(7) = 0


ZEROSAVE:
```

```
        OPEN "ZEROS.NUM" FOR OUTPUT AS #4
    FOR I = 1 TO 7
        WRITE #4, BP!(I)
    NEXT I
        CLOSE #4
CLS
GOTO DRAWSCREEN

RETURN



'THIS SUBROUTINE IS FOR SHEET INSERTION

SAMPLEIN:
CALL XODV(PORT1, SM.IN.MASK, OUTP.HI)
DELTIME# = 0.50: GOSUB DELAY
CALL XODV(PORT1, SM.IN.MASK, OUTP.LO)
SLIDE$ = "IN "
COLOR 15, 4
LOCATE 12, 50
 PRINT SLIDE$;
COLOR 0, 7
RETURN



'THIS SUBROUTINE IS FOR SHEET WITHDRAWAL

SAMPLEOUT:
CALL XODV(PORT1, SM.OU.MASK, OUTP.HI)
DELTIME# = 0.50: GOSUB DELAY
CALL XODV(PORT1, SM.OU.MASK, OUTP.LO)
   SLIDE$ = "OUT"
COLOR 15, 4
LOCATE 12, 50
 PRINT SLIDE$;
COLOR 0, 7
RETURN


SCANNER:

'THIS SUBROUTINE CONTROLS SCANNING OF THE MOISTURE SENSOR.

'THE DIRECTION OF MOTION AND ALL WINDINGS OFF (AWO) COMMANDS ARE
CONTROLLED
'BY TTL-LEVEL SIGNALS FROM DIGITAL OUTPUT PORT 0 OF THE DT-2801A BOARD TO
'THE EXTERNAL INDEX INPUT PORT OF THE SLO-SYN SP255.

'THE MOTOR START AND CLEAR/LOAD COMMANDS REQUIRE HIGHER LEVEL (5 V)
'SIGNALS, WHICH ARE SUPPLIED BY ANALOG OUTPUT PORTS 0 AND 1 OF THE DT-2801A
```

```
'BOARD TO THE TERMINAL STRIP OF THE SLO-SYN SP255.

'THE ANGULAR MOVEMENT PER STEP IS SET BY ADJUSTING THE DIP SWITCHES ON
'THE CONTROLLER. THE NUMBER OF STEPS AND DELAY BETWEEN STEPS ARE SET IN
'SOFTWARE.

'
'COMMANDS TO THE SLO-SYN SP255 INDEXER DRIVE ARE THE FOLLOWING: '

'DIGITAL COMMANDS:

'XODV (0, CCW.MASK, OUTP.LO)   'COUNTERCLOCKWISE MOTION OFF
'XODV (0, CCW.MASK, OUTP.HI)   'COUNTERCLOCKWISE MOTION ON
'XODV (0, AWO.MASK, OUTP.LO)   'ALL WINDINGS OFF OFF
'XODV (0, AWO.MASK, OUTP.HI)   'ALL WINDINGS OFF ON

'ANALOG COMMANDS

'XDV (0, 0)           'MOTOR START OFF
'XDV (0, 4095)        'MOTOR START ON
'XDV (1, 0)           'CLEAR/LOAD OFF
'XDV (1, 4095)        'CLEAR/LOAD ON

COLOR 15, 4

'LOAD DIRECTION

CALL XODV (0, CCW.MASK, OUTP.LO)     'INITIAL DIRECTION IS CLOCKWISE
CALL XDV (1, 4095)
DELTIME# = STEP.DEL#: GOSUB DELAY
CALL XDV (1,0)
DELTIME# = STEP.DEL#: GOSUB DELAY


'MOVE MOTOR CLOCKWISE

FOR ITER = 1 TO STEPS

IRANGLE = IRANGLE + 1
LOCATE 18, 22
PRINT USING " ###"; IRANGLE          'IR SENSOR POSITION

CALL XDV(0, 4095)                'MOTOR START ON
DELTIME# = STEP.DEL#: GOSUB DELAY
CALL XDV (0,0)                   'MOTOR START OFF
DELTIME# = DELSTEP!- STEP.DEL#: GOSUB DELAY

NEXT ITER


'REVERSE DIRECTION
```

```
CALL XODV (0, CCW.MASK, OUTP.HI)      'NEW DIRECTION IS COUNTERCLOCKWISE
CALL XDV (1, 4095)                    'LOAD MOTION DIRECTION
DELTIME# = STEP.DEL#: GOSUB DELAY
CALL XDV (1,0)
DELTIME# = STEP.DEL#: GOSUB DELAY


'MOVE MOTOR COUNTERCLOCKWISE

FOR ITER = 1 TO STEPS
IRANGLE = IRANGLE - 1
LOCATE 18, 22
PRINT USING " ###"; IRANGLE           'IR SENSOR POSITION

CALL XDV(0, 4095)                     'MOTOR START ON
DELTIME# = STEP.DEL#: GOSUB DELAY
CALL XDV (0,0)                        'MOTOR START OFF
DELTIME# = DELSTEP! - STEP.DEL#: GOSUB DELAY

NEXT ITER
RETURN


'THIS SUBROUTINE CONVERTS DIGITAL DATA INTO PHYSICAL QUANTITIES

CONVERSION:

'CONVERT TEMPERATURES

FOR I = 0 TO 7
TEMP! = BITS%(I)
CHIP% = I + 1
GOSUB TEMP
RDGS!(I+1) = TEMP!
NEXT I


'CONVERT OUTPUT OF LINEAR INSTRUMENTS (PRESSURE GAUGES, PYROMETERS,
'                          MOISTURE SENSOR, FLOWMETER)
FOR I = 8 TO 15
RDGS!(I+1) = MP!(I-7) * BITS%(I) + BP!(I - 7)
NEXT I


'RECORD IR POSITION

'GOSUB SCANNER               'GET SENSOR HEAD POSITION FROM SUBROUTINE
RDGS!(17) = IRANGLE          'CURRENT POSITION OF IR SENSOR

' COMPUTE MASS FLUX
```

```
TEMP! = .5 * (RDGS!(1) + RDGS!(2)) + 273.2
RHO! = 1000 * PREGA! / (RS! * TEMP!)          'DENSITY, KG/M^3
RDGS!(18) = (RDGS!(13) * RHO!/ AREA!)/1000     'MASS FLUX, KG/M^2-S

' COMPUTE DRYING RATE

DELTAX! = RDGS!(15) - OLDX!
DELTATIME# = RDGS!(O) - OLDTIME#
IF DELTATIME# <> 0 THEN
RDGS!(19) = -3.6 * BW! * DELTAX! / DELTATIME#
ELSE
RDGS!(19) = 0
END IF

OLDX! = RDGS!(15)          'THE CURRENT TIME AND MOISTURE CONTENT ARE
OLDTIME# = RDGS!(0)          'STORED HERE TO BE USED AS ORIGINS THE
                            'NEXT TIME THE SUBROUTINE IS CALLED.

RETURN

'THIS SUBROUTINE AGITATES SENSOR ONCE

SCANMAN:

'STEPPER MOTOR INITIALIZATION

CALL XODV (0, AWO.MASK, OUTP.LO)       'SUPPLY CURRENT TO MOTOR WINDINGS
CALL XDV (1, 4095)
DELTIME# = STEP.DEL#: GOSUB DELAY
CALL XDV (1, 0)
DELTIME# = STEP.DEL#: GOSUB DELAY

GOSUB SCANNER

'TURN MOTOR WINDINGS OFF

CALL XODV (0, AWO.MASK, OUTP.HI)    'ALL WINDINGS
CALL XDV (1, 4095)                  'CLEAR/LOAD
DELTIME# = STEP.DEL#: GOSUB DELAY
CALL XDV (1, 0)
DELTIME# = STEP.DEL#: GOSUB DELAY

RETURN

'THIS SUBROUTINE MOVES SENSOR ONE STEP AWAY FROM USER

CWSTEP:

'STEPPER MOTOR INITIALIZATION
```

```
CALL XODV (0, AWO.MASK, OUTP.LO)        'SUPPLY CURRENT TO MOTOR WINDINGS
CALL XDV (1, 4095)
DELTIME# = STEP.DEL#: GOSUB DELAY
CALL XDV (1, 0)
DELTIME# = STEP.DEL#: GOSUB DELAY

'LOAD DIRECTION

CALL XODV (0, CCW.MASK, OUTP.LO)      'DIRECTION IS CLOCKWISE
CALL XDV (1, 4095)
DELTIME# = STEP.DEL#: GOSUB DELAY
CALL XDV (1,0)
DELTIME# = STEP.DEL#: GOSUB DELAY

'MOVE MOTOR CLOCKWISE ONCE

IRANGLE = IRANGLE + 1
LOCATE 18, 22
PRINT USING " ###"; IRANGLE          'IR SENSOR POSITION

CALL XDV(0, 4095)                 'MOTOR START ON
DELTIME# = STEP.DEL#: GOSUB DELAY
CALL XDV (0,0)                    'MOTOR START OFF
DELTIME# = 0.5#: GOSUB DELAY

'TURN MOTOR WINDINGS OFF

CALL XODV (0, AWO.MASK, OUTP.HI)    'ALL WINDINGS
CALL XDV (1, 4095)                'CLEAR/LOAD
DELTIME# = STEP.DEL#: GOSUB DELAY
CALL XDV (1, 0)
DELTIME# = STEP.DEL#: GOSUB DELAY

RETURN

'THIS SUBROUTINE MOVES SENSOR ONE STEP TOWARDS USER

CCWSTEP:

'STEPPER MOTOR INITIALIZATION

CALL XODV (0, AWO.MASK, OUTP.LO)        'SUPPLY CURRENT TO MOTOR WINDINGS
CALL XDV (1, 4095)
DELTIME# = STEP.DEL#: GOSUB DELAY
CALL XDV (1, 0)
DELTIME# = STEP.DEL#: GOSUB DELAY

'LOAD DIRECTION

CALL XODV (0, CCW.MASK, OUTP.HI)     'DIRECTION IS COUNTERCLOCKWISE
CALL XDV (1, 4095)                'LOAD MOTION DIRECTION
DELTIME# = STEP.DEL#: GOSUB DELAY
```

```
CALL XDV (1,0)
DELTIME# = STEP.DEL#: GOSUB DELAY


'MOVE MOTOR COUNTERCLOCKWISE ONCE

IRANGLE = IRANGLE - 1
LOCATE 18, 22
PRINT USING " ###"; IRANGLE          'IR SENSOR POSITION

CALL XDV(0, 4095)                   'MOTOR START ON
DELTIME# = STEP.DEL#: GOSUB DELAY
CALL XDV (0,0)                      'MOTOR START OFF
DELTIME# = 0.5#: GOSUB DELAY

'TURN MOTOR WINDINGS OFF

CALL XODV (0, AWO.MASK, OUTP.HI)    'ALL WINDINGS
CALL XDV (1, 4095)                  'CLEAR/LOAD
DELTIME# = STEP.DEL#: GOSUB DELAY
CALL XDV (1, 0)
DELTIME# = STEP.DEL#: GOSUB DELAY

RETURN
```