Institute of Paper Science and Technology

SLIDE MATERIAL

To The

PROCESS SIMULATION AND CONTROL

PROJECT ADVISORY COMMITTEE

December 20, 1990
Georgia Power Technology Application Center
Atlanta, GA

Atlanta, Georgia

PAPERMAKING
PROJECT ADVISORY COMMITTEE

IPST LIAISON: RICHARD ELLIS

Mr. Benjamin A. Thorp (*Chairman*)
Senior Vice President Engineering
James River Corporation
Post Office Box 2218
Richmond, VA 23217-2218
(804) 649-4335
(804) 343-8592 FAX

Mr. Jack F. Brown
Manager Paper & Coatings
Boise Cascade Corporation
4435 North Channel Avenue
Portland, OR 97217-0000
(503) 286-7418
(503) 286-7467 FAX

Dr. David S. Dillard, Jr.
Director of Research and Development
Georgia-Pacific Corporation
100 Wisconsin River Drive
Port Edwards, WI 54469-0000
(715) 887-5111
(715) 887-5555 FAX

Mr. Robert V. LaBruzzo
Technical Manager
Tennessee River Pulp and Paper
Post Office Box 33
Counce, TN 38326
(901) 689-5199

Mr. Steve Smith
#1 Machine Supervisor
Westvaco Corporation
5600 Virginia Avenue
Charleston, SC 29411-2905
(803) 745-3211
(803) 745-3318 FAX

Mr. John W. Stolarz
Group Leader Papermaking
Mead Corporation
Eighth & Hickory Streets
Chillicothe, OH 45601-0000
(614) 772-3441
(614) 772-3595

Mr. James C. West
Containerboard Manufacturing Manager
Weyerhaeuser Paper Company
5410 79th Avenue Court
West Tacoma, WA 98467
(206) 924-2345

Mr. Allen Rosen
Section Leader Processes
Research & Development Division
Union Camp Corporation
Post Office Box 3301
Princeton, NJ 08543-3301
(609) 896-1200

AGENDA

PAPERMAKING
PROJECT ADVISORY COMMITTEE

December 20, 1990
Institute of Paper Science and Technology
Atlanta, GA

THURSDAY--December 20

8:30	Introduction and Antitrust Statement	Thorp/Yeske
8:30-9:00	PAC Organization	Yeske
9:00-10:00	DRYING Fundamentals of Drying	Orloff
10:00-10:15	Break	
10:15-11:00	DISPL Displacement Dewatering	Lindsay
11:00-11:45	COATS Fundamentals of Coating Systems	Aidun
11:45-12:15	WTPRS Fundamentals of Water Removal Processes	Aidun/Lindsay
12:15-1:00	Lunch (Discussion of New Projects - Investigation of Sheet Fluttering Effects in the Dryer)	
1:00	Adjournment	

DUES FUNDED RESEARCH PROGRAM

PAPERMAKING

PROJECT	TITLE	FY 90-91 BUDGET (K$)
DRYNG	Fundamentals of Drying	200
WTPRS	Fundamentals of Water Removal Processes	160
DISPL	Displacement Dewatering	160
COATS	Fundamentals of Coating Systems	100

FUNDAMENTALS OF DRYING
PROJECT 3470

December 20, 1990
Institute of Paper Science and Technology
Atlanta, Georgia

DUES-FUNDED PROJECT SUMMARY FORM
FY 90-91

Project Title:	FUNDAMENTALS OF DRYING
Project Code:	DRYNG
Project Number:	3470
Division:	Engineering and Paper Materials Division
Project Staff:	David Orloff
FY 90-91 Budget:	$200,000

PROJECT OBJECTIVE: With joint DOE support, to develop an understanding and a database sufficient for commercialization of impulse drying of paper.

RATIONALE: Impulse drying is an innovative water removal method that holds great promise for inexpensive water removal from paper webs, and for the improvement of several important paper and paperboard properties. The method involves pressing in a heated nip, so that water in the paper web forms steam upon contact with the heated surface, and this steam displaces liquid water from the sheet as it expands. The exposure of the wet paper surface to a heated nip also offers improved surface strength and densification.

However, delamination of the paper web during impulse drying has prevented the commercialization of this water removal method for heavyweight grades. Delamination occurs when superheated water remaining in the sheet expands to split the sheet when the constraint of the nip is relaxed on the exit side. The problem of delamination must be resolved before impulse drying can be commercialized.

Recent studies performed at the Institute have shown that delamination can be suppressed by limiting the energy transferred into the wet web by use of a heated surface with low heat transfer potential, such as a ceramic. The effectiveness of ceramic heat transfer surfaces is being explored by the Institute as a means of eliminating delamination in heavyweight grades.

GOALS FOR 1990-1991:

1. A master drying curve will be developed to show the influence of operating conditions such as: ingoing sheet moisture, preheat temperature, impulse and initial platen temperature on the impulse drying performance of plasma sprayed zirconium oxide surfaces for 205 gsm linerboard. In addition, heat flux measurements during the impulse drying process will be used to determine the mechanism of operation of the ceramic surfaces and their energy efficiency.

2. Steel pilot rolls will be coated with ceramic coatings optimized for both infrared and induction heating. These rolls will be evaluated on the pilot dryer using a typical linerboard furnish. The performance of these rolls will be compared to steel rolls in terms of water removal and delamination control. Roll durability will also be investigated.

3. The range of applicability for various grades, furnishes and process conditions will be investigated on the pilot press.

4. Various concepts, to improve the performance of impulse drying roll surfaces will be explored on the electrohydraulic press impulse drying simulation.

ACCOMPLISHMENTS TO DATE:

An electrohydraulic press was used to simulate impulse drying and to investigate the effectiveness of the ceramic surfaces in suppressing sheet delamination.

A series of experiments, in which the platen temperature was held constant while dwell time, basis weight and felt moisture were varied, showed that there are two regimes of delamination. One regime at short dwell times and another at longer dwell times. It was also discovered that ceramic surfaces require the application of a release agent to prevent sticking of the sheet to the ceramic surface as the nip opens.

Short dwell time experiments were designed to investigate the effect of ingoing sheet temperature and use of a high temperature polymer release agent on the performance of ceramic surfaces. The work demonstrated that preheating the sheet significantly improves water removal at all platen surface temperatures, and that the polymeric release agent prevented sticking.

As part of the work to construct a master drying curve, a wet pressing baseline study was undertaken to correlate water removal as a function of ingoing sheet temperature, ingoing solids and impulse. The study confirmed that increased ingoing sheet temperature and increased impulse result in increased water removal. The study provides a comparison to impulse drying at similar conditions of sheet preheat, impulse and ingoing solids.

As part of the same study, the impulse drying performance of a prototype ceramic surface was compared to a steel surface where both surfaces were coated with the high temperature release agent. The experiments were performed at a short dwell time of 20ms and over a range of peak pressures from 3 to 6 MPa. At these short dwell times water removal was found to be dependent on platen surface temperature and independent of platen material. Using z-directional ultrasound to quantify delamination, the experiments showed that the prototype ceramic surfaces can be operated at substantially higher temperatures and peak pressures without causing sheet delamination. At high surface temperature and high peak pressure, substantial strength improvements were realized. The ultrasound data also suggests that as a result of reduced flashing, a more uniform z directional density profile may result.

As part of the master drying curve development, a new surface thermocouple has been designed to measure heat flux during impulse drying with the prototype ceramic platen. The new thermocouples should allow the energy efficiency of the new surfaces to be evaluated and help explain the mechanism of delamination suppression.

Progress has also been made in demonstrating a ceramic coated roll on the pilot impulse drying press. A steel roll was plasma spray coated with a multi layer zirconium oxide surface which was also coated with the high temperature release agent. Linerboard, produced at the Institute, has been dried on the pilot press using the ceramic coated roll. Preliminary results show that high roll temperatures can be used without delaminating the sheets.

RELATED PROJECTS: This dues-funded project constitutes the IPST cost-sharing for a companion project of the same name, which is funded by the U.S. Department of Energy at a rate of approximately $350,000 per year for three years.

FUNDAMENTALS OF DRYING

PROJECT 3470

Engineering and Paper Materials Division

David I. Orloff Ph.D.

PROJECT GOALS FOR FY90-91

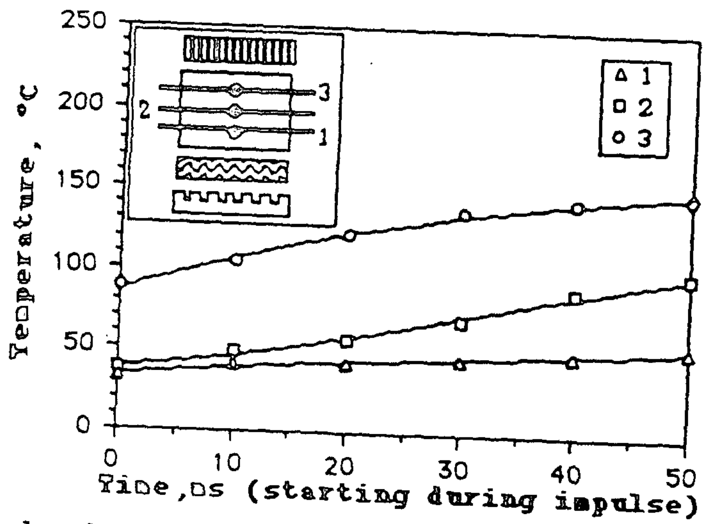
A master drying curve will be developed to show the influence of operating conditions such as: ingoing sheet moisture, preheat temperature, impulse and initial platen temperature on impulse drying performance of plasma sprayed zirconium oxide surfaces for 205 gsm linerboard. In addition, heat flux measurements during the impulse drying process will be used to determine the mechanism of operation of the ceramic surfaces and their energy efficiency.

Steel pilot rolls will be coated with ceramic coatings optimized for both infrared and induction heating. These rolls will be evaluated on the pilot dryer using a typical linerboard furnish. The performance of these rolls will be compared to steel rolls in terms of water removal and delamination control. Roll durability will also be investigated.

The range of applicability for various grades, furnishes and process conditions will be investigated on the pilot press.

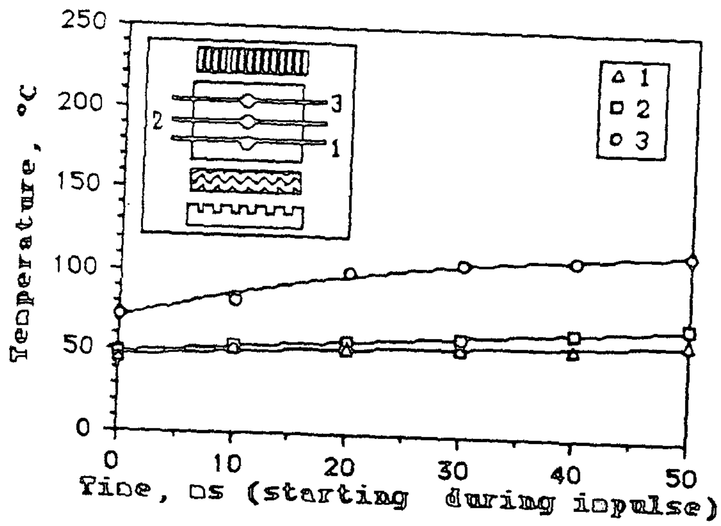
Various concepts, to improve the performance of impulse drying roll surfaces will be explored on the electrohydraulic press impulse drying simulation.

INTERNAL SHEET TEMPERATURES
DURING IMPULSE DRYING WITH A STEEL PLATEN



Internal sheet temperature of 205 gsm linerboard as a function of time during impulse drying using a steel platen. Ingoing sheet temperature=20°C, peak pressure=3.4MPa, initial platen temperature=260°C, ingoing felt moisture=16%.

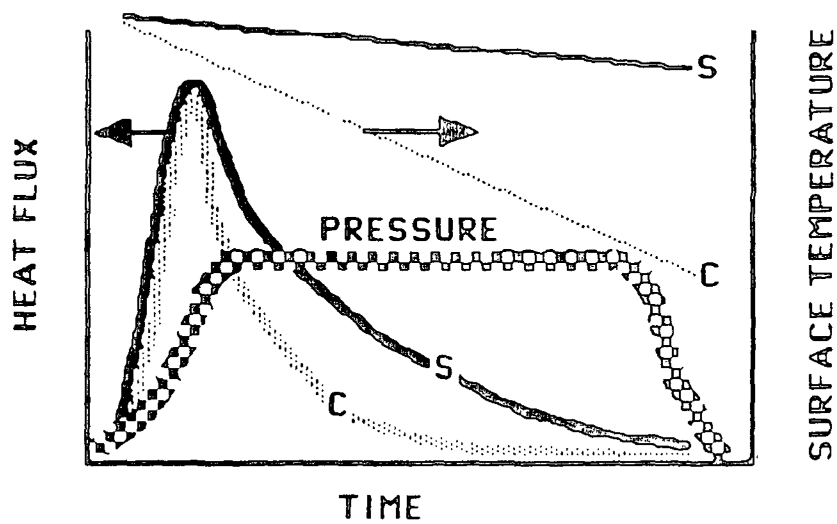
INTERNAL SHEET TEMPERATURES
DURING IMPULSE DRYING WITH A COTRONICS CERAMIC PLATEN



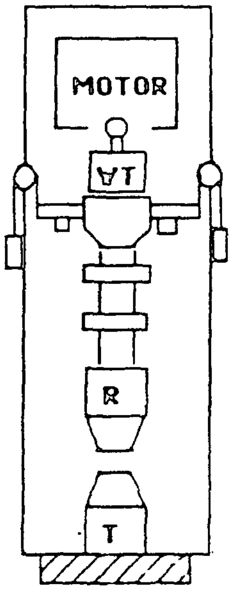
Internal sheet temperature of 205 gsm linerboard as a function of time during impulse drying using a Cotronics ceramic platen. Ingoing sheet temperature=20°C, peak pressure=3.4MPa, initial platen temperature=260°C, ingoing felt moisture=16%.

IPST CONCEPT FOR DELAMINATION SUPPRESSION

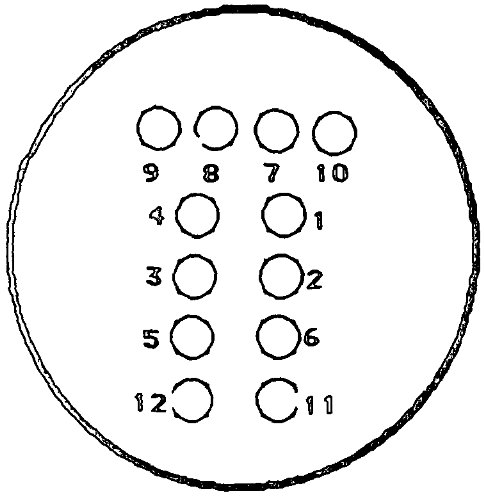
S= Steel, C= Ceramic



EXPERIMENTAL METHODS: Z-DIRECTION ULTRASOUND

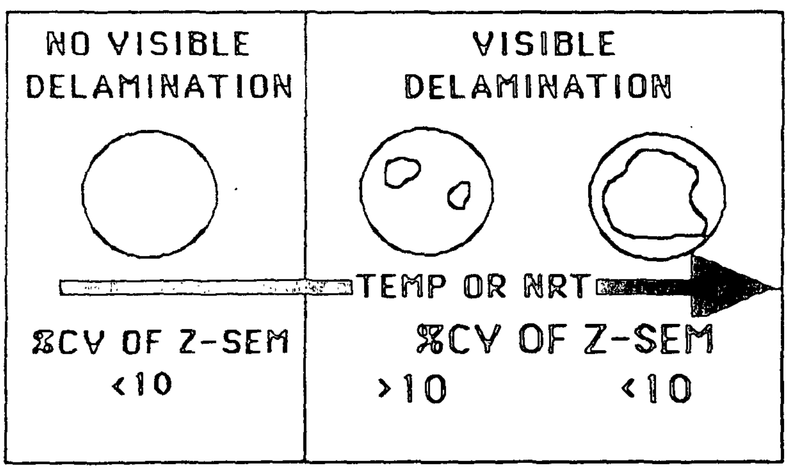


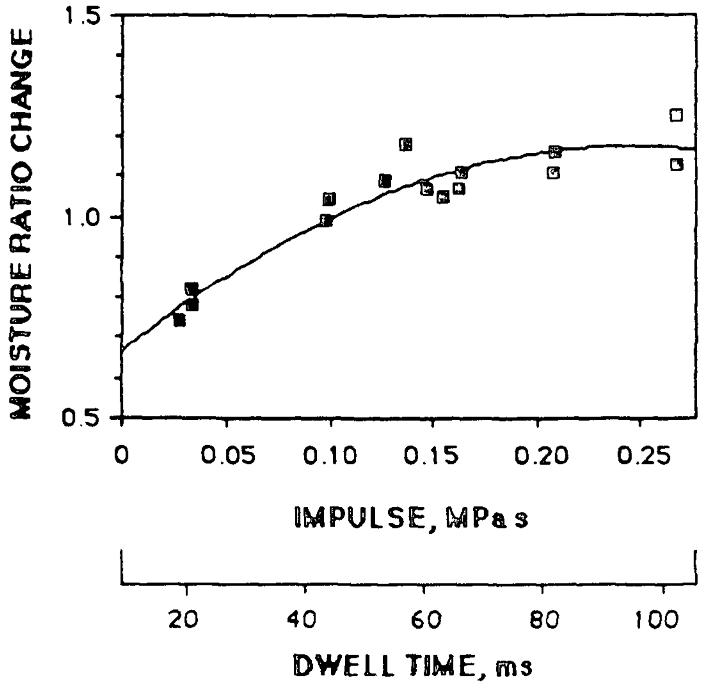
Z-DIRECTION
3/8" ULTRASONIC
TESTER



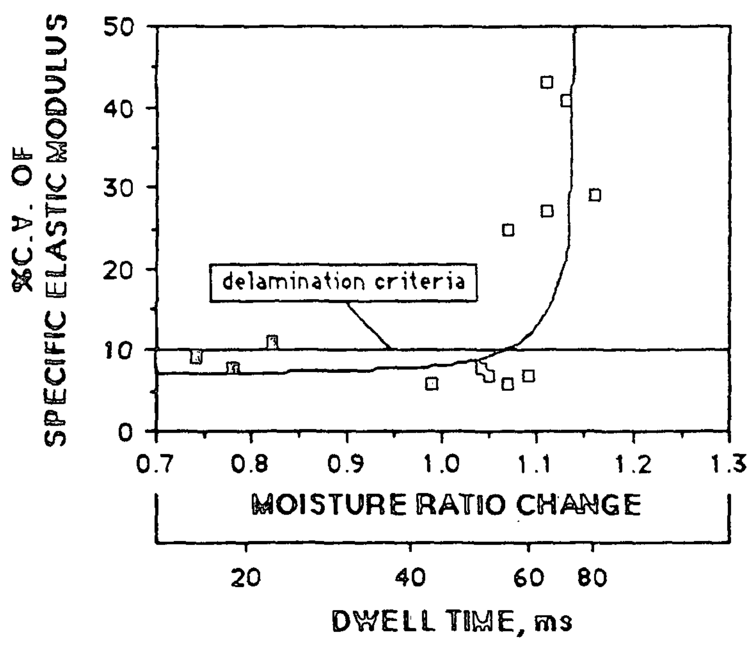
5.0" DIAM
SAMPLE

EXPERIMENTAL METHODS: DELAMINATION DETECTION





Moisture ratio change vs. Dwell time (Impulse) for 205 gsm linerboard ingoing at 30% solids and 25°C, impulse dried by a zirconium oxide platen at 315°C using a 16% moisture felt.



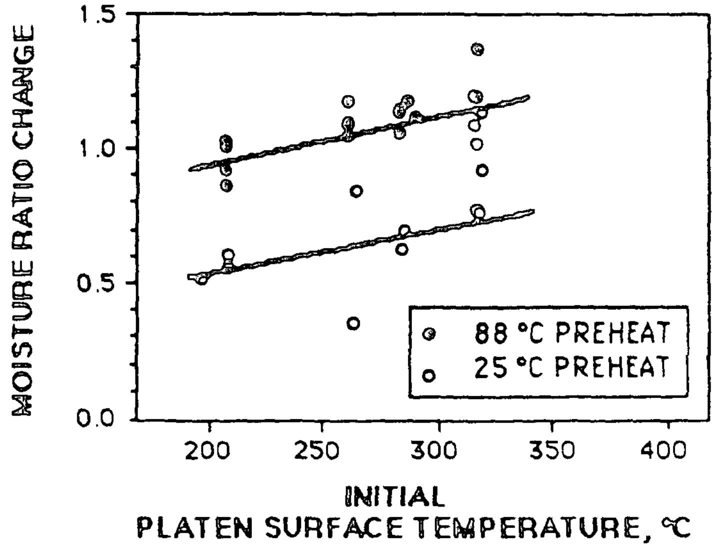
Coefficient of variation of specific elastic modulus vs. Moisture ratio change (Dwell time) for 205 gsm linerboard ingoing at 30% solids and 25°C, impulse dried by a zirconium oxide platen at 315°C using a 16% moisture felt.

OBSERVATIONS

Experiments without a release agent showed that the zirconium oxide surface was more susceptible to sticking than the chrome plated steel surface. In future work, a high temperature release agent should be identified that solves the sticking problem and which can be used on the pilot rolls as well as on the electrohydraulic press.

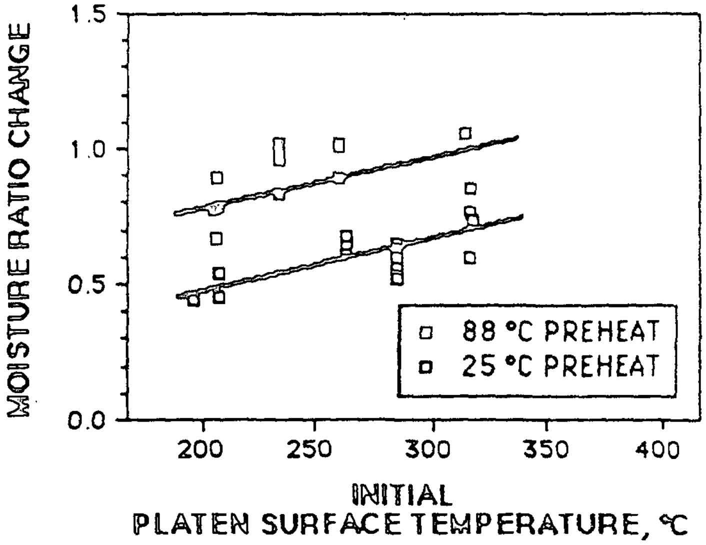
Previous experiments with ceramic platens have examined dwell times in excess of 50 ms. The current fixed temperature experiments, at dwell times from 20 to 100 ms, demonstrate two regions of delamination. The first delamination region occurs at about 20 ms, while the dwell time where the second region begins depends on: basis weight, felt moisture and the thermal diffusivity of the platen surface.

IMPULSE DRYING 155 gsm LINERBOARD
WITH A ZrO2 PLATEN



Moisture ratio change vs. Initial platen surface temperature for 155 gsm linerboard ingoing at 30% solids, impulse dried by a zirconium oxide platen for 20 ms at various ingoing sheet temperature.

IMPULSE DRYING 205 gsm LINERBOARD
WITH A ZrO2 PLATEN



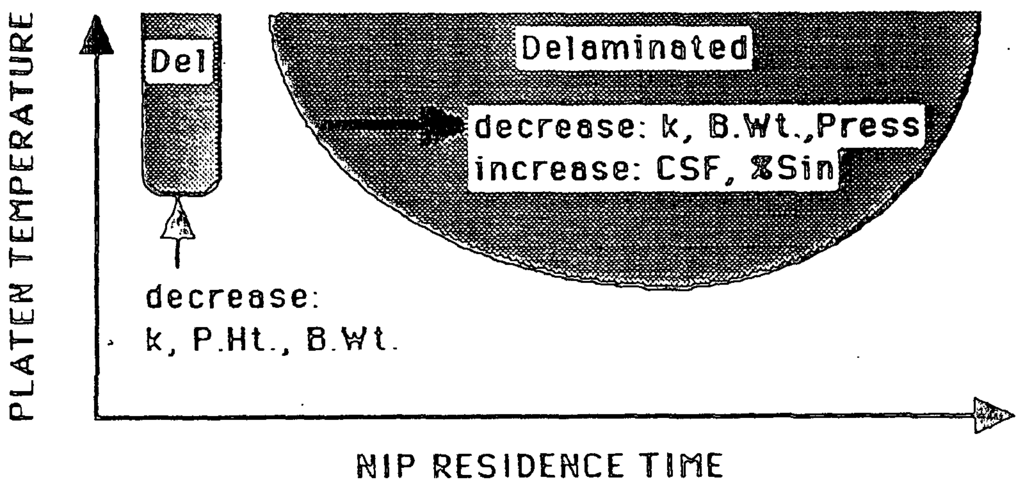
Moisture ratio change vs. Initial platen surface temperature for 205 gsm linerboard ingoing at 30% solids, impulse dried by a zirconium oxide platen for 20 ms at various ingoing sheet temperature.

OBSERVATIONS

Impulse drying results in enhanced water removal compared to conventional single felted hot pressing.

Preheating the sheet improves water removal at all platen temperatures.

DELAMINATION BOUNDARIES



IPST PROTOTYPE PRESS ROLL CONCEPT

To minimize sheet delamination a press roll coating should have the following characteristics:

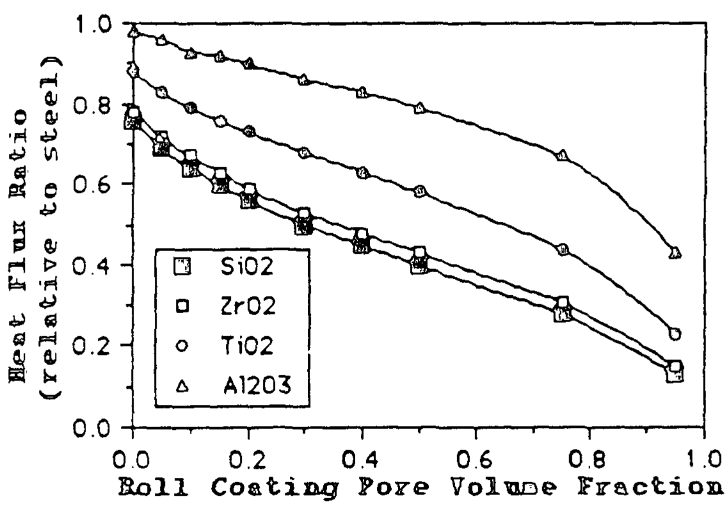
It should have as low a value of K as practical.

It should be designed to resist spalling due to mismatch of coating and the base roll thermal expansion coefficients.

Its surface should be sealed to prevent steam vapor venting and absorption.

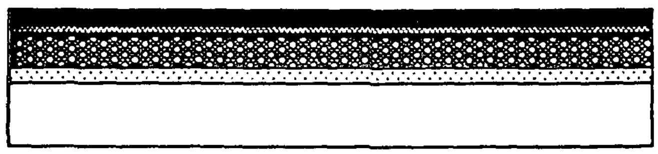
Its surface should also provide a low surface energy to minimize sticking.

PROTOTYPE PLATEN: MATERIALS SELECTION

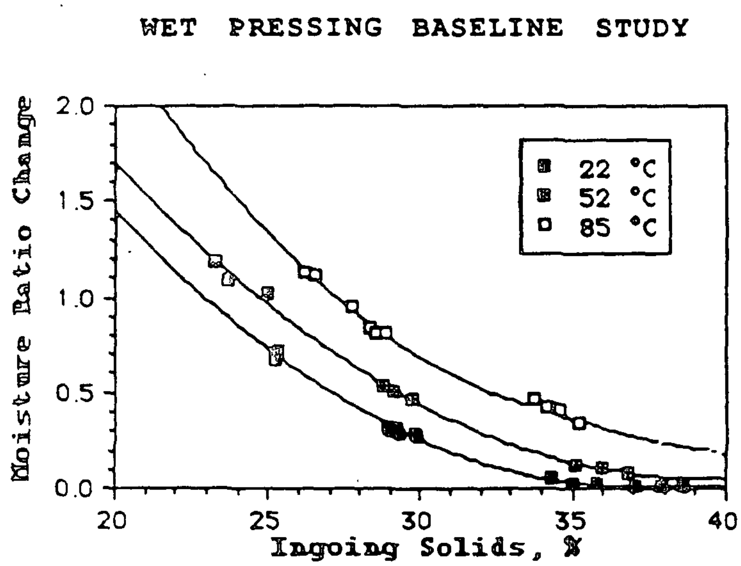


Calculated heat flux ratio (relative to steel) as a function of the internal porosity of the plasma-sprayed ceramic coating for various ceramic compositions at 300°C.

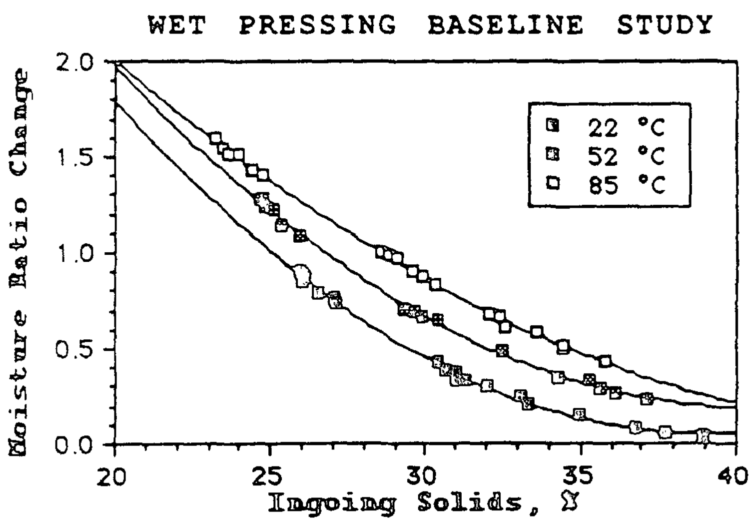
IPST PROTOTYPE PLATEN



LAYER	CHEMISTRY
H.T. RELEASE	H.C. POLYMER
L.P. CERAMIC	ZIRCONIUM OXIDE
H.P. CERAMIC	ZIRCONIUM OXIDE
BOND COAT	NICKEL CHROMIUM
BASE	STEEL

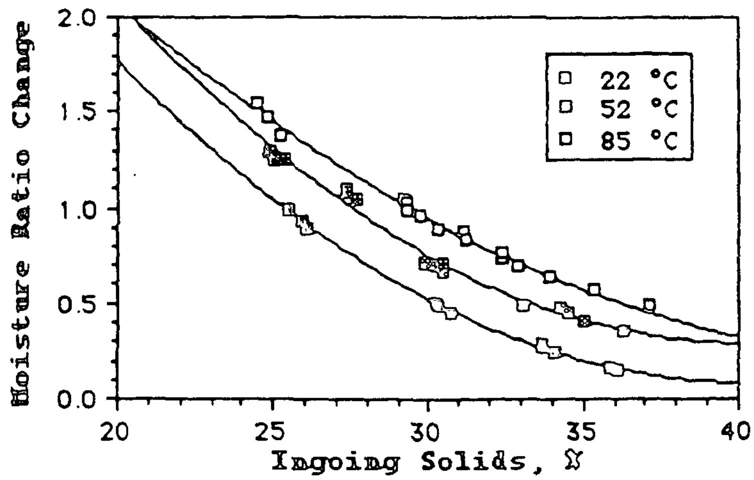


Moisture ratio change for single felted wet pressing of 205 gsm linerboard as a function of ingoing solids and ingoing sheet temperature. Dwell time=20ms, peak pressure=1.7MPa, impulse=0.015MPas



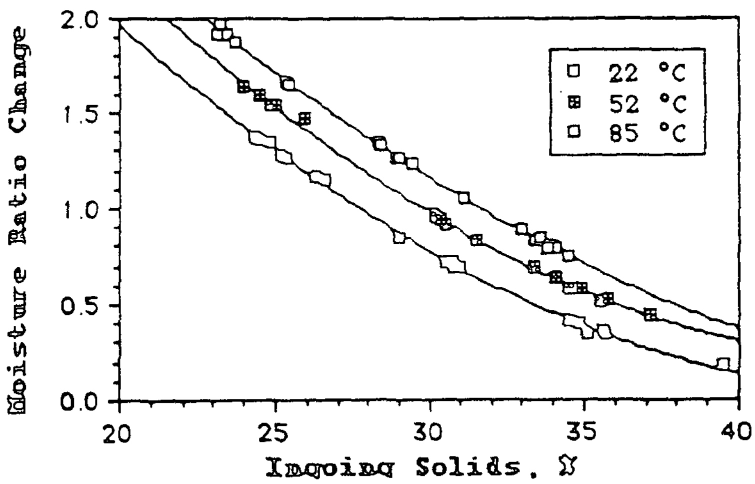
Moisture ratio change for single felted wet pressing of 205 gsm linerboard as a function of ingoing solids and ingoing sheet temperature. Dwell time=20ms, peak pressure=3.1MPa, impulse=0.028MPas.

WET PRESSING BASELINE STUDY

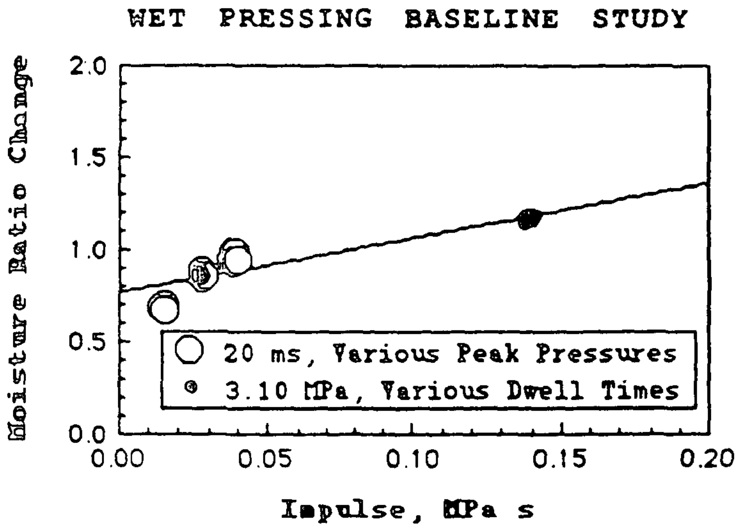


Moisture ratio change for single felted wet pressing of 205 gsm linerboard as a function of ingoing solids and ingoing sheet temperature. Dwell time=20ms, peak pressure=4.8MPa, impulse=0.044MPas.

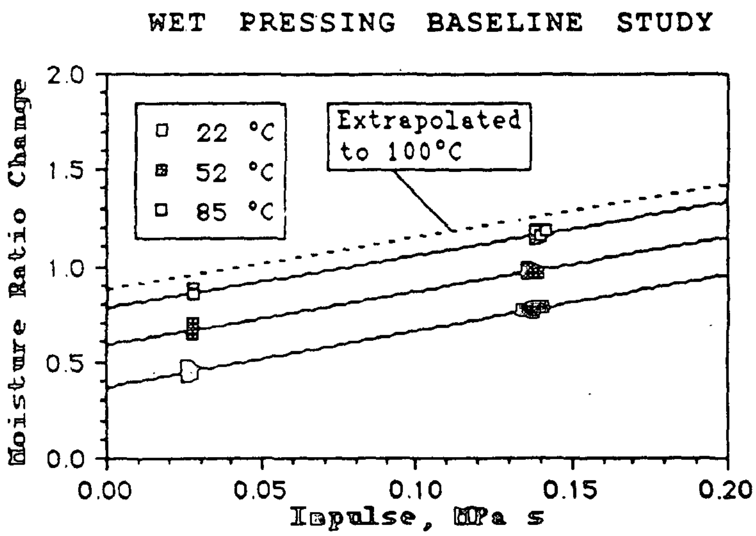
WET PRESSING BASELINE STUDY



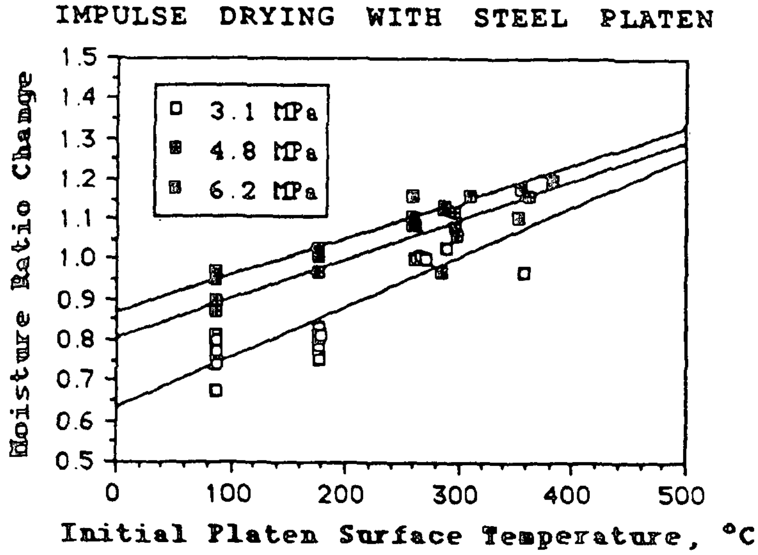
Moisture ratio change for single felted wet pressing of 205 gsm linerboard as a function of ingoing solids and ingoing sheet temperature. Dwell time=60ms, peak pressure=3.1MPa, impulse=0.140MPas.



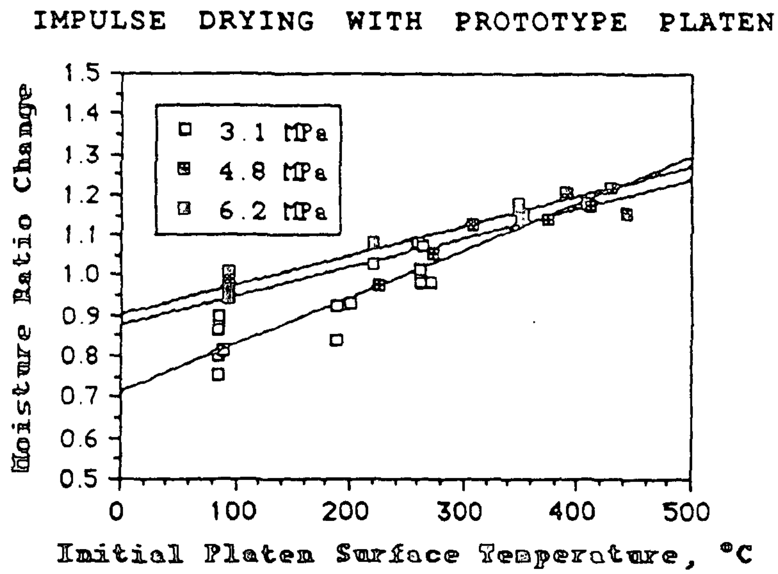
Moisture ratio change for single felted wet pressing of 205 gsm linerboard as a function of impulse. Ingoing sheet temperature=85°C, ingoing solids=30%.



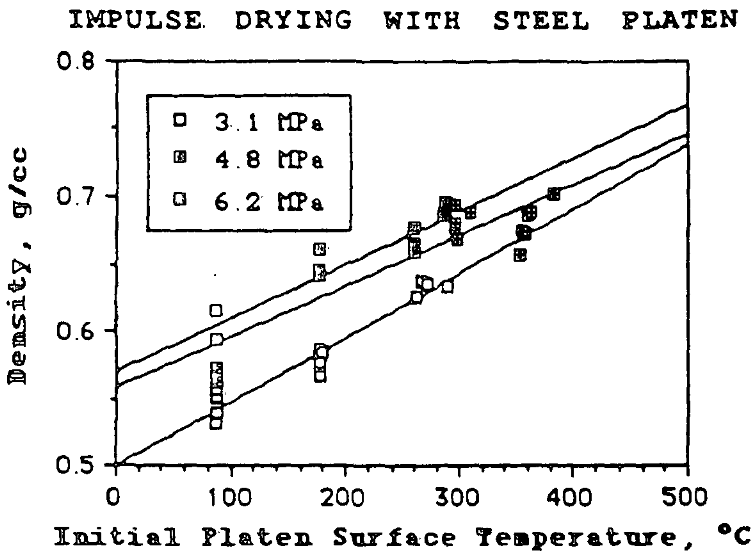
Moisture ratio change for single felted wet pressing of 205 gsm linerboard as a function of impulse and ingoing sheet temperature. Ingoing solids=30%.



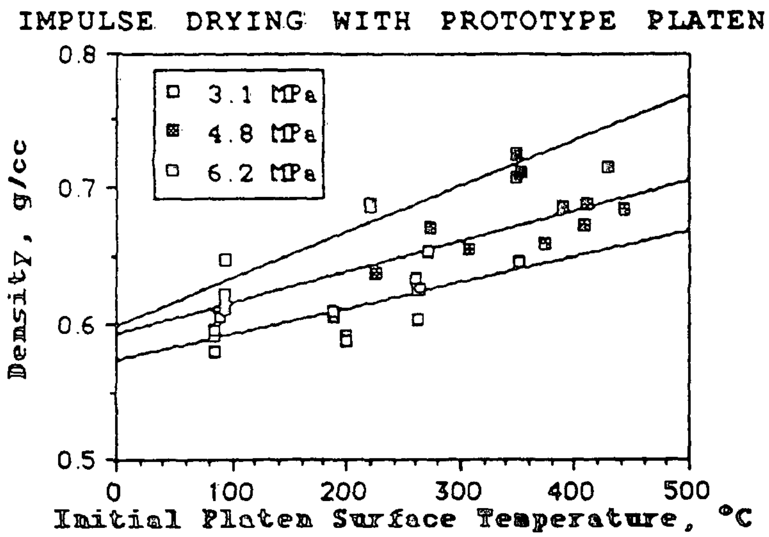
Moisture ratio change for impulse drying of 205gsm linerboard with a steel platen as a function of initial platen surface temperature and peak pressure. Dwell time=20ms, ingoing sheet temperature=85°C, ingoing solids=30%.



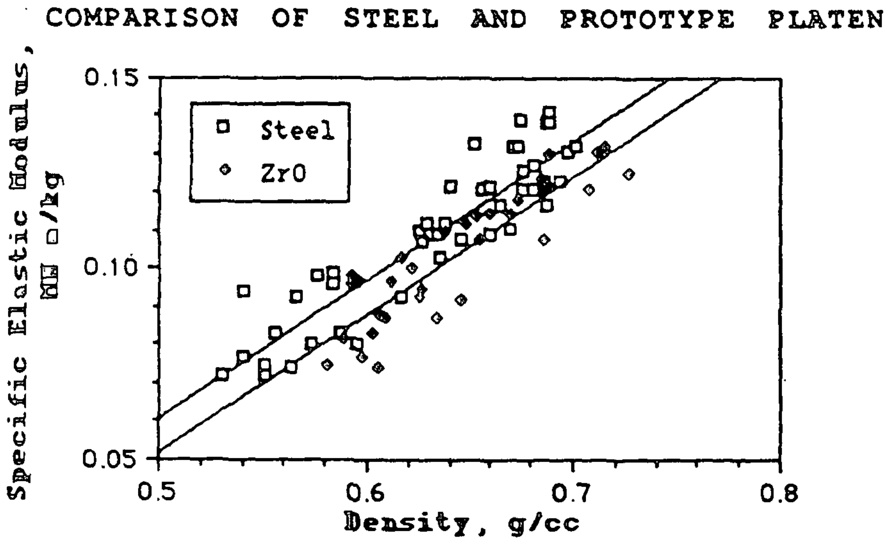
Moisture ratio change for impulse drying of 205gsm linerboard with the prototype zirconium oxide platen as a function of initial platen surface temperature and peak pressure. Dwell time=20ms, ingoing sheet temperature=85°C, ingoing solids=30%.



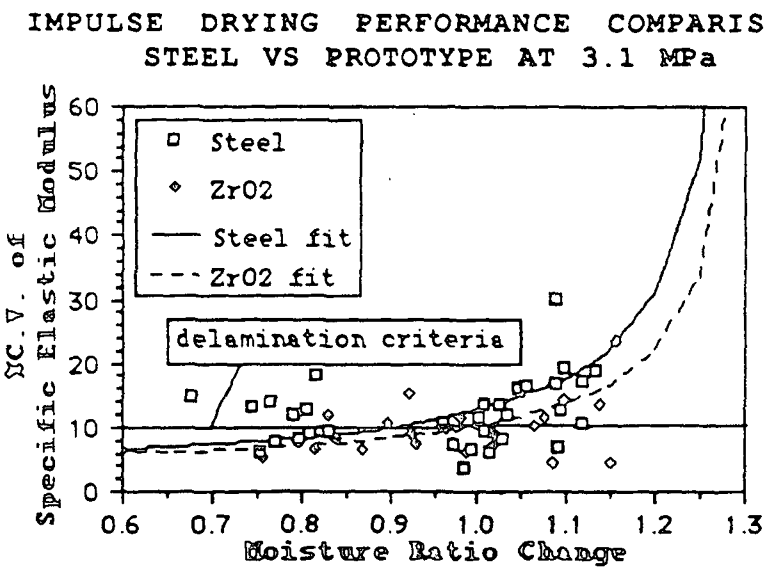
Soft platen density for impulse drying of 205gsm linerboard with a steel platen as a function of initial platen surface temperature and peak pressure. Dwell time=20ms, ingoing sheet temperature=85°C, ingoing solids=30%.



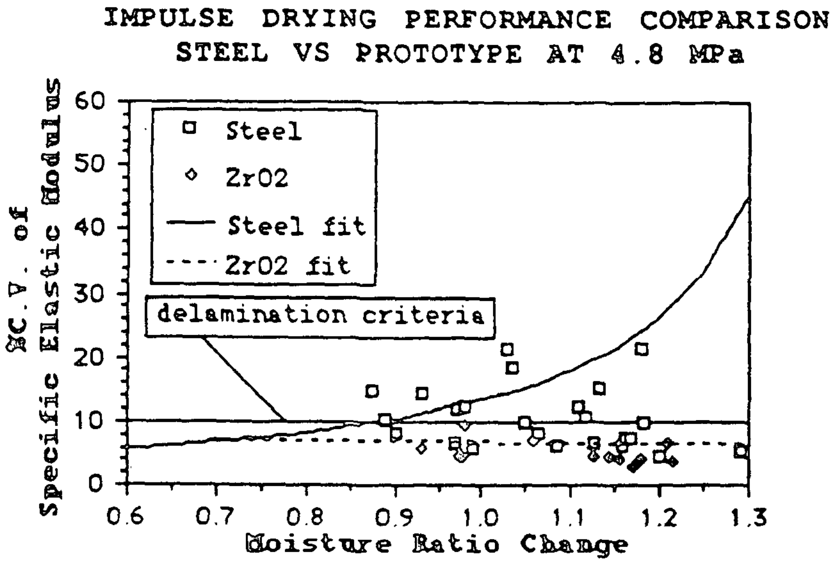
Soft platen density for impulse drying of 205gsm linerboard with the prototype zirconium oxide platen as a function of initial platen surface temperature and peak pressure. Dwell time=20ms, ingoing sheet temperature=85°C, ingoing solids=30%.



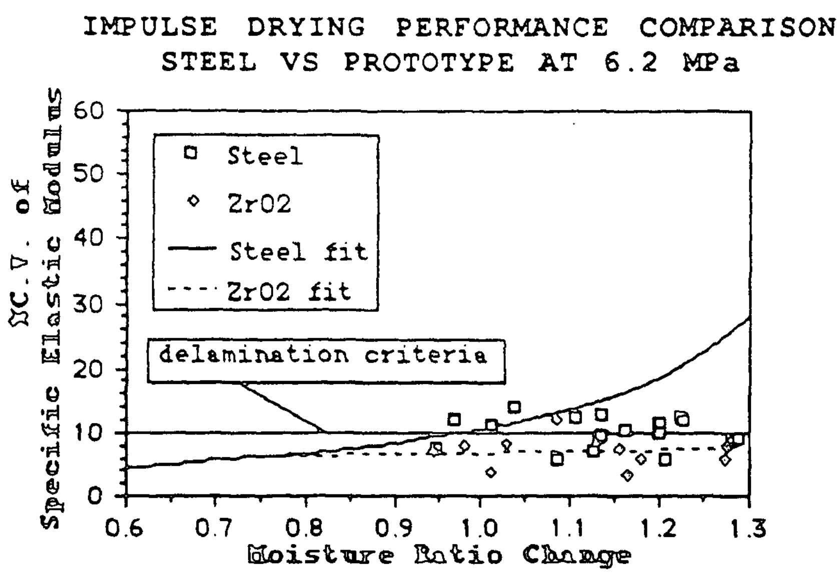
Specific elastic modulus for impulse drying of 205gsm linerboard as a function of soft platen density for the steel and prototype zirconium oxide platens. Dwell time=20ms, ingoing sheet temperature=85°C, ingoing solids=30%.



Coefficient of variation of specific elastic modulus as a function of moisture ratio change for impulse drying of 205gsm linerboard with steel and with the prototype zirconium oxide platens at a peak pressure of 3.1MPa. Dwell time=20ms, impulse=0.028MPas, ingoing sheet temperature=85°C, ingoing solids=30%.



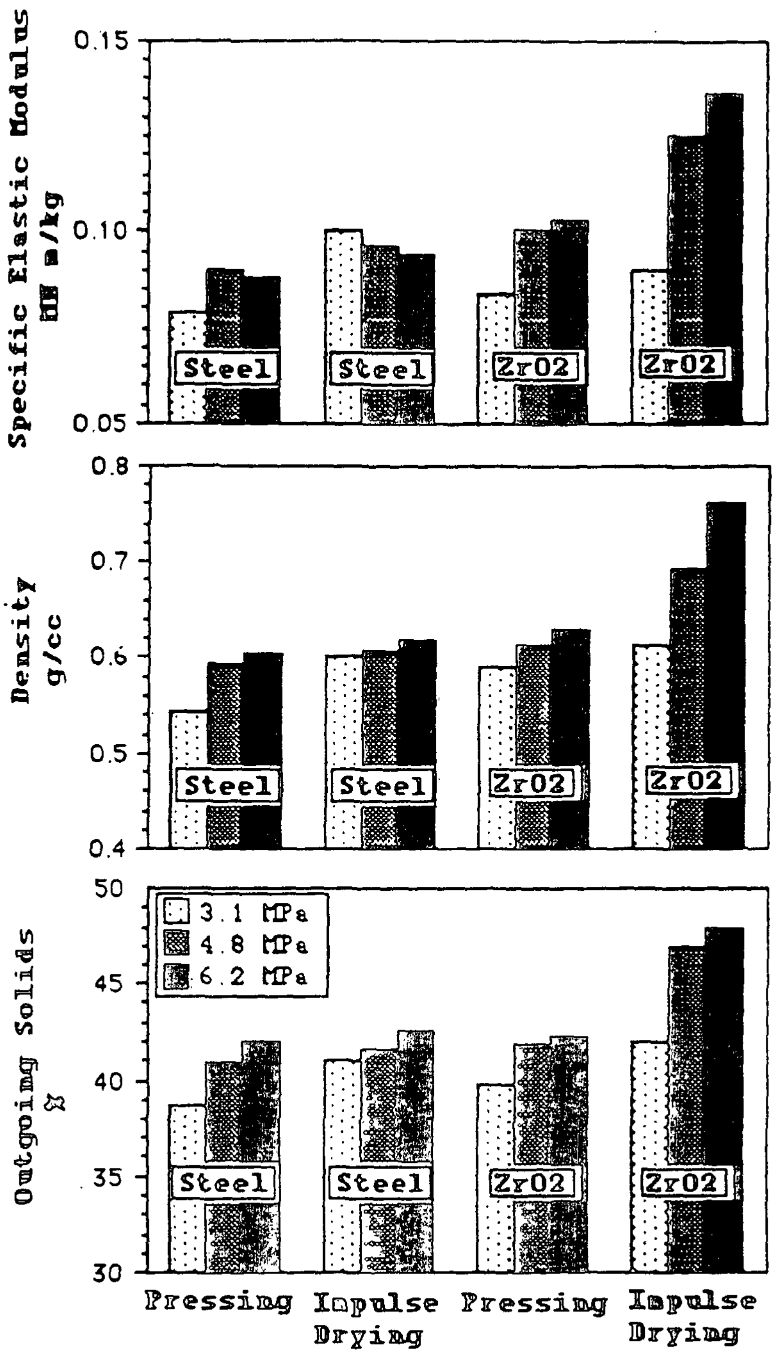
Coefficient of variation of specific elastic modulus as a function of moisture ratio change for impulse drying of 205gsm linerboard with steel and with the prototype zirconium oxide platens at a peak pressure of 4.8MPa. Dwell time=20ms, impulse=0.044MPas, ingoing sheet temperature=85°C, ingoing solids=30%.



Coefficient of variation of specific elastic modulus as a function of moisture ratio change for impulse drying of 205gsm linerboard with steel and with the prototype zirconium oxide platens at a peak pressure of 6.2MPa. Dwell time=20ms, impulse=0.062MPas, ingoing sheet temperature=85°C, ingoing solids=30%.

MAXIMUM WATER REMOVAL VS PEAK PRESSURE

PLATEN	PRESSURE MPa	MAXIMUM MRC (Ultrasound)	MAXIMUM TEMP, °C (Ultrasound)	MAXIMUM MRC (Visible)	MAXIMUM TEMP, °C (Visible)
Steel	3.1	0.90	211	0.95	252
	4.8	0.88	77	0.93	128
	6.2	0.98	116	1.03	171
Prototype	3.1	1.00	245	0.95	203
	4.8	>1.20	444	>1.20	444
	6.2	>1.25	470	1.27	498



Maximum outgoing solids, soft platen density and specific elastic modulus as a function of peak pressure resulting from wet pressing and impulse drying of 205gsm linerboard with a steel platen and the prototype zirconium oxide platen. Dwell time=20ms, ingoing sheet temperature=85°C, ingoing solids=30%.

OBSERVATIONS

Water removal was found to be dependent on platen surface temperature and independent of platen material.

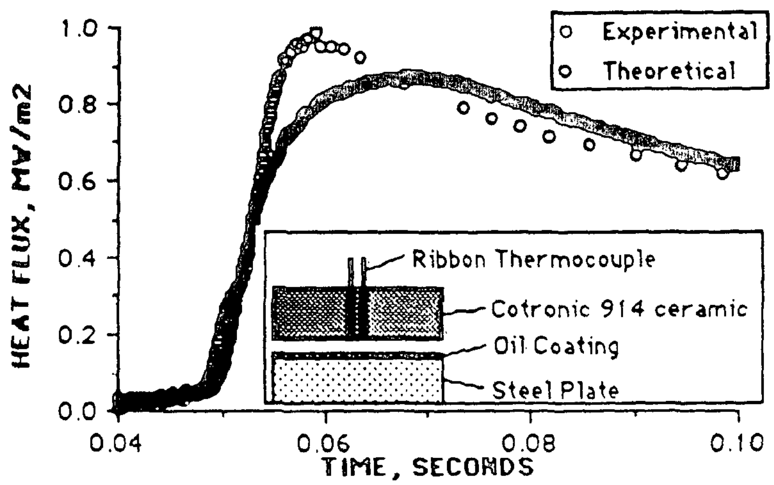
The prototype platen can be operated at substantially higher temperatures and pressures without causing sheet delamination.

At high surface temperatures and high peak pressures, substantial strength improvements were achieved.

Difference in strength vs. density suggests more uniform z-direction density profile resulting from reduced flash evaporation.

DESIGN OF A SURFACE THERMOCOUPLE TO MEASURE HEAT FLUX FROM THE PROTOTYPE PLATEN DURING IMPULSE DRYING

Thermocouple correctly measures heat flux during contact between hot ceramic platen and cold steel platen.



PILOT SCALE DEMONSTRATION
OF THE
PROTOTYPE CERAMIC COATED PRESS ROLL

A steel roll was plasma spray coated with the prototype multi layer ceramic coating.

Rolls of 205 gsm linerboard have been produced at 30% solids.

Preliminary impulse drying experiments have been performed. Infrared roll surface temperature measurements will be used in future work to control roll temperature.

DISPLACEMENT DEWATERING
PROJECT 3680

December 20, 1990
Institute of Paper Science and Technology
Atlanta, Georgia

DUES-FUNDED PROJECT SUMMARY FORM
FY 90-91

Project Title:	DISPLACEMENT DEWATERING
Project Code:	DISPL
Project Number:	3680
Division:	Engineering and Paper Materials Division
Project Staff:	Jeff Lindsay
FY 90-91 Budget:	$160,000

PROGRAM OBJECTIVE: Develop efficient water removal processes which give the papermaker improved control over paper properties.

PROGRAM AREAS: Reduced Cost, Capital Effectiveness, End Use Performance.

RATIONALE: With conventional wet pressing, sheet properties such as density are closely tied to the degree of water removal. Novel processes may be able to achieve high water removal rates while maintaining bulk. Gas-driven displacement processes are being explored in which a pressurized gas phase such as steam or air is used to drive out liquid water in a sheet under simultaneous mechanical pressure. The ability to remove water efficiently while maintaining bulk could be of significant economic value.

ACCOMPLISHMENTS TO DATE:

The displacement dewatering concept has been tested in several ways using computer-controlled pressing equipment developed at the IPST. Both air and superheated steam have been explored as the displacing medium in several types of sheets. Unfortunately, the results to date have been negative. Efficient water removal with displacement processes requires long nips (50-200 ms) in which creep effects cause higher densification than would normally be achieved with conventional nips. Even with low applied mechanical pressures, the densification occurring in long displacement dewatering nips can be more than would occur for a high-pressure conventional nip that removed the same amount of water. In other words, displacement dewatering seems to do worse than wet pressing in maintaining bulk. Early IPC data from displacement processes failed to consider this creep effect in pressing with long nips, and thus did not detect this drawback to the displacement dewatering concept.

(Work involving permeability and modeling of flow processes has been shifted to Project 3480, Fundamentals of Water Removal).

GOALS FOR Oct. 1990 - April 1991:

1. Examine use of high-pressure gas and short nips in displacement dewatering to see if a regime exists where good dewatering is possible without creep densification.

2. Examine properties (opacity and strength) of displacement dewatered sheets.

RELATED PROJECTS:

Gary Rudemiller, Ph.D. Thesis "A Fundamental Study of Boiling Heat Transfer Mechanisms Related to Impulse Drying," (Completed 1989).

James R. Burns, Ph.D. Thesis "Investigation of the Constrained Expansion Phase of Wet Pressing, "Ph.D. Dissertation (in progress).

Joseph C. Zavaglia, M.S. Project "An Examination of Multiphase Flow During Impulse Drying Through Flash X-ray Visualization," (Completed March 1989).

James R. Burkhead, M.S. Project "A Study of the Effects of Felt Properties on Delamination During Impulse Drying," (Completed March 1989).

Jill R. Wallin, M.S. Project "A Fundamental Investigation of the In-plane Permeability of Paper," (in progress).

John Frazier, M.S. Project "Internal Hydraulic Pressure Gradients During the Pressing of Stratified Porous Media," (in progress).

Project 3680:
Displacement Dewatering

CONCEPT:

Pressurized gas (air or steam) is injected directly into a compressed sheet to displace free liquid.

GOAL:

To dewater paper with less densification than conventional pressing.

CONCLUSIONS TO DATE:

The concept has not lived up to its promise. The long nip times required lead to creep effects which result in high densification, even under low mechanical pressures.

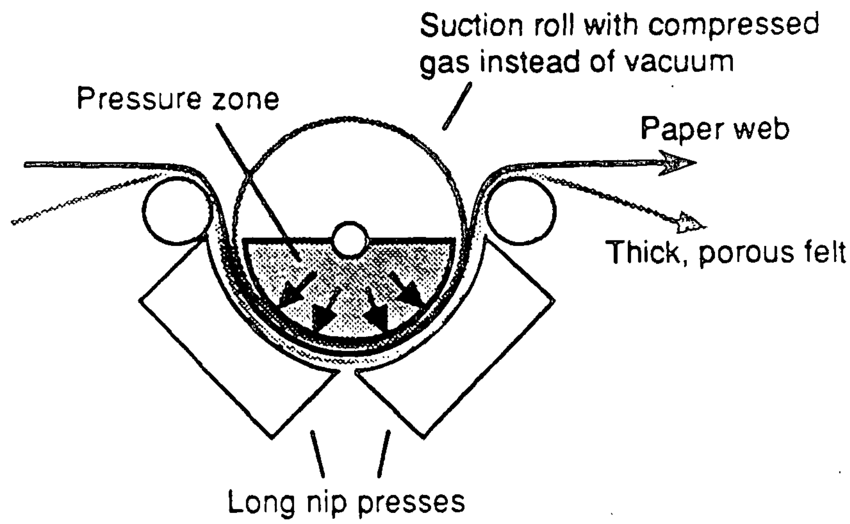


Figure 1. Possible implementation of the displacement dewatering concept.

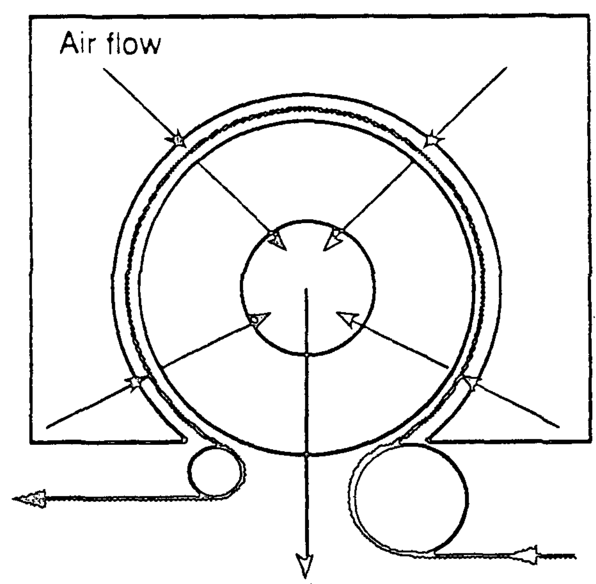


Figure 2. A cylindrical through dryer.

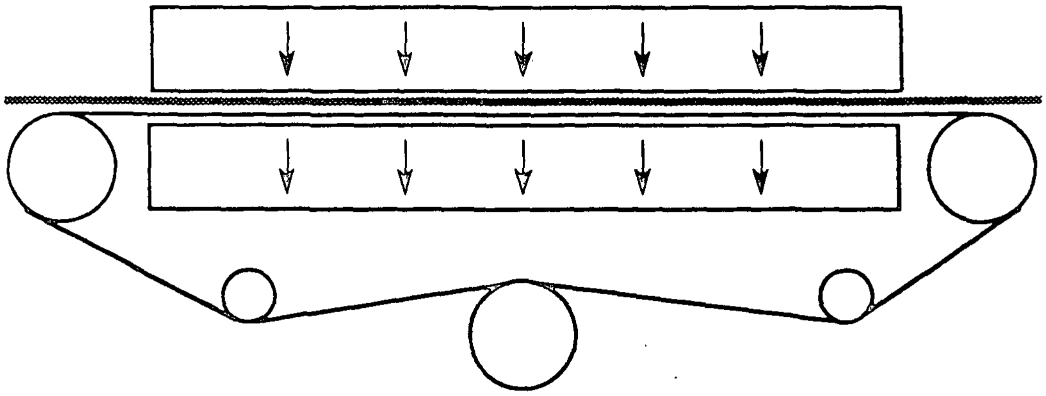


Figure 3. A flat bed through dryer.

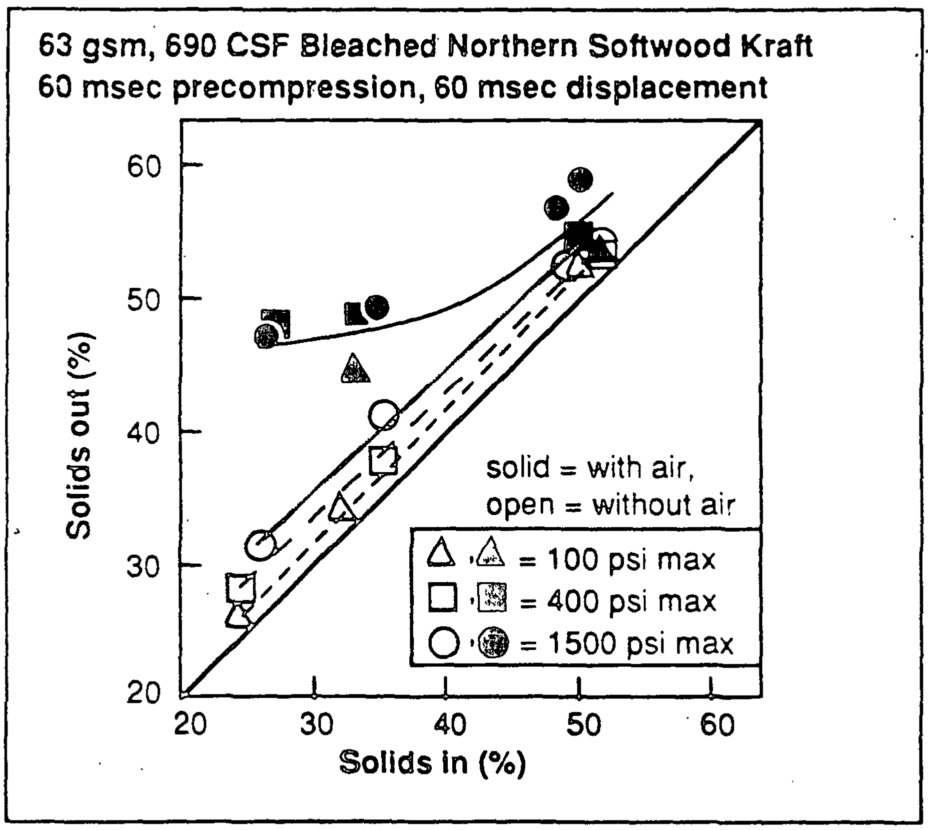


Figure 4. Dewatering results obtained with early displacement dewatering equipment at the IPST.

Time required for one-dimensional gas displacement of liquid in a saturated sheet of thickness L, permeability K, and porosity ε:

$$V = \frac{-dx}{dt} = \frac{K}{\varepsilon\mu}\frac{\Delta P}{x} \qquad (1)$$

$$\int_L^0 -x\,dx = \int_0^t \frac{K\Delta P}{\varepsilon\mu}\,dt' \qquad (2)$$

$$t = \frac{\varepsilon\,\mu\,L^2}{2K\,\Delta P} \qquad (3)$$

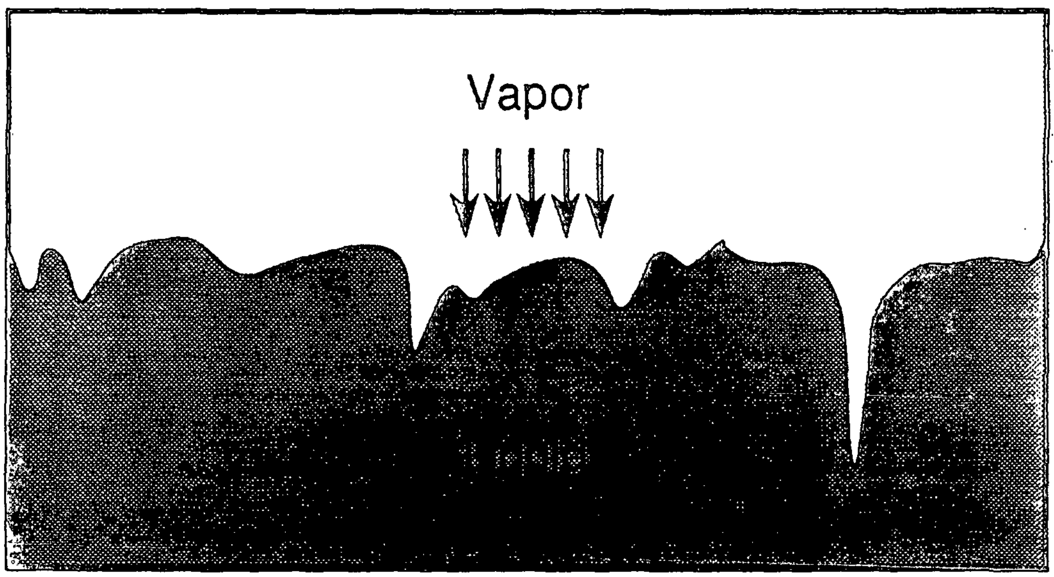


Figure 5. Viscous fingering in a porous medium as a gas displaces a liquid.

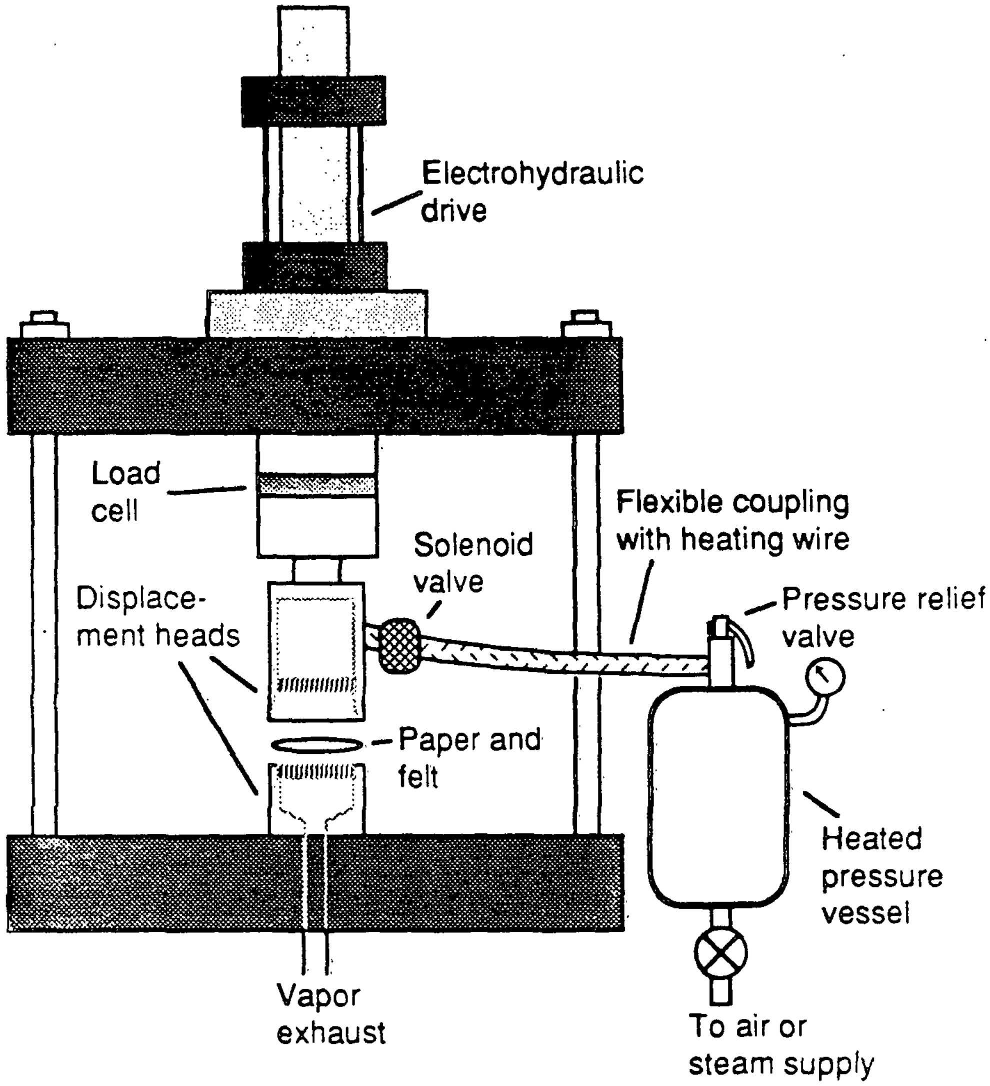


Figure 6. The experimental displacement apparatus.

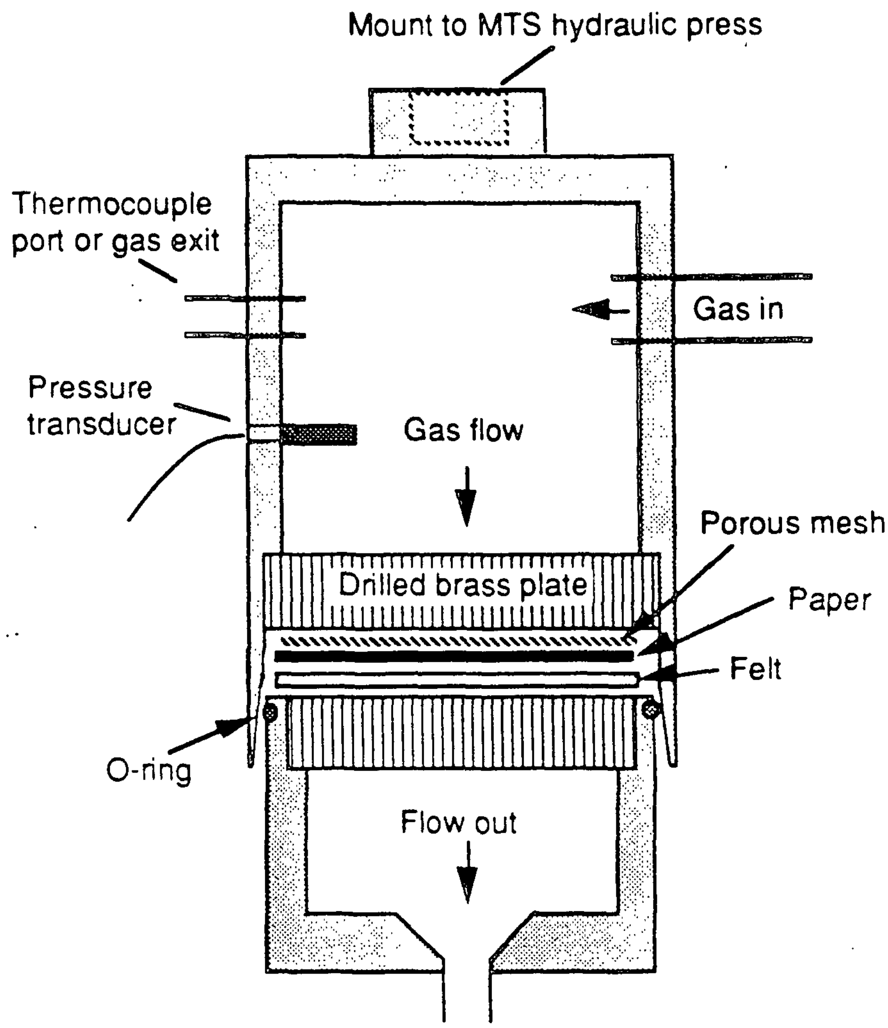


Figure 7. Detail of the displacement heads.

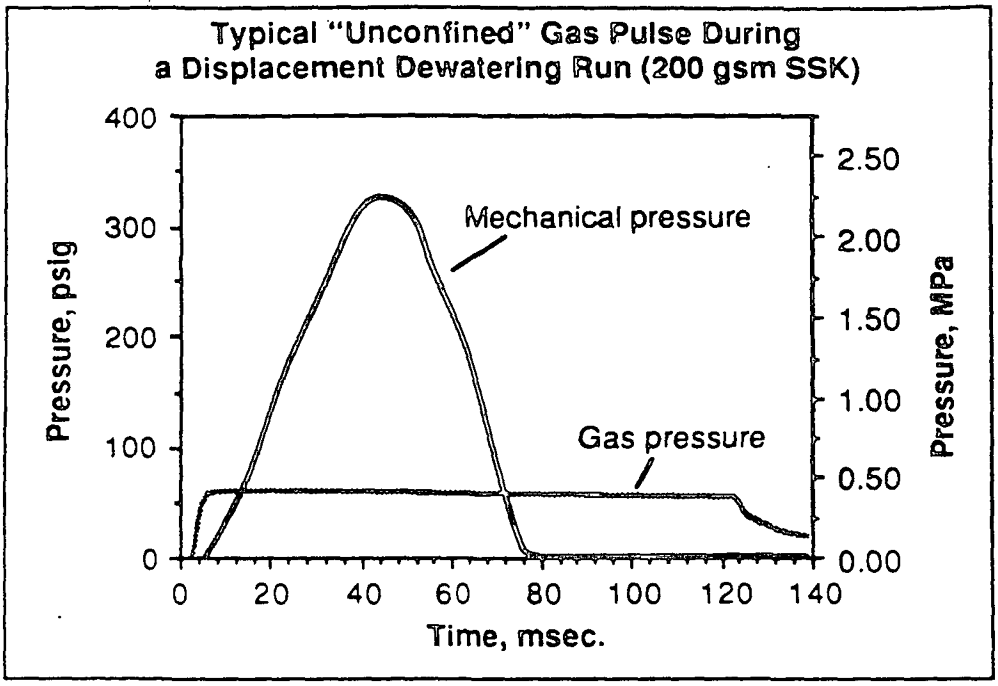


Figure 8. Applied gas and mechanical pressure pulses during a typical "unconfined" displacement dewatering run. The gas pulse is not confined within the mechanical pressure pulse, but extends well beyond.

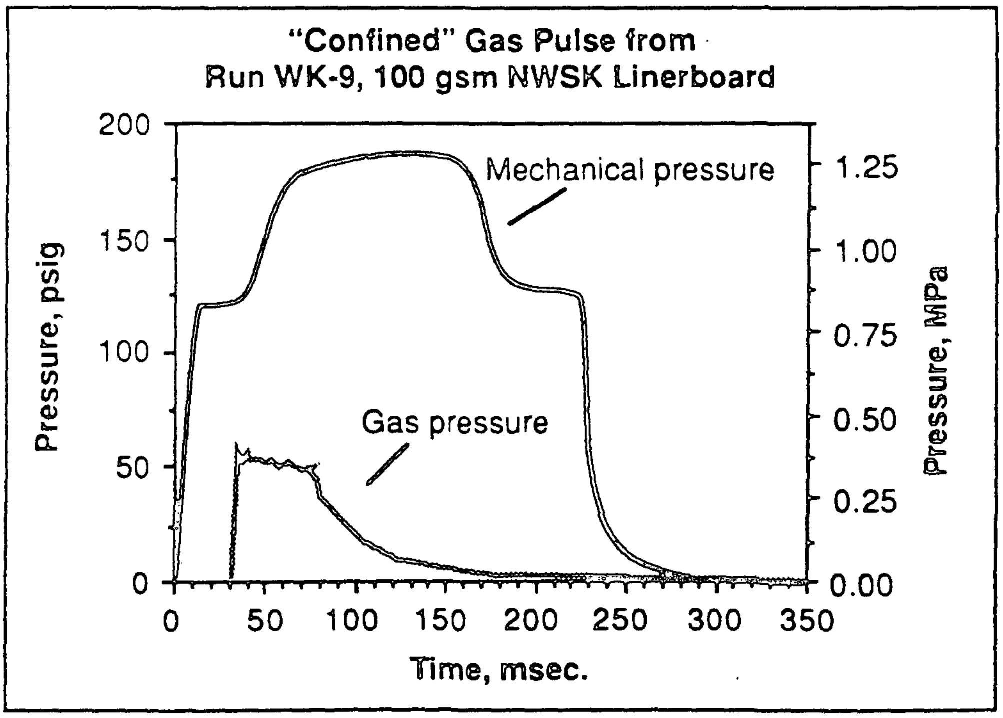


Figure 9. Applied gas and mechanical pressure pulses during a typical "confined" displacement dewatering run.

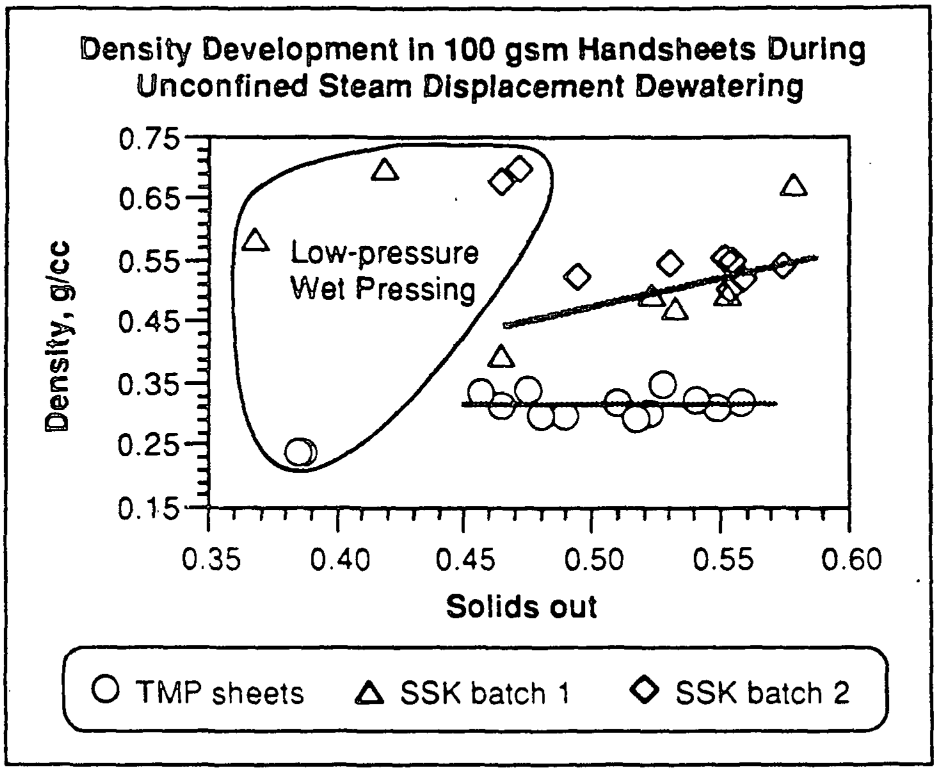


Figure 11. Density-dryness relationship for unconfined displacement dewatering with superheated steam.

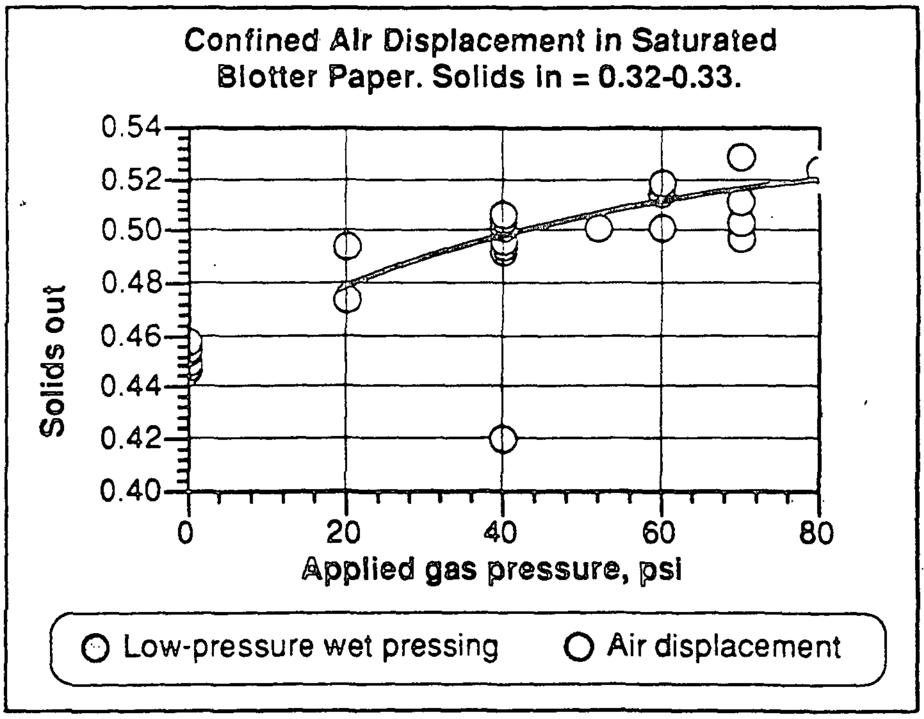


Figure 12. Air displacement results in saturated blotter paper.

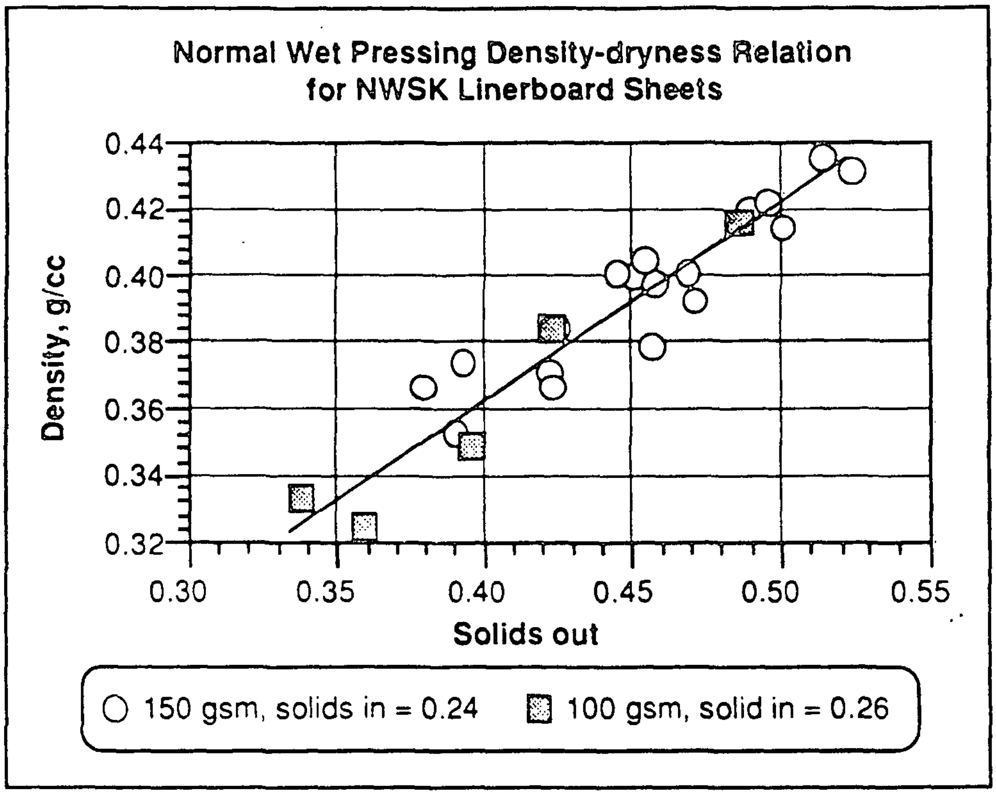


Figure 13. Dryness-density relationship for normal wet pressing in Northwestern softwood unbleached kraft (NWSK) handsheets.

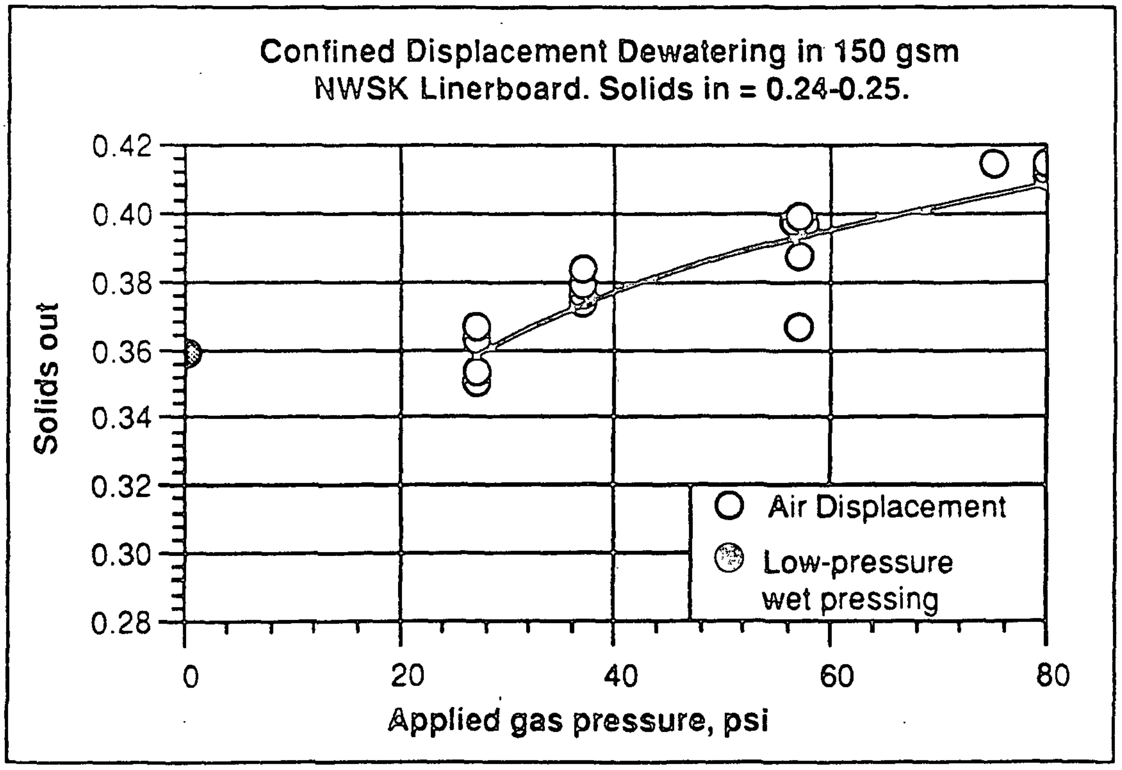


Figure 14. Confined air displacement in 150 gsm NWSK sheets.

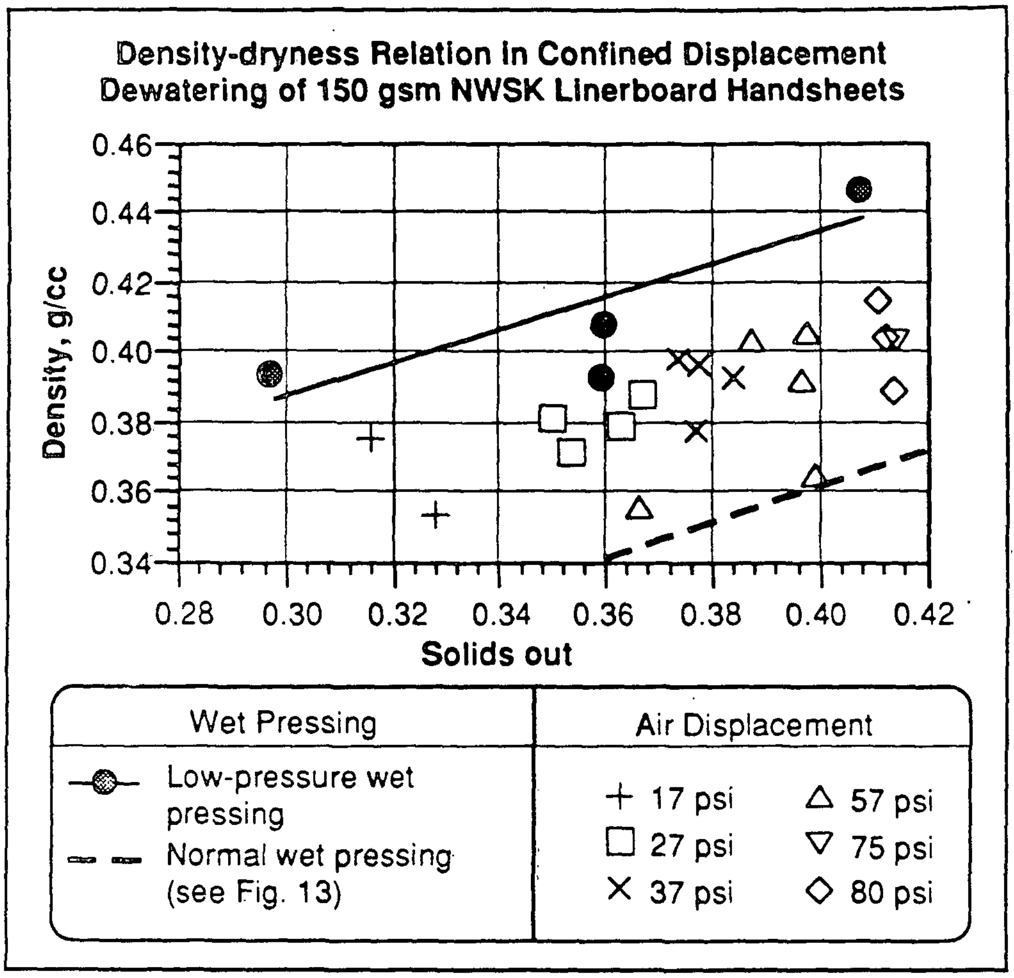


Figure 15. Density-dryness relation for data of Figure 14.

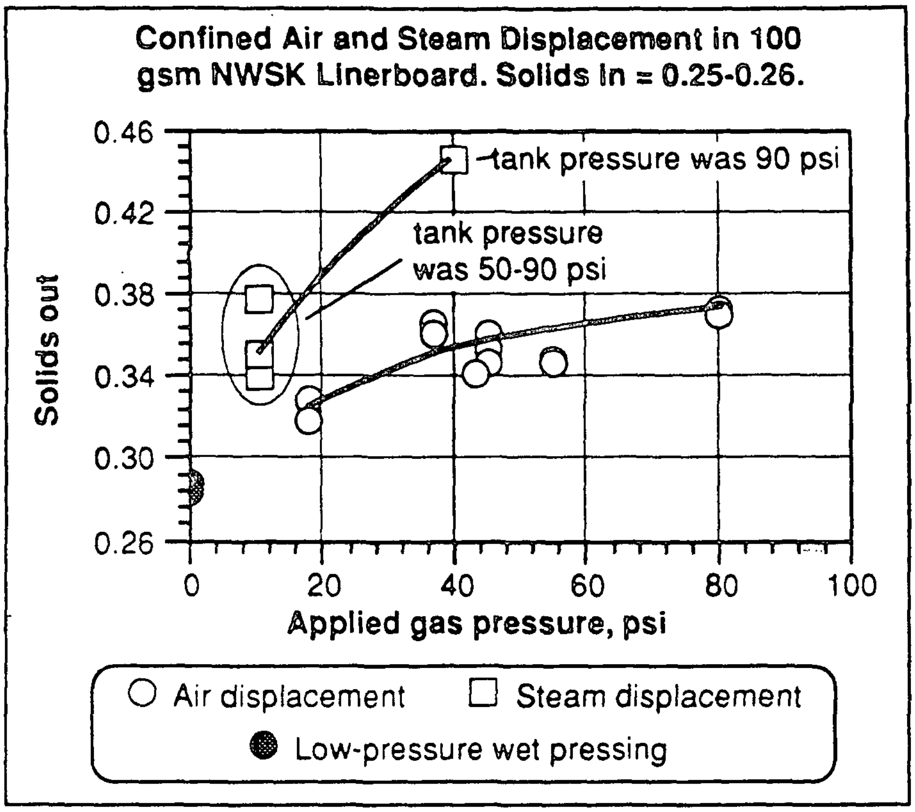


Figure 16. Steam and air displacement in 100 gsm NWSK sheets. Peak mechanical pressures were 180-200 psi.

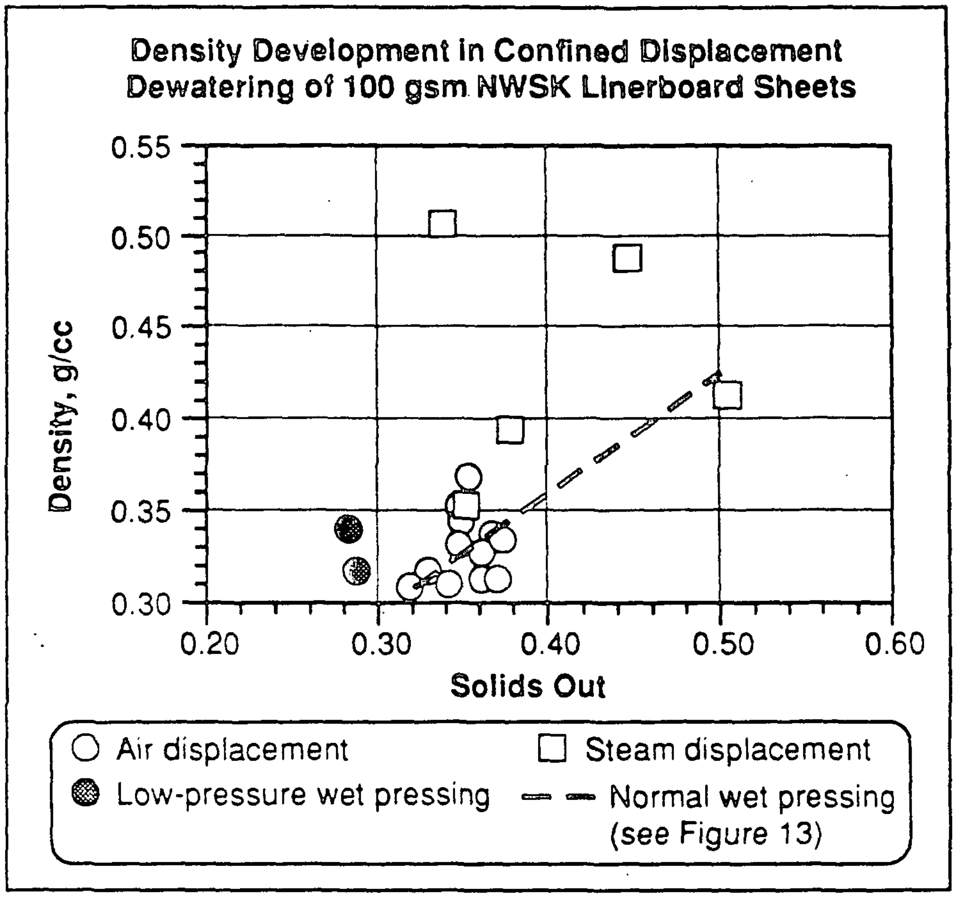


Figure 17. Density-dryness relationship in steam and air displacement dewatering of 100 gsm NWSK sheets.

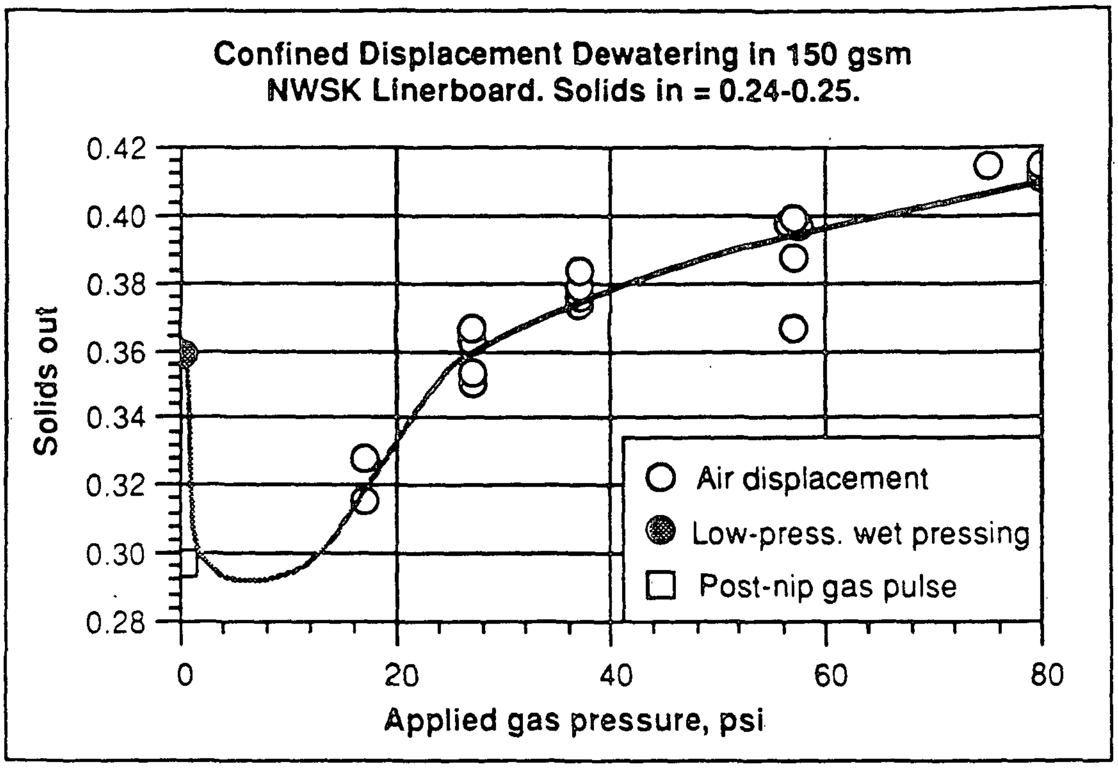


Figure 18. Confined air displacement in 150 gsm NWSK sheets.

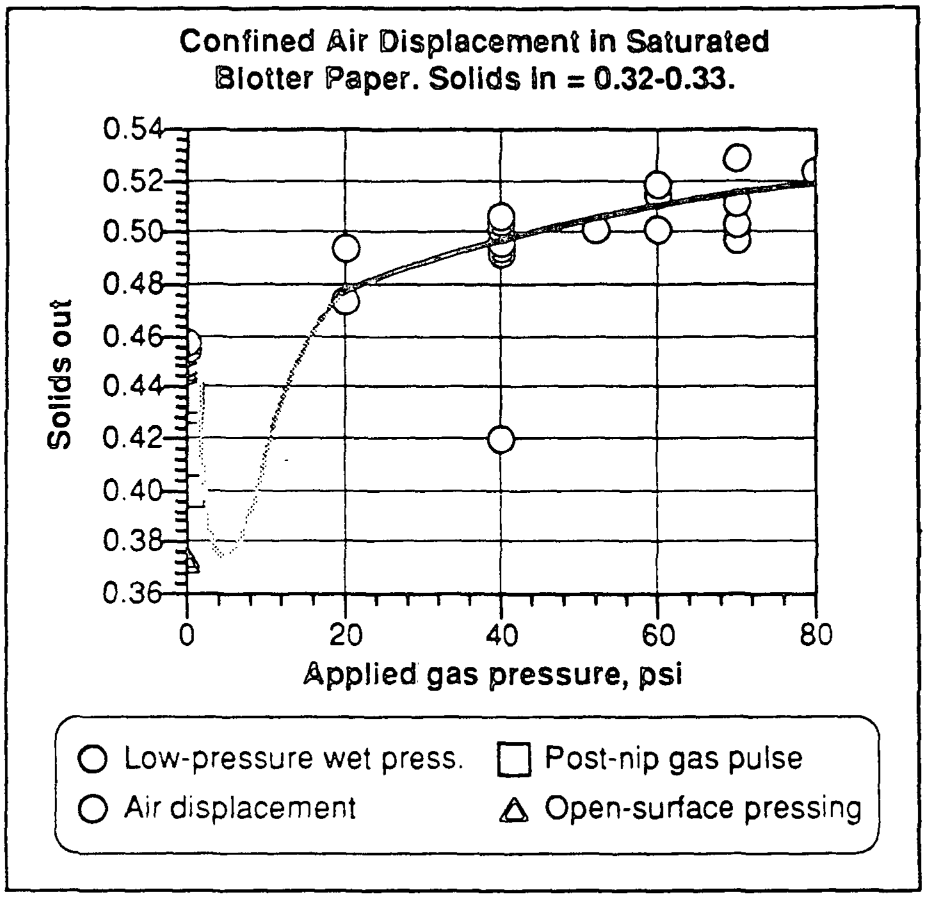


Figure 19. Full data set of air displacement results in saturated blotter paper (partially shown in Figure 12).

Project 3680

Goals for Oct. 1990 - April 1991:

1. Examine the use of high-pressure gas and short nips in displacement dewatering to see if a regime exists where good dewatering is possible without creep densification.

2. Examine properties (opacity and strength) of displacement dewatered sheets.

FUNDAMENTALS OF WATER REMOVAL PROCESSES
PROJECT 3480

December 20, 1990
Institute of Paper Science and Technology
Atlanta, Georgia

DUES-FUNDED PROJECT SUMMARY FORM
FY 90-91

Project Title:	Fundamentals of Water Removal Processes
Project Code:	WTPRS
Project Number:	3480
Division:	Engineering and Paper Materials Division
Project Staff:	Jeffrey Lindsay
FY 90-91 Budget:	$160,000

PROJECT OBJECTIVE: To investigate the fundamentals of sheet deformation and consolidation in wet pressing using direct measurement and flow visualization techniques, and apply this information to improve property development and dewatering rate.

RATIONALE: Wet pressing is a key process on almost all paper machines, but one that is not yet fully understood nor optimized. To a considerable extent, wet pressing controls many paper properties and the load on the dryer section. Process performance is limited by our lack of understanding of such issues as mechanics of sheet deformation, rewetting, nip expansion processes and spring back, incipient crushing, the mechanisms of hot pressing and chemical additives. All current models of the wet pressing process fall far short of describing or characterizing the actual process. A fundamental model which can characterize the dynamics of web consolidation does not exist.

Improved wet pressing received high marks in the RAC survey and in the PAC analysis of opportunity areas, indication that work in this area would be highly valued by the industry. Through its work on impulse drying and displacement pressing, the Institute has developed a set of unique measurement techniques and wet pressing simulators which make success in this area much more likely.

FY 90-91 GOALS:

(1) Extend the experimental work on anisotropic permeability:
   (a) Measure the full permeability tensor in several more paper types.
   (b) Establish a relationship between fiber orientation and the MD/CD permeability ratio.

(2) Develop improved methods for tracking densification in a sheet during a pressing event.

(3) Incorporate a numerical model of sheet densification to the MIPPS numerical model of displacement and impulse drying, with the objective of treating wet pressing *per se*.

(4) Continue development of x-ray radiography tools for analysis of pressing dynamics (Cyrus Aidun).

ACCOMPLISHMENTS TO DATE:

Improved experimental equipment for in-plane and transverse permeability has been developed.

Anisotropic permeability has been measured in several more paper types with greatly improved accuracy. The ratio of transverse to in-plane permeability ranges from about 2-10 in the samples studies to date. The ratio of MD/CD permeability tends to be around 1.1 to 1.3. Applications exist in any process with 2-D flow in paper, such as wet pressing, blade coating, and edge penetration during development in photographic paper.

Related student work has helped establish a state-of-the-art method for in-situ, dynamic measurement of density in various layers of a paper sheet during pressing. This technique has provided valuable information about the dynamics of pressing.

Image analysis has been applied to flash x-ray images taken during pressing events to provide information about densification and shear.

GOALS FOR OCT. 1990 - APRIL 1991:

1. Implement a model of compressible media in MIPPS.
2. Compare fiber orientation information to MD/CD permeability ratios.

Project 3480: Fundamentals of Water Removal

OBJECTIVE:

To investigate the fundamentals of pressing processes through dynamic measurement and simulation of sheet density, hydraulic pressure, water flow, etc.

APPROACH:

Measurement tools include flash x-ray radiography, eddy-current transducers for local sheet density, and capillary inserts for hydraulic pressure.

Anisotropic permeability has been investigated through special flow equipment developed at the IPST.

Recent Results

- SHEET DENSIFICATION

  Cyrus Aidun has continued analysis of flash x-ray radiographs showing shear and densification in a nip.

  Jeff Lindsay is developing numerical simulation tools for sheet densification to incorporate with MIPPS.

  (Dynamic compressibility has been explored in student work by James Burns, a Ph.D. candidate.)

- REWET AND Z-DIRECTION HYDRAULIC PRESSURE

  No action, except for related student work by John Frazier.

- ANISOTROPIC PERMEABILITY

  Improved techniques have been developed for lateral and transverse permeability measurements.

  Transverse and lateral permeability has been measured in several new paper specimens.

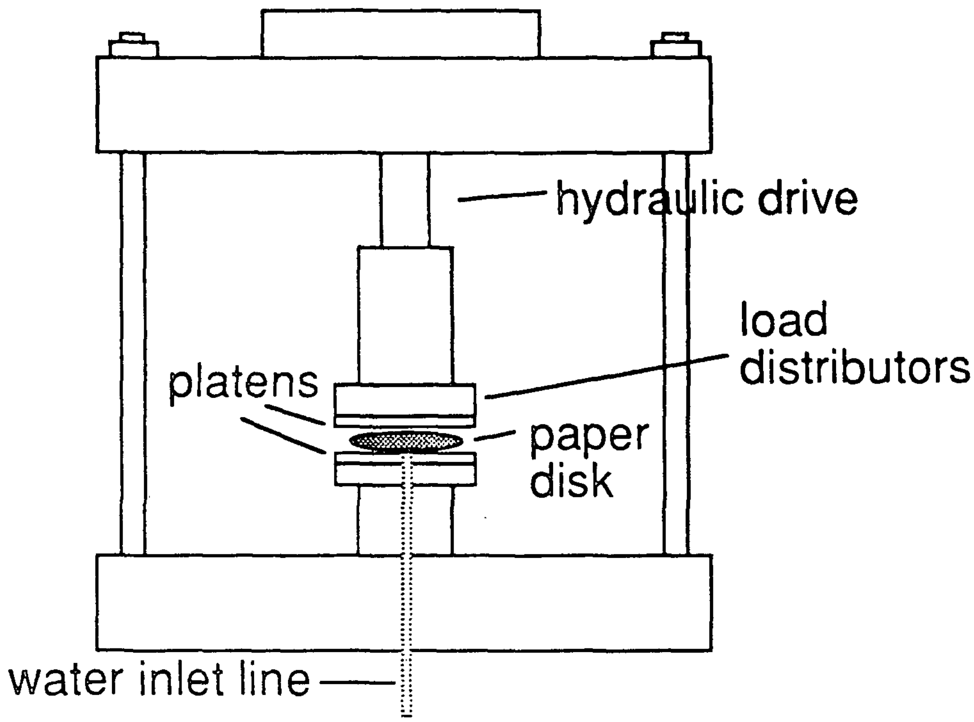
  The ratio of lateral to transverse permeability in paper tends to fall in the range of 2-10, depending on fiber type and degree of compression.

Anisotropic Permeability

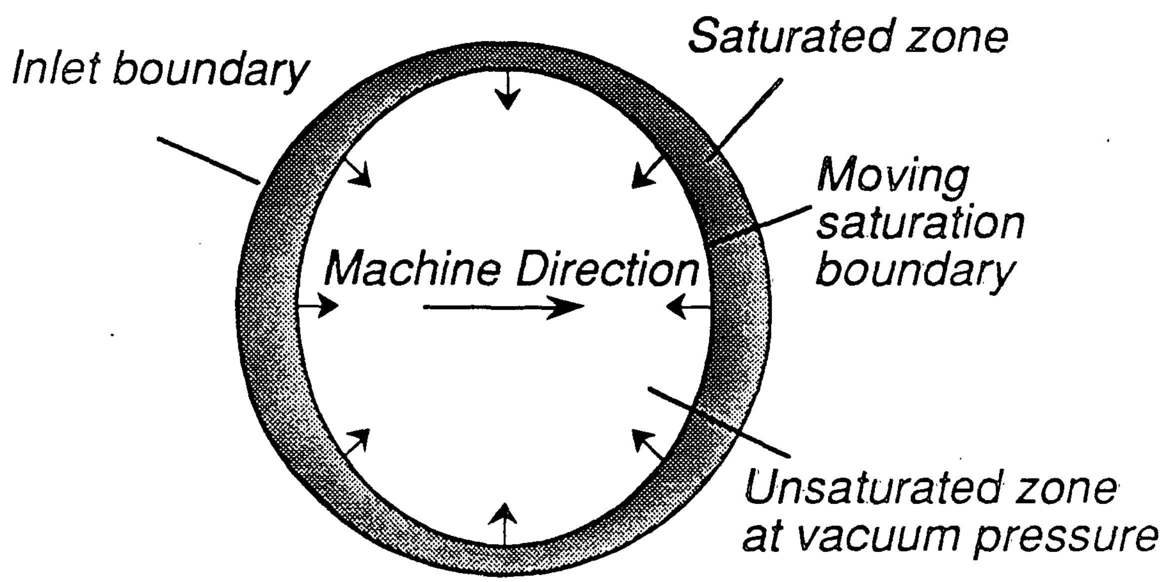
- Important in two-dimensional flows
  - Wet pressing
  - Coating application
  - Edge penetration (photography)
  - Displacement processes
- No previous data for paper!

- Experimental approach:
  - Force radial flow in a sheet
  - Control compression (porosity)
  - Preclude channeling
  - Measure fluid boundary shape,size
- Numerical methods needed to reduce data (finite difference simulations)

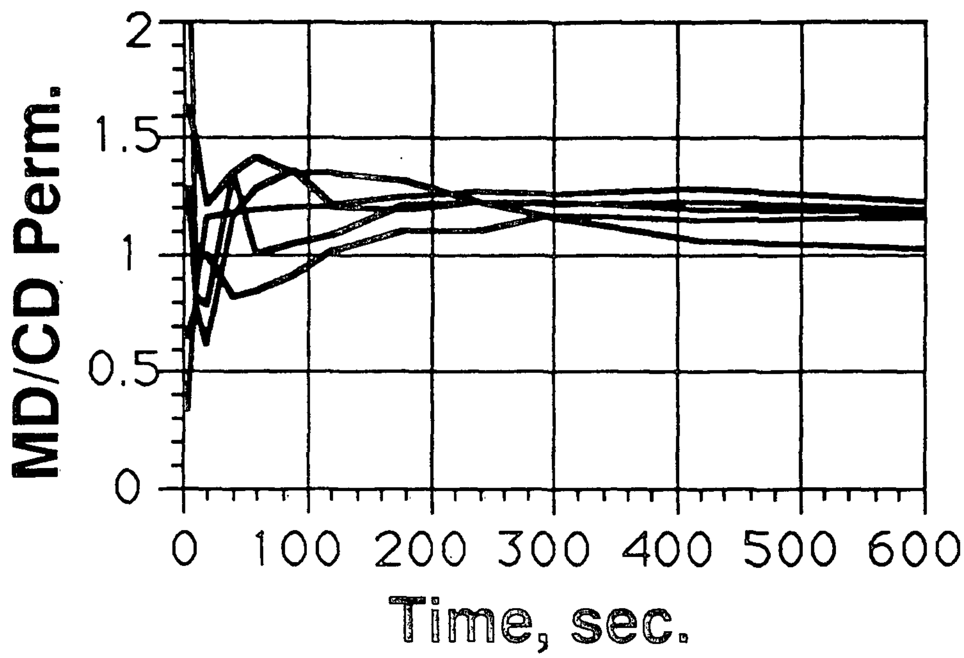
Radial Injection of Fluid



Inward Radial Flow



Photographic Paper



Results to Date

- Lateral permeability exceeds trans-verse permeability by a factor of 2-10
- The MD/CD permeability ratio is slightly greater than 1
- Simple models of fibrous media underpredict anisotropy

KEY EQUATIONS:

$$\mathbf{v} = \frac{-\mathbf{K} \cdot \nabla P}{\mu}, \tag{1}$$

$$\mathbf{K} = \begin{bmatrix} K_x & 0 & 0 \\ 0 & K_y & 0 \\ 0 & 0 & K_z \end{bmatrix}, \tag{2}$$

$$\alpha = \frac{K_y}{K_x}. \tag{3}$$

$$\beta = \frac{(K_x + K_y)}{2\,K_z} = \frac{K_r}{K_z}. \tag{4}$$

$$\nabla \cdot \mathbf{v} = 0 \quad . \tag{5}$$

$$\nabla \cdot \mathbf{K} \cdot \nabla P = 0\,. \tag{6}$$

$$K_r \equiv \frac{K_x + K_y}{2} = \frac{Q\,\mu\,\ln(R_o/R_i)}{2\pi\,L\,\Delta P}, \tag{7}$$

$$\varepsilon = 1 - \frac{m}{A\,L\,\rho_c}, \tag{8}$$

$$K_z = \frac{L}{\dfrac{A_{flow}\,\Delta P}{Q\,\mu} - R_f}, \tag{9}$$

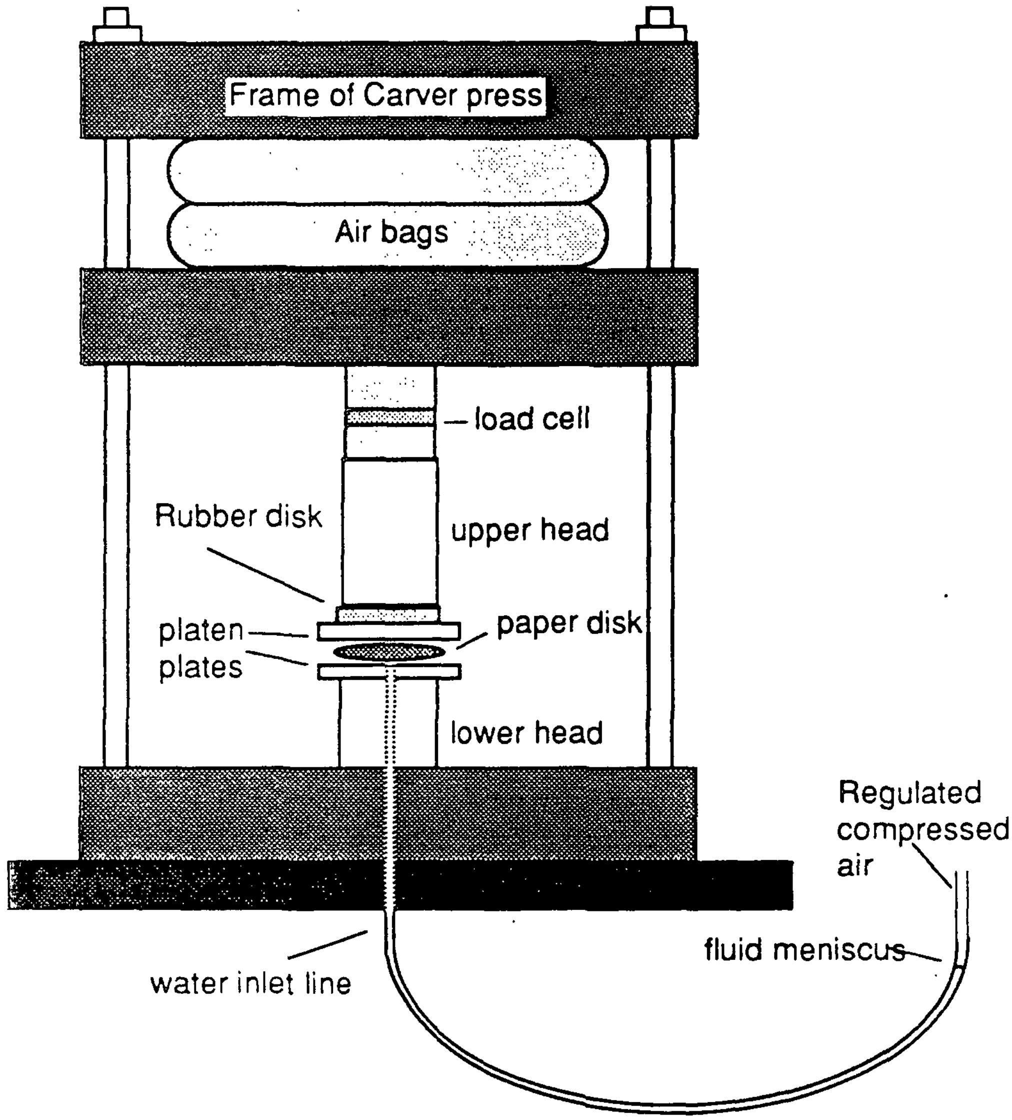


Figure 1. Schematic of the lateral permeability setup.

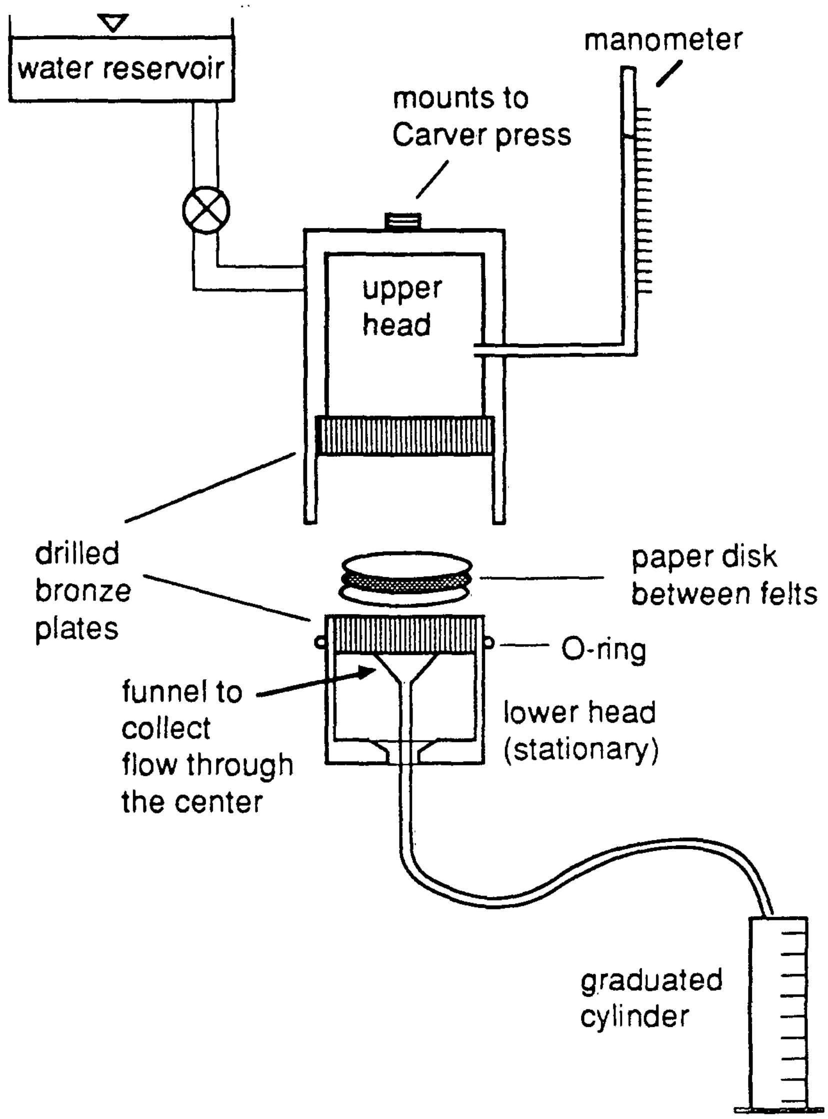


Figure 2. Schematic of the water flow system for transverse permeability measurements.

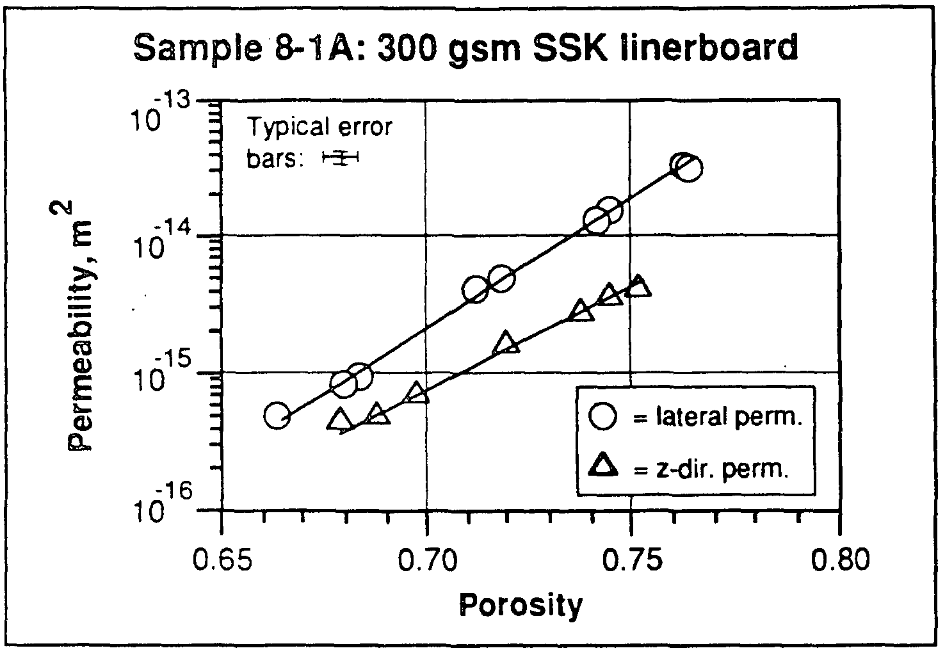


Figure 3. Lateral and transverse permeability in a linerboard handsheet.

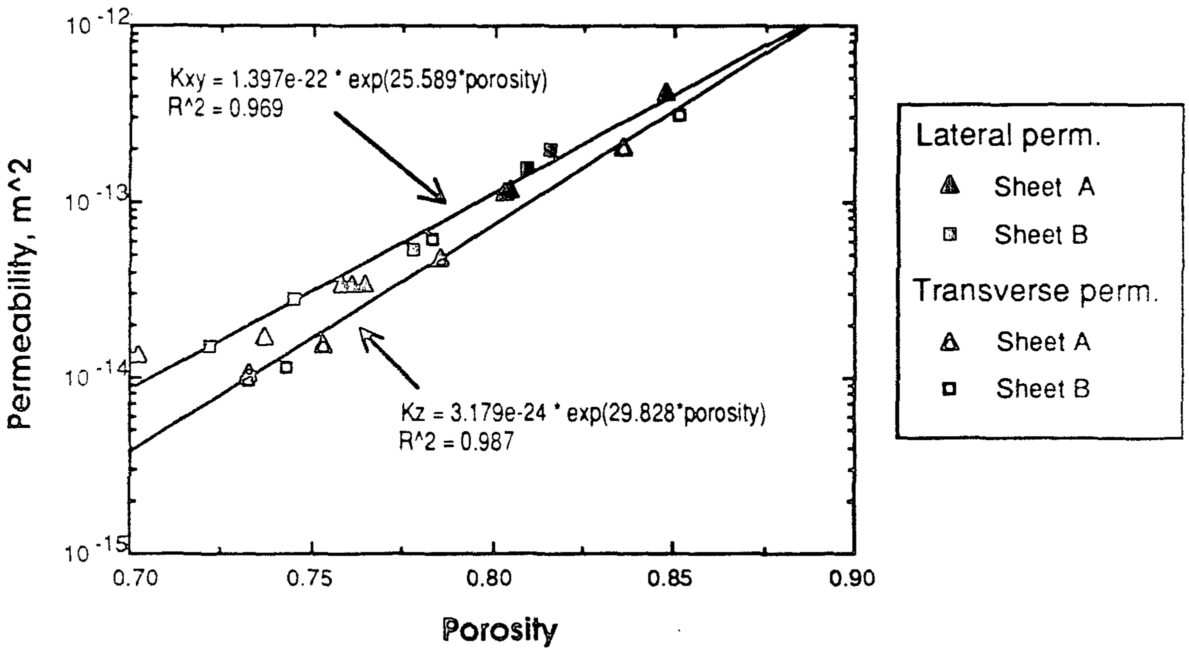


Figure 4. Previously published results for lateral and transverse permeabilities in linerboard handsheets from another SSK furnish.

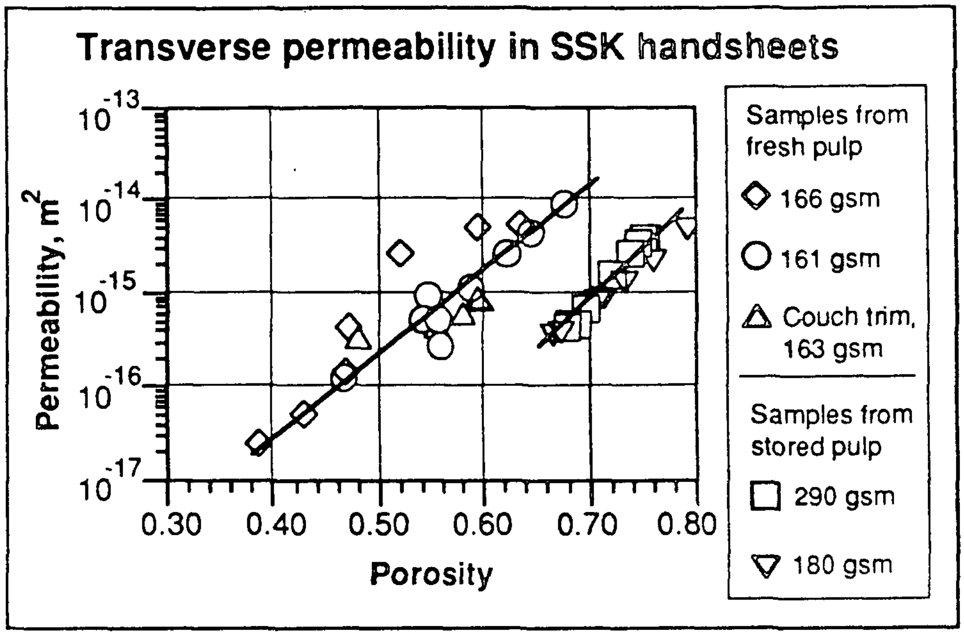


Figure 5. Comparison of transverse permeability measurements in two sets of samples from SSK linerboard pulp.

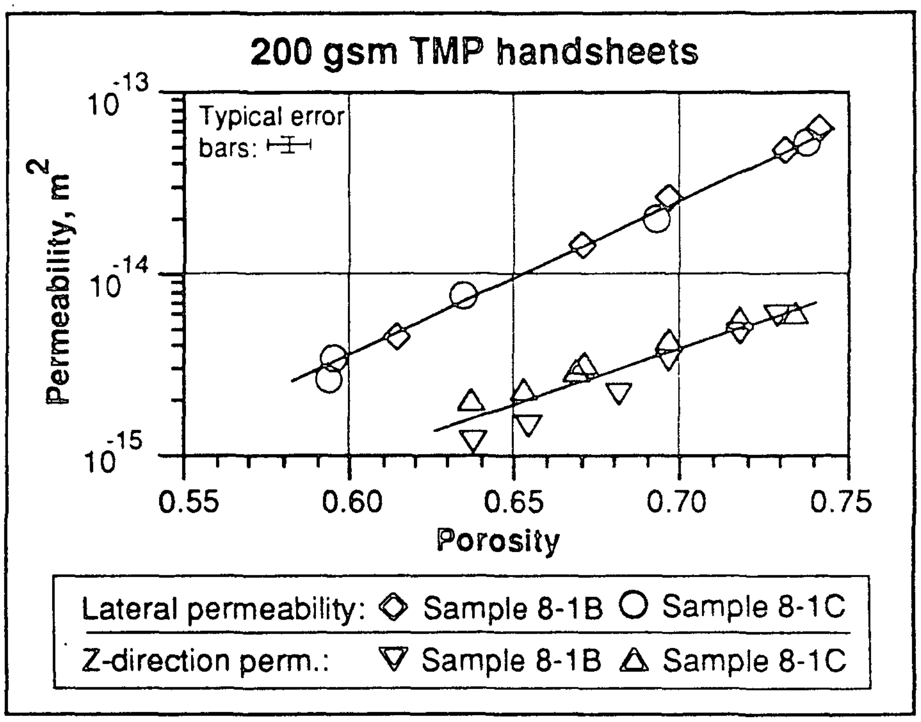


Figure 6. Lateral and transverse permeabilities in two 200-gsm TMP handsheets.

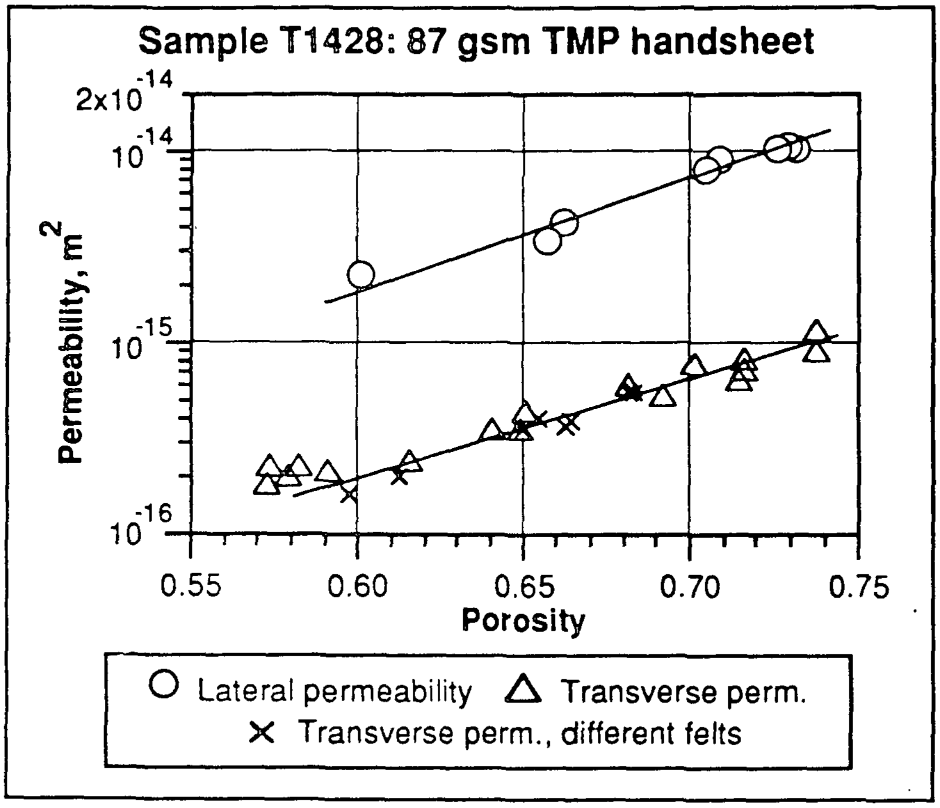


Figure 7. Lateral and transverse permeability measurements in an 87 gsm TMP handsheet.

FLASH X-RAY STUDIES OF WEB CONSOLIDATION

Project Staff: Cyrus K. Aidun

OBJECTIVE

Investigate the feasibility of using the flash x-ray technique for measurement of sheet deformation in a roll press

Project 3480

Goals for Oct. 1990 - April 1991:

1. Implement a model of compressible media in MIPPS.

2. Compare fiber orientation data to MD/CD permeability ratios.

Student projects related to Project 3480

James Burns, Ph.D. candidate: Dynamic compressibility of paper sheets

Jill Wallin, A190, 1990: In-plane permeability

John Frazier, A190, 1991: Hydraulic pressure gradients in the z-direction during pressing

Marty Hoskins, A190, 1991: Vapor-liquid distributions in porous media during phase-change heat transfer processes

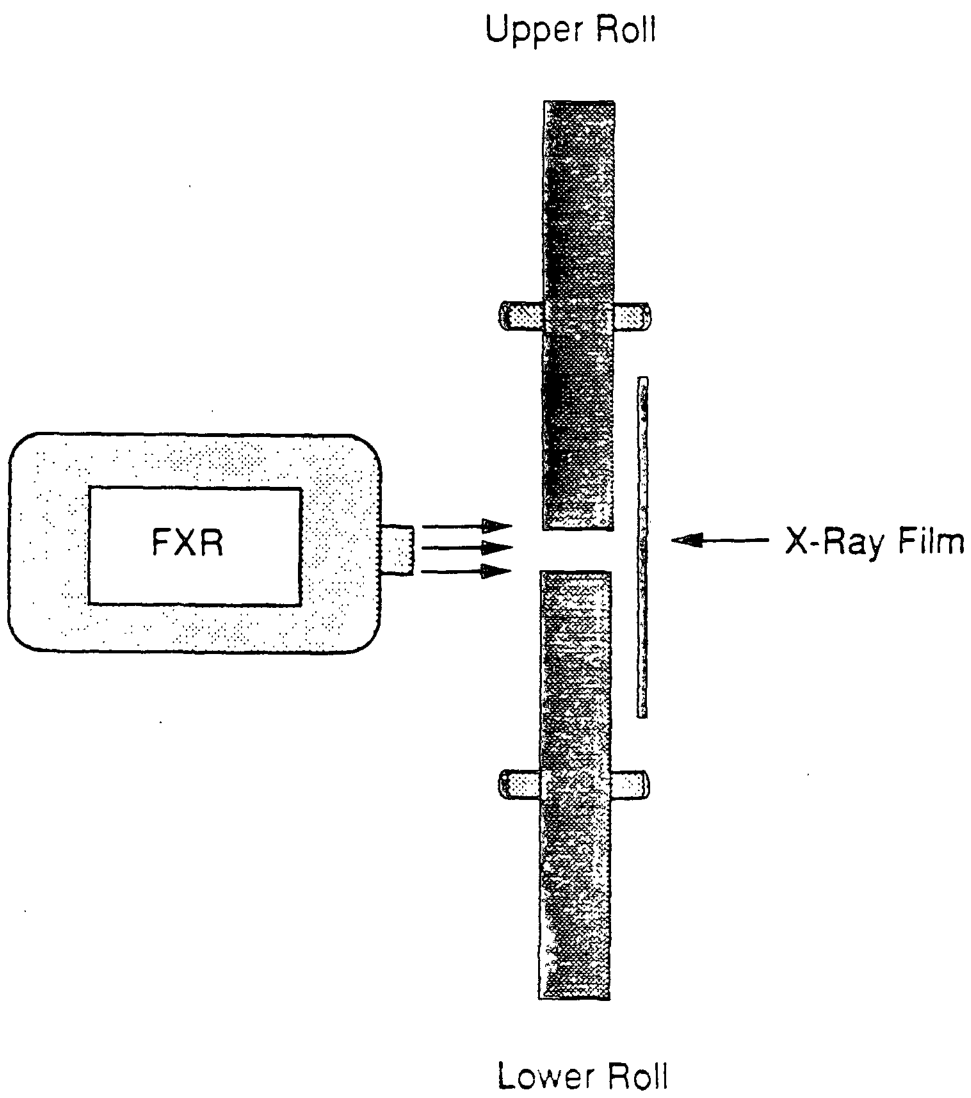


Figure 2. Schematic diagram of the relative position of the x-ray source, x-ray film, and the rolls.

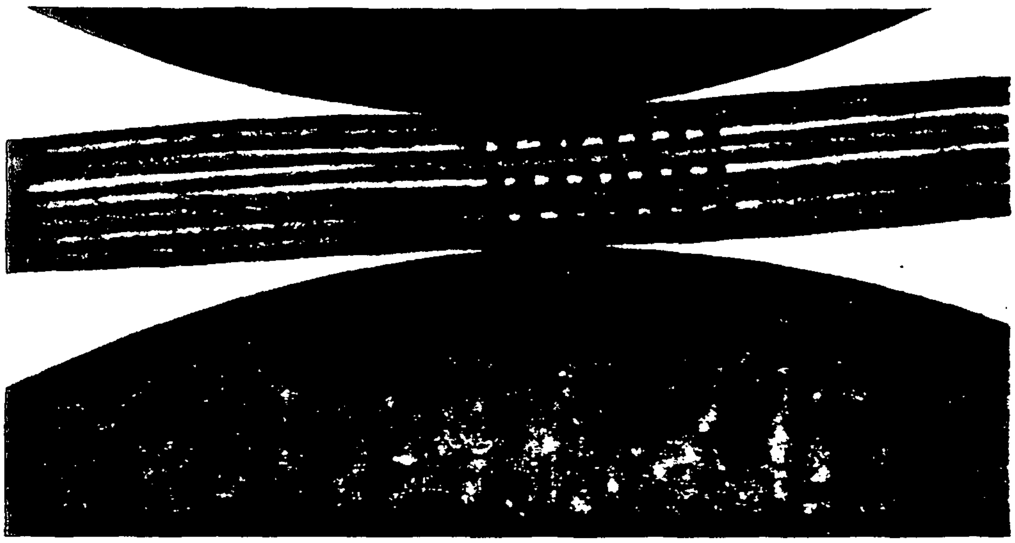


Figure 3a. Flash X-ray Radiograph of Target Particles (zero load)

Figure 3b. Flash X-Ray Radiograph of Target Particles (compressed)

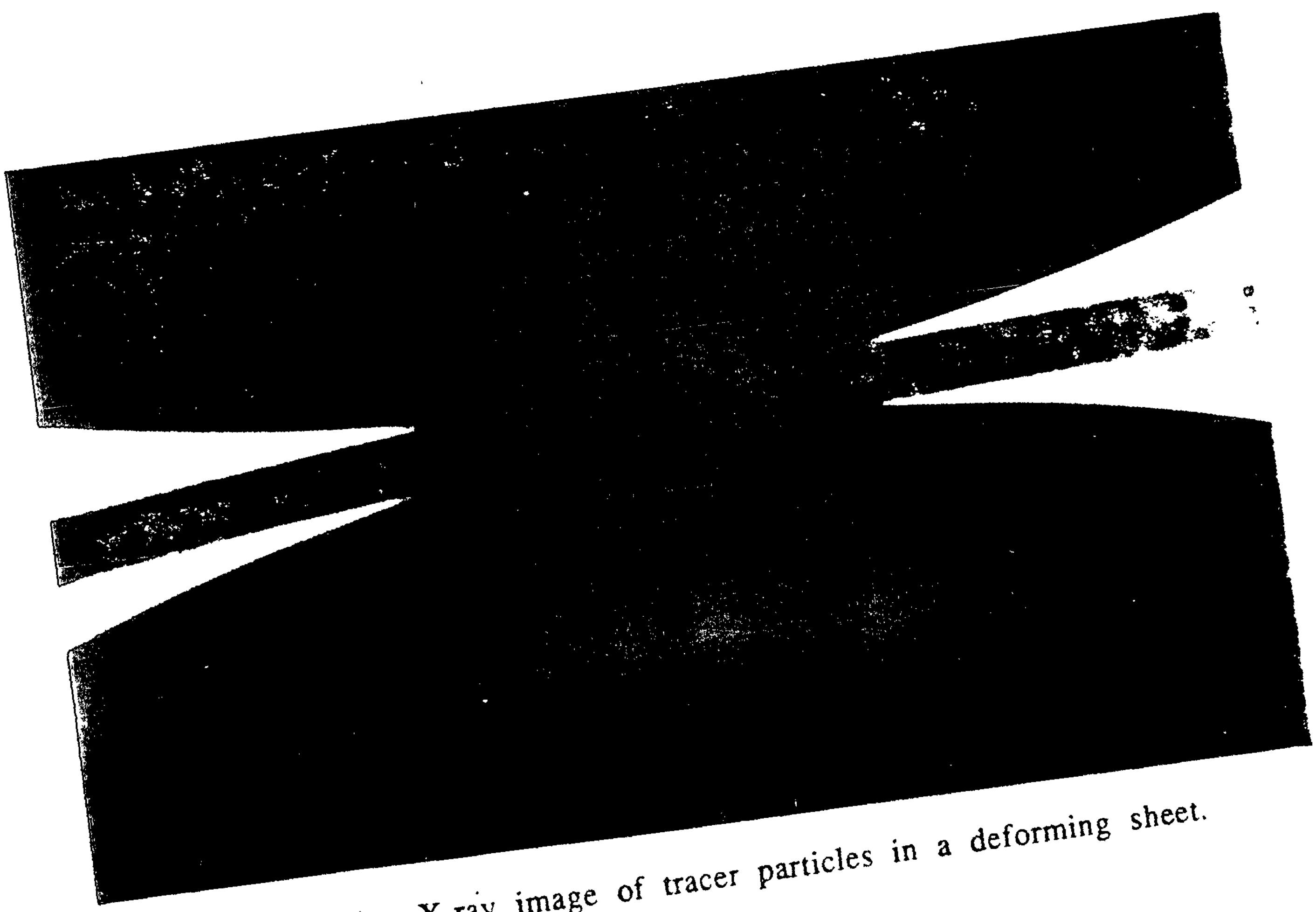


Figure 4. X-ray image of tracer particles in a deforming sheet.

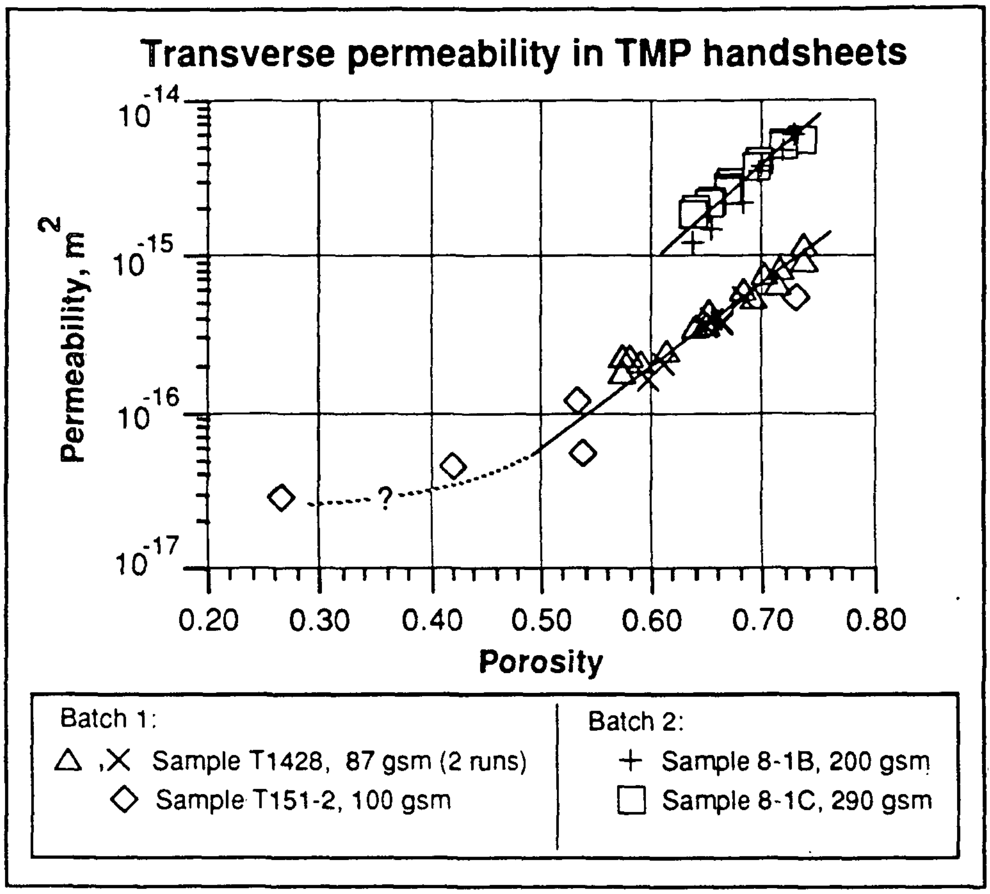
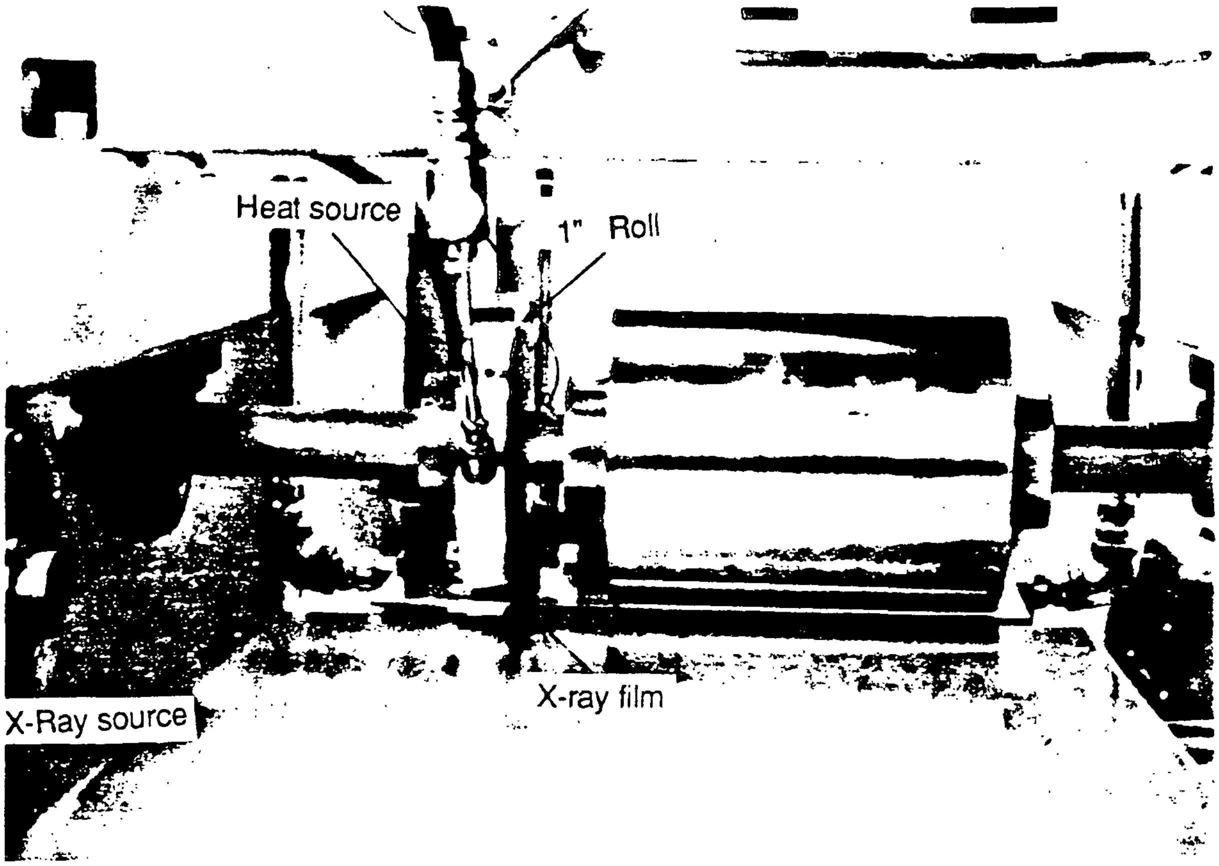


Figure 8. Comparison of transverse permeability measurements in two batches of TMP sheets prepared at different times and by different people.

a)



b)

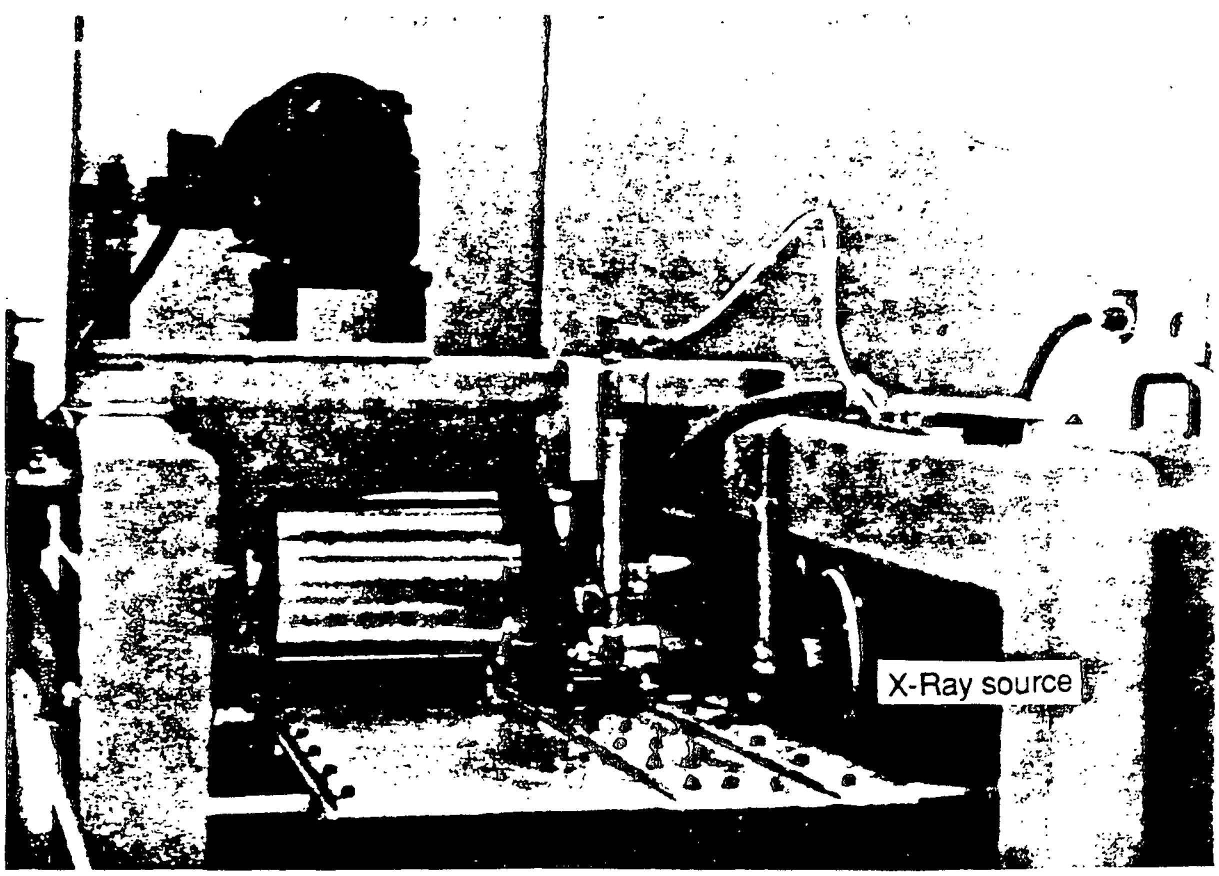


Figure 1. X-Ray Roll Press a) exit side b) entering side

Composite Sheet Pressing

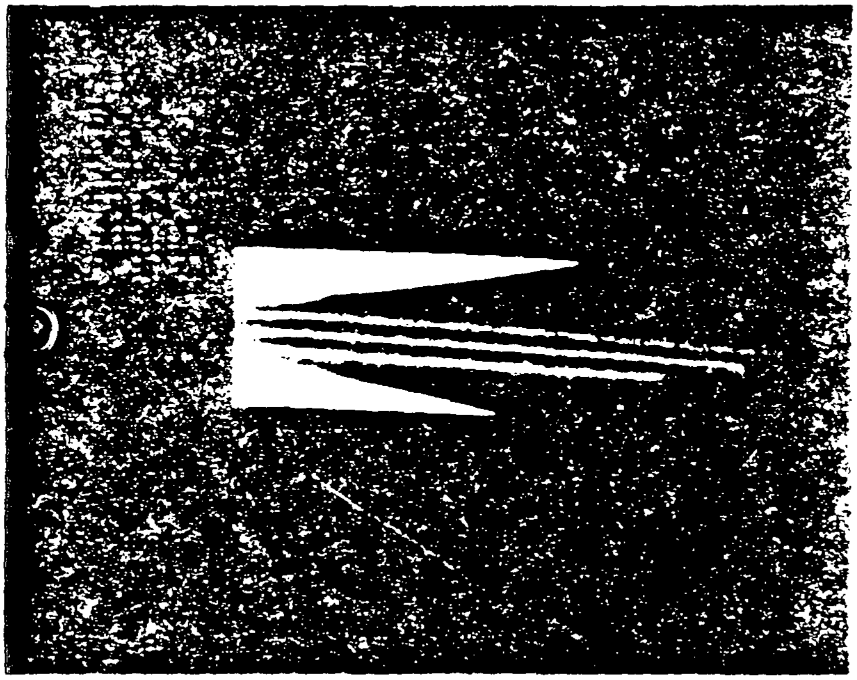
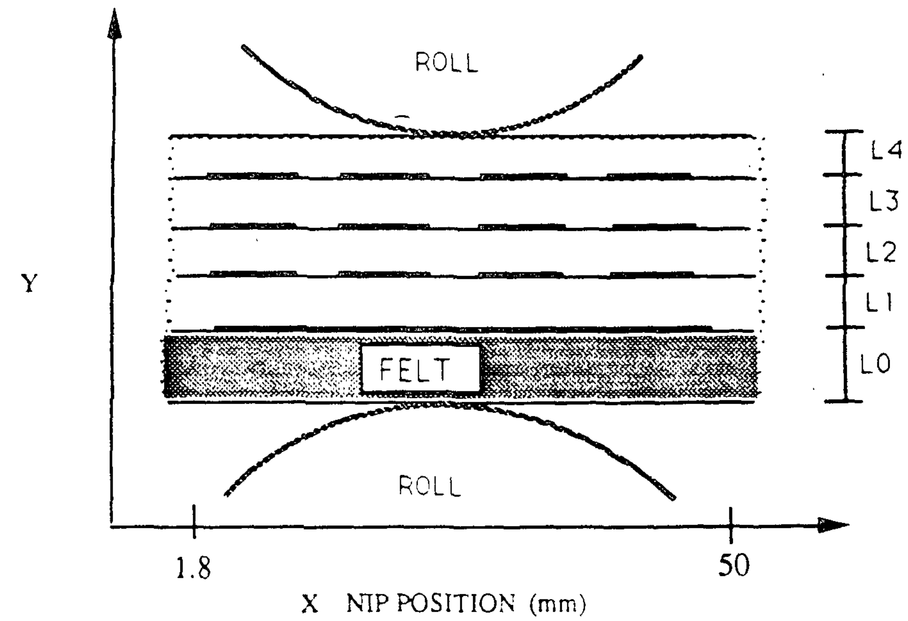


Figure 6. X-ray image of continuous tungsten wires in a sheet at the exit side of the nip.

(a)



(b)

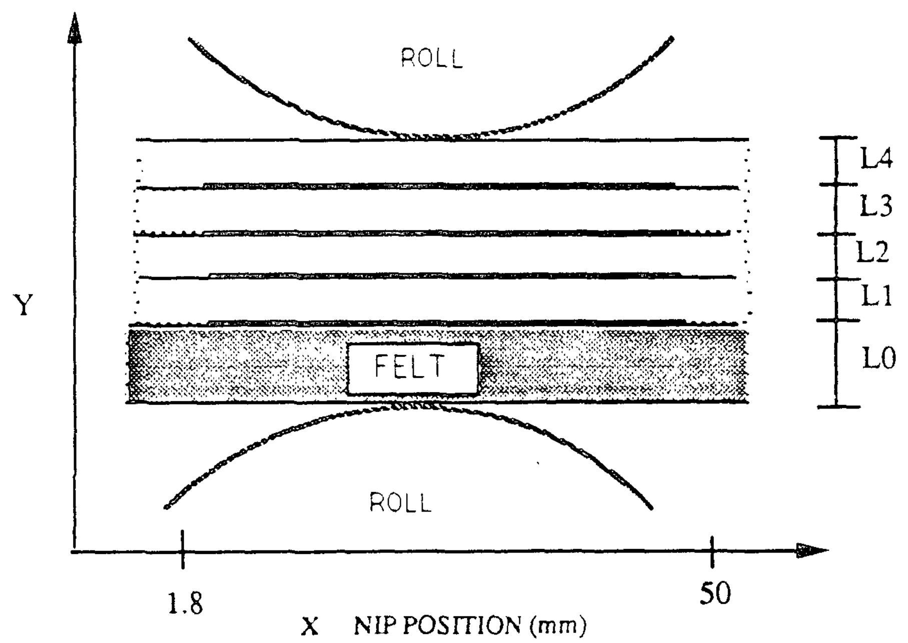
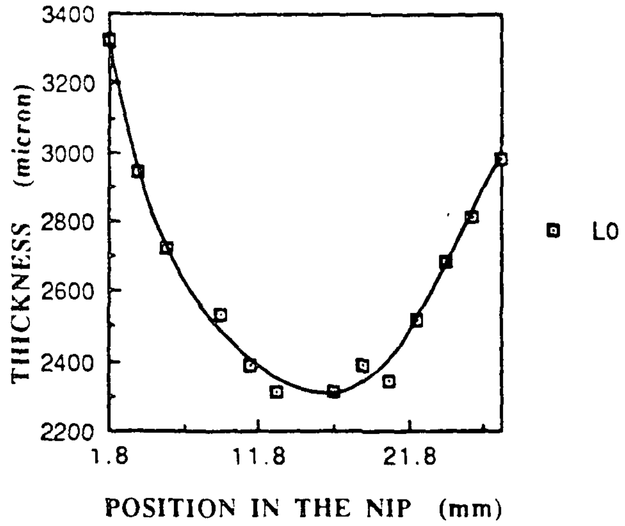
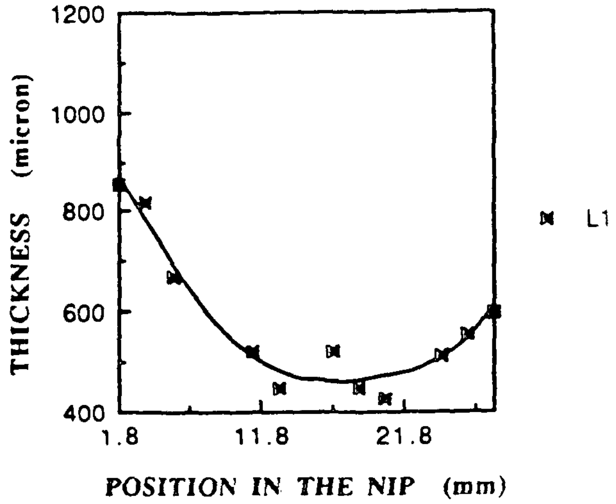
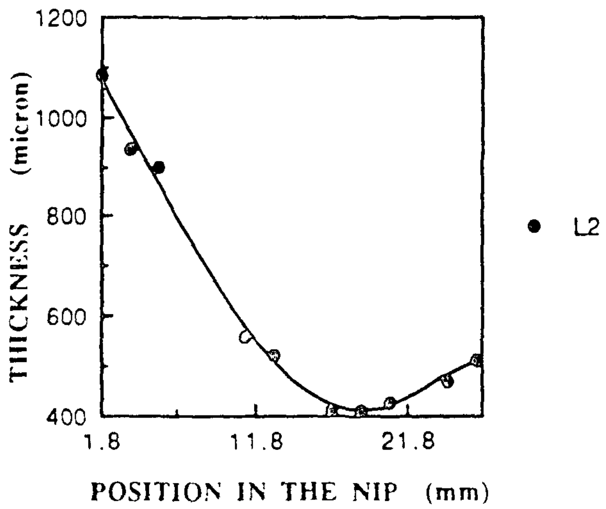
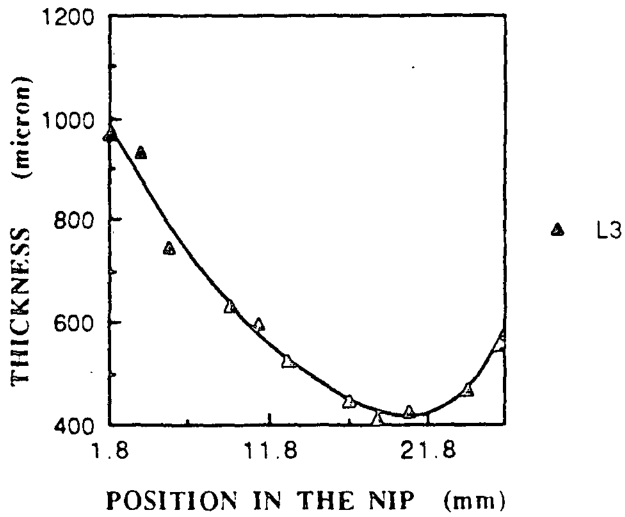


Figure 7. Schematic of the test samples.
4 layers of paper, L1 through L4, each with 150 g/m2 basis weight, 28% solids.
X-Ray shuts are at two different pressures, 50 and 60 psi. Roll press speed is at 17 ft/min.
Selection of axes for analyzing the x-ray films and the thickness measurements with the image analyzer are also shown. Targets : 50 microns, tungsten wires (99.95%) are located between the sheets in two different arrangements : (a) Discontinuous wires 5 mm long and 2 mm apart, and (b) Continuous wires 4 " long. Also a continuous wire is placed between the sheet and the felt in both sets.









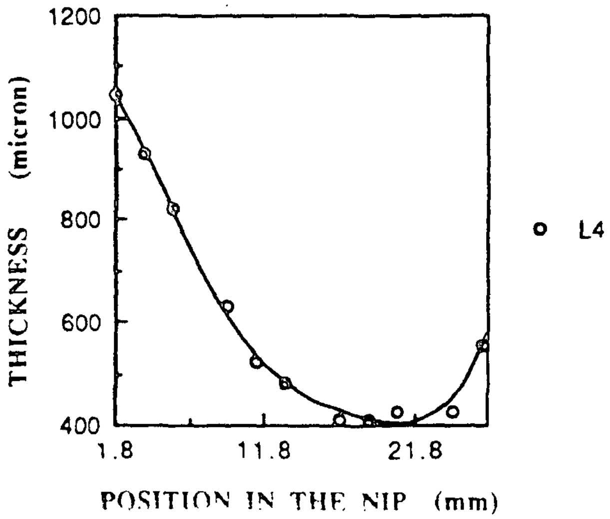
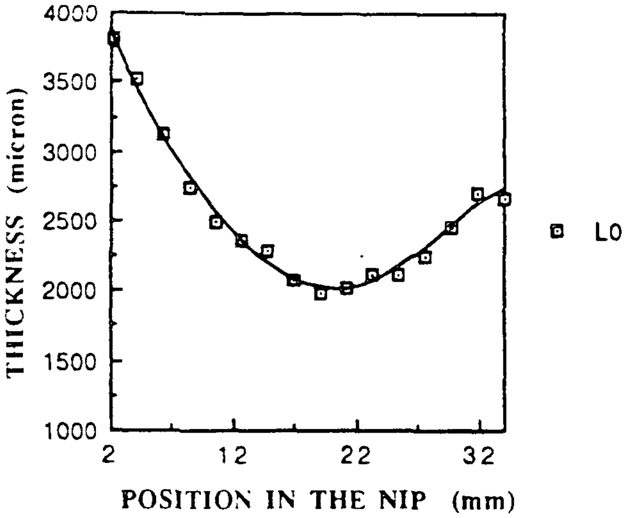
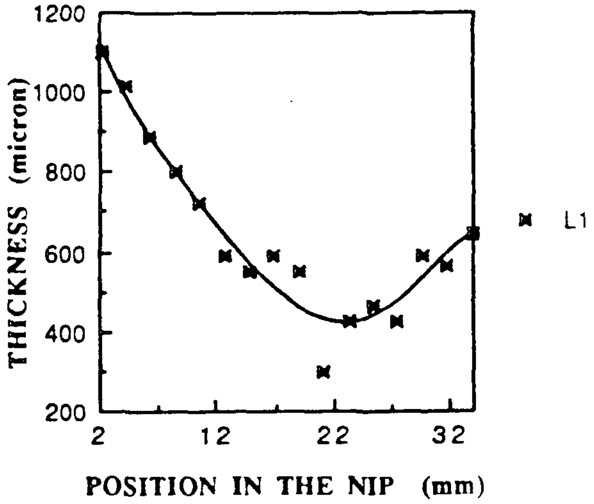
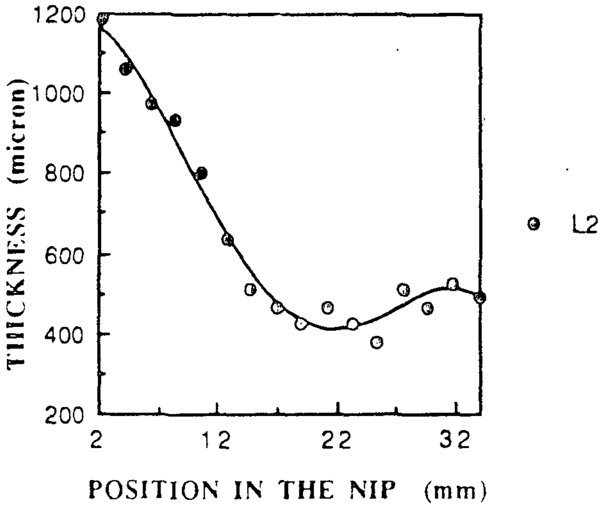
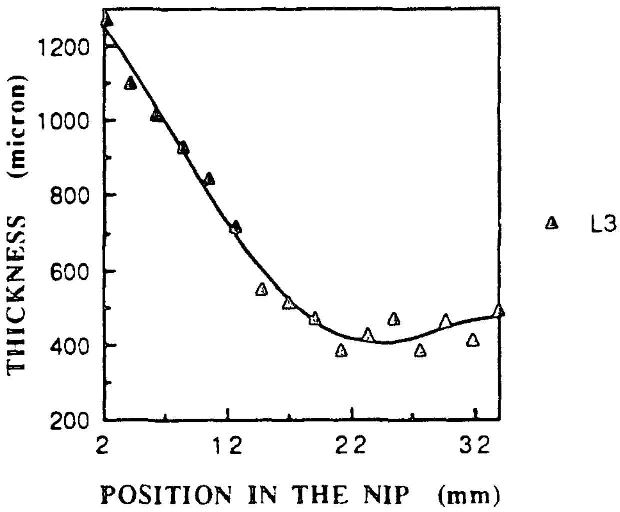


Figure 8. Thickness variation of individual free sheets in wet pressing at 60 psi, discrete target arrangement. For sample description, see Fig. 7a. Graphs show first half of the nip.









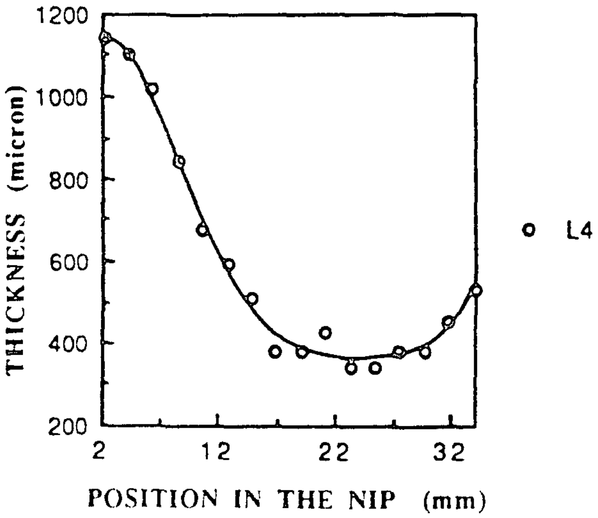
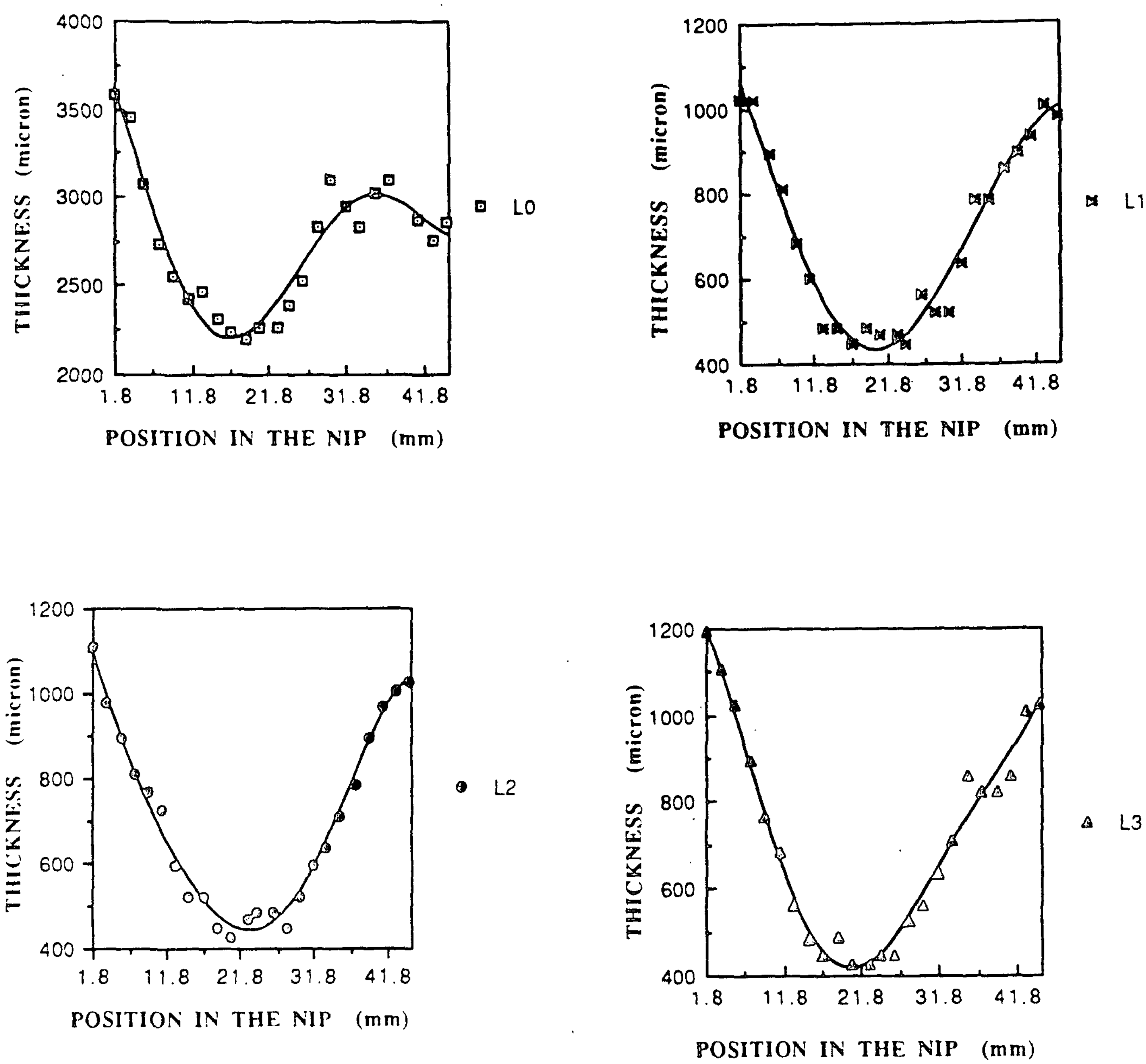


Figure 9. Thickness variation of individual free sheets in wet pressing at 60 psi, continuous target arrangement. For sample description, see Fig. 7b.



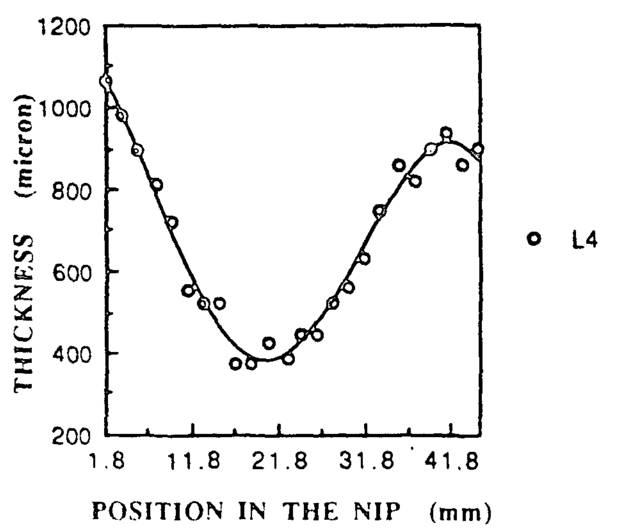
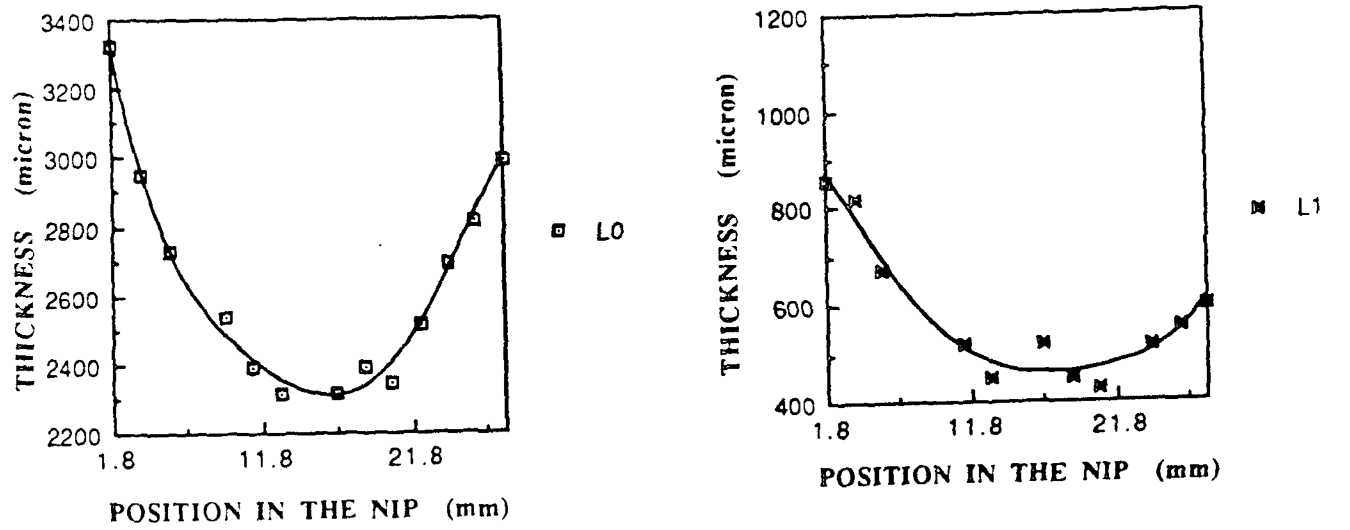
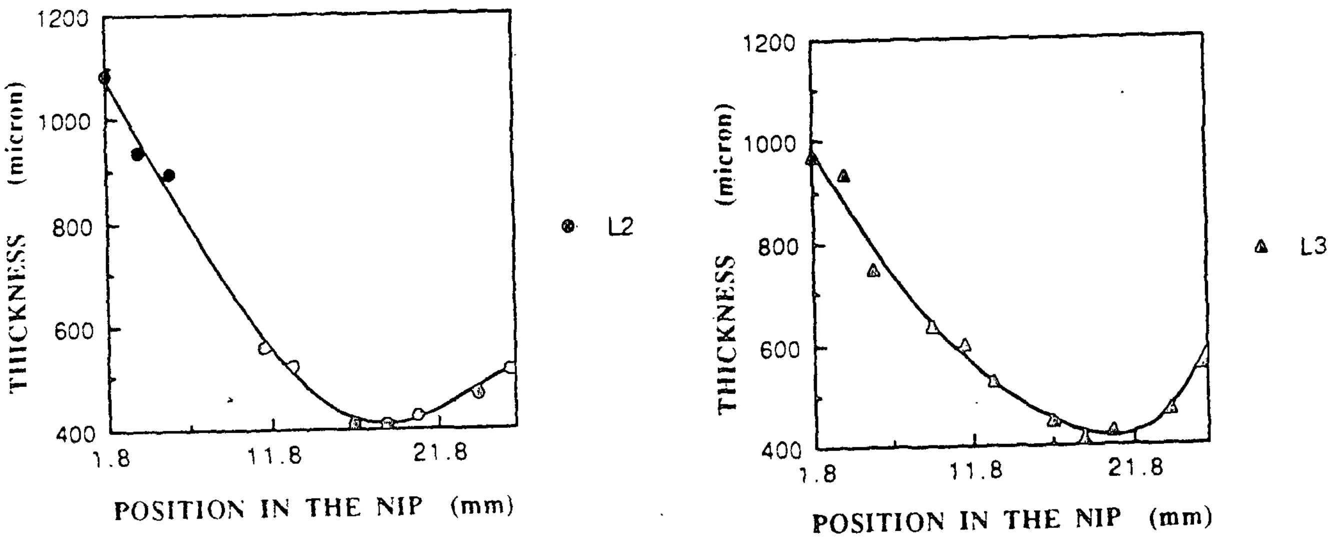


Figure 10. Thickness variation of individual free sheets in wet pressing at 50 psi continuous target arrangement. For sample description, see Fig. 7b.





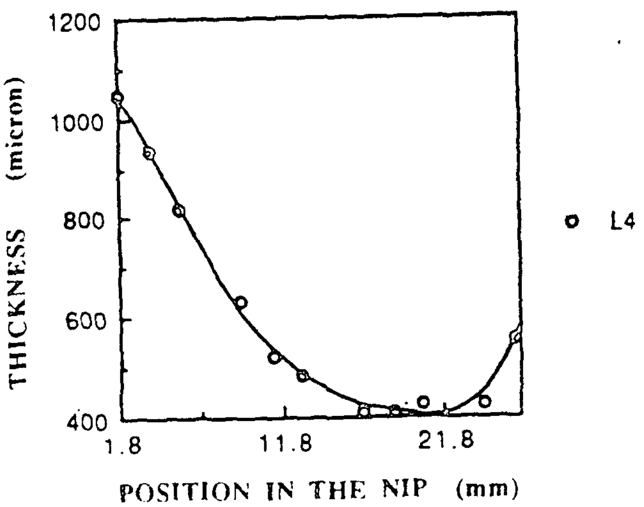
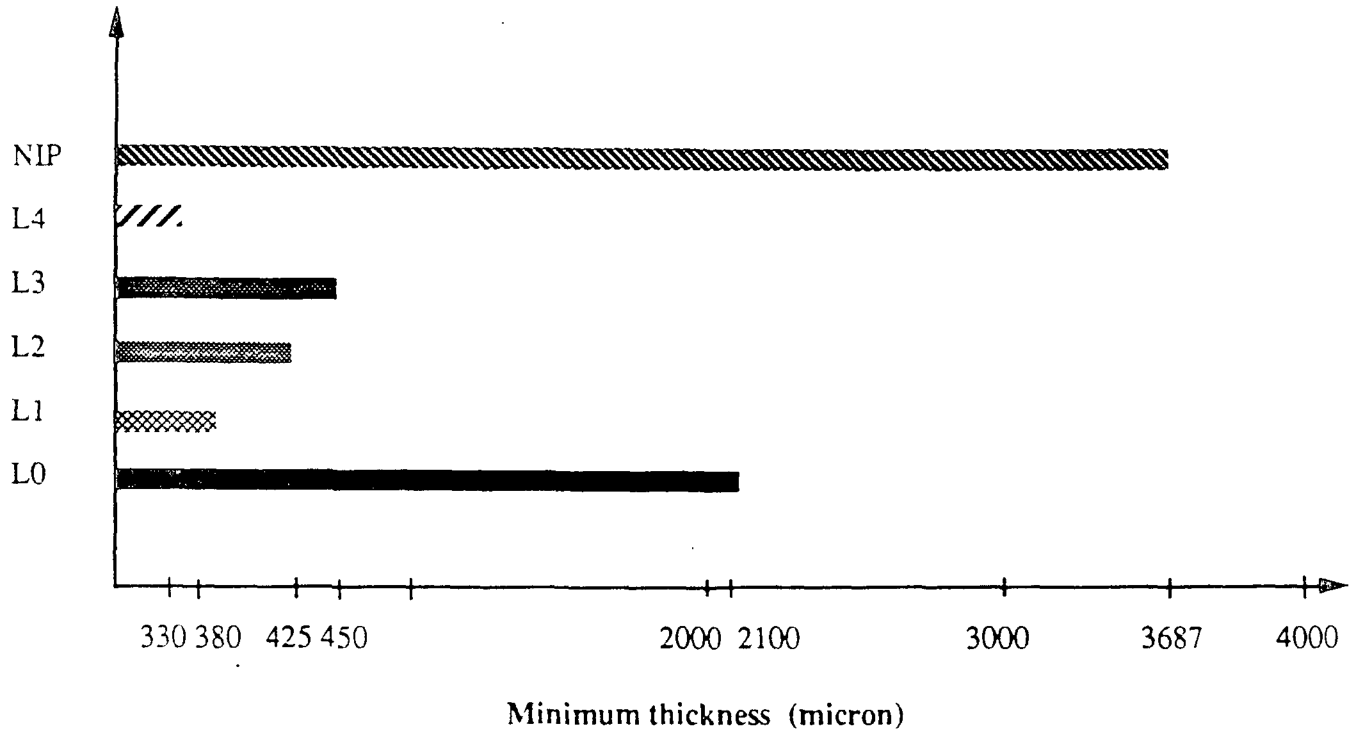
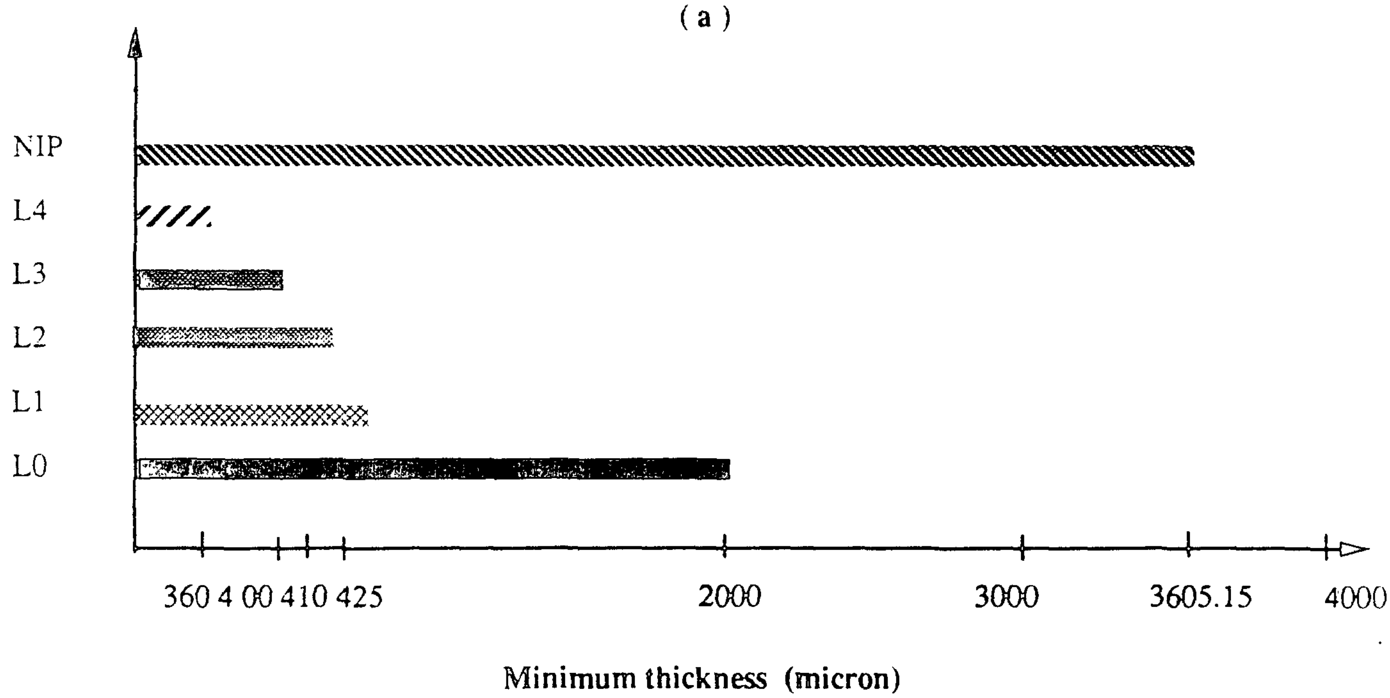


Figure 11. Thickness variation of individual free sheets in wet pressing at 50 psi, discrete target arrangement. For sample description, see Fig. 7a. Graphs show first half of the nip .



(a)



(b)

Figure 12. Minimum thickness of each individual sheet.
(a) Discontinuous wires at 60 psi and (b) Continuous wires at 60 psi.

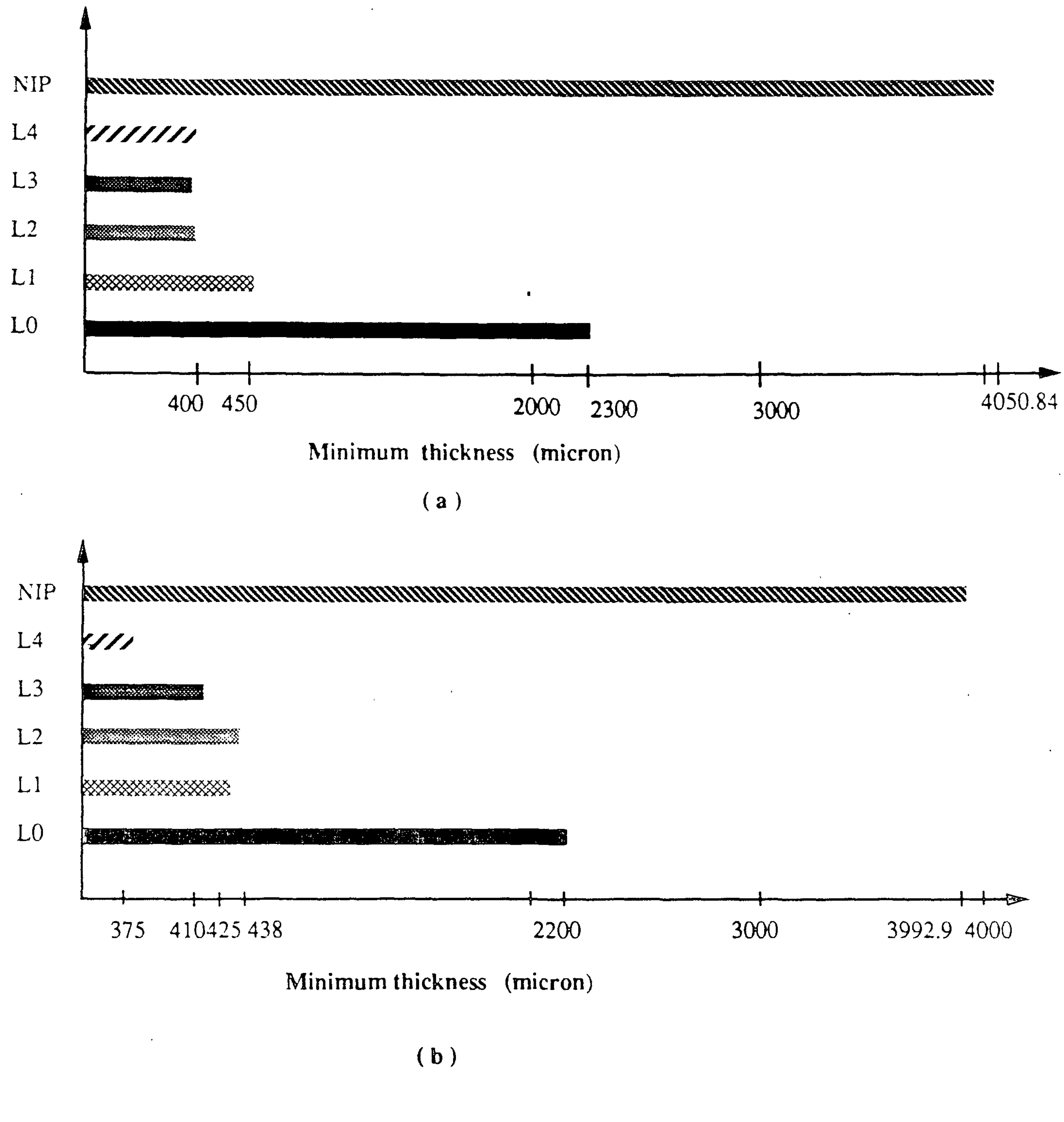


Figure 13. Minimum thickness of each individual sheet.
(a) Discontinuous wires at 50 psi and (b) Continuous wires at 50 psi.

CONCLUSIONS

- The thinnest target wire which can be resolved inside a sample sheet is 50 μm in diameter
- The resolution of the flash x-ray is not sufficient to measure deformations in single light-weight sheets
- The technique can be used to study multi-layer sheet pressing

GOALS FOR OCTOBER 1990 - APRIL 1991

- Write the final report for this project and publish the results

FUNDAMENTALS OF COATING SYSTEMS
PROJECT 3674

December 20, 1990
Institute of Paper Science and Technology
Atlanta, Georgia

DUES-FUNDED PROJECT SUMMARY REPORT
FY 90-91

Project Title:	FUNDAMENTALS OF COATING SYSTEMS
Project Code:	COATS
Project Number:	3674
Division:	Engineering and Paper Materials Division
Project Staff:	Cyrus Aidun
FY 90-91 Budget:	$100,000

PROJECT GOAL: To improve quality, increase production flexibility, and reduce the operating cost of surface application. To investigate the influence of pressure, dwell time, fluid and paper properties on the interaction between the paper surface and the coater in the application process, and to optimize the substrate, coating material, and the coating device as a system for best quality and minimum operating cost.

PROGRAM AREAS: Capital Effectiveness, End Use Performance.

RATIONALE: The need for fundamental research in coating processes in the paper and board industry has been recognized and reported in various forms (1-3). Coating can provide "quality" and "flexibility" to the paper industry, the key words for success in the market (1). High quality coated papers are becoming an increasingly important segment of the total paper market. At the same time, users are demanding continually improving quality and foreign suppliers are generating more competition. Hence, coated paper producers are forced to seek ways to improve quality, increase productivity, and reduce costs to remain competitive in this market.

The current blade coating technology suffers from problems with regard to runnability of coating material at the desired solid levels and speed, and inflexibility to vary coating weight over a required range. The operant speeds are severely limited due to flow instability, air entrainment, and problems will greatly enhance quality and reduce the production cost of coated papers to a level compatible with the ever increasing market demand.

ACCOMPLISHMENTS TO DATE:

1. At a critical machine speed to viscosity ratio, the steady two-dimensional flow in the pond of a short dwell coater destabilizes and becomes time-periodic and three-dimensional indirectly influencing coat weight nonuniformities (streaks).

2. Multiple flow patterns were discovered (4,5) which exist and compete with the ideal two-dimensional state under identical operating conditions. This explains the multiple operating states and unpredictable nature of short dwell coaters.

3. When the flow in the pond becomes time-periodic, we have shown solid particle mixing intensity variations are generated in CD. This of course results in coating color viscosity variations, the effects of this phenomenon on coat weight uniformity and runnability is currently under investigation.

4. The flow parameters and the roll speed for transition from steady state to unsteady flow of a Newtonian fluid in a rectangular cavity simulating the pond of a short dwell coater has been measured with the new data acquisition system.

GOALS FOR 1990-1991:

1. Pinpoint the relation between the flow instabilities in the SDC pond and the resulting coat weight nonuniformities.

2. Develop the techniques to analyze the dynamics of highly viscous opaque fluids in a coating system by using a Hot-Film Anemometer and the Coating Machine Simulator at IPST.

3. Install a series of HFA's on a pilot coater to investigate the fluid dynamics of coating colors at high speed.

4. Measure the effects of span aspect ratio on the critical speed for the onset of time dependent flow in the pond of short dwell coaters using a) viscous Newtonian fluid, and b) shear-thinning fluids with typical coating color rheological characteristics.

5. Study the effects of pond geometry on the appearance of multiple steady flow patterns in the pond of a short dwell coater.

6. Develop a computational technique based on spectral decomposition for stability analysis of rheologically complex coating colors, and compute the effects of nonuniform normal stress variations in CD and its effects on the blade deflection and subsequent coat weight nonuniformities.

RELATED PROJECTS: A proposal submitted for computational time on an NSF-sponsored supercomputer system has been accepted for funding 85 service units. This project involves large-scale computational simulation of the instability and transition from steady to time-periodic flow in the pond of a short dwell coater.

RELATED STUDENT PROJECTS:

Daniel Bunker, Ph.D. Project, "The Influence of Drying Rate on the Z-Directional Pore Volume Distribution of Pigment Films," (in progress).

John McKibben, Ph.D. Thesis, "Development of a Computer Code for Analysis of Three-dimensional Free-Surface Flows with Dynamic Contact Lines (in progress).

Peter Veverka, M.S. Project, "Investigation of Dynamic Contact Line Instability and Air-entrainment in Coating and Sizing Systems," (in progress).

Philip Harding, M.S. Project, "Investigation of Misting Effects in Air-Knife Coaters," (in progress).

GOALS FOR
OCT. 1990 - APRIL 1991:

1. Install and calibrate a hot-film anemometer to analyze the feasibility of this technique for measurement of the dynamics of flow field of coating colors (opaque) in various pilot and full scale coating systems.

2. Measure the effects of span aspect ratio on the critical speed for the onset of time dependent flow in the pond of short dwell coaters using viscous Newtonian fluid.

3. Compute the velocity and pressure field in a typical short-dwell coater and investigate the possibility of flow cavitation using a) Newtonian fluids, and b) shear-thinning fluids with typical coating color rheological characteristics.

4. Modify the application technique in a blade coating system for superior performance. This is part of a long-term exploratory research within the project for development of novel coating systems.

REFERENCES:

1. Jerkeman P., "Coating Technology vs. Market Demand," TAPPI J., Aug. 1988.

2. Ruschak, K.J., "Coating Flows," Ann. Rev. Fluid Mech., vol. 17, 1985.

3. Scriven, L.E., "Coating Fundamentals, "TAPPI Coating Conference, 1985.

4. Aidun, C.K., and Triantafillopoulos, N.G., "Global Stability of the Flow in a Short Dwell Coater Pond," International Symp. Mechanics of Thin-Film Coating, National AIChE Conference, March 18-22, 1990.

5. Triantafillopoulos, N.G., and Aidun, C.K., "Fluid Dynamics of Short-Dwell Coater Ponds and Their Relationship to Coat Weight Nonuniformities, 1990 George Olmsted Award Paper, American Paper Institute, available as IPST Technical Paper Series #367, Institute of Paper Science and Technology, Atlanta, GA, (1990).

Project 3674

Fundamentals of Coating Systems

Project Leader: Cyrus K. Aidun

RELATED PROJECTS
PROJECT 3687

A proposal for NSF-sponsored supercomputer time has been approved.

This project involves large-scale computational analysis of the 3-D instability in the pond of short-dwell coaters.

OBJECTIVES

1. Investigate the cause and origin of coat weight nonuniformities in high-speed blade coating.

2. Explore novel coating systems for uniform coating at high machine speeds.

CRITICAL COATING PROBLEMS

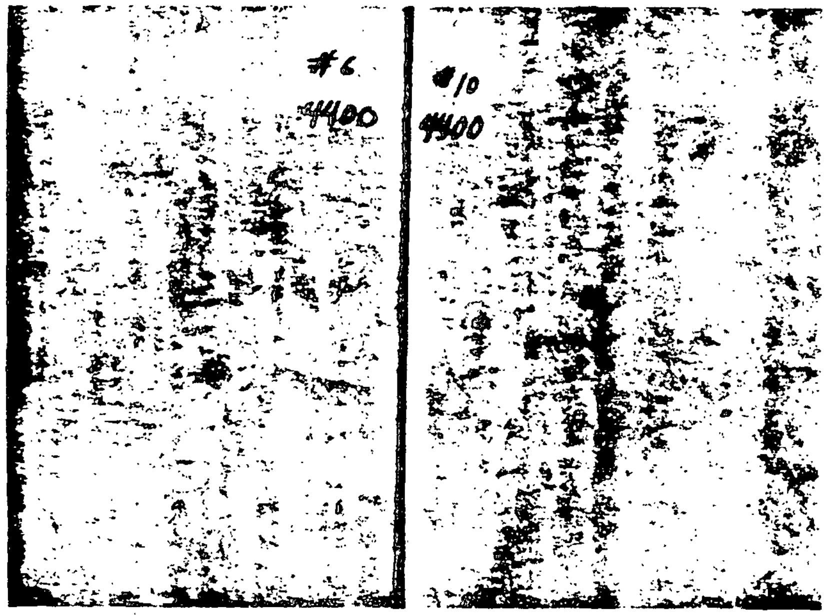
1. COATING FILM THICKNESS NONUNIFORMITIES:

    (a) Large Scale (striations, streaks, etc.)

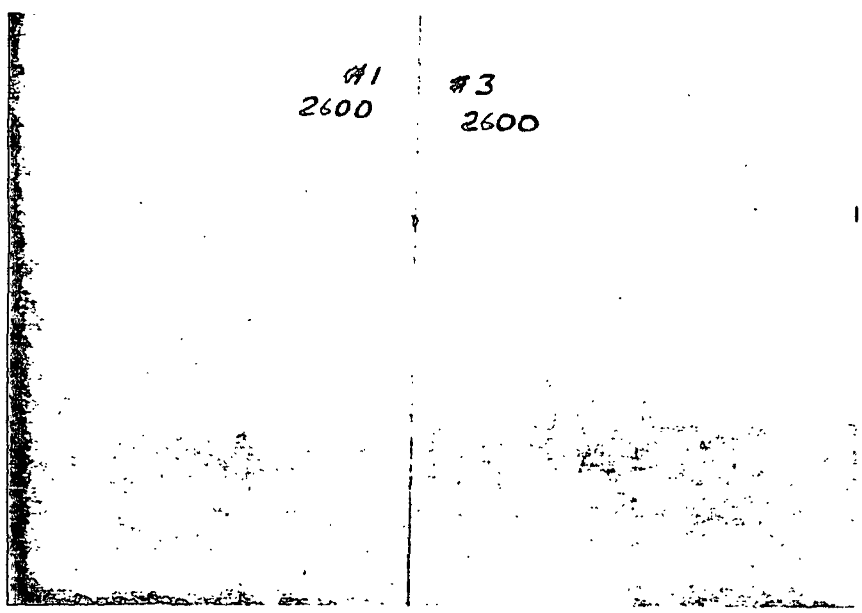
    (b) Small Scale (microstriations)

2. Air Entrainment

3. Inability to predict and control the amount and nature of coating and fluid migration into the base sheet



(a)



(b)

Figure 1. Macroscale and microscale nonuniformities in coat weight (or solids content) distribution for a LWC paper coated at (a) 4,400 fpm and (b) 2,600 fpm machine speeds.

Large Scale Nonuniformities (Streaks)

- o Coating characteristics change with disturbances
- o Identical Short Dwell Coaters Show Different Coating Characteristics

The Evidence Points To Hydrodynamic Instability

APPROACH:

- INDUSTRIAL PILOT TRIALS
- LABORATORY EXPERIMENTS
- THEORETICAL ANALYSIS

APPROACH

1. Industrial Pilot Trials
2. Laboratory Experiments
3. Mathematical Analysis

BACKGROUND

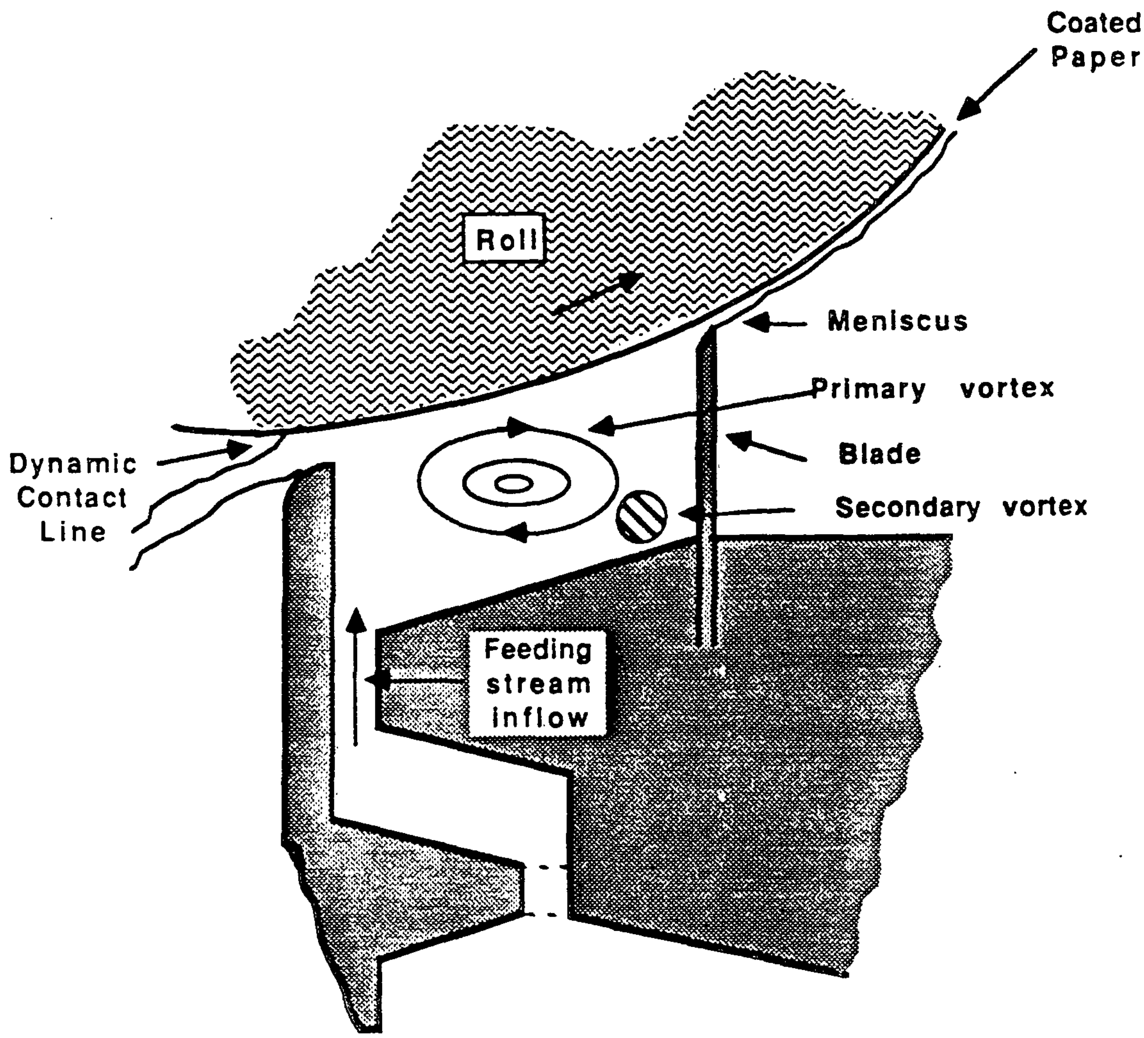
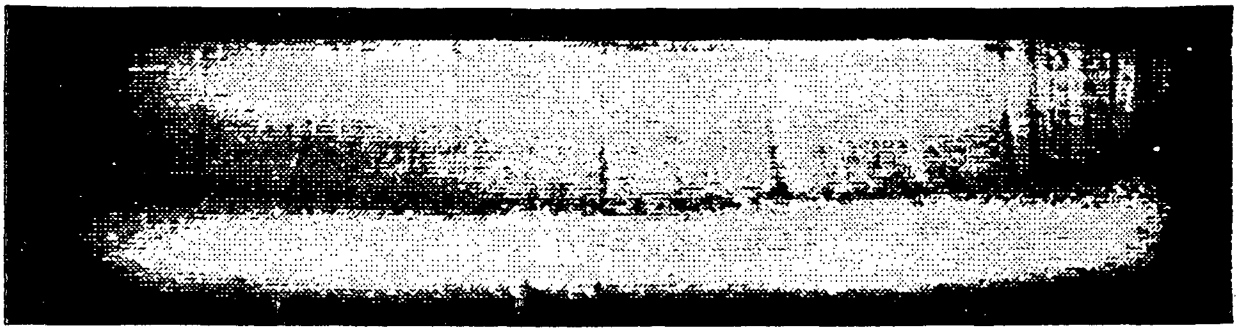


FIGURE 2. Schematic of a short dwell coater



HOW CAN IDENTICAL COATERS SHOW DIFFERENT FLOW CHARACTERISTICS ?

CONCLUSIONS FROM LABORATORY EXPERIMENTS

It is discovered that the flow inside the pond is globally unstable

At least three 3D structures compete with the ideal 2D flow pattern

The 3D flow patterns could generate streaks

As the machine speed increases the 3D flow patterns oscillate in CD

CONCLUSIONS FROM MATHEMATICAL ANALYSIS

Due to the spanwise oscillation of the 3D flow patterns, the solid particles could follow chaotic trajectories (strong mixing) at the boundary of recirculating vortices

Stronger mixing at the boundary of the cells relative to the core could result in solid concentration gradient in CD

Solid concentration gradient in CD will result in streaks

CONCLUSIONS FROM PILOT COATER TRIALS

The instability of the primary vortex in the pond is partly responsible for the streaks

Increasing the coating injection rate has a tendency to suppress the streaks

FUTURE PLANS

- Quantitative laboratory measurements of the critical machine speed for steady flow in the pond of a short dwell coater.

- The effects of geometry on the operational stability

RECENT PROGRESS
IN
EXPERIMENTAL ANALYSIS

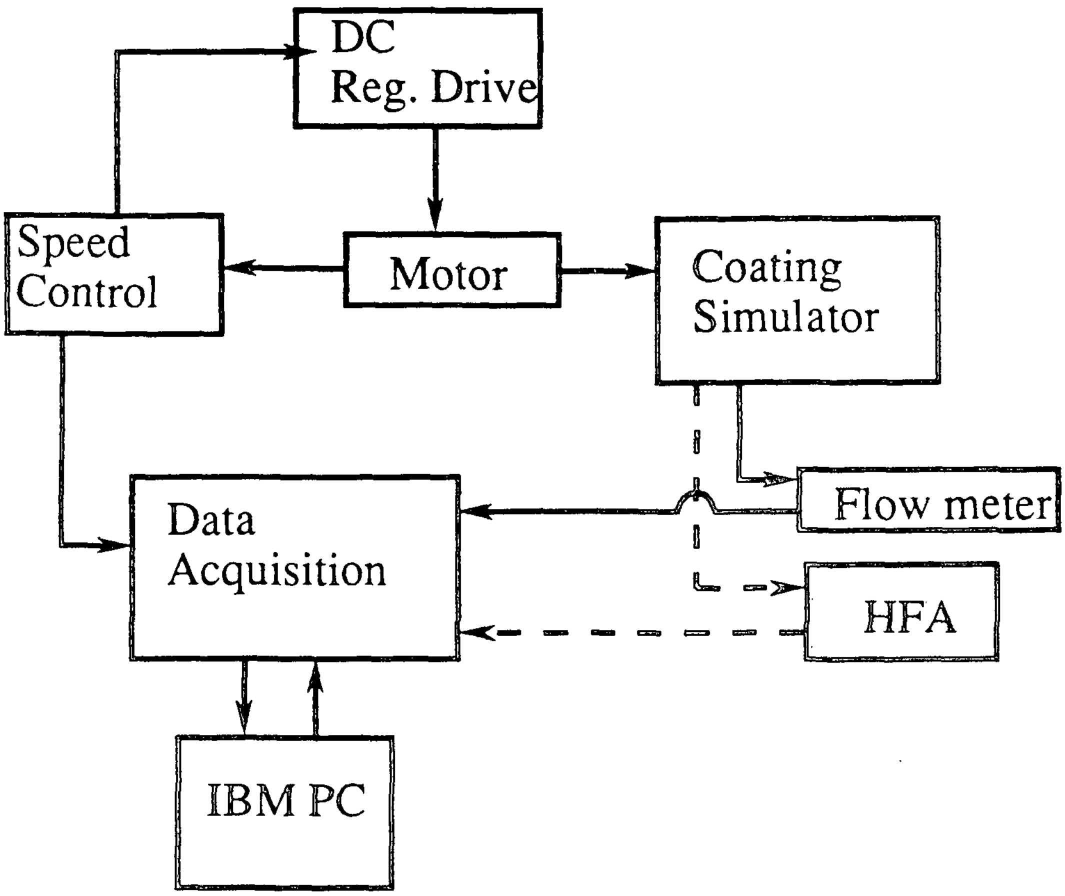
1. Modified the SDC Simulator for accurate quantitative measurements. Modifications include:

   o a data acquisition system

   o digital speed control

   o accurate on-line flow meter

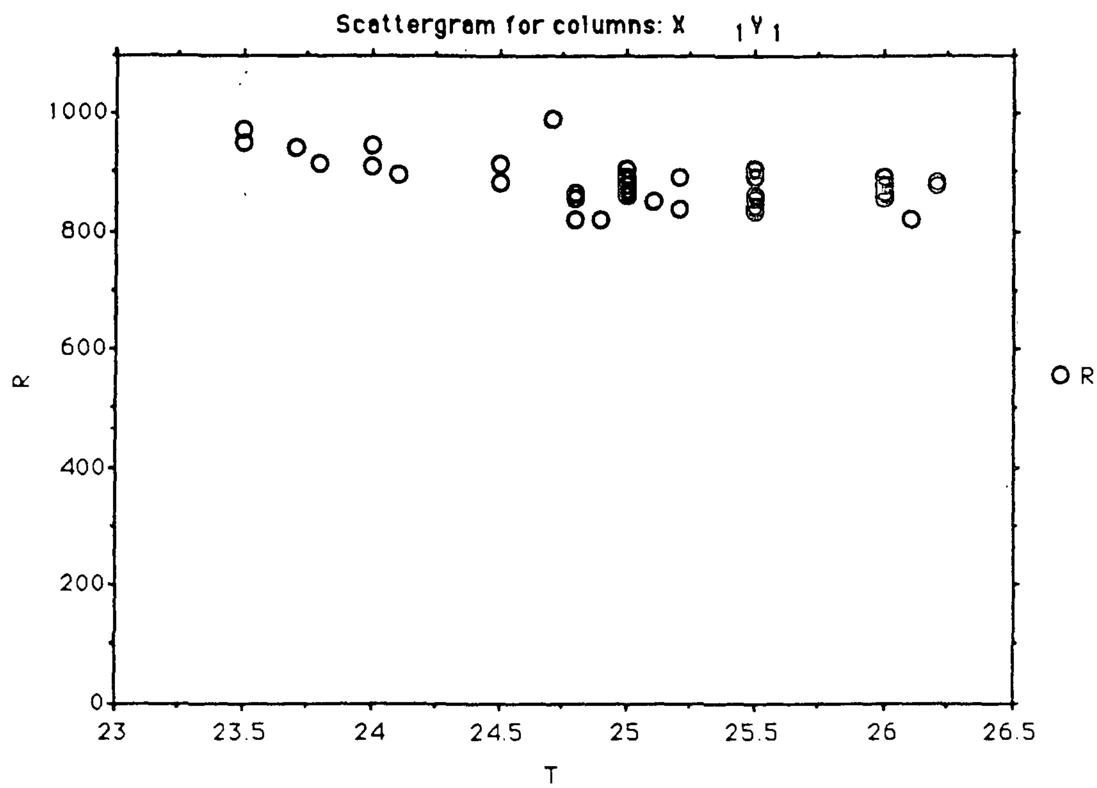
Coating Simulator Facility



RECENT PROGRESS IN EXPERIMENTAL ANALYSIS (cont'd)

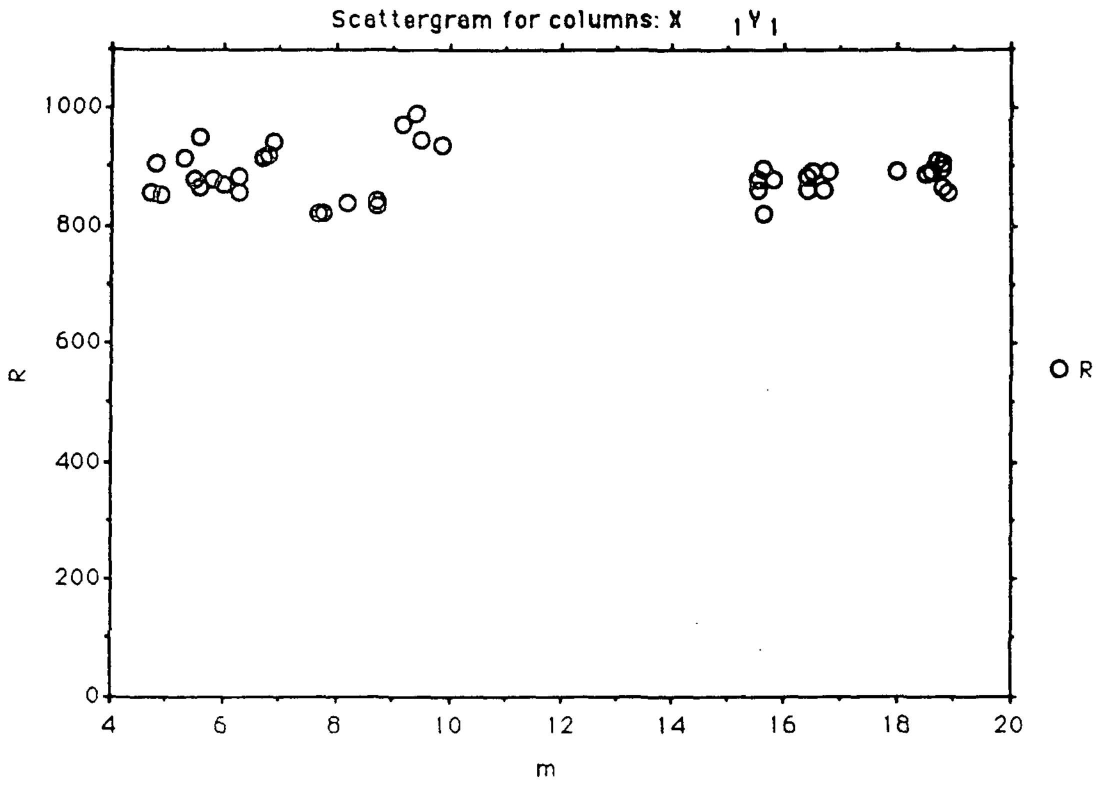
2. Measured critical roll speed for onset of unsteady flow as a function of fluid viscosity and net mass flow rate.

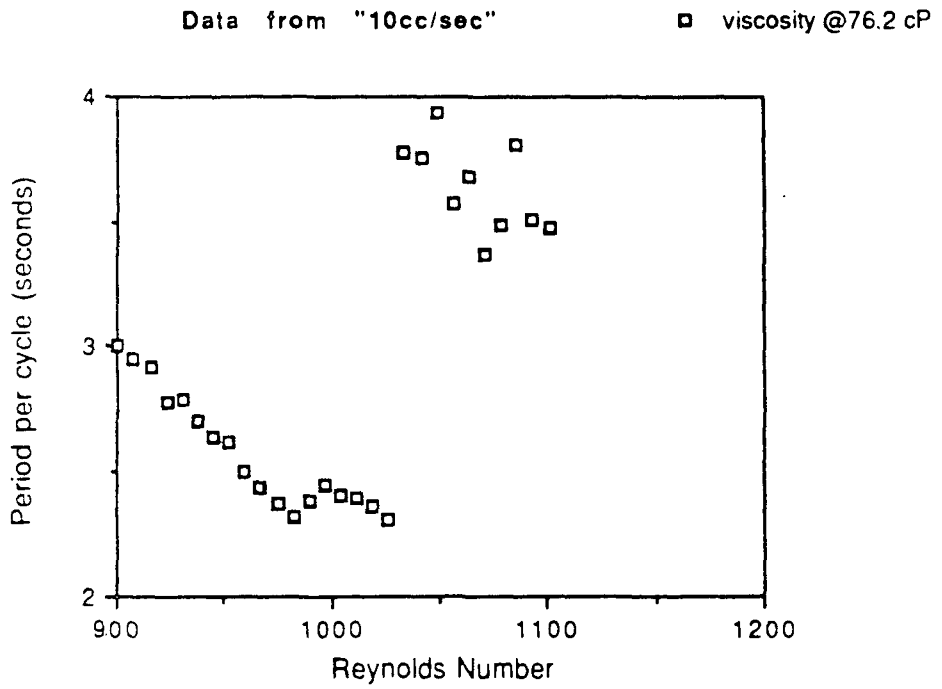
R VS. T

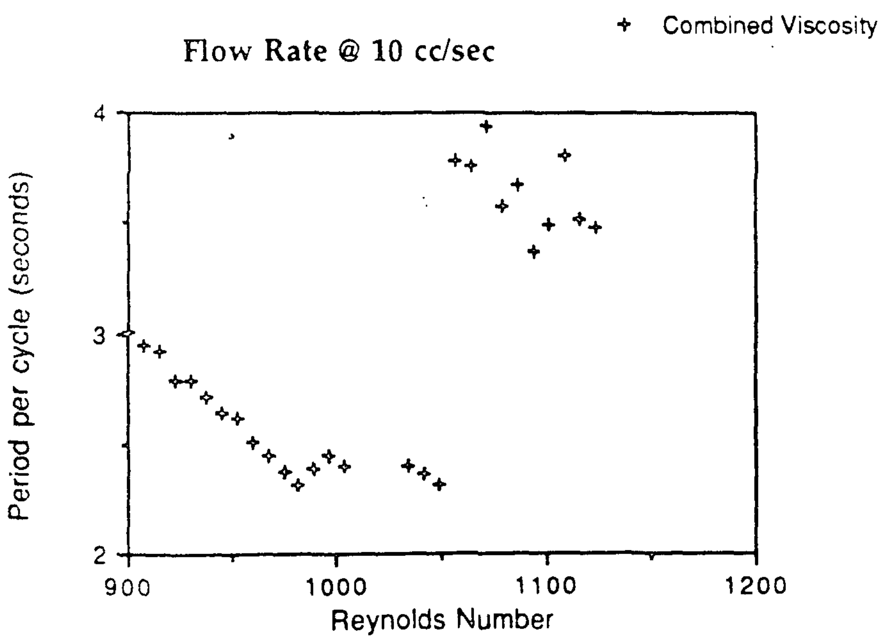


Scattergram for columns: X 1 Y 1
1000
800
600
400
200
0
R
23
23.5
24
24.5
25
25.5
26
26.5
T
R

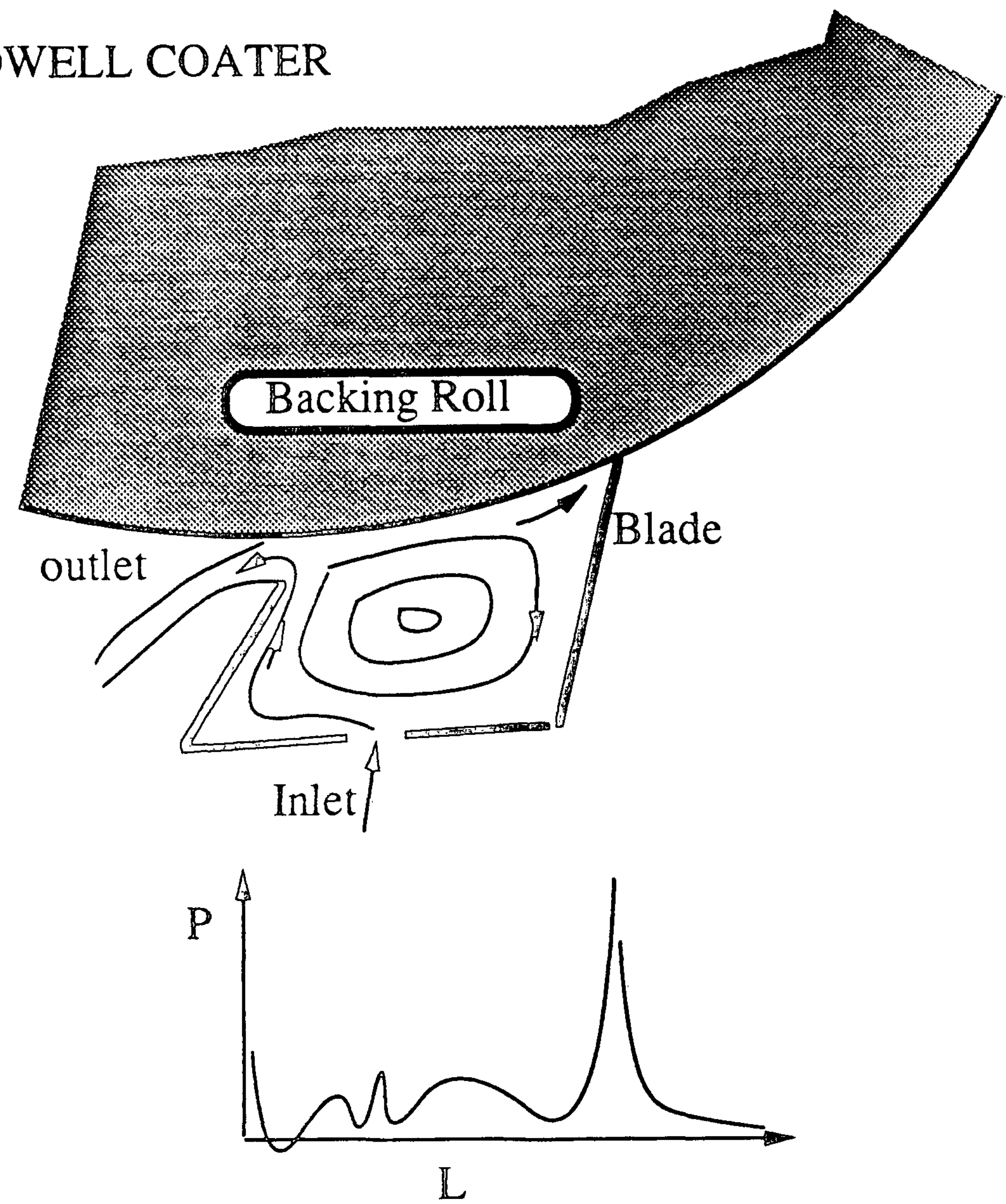
R VS. FLOW-RATE




Data from "10cc/sec"
viscosity @76.2 cP
4
3
2
Period per cycle (seconds)
900
1000
1100
1200
Reynolds Number


Flow Rate @ 10 cc/sec
Combined Viscosity
4
3
2
Period per cycle (seconds)
900
1000
1100
1200
Reynolds Number

SHORT DWELL COATER



RECENT PROGRESS
IN
COMPUTATIONAL ANALYSIS

1. Computed the 2-D flow field in a SDC to examine the pressure distribution. In contrast to other studies, this analysis includes:

   o dynamic wetting point at the overflow baffle

   Future studies will incorporate:

   o free-surface flow at the blade

COMPUTATIONAL PARAMETERS

machine speed, U =	1200 m/min
viscosity, μ =	1500 mPa.s
surface tension, σ =	.05 N/m
flow rate, m =	166 *l*/min.m
cavity depth, D =	.05 m

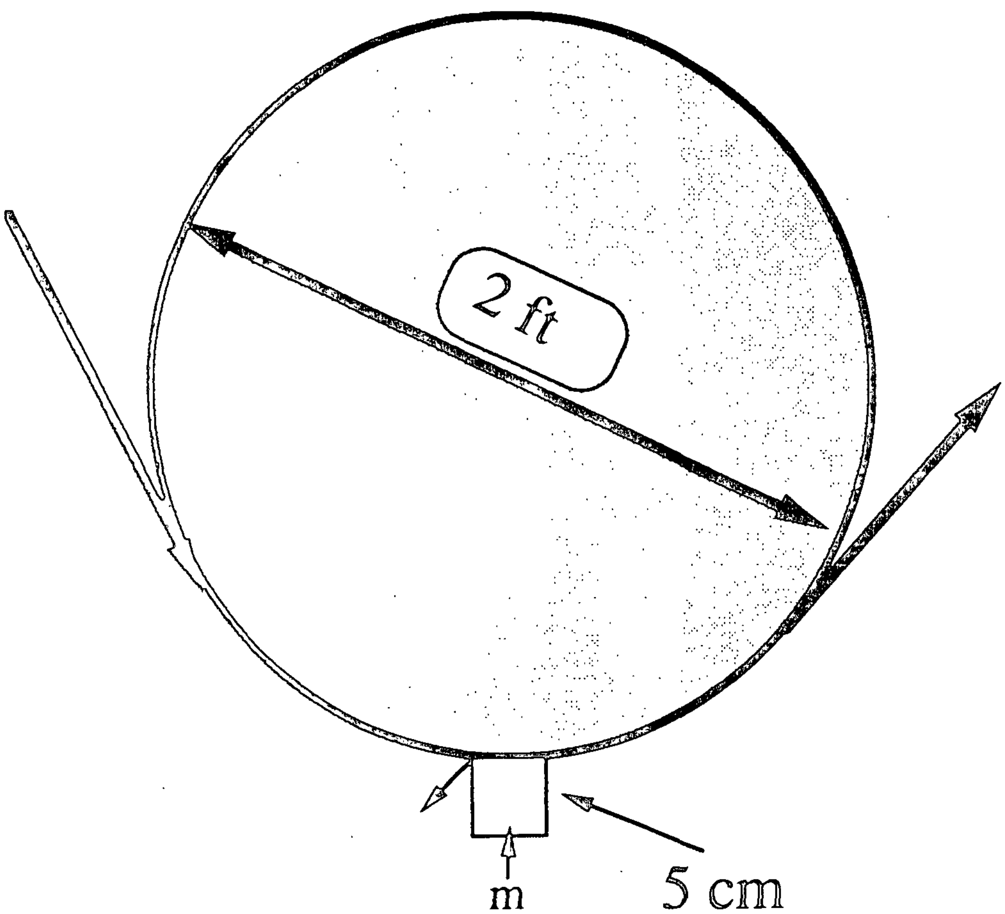
$Re = \rho UD/\mu = 666$

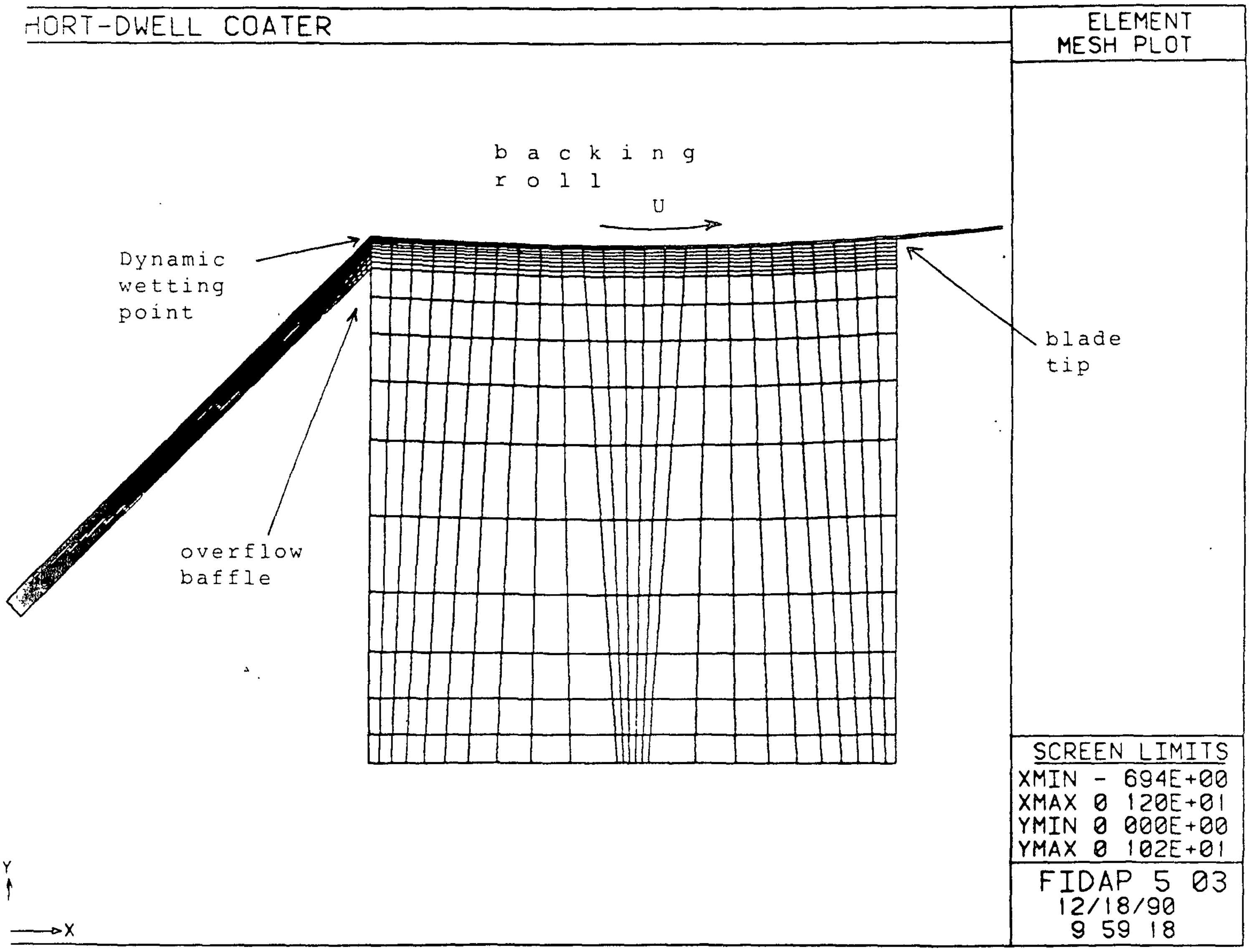
$Ca = \mu U/\sigma = 600$

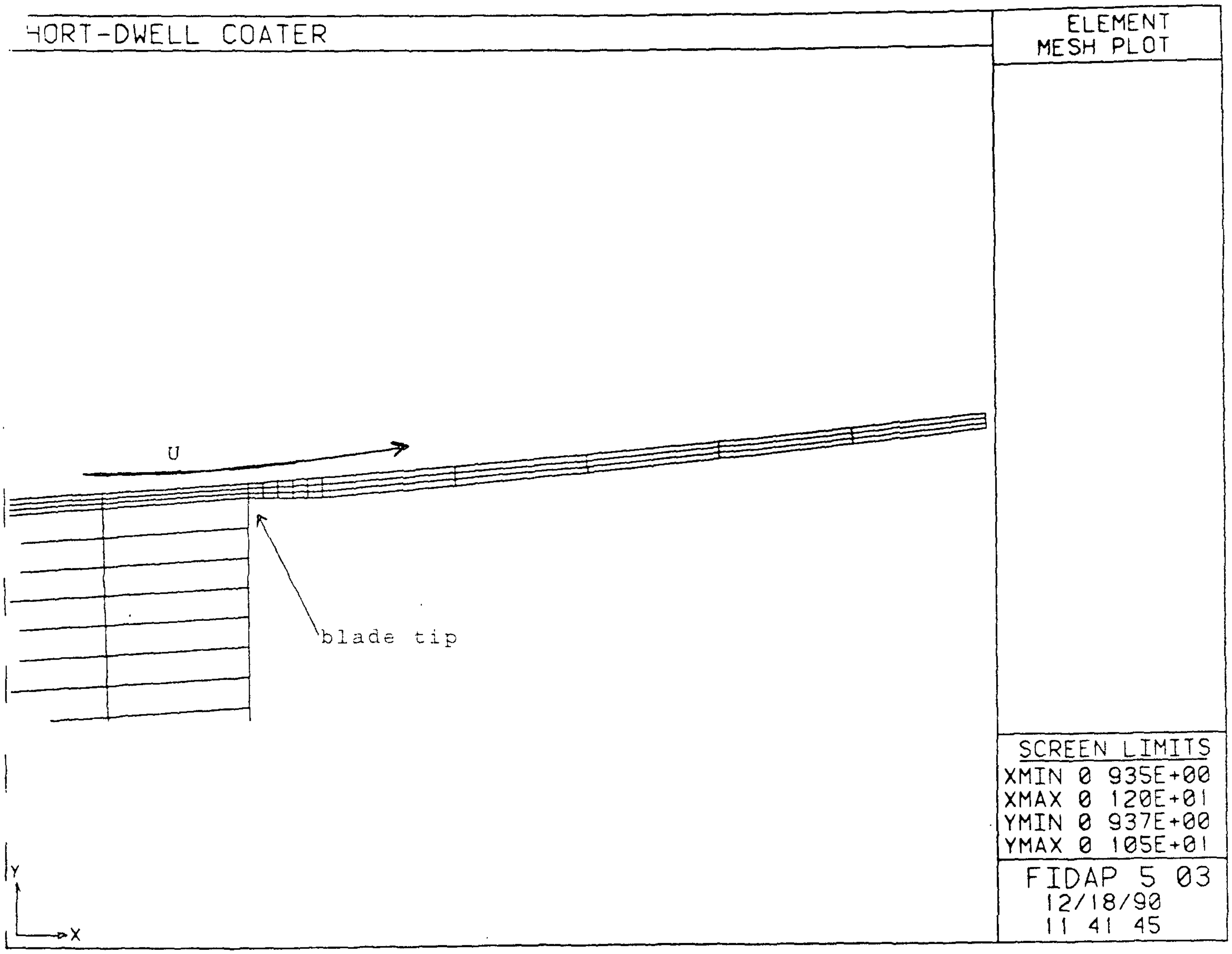
$St = \rho g D2/\mu U = .8167$

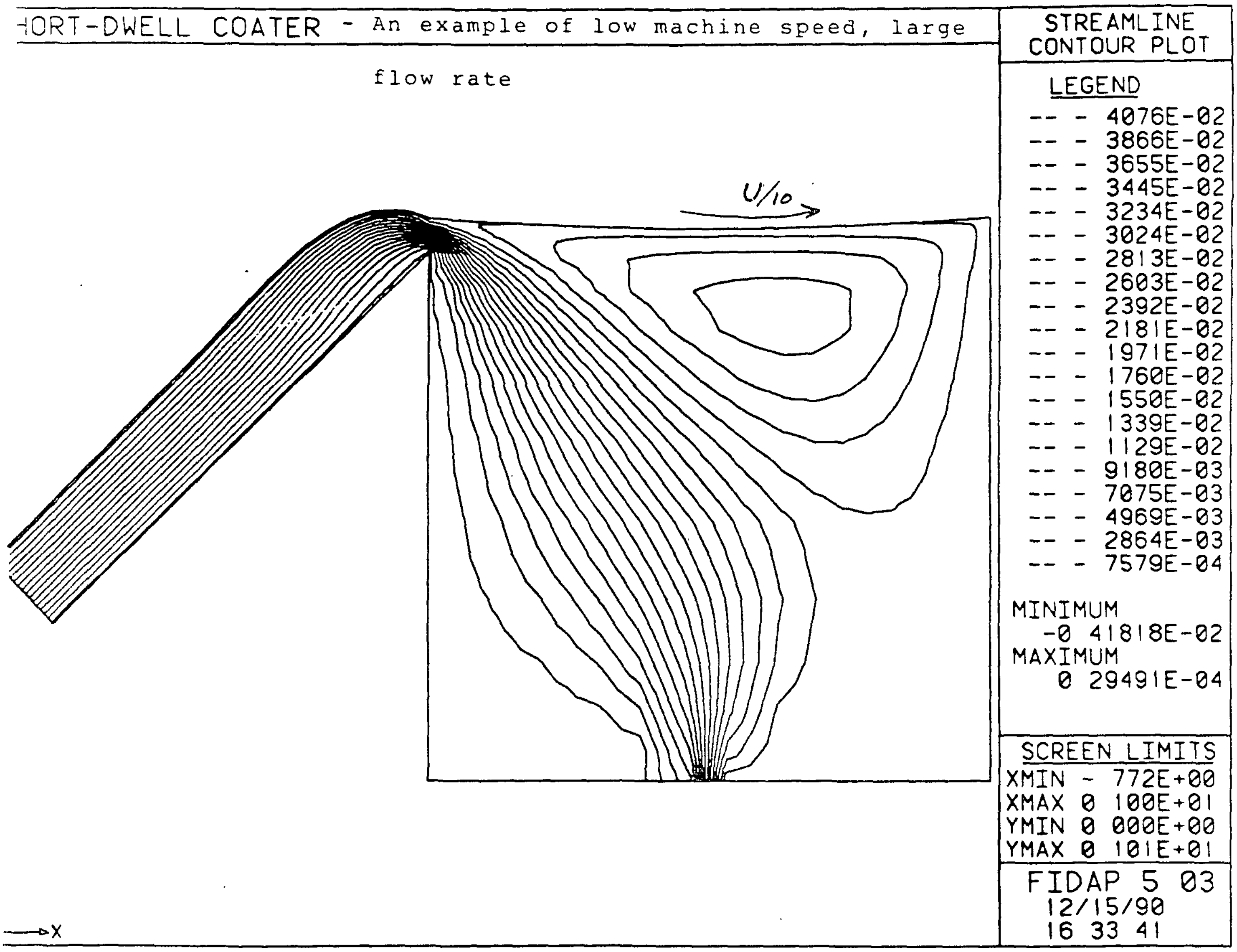
$Re' = \rho m/\mu = 1.85$

COMPUTATIONAL ANALYSIS OF A SHORT-DWELL COATER

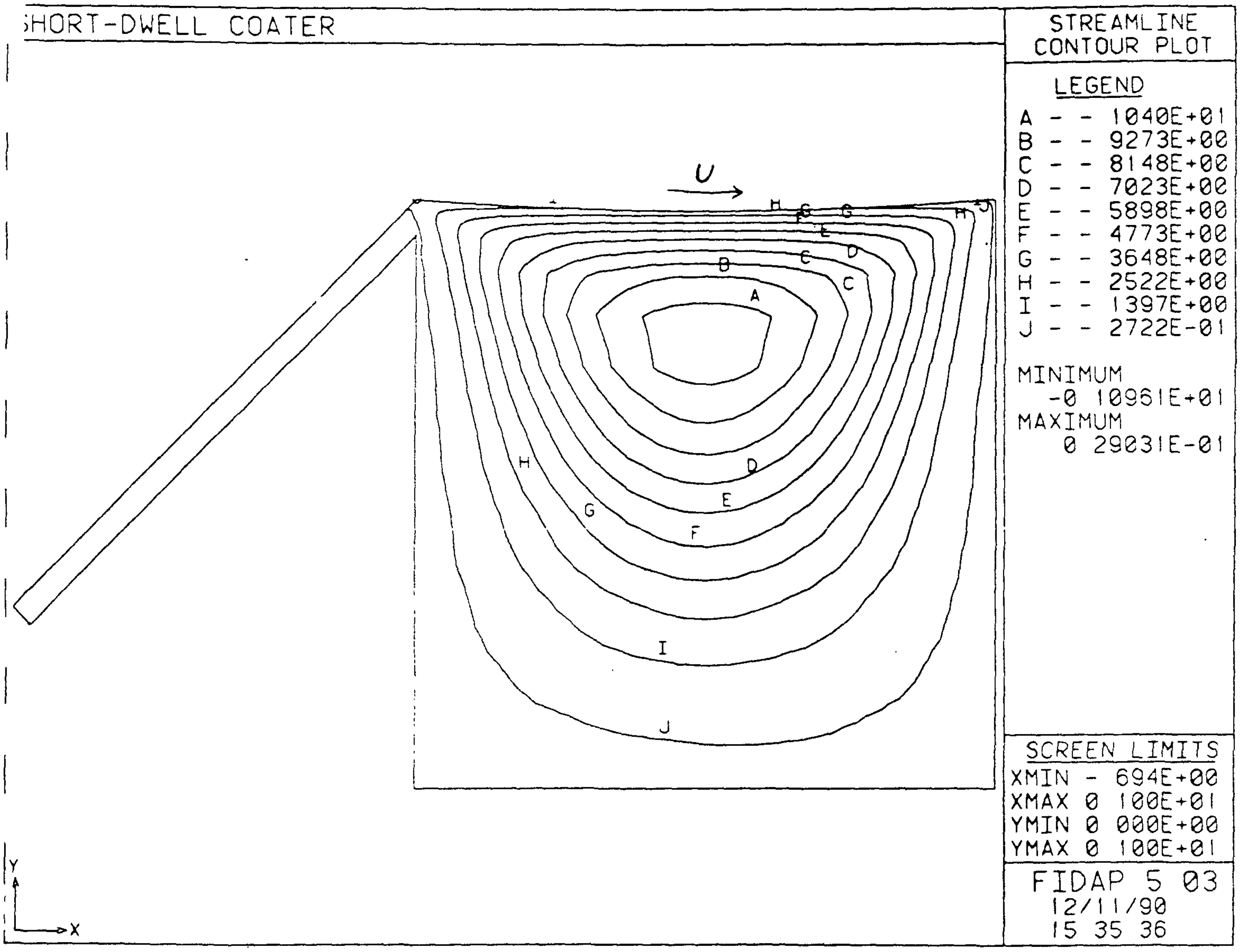



HORT-DWELL COATER
ELEMENT MESH PLOT
backing
roll
U
Dynamic
wetting
point
overflow
baffle
blade
tip
SCREEN LIMITS
XMIN - 694E+00
XMAX 0 120E+01
YMIN 0 000E+00
YMAX 0 102E+01
FIDAP 5 03
12/18/90
9 59 18
Y
X

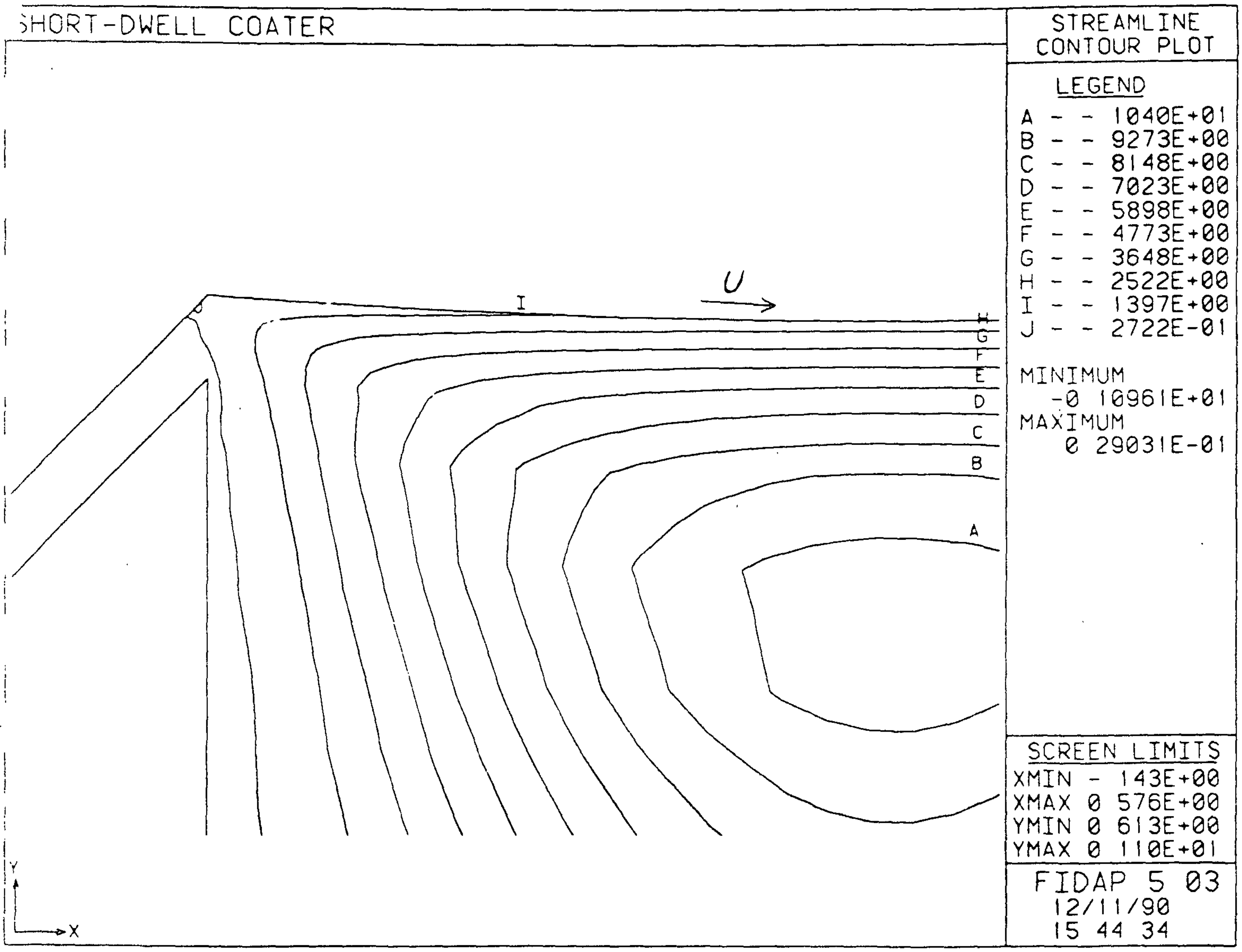

HORT-DWELL COATER
ELEMENT
MESH PLOT
U
blade tip
SCREEN LIMITS
XMIN 0 935E+00
XMAX 0 120E+01
YMIN 0 937E+00
YMAX 0 105E+01
FIDAP 5 03
12/18/90
11 41 45
Y
X



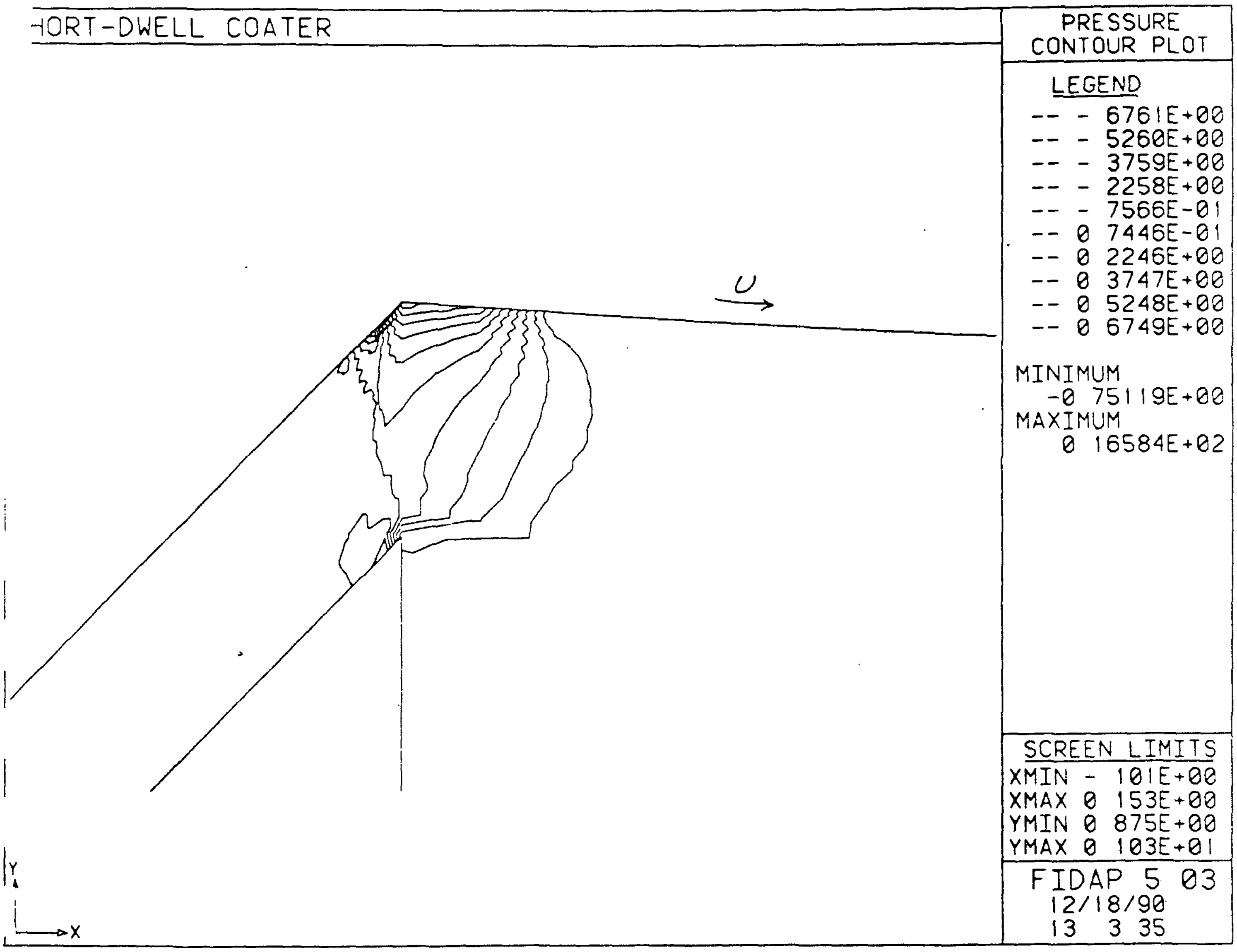
HORT-DWELL COATER - An example of low machine speed, large
flow rate
STREAMLINE
CONTOUR PLOT
LEGEND
-- - 4076E-02
-- - 3866E-02
-- - 3655E-02
-- - 3445E-02
-- - 3234E-02
-- - 3024E-02
-- - 2813E-02
-- - 2603E-02
-- - 2392E-02
-- - 2181E-02
-- - 1971E-02
-- - 1760E-02
-- - 1550E-02
-- - 1339E-02
-- - 1129E-02
-- - 9180E-03
-- - 7075E-03
-- - 4969E-03
-- - 2864E-03
-- - 7579E-04
MINIMUM
-0 41818E-02
MAXIMUM
0 29491E-04
SCREEN LIMITS
XMIN - 772E+00
XMAX 0 100E+01
YMIN 0 000E+00
YMAX 0 101E+01
FIDAP 5 03
12/15/90
16 33 41
U/10
X



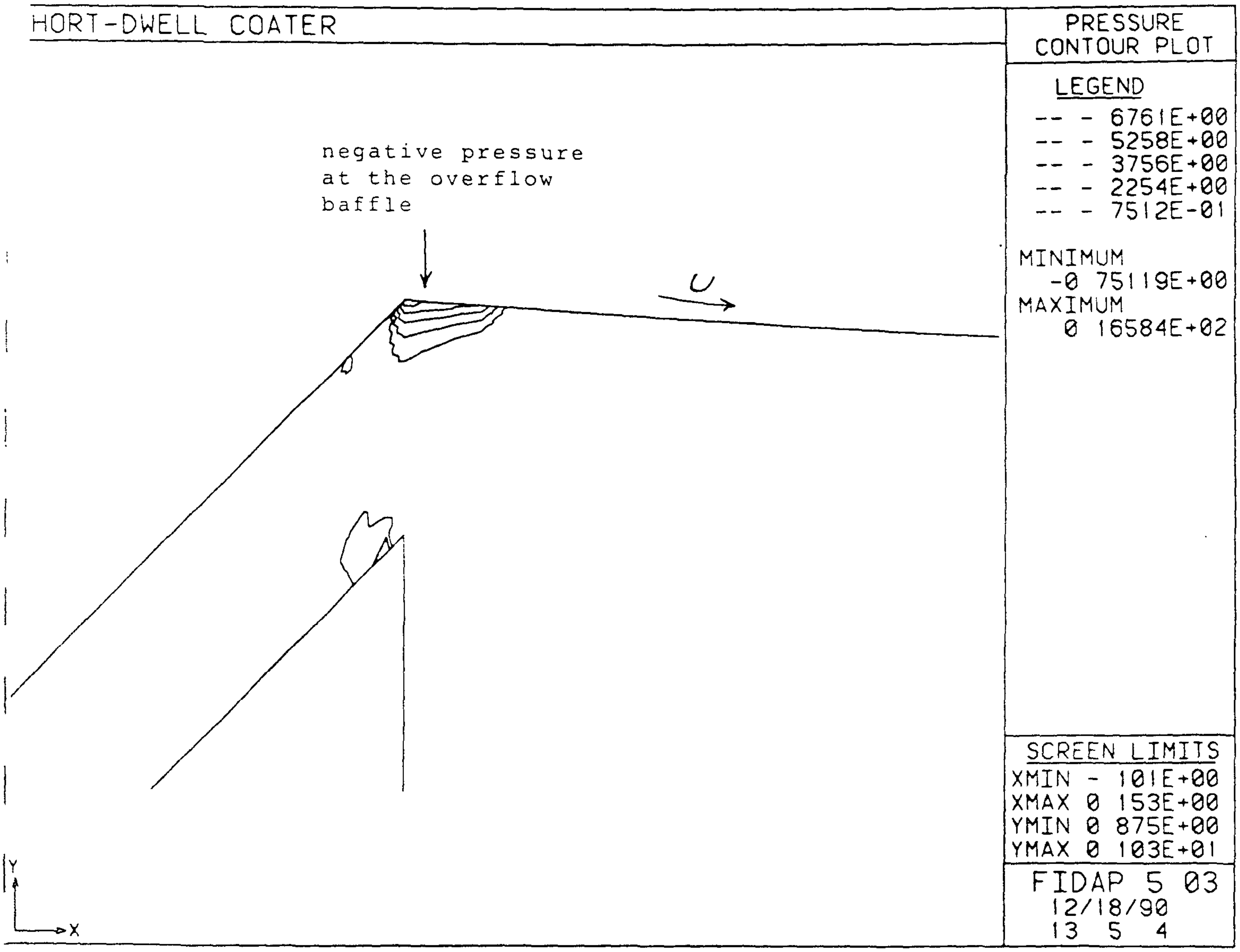
SHORT-DWELL COATER
STREAMLINE CONTOUR PLOT
LEGEND
A - - 1040E+01
B - - 9273E+00
C - - 8148E+00
D - - 7023E+00
E - - 5898E+00
F - - 4773E+00
G - - 3648E+00
H - - 2522E+00
I - - 1397E+00
J - - 2722E-01
MINIMUM
-0 10961E+01
MAXIMUM
0 29031E-01
SCREEN LIMITS
XMIN - 694E+00
XMAX 0 100E+01
YMIN 0 000E+00
YMAX 0 100E+01
FIDAP 5 03
12/11/90
15 35 36
U
A
B
C
D
E
F
G
H
I
J
Y
X



SHORT-DWELL COATER
STREAMLINE CONTOUR PLOT
LEGEND
A - - 1040E+01
B - - 9273E+00
C - - 8148E+00
D - - 7023E+00
E - - 5898E+00
F - - 4773E+00
G - - 3648E+00
H - - 2522E+00
I - - 1397E+00
J - - 2722E-01
MINIMUM
-0 10961E+01
MAXIMUM
0 29031E-01
SCREEN LIMITS
XMIN - 143E+00
XMAX 0 576E+00
YMIN 0 613E+00
YMAX 0 110E+01
FIDAP 5 03
12/11/90
15 44 34
U
Y
X



HORT-DWELL COATER
PRESSURE CONTOUR PLOT
LEGEND
-- - 6761E+00
-- - 5260E+00
-- - 3759E+00
-- - 2258E+00
-- - 7566E-01
-- 0 7446E-01
-- 0 2246E+00
-- 0 3747E+00
-- 0 5248E+00
-- 0 6749E+00
MINIMUM
-0 75119E+00
MAXIMUM
0 16584E+02
SCREEN LIMITS
XMIN - 101E+00
XMAX 0 153E+00
YMIN 0 875E+00
YMAX 0 103E+01
FIDAP 5 03
12/18/90
13 3 35
U
Y
X


HORT-DWELL COATER
PRESSURE CONTOUR PLOT
LEGEND
-- - 6761E+00
-- - 5258E+00
-- - 3756E+00
-- - 2254E+00
-- - 7512E-01
MINIMUM
-0 75119E+00
MAXIMUM
0 16584E+02
negative pressure
at the overflow
baffle
U
SCREEN LIMITS
XMIN - 101E+00
XMAX 0 153E+00
YMIN 0 875E+00
YMAX 0 103E+01
FIDAP 5 03
12/18/90
13 5 4
Y
X

GOALS
FOR
OCTOBER 1990 - APRIL 1991

1. Study the feasibility of using a hot-film anemometer for measuring the dynamics of coating colors in pilot and full-scale systems.

GOALS
FOR
OCTOBER 1990 - APRIL 1991
(Cont'd)

2. Measure the effects of span-aspect-ratio on the critical speed for instability in a SDC (Newtonian fluid).

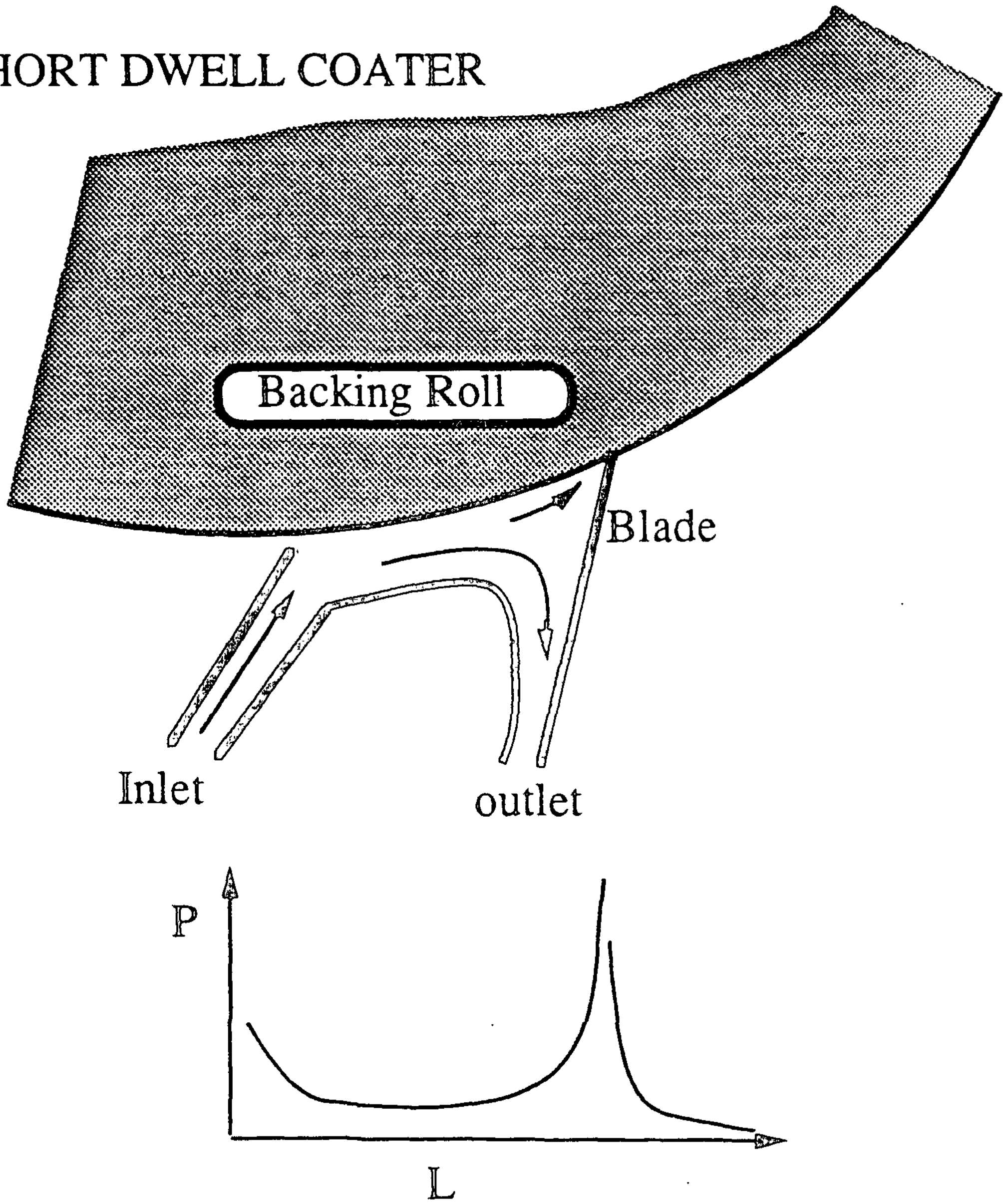
GOALS
FOR
OCTOBER 1990 - APRIL 1991
(Cont'd)

3. Compute the pressure field in a SDC to investigate flow cavitation using shear-thinning fluids with typical coating color rheological characteristics.

GOALS
FOR
OCTOBER 1990 - APRIL 1991
(Cont'd)

4. Use CFD analysis to examine novel application systems for design of a superior SDC.

MODIFIED SHORT DWELL COATER



LONG-TERM GOALS

1. Develop the next generation of high-speed blade coaters (Super SDC).
2. Develop a non-blade high-speed coater.

INVESTIGATION OF SHEET FLUTTERING EFFECTS IN THE DRYER

December 20, 1990
Institute of Paper Science and Technology
Atlanta, Georgia

INVESTIGATION OF SHEET FLUTTERING EFFECTS IN THE DRYER

A PROPOSAL

BY

CYRUS K. AIDUN
AND
GEORGE M. FADEL

INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY

AND

GEORGIA INSTITUTE OF TECHNOLOGY

RATIONALE AND OBJECTIVES

1. Analyze the aerodynamics and structural mechanics of sheet flutter

2. Correlate the onset of break or sheet damage "pain threshold" with various appropriate parameters

RATIONALE AND OBJECTIVES
(Cont'd)

3. Novel schemes to reduce sheet flutter

4. Optimize the moisture removal mechanism in the dryer section

APPROACH

1. Experiments
2. Mathematical analysis
3. Computer-aided computational analysis

COMPUTER-AIDED COMPUTATIONAL ANALYSIS

1. Thin-shell FEM analysis
   - o steady state
   - o 3-dimensional
   - o linear
   - o isotropic material behavior

2. Include non-linear and non-isotropic material behavior

COMPUTER-AIDED COMPUTATIONAL ANALYSIS (Cont'd)

3. Include time-dependent conditions

4. CFD analysis to compute lift and drag on the surface with varying angles

5. Coupling of the solid-fluid effects

COMPUTER-AIDED COMPUTATIONAL ANALYSIS (Cont'd)

6. Parametric variation and comparison of the analysis with the experimental results

EXPERIMENTS

1. Wind tunnel experiments at Georgia Tech

2. Investigate free-drawn web flutter

EXPERIMENTS
(Cont'd)

3. Investigate the drag-along action of the fabric, boundary layer profile, and air/sheet interaction

4. Measure the elastic constants of paper as a function of moisture

5. Add external air-jet devices as designed by computer-aided analysis

FUNDING SOURCES

1. IPST Member companies
2. Georgia Tech (wind-tunnel facilities)
3. TAPPI
3. DOE
4. EPRI
5. NSF