FINAL REPORT

ENERGY CONSERVATION RESEARCH IN THE PAPER AND ALLIED PRODUCTS INDUSTRY
PHASE I

By

J. L. Clark, W. D. Holcombe, E. M. Hartley, and W. W. Carr

Prepared for

DEPARTMENT OF ENERGY
OFFICE OF CONSERVATION AND SOLAR APPLICATIONS
DIVISION OF INDUSTRIAL ENERGY CONSERVATION

Under
Contract No. DE–AS05–78CS–40098
(Formerly EM–78–S–05–5961)

OCTOBER 1979

GEORGIA INSTITUTE OF TECHNOLOGY

Engineering Experiment Station
Atlanta, Georgia 30332

1979

ENERGY CONSERVATION RESEARCH IN THE PAPER AND ALLIED PRODUCTS INDUSTRY

PHASE I

Investigators:

J. L. Clark
W. D. Holcombe
E. M. Hartley
W. W. Carr

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Atlanta, Georgia 30332

October, 1979

Prepared for the

Department of Energy
Office of Conservation and Solar Applications
Division of Industrial Energy Conservation
Contract No. DE-AS05-78CS-40098
(Formerly EM-78-S-05-5961)

ABSTRACT

The Engineering Experiment Station of the Georgia Institute of Technology has conducted for the Department of Energy a study of certain concepts for energy conservation in the paper manufacturing industry. The primary emphasis of the study was evaluation of a textile industry device called a Machnozzle as an aid to dewatering of the press section felts. Experimental results indicate that significant reduction in felt moisture may be obtained by installing and operating the Machnozzle just prior to the suction box. Analysis of the economic and energy impact is hampered by lack of a clear understanding of the relationship between felt moisture and paper sheet moisture. Further study in this area is recommended.

Also addressed in this project is the concept of maintaining higher feedstock temperatures, particularly through retention of thermal energy from the pulping process. Various problems relating to high temperature processing are discussed.

ACKNOWLEDGEMENTS

Assistance on this project has been provided by numerous people outside of the Georgia Tech community. During the survey of relevant literature, information was solicited and received from many sources in the felt manufacturing industry, and their contributions are appreciated.

During the tests conducted at the Herty Foundation, members of the staff provided valuable recommendations and commentary in addition to the facilities and services supplied formally. Individuals to whom thanks is particularly due include William L. Belvin, Director, J. Robert Hart, Assistant Director, and Eugene "Red" Kraszeski, Pilot Plant Manager.

Before and during the tests conducted on the experimental press section at Albany Felt Company, several members of the Albany research staff made considerable contribution to the program. In particular, appreciation is expressed to Edward F. DeCrosta, Director of Research and Development, Wesley Plaistead, Senior Development Engineer, and Al Caprood, Junior Development Engineer. Wes Plaistead and John Lewyta, Development Engineer, also provided assistance during a portion of the testing at the Herty Foundation.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SECTION I

INTRODUCTION AND PROGRAM PLAN

This report summarizes the work performed by the Georgia Institute of Technology's Engineering Experiment Station for the U. S. Department of Energy under contract number DE-AS05-78CS-40098. The purpose of the project was to investigate various techniques for the reduction of energy consumption in the paper manufacturing process.

A portion of the project addressed the feasibility of utilizing higher feedstock temperatures. In principle, the high temperatures of the pulping process could be retained to the head box. This not only would allow for reduced viscoscity and surface tension during drainage at the wire, but would also mean that less heat would be required to raise the temperature of the sheet and evaporate water in the dryer section. Problems associated with this concept are discussed in Section III of this report.

The primary objective of the project, however, was the evaluation of a device called a Machnozzle as an aid to dewatering the felt in the press section. One of the purposes of the press section felt is to absorb water from the sheet of paper as it passes through the nip of the press rolls. In addition to the water removed from the paper sheet, water is added to the felt by showers which are intended to remove contaminants and pulp fibers from the felt.

The felt forms a continuous loop, and the water must be removed before the felt again passes through the nip. Normally, the water is removed by a suction box or vacuum box which draws air through the felt, entraining the water in the air flow.

The suction box does not completely dry the felt, and there is always a significant residual mositure in the felt as it returns to the nip. Generally, a lower residual felt moisture will allow for greater moisture absorption from the paper. This relationship is not necessarily always true, and there is disagreeement among authorities in the field as to just how important felt moisture is to press performance.

The consideration of an optimum felt moisture is discussed later in this report. For the moment, however, it is adequate to note that mill operators are generally interested in obtaining a drier felt as is evident from the work which has been conducted to improve suction box performance. Therefore, tests were conducted to evaluate the Machnozzle as a means of obtaining improved felt dewatering.

The Machnozzle is a device designed and marketed by Brugman Machinefabriek of the Netherlands as a component for a fabric washing and drying system for the textile manufacturing industry. The Machozzle is basically a heavy-walled pressure vessel with a very narrow exit slit. It is designed to be operated with either high pressure steam or compressed air. The operating fluid leaves the Machnozzle at a very high velocity. Because of the very small size of the slit, however, the mass flow rate is relatively low.

The cross-section of the Machnozzle is illustrated in Figure 1 showing the fabric passing across the nozzle at the exit slit. A cut-away view is presented in Figure 2. In the textile manufacturing process, the Machnozzle is able to contribute significantly to the dewatering process. Placed between a wringer and a steam drum dryer, it can provide a lower moisture content than the wringer and uses less energy than the steam drums.

In the textile role, however, the fabric is much thinner than a press felt and is moving much slower. Therefore, prior to this project, the Machnozzle had not been tested in an application at all similar to a paper machine press section. In a

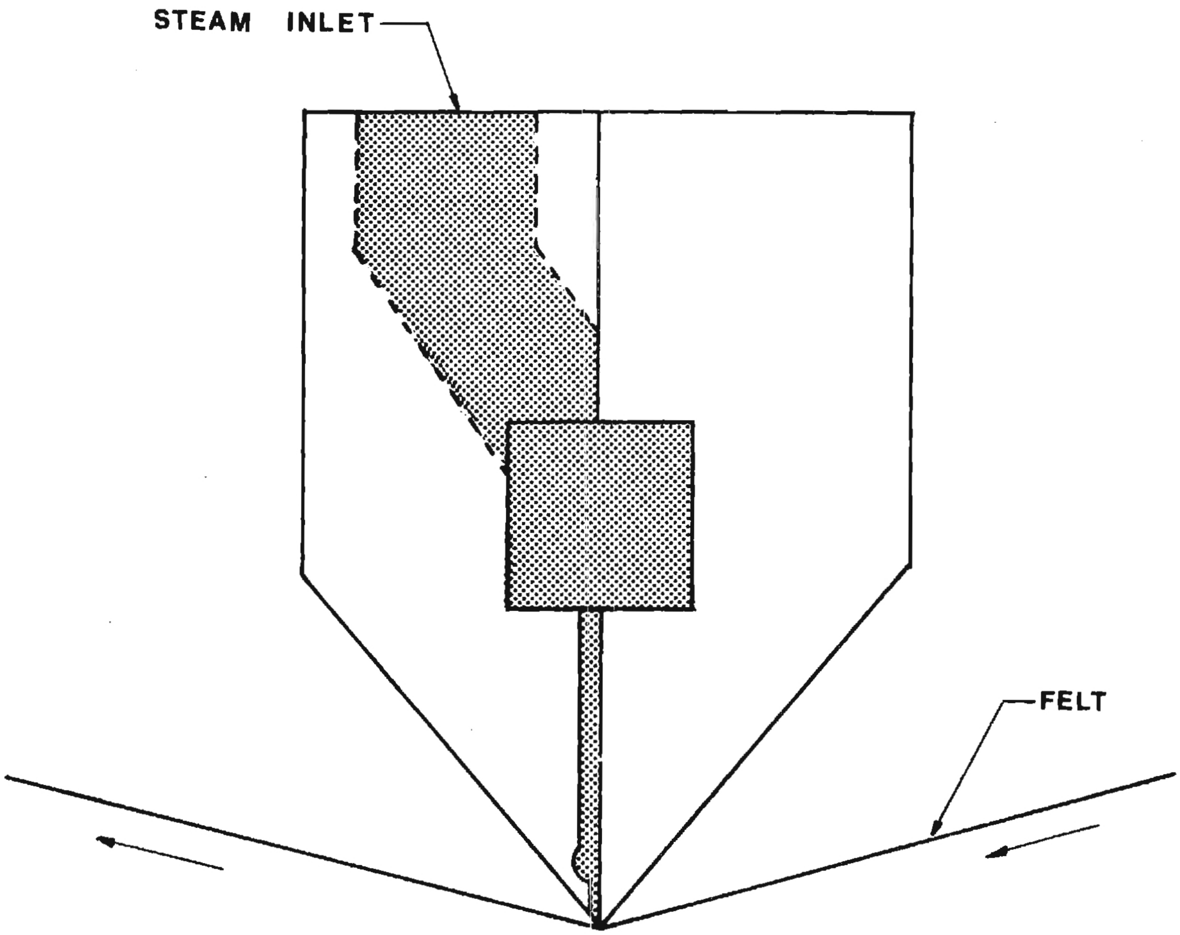
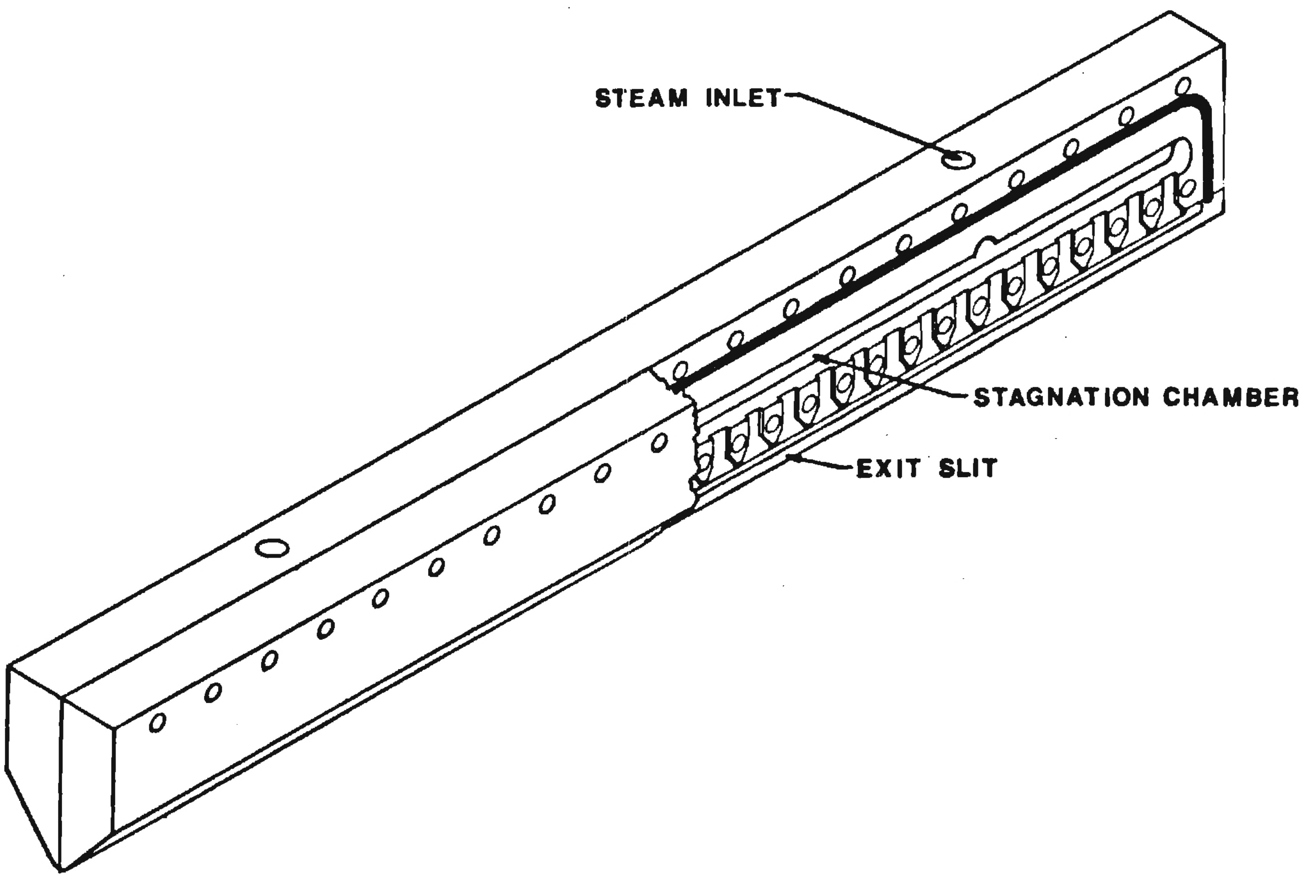


FIGURE 1: MACHNOZZLE CROSS SECTION



MACHNOZZLE - CUT AWAY VIEW

FIGURE 2

completely unrelated study, J. B. Wheeldon and G. Ackworth have investigated a similar phenomena for felt dewatering. (1)

The test program, as originally planned, was to have been conducted in its entirety on the 36 inch Fourdrinier pilot machine at the Herty Foundation in Savannah, Georgia. The Herty Foundation is a state-owned, contract research and testing facility devoted entirely to the pulp and paper industry.

Specific tasks to be conducted on the pilot machine included the following:

1. Establish a baseline of the moisture content of the sheet at various points through the machine.
2. Establish a baseline of the mass and energy flows for the machine.
3. Install the Machnozzle on the press section and measure its effect on felt moisture, sheet moisture, and energy flows.

While each of these tasks was performed and is covered in this report, it was determined early in the program that the test plan must be modified in order to provide the most useful results. This decision was based on shortcomings in the capabilities of the pilot machine. In particular, the maximum speed available was of the order of 200 to 250 feet per minute, and the drying capacity was far in excess of that required. These two features are so atypical of most production equipment that it was felt that the research results would not be readily accepted by the industry. Personnel at the Herty Foundation indicate that they have never developed a process on the pilot machine that could not be duplicated later on production equipment. However, the evaluation of the Machnozzle involves such time and speed dependent phenomena that there was reservation about the suitability of this pilot machine as a sole test facility.

For these reasons, arrangements were made with Albany Felt Company to utilize a portion of their research facilities in Albany, New York. Tests were conducted on an experimental press section which permitted thorough evaluation of the Machnozzle's ability to aid in felt dewatering to speeds as high as 3000 feet per minute.

This experimental press section did not provide for evaluating the effect of the improved felt dryness on sheet moisture since there was no paper sheet being processed. Since the tests at the Herty Foundation also were less than conclusive, the testing conducted under this project can state with conviction only how effective the Machnozzle is in dewatering the felt. While estimates of sheet drying are discussed based on the work of other researchers, further tests with the Machnozzle will be necessary in order to make definitive conclusions as to energy conservation and economic impact of this device for the paper industry.

SECTION II

SUMMARY AND RECOMMENDATIONS

Under this research program, experimental work was conducted to evaluate the applicability of a Machnozzle as an aid to dewatering of the press section felts. Tests conducted on an experimental press section investigated a variety of operating conditions considered representative of production equipment. Speeds from 500 to 3000 ft/min were examined. The test methodology involved establishing a baseline operating condition and measuring felt moisture after the suction box, then turning on the Machnozzle and determining the change in felt moisture.

The conclusions from these tests include the following:

1. The Machnozzle clearly aids in suction box dewatering of a press section felt.
2. The Machnozzle is not suitable as a replacement for a suction box.
3. Using steam or compressed air as the operating fluid will provide similar results if similar pressures are used; however, the mass flow rate of the air will be higher.
4. The Machnozzle should be installed against the back side of the felt and just upstream of the suction box.
5. At an operating pressure of 100 psig, the steady-state moisture content of the felt may be reduced approximately 11%. If the Machnozzle slit is shimmed open by 0.002 inches, the moisture level may be reduced by approximately 22%.

Further tests were conducted on a pilot paper machine. The initial tests involved establishing a baseline for the mass and energy flows. During these tests, measured flows accounted for 99% of the pulp and 99.2% of the water entering the headbox. The energy balance on the dryer section accounted for 98.9% of the steam energy supplied.

Tests of the Machnozzle on the pilot paper machine confirmed the effect on felt moisture. The effect on sheet moisture was obscured by variability in the data. Knowledge of the relationship between felt moisture and sheet moisture is essential in order to assess the economic and energy impact of the Machnozzle.

It is recommended that further study of the use of the Machnozzle in this application be conducted with emphasis on determining directly the effect of the nozzle on sheet moisture out of the press and the resulting implications to the industry. Various potential operating problems must also be evaluated.

Also under this project, the effect of maintaining higher feedstock temperatures was studied through a review of the relevant literature. Maintaining a high sheet temperature (66°C) on the fourdrinier and in the press section has several advantages: increased water removal which effects a savings in dryer section steam requirement or increased production rate, a decrease in dryer steam to bring the sheet up to dryer temperature, increased sheet strength from hot pressing, freight savings from higher sheet density and a reduction in breaks on the paper machine. The disadvantages of using steam showers to heat the web are avoided; these disadvantages being cost of steam and additional moisture removal load from the condensed steam.

In receiving high temperature stock from the pulp mill and maintaining this high temperature through stock preparation and paper forming, there can be potential problems in several areas. Stock preparation refining in a disc refiner apparently results in a lower tear strength, although other strength tests such as burst and tensile apparently can be achieved with less energy. As the stock temperature increases, formation problems increase, although newsprint and linerboard machines are now running at 66°C without prohibitive formation problems. Fine paper machines where formation is critical would require close study.

With higher stock and sheet temperature, corrosion increases and microbiological activity changes. The industry is currently undergoing a move to close up the white water system which results in and is necessary for higher sheet temperature, so these problems are being dealth with. Closing up the white water system effects a water savings but introduces problems with build up of dissolved solids, fiber fines and colloidal organics.

Energy savings from reduced dryer steam requirement are on the order of $1.40 per ton, reduced refining savings are on the order of $0.37 per ton; and water savings are on the order of $0.57 per ton. The total savings of $2.34 per ton can be more than offset by the increased costs of corrosion and additives to control deposits, foaming, depositions, corrosion, microbiological activity.

Higher sheet temperature in the stock preparation equipment such as chest agitation, screens and cleaners reportedly can be achieved at a lower energy expenditure, but no cost data is available.

This study should be expanded to include:

1. Pulp mill costs to supply stock to the paper mill at high temperature, 60°C.

2. A quantitative evaluation of energy requirements of higher temperature stock for stock chest agitation, screens, and cleaners.

3. Paper mill capital costs for equipment to filter or otherwise cleanup recycled white water.

4. Research on stock preparation refining to eliminate a loss of tear strength.

5. An evaluation of savings from:

   a. Higher sheet strength from hot pressing

b. Breaks reduction

c. Freight savings from higher sheet density

6. A more detailed study of individual model mills; linerboard, mechanical pulp, fine paper, etc.

SECTION III

EFFECTS OF MAINTAINING HIGHER FEEDSTOCK TEMPERATURES

Introduction

Higher sheet temperature on the paper machine, from the headbox to the first dryers, has well known benefits. The lower viscosity of the water in the sheet affords increased drainage through the fourdrinier fabric and in the wet presses. This means a dryer sheet into the dryer section and a decreased dryer steam requirement to vaporize the remaining water in the sheet. Mechanically removing water on the fourdrinier and in the wet presses is generally 40 times more economical than the phase change removal in the dryers. A second benefit is the decrease in steam required in the dryers for sensible heat to bring the sheet up to temperature. A common practice in papermaking is to add steam to the paper machine wirepit and/or to use a steam shower on the fourdrinier after the dry line and/or at the entrance to the wet press nips. The steam shower steam condenses on and in the surface of the sheet thereby transferring the heat of condensation to the sheet and raising the sheet temperature. The penalty for this process is the cost of the steam and the increased water (condensed steam) to be removed from the sheet. Because the steam cost for the steam showers and/or wire pit is at best marginally less than the steam costs saved in the dryers, this practice is used mainly on linerboard machines which are production limited by the dryer section capacity. Decreased sheet moisture into the dryers affords an increased production rate.

This study consists of a survey of the literature to determine the feasibility of maintaining high stock temperature thorughout the paper mill to the paper machine dryers. The temperature of the pulp from the digesters or mechanical pulp refiners is near the saturation temperature, $100^{+o}C$. The requirements for maintaining the pulp at a high temperature throughout the pulp mill processes of washing, screening, etc., are beyond the scope of this study. However, there are no technical reasons why this couldn't be accomplished and the pulp delivered to the paper mill at the same temperature as is reached by the steam shower application. The economics of maintaining high pulp temperature through the pulp mill would require a separate study. Maintaining higher than usual stock temperatures in paper mill processes where normally a lower temperature stock is processed are considered. These processes include:

High temperature stock agitation in stock surge and storage chests

High temperature stock preparation refining

Sheet formation on the fourdrinier

Corrosion

Microbiological activity

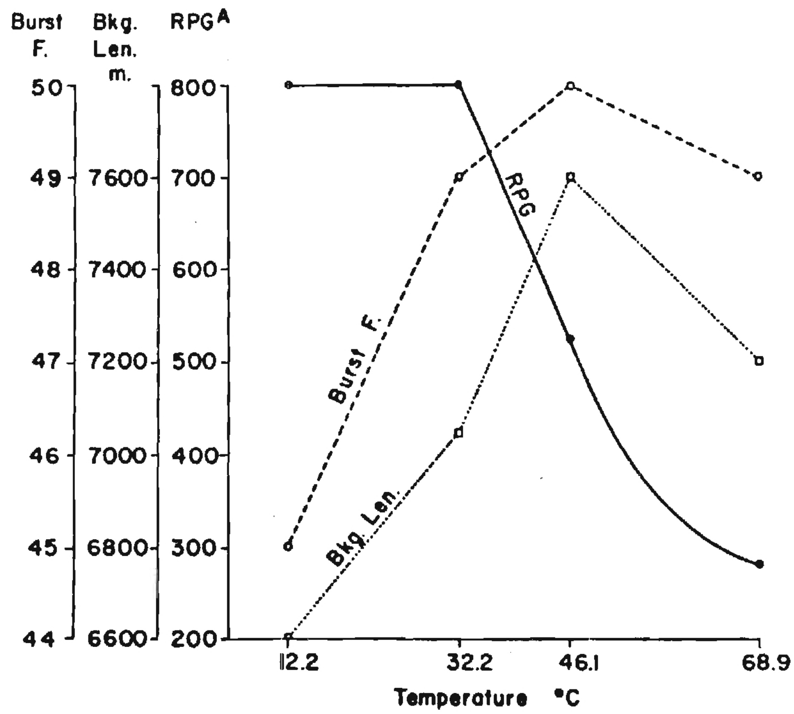
Screens and cleaners operation

The Effect of Temperature on Stock Preparation Refining

The opinion of one knowledgeable scientist (2) is that temperature of Kraft pulp stock preparation refining causes secondary effects. At higher temperatures the water will extract more soluble carbohydrates and other components yielding higher BOD and COD in the effluent. This extractive process is suspected to affect the ease or difficulty of developing strength and affect the drainage resistance at a given energy imparted to the pulp.

One manufacturer (3) of refining equipment includes the following information on refining of unbleached Southern Kraft pulp in their company publication: As temperature increases, energy requirement to achieve any freeness decreases;

bulk, tear, and fiber length are reduced with corresponding increase in bonding strength. The values given in this reference have been graphed, Figures 3 and 4. This work was done on a Kollergang laboratory beating device, the procedure for which is covered by TAPPI Suggested Method T225 SM-60, 1943. The energy of beating is represented by the RPG, that is, the number of revolutions of the rollers per gram of pulp. As can be seen in Figures 3 and 4, as the temperature was increased from 32.2°C to 69.8°C, the energy required for beating to a Canadian Standard Freeness (CSF) of 550 ml was markedly reduced from 800 to 280 RPG. The CSF of the pulp is interpreted by some as a measure of the rate of drainage on the Fourdrinier and (inversely) the strength of the web. This interpretation has been disputed (4) and there is some question as to whether the two pulps, one at 12-32°C and one at 69°C would perform the same on the fourdrinier from the standpoint of their physical and chemical condition. One would anticipate a higher drainage rate by virtue of the decreased viscosity of water at the higher temperature. Speculation as to the strength is not necessary as test results are provided. Fiber length was reduced, and as would be expected, the tear factor also decreased. This would ordinarily be interpreted as an increase in cutting of the fibers. The two strength tests, burst and breaking length performed similarly in that each peaked at 46.1°C and fell off at 68.9°C with the cause not immediately apparent. The pertinent question is whether or not the results of kollergang lab beating are representative of results in a mill using full size disc refiners. If these were to be considered representative, then to refine successfully at high temperature, the intensity of refining should be decreased to prevent cutting of the fiber. Other investigations to prevent decrease of strength tests would be called for, although the burst and breaking length, while less at 68.9°C than at 46.1°C, are equal to or higher than at the two lower temperatures.

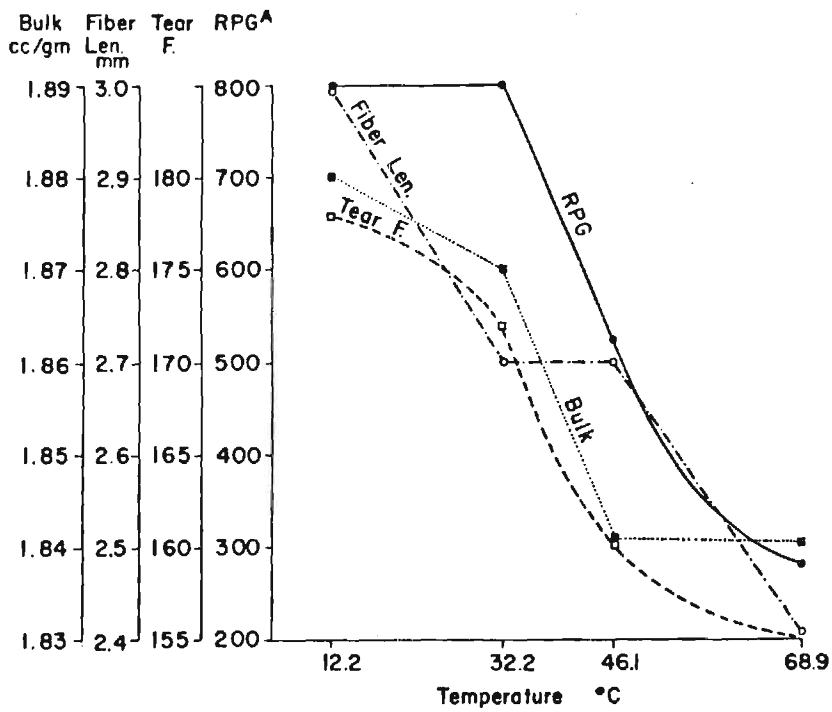


^A Beating Extent,
Rev. Per Gram

Constants : CSF = 550 Ml
Cons. = 1.1%
Clearance = 0.0049 In
Rotor Vel. = 1360 Fpm

EFFECT OF KOLLERGANG BEATING TEMPERATURE ON BLEACHED SOUTHERN PINE – KRAFT

FIGURE 3



ABeating Extent, Rev Per Gram

Constants: CSF = 550 Ml
Cons. = 1.1%
Clearance = 0.0049 In
Rotor Vel. = 1360 Fpm

EFFECT OF KOLLERGANG BEATING TEMPERATURE ON BLEACHED SOUTHERN PINE

FIGURE 4

Clark (4), page 309, cites Stephenson (18), and Richter (9) as evidence that an increase in temperature slows down the rate of beating. Richter (9) is discussed below and contains no evidence of the temperature affect on beating above 45°C. Stephenson's work, however, gives data on beating at 64°C vs. 23°C for 5 hours. The burst, folding and stretch decreased appreciably. Again, this implies that increased beating time hence increased energy is required to reach the same strength at higher temperature. The author makes the interesting point that beating to a freeness as a measure of beating leads to conflicting data. This is because it will take longer to reach a freeness value at higher temperature as production of debris is decreased. The softening of the fibers by the warmth makes them less liable to fracture and there is an increased tendency for the debris to form aggregates. The result then may be that to refine to a predetermined freeness value will give a stronger pulp, not because of the higher temperature but because of the additional beating needed to reach that freeness because of decreased fines production.

The author states that at high temperature (with the resulting lowered viscosity) the cushioning effect of the water between the fibers in a wad diminishes and the absorbed molecular layers around their interior surfaces become thinner. The increased temperature likely decreases fibrillation by not permitting splits to separate as far and allow adjacent surfaces in splits a greater opportunity to reunite.

The Beloit Corp., Jones Div., Dalton, MA, was extremely helpful and cooperative in assisting with this project (5). Figures 5, 6, 7, and 8 are results from recent unbleached Kraft pulp disc refiner trials at temperatures of 32.2°C, 43°C, and 54.4°C made at Beloit Research. In Figure 5, the specific energy consumption was 56.8 MJ/t less at 43° and 54.4°C than at 32.2°C. this tends to qualitatively verify the data in the Beloit publication (3) showing lower energy consumption at

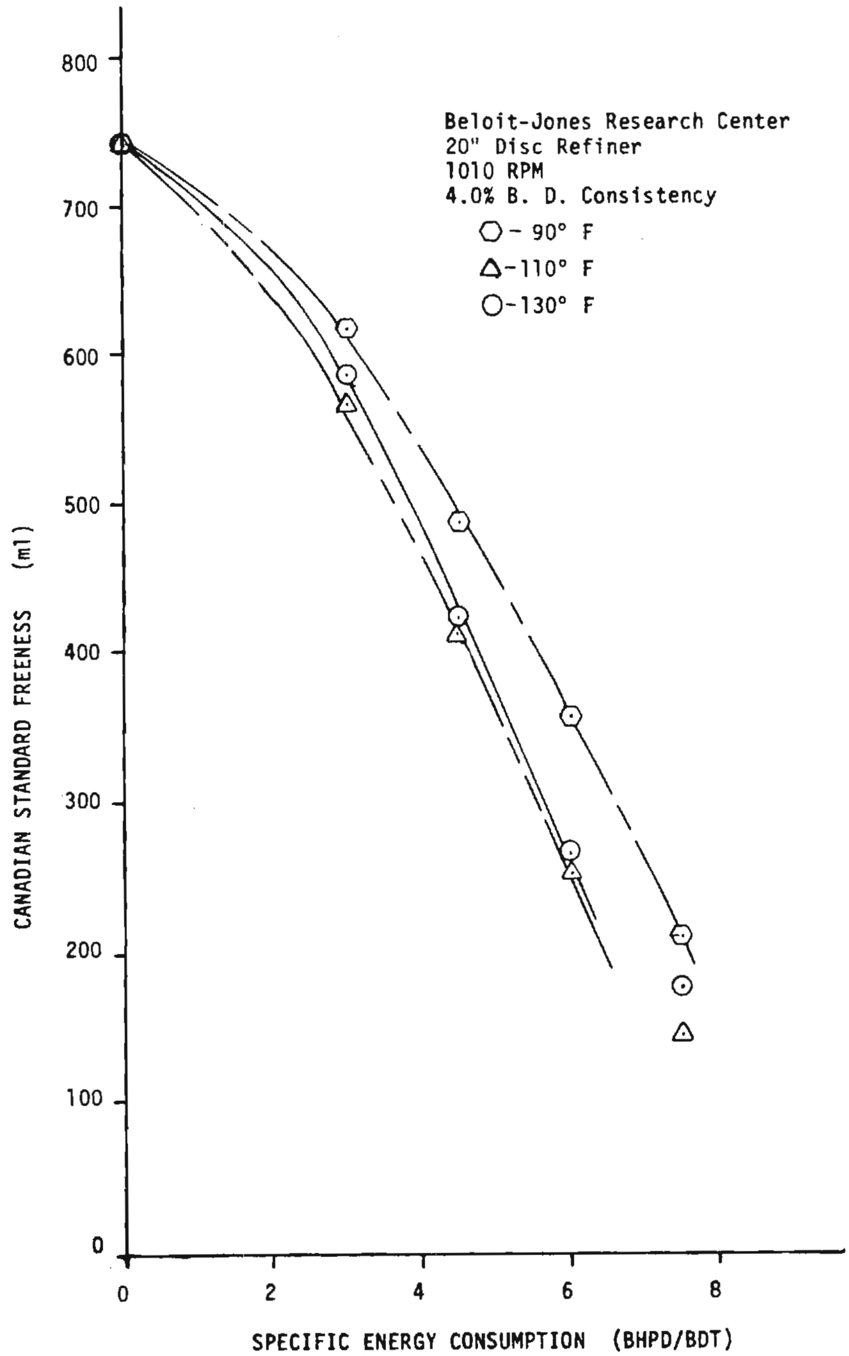


FIGURE 5: EFFECT OF BEATING TEMPERATURE ON ENERGY CONSUMPTION

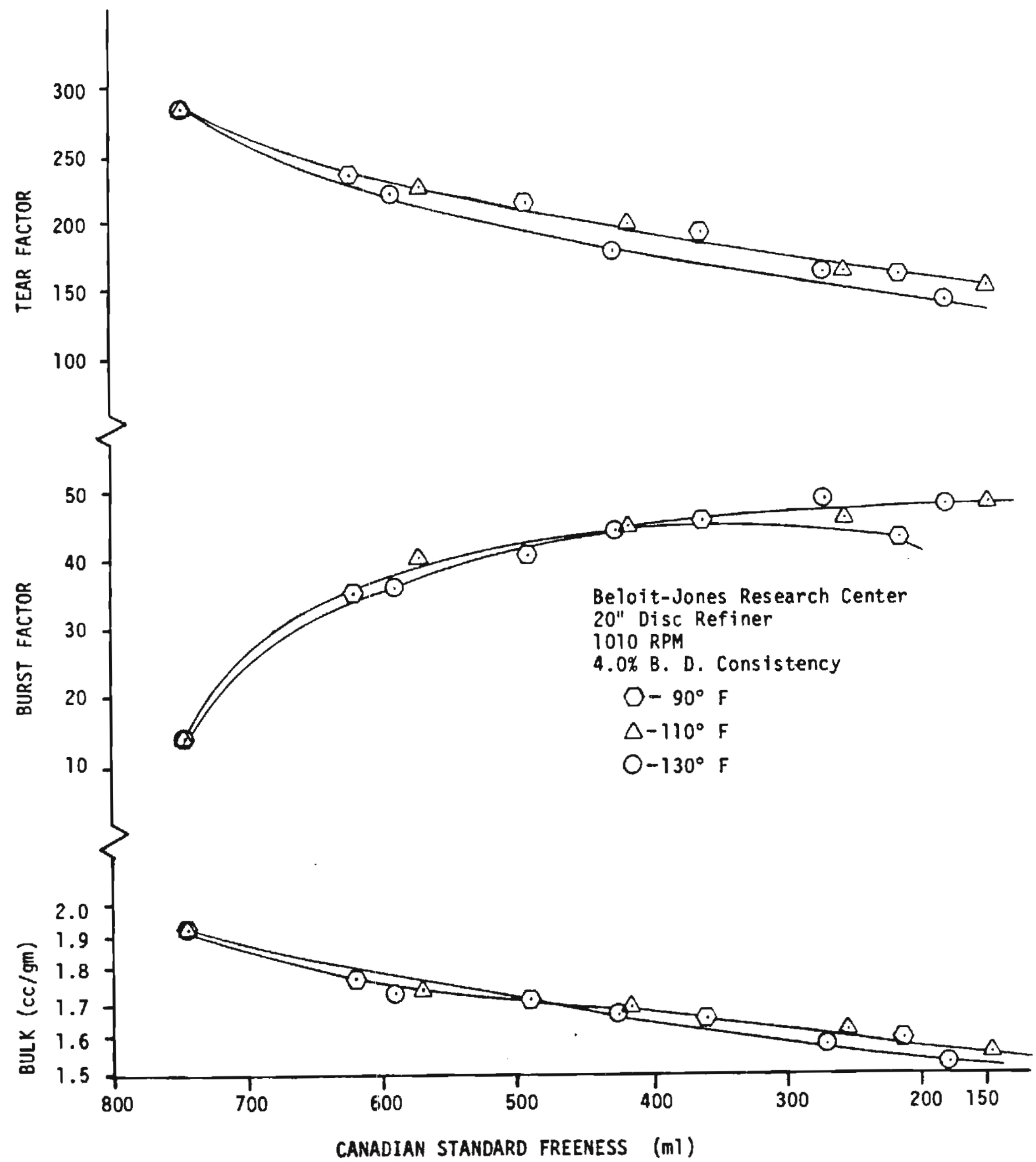


FIGURE 6 EFFECT OF BEATING TEMPERATURE ON STREGTH

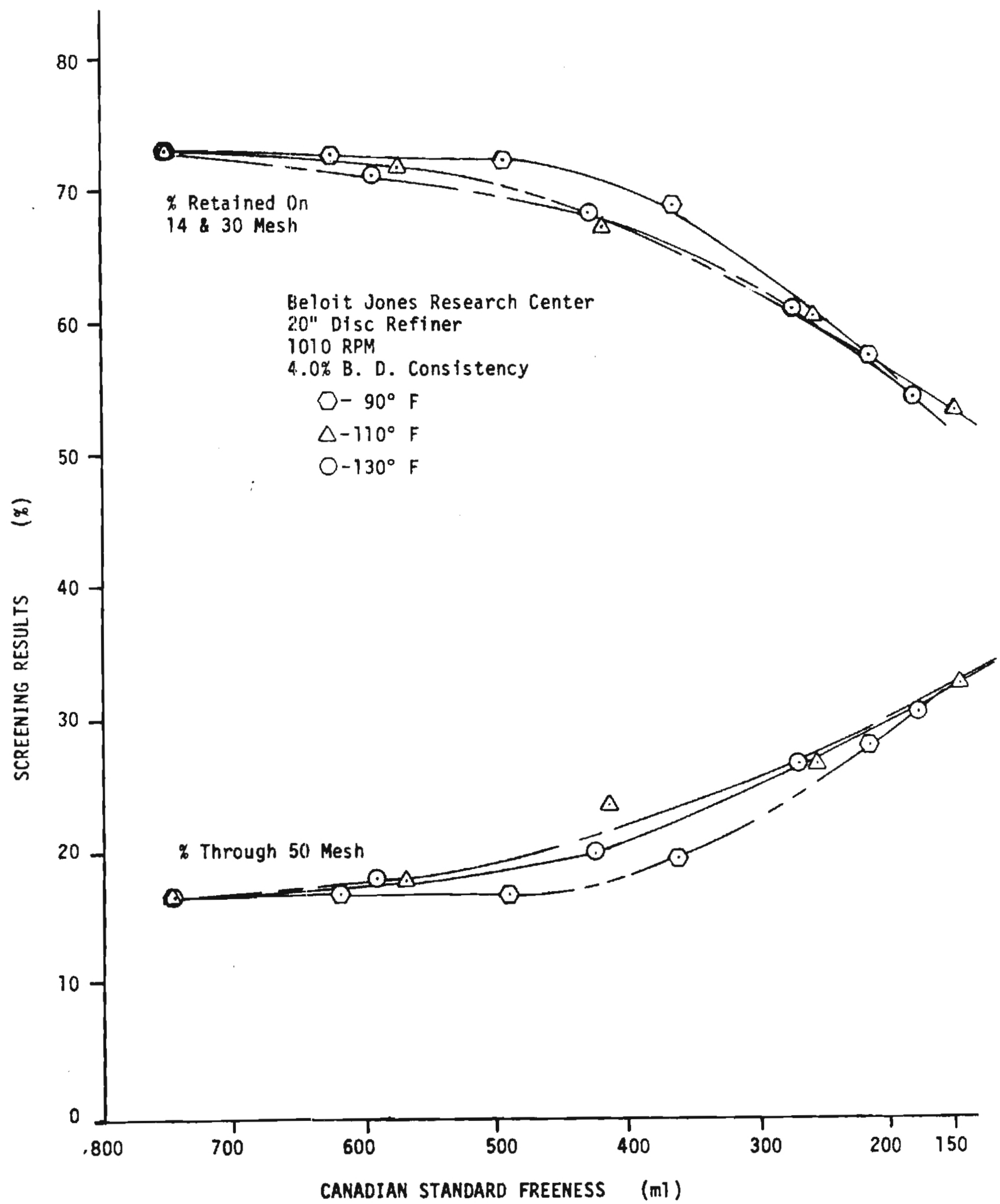


FIGURE 7 EFFECT OF BEATING TEMPERATURE ON SCREENING RESULTS

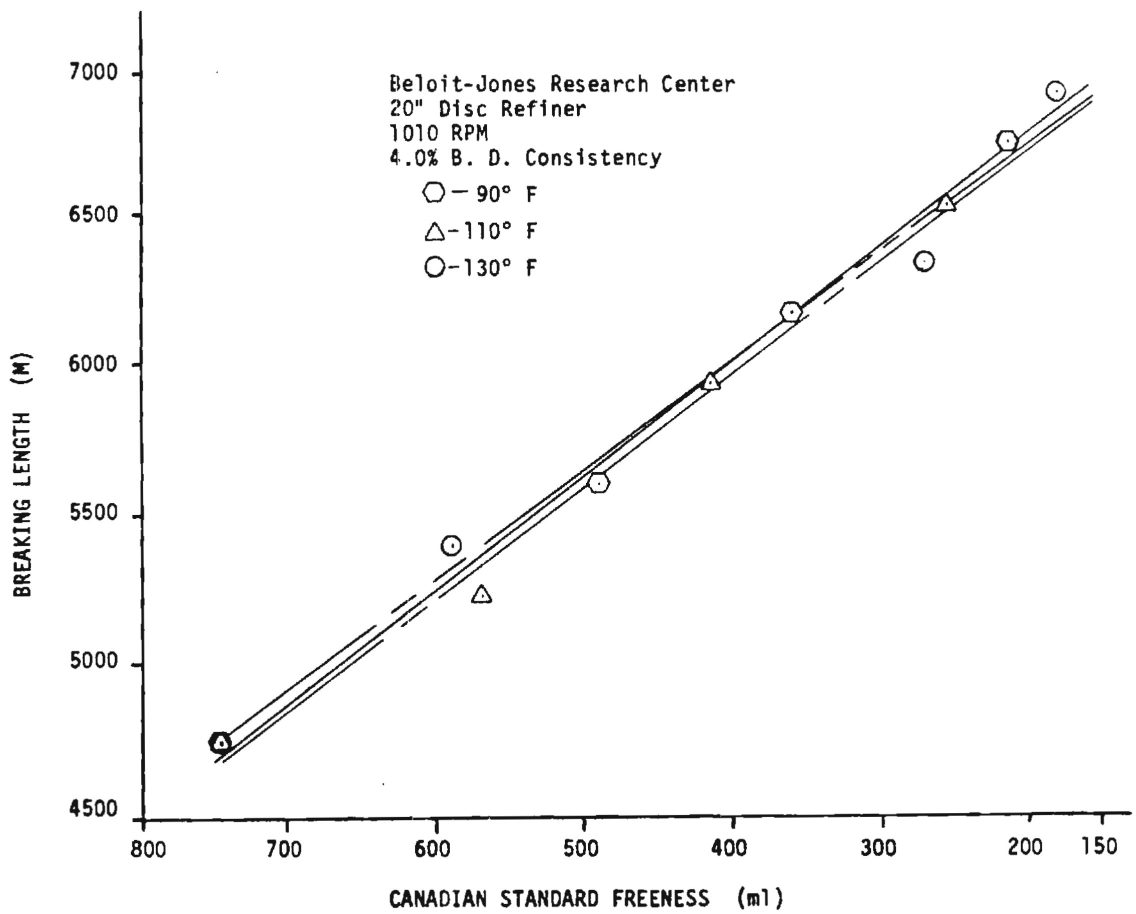


FIGURE 8 EFFECT OF BEATING TEMPERATURE ON BREAKING LENGTH

higher temperature. The strength tests at all three temperatures are close to being the same; Figures 6 and 7. Tear factor, Figure 7, was a bit lower at the high temperature with about the same change as with the kollergang method reported in the Beloit publication (2). Long fiber retention, Figure 8, was slightly higher at 32.2°C than at 43°C and 54.4°C. This tends to verify the kollergang data, indicating an increase in cutting at higher temperature. The well known text by Casey (6) lists high temperature, 50 to 90°C, in the second stage of refining as necessary for developing maximum strength of semichemical pulp. Refining of semichemical pulp is ordinarily done in two stages. The first stage is done after cooling and is primarily a defiberizing action. It is generally done at high temperature, 93°C. The second stage of refining is similar in nature and purpose to the stock prep refining of Kraft pulp and is done for strength development.

Espenmiller (7) states that stock temperature is a minor refining variable. The cooler the water temperature the better the quality of stock produced, but in the range of 15.5° to 54.4°C the temperature effect is not too significant. At 71.1°C and higher, less strength will be developed at the same specific energy input. This publication contains no supporting data or references but, according to the author, is a condensed version of a Black Clawson Co. unpublished internal report.

Glasl (8) states high temperature decreases efficiency in refining because the increase in specific surface by fiber swelling is diminished. There is no data or references supporting this position. Richter (9) gives data on sulphite-base alpha-fiber beaten in a ball mill at temperatures of 45°C, 24°C, and 2°C, as shown in Table I.

Since 45°C can be considered a normal refining temperature in many mills, this data can be considered a measure of lower than normal refining temperature. The data shows that at the same beating time, lower temperature favors a higher

TABLE I. EFFECT OF BEATING TEMPERATURE
ON SLOWNESS AND STRENGTH

	45^oC	24^oC	2^oC	2^oC
Time of beating, min.	100	100	100	75
Slowness	7	10	18	8
Shrinkage, %	18	19.5	22	19
Burst	104	110	116	109
Tear	250	250	245	265

slowness and, as would be expected, a higher burst strength. Tear change was slight. This indicates that as temperature of beating is reduced from normal, less energy is required to reach a given slowness and strength. According to the author, the faster hydration rate is probably explained by greater swelling and hence a looser fiber structure which promotes easier fibrillation and greater rupture of internal bonds. The author mentions another set of experiments in which undried softwood kraft pulp showed a 7% loss in maximum burst when beating temperature was 45^{o}C rather than 20^{o}C and a dried sulphite pulp showed a 12% loss in maximum strength. Fifteen per cent additional beating time was required to reach a slowness of 10 with undried kraft and 40% additional with commercially dried sulphite base. The author states low beating temperature benefits certain grades such as the glassines and higher temperature favors flatness and dimensional stability. This is probably due to the lower shrinkage at higher temperature in the data above. The question as usual is how well does ball mill beating agree with modern disc refiner beating. The author also gives data confirming that stock beaten at low temperature suffers no strength loss when raised to a high temperature but does have a significant decrease in slowness, hence will have improved drainage rate on the wires. This, of course, is common knowledge to paper makers.

In a series of tests, circa 1937, using a laboratory ball mill (10), a pulp was beaten for the same length of time and the same 30,000 revolutions at four different temperatures. As can be seen in the data of Table II, lower temperature favors a higher strength development.

To confirm these phenomena, in another test, the pulp was beaten to the same 45^{o} S.R. freeness and the higher temperature required the longest beating time. According to the author, this data proves the temperature of the water does not have any bearing on the character of the beating, only on its speed. This data, in

TABLE II. RELATION BETWEEN BEATING TEMPERATURE AND BEATING DEGREE

Beating temperature, ^{o}C	6	15	20	30
^{o} S.R.	45	41	39	36
Relative bursting strength	103.0	101.1	100.0	99.6
Relative tensile strength	101.3	102.5	200.0	99.5

Table III, shows that a lower than normal temperature allows a given strength development in a shorter period of time and possibly at a lower energy consumption.

Feltman (11), circa 1958, states 9 HP - days per ton should be available for summer refining of foodboard and 8 HP for winter refining. This is an increase of 12.5% in energy required for the higher temperature refining. Although no other details are given, the author states that water temperature has a great deal to do with type of physical characteristics retained by sheet during refining and water temperature above 26.7°C requires additional horsepower to give the same physical tests to the sheet.

Casey (12), 1960, states that temperature is an important variable in the beating of pulp. Beating qualities are affected by the difference in water temperature between summer and winter in many mills. The references cited by Casey, numbering eighteen, are dated from 1916 to 1958 and none contain any data on effect on temperature on refining in a disc refiner. Casey cites Libby and Ronning (14), circa 1949, who found that in beating strong sulfite pulp in the Noble and Wood laboratory beater, beating rate was increased progressively when the temperature of beating was lowered from 80 to 5°C when wet-lap pulp was used. However, the author says that higher strength results from higher temperatures, (40°C gave best all-around strength results) at the same drainage times, and this is contrary to the result of most other investigators. Apparently the difference in results depends on the type of beating. Libby and Ronning found that lower beating temperatures at the same freeness value gives a higher drainage time.

The advantages of low temperature beating for fiber swelling and fiber bonding is partly explained by the fact that fiber swelling is an exothermic reaction (15). Cellulose is probably more nearly "soluble" in cold water. Cellulose fibers become more or less dehydrated, brittle, and shrink at high temperature. Heating

TABLE III. RELATION BETWEEN BEATING TEMPERATURE AND BEATING TIME

Beating temperature, °C	6	15	20	30
° S.R.	45	45	45	45
Relative beating time	87.3	94.1	100.0	107.6
Relative bursting strength	100.0	100.4	100.0	99.8
Relative tensile strength	101.0	99.1	100.0	100.8

chemical wood pulps to the boiling point decreases the strength markedly (16). Exactly the opposite effect is obtained on groundwood, which at a consistency of 2% or less gains strength if heated to 75 - 85^{o}C (17). According to Rubin (13), 1935, the best and strongest paper has been reported as made in the fall and spring when water temperature is 4.4 - 10^{o}C.

Three observations result from a study of the temperature effect on refining of chemical pulp:

1. Published data of recent work on a modern disc refiner is very scarce. In this study none was found.
2. The data on energy requirements to reach the same strength development at various temperatures are contradictory.
3. Data is commonly reported in the form of beating time at various temperatures to develop the same freeness. According to one author (4), this may be misleading. A better measure of refining is energy required at various temperatures to reach the same strength development with effect on drainage also reported.

Reference (3) provides data on unbleached Southern Kraft in a Kollergang lab beater which show a 65% decease in energy required to reach a CSF of 550 ml when temperature is increased from 32.2^{o}C to 68.9^{o}C. The burst test and breaking length were highest at 46.1^{o}C and decreased only 2% and 5% respectively at 68.9^{o}C. Tear factor and fiber length decrease 13% and 20% respectively. The implication being that cutting was increased at the higher temperature and if avoided, the strength possibly could have increased at 68.9^{o}C rather than resulting in the 2% and 5% decrease. Reference (12) has a statement to the effect that higher strengths result from higher temperatures. To the contrary, references (4), (8), (9), (10), (11), (12), either report a higher energy requirement at higher temperatures for equal strength development or they report data which implies the same. Reference (10) gives data on Kraft pulp beaten in a Lampen mill at temperatures of from 6 to 30°C. The beating time (energy requirement) was increased 23% at 30°C to give essentially the same burst and tensile strength as at 6°C. This data indicates that energy savings result from refining at temperatures below 30°C and does not speak of temperature above 30°C as does reference (2) discussed above. Reference (9) is similar to Reference (10) in that temperatures of 45°C and below are covered. References (2) and (7) suggest temperature is a secondary or minor variable. Reference (7) states temperature effect is not too significant in the range 15.5 to 54.4°C. Reference (12) mentioned above states the difference in results apparently is caused by differences in types of beating. Reference (5), unpublished, is the only data found covering a modern disc refiner. Unbleached Kraft pulp was refined at 32.2°C, 43°C, and 54.4°C (pulp exited refiner at 60°C). To reach approximately the same strengths, 0.8 HPD/T less energy was required at 43°C and 54.4°C than at 32.2°F. At the higher temperature, long fiber retention and tear factor were a bit lower.

The physical effects on the fibers at higher temperature refining were reported as follows: Reference (4); at higher temperatures, the fiber is softened, making it less liable to fracture, and there is an increased tendency for debris to form aggregates. So, with a decreased tendency for debris to form and increased tendency for debris to agglomerate, a longer time is required to reach a given freeness, and the pulp will be stronger because of fewer fines. At higher temperature and lower viscosity of water, the cushioning effect of the water decreases, and the absorbed water layers in the fiber interior become thinner. Fibrillation is decreased because splits cannot separate as far and adjacent surfaces in splits can reunite easier. Reference (7); the lower water viscosity and high temperature tends to drive off the so-called water hydration. Reference (8); high temperature decreases efficiency in refining because the increase in specific surface by fiber swelling is diminished. Reference (9); at the lower temperatures, hydration rate is faster, and this is explained by greater swelling, a looser fiber structure, easier fibrillation, greater rupture of internal bonds. Higher temperature favors flatness and dimensional stability because of lower shrinkage. Reference (12); fiber swelling is an exothermic reaction favored by lower temperature. Cellulose is more nearly "soluble" in cold water. Fibers dehydrate, become brittle and shrink at high temperature.

Some reported advantages then to high temperature chemical pulp refining are reduced fines production, possibly lower no load energy requirement because of lower water viscosity.

The strength and drainage characteristics of high temperature refined pulp may be affected by the higher extraction by the hot water. The BOD and COD of the effluent will be higher; Reference (2). Stock preparation refining of semi-chemical pulp is improved by high temperature; Reference (6). Mechanical pulp, as in common knowledge, is refined at temperatures near or at the boiling point (TMP). Heating mechanical pulp results in the pulp gaining strength; Reference (12).

Steam Shower Effects

Hodges (19) has done experimental work on raising sheet temperature by steam showers on the fourdrinier and presses for three types of paper machines; fine papers, linerboard, and bleached board.

Fine Paper: In heating the sheet from 37.8°C, the following was reported for 66.6 g/m^2 and 103.6 g/m^2 basis weight grades

Steam box on 1st press: $$\frac{0.052 \frac{\text{kg moi.}}{\text{kg fiber}} \text{ decrease in moisture to dryers}}{32.22^{\circ}\text{C increase in sheet temperature}}$$

or $0.00160 \frac{\text{kg moi.}}{\text{kg fiber-}^{\circ}\text{C}}$ over a range of 37.8°C to 70°C

Steam box on 2nd press: $$\frac{0.060 \frac{\text{kg moi.}}{\text{kg fiber}} \text{ decrease in moisture to dryers}}{33.88^{\circ}\text{C increase in sheet temperature}}$$

or $0.00177 \frac{\text{kg moi.}}{\text{kg fiber-}^{\circ}\text{C}}$ over a range of 37.8°C to 7.17°C

Steam box on 3rd press, calculated:

$$\frac{0.024 \frac{\text{kg moi.}}{\text{kg fiber}} \text{ decrease in moisture to dryers}}{5.555^{\circ}\text{C increase in sheet temperature}}$$

or $0.00432 \frac{\text{kg moi.}}{\text{kg fiber-}^{\circ}\text{C}}$

The Gurley air resistance increased as a result of the sheet being more closed.

Linerboard: In heating the sheet from 54.4°C (all tests included a steam box on the fourdrinier):

Steam box on 1st press: $\dfrac{0.017\ \frac{\text{kg moi.}}{\text{kg fiber}}\ \text{decrease in moisture to dryers}}{12.8^{\circ}\text{C increase in sheet temperature}}$

or $0.00133\ \dfrac{\text{kg moi.}}{\text{kg fiber-}^{\circ}\text{C}}$ over a range of 54.4°C to 67.22°C

Steam box on 2nd press: $\dfrac{0.023\ \frac{\text{kg moi.}}{\text{kg fiber}}\ \text{decrease in moisture to dryers}}{14.44\ ^{\circ}\text{C increase in sheet temperature}}$

or $0.00159\ \dfrac{\text{kg moi.}}{\text{kg fiber-}^{\circ}\text{C}}$ over a range of 54.4°C to 68.9°C

Steam box on 3rd press: $\dfrac{0.042\ \frac{\text{kg moi.}}{\text{kg fiber}}\ \text{decrease in moisture to dryers}}{16.7^{\circ}\text{C increase in sheet temperature}}$

or $0.00252\ \dfrac{\text{kg moi.}}{\text{kg fiber-}^{\circ}\text{C}}$ over a range of 54.4°C to 71.1°C

Data is given for a steam box on the 3rd press and fourdrinier heating the sheet from 65.6°C:

$$\dfrac{0.063\ \frac{\text{kg moi.}}{\text{kg fiber}}\ \text{decrease in moisture to dryers}}{23.3^{\circ}\text{C increase in sheet temperature}}$$

or $0.0027\ \dfrac{\text{kg moi.}}{\text{kg fiber-}^{\circ}\text{C}}$ over a range of 65.6°C to 88.9°C

Porosity was reduced and there was inconclusive evidence that burst and tensile were improved. If true, an improvement in strength would result in a savings in stock preparation refining energy consumption. Benefits from a shower on a press was found to be additive to the benefits from a shower on the fourdrinier. A reduction in breaks also was found, and this would result in a production increase per unit of energy expended.

Bleached Board. The steam shower on the fourdrinier and ahead of the dual press resulted in approximately 2% moisture reduction. Data was not given on increase in sheet temperature, but the reported moisture reduction results are quite similar to linerboard data. A density increase was found which could result in a higher weight per roll of finished board and effect a freight savings, hence a transportation energy savings.

Potential moisture removal by maintaining high sheet temperature is increased over the results above because it would be simulating high head box temperature, a steam shower on the fourdrinier and on all three presses. The data above is for a single steam shower location except as noted. No data is given on the moisture content of the sheet at the various locations. A wetter sheet into a press usually results in increased water removal. Steam shower steam consumption, kg steam/kg additional moisture removal, was shown and ranged from a low of about 4 on the linerboard third press to a high of about 33 on the fourdrinier of the fine paper machine. A corrugating medium machine at Green Bay Packaging (20) running 26 lb board of 80% NSSC and 20% box clippings was reported to reduce sheet moisture at the reel by 6% with a steam shower on the fourdrinier. An additional 2% reduction in sheet moisture was obtained by an additional steam shower located on the first press. Sheet temperature immediately after the fourdrinier shower was increased from 63.3^{o}C to 85^{o}C and after the first press nip was 68.3^{o}C. Wire pit temperature was maintained at 65.5^{o}C. Sheet temperature into the dryers was 60^{o}C. Because of the higher temperature in the first press nip, sheet density was increased and concora crush was increased 3 to 4 points. Again, the density effect results in transportation energy savings and the strength increase reduces refining energy requirements.

An unbleached western softwood kraft linerboard machine (21) at a Hoerner Waldorf mill accomplished significantly higher machine speeds by putting steam showers on the first two presses of the machine's three wet presses. For the lighter weights, 127 and 161 g/m^2, the machine was not dryer limited, and the second press shower was not used. For the heavier weights, up to 439.4 g/m^2 basis weight, the machine speed increase afforded by steam shower is translatable to a decreased dryer steam consumption at a constant machine speed.

A decreased steam usage in the dryers at constant machine speed results from increasing the sheet temperature on the fourdrinier and in the press nip, but generally the steam shower steam requirement is higher than the steam savings in the dryers. Therefore, only when a machine is dryer limited are steam showers used as the increase in production is worth many times the cost of steam shower steam.

Experimental data is given for a fourdrinier newsprint machine (23) running 70 - 74% stone groundwood and 26 - 30% slush semi-bleached kraft at 823 - 915 meters/min. For a headbox temperature increase of 11.11°C (from 32.22°C to 43.33°C) the decrease in moisture to the dryers was 0.11 kg moisture/kg fiber (from 1.62 to 1.51 kg moi./kg fiber) or $\frac{\text{0.01 kg moi. decrease in moi. to the dryers}}{\text{kg fiber-}^{\circ}\text{C}}$.

This is significantly higher benefit than that found by Hodges for fine paper, linerboard, or bleached board. This is probably due to the free nature of the mechanical pulp. Data is needed for moisture reduction by increased sheet temperature in the presses, since Hodges found that the last press nip shows the greatest benefit. Some data is also given on the effect of felt shower water temperature. Tentatively a 17 - 22°C increase in water temperature decreases press sheet moisture by 1%. Wet end breaks were more likely to occur with low shower water temperature. A dryer steam consumption of 1.5 kg per kg of water evaporated was assumed in this study.

Summary - Steam Shower Effects

Use of steam showers to raise sheet temperature and thereby decrease moisture to the dryers is common practice on dryer limited machines to increase production rate. If pulp or sheet high temperature could be maintained throughout the paper mill processes to the dryers, thereby eliminating steam shower costs, increased dewatering on the fourdrinier and in the wet presses would result in a savings in dryer steam or an increased production rate or both. This increased water removal is documented above for fine paper, linerboard, bleached board and newsprint. In most paper machine operations involving dewatering during and/or immediately following sheet formation, wet pressing, and drying, this philosophy is a valid potential energy saver. Increased moisture removal is a linear function of sheet temperature over the ranges investigated. An energy saving results from higher sheet temperature into the dryers by saving the steam required to heat the sheet to the dryer temperature. The calculation is as follows:

$$\frac{\text{kg fiber}}{\text{kg product}} \times (\Delta\text{T of sheet, }^{o}\text{C}) \times \frac{\text{kg steam condensed}}{\text{kg moisture evaporated}} \times$$

$$\frac{1}{\text{Heat of vapor. of sheet moi.,}\frac{\text{kcal}}{\text{kg moi.}}} \times \left[\frac{\text{kg moi. into dryer}}{\text{kg fiber}} \times \right.$$

$$\left. \text{Heat cap. of sheet moi. } \frac{\text{kcal}}{\text{kg-}^{o}\text{C}} + \text{Heat cap. of sheet fiber, } \frac{\text{kcal}}{\text{kg-}^{o}\text{C}}\right]$$

Example, (linerboard), assume:

6% product moisture; $\frac{94 \text{ kg fiber}}{100 \text{ kg product}}$

Temperature of sheet into dryer: $50^{o}C$

Temperature of sheet in constant drying rate section of dryer: $82^{o}C$

$$1.5\ \frac{\text{kg steam condensed in dryer}}{\text{kg moisture evaporated}}$$

$H_{vap.}$ of sheet moisture in dryers: $550\ \frac{\text{kcal}}{\text{kg moi.}}$ at $82^{o}C$

63% sheet moisture into dryer: $\frac{\text{60 kg moi.}}{\text{40 kg fiber}}$

C_p sheet moi.: $\frac{\text{1 kcal}}{\text{kg moi.-}^{o}\text{C}}$

C_p sheet fiber: $\frac{\text{0.3 kcal}}{\text{kg fiber-}^{o}\text{C}}$

$$\frac{\text{94 kg fiber}}{\text{100 kg product}} \times (32^{o}C) \times 1.5\frac{\text{kg steam cond.}}{\text{kg moi. evap.}} \times \frac{\text{kg moi.}}{\text{550 k cal}} \times$$

$$\left[\frac{\text{63 kg moi.}}{\text{37 kg fiber}} \times \frac{\text{1kcal}}{\text{kg-}^{o}\text{C}} + \frac{\text{0.3 kcal}}{\text{kg-}^{o}\text{C}}\right] = 0.1643\frac{\text{kg steam conserved}}{\text{kg product}}$$

For the same case, the savings in steam by dewatering is calculated:

$$0.00544\ \frac{\text{kg decrease in moi. to dryers}}{\text{kg fiber - }^{o}\text{C}} \times 32^{o}C =$$

$$\frac{\text{0.1741 kg decrease in moi. to dryer}}{\text{kg fiber}}$$

$$0.1741\ \frac{\text{kg moi.}}{\text{kg fiber}} \times 1.5\ \frac{\text{kg steam condensed}}{\text{kg moi. evap.}} \times \frac{\text{94 kg fiber}}{\text{100 kg product}} =$$

$$0.2455\frac{\text{kg steam conserved}}{\text{kg product}}$$

Total steam conservation in the dryers then is 0.1643 kg steam plus 0.2455 kg steam or 0.4098 kg dryer steam per kg product. Steam shower steam requirement:

$$4 \frac{\text{kg steam}}{\text{kg additional moi. removed}} \times 0.00544 \frac{\text{kg additional moi. removed}}{\text{kg fiber - }^{o}\text{C}}$$

$$\times \; 32^{o}\text{C} \times \frac{94 \text{ kg fiber}}{100 \text{ kg product}} = 0.6545 \frac{\text{kg steam shower steam required}}{\text{kg product}}$$

This demonstrates that more steam is required in the shower, 0.6545 kg/kg product than is saved in the dryers, 0.4098 kg/kg product at constant production rate. By maintaining high sheet temperature without the steam shower requirement, 0.4098 kg dryer steam/kg product is saved. Additional potential savings are decreased refiner power because of higher sheet strength when pressed hot, decreased paper machine energy requirement per unit of production because of a decrease in breaks and decreased energy in transporting the product paper because of increased density.

Industry-Wide Potential Savings:

Statistics of Paper and Paperboard (23), lists production of all grades of paper and paperboard for 1977 as 55 million metric tons. Of this total, probably 22 million tonnes of board and 20 million tonnes of paper are eligible for energy saving by maintaining a high stock temperature. Integrated mills have a potential source of high temperature stock. For this case savings in dryer steam are estimated as follows:

$$\frac{22 \text{ million tonnes board}}{\text{year}} \times 0.4098 \frac{\text{tonne dryer steam}}{\text{tonne board}}$$

$$\times \frac{\$6.60}{\text{tonne incremental steam}} = \frac{\$59{,}502{,}960}{\text{year}}$$

$$\frac{20 \text{ million tonnes paper}}{\text{year}} \times \frac{0.3995 \text{ tonne dryer steam}}{\text{tonne paper}}$$

$$\times \frac{\$6.60}{\text{tonne incremental steam}} = \frac{\$52{,}734{,}000}{\text{year}}$$

The calculation for paper assumes a sheet temperature of 75°C in the dryers and $0.00769 \frac{\text{kg moi}}{\text{kg fiber - }^{\circ}\text{C}}$ Total potential energy savings $= \frac{\$112{,}236{,}960}{\text{year}}$

From this potential savings must be subtracted the pulp mill cost to maintain the pulp temperature and paper mill costs to maintain high stock temperature.

Corrosion, Microbiological Activity and Water Characteristics

A rule of thumb for estimating corrosion rate as a function of stock temperature in a paper mill is that the corrosion rate will double for each 11°C increase in stock temperature above 43°C (25). Bowers (24) gives the following data on corrosion of type 304 stainless steel and mild steel wire trays by white water at pH 4.5-6.7 as a function of temperature:

	Corrosion Rate, mm/year	
Temperature, °C	Mild Steel	Type 304
22.2-26.7 (avg. 24.5)	1.65-1.73 (avg. 1.69)	0.006-0.008 (avg. 0.007)
35.0-48.9 (avg. 42.0)	2.9	0.015-0.019 (avg. 0.017)

The data above is for a paper machine producing fine paper with a 35-50% closed system. This data gives for 304 stainless steel: 75% increase in corrosion rate per $11^{o}C$ increase from $24.5^{o}C$ to $42^{o}C$, which is consistent with the rule of thumb 100% increase per $11^{o}C$ increase in temperature for temperature increases above $43^{o}C$.

The calculation is as follows: to find the factor by which corrosion increases for an incremental increase in temperature, use the equation $R_c = R_o X^y$ or $X = (R_c/R_o)^{-y}$

where R_c = corrosion rate, mm/year

R_o = corrosion rate at $t_o{}^{o}C$, mm/year

X = factor by which corrosion rate increases for each (ΔT) increase in temperature above $t_o{}^{o}C$

t_o = base temperature, ^{o}C

(ΔT) = increment in temperature for which corrosion rate increase factor is applicable

$$y = \frac{t-to}{\Delta t}$$

for SS304 data above, $y = \frac{42-24.5}{11} = 1.591$

$$X = (0.017/0.007)^{\frac{1}{1.591}} = 1.747$$ or a 75% increase in corrosion rate for each $11^{o}C$ rise in temperature

The paper industry has been one of the larger users of fresh water. Unbleached kraft mills typically have used 83 to 125 $\frac{m^3}{\text{metric ton}}$ (26)
For economic and environmental reasons, most mills are either in process of closing up their water systems or are in the planning and pre-evaluation stage. Advantages include:

1. Decreased loss of fiber and filler

2. Decreased waste water treatments costs in smaller equipment size and reduction in effluent loading
3. Decreased cost of fresh water supply
4. Better water removal from the sheet by thermal energy build up.

To maintain high stock temperatures in the paper mill, either the headbox, wire and felt shower water must be heated, or recycled white water must be used, or a combination thereof. Since environmental and fresh water availability considerations indicate a closeup to the maximum economical extent, increased sheet temperature and the accompanying savings in better dewatering will result regardless of whether or not increased sheet temperature is the primary goal. A cost of $0.04457/$m^3$ water has been reported for well depreciation, maintenance, power, and waste treatment. Water useage for a 6 m fourdrinier machine was 340.68 m^3/hr for showers and sprays (26). Theoretically, the only fresh water requirement is makeup for the 10 to 15% lost in the product, evaporation, and miscellaneous losses. Practically, the fresh water requirement, or mill close-up will be determined by the tolerance of the disadvantages:

1. Corrosion and erosion
2. Foam
3. Pitch
4. Slime and dirt
5. Sizing problems from temperature
6. Fines
7. Felt, wire, plugging and life
8. Odor
9. Scale, deposits and precipitation
10. Color
11. Machine room temperature

12. Shower plugging
13. Product mottle
14. Vacuum pump water requirement

Extra costs would be anticipated for:

1. Anti foam additives, increased quality and usage rate.
2. Strainers and clarification equipment to remove long fibers, scale, etc., from the water
3. Increased use of expensive materials of construction, i.e., stainless steel 316
4. Increased use of deposit control chemicals including felt shower water deposit control agents, pitch dispersants, etc.
5. Better efficiency of removing organics in the brown stock washer
6. Increased use of biocides
7. Increased use of retention aids on foundrinier and save-alls
8. Increased use of vacuum pump cooling water towers and water treatment
9. Increased equipment for pH control
10. Air conditioned control rooms

As the mill water system is closed and as system temperature increases, microbiological activity changes. As the temperature approaches 65°C, the aerobic microorganism population decreases. Thermophilic organisms will survive. The relationship of thermophilic organisms to corrosion and deposits has had very little coverage in the literature. In a study of a waste paper reprocessing mill with an entirely closed water system (27), a marked increase in the number of anaerobic microorganisms and a decrease in aerobic microorganisms was found as compared to mills with open system. Corrosion problems increased because of the metabolic products, organic acids and hydrogen sulfide. Volatile acids, acetic, butyric, and propionic, were found in high concentrations in the closed system process water and these often cause odor problems in the mill and finished paper. For non-volatile acids, lactic, succinic, and oxalic, the differences were less pronounced. Lactic acid was present in high concentrations in both closed and open systems. Neutral distillation products, ethanol, butanol, isopropanol, and propanol were found in low concentrations and except for ethanol, were restricted to the closed system. Sulphate reducing bacteria were more numerous in the closed system. Coliforms, yeasts, and molds were less numerous in the closed system. Aerobic and anaerobic spore formers were at the same concentrations in both mills.

Davy and Mueller (28) report \$0.306 per ODt of kraft forming and drying capital cost due to corrosion in Canadian pulp and paper mills, 1968. The operating cost is given as \$0.586/ODt for a total corrosion cost of \$0.893/ODt. This cost is assumed to be doubled in the last 10 years because of inflation and is assumed to be representative of U. S. mills. The cost of additives in a kraft linerboard mill is typically \$0.60/ton which includes defoamer, biocides and dispersants. This figure could easily triple if stock temperature were increased from 49°C to 66°C by closure of the water system.

Pulp Storage Chests Agitation

There is no published data in the open literature, but as temperature increases, power required for agitation decreases (29). Normally, no more than 5-6% of the power delivered to the mixer is consumed in bearing and stuffing box losses. The balance is converted to heat and results in an increase in the internal energy of the fluid. This effect is useful in maintaining stock temperature in that heat added to the stock by agitators helps offset heat loss in stock to the ambient surroundings.

Centrifugal Cleaners

Again, no information seems to be available in the public literature on the effect of higher stock temperature. Discussions with one of the major cleaners manufacturers suggests at higher temperature, less energy would be required for the same level of cleaners efficiency (32).

Formation

Only one reference was found in the literature on the effect of stock temperature on sheet formation on the foundrinier or former. However, newsprint machines run at 54-60°C without prohibitive formation problems (30) as do linerboard machines. Rubin (13) states that it is generally known that a reduction of stock temperature decreases drainage rate, enhances the effect of shake, thereby improving sheet formation.

With the decrease in water viscosity, any zeta potential forces tending to flocculate the fibers are enhanced with a resulting decrease in formation quality. This negative effect then is a function of the zeta potential of the stock. The improved drainage rate on the foundrinier would allow a decrease in headbox consistency, however, benefits of a dryer sheet off the couch could be negated by the higher water removal requirement of the foundrinier equipment.

Screens

Machine screens are commonly used just ahead of the headbox for removing foreign material (such as scale), fiber bundles, and for deflocculating the stock. At elevated stock temperature, the capacity of the screen is increased with perhaps a slight decrease in specific energy requirement (31). There is no reported adverse effect of a higher stock temperature.

Overall Economics of Higher Stock Temperature

Sample Calculation; Unbleached Integrated Kraft linerboard; per 1000 t of MD product at 6% moisture. Assume an increase in stock temperature from 49^{o}C to 65.6^{o}C. Assume the stock from the pulp mill is at 60^{o}C and is maintained at this temperature by insulating tanks and pipe lines. Temperature losses are offset by heat added to the stock by agitators and pumps and by using recycled white water for consistency regulation dilution at 60-66^{o}C. The stock preparation refiners will typically increase stock temperature from 60^{o}C to 65.6^{o}C. This temperature is maintained to the dryers with the assistance of white water system closure. As discussed above, no adverse effect of high stock temperature in the agitation, screening, or cleaners is anticipated. If anything, a decrease in energy requirements (with no penalty in stock quality) results, but since no quantitative data is available, no energy credit is claimed. The temperature of 65.6^{o}C was chosen because it is considered a "safe" temperature from the standpoint of refining, corrosion, microbiological activity and formation. By using the proper values in the calculations below, any temperature increment can be evaluated.

Refiners: Assuming the Beloit data of 56.8 MJ/t energy savings for stock at 54^{o}C applies at 60^{o}C.

$$\frac{56.8\text{MJ}}{\text{ODt}} \times 1000 \text{ t prod.} \times \frac{940 \text{ ODt}}{100 \text{ t prod}} \times \frac{\$0.007}{\text{MJ}} = \$374 \text{ saved}$$

Dryers:

Dryer steam saved by not requiring sheet be heated from 49°C to 66°C:

$$\frac{0.94 \text{ kg fiber}}{\text{kg prod}} \times 10^6 \text{ kg product} \times (65.6\text{-}49)^\circ\text{C} \times \frac{1.5 \text{ kg steam condensed}}{1 \text{ kg moisture evap.}}$$

$$\times \frac{1 \text{ kg moisture}}{550 \text{ kcal}} \times \left[\frac{0.63 \text{ kg mois.}}{0.37 \text{ kg fiber}} \times \frac{1 \text{ kcal}}{\text{kg - }^\circ\text{C}} + \frac{0.3 \text{ kcal}}{\text{kg - }^\circ\text{C}}\right]$$

$$= 85{,}227 \text{ kg steam saved}$$

Dryer steam saved by a lower sheet moisture into dryer:

$$\frac{0.0054 \text{ kg decrease in mois. to dryer}}{\text{kg fiber - }^\circ\text{C}} \times (65.6\text{-}49)^\circ\text{C} \times \frac{1.5 \text{ kg steam condensed}}{\text{kg mois. evap.}}$$

$$\times \frac{0.94 \text{ kg fiber}}{\text{kg product}} \times 10^6 \text{ kg product} = 126{,}392 \text{ kg steam saved}$$

Total dryer steam saved = 211,619 kg

$$211{,}619 \text{ kg steam} \times \frac{\$6.60}{\text{incremental t steam}} \times \frac{\text{t}}{1000 \text{ kg}} = \$1400 \text{ saved}$$

Corrosion:

$$C = C_b X^y$$

where C = corrosion cost an any temperature T°C above 43°C

C_b = Corrosion cost at base temperature (above 43°C) = $1.79/ODt

X = factor by which corrosion rate increases for each ΔT°C temperature increment = 2

$$y - \frac{T - T_o}{\Delta T}$$

T_o = base temperature assume 49^oC

T = higher temperature at which corrosion cost is to be calculated, = 66^oC

ΔT = temperature increment to which X applies, = 11^oC

$$C = \$1.79\,(2)^{(65.6-49)/11} = \$5.09/ODt$$

$$\frac{(\$.09 - \$1.79)}{ODt} \times \frac{1.044\ ODt}{MDt} \times 1000\ MDt - \$3445 \text{ lost}$$

Fresh Water Saved:

Assume 635 t/day production rate of product board. By reusing water on the paper machine, well, delivery costs, and waste treatment costs are saved

$$\frac{day}{635t} \times 340.68\frac{m^3\ water}{hr} \times \frac{24\ hr}{day} \times \frac{\$0.04457}{m^3\ water} \times 1000\ t = \$574 \text{ saved}$$

Additives:

$$\frac{\$1.80-.60}{t} \times 1000\ t = \$1200 \text{ lost.}$$

Summary:

Refiners	\$374
Dryers	1400
Corrosion	-3445
Fresh water	574
Additives	-1200
	-\$2297/1000 metric tons

As can be seen from the above figures, corrosion costs can be a most significant factor in increasing the stock and sheet temperature in the paper mill. Actual mill costs for refining, dryer steam, corrosion, water, and additives would have to be evaluated carefully before a predicted savings or loss could be determined. For the costs assumed in this study, a loss of \$2.30/t results from running at high temperature. For any given mill situation, these costs, particularly corrosion, could be quite different from these figures, and the economics could be considerably changed. To evaluate and minimize properly cost associated with higher temperatures, these factors must be the primary consideration. For an example, additives to reduce corrosion could result in substantial savings, but if the additive cost is too high, the economic result could be a stand-off.

In addition to the above considerations, capital costs of operator comfort facilities such as air conditioned control rooms must be considered. For white water close-up, there will be equipment costs for filtration, etc.

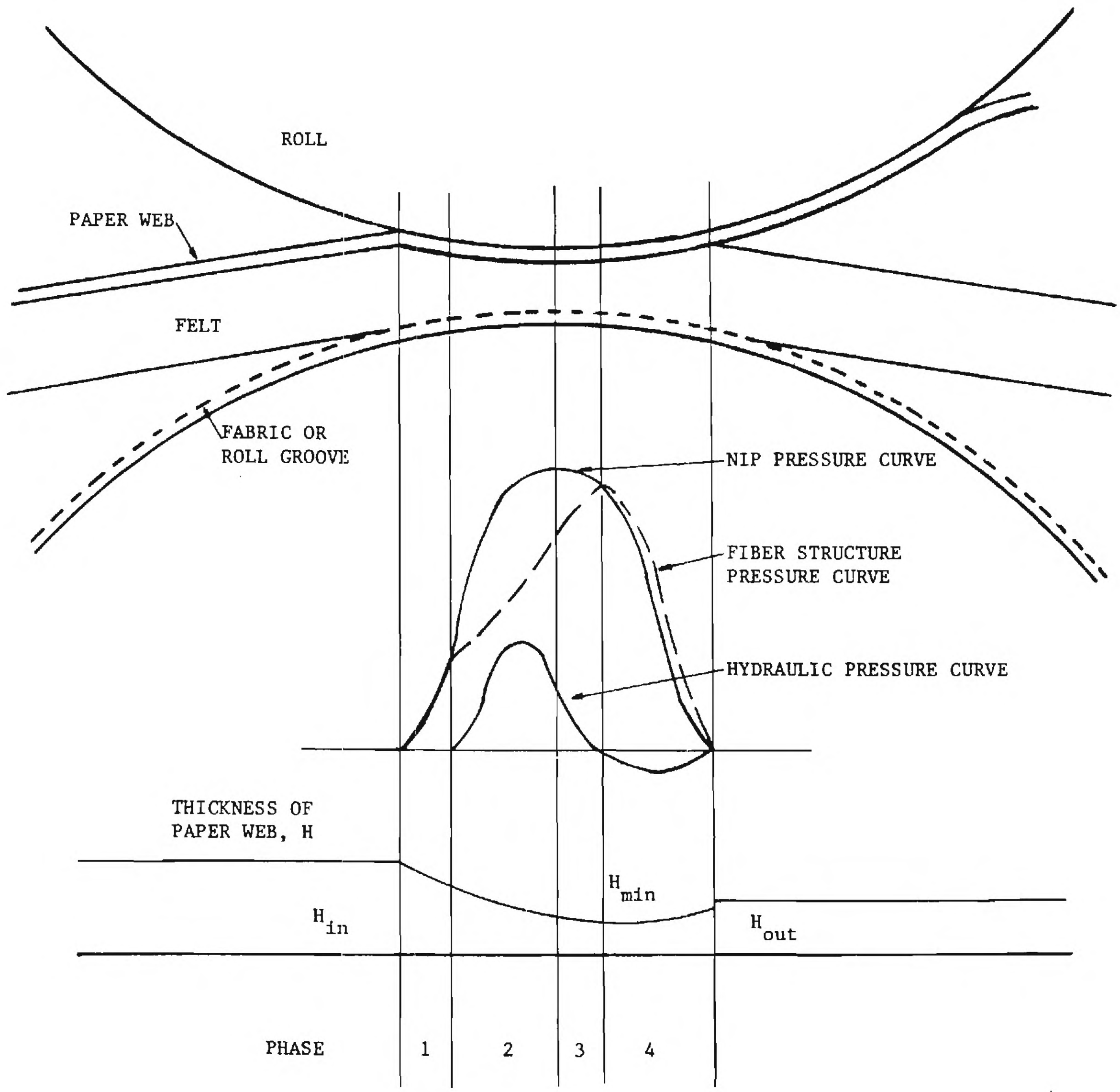
SECTION IV

A SURVEY OF THE LITERATURE ON PRESS DEWATERING

A literature survey was conducted to determine the optimum felt characteristics and optimum operating felt moisture level based on energy requirements for predrying and drying, useful felt life, and felt contamination problems. A computer data base was searched and pertinent articles were collected and reviewed. A summary of this information follows.

Water removal from a paper sheet in the press section of a paper machine involves complex relationships between a large number of parameters. The water removal is affected by the machine design, the felt characteristics, the machine operating conditions, and the properties of the paper sheet itself. These vary greatly from machine to machine and from process to process. Advances have been made in the areas of presses and press configurations and felt designs. The trend has been toward transversal or vertical flow presses such as the suction press, grooved press, and presses clothed with inner fabrics, shrink sleeves, or combination felts. Borje Wahlstrom's theory of water removal at the nip of a transverse press, proposed in 1960 and generally accepted today, has been important to the development of new press configurations and press clothing designs (see Figure 9). (33, 34)

There have been great changes in press felt design during the past twenty years. Until 1960, most press felts were conventional 100% wool, woven felts. Since then, synthetic fibers and new felt designs have improved pressing efficiency and increased felt life. Six felt types are described below. (33, 35)



Phase 1 starts at the entrance of the nip where the pressure curve begins and extends until the paper has become saturated. The felt is shown unsaturated in Phase 1. No hydraulic pressure develops in Phase 1.

Phase 2 extends from the point of saturation to mid nip, or more accurately, to the maximum point of the total nip pressure curve. In this phase, the felt also reaches saturation.

Phase 3 extends from the maximum point of the nip curve to the point of maximum paper dryness. This maximum dryness point corresponds to the maximum in the paper structure pressure curve, and zero hydraulic pressure in the paper. In this expanding part of the nip, the felt passes zero hydraulic pressure and becomes unsaturated.

Phase 4 covers the point where the paper starts to expand and becomes unsaturated, creating a two-phase system of water and air. The felt is unsaturated through this whole phase and expands continuously.

Source: Reference 34

FIGURE 9 TRANSVERSAL FLOW NIP

Conventional Woven Felt. These felts are woven from all-wool or wool and synthetic blend, spun yarn, then mechanically felted. Conventional felts are rarely used today.

Batt-on-Base. These felts consist of a batt of short fibers needled on to a base fabric, woven of spun yarn. They can be made from up to 100% synthetic fibers. The needling process gives the batt fibers a vertical orientation which reduces the flow resistance in the vertical direction.

Knuckle-Free or Fillingless. The cross-machine direction yarns and knuckles are eliminated from the base fabric in this construction. As a result, flow resistance in the machine direction is reduced and dewatering is improved.

Batt-on-Mesh. An open mesh, screen type fabric, woven from multifilament and sometimes monofilament yarns, is used as the base fabric. This results in lower resistance to flow.

Combination. These felts combine a felt and an inner fabric; effectively converting a press into a fabric press without adding a separate fabric. The base fabric, a double-layered weave of monofilaments and multifilaments, can store water in voids which exist even under high nip loads. A fiber batt is needled to this base to provide a smooth surface for the paper. Variations of combination felts include "crossless" base fabrics and felts with a "grooved" back side.

Baseless or Nonwoven. Felts have recently been developed which completely eliminate the fabric base structure. This type of felt has the lowest flow resistance and the most uniform pressure distribution in the press nip.

The press felt must serve a number of functions such as follow:

(1) Absorb the water expressed from the sheet in the press nip
(2) Support the sheet in the press nip to prevent crushing
(3) Provide uniform pressure distribution over the paper in the nip
(4) Impart a desirable surface finish to the sheet

(5) Equalize pressure distribution over void and land areas of the roll to eliminate or reduce shadow marking caused by grooved or suction press rolls

(6) Transfer the sheet from one position to another

(7) Act as power transmission belt, driving all undriven rolls in the press section. (33)

As a result, the felt design becomes a compromise. According to Wahlstrom, the optimum felt should give a perfectly uniform pressure distribution, lowest possible flow resistance in the fluid flow region, and a smallest possible rewetting in the outgoing part of the nip. Flow resistance in the felt can be reduced through the use of transverse presses which minimize the flow distance through the felt by providing voids beneath the felt to receive the water; by reducing the volume of flow through the felt by running a dryer felt; by operating at higher temperatures to reduce the viscosity of the water; as well as by changing the characteristics of the press felt. (34)

Press felts have been developed to reduce water flow resistance. One felt company has developed a machine to measure water flow resistance through the felt in the machine direction, the cross-machine direction, and the verticial direction. Table IV shows relative rankings of water flow resistance for six types of press felt. Their results indicate that the flow resistance of the felt in all three directions is important, even in transverse flow presses. An effective felt conditioning system should be used to maintain a low water flow resistance throughout the felt life.

In certain operating conditions, felt flow resistance is low enough that the flow resistance in the paper becomes the limit to dewatering in the nip. Many mills are using double-felted presses to overcome this limit. Double felting cuts the water path length in the paper in half and doubles the flow area.

TABLE IV. FELT FLOW RESISTANCE RANKING

Felt	Flow Resistance Ranking L (Machine Direction)	X (Cross-Machine Direction)	Z (Vertical Direction)
Conventional	100	100	100
Batt-on-base	98	90	36
Knuckle-free	30	23	42
Batt-on-mesh	25	29	44
Combination	13	15	37
Nonwoven	18	12	16

Source: Reference 33

The paper sheet reaches a minimum moisture level near the center of the press nip. As the paper and felt begin to expand on the exit side of the nip, the paper picks up water from the felt. The following three mechanisms of "rewetting" have been suggested: (34)

i) Pressure differential between the paper and the felt due to expansion
ii) Capillary transfer of water between the paper and the felt
iii) Splitting of a water film between the paper and the felt

The relative importance of these mechanisms is still in question. There is, however, agreement as to the potential for increased water removal by reducing rewetting. (36, 37, 38, 39) Warren indicates that sheet moisture content at mid-nip is 10 to 20% lower than the exiting moisture level. (36) References 36 and 37 discuss experimental felts, designed to reduce sheet rewetting. If rewetting can be reduced through changes in felt design, energy savings can be realized without any capital investment or increased drive energy consumption.

Uniformity of pressure distribution in the nip is very important to the pressing efficiency. (34, 40, 41) Reference 40 reports the results of a study of the pressure distribution for several types of felt under compression. The study indicated that the distribution was quite uneven. Improving the pressure distribution through changes in the press felt will improve sheet dewatering and allow increased nip loadings. Nip load is limited to the point where the hydraulic pressure causes a disruption of the sheet, that is, where sheet crushing sets in.

Compressibility is another important felt parameter. The compressibility of the felt influences the shape and maximum value of the nip pressure pulse as well as the width of the nip. Press roll diameter and hardness, sheet properties, and machine speed are also involved. All of these factors must be considered in determining the desired felt compressibility. (34)

There is disagreement in the paper industry as to the relationship between felt moisture and sheet moisture exiting the press. Reference 42 reports the results of a series of tests with different press configurations, felt types, and press loads. The tests indicated that the felt moisture did affect the exiting sheet moisture, especially in the case of a double felted press. Reference 41 indicated that tests over a range of operating conditions had not shown a clear relationship between felt moisture and exiting sheet moisture. Reference 43 speculated that the felt should be dry enough so as not to become saturated under compression in the nip. It is likely that the importance of felt moisture varies with the felt type, machine configuration, operating conditions, and paper properties. Felt moisture should be considered in any optimizing procedure.

There are many interrelated parameters which affect the press operation. Optimum values for these parameters will be hard to find and will vary from machine to machine. References 44, 45, and 46 describe systematic programs for improving the performance of the press section. These programs include evaluating current press performance, establishing performance goals, varying felt combinations, and effective, persistant documentation of results. Reference 47 describes such a program which was carried out on two tissue machines, resulting in significant savings in energy and water.

SECTION V

BASELINE TESTS ON A PILOT PAPER MACHINE

Much of the experimental work on this project was conducted on the 36 inch Sandy Hill Corporation pilot paper machine at the Herty Foundation in Savannah, Georgia. A photograph of this fourdrinier machine is presented in Figure 10, and the layout is illustrated in Figure 11. The machine was designed to operate at speeds from 5 ft/min to 300 ft/min. The headbox is capable of static, pressure, or vacuum operating modes, and the table section may be equipped with either foils or rolls.

The press section consists of two main presses. The first is a straight through plain press, and the second is a plain reversing press. The first press may be operated as either single or double felted. Figure 12 provides a detailed illustration of the press section.

There are two dryer sections with seven drums in the first and five in the second. In the first section, there is a felt drying drum for both the top and bottom felts. Steam is supplied to the drums individually or in groups through pressure controllers from a common supply header, and a common condensate line is used. There is no cascading of the steam flow.

Prior to the first dryer section, there is a smoothing press. Between the sections is a combination vertical and horizontal size press with provision for feeding from a roll at this point. After the last dryer is a calendar stack of eight rolls. None of these items of equipment were utilized during the test program. A reel with the capability of handling 40 inch diameter rolls ends the machine.

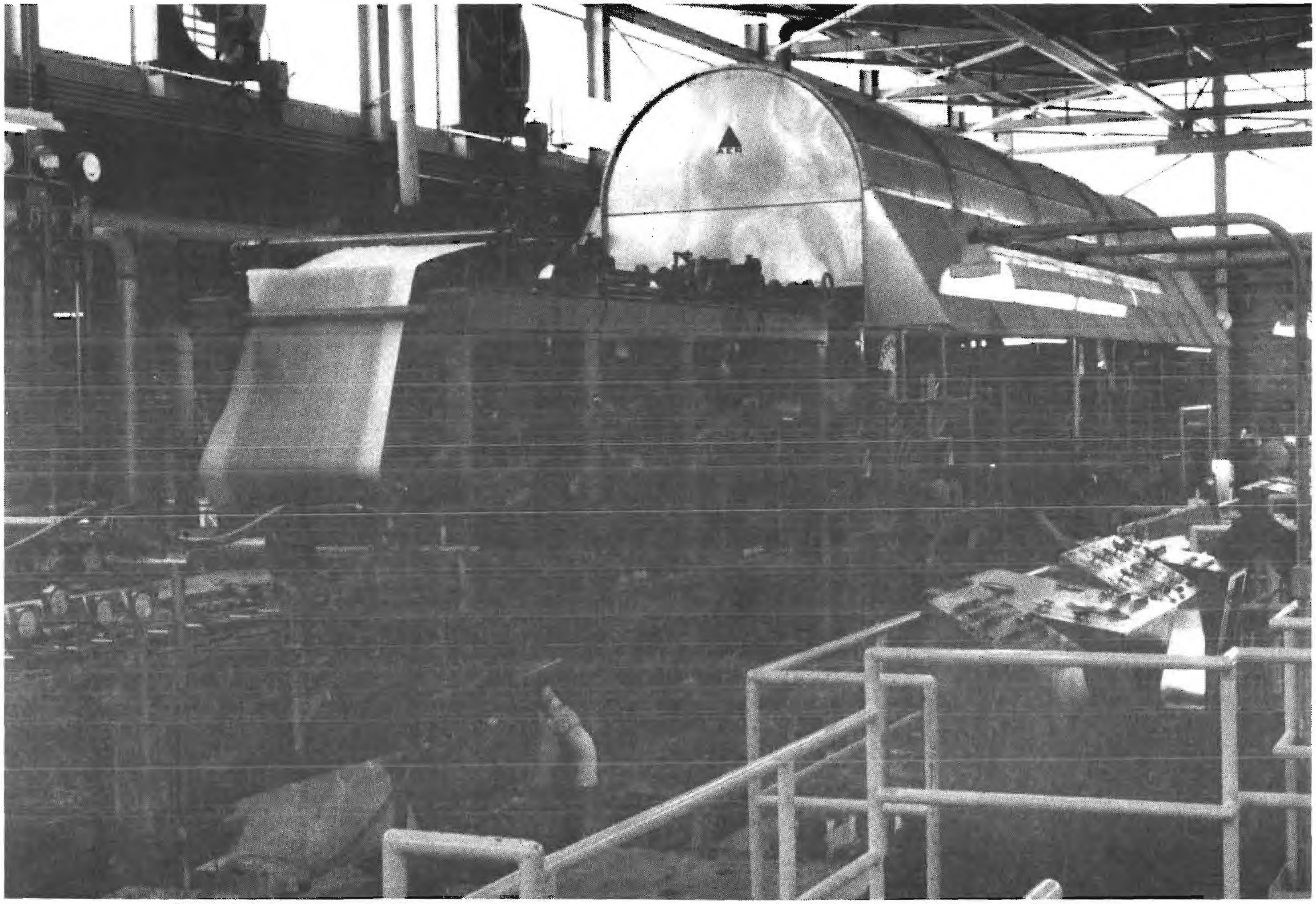


FIGURE 10. PILOT PAPER MACHINE.

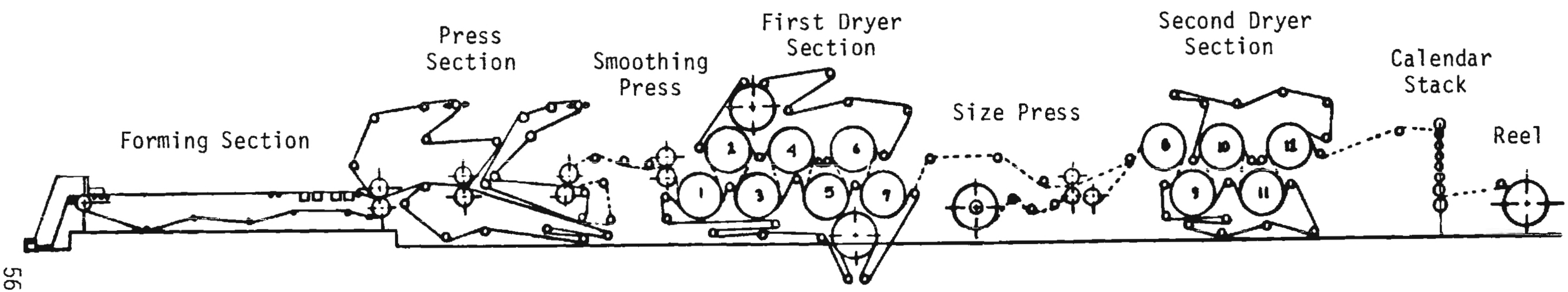


Figure 11. HERTY FOUNDATION PILOT PAPER MACHINE LAYOUT

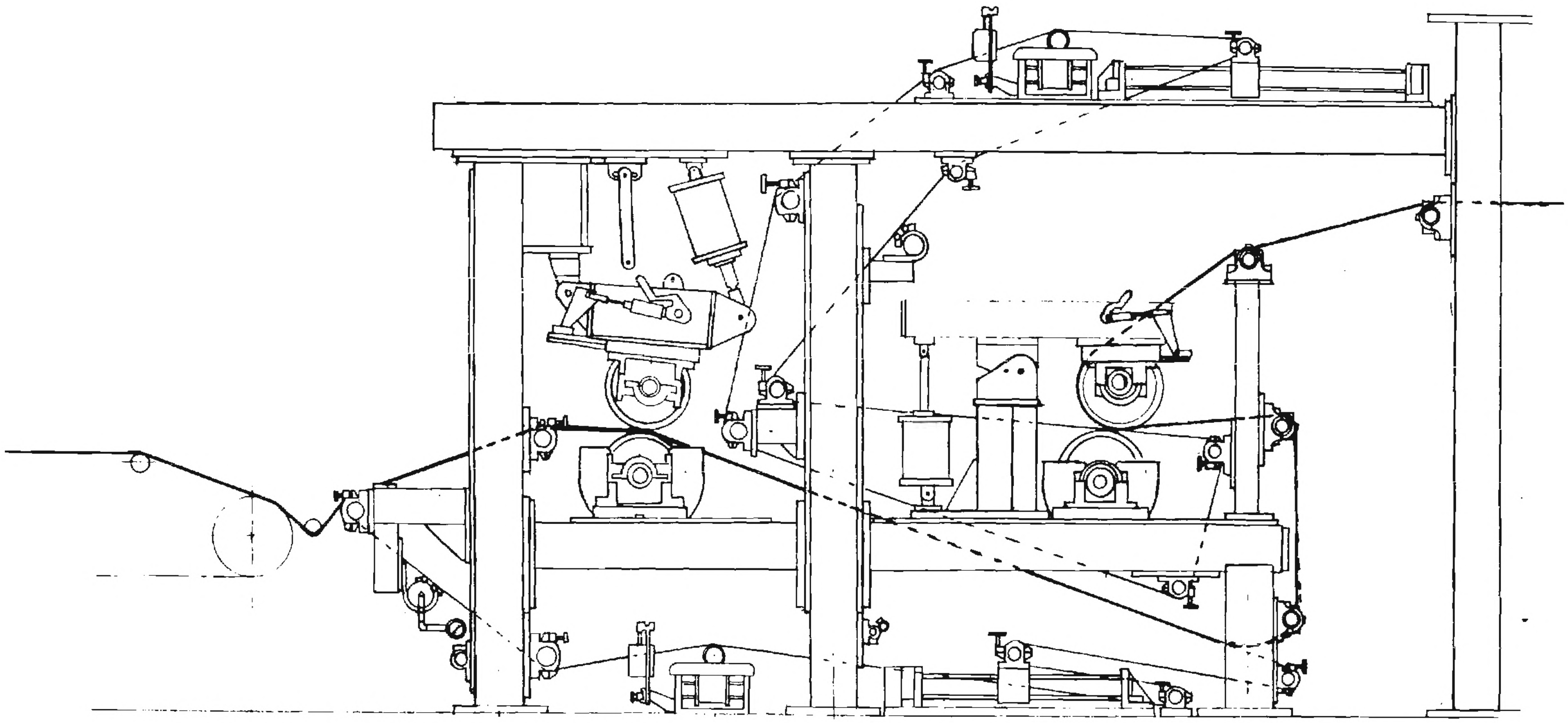


FIGURE 12: PILOT MACHINE PRESS SECTION

The purpose of the preliminary tests on this machine was to establish, for a typical process, a baseline of the moisture content of the sheet as it progressed through the machine and a mass and energy flow balance. The machine direction moisture profile was established by means of lab analysis of grab samples collected at the couch roll, after the presses, after the first dryer section, and at the reel.

For the energy balance, only thermal energy was considered due to the nature of the project at hand. Steam flow to the dryers was measured by means of orifice plates which were installed in each of the steam lines.

Moisture and energy content of the exhaust air from the dryer section hood were estimated by measuring the wet bulb and dry bulb temperatures in the duct. The velocity profile in the duct, as measured by a pitot tube, was used to determine the exhaust flow rate.

In addition, for the mass balance, measurements were made of the feedstock flow rate and consistency, the whitewater free drainage rate, the drainage rates through the suction foils and suction boxes on the wire, the sheet trim dimensions, and the final sheet dimensions.

Water removal at the presses could not be measured readily due to the configuration of the piping from the vacuum boxes on the felts. Therefore, the quantity of water removed in the press section was assumed to match the value calculated from the sheet moisture levels entering and leaving the press section.

For this work, a 44 pound basis weight sheet was produced at a reel speed of 60 feet per minute. All of the dryer drums were operated at a supply steam pressure of 50 psig. This resulted in a dryer sheet than would normally be obtained in a commercial process.

The data collected and the computations for the mass and energy flow rates are provided below. The balances which were computed provide extremely good agreement. Measured flows accounted for 99% of the pulp and 99.2% of the water entering the headbox. The analysis of the energy balance in the dryer section accounted for 98.9% of the steam energy supplied. A graphical presentation of the flow rates and balances is presented in Figure 13.

In the energy analysis of the dryer, much of the energy use may be attributed to losses to the environment through radiation, conduction through frame members, and convection currents which did not flow through the exhaust duct. An estimate of these losses was obtained by operating the dryer section without processing the paper sheet. The diference between the energy supplied by the steam and that carried away by the air in the exhaust duct was attributed to those miscellaneous losses. It was then assumed that the presence of the sheet would not materially affect these losses, and the same energy loss value was used to calculate the balance. The high agreement (98.9%) of the balance indicates the assumptions and methods were suitable for the purposes of this project.

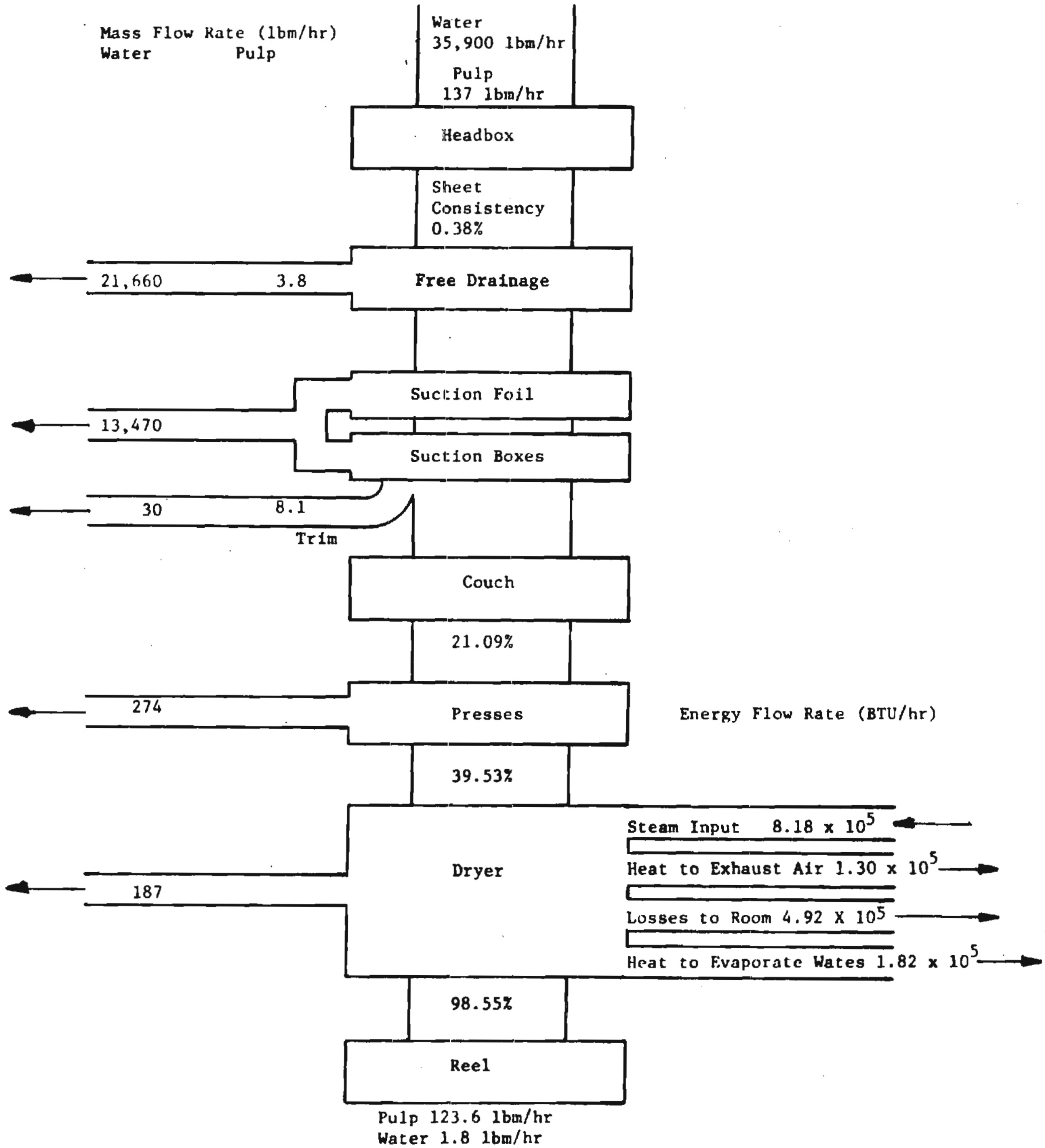


FIGURE 13: PILOT PAPER MACHINE'S MASS & ENERGY FLOWS

Data Summary

1.	Flow to headbox	72.0 gal/min
2.	Headbox pulp consistency	0.38%
3.	Whitewater free drainage rate	361 lbm/min
4.	Suction foil and suction box drainage rate (total)	224.5 lbm/min
5.	Sheet width prior to trim	32.5 in.
6.	Sheet width after trim	30.5 in.
7.	Water drainage at suction couch roll	Not measured
8.	Sheet consistency after couch roll	21.09%
9.	Water drainage at presses	None
10.	Water removed at felt suction boxes	Not measured
11.	Sheet consistency after second press	39.53%
12.	Dryer steam consumption (no paper sheet, all drums at 50 psig)	
	Drum No.1	60.0 lbm/hr
	Drum No. 2	44.4 lbm/hr
	Drums No. 3 & 4	87.3 lbm/hr
	Drums No. 5, 6, 7 & felt dryers	216 lbm/hr
	Drums No. 8, 10 and 12	160 lbm/hr
	Drums No. 9 & 11	114 lbm/hr
	Total	682 lbm/hr
13.	Dryer steam consumption (with paper sheet, all drums at 50 psig)	
	Drum No. 1	123 lbm/hr
	Drum No. 2	120 lbm/hr
	Drums No. 3 & 4	127 lbm/hr
	Drums No. 5, 6, 7 & felt dryers	227 lbm/hr
	Drums No. 8, 10, & 12	180 lbm/hr
	Drums No. 9 & 11	120 lbm/hr
	Total	897 lbm/hr

14.	Sheet consistency after 1st dryer section		97.79%
15.	Sheet consistency after 2nd dryer section		98.55%
16.	Ambient air conditions		
	Dry bulb temp.		83^oF
	Wet bulb temp.		61^oF
	Relative humidity		26%
	Specific humidity		45 gr. H_2O/lbm air
	Enthalpy		27 Btu/lbm
17.	Dryer exhaust air conditons (no sheet)		
	Dry bulb temp.		119^oF
	Enthalpy		35 Btu/lbm
18.	Dryer exhaust air conditons (with paper sheet)		
	Dry bulb temp.		114^oF
	Wet bulb temp.		82^oF
	Relative humidity		26.5%
	Specific humidity		114 gr. H_2O/lbm air
19.	Dryer exhaust air flow	Approx.	4000 ft^3/min
20.	Sheet temperature entering dryer		60^oF
21.	Sheet temperature leaving dryer		185^oF
22.	Sheet width at reel		28.5 in.
23.	Reel speed		60 ft/min.
24.	Basis weight		44 lbm/3000 ft^2

Calculations

1. Pulp at reel

$$\frac{44 \text{ lbm}}{3000 \text{ ft}^2} \times .9855 \times \frac{60 \text{ ft}}{\text{min}} \times \frac{28.5}{12} \text{ ft} = 2.060 \text{ lbm/min}$$

2. Pulp at headbox

$$\frac{72.0 \text{ gal}}{\text{min}} \times \frac{8.34 \text{ lbm}}{\text{gal}} \times 0.38\% = 2.282 \text{ lbm/min}$$

3. Pulp trimmed at end of wire

$$\frac{32.5'' - 30.5''}{30.5''} \times 2.060 \ \text{lbm/min} = 0.135 \ \text{lbm/min}$$

4. Pulp drainage with whitewater

$$\frac{361 \ \text{lbm water}}{\text{min}} \times \frac{1.48 \ \text{lbm pulp}}{1000 \ \text{gal}} \times \frac{1 \ \text{gal}}{8.34 \ \text{lbm water}} = 0.064 \ \text{lbm/min}$$

5. Water at headbox

$$(1 - .0038) \times \frac{72.0 \ \text{gal}}{\text{min}} \times \frac{8.34 \ \text{lbm}}{\text{gal}} = 598.4 \ \text{lbm/min}$$

6. Water in sheet after couch roll

$$2.060 \ \frac{\text{lb pulp}}{\text{min}} \times \frac{78.91\% \ \text{water}}{21.09\% \ \text{pulp}} = 7.71 \ \text{lbm/min}$$

7. Water in sheet prior to trimming

$$\frac{32.5''}{30.5''} \times 7.71 \ \text{lbm/min} = 8.21 \ \text{lbm/min}$$

8. Water in sheet after the presses

$$2.060 \ \frac{\text{lbm pulp}}{\text{min}} \times \frac{60.47\% \ \text{water}}{39.53\% \ \text{pulp}} = 3.15 \ \text{lbm/min}$$

9. Water out the dryer hood

$$\frac{4000 \ \text{ft}^3}{\text{min}} \times \frac{1 \ \text{lbm air}}{14.80 \ \text{ft}^3} \times \left[\frac{114 \ \text{gr} \ H_2O}{\text{lbm air}} - \frac{45 \ \text{gr.} \ H_2O}{\text{lbm air}}\right] \times \frac{1.429 \times 10^{-4} \ \text{lbm}}{\text{grain}}$$

$$= 2.7 \ \text{lbm/min}$$

10. Water in the sheet after the dryers

$$\frac{2.060 \text{ lbm pulp}}{\text{min}} \times \frac{1.45\% \text{ water}}{98.55\% \text{ pulp}} = 0.03 \text{ lbm/min}$$

11. Energy delivered to dryers with no sheet

$$682 \text{ lbm steam/hr} \times 912 \text{ Btu/lbm} = 6.22 \times 10^5 \text{ Btu/hr}$$

12. Mass flow of exhaust air

$$\frac{4000 \text{ ft}^3}{\text{min}} \times \frac{1 \text{ lbm}}{14.8 \text{ ft}^3} \times \frac{60 \text{ min}}{\text{hr}} = 16200 \text{ lbm/hr}$$

13. Heat to warm the exhaust air

$$16{,}200 \text{ lbm/hr} \times \left[35 \frac{\text{Btu}}{\text{lbm}} - 27 \frac{\text{Btu}}{\text{lbm}}\right] = 1.30 \times 10^5 \text{ Btu/hr}$$

14. Energy delivered to dryers with paper sheet

$$897 \text{ lbm steam/hr} \times 912 \text{ Btu/lbm} = 8.18 \times 10^5 \text{ Btu/hr}$$

15. Heat to warm the paper sheet

$$\frac{1.060 \text{ lbm}}{\text{min}} \times \frac{0.31 \text{ Btu}}{\text{lbm - F}} \times \left[185 \text{ F} - 60 \text{ F}\right] \times \frac{60 \text{ min}}{\text{hr}}$$

$$= 0.05 \times 10^5 \frac{\text{Btu}}{\text{hr}}$$

Balances

1. Pulp balance for the machine

(headbox pulp) - (whitewater pulp) - (trim pulp) - (reel pulp)
= imbalance

(2.282 lbm/min) - (0.064 lbm/min) - (0.135 lbm/min) - (2.060 lbm/min) = 0.023 lbm/min

$$\frac{0.023 \text{ lbm/min}}{2.282 \text{ lbm/min}} \times 100\% = 1.00\% \text{ imbalance for pulp}$$

2. Water balance for the forming section

(headbox water) - (free drainage) - (suction drainage) - (water in sheet) = imbalance

(598.4 lbm/min) - (361 lbm/min) - (224.5 lbm/min) - (8.21 lbm/min) = 4.7 lbm/min

$$\frac{4.7 \text{ lbm/min}}{598.4 \text{ lbm/min}} \times 100\% = 0.8\% \text{ imbalance}$$

3. Water balance for press section

This balance cannot be computed since no actual measurements were made of water removed in the press section. Based on the change in consistency, the water removal is as follows:

(water to the press) - (water from the press) = water removed

7.71 lbm/min - 3.15 lbm/min = 4.6 lbm/min

4. Water balance for the dryer section

(water to the dryers) - (water out the hood) - (water remaining in sheet) = imbalance

3.15 lbm/min - 2.7 lbm/min - 0.03 lbm/min = 0.42 lbm/min

$$\frac{0.42 \text{ lbm/min}}{3.15 \text{ lbm/min}} \times 100\% = 13.3\% \text{ imbalance}$$

5. Water balance for the entire machine

(headbox water) - (free drainage) - (suction drainage) - (press water removal) - (water out dryer hood) - (water remaining in the sheet) = imbalance

(598.4 lbm/min) - (361 lbm/min) - (224.5 lbm/min) - (4.6 lbm/min) - (2.7 lbm/min) - (0.03 lbm/min) = 5.57 lbm/min

$$\frac{5.57 \text{ lbm/min}}{598.4 \text{ lbm/min}} \times 100\% = 0.93\% \text{ imbalance}$$

6. Energy balance for the dryer section

(a) Heat loss to room (no sheet)

(energy supplied) - (heat to warm exhaust air) = heat loss

$(6.22 \times 10^5 \text{ Btu/hr}) - (1.30 \times 10^5 \text{ Btu/hr}) = 4.92 \times 10^5 \text{ Btu/hr}$

(b) Heat to evaporate water from sheet

$\left[(\text{water in}) - (\text{water out})\right] \times \text{heat of vaporization} = \text{heat required}$

$$\left[(3.15 \text{ lbm/min}) - (.03 \text{ lbm/min})\right] \times (970.3 \text{ Btu/lbm}) \times \frac{60 \text{ min}}{\text{hr}} = 1.82 \times 10^5 \text{ Btu/hr}$$

(c) Energy balance (with paper sheet)

(energy supplied) - (heat to exhaust air) - (losses to room) - (heat to sheet) - (evaporate water) = imbalance

$(8.18 \times 10^5 \text{ Btu/hr}) - (1.30 \times 10^5 \text{ Btu/hr}) - (4.92 \times 10^5 \text{ Btu/hr}) - (1.82 \times 10^5 \text{ Btu/hr}) = 9 \times 10^3 \text{ Btu/hr}$

$$\frac{9 \times 10^3 \text{ Btu/hr}}{8.18 \times 10^5 \text{ Btu/hr}} \times 100\% = 1.1\% \text{ imbalance}$$

SECTION VI

FELT DEWATERING WITH THE MACHNOZZLE

At the onset of the project all of the testing of the Machnozzle was planned to be conducted on the Herty Foundation's pilot machine. Due to the anticipated problems with this test plan as outlined in the introduction to this report, arrangements were made to utilize the experimental press section at the research facilities of Albany Felt Company in Albany, New York.

These research facilities do not include a sheet forming capability and did not allow evaluation of the effect of test parameters on sheet moisture. Nevertheless, the test press section provided an excellent set-up for determining the effect of the Machnozzle on the felt moisture content.

The Test Facilities

The experimental press, a photograph of which is shown in Figure 14, is full scale in the elevation view. The rolls are 30 inches wide, and a 27-inch felt is normally used. The press may be operated either single- or double-felted, and a variety of plain, grooved, and suction press rolls are available. The machine is capable of controlled speeds to 4500 ft/min, and by means of replacing a gearbox in the drive, speeds as high as 6000 ft/min have been demonstrated.

The machine is equipped with a suction box with interchangeable covers having a variety of slot configurations. For this test, a straight-sided slot 3/8 inch across was used. The controlled vacuum level is measured by a manometer, and the volumetric flow rate is measured by means of two orifice plates. One is installed on the outlet of the vacuum pump and the other on the bleed line inlet.

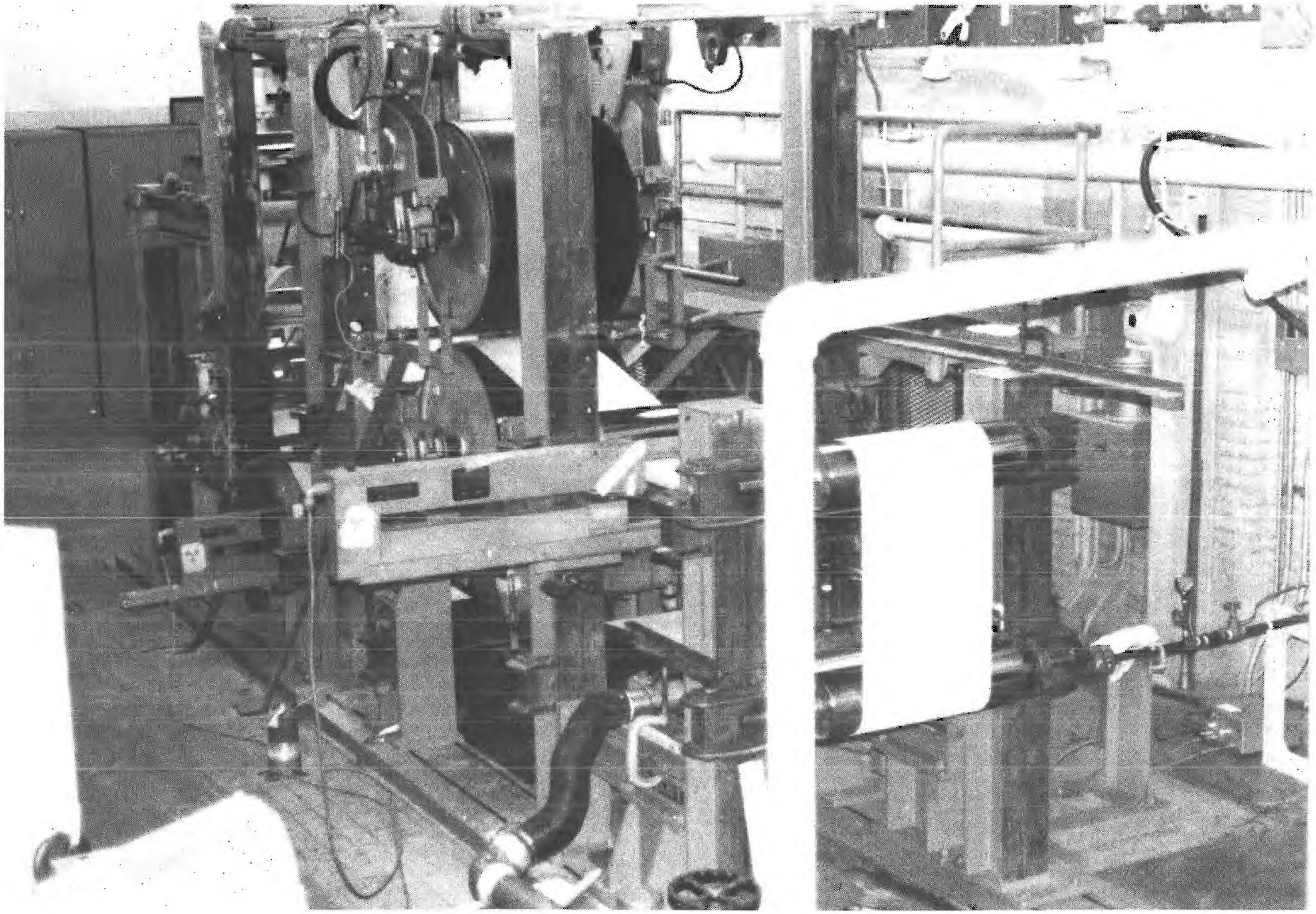


FIGURE 14. EXPERIMENTAL PRESS SECTION.

The difference between the measured flow rates is the flow through the suction box.

Three Beta gages (Figure 15) are available which may be installed at various points along the felt path. These measure total mass of the felt and water and permit computation of moisture content.

The machine configuration used for these tests is illustrated in Figure 16. A single felt was used, and the Machnozzle was installed inside the felt loop against the back of the felt. Based on preliminary testing with lightweight fabrics, it was believed that the wrap angle of the fabric around the nozzle's tip was a parameter of great importance to performance. For this reason, two small rollers were mounted on the Machnozzle support bracket in such a manner as to provide adjustable guides for the felt, as illustrated in Figure 17.

It was determined very quickly that high wrap angles were unsatisfactory for the fabric weight and speeds being tested. Significant felt wear was evident with the high wrap angle, so all tests were conducted with a minimum wrap which just assured felt-to-nozzle contact.

For most of the testing, the Machnozzle was installed just prior to the suction box (9 7/8 inches from the nozzle tip to the leading edge of the suction box slot). Other locations were tried on a limited basis and are discussed later in this section. The arrangement used for most of the testing is shown in Figure 18.

One Beta gauge was installed upstream of the Machnozzle and provided measurement of the moisture content of the felt entering the Machnozzle/suction box region. A second Beta gage was installed after the suction box and provided moisture content readings for the exiting felt.

All of the water entering the felt was provided by a single shower. Because of the positioning of the Beta gages, it was necessary to install the shower at the rather untypical position of just upstream of the press nip rather than upstream of

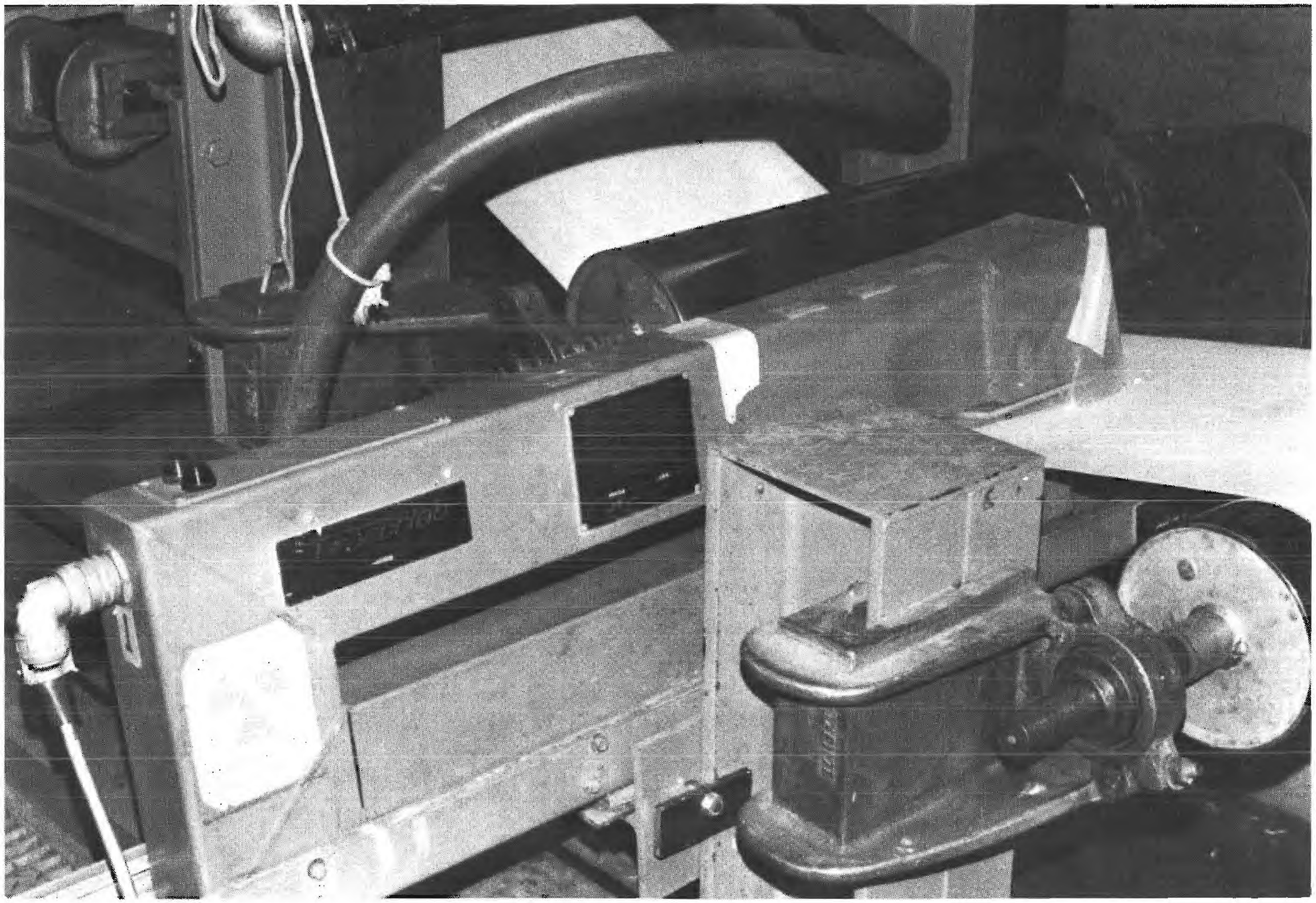


FIGURE 15. BETA GAGE.

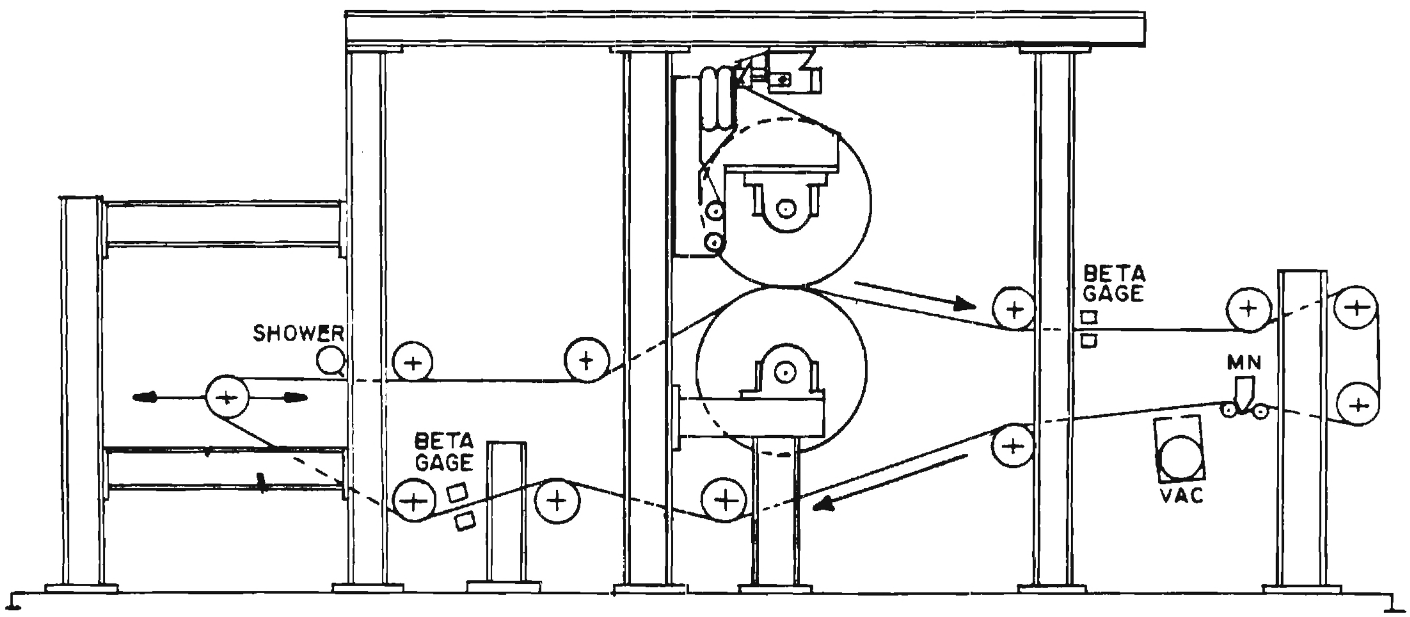


FIGURE 16: EXPERIMENTAL PRESS CONFIGURATION

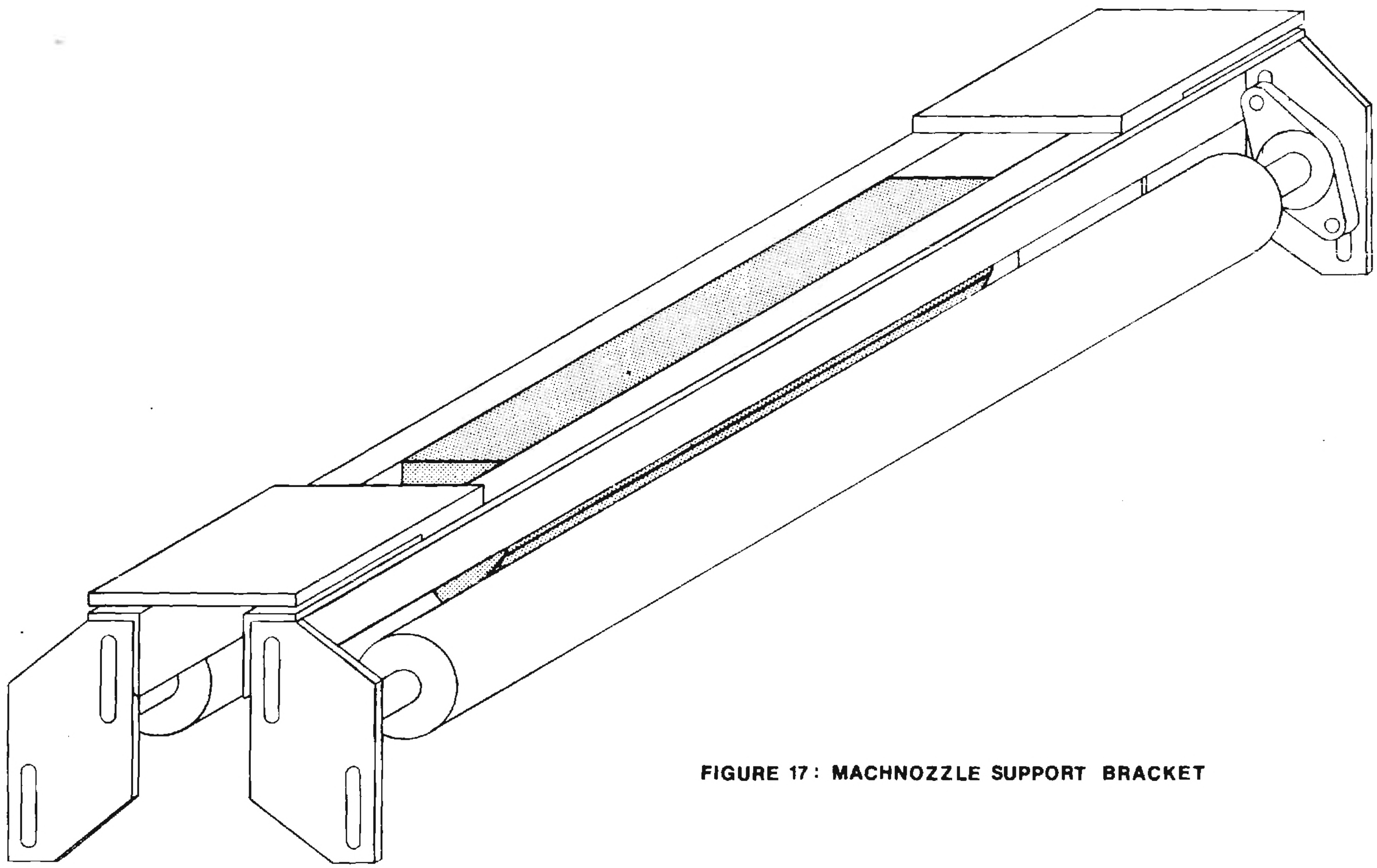


FIGURE 17: MACHNOZZLE SUPPORT BRACKET

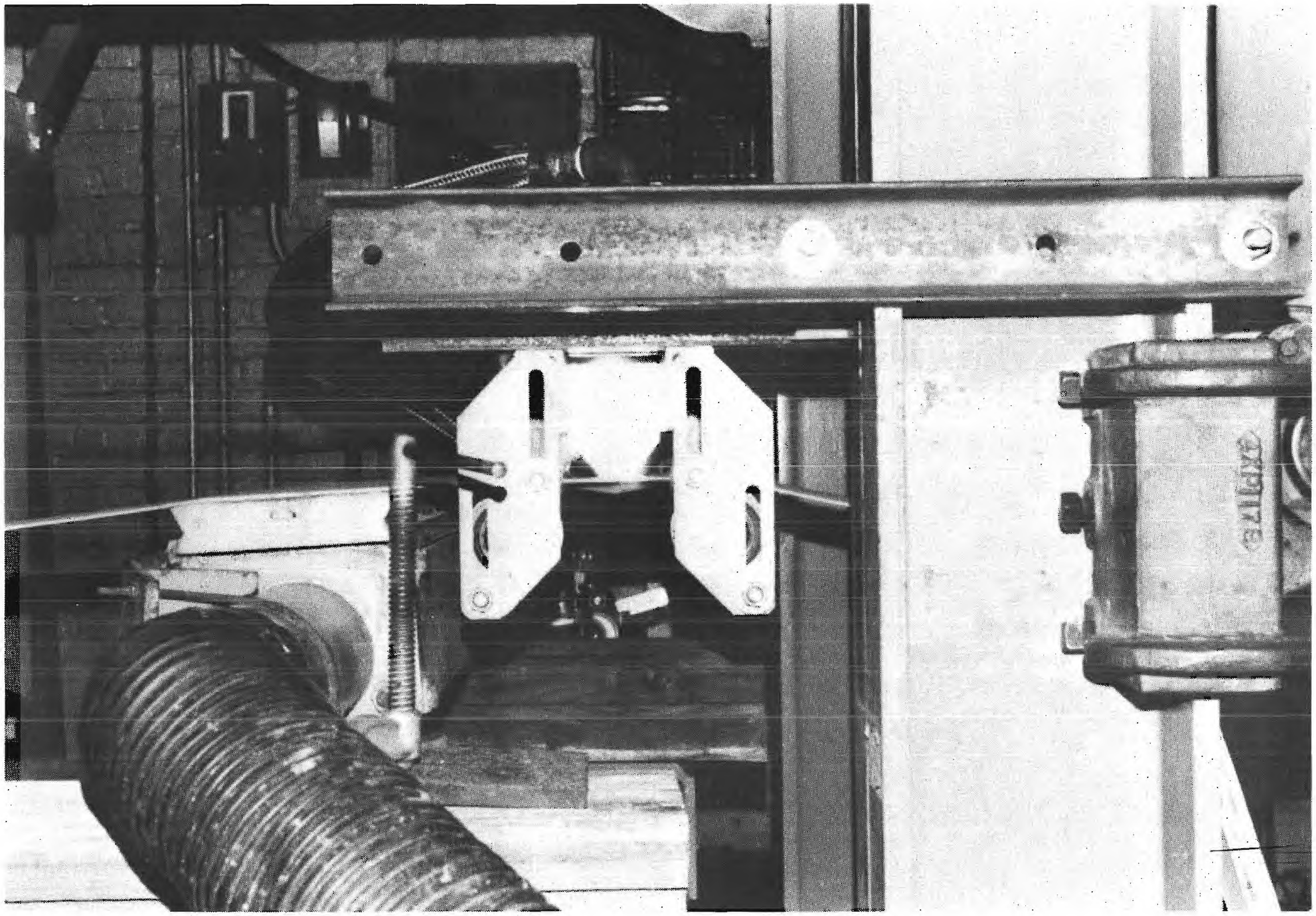


FIGURE 18. MACHNOZZLE/SUCTION BOX ARRANGEMENT.

the suction box. This positioning obviously resulted in non-representative conditions at the nip. However, this was not a point of interest in the tests, and this shower position was considered acceptable for the measurement of dewatering performance.

Since the felt was wider than the Machnozzle used for these tests, both the suction box slot and the shower pipe were taped to reduce their effective size to match the Machnozzle (Figure 19).

The Test Methodology

Two different, possible test methodologies were considered. The first of these involves maintaining a constant felt moisture approaching the Machnozzle. Measuring how much the felt moisture after the suction box could be reduced by operating the Machnozzle would directly evaluate how much additional water was being removed from the felt.

The problem with this method is that in a production environment, a drier felt leaving the suction box would normally mean the felt would still be drier as it left the nip and approached the suction box again. That is, if a suction box attains improved performance, the felt moisture content should be lower at all points along the felt path.

The second possible methodology is to establish a baseline moisture content by operating the system at a steady-state with the Machnozzle turned off. The nozzle is then turned on without changing any other operating conditions, and a new, steady-state moisture content is measured.

The weakness in this approach is that a constant shower rate would not reflect the additional water expected to be absorbed from the paper sheet on a production machine. This additional water flow should be very small in comparison

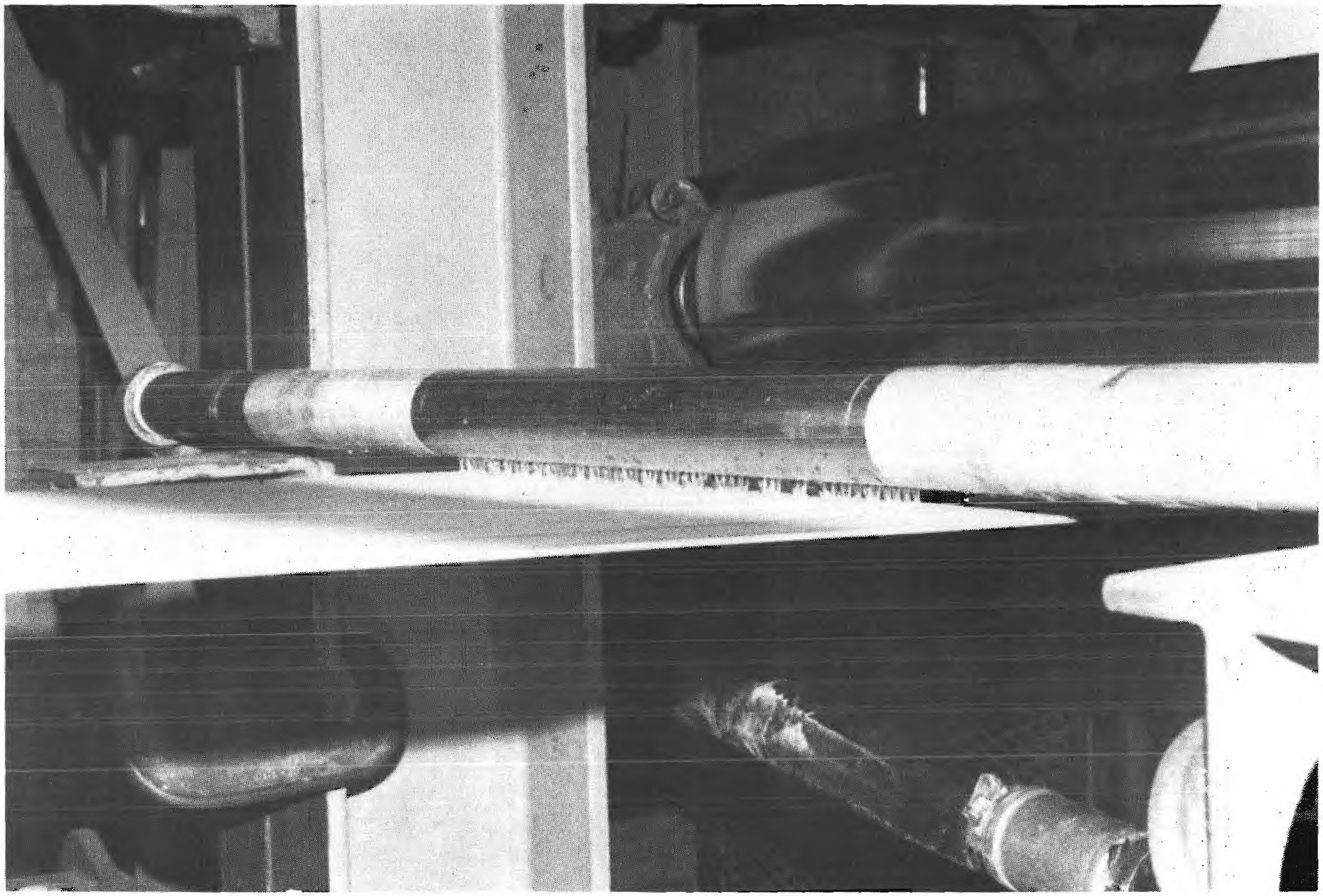


FIGURE 19. FLOODING SHOWER.

to the sum of the total water absorbed and the shower water flow. Therefore, the second methodology was selected for this series of tests. As a result, it is not meaningful to discuss how much more water is removed from the felt when using the Machnozzle. The same amount of water is removed but at a lower residual felt moisture.

The Test Variables

Using this methodology, the following test parameters were investigated:

1. Felt type
2. Machine speed
3. Suction box vacuum
4. Shower water flow rate
5. Machnozzle operating fluid
6. Machnozzle operating pressure
7. Machnozzle position
8. Machnozzle exit slit opening

Each of these test pararmeters is discussed below followed by an outline of the results obtained.

Two different felts were used with both being of a batt-on-mesh construction. One had a dry weight of 3.30 oz/ft^2 and an initial permeability of 36 cfm/ft^2 @ 0.5 inch WC. The second weighed 2.45 oz/ft^2 and had an initial permeability of 130 to 140 cfm/ft^2 @ 0.5 inch WC. The permeability of both felts decreased during the tests as the felts were run in.

Machine speeds from 500 ft/min to 3000 ft/min were tested with most of the data being collected at a baseline of 1500 ft/min. With the lower permeability felt there was a problem with press bounce and speed was restricted to a maximum of 2000 ft/min.

Vacuum levels of 7 in. Hg and 14 in. Hg were tested. The 14 inch vacuum level was very nearly the maximum that could be maintained with the high permeability felt. Specific shower rates of 0.06 and 0.20 lbm water/lbm felt were used. Constant specific shower rates were maintained by adjusting water flow as felt speed was changed and when the different weight felts were switched. This was considered to be a more meaningful test procedure than maintaining a constant absolute flow rate (gpm), as conditions were varied.

Together, vacuum level and shower rate were found to provide a range of baseline felt moistures. However, it was determined that the means of obtaining a particular baseline moisture level was irrelevant as far as Machnozzle performance was concerned. That is, by increasing both the shower rate and the vacuum, a similar moisture level could be obtained. When the Machnozzle was then operated, the improvement was independent of the particular vacuum and shower settings.

Most testing was conducted with steam as the operating fluid. However, limited testing was conducted with compressed air in order to evaluate how much of the drying effect was due to thermal energy of the steam rather than mechanical energy of the sonic flow.

A 125 psig steam boiler was used to drive the Machnozzle; however, a swing in boiler pressure resulted in 100 psig being the highest pressure which could be maintained reliably. This pressure was regulated by a controller just prior to flow-measuring equipment and the Machnozzle. Data was then taken for steam pressures of 60, 80, and 100 psig. In the graphical presentations of data that follow, the 0 psig data points represent conditions with the Machnozzle turned off.

Air was taken from the facility's central compressor system. A pressure of 90 psig was the maximum that could be maintained at the nozzle, and at times the maximum was 80 psig. Data was recorded with the air turned off (0 psig) and at 40, 60, 80, and 90 psig.

The Machnozzle's exit slit is nominally 0.025 mm across (approximately 0.001 inch). In order to assess the effect of increased flow, shims were installed between the halves of the nozzle assembly for part of the testing. These shims were 0.001 inch thick, and one or two shims at a time were used, giving nominal slit widths as high as 0.003 in.

The Test Results

The first tests conducted were directed at determining whether there was a favorable relationship between Machnozzle use and felt moisture and how this relationship depended on machine speed. Figure 20 presents the results of this test. The vertical axis represents steady-state felt moisture content after the suction box (lbm water/lbm felt x 100), and the horizontal axis is machine (felt) speed. Data are presented for both of the felts tested.

The general trend of the lines from low moisture at low speeds to high moisture at high speeds may be attributed to the reduced residence time of the felt in front of the suction box slot. As speed was increased, the shower water flow was increased proportionately to maintain a constant specific shower rate. The reduced residence time resulted in a higher residual moisture content in order for the water to be removed by the suction box.

For each felt, two lines are presented. One represents the moisture level achieved with the suction box acting alone and the other with the Machnozzle turned on at 100 psig. The separation distance between the two lines is an indicator of the contribution made by the Machnozzle to the dewatering effort. A shower rate of .20 lbm water/lbm felt was used for all of this test. With the high permeability felt, a 7 in. Hg vacuum level was used while a 14 inch vacuum level was used with the low permeability felt. The differences between the two sets of curves may be attributed to felt permeability, dry weights of the felts, and vacuum levels.

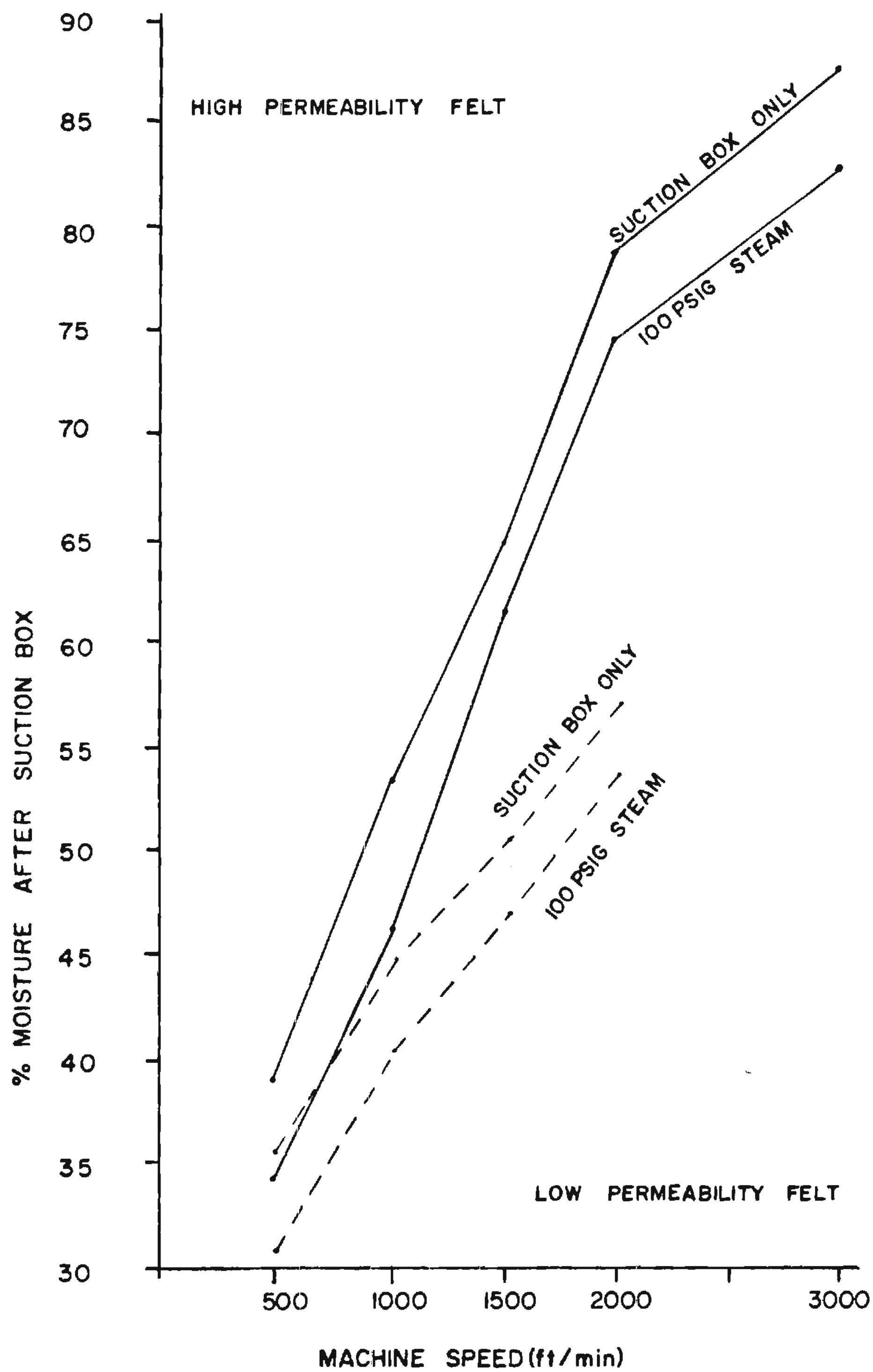


FIGURE 20 FELT MOISTURE VS. SPEED

The primary conclusions from this initial test were that a favorable relationship does exist and that the amount of improvement provided by the Machnozzle is relatively independent of felt type or operating speed.

The break in the curves for the high permeability felt at 2000 ft/min was caused by felt saturation. At the very high moisture levels, water was being removed at the press nip and at some of the guide rolls.

Speeds with the low permeability felt were limited to 2000 ft/min by a press bounce problem, indicating a felt defect. Due to this problem and some minor felt wear and damage caused during the preliminary tests of high wrap angles of the fabric around the Machnozzle tip, most of the remaining tests were conducted with the high permeability felt.

The next test phase investigated the effects of steam pressure, shower rate, and vacuum level. A baseline felt speed of 1500 ft/min was selected for this phase as well as all of the remaining tests with steam. The results are presented in Figure 21.

The four lines represent combinations of low and high shower rates and low and high vacuum levels. The vertical axis again is felt moisture after the suction box, and the horizontal axis is the steam pressure. The data points for 0 psig imply the baseline conditions with the nozzle turned off.

On this and all the graphs, lines are presented point-to-point between the measured values rather than assuming a particular curve shape for a regression analysis. It appears that a linear relationship is appropriate for the dependence on steam pressure.

In this graph the slope of the line indicates the contribution of the Machnozzle with increasing pressure.

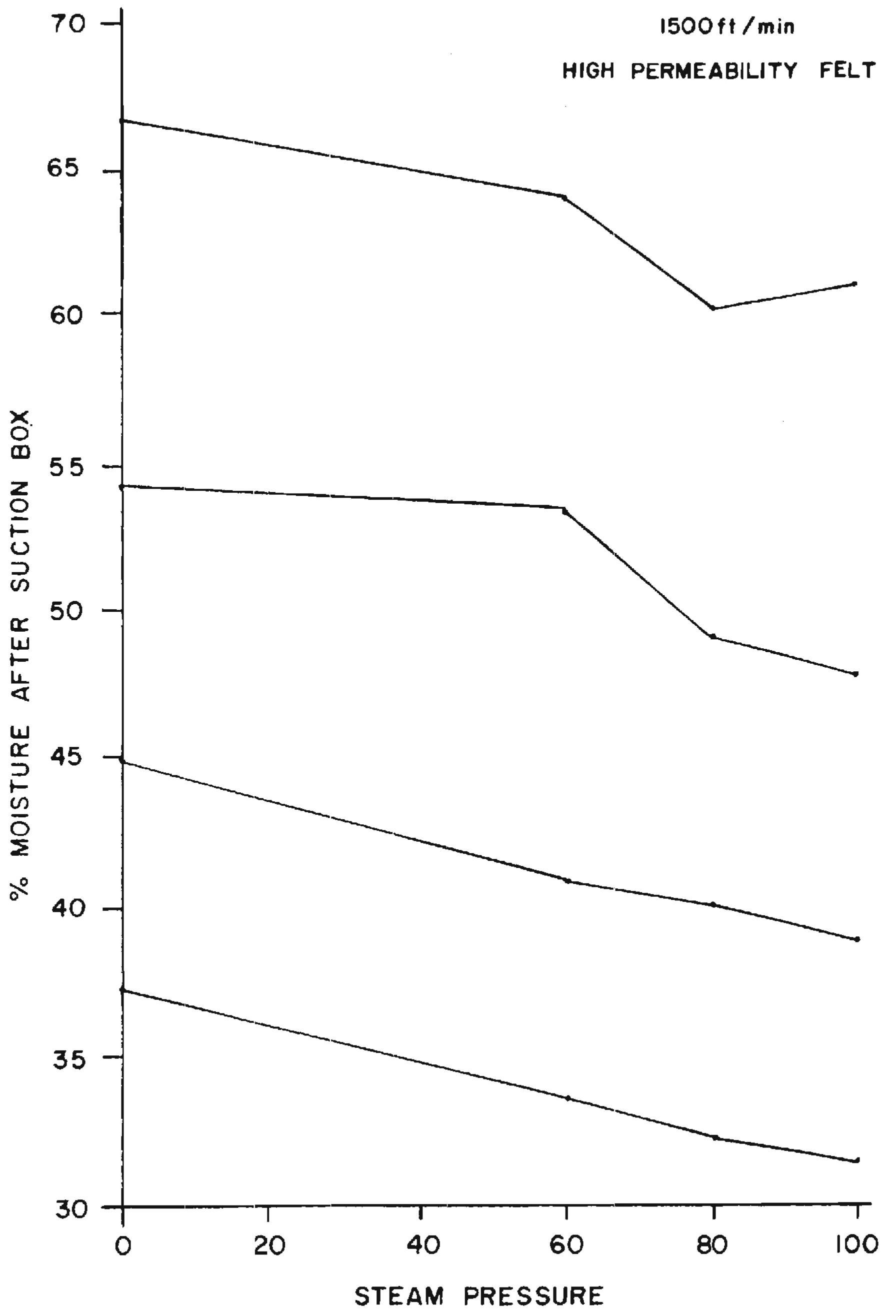


FIGURE 21 FELT MOISTURE VS. STEAM PRESSURE

It is evident that the slopes of the lines are very similar, which indicates that the contribution of the Machnozzle is relatively independent of the baseline moisture content, regardless of what vacuum level or shower rate is used to establish the baseline.

As pressure is increased, the mass flow rate of the steam through the Machnozzle increases. From the results presented thus far, it is not clear whether the important parameter is steam pressure or steam flow. In order to separate these variables, shims were installed between the halves of the Machnozzle. These were made from 0.001 inch stainless steel shimstock. Either one or two of the shims were used at a time, increasing the nozzle opening from its nominal 1 mil to 2 or 3 mils.

Tests were then repeated for the various operating pressures, and Figure 22 presents the results. The line labeled "With No Shims" is directly taken from the previous graph for reference. From this figure, it is seen that the Machnozzle's contribution to dewatering improves (steeper slope) as flow area is increased over the range investigated. Thus, it appears that performance is related to flow rate, while it is of minor importance, if any, whether the increased flow is obtained by higher operating pressure or greater cross-sectional area.

From this same figure, one additional point deserves note. The three data points for a pressure of 0 psig (nozzle off) represent identical test conditions, and theoretically should have resulted in the same value of felt moisture. Thus, the divergence of these data points is an indication of the repeatability of all of the data collected during this series of tests.

Since the economics of a Machnozzle installation will be dependent on steam consumption, the mass flow rates were recorded with the aid of an orifice plate and a digital flow monitor. Later in the project, some concern was developed as to the reproducibility of steam flow rates. This problem is discussed later in this

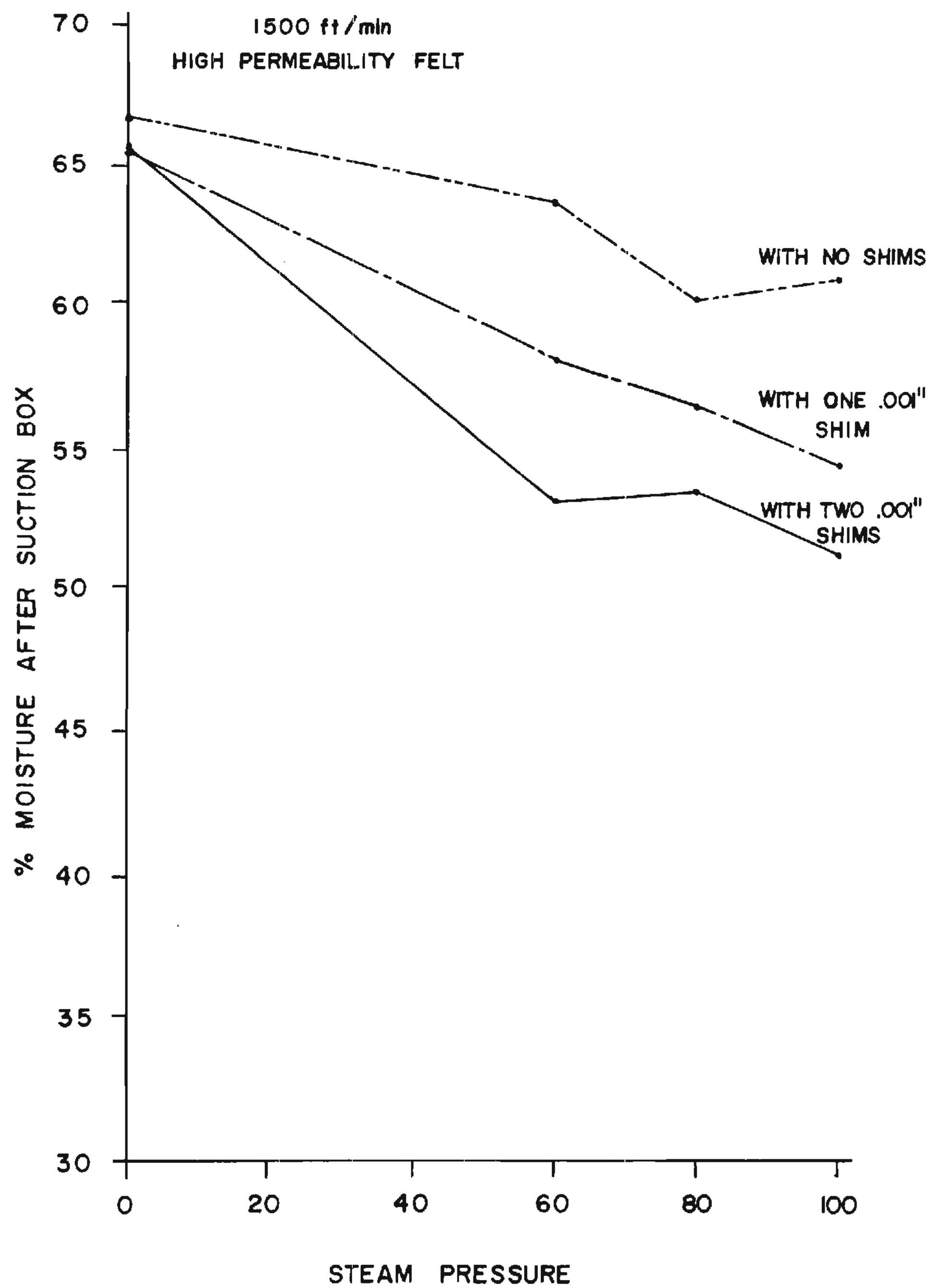


FIGURE 22 FELT MOISTURE VS. STEAM PRESSURE AND MACHNOZZLE OPENING

report, but for the present, the flow rates measured during testing at Albany are presented in Figure 23.

The flow rate is presented in terms of lbm/hr per inch of Machnozzle length (felt width). Flow rate was linear with pressure, and the flow with two shims (3 mil slit) is roughly three times the flow with no shims (1 mil slit).

As an introduction to the remaining tests, it is appropriate to discuss the operating principle through which the Machnozzle dries a fabric. Several principles have been suggested, but none have been uniformly accepted. At various times, the manufacturer of the device has suggested two explanations as to how the Machnozzle works in its ususal textile manufacturing application.

The first is that shock waves are created in the flow downstream of the nozzle, and these pressure disturbances vibrate the fabric as a whole or individual fibers and thus shake the water out.

The second suggested explanation is that the high differential pressure simply blows the water out. That is, a suction box cannot get a pressure differential above 14.7 psi, but the Machnozzle may provide 100 psi.

A variant to this explanation which is applicable to the Machnozzle/suction box combination suggests that the Machnozzle alters the moisture distribution inside the felt so that the water is closer to the suction box and more easily removed. (By the end of the test program, this alternative appeared most promising as an explanation of the Machnozzle's operating principle on a press felt.)

One additional explanation which has often been suggested is that the heat supplied by the steam reduced the viscosity and surface tension of the water, allowing it to flow more freely into the suction box. That is, a thermal effect was dominant rather than a mechanical effect.

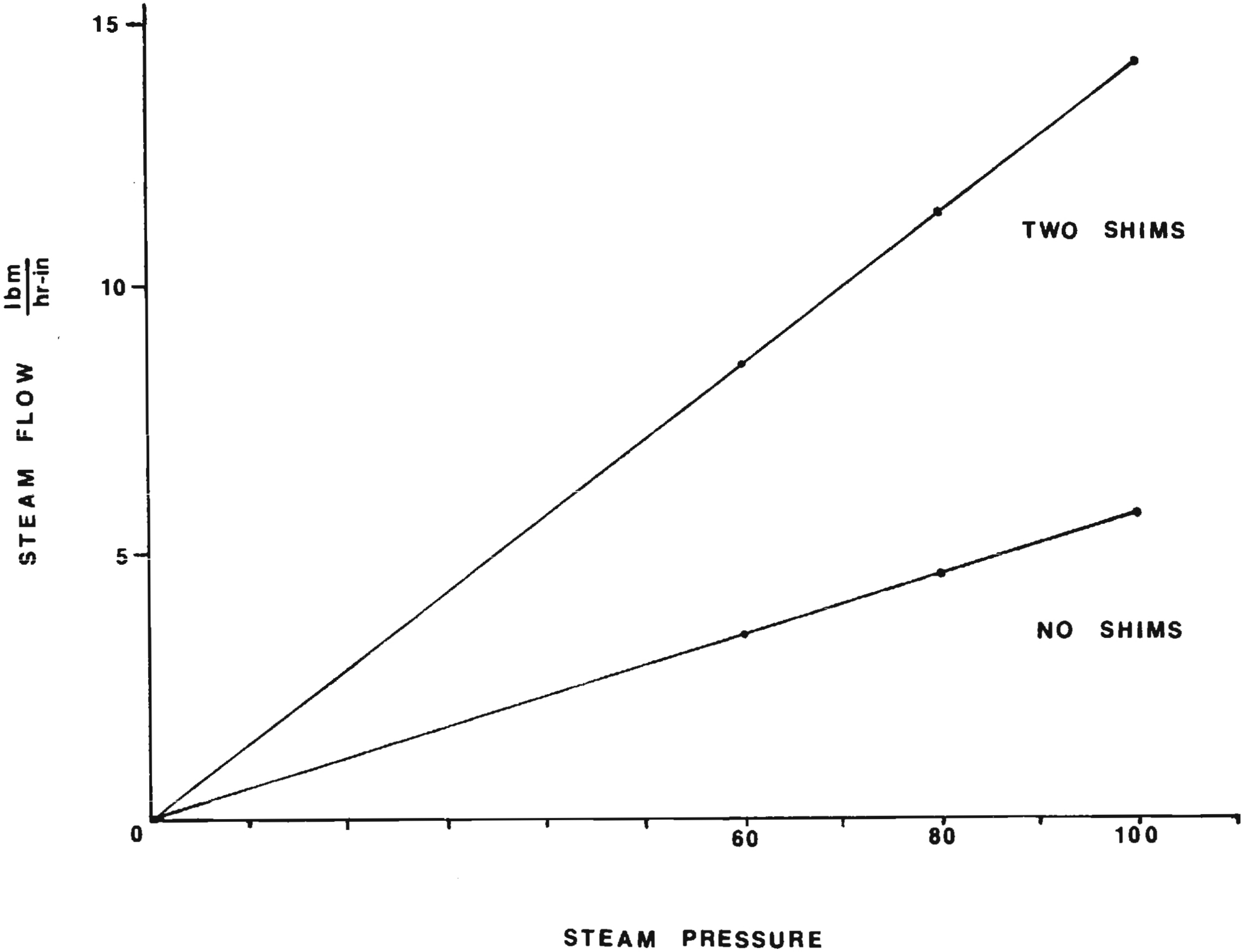


FIGURE 23: STEAM FLOW RATES DURING EXPERIMENTAL PRESS TESTS

In order to investigate these suggested operating principles, the following series of tests was conducted:

1. Use air instead of steam to investigate the thermal effect.
2. Try the Machnozzle alone, without the suction box.
3. Install the Machnozzle at various locations with respect to the suction box.

The results of the tests with compressed air are presented in Figure 24. When this figure is compared to Figure 22 for steam, it is evident that the results are similar. The conclusion was that the thermal effect was not significant even though the temperature of the felt surface increased by 25 to $45^{\circ}F$ on the nozzle side when steam was used.

In fact, it was found that the percentage reduction in steady-state moisture content was almost identical for compressed air and steam when both were used at the same pressure. On the other hand, at the same pressure, mass flow rates for air were higher than steam. The difference in flow rates has been attributed to the higher molecular weight of air, the higher density of air due to lower temperatures, and an unexplained tendency of the Machnozzle to give higher volumetric flow rates at a lower nozzle temperature. It is noted that the higher sonic velocity of steam would tend to balance the above effects.

When the Machnozzle was tested by itself by turning off the vacuum pump, the unit was totally ineffective. It was very evident that the nozzle alone was not capable of removing enough water to meet the requirements. Thus the Machnozzle may be considered as an addition to a suction box system, but not as a replacement.

Most of the testing was conducted with the tip of the Machnozzle 9 7/8 inches upstream from the leading edge of the suction box slot. Limited testing was

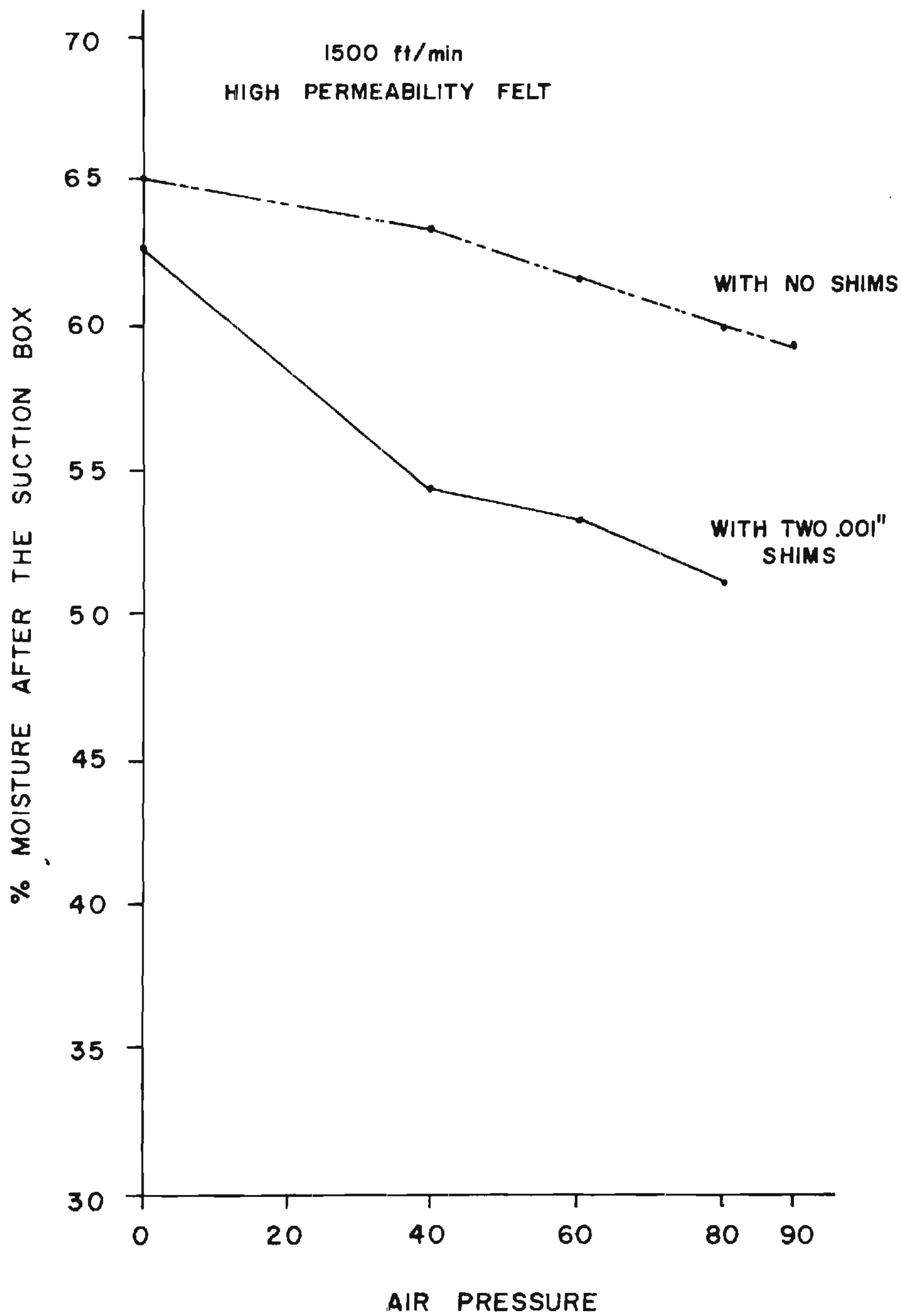


FIGURE 24 FELT MOISTURE VS. AIR PRESSURE AND MACHNOZZLE OPENING

also conducted with the nozzle 6½ inches and 20½ inches ahead of the suction box, which represented the extremes that could be achieved due to interferance of structural members on the test apparatus. Tests were also conducted with the nozzle approximately 14 inches downsteam of the suction box and directly opposite the leading edge of the suction box slot.

The conclusions reached from this series of tests are as follows:

1. Precise positioning of the Machnozzle upstream of the suction box is not a critical parameter over the interval investigated.

2. With the Machnozzle installed directly opposite the suction box, dewatering performance is equivalent to that obtained with the nozzle upstream of the suction box. However, there is a significant potential for pinching the felt between the nozzle and the suction box, so this location cannot be recommended.

3. With the Machnozzle downstream of the suction box, the data is not conclusive. When compressed air is used, there is not a measurable change in the felt moisture. When steam is used, there appears to be a positive effect, but it is much less than that obtained with an upstream installation.

Based on these findings, the recommended position for installing the Machnozzle is just upstream of the suction box and on the opposite side of the felt. In retrospect, it is clear that testing with the Machnozzle on the same side of the felt as the suction box could have provided answers to several questions which have been raised. This positioning is not expected to provide as good a dewatering performance, but the convenience which such a configuration would provide the mill during felt changes may warrant investigation of such an installation position in future testing.

The findings from the series of tests conducted on the experimental press section may be summarized as follows:

1. The Machnozzle clearly aids in suction box dewatering of a press section felt.

2. The Machnozzle is not suitable as a replacement for a suction box.

3. Using steam or compressed air as the operating fluid will provide similar results if similar pressures are used; however, the mass flow rate of the air will be higher.

4. The Machnozzle should be installed against the back side of the felt and just upstream of the suction box.

5. At an operating pressure of 100 psig, the steady-state moisture content of the felt may be reduced approximately 11%. If the Machnozzle slit is shimmed open by 0.002 inches, the moisture level may be reduced by approximately 22%.

Tests on the Pilot Paper Machine

After the tests on the experimental press section were completed, testing was resumed on the pilot paper machine at the Herty Foundation. On the experimental press section, a 400 mm long Machnozzle was used. For the pilot paper machine tests, an 1100 mm nozzle was purchased and installed just before the suction pipe (Figure 25). In order to minimize the number of variables, the machine was operated with only one press and only one felt.

Tests were conducted with the machine producing a 36 lbm sheet (3000 ft^2 basis) at speeds of 150 and 200 ft/min.

The results of these tests were not completely satisfactory. The primary problem was the very high steam flow through the new Machnozzle. Temporary flow rates as high as 23 lbm/hr per inch of nozzle length were recorded with no shims installed. Due to the high flow rate and the associated frictional losses in the piping system, a pressure of 70 psig was the maximum that could be

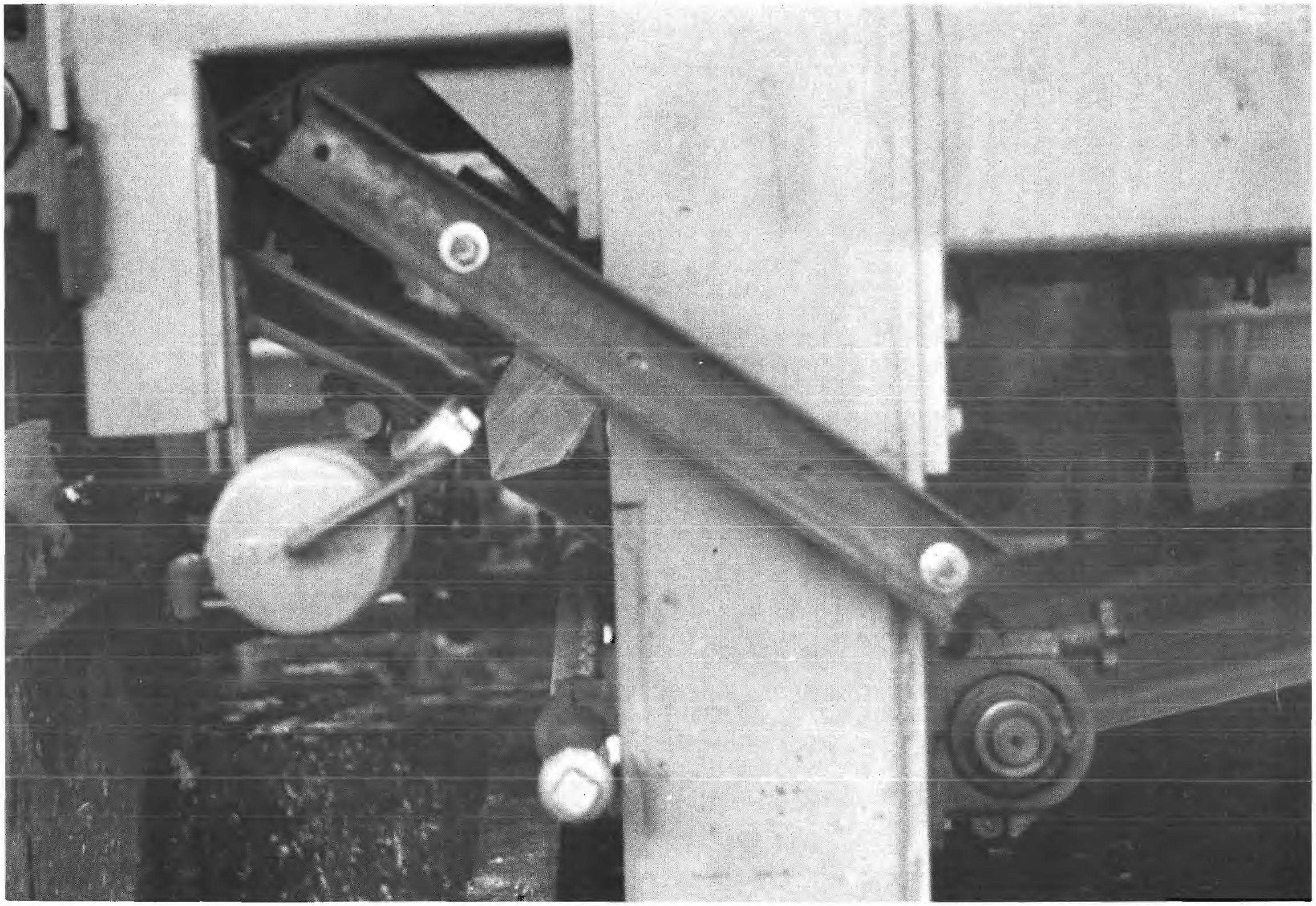


FIGURE 25. MACHNOZZLE ON THE PILOT PAPER MACHINE.

maintained. At this pressure the steady-state mass flow rate was approximately 15 to 16 lbm/hr per inch. This may be contrasted to the flow obtained with the 400 mm nozzle which, at 100 psig, was approximately 5.5 lbm/hr per inch with no shims and 14.3 lbm/hr per inch with 2 mils shims. Thus, with no shims the 1100 mm nozzle was consuming as much steam per unit length at 70 psig as the 400 mm nozzle consumed at 100 psig with the shims.

The reason for the discrepancy in observed flow rates is not fully understood at this time. Later tests were conducted on the Georgia Tech campus using the same steam supply for both nozzles. In these tests, with no felt present, the measured flow rates per unit length differed by less than 10%.

Attempts have been made to measure the slit openings; however, the small dimension and the fact that it may change with temperature have interfered with a clear conclusion. An analysis of the fluid flow inside the Machnozzle was conducted to aid in understanding the phenomena which could have caused this flow discrepancy. The results of this analysis are presented later in this report.

The information obtained from the measurements of felt moisture and sheet moisture was difficult to assess. Felt moisture was measured by portable equipment provided by Albany Felt Company (Figure 26). The felt moisture content was reduced by 17% to 20%, which is comparable to that obtained on the experimental press section with the shims installed in the Machnozzle. Thus, it appears that regardless of the cause of the high steam flow with the 1100 mm nozzle, the dewatering effect is similar to that obtained when the flow rate is deliberately increased with increased pressure and increased flow area.

The effect on sheet moisture was studied by lab analysis of grab samples taken after the couch roll and after the press. Variability in the values obtained for moisture after the couch roll makes the data difficult to analyze. It is not known whether the variation was in the process or the lab analysis.

FIGURE 26. MEASURING FELT MOISTURE CONTENT.

If the measured numbers are accepted as correct, water removal from the sheet at the press was increased approximately 2.3% by use of the Machnozzle. Percent variation in the numbers, however, are of the same order of magnitude as the improvement, thereby encouraging little confidence in this figure.

In summary, the test program on the pilot paper machine raised questions regarding steam flow rates, confirmed the earlier tests of the ability to improve the felt dewatering process with the Machnozzle, and left unresolved the question of the relationship between felt moisture and sheet moisture.

SECTION VII

BARRIERS TO IMPLEMENTATION OF THE MACHNOZZLE

There are several obstacles yet to be overcome before the industry can be expected to utilize the Machnozzle on production equipment. Questions which mill personnel can be expected to raise include the following:

1. Is the Machnozzle a specialty item, or is it readily available in a form for our use?
2. What will a Machnozzle cost to purchase and install?
3. What kinds of operating problems may be expected?
4. How much steam (compressed air) will the nozzle use?
5. Which operating fluid should be used?
6. How much will a drier felt help in drying the paper sheet?
7. What additional benefits might be attained by use of the Machnozzle?

Each of these questions will be addressed briefly in this section.

Availability

The Machnozzle is a patented device, developed and manufactured by Brugman Machinefabriek B. V. of Almelo, Holland. Brugman is a textile machinery manufacturer and does not direct marketing to the paper industry. It is expected that if testing verifies the commercial potential of the Machnozzle in the paper industry, a manufacturer of suction boxes or other felt-related equipment would obtain a license to manufacture and market a felt drying system incorporating the nozzle. Based on testing conducted under this project, there appear to be several minor design improvements which could be made.

Cost

Cost of the Machnozzle will, of course, depend on the width of the felt to be covered. The nozzle is currently available in length increments of 10 cm, but the longest one yet fabricated was three meters. It is felt that an optimal installation on a press section would use several nozzles butted end to end with each having a length of perhaps 1 to 1½ meters. Such an arrangement would minimize later replacement costs if damage occurred to one section of the nozzle. If each segment were individually pressure controlled, an additional process control tool would be available for adjusting moisture profiles.

Detailed cost estimates have not been prepared for such a system, but a rough idea of the cost range may be extrapolated from the costs of the two experimental Machnozzles which Georgia Tech has purchased:

	Length	Cost	Delivery
#1	400 mm	$3,200	1978
#2	1100 mm	$6,450	1979

It is evident that there is some economy of scale for nozzle length, and similar savings may be available through purchase of multiple units. Thus, it is expected that the nozzle alone should not exceed $30,000 to $35,000 for a 20 ft. wide press. The cost of auxilliary equipment, mounting hardware, and installation will depend on the complexity of the system design. Ideally, there should be provisions for disengaging the nozzle from the felt while the machine is running, plus consideration must be given to the procedures for changing felts.

Anticipated Operating Problems

During the test program, several potential operating problems were identified, but none of them appear to present insurmountable difficulties. First, there was occasionally a difficulty in initiating steam flow through the Machnozzle. If the nozzle and piping are filled with condensate, the flow of liquid through the small exit slit is so restricted that the initial flow rate is extremely low. Heat transfer from the nozzle to the cool felt can result in condensate being formed more rapidly than it can be expelled so that the nozzle remains filled with water. To alleviate these problems, some provision must be made to drain the condensate completely prior to startup.

Second is the problem of contaminants plugging the nozzle. At the beginning of the tests at Albany Felt Company, a flexible steam line with a soft "rubber" lining and coating was used to connect the Machnozzle to the boiler. Even though this line was intended for use with high pressure steam, there was a serious problem with gummy deposits accumulating in the nozzle, Figure 27. The problem was so severe that the nozzle completely plugged several times, and rigid piping was installed prior to collection of test data.

This problem accentuated the need for an adequate filter in the line of a permanent installation to remove the contaminants that can normally be expected in the steam supply.

The final operating problem identified is the potential for felt damage or excessive wear. The Machnozzle presents a stationary, steel surface constantly in contact with the back side of the felt. During testing, it was demonstrated that in

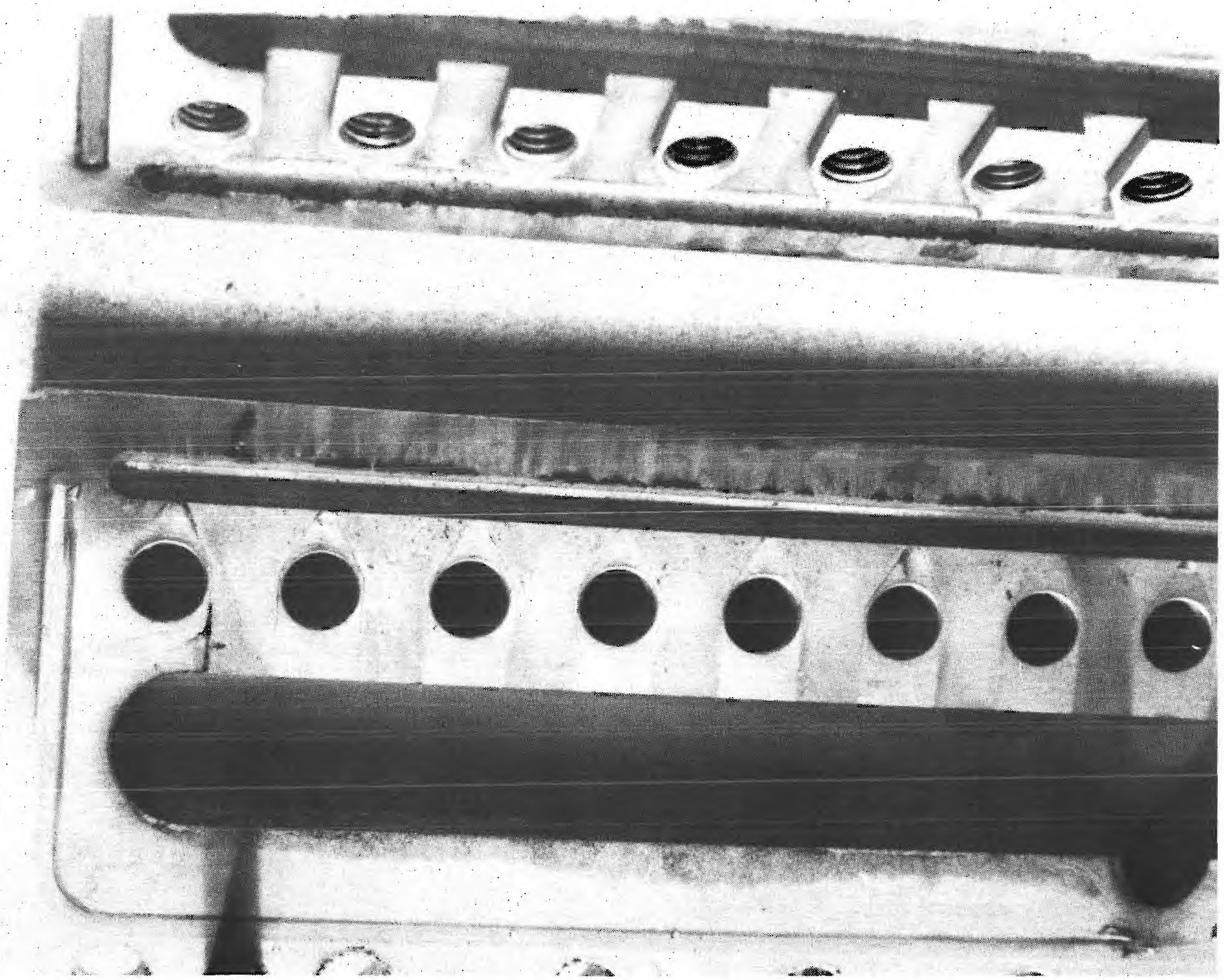


FIGURE 27. MACHNOZZLE PLUGGED WITH CONTAMINANTS.

some positions, the nozzle can rapidly damage the felt. In the recommended installation, however, no significant damage or wear is evident over the short period of time represented by the test program. Extended run tests will be necessary to determine the effect, if any, on felt life.

Steam Consumption

Steam consumption rate is an unresolved question. As noted previously, there was a significant discrepancy between flow rates for the two nozzles used in the tests.

Thus, it would be difficult to predict in advance what flow a new nozzle would give at a particular operating pressure. Section IX of this report presents an analysis of the internal fluid flow and discusses the factors which affect flow rate.

This problem is not critical, however, since the flow may be controlled by means of shims and pressure adjustments. The dewatering performance appears to be related to flow rate rather than the particular pressure or flow area. Based on the tests conducted, a flow of approximately 14.3 lbm/hr per inch of felt width will reduce the moisture content by 22% downstream of the suction box.

The decision as to which operating fluid should be used must be based on the availability and relative cost of steam and compressed air at the appropriate pressure in the particular mill. As noted, the dewatering performance is independent of the fluid, provided the same operating pressure is used.

Sheet Dryness

The primary obstacle remaining is the uncertainty as to how much benefit a drier felt is to drying the paper sheet. The tests conducted under this program were inconclusive due to variability of data and the fact that the test conditions did not properly simulate a production environment. In the literature, it is evident that the authorities have not reached a consensus on this topic, and further research in this area will be necessary in order for a thorough analysis of the Machnozzle's importance to be conducted. Futher discussion of felt moisture versus sheet moisture is presented in Section VIII of this report.

Additional Benefits

In addition to providing a drier sheet directly, there are several items of potential value in a Machnozzle installation. These include:

1. Improved removal of contaminants from the felt, allowing better water flow.
2. Reduced requirement for shower water.
3. Increased nip pressures permitted with a drier felt.
4. Fewer sheet breaks in the nip with a lower hydraulic pressure.

None of these potential improvements have been investigated under this project, since they only relate indirectly to energy conservation.

SECTION VIII

SOME ECONOMIC PROJECTIONS

Analyzing the economic significance of a Machnozzle installation in a production mill requires estimates of the capital investment, operating costs, cost reductions obtained, increases in revenue, and (for a detailed study) the timing of the cash flows.

None of these items is known with accuracy at this time. A few projections are presented here to provide some perspective to the potential impact of the Machnozzle.

The primary difficulty lies in the lack of information about the relationship between felt moisture and the water removed from the sheet. As indicated earlier, the literature on this topic is filled with contradictions, both in data and in opinions. It seems quite probable that the relationship is dependent on the particular process and machine, giving rise to different findings when research is conducted at different facilities.

It is difficult to select and justify a particular published work on which to base projections. Nevertheless, one has been identified which considers quite a variety of operating conditions and which is presented in a form that is particularly convenient for use here. This is "From the Laboratory to the Paper Mill - A Study of Pressing," by Edward F. Decrosta and Wesley E. Plaistead of Albany Felt Company. (42) This paper was presented at the 1978 TAPPI Engineering Conference and appeared in the September, 1978, TAPPI magazine.

DeCrosta and Plaistead used the same experimental press section that was used for this project and passed handsheets through the press. The test matrix investigated grooved and suction press rolls, three felt construction types, single and double felting, different incoming sheet moisture contents and felt moisture contents, press loads, and residence time in the nip.

The results obtained were analyzed with a multiple-correlation, multiplicative regression model. The final form of the model equation is:

$$\binom{\text{Exiting}}{\text{Moisture}} = C_o \binom{\text{Entering}}{\text{Moisture}}^{C_1} \binom{\text{Felt}}{\text{Moisture}}^{C_2} \binom{\text{Nip}}{\text{Pressure}}^{C_3} \binom{\text{Residence}}{\text{Time}}^{C_4}$$

If this model and the experimentally-determined coefficients are accepted, the relationship may be calculated between sheet moisture leaving the nip and any or all of the controlled variables. If everything is considered constant except the incoming felt moisture, the exiting sheet moisture will be proportional to the felt moisture raised to the power C_2.

The experimental results showed a range of C_2 from -0.065 to +0.644. The negative value implies that for some of the test conditions, the drier felt actually gives a wetter sheet of paper. The general trends in response to felt moisture are that grooved-roll presses are more sensitive than suction-roll presses and that double-felted presses are more sensitive than single-felted presses. Felt construction is also a relevant parameter. However, the felt type which produces the most change in sheet moisture with a change in felt moisture is dependent on the type of rolls and the number of felts.

Using the results of DeCrosta and Plaistead's research, it is possible to project the range of improvement in sheet moisture which may be obtained by use of the Machnozzle. As reported in a previous section, tests with the Machnozzle indicate that a steam flow rate of 14.3 lbm/hr per inch will reduce felt moisture to approximately 78% of its original value.

As an example, assume the final press on a machine has an exiting sheet moisture of 1.63 lbm water/lbm fiber, which is a consistency of 38%. If the highest value of C_2 found by DeCrosta and Plaistead (+0.644) is appropriate for this press, the use of the Machnozzle would reduce the sheet moisture as follows:

$$\text{New Sheet Moisture} = \text{Old Sheet Moisture} \times \left(\frac{\text{New Felt Moisture}}{\text{Old Felt Moisture}}\right)^{C_2}$$

$$= 1.63 \times (.78)^{.644}$$

$$= 1.39 \text{lbm water/lbm fiber or } 41.9\% \text{ consistency}$$

Such an improvement would mean that approximately 15% less steam energy would be required in the dryer section. From another viewpoint, if the machine is dryer-limited, a capacity increase of as much as 15% may be possible. A third possible way of viewing this improvement is that a new machine of similar design could reduce the capital investment required by installing the Machnozzle instead of 15% of the drying capacity.

Of course, these figures represent the maximum response found by DeCrosta and Plaistead. If a lower value of C_2 is appropriate, perhaps as low as +0.100, the consistency may be increased from 38% to 38.6%. This would provide an energy savings in the dryer section of 2½%.

In the extreme, there are those values of C_2 which are negative and imply that any effort to dry the felt would be counter-productive. Thus, the value of the Machnozzle is highly dependent on the sheet moisture vs. felt moisture relation for the particular paper machine.

For purposes of this economic projection, a mid-range value of C_2 of +0.200 will be used. This value would imply a consistency increase in the example above from 38% to 39.2% and an energy savings of approximately 5%.

If the machine is producing 900 TPD, total steam consumption in the dryer section will be about 3.6 million pounds per day. The improved consistency out of the press would mean a savings of about 180,000 lbm of steam per day. In order to achieve this, if the machine is 20 ft wide, the Machnozzle will consume about 82,000 lbm of steam per day for a net savings of 98,000 lbm/day. In the course of a year, this could represent savings of well over $100,000.

As indicated in the previous section, the projected cost of a Machnozzle for this size machine is $30,000 to $35,000. Installed cost may be of the order of $50,000 to $60,000. Thus, the projected payback period and long term net value are very favorable. It must be pointed out, however, that the value on a particular machine may be much higher or much lower. There is considerable leverage inherent in the sheet moisture vs. felt moisture relationship. Also, it may be that a Machnozzle installation is appropriate on several press felts on the same machine.

This example considers only the viewpoint of using the Machnozzle to reduce total steam consumption. As an alternative on a dryer-limited machine, production may be increased so as to give both a reduced energy consumption per pound of paper and an increased revenue and profit.

In the example above, the 900 TPD machine could potentially be speeded up 5% to give another 16,000 or so tons of production each year. The value of this production is dependent on incremental operating costs and the current market, but it is evident that considerable profit may be obtained while saving energy.

In summary, the Machnozzle offers considerable potential for both energy and monetary benefits. A number of questions must be resolved first, however, in order to determine just where an installation is appropriate and just how much the savings will be.

SECTION IX

ANALYSIS OF THE FLUID FLOW IN A MACHNOZZLE

The inventors of the Machnozzle have presented analyses (48, 49) giving brief explanations of the flow inside of the Machnozzle. One of the analyses was based on an obvious erroneous assumption that the flow in the slit of the Machnozzle (see Figure 28) is isothermal. In the other analysis, the flow in the slit was assumed to be adiabatic, which is a much better assumption. Both analyses were incomplete and did not present expressions relating either of the two quantities of interest (the steam mass flow rate through the Machnozzle and steam properties at the exit of the Machnozzle slit) with steam properties at the entrance of the Machnozzle.

Since previous analyses of the Machnozzle have been incomplete, a more thorough analysis has been conducted. Nomenclature for this analysis is given in Table V. In analyzing the flow through the Machnozzle, three regions of flow (see Figure 28) were considered: 1) from the entrance of the converging section of the Machnozzle to the nozzle throat, 2) along the nozzle slit from the nozzle throat to the slit exit, and 3) beyond the exit of the slit. The variations of steam properties in regions one and two were described quantitatively with equations. Analysis of the third region is very difficult and was beyond the scope of this study.

Several assumptions concerning the flow in the Machnozzle have been made. Steady flow conditions are assumed to exist throughout the Machnozzle, and the flow is assumed to be one dimensional (that is, all fluid properties are uniform over any cross section of the Machnozzle). The flows in regions one and two are considered to be isentropic and adiabatic, respectively. Changes in flow due to differences in elevation are assumed to be negligible compared to other effects.

TABLE V. NOMENCLATURE IN THE FLOW ANALYSIS

A	area
c	velocity of sound
c_p	specific heat at constant pressure
D	hydraulic diameter
f	coefficient of friction
h	enthalpy per unit mass
k	ratio of specific heats
ρ	density
τ_w	wall shearing stress
$(\ )^*$	signifies state at which $M = 1$ for adiabatic, constant-area flow with friction
L	duct length
L_{max}	maximum duct length for continuous flow
M	Mach number
p	pressure
R	gas constant
T	absolute temperature
V	velocity
w	mass rate of flow
x	Cartesian coordinate
$(\ )_o$	signifies stagnation state

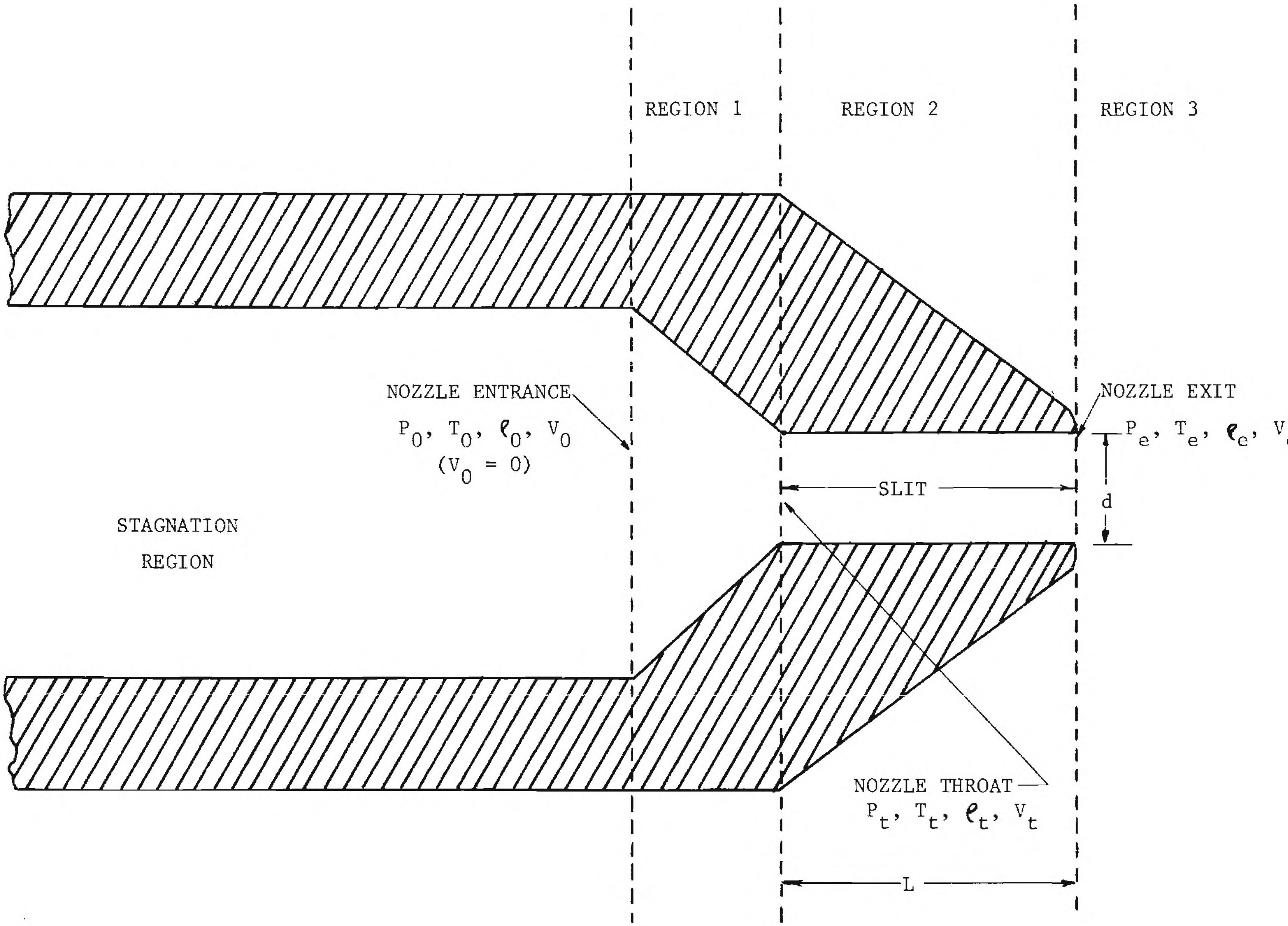


FIGURE 28 SCHEMATIC OF MACHNOZZLE SHOWING REGIONS OF FLOW

For temperature and pressures close to the saturated vapor line, steam acts much like an ideal gas. Since the properties of the steam in the Machnozzle are reasonably close to the saturation line, the steam was treated as an ideal gas. As the steam expands through the Machnozzle, the static pressure and temperature of the steam fall below the saturation line on the Mollier Chart, and a wet mixture of saturated vapor and saturated liquid might be expected. However, experiments show that the precipitation of moisture is delayed beyond the point where saturation normally occurs under equilibrium conditions. This phenomenon is referred to as supersaturation. Experiments have indicated that water vapor does not precipitate until the static temperature of the steam is about 110°F below the temperature at which saturation is reached. The line of condensation lies approximately 50 to 60 Btu/lbm below the saturation line (50). For the steam pressures and temperatures used with the Machnozzle, the static enthalpy of the steam lies above the line of condensation. Thus the treatment of the steam as a saturated vapor is reasonable.

In discussing flow through nozzles, two types of properties (static and stagnation) are useful. When a stream is moving at a velocity V, the properties of the stream as would be measured by an observer moving with the stream at the velocity V are called <u>static properties</u>. If the stream were decelerated isentropically (that is, by a reversible process) to zero velocity, the properties at the zero velocity are referred to as <u>isentropic stagnation properties</u>. Since no real process is ever completely reversible, isentropic stagnation density and pressure are never completely obtained. However, if the process is adiabatic (no heat transferred to or from the stream), the final stream temperature is equal to the isentropic stagnation temperature for either reversible or irreversible deceleration.

Stream Properties in Region 1

The variations in stream properties in Region 1 (the converging section of the nozzle) will be considered first. Since the flow in the converging section of a nozzle usually closely approximates an isentropic process, the assumption of isentropic flow in Region 1 is used. The variations in flow properties of an ideal gas flowing isentropically through a converging nozzle are given in reference 49. The relationships are:

$$\frac{T_o}{T} = 1 + \frac{k-1}{2} M^2 \qquad (1)$$

$$\frac{P_o}{P} = (1 + \frac{k-1}{2} M^2)^{\frac{k}{k-1}} \qquad (2)$$

$$\frac{\rho_o}{\rho} = (1 + \frac{k-1}{2} M^2)^{\frac{1}{k-1}} \qquad (3)$$

Equations (1) through (3) relate the ratios of isentropic stagnation properties to static properties in terms of Mach number M (ratio of stream velocity to local speed of sound) and the ratio of specific heats k. The flow in Region 1 is assumed to be isentropic; therefore, the isentropic stagnation properties (T_o, P_o, and ρ_o) are the same for all locations from the entrance of the nozzle to the throat. Since the velocity at the entrace of the nozzle is negligibly small (assumed to be zero), the properties given at the entrance of the nozzle are isentropic stagnation properties. Thus, Equations (1) through (3) relate the unknown stream static properties at any point from the nozzle entrance to the nozzle throat to the known stream properties at the nozzle entrance. Since the ratio of specific heats for steam is approximately 1.324, the only unknown on the right hand side of Equations (1) through (3) is the Mach number. When the Mach number at the throat of the nozzle is substituted into Equations (1) through (3), the static properties at the throat are obtained.

$$\frac{T_o}{T_t} = 1 + \frac{k-1}{2} M_t^2 \tag{4}$$

$$\frac{P_o}{P_t} = (1 + \frac{k-1}{2} M_t^2)^{\frac{k}{k-1}} \tag{5}$$

$$\frac{\rho_o}{\rho_t} = (1 + \frac{k-1}{2} M_t^2)^{\frac{k}{k-1}} \tag{6}$$

Note that the subscript "t" refers to the nozzle throat. The Mach number M_t must be determined before the static properties at the throat can be calculated using equations (4) through (6). Since M_t depends on the conditions down stream of the nozzle throat in Regions 2 and 3, the flow in Regions 2 and 3 will be discussed before a procedure for determining M_t is given.

Stream Properties in Region 2

Consider the flow in Region 2 (along the nozzle slit from the nozzle throat to the slit exit). The cross-sectional area of the slit is assumed to be constant (equal to the product of the slit width W and the slit thickness d). No special attempt is made to transfer heat to or from the stream, and the slit is extremely short (L = 7mm). Thus, the flow in Region Two is assumed to be adiabatic. Since the sit cross-sectional area is constant and the flow is adiabatic, the chief factor causing changes in fluid properties in Region 2 is wall friction.

The variations in fluid properties for adiabatic flow through constant-area ducts with friction have been analyzed in Reference 50. Since the analysis was based on assumptions identical with those made for Region 2, the results of the analysis apply to Region 2 of the flow thorugh the Machnozzle.

Figure 29 shows a control surface for analysis of adiabatic, constant-area flow. The changes in fluid properties and flow parameters over a distance dx along

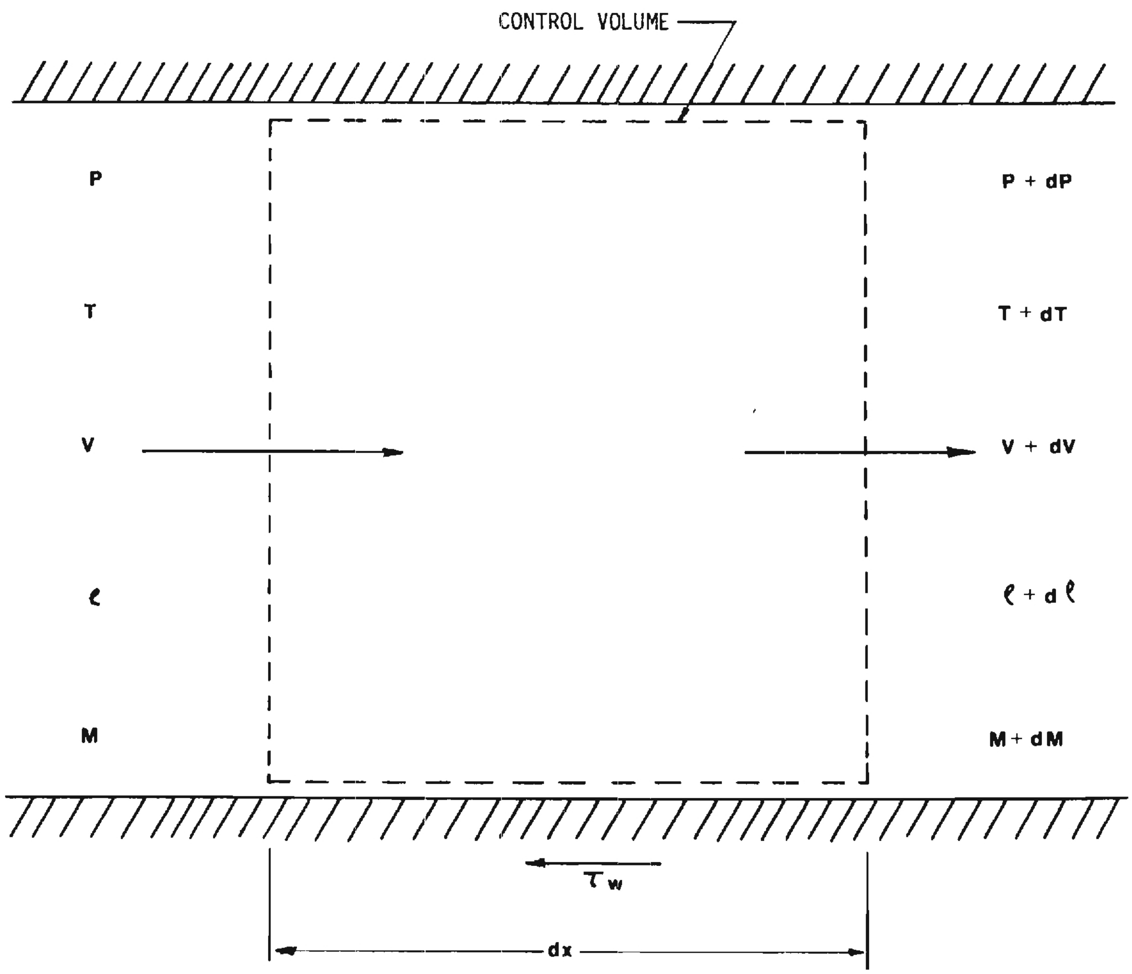


FIGURE 29 CONTROL VOLUME FOR ANALYSIS OF ADIABATIC, CONSTANT-AREA FLOW

the slit are due to viscous friction. The stream stress τ_w is exerted on the stream by the walls as a result of viscous friction. The expressions for the variations in fluid properties and flow parameters can be obtained by writing the governing equations (conservation of mass, momentum, and energy), utilizing the ideal-gas relationship, and employing various definitions of flow parameters. The resulting differential relationship between the viscous friction parameter 4fdx/D and the Mach number M at an arbitrary cross section x in the slit is

$$\frac{4f\,dx}{D} = \frac{1-M^2}{kM^4(1+\frac{k-1}{2}M^2)}\,dM^2 \qquad (7)$$

The ratio of specific heats k is assumed to be constant for steam and equal to 1.324. The symbol f denotes the coefficient of friction which is defined as the ratio of the wall shearing stress to the dynamic head of the stream. Thus,

$$f \equiv \frac{\tau_w}{\rho V^2/2} \qquad (8)$$

The symbol D (the hydraulic diameter) is defined as four times the ratio of cross-sectional area to wetted perimeter

$$D \equiv \frac{4Wt}{2(W+t)} \approx 2t \qquad (9)$$

The variables in Equation (7) are separated, so the expression can be integrated directly

$$\int_0^{L_{max}} \frac{4f}{D}\,dx = \int_{M^2}^{1} \left(\frac{1-M^2}{kM^4(1+\frac{k-1}{2}M^2)}\right) dM^2 \qquad (10)$$

Here, the limits of integration are taken at: (1) the section where the Mach number is M and x is arbitrarily set equal to zero, and (ii) the section where Mach number is one and x equals L_{max} (the length of slit required for the Mach number to change from M to one).

The second limit of integration requires some explanation. Since the constant-area slit is fed by a converging nozzle, the maximum obtainable Mach number in either the nozzle or slit is one. The flow accelerates through the nozzle, and the Mach number increases from approximately zero at the nozzle entrance to some Mach number M_t at the nozzle throat. The value of M_t will be less than or equal to one. The Mach number M_t can be equal to one only if the slit length is zero or if the slit is frictionless. Also, in both cases, the environmental pressure at the slit must be sufficiently low for M_t to attain a value of one. However, neither case applies to the Machnozzle; therefore, the flow at the throat is subsonic ($M_t < 1$).

As the fluid moves down the slit, viscous friction causes the flow to accelerate, that is, the stream velocity increases with distance from the nozzle throat. For steady state, the continuity equation requires the flow rate to remain constant throughout Regions 1 and 2 of the Machnozzle. The equation expressing this is

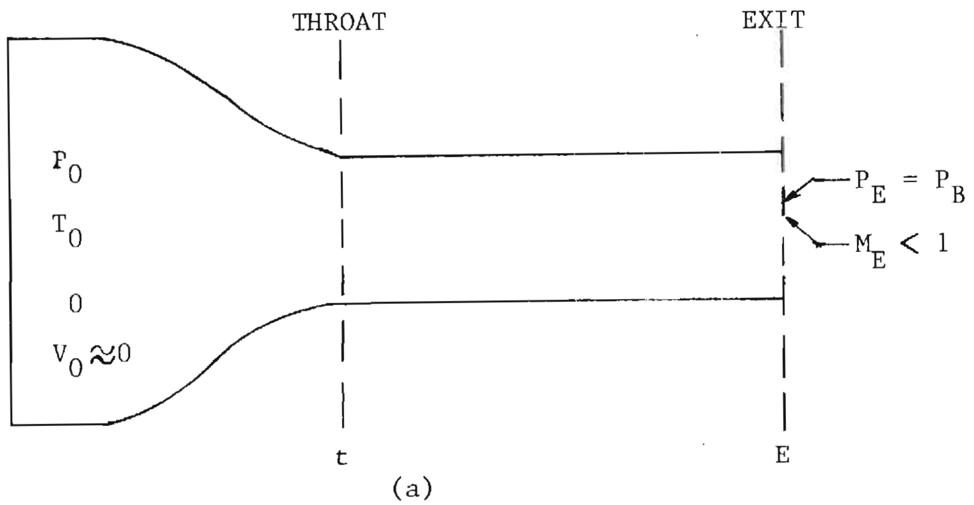
$$W = \rho VA = \text{Constant} \tag{11}$$

Since the cross-sectional area A of the slit is constant, ρV (the product of stream static density ρ and stream velocity V) must also remain constant. Thus, as the velocity increases along the slit, the stream static density must decrease. The viscous friction also causes the stream pressure (both static and stagnation) to be dissipated as the fluid moves down the slit and away from the nozzle throat.

As the flow accelerates down the slit, a Mach number of one may or may not be reached, depending on the slit length, the properties of the steam at nozzle entrance, and the pressure of the environment to which the Machnozzle exhausts. If a Mach number of one is reached, it occurs at the exit of the slit. For this case, L_{max} in Equation (10) simply represents the distance from the cross-section where the Mach Number is M and x equals zero to the cross-section at the exit of the slit.

If the pressure of the environment to which the Machnozzle exhausts is too great for sonic velocity ($M = 1$) to be obtained at the nozzle exit, the significance of L_{max} requires further explanation. Figure 30(a) illustrates the condition where the environmental pressure, or as it is usually referred to, back pressure (P_B), is too large for flow at the slit exit to be sonic. For this case, the stream static pressure at the exit, P_E, is equal to P_B. Suppose the slit is lengthened (see Figure 30b) and P_B is allowed to decrease so that the conditions in the slit from the throat to the original exit do not change. The stream velocity at the exit of the "fictitious" section of slit would increase as the length of the section was increased. Finally, at some additional length of slit, the Mach number at the exit of the "fictitious" section would equal one. It should be emphasized that the back pressure P_B at the exit of the fictitious section was decreased with the increasing slit length in such a manner that the conditions in the slit from the nozzle throat to the original exit do not change. Therefore, if the "fictitious" case where the Mach number equals one at the slit exit can be solved, the solution for the flow variations from the nozzle throat to the original slit exit would be identical to that for the actual slit.

If the Mach number at the exit of the Machnozzle is less than one, the fictitious section described above is added to the slit for analysis purposes. Then, L_{max} in Equation (10) represents the distance from the cross section where the Mach number is M and x equals zero to the exit fo the slit including the fictitious section (see Figure 30b).



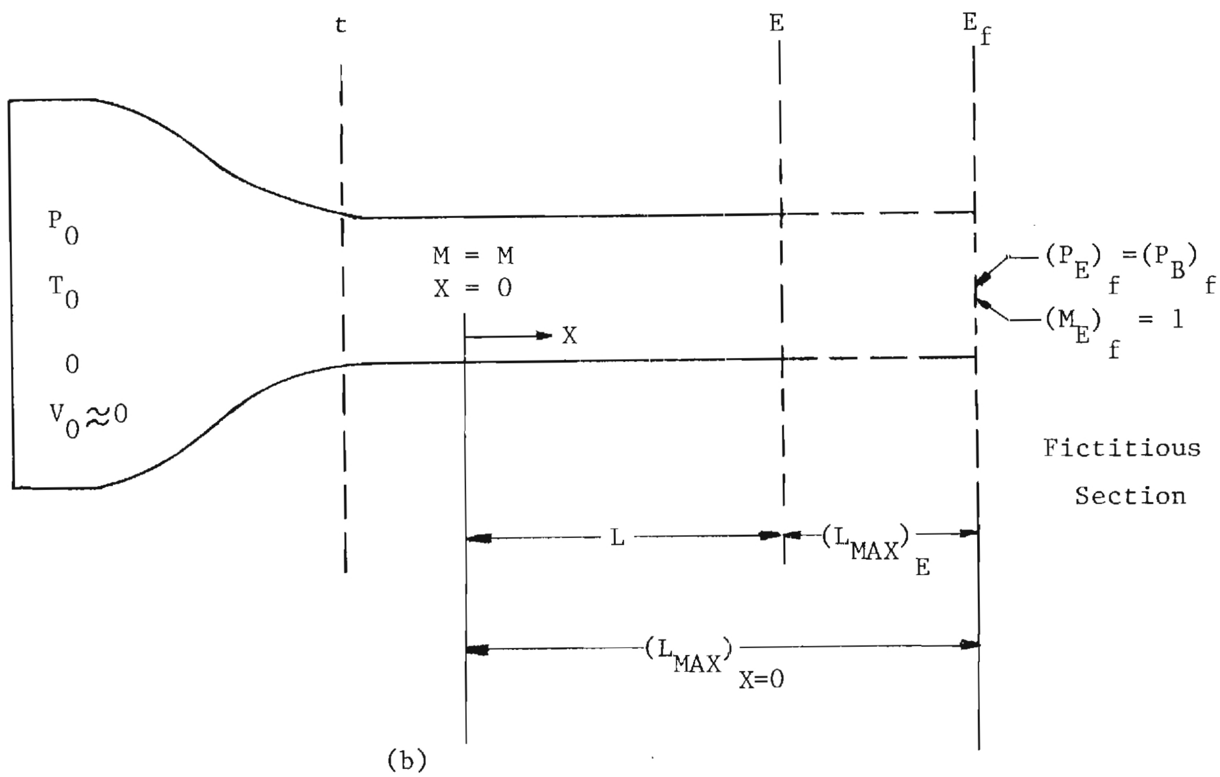


FIGURE 30 Schematic Illustrating The Use Of A "Fictitious" Section Of Slit For Cases Where $M_E < 1$

If the integration indicated in Equation (10) is carried out, the following expression can be obtained:

$$4\bar{f}\frac{L_{max}}{D} = \frac{1 - M^2}{kM^2} + \frac{k+1}{2k} \ln \frac{(k+1)M^2}{2(1 + \frac{k-1}{2} M^2)} \tag{12}$$

The symbol $\bar{f}$ denotes the mean coefficient of friction with respect to length, defined by

$$\bar{f} = \frac{1}{L_{max}} \int_0^{L_{max}} f dx \tag{13}$$

Since $4\bar{f}L_{max}/D$ is a function only of M, the length of slit L required for the flow to pass from a given initial Mach number M_1 to a given final Mach Number M_2 can be determined from the expression

$$(4\bar{f}\frac{L}{D}) = (4\bar{f}\frac{L_{max}}{D})_{M_1} - (4\bar{f}\frac{L_{max}}{D})_{M_2} \tag{14}$$

To illustrate how Equation (14) is useful, the example discussed above where the Mach number is less than one at the slit exit will be utilized. If the Mach number at the slit exit, M_E, is known, Equation (12) can be used to calculate $(\frac{4fL_{max}}{D})_E$. Next, $(\frac{4fL}{D})$ for the length of slit between x equal to zero and the slit exit is calculated. By rearranging Equation (14) and substituting for $(\frac{4fL_{max}}{D})_E$ and $(\frac{4fL}{D})$, the value of $(\frac{4fL_{max}}{D})$ at x equal to zero can be determined. Then Equation (12) can be used to calculate M for x equal to zero.

As mentioned previously, the change in fluid properties and flow parameters with position x along the slit are due solely to viscous friction. As a result, the variations in fluid properties and flow parameters can be written in terms of the viscous flow parameter $(\frac{4fdx}{D})$. Since Equation (10) relates $(\frac{4fdx}{D})$ at an arbitrary cross-sectional position x along the slit length with the local Mach number, the local fluid properties and flow parameters can be written in terms of the local Mach number. The variables in the expressions can be separated, and equations can be integrated. The resulting relationships are

$$\frac{p}{p^*} = \frac{1}{M}\sqrt{\frac{k+1}{2(1+\frac{k-1}{2}M^2)}} \tag{15}$$

$$\frac{V}{V^*} = M\sqrt{\frac{k+1}{2(1+\frac{k-1}{2}M^2)}} \tag{16}$$

$$\frac{T}{T^*} = \frac{c^2}{c^{*2}} = \frac{k+1}{2(1+\frac{k-1}{2}M^2)} \tag{17}$$

$$\frac{\rho}{\rho^*} = \frac{V^*}{V} = \frac{1}{M}\sqrt{\frac{2(1+\frac{k-1}{2}M^2}{k+1}} \tag{18}$$

$$\frac{p_o}{p_o^*} = \frac{1}{M}\sqrt{\left[\frac{2(1+\frac{k-1}{2}M^2)}{k+1}\right]^{\frac{k+1}{k-1}}} \tag{19}$$

The quantities marked with an asterisk in these expressions, such as p*, V*, etc. represent the values of the stream properties at the section of the slit where M=1. Since they are constants for a given constant-area flow, they may be regarded as convenient reference values for normalizing the equations.

Relationships Applying to Regions 1 and 2

Since Regions 1 and 2 are assumed to be adiabatic, the energy equation for steady flow for the two regions is

$$h + \tfrac{1}{2}V^2 = h_o \tag{20}$$

For an ideal gas,

$$dh = C_p dT \tag{21}$$

Thus

$$\int_h^{h_o} dh = \int_T^{T_o} C_p dT \tag{22}$$

and

$$h_o - h = C_p(T_o - T) \tag{23}$$

The Mach number is defined as the ratio of stream velocity to the local speed of sound, i.e.,

$$M = \frac{V}{C} \tag{24}$$

For an ideal gas,

$$C = \sqrt{kRT} \tag{25}$$

Rearranging Equation (24) and substituting for C using Equation (25) gives

$$V^2 = M^2 kRT \tag{26}$$

Combining Equations (20), (23), and (26) gives

$$T = \frac{2C_p T_o}{2C_p + M^2 kR} \tag{27}$$

If the Mach number is known at any cross section, Equation (27) can be used to calculate the local static stream temperature.

Determination of Stream Properties in the Machnozzle

The equations presented above were used to determine stream properties at two locations in the Machnozzle: the nozzle throat and the slit exit. Seven flow parameters had to be specified before the equations could be used to determine the stream properties. Six flow parameters were readily specified; however, specifying the seventh parameter required selecting between two parameters.

The pressure of the steam supplied to the Machnozzle was measured, and the steam was assumed to be saturated as it entered the converging section of the nozzle. Thus, three stream properties, P_o, T_o, ρ_o, at the nozzle entrance were known. Also, the velocity of the stream at the nozzle entrance was assumed to be negligible, i.e., V_o equals zero. The fifth and sixth flow parameters assumed known were the slit length L and the slit width d.

Two options were available for specifying the seventh flow parameter. One was to determine the mean coefficient of friction ($\bar{f}$) from the literature and use it as the seventh flow parameter. The other was to use the mean mass flow rate through the Machnozzle, which had been measured using an orifice plate.

In analyzing fluid flow problems, $\bar{f}$ is normally determined from tables, charts, etc., available in the literature. However, information concerning $\bar{f}$ for a compressible fluid flowing through an extremely narrow slit could not be found. In order to make calculations, $\bar{f}$ was estimated from Moody Charts for incompressible fluid flowing through pipes. When this was done, the results of the calculations were highly questionable. For example, for a steam supply pressure of 100 psig, the following results were obtained: 1) the calculated mass flow rate was less than

25% of the measured mass flow rate; 2) the calculated Mach number at the slit exit was 0.95; and 3) the calculated static pressure at the slit exit was equal to atmospheric pressure. It is highly unlikely that the Machnozzle would be effective if the stream pressure at the slit exit were equal to atmospheric pressure. Also, it is highly unlikely that the measured mass flow rate was off by a factor of four. Therefore, $\bar{f}$ estimated from Moody Charts for an incompressible fluid flowing through pipes does not appear to be applicable to the compressible flow through the extremely narrow slit in the Machnozzle. Since the results obtained when $\bar{f}$ was specified as the seventh flow parameter were unreasonable, the steps in solving the equations for the stream properties will not be outlined for this case.

The other option for specifying the seventh flow parameter was to use the mean mass flow rate through the Machnozzle, which was measured using an orifice plate. When the mean mass flow rate was taken as the seventh flow parameter and the calculations were made, the results were quite different from those when $\bar{f}$ was specified. For example, for a steam supply pressure of 100 psig, the following results were obtained: 1) the calculated Mach number at the slit exit was 1.0 (the corresponding flow velocity was 1582 ft/sec); 2) the calculated static pressure at the slit exit was 47 psig; and 3) the calculated value of $\bar{f}$ was 0.00246 which is approximately 40 times smaller than the value obtained from the Moody Charts.

The calculated results when mean mass flow rate was specified as the seventh flow parameter were considered to be reasonable. The steps in the procedure for determining stream properties when mass flow rate was specified will be briefly outlined. The steps were:

1. Assume that the Mch number at the slit exit (M_E) is unity.
2. Calculate T_E and V_E using equations (27) and (26), respectively.
3. Calculate ρ_E using Equation (11).
4. Calculate the ratio ρ_E / ρ_o.

5. Note that:

(a) $$(\rho_E)/\rho_o = (\rho_E/\rho_t)(\rho_t/\rho_o) \tag{28}$$

(b) (ρ_E/ρ_t) is a function of M_t as given in Equation (18)

(c) (ρ_t/ρ_o) is a function of M_t as given in Equation (3)

6. Use Equations (3), (18) and (28) to determine M_t by trial and error.

7. Once M_t is determined, use Equations (1) - (3) to determine P_t, ρ_t, and T_t.

8. Use Equation (75) to calculate P*.

9. If $P^* > P_B$, then the assumption that $M_E = 1$ was correct, and $P^* = P_E$. Equation (12) can be used to calculate $\bar{f}$. If $P^* < P_B$, then the assumption that $M_E = 1$ was incorrect. In that case, an iterative solution is required. A value of M_E less than 1.0 is assumed, and Steps 2. to 8. are carried out iteratively until $P^* = P_B$. Then the assumed value of M_E is correct, and Equations (12) and (14) can be used to calculate $\bar{f}$. Note that if an iterative approach is required, Equation (28) will have to be rewritten as

$$\rho_E/\rho_o = (\rho_E/\rho^*)(\rho^*/\rho_t)(\rho_t/\rho_o) \tag{29}$$

where

ρ_E/ρ^* can be calculated using Equation (18)

(ρ^*/ρ_t) is a function of M_t as given in Equation (18)

(ρ_t/ρ_o) is a function of M_t as given in Equation (3)

Summary of Analysis

During the experimental phase of this research program, several questions were raised which related to the nature of the fluid flow through the Machnozzle. There appeared, at times, to be uncertainty as to the mass flow rates to be expected and as to the effect of various factors on the flow rate. In addition, the basic phenomena through which the Machnozzle affects the water in the felt are not clearly understood.

This analysis has attempted to provide a basic explanation of the relationships inovlved in the internal regions of flow. It has presented two techniques for prediction of fluid properties within the nozzle. The first of these techniques requires an assumed or experimentally-determined friction factor. The existing literature does not include studies of fluid friction in the realm of interest: compressible flow with very high velocities between closely-spaced, parallel walls. The experimental investigation of this flow regime may be of considerable academic interests, and the results would have greatly aided this analysis. However, such an experimental study was felt to be outside the scope of this research project.

The second analytical technique utilizes the flow rates observed during testing as a means to estimate the friction factor. This technique produces results compatible with experimental evidence and provides the mechanism for prediction of flow rates and fluid properties under various operating conditions.

BIBLIOGRAPHY

1. Wheeldon, J. B., and Ashworth, G., "First Report on Super Dewatered Press Felts," Paper Technology and Industry, 19, No. 6, 202-204, (July/August, 1978)

2. Personal Communication, A. H. Nisson, Westvaco Corp., N.Y., N.Y., Nov. 22, 1978.

3. "Refining in the Pulp, Paper and Board Industry," Compiled by Jones Division, Beloit Corporation, Dalton, Massachusetts, p. 8 (1975).

4. Clark, J. d'A., "Pulp Technology and Treatment for Paper," Miller Freeman Publicaitons, Inc., San Francisco (1978).

5. Personal Communication, G. R. Flohr, Beloit Corp., Dalton, Mass., Jan. 8, 1979.

6. Casey, J. P., "Pulp and Paper," Vol. 1, Second Edition, P. 350, Interscience Publishers, Inc., New York (1960).

7. Espenmiller, H. P., "The Theory and Practice of Refining," Southern Pulp and Paper Manufacturer (April 10, 1969).

8. Glasl, E., "Power Saving in Refining," Paper Technology and Industry, (September 1976).

9. Richter, G. A., "Some Aspects of Papermaking Properties of Wood Pulps," TAPPI, V. 41, No. 12, p. 776 (December 1958)

10. Hall, G., Paper Makers Assoc. Gt. Brit. and Ireland, Sec. Proc., 18, Part I, B 229 (October 1937)

11. Feltman, A. J., "Theory and Mechanics of Refining Stock for Paper and Board Manufacture," Paper Trade Journal, 142, No. 10, 36-40, (March 10, 1958).

12. Casey, J. P., "Pulp and Paper," Vol. 2, Second Edition, p. 633-635, Interscience Publishers, Inc., New York (1960).

13. Rubin, M. M., "Sheet Formation on Fourdrinier Wire," Paper Trade Journal, 101, No. 6, 67-71 (August 8, 1935).

14. Libby, C. E., and Ronning, O. K., unpublished thesis, "The Influence of Temperature during the Beating Process," New York State College of Forestry, Syracuse, N.Y., (February, 1949) cited in Ref. (11).

15. Tolvi, E., Paper and Timber (Finnish), 32, No. 3 (March 1950) cited in Ref. (12).

16. Clark, J. d'A., Paper Makers' Assoc. of Gt. Brit. and Ireland, Proc. Tech. Sec., 24, 30-54 (December, 1943) cited in Ref. (12).

17. Lindberg, N. J., and Mac Laurin, D. J., Paper and Timber (Finnish), 37, No. 8, 409-416 (Sept. 5, 1955) cited in Ref. (12).

18. Stephenson, J. N., Paper, 17, No. 26, 16-19 (March 8, 1916).

19. Hodges, C. R., "Optimum Use of Steam Showers for the Paper Machine," TAPPI, 60, No. 7, 94-97 (July 1977).

20. "Preheaters on Corrugating Medium Machine Boost Production at Green Bay Packaging," Paper Age (August 1974).

21. "How Hoerner Waldorf Mill Raised Its Liner Output and Reduced Costs," Pulp and Paper

22. Smook, G. A., Cutshall, K. A., Mardon, J., "Variables Affecting Press Performance on High Speed Newsprint Machines," Transactions of the Technical Section, Canadian Pulp and Paper Association, 1 (2), 38-48 (June 1975)

23. "Statistics of Paper and Paperboard," 1978, American Paper Institute, Inc., New York, N.Y.

24. Bowers, D. F., "Corrosion in Closed White Water Systems," TAPPI, 61, No. 3, 57-61 (March 1978)

25. Personal Communication, A. J. Piluso, Betz Laboratories, Inc., Trevose, Pa, (April 1979).

26. Askew, A. A., "Mill Water Close-up Problems and Specialty Chemical Answers," Southern Pulp and Paper Manufacturer, 20-22 (April 1979)

27. Jung, W. K., Kutzner, H. J., "Microbiologic Problems Associated with Closed Process Water Systems in the Paper Industry," European Journal of Applied Microbiology and Biotechnology, 5, 215-224 (1978)

28. Davy, M. F., Mueller, W. A., "Pulp and Paper Industry Worldwide Corrosion Costs," Proceeding of Pulp and Paper Industry Corrosion Problems, Joint TAPPI, NACE, Tech Sect., CPPA, Chicago, 1974.

29. Personal Communication, J. Y. Oldsue, Mixing Equipment Co., April 16, 1979

30. Personal Communication, Dr. Dan Manson, S. D. Warren Co., Westbrook, Maine, May 1979.

31. Personal Communication, Don Lehman, Black Clawson Co., Middletown, Ohio, May 1979.

32. Personal Communication, James Clay, Combustion Engineering, Inc., Springfield, Ohio, May, 1979.

33. Albany International Corporation. Paper Machine Felts and Fabrics, Albany, New York: Albany International Corporation, 1976, pp. 62-68, 81-86.

34. Wahlstrom, P. Borje. "Our Present Understanding of the Fundamentals of Pressing." Pulp and Paper Magazine of Canada Vol. 70, No. 19 (October 3, 1969), pp. 76-96.

35. Tenfalt, Eric. "The Development of Press Felts." Svensk Papperstidning (November 10, 1978) pp. 308-315.

36. Warren, C. A. "Practical Limitations to Water Removal at the Presses." Paper Technology and Industry, September 1976, pp. 196-199.

37. Cottigny, Cy M. and Liu, Thomas J. "Minimizing Sheet Rewet by Inverse Batt Stratification." Presented at TAPPI Engineering Conference, San Francisco, September 18-21, 1978.

38. Wicks, Laurie D. "Press Section Water Removal Principles and Their Application." Southern Pulp and Paper Manufacturer Vol 41, No. 1 (January 1978) pp. 14-17.

39. Wiseman, Nick. "The Effect of Felt Properties on the Pressing of Paper." Pulp and Paper Canada Vol. 77, No. 9 (September 1976), pp. 29-33.

40. Oliver, J. F. and Wiseman, N. Water Removal in Wet Processing: The Effect of Felt Roughness. Pointe Claire: Pulp and Paper Research Institute of Canada, (February 1977).

41. Ingalls, Joseph M. Huyck Research Center, Rensselaer, New York. Private Communication, 14 March 1979.

42. DeCrosta, Edward F. and Plaistead, Wesley E. "From the Laboratory to the Paper Mill: A Study of Pressing." TAPPI, Vol. 61, No. 9 (September 1978), pp. 29-32.

43. Plaisted, Wesley E. "Equlibrium Moisture Ratio of Press Felts Under Simulated Paper Machine Conditions." TAPPI, Vol. 59, No. 3 (March 1976), pp. 93-95.

44. Waugh, Robert W. "Key Considerations in Selecting Wet Felts for Energy Savings." TAPPI, Vol. 60, No. 8 (August 1977), pp. 86-89.

45. LaMarche, L. J. "Optimization of Pressing and Drying." Southern Pulp and Paper Manufacturer, Vol. 42, No. 1 (January 1979), pp. 18-20.

46. Wilson, C. M. W. and Bissell, M. J. "Optimization of Press Section Operation." Presented at International Water Removal Symposium, London, March 18-20, 1975.

47. Cosgrove, T. W. "Energy Conservation in the Felt Section of Yankee Tissue Machines." Presented at TAPPI Papermakers Conference, Atlanta, April 27, 1976.

48. van der Linden, H., Wassink, J., and Theusink, C. "Andwendung der Schallströmung von Gasen und Dämpfen in der Textilveredlung," Melliand Textilberichte 57 (1976), 53-56.

49. Theusink, C., "An Application of Sonic and Supersonic Vapor Flows in Textile Finishing," AATCC Book of Papers International Technical Conference 227, (1976).

50. Shapiro, A., The Dynamics and Thermodynamics of Compressible Fluid Flow, Volume 1, The Ronald Press Company, 1953.