A STUDY OF THE WOUND-ON-TENSION

MEASUREMENT METHOD

By

JOHNNY LEE HARTWIG

Bachelor of Science

Oklahoma State University

Stillwater, Oklahoma

1998

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
May, 2000

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Thesis Approved:

Thesis Advisor

Dean of the Graduate College

ACKNOWLEDGMENTS

I would like to thank everyone that has helped me to reach this goal in my life, with out the support and the help of countless others none of this would have been possible. First and foremost I would like to thank Dr. J. K. Good, I certainly would not have made it this far with out his unerring guidance and help. I would like to thank Dr. Dick Lowery and Dr. C. E. Price for being the mentors, the engineers and men that I would most want to emulate. The people of The Web Handling Research Center, Ron Markum and Robert Taylor for lending their advice and expertise. My good friends Lyle Dolezal and Pat Straughan for being there to share the suffering. I would like to thank my Mom and Dad for their unending support and believing me. Also I would like to thank my brother Jim for giving me the inspiration to become an engineer and to pursue a masters degree. Lastly I would like to thank my wife Micah, thank you for your patience, support and loving me when all I had was potential.

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NOMENCLATURE

WOTM	Wound on Tension Measurement
WOT	Wound on Tension
WHRC	Web Handling Research Center
FSR	Force Sensitive Resistor
WLT	Web Line Tension
PLI	Pounds per Linear Inch
Er	Radial/Stack Modulus
Et	Tangential Modulus
K1	Offset and Scale Factor
K2	Basic Spring Constant of the Material
DAC	Data Acquisition Card
δP	Interlayer pressure at a point in the roll
s	outside roll radius/core radius (unit less)
h	Web thickness/ core radius (unit less)
COF	Coefficient of Friction
KCOF	Kinetic Coefficient of Friction

CHAPTER I

INTRODUCTION

The winding process can be broken down to a relationship of input variables to output results. The winding of a roll can be the most critical part of a web handling process. This becomes even more true if there is a nip or lay on roller at the winding roll station. In order to be able to predict the state of pressure or stress in the winding roll the user must be able to perform some kind of test or use some type of analytical prediction method. The pressure in a wound roll is one the most important factors which influences whether a web will successfully be converted to a final product or just become waste. To little pressure increases the risk of slippage related defects, the worst being telescoping, which often results in the roll being lost. High pressure can result in "blocking" defects in which the web layers may adhere to one another or it may result in inelastic deformation of the web, often described as baggy lanes. Thus the need to predict the pressure in a wound roll is of significant commercial value. Wound roll models are not sufficient by themselves to predict these pressures, as all models to date include an assumption of no interlayer slippage. Many center winders and all surface winders have a roller impinged onto the outer surface of the winding roll, which induces slippage. The main objective of this study is to develop a method which will allow the pressure versus wound roll radius profile in a wound roll to be determined quickly and accurately. This method would be used to help generate results for a large number of winding conditions to verify new wound roll models that do account for slippage. The method may also have potential for commercial application. If the researcher or manufacturer has the ability to properly measure or predict the roll pressures they can make static or dynamic changes to the winding parameters to improve roll quality or change specific requirements that are desired by a customer.

The Wound-On-Tension measurement (WOTM) is a nondestructive type of measurement, which makes it ideal for the laboratory and manufacturing environment. The concept of this type of measurement has to be partially credited to Pfeiffer [1]. Although this method is nondestructive, it is unknown whether the method interferes with the winding process and results in a different roll pressures than would have occurred without making the measurement. To satisfy the main objective, the WOTM method will be investigated. After determining whether the method interferes and if corrections can be made, the method will be used to explore several winding conditions.

CHAPTER II

LITERATURE SURVEY

The need for a precise measurement of the structure in wound rolls has been the driving force behind the development of several different types of measurement devices. These devices are used to study roll quality and to verify prediction mathematical models that help the researcher and manufacture to develop better methods for the construction of wound rolls. This structure prediction takes on several different forms such as the pressure distribution or roll hardness wound into the roll.

2-1 WOUND ROLL STRUCTURE MEASUREMENT DEVICES

The Smith Roll Tightness Tester measures the force required to penetrate a needle indentor into the face of a wound roll to a depth only as far as the degree of roll tightness [2]. The needle slips in-between the layers of the wound roll and the gauge measure the force required to over come the friction force between the web and the needle and the force required to separate the layers of the web. The users of the Smith Roll Tightness Tester would develop a graph of depth of penetration verses radial distance from the core. The disadvantages to this method are that the pressure at the edge of a wound roll is often higher than those pressures in the interior as the thickness of the slit edge is greater that the nominal web thickness. Insertion of the Smith Needle can introduce small web tears on the web edge, which makes this a destructive method.

The Rho-Meter was developed by J.D. Pfeiffer and is a roll structure measurement device that judges the hardness of the roll after being struck [2]. The Rho-Meter measures the hardness of the roll by impacting the surface with a striker; the meter is instrumented with an accelerometer. The accelerometer circuitry is used to measure the peak impulsive deceleration of the striker and it converts this into a reading, in units of Rhos, on the meter. These devices come in a hand held format and a unit mounted format that can transverse on ways over the width of the roll. There are several drawbacks to using the Rho-Meter. Hardness is not a fundamental property of the roll structure and it is very technique intensive. There are several factors that change the precision of the Rho-Meter such as roll diameter and grades of paper. The Rho-Meter yields a measure of hardness at a particular outside diameter, and as such may be impacted very little by winding conditions at lesser diameters. It is possible to wind a roll at high-tension and then step down to a low-tension, which at the exterior would appear very soft. Another roll wound at the same low-tension value through out the duration of the wind would appear to have the same hardness.

The Schmidt Hammer is very similar to the Rho-Meter in that it is an impact device [2]. The Schmidt hammer was originally used to measure the hardness of concrete and has been modified to use on web materials. It is placed against the surface of the roll until a spring-loaded hammer is compressed and is triggered. Once the hammer is triggered it comes into contact with the surface and is rebounded. The magnitude of the rebound is recorded on a scale and from this, the scale roll hardness is inferred. Because the Schmidt Hammer is so insensitive to actual changes in roll structure, it has been found that this device is not an accurate method of determining roll structure.

Force Sensitive Resistors (FSR) are another type of measurement device that predicts roll structure [4]. These devices have a varying output resistance which depends upon the level of force applied; this change in resistance can be related to the pressure distribution within the roll and they provide a direct measure of pressure. FSRs are different from the aforementioned methods in that they are wound into the structure of the roll and are unique in that they can be manufactured in various forms and shapes. They have been used in arrays to sense pressure variations across the width of the wound rolls [10]. There are difficulties in using these devices as their output also varies with time and temperature, even at constant pressure. Their use is not suited to the production environment since the resistors are wound into the rolls.

The Cameron Gap test is a TAPPI measurement method to estimate the level of circumferential strain in the outer layer of a wound roll. This is another type of roll structure prediction in that it infers strain, a fundamental state, in the wound roll. To perform the Cameron Gap test, a wound roll is cut across the Cross-Machine Direction and the separation of the two sides of the cut is measured. The separation of the outer layer is used to calculate strain based on the width of the separation and the diameter of the wound roll [3]. This method of measurements has drawbacks in that it is destructive and it is very labor and time intensive. The Cameron Gap Test results can be skewed because of the expansion of the layer underneath the layer that is cut. Once the outer layer is cut, the pressure gradient is reduced which allows for expansion of the second layer causing the gap to appear to have a larger expansion creating an error in strain estimation.

Another type of roll structure measurement device is the Pull-Tab. The Pull-Tab is similar to the FSR in that they are wound into the structure of the roll and they measure interlayer pressure. The Pull-Tab itself can be made of steel or plastic and can be inserted in envelopes of brass, which provides more consistent results since dissimilar materials have lower coefficients of friction (See Figure 3-2). In addition, they can be inserted into the winding roll at varying radial locations [3,4,5]. The radial pressure can be related to the force required to dislodge the pull-tab through Admonton's Law. The Pull-Tab and envelope reaches completely across the width of the web material, which provides a constant area of contact during any movement of the pull-tab during the pull to determine the force. The pull-tabs can be calibrated with the use of a tensile testing machine, a stack of web material, and a force transducer. The ease of manufacture, calibrating, and testing makes the pull-tab a cost effective and easy method to determine roll structures. The disadvantages of pull-tabs are that they are intrusive and are time and labor intensive. In addition, the pressure inferred must be interpreted as an integrated average pressure level across the roll width at that radial location.

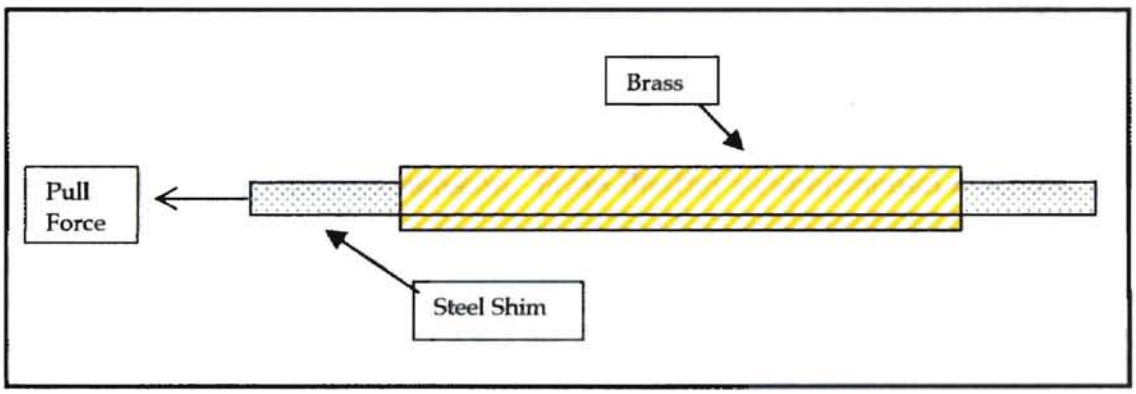


Figure 2-1: Diagram of Steel/Brass Pull-Tab

2-2 WOUND ROLL STRUCTURE MATHEMATICAL PREDICTION

The need to predict roll structure has inspired several different researchers to produce mathematical models to predict how roll structure can be affected by various winders and winder operating parameters. The measurement devices discussed in Chapter 2 Section 1 attempt to provide discrete measures of roll structure at discrete radial locations, wound roll models have been developed in an effort to learn how to predict how the roll structure is affected by winding parameters and web material properties. These mathematical models can also be used to deduce winding strategies for new types of web materials and winding machines.

J.D. Pfeiffer [7] developed an experimental winding machine in 1975 that would allow for the measurement of wound-on-tension with the intention of producing a mathematical model to predict pressure distribution in the wound roll. Wound-on-tension (WOT) is the amount of tension that enters the winding roll. In the center winding mode with an impinging nip roller, WOT consists of the amount of web line tension plus the tension induced from slippage caused by the nip roller or nip-induced-tension. From Pfeiffer's experimental machine, the WHRC has developed its current configuration of the WOT device. Pfeiffer also developed a mathematical model for the prediction of pressure throughout the wound roll. One draw back to Pfeiffer's wound-in-tension device was that the nip load was affected by the web tension, an error which increased as the wound roll grew in diameter. Pfeiffer also coined the following expression which is useful for relating the pressure (P) and the strain (ε) in a stack of web material:

Equation 1:

$$P = K_1[\exp(K_2\varepsilon) - 1] \qquad (1)$$

$$E_r = \frac{dP}{d\varepsilon} = K_1 K_2 \exp(K_2\varepsilon)$$

$$E_r = K_2(K_1 + P)$$

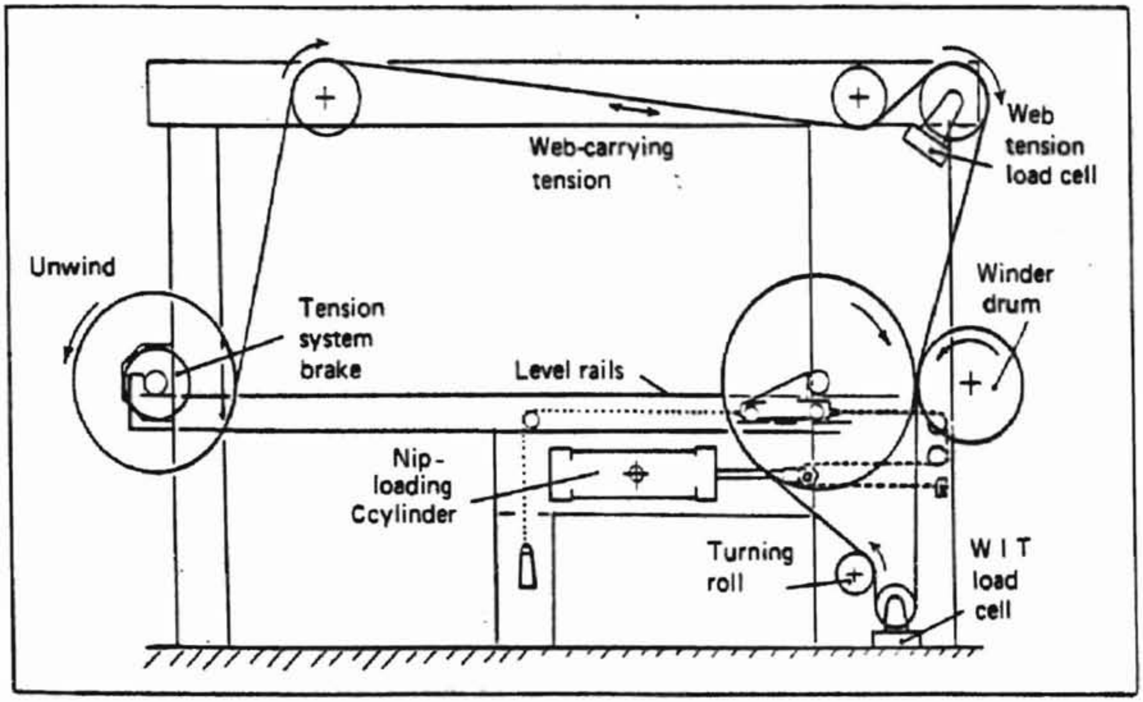


Figure 2-2: J.D. Pfeiffer Winding Machine

Another researcher that developed a mathematical model to predict wound roll pressure/stress was Hakiel [9]. Some assumptions that Hakiel made were that the winding roll was a perfect cylinder and the web has uniform thickness, flatness, and behaves in a plane stress manner. Further assumptions are that the roll is a collection of concentric hoops and the roll is considered an orthotropic-elastic cylinder and material properties are constant during one lap of a wind . This model does account for a radial modulus (Er), which is a function of pressure.

The model that Hakiel derived from classical theory of elasticity is as follows:

(2) $$r^2 \frac{d^2(\partial P)}{dr^2} + 3r\frac{d(\partial P)}{dr} - \left(\left(\frac{Er}{Et}\right) - 1\right)\partial P = 0$$

To solve this second order differential equation two radial pressure boundary conditions are required. At the outside of the winding roll, the incremental inter-layer pressure caused by the winding of the last layer of the stack is equal to the classical hoop stress equation [9]:

(3) $$\partial P\big|_{r=s} = \frac{WLT\big|_{r=s}}{s} h$$

At the inside radius of the wound roll, the deformation of the outside of the core and the inside of the wound roll must be compatible. Using the strain and constitutive relationships, this boundary condition can be written in terms of a derivative of the radial pressure.

(4) $$\left.\frac{d(\partial P)}{dr}\right|_{r=1} = (Et/Er - 1 + \upsilon)\partial P$$

This differential equation is solved many times to model the effects of the roll's growth during the winding. Each time the equation is solved, the differential pressures are summed to determine the total pressure and the radial modulus of the wound roll is updated at each radial location as a function of total pressure at that location.

Several methods discussed in the literary survey were employed during this investigation into the wound-on-tension measurement method. The use of pull-tabs and Hakiel's model will be demonstrated later in this study.

CHAPTER III

EXPERIMENTAL PROCEDURE AND SETUP

3-1: EXPERIMENTAL MACHINE SETUP

In order to perform experiments for this investigation the testing platform needed to be modified into its present condition (Figure 3-1). The testing platform consists of four major areas: the unwinding station, lateral web guide, nip load application/winding station and the wound-on-tension measurement load cell. For this investigation, the machine was configured in the center-winding mode. In the center-winding mode, a motor drives the center of the winding roll (9, Figure 3-1) and the nip roller is free spinning. All experiments were carried out with the same configuration of the machine except for the changing of the nip roll diameter.

Winding Machine Running Parameters			
	Speed (ft/min)	300	
	Web Tension (lbs)	6	
	Nip Diameter (in)	4,10	

Table 3-1: Winding Machine Parameters

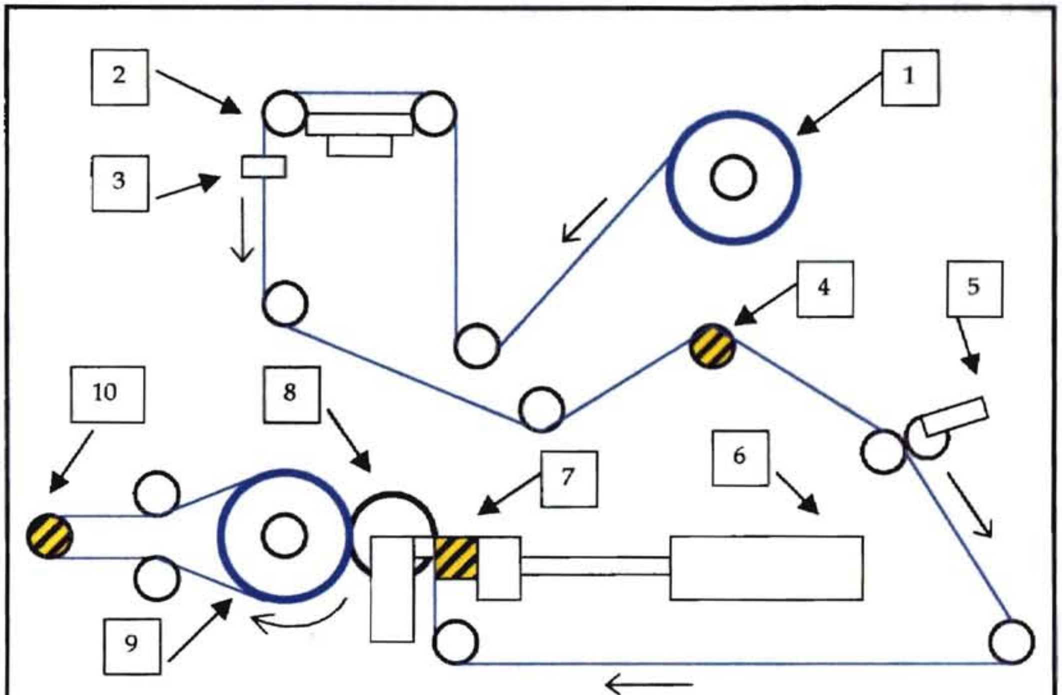
The first stage on the experimental setup is the unwinding station (1, Figure 3-1). The unwinding roll is mounted upon a Magnetic Hysteresis Brake (MAGTROL, Model: 805-2) which is in a force-feed back loop using a web line tension load cell (DIGITRAC Tension Sensor, Model: CL250) (4, Figure 3-1) to measure web line tension. The load cell and magnetic brake are controlled by the MAGPOWR DIGITRAC- Digital Tension Readout and Control system. This controller, load cell, and brake system allow for the precise control the Web Line Tension (WLT).

The next stage on the winding machine is the web line guide, which adjusts the lateral movement of the web going to the winding station. The lateral movement is performed by a FIFE Model: OPG-LRA Web Guide and an infrared gate sensor and is controlled by a FIFE A-9 Signal Processor (2,3, Figure 3-1). After leaving the web guide, the web passes over the WLT load cell and then passes under the web line speedometer.

The speed of the web line is controlled through feed back from a roller servotachometer that is spun by the passing of the web. (5, Figure 3-1). The servotachometer provides a reference signal to the Reliance Electric Motor Controller Model: GV-3000, which controls the Reliance Electric 5HP, 1718-RPM Vector A-C Drive, which has similar performance characteristics to a DC drives but does so without brushes. The A-C drive is connected to a Turner Uni-Drive 5-speed GearBox that allows webs to be wound at speeds below and above the range of speed that would have been possible in a direct drive scenario.

The nip roller carriage allows the researcher the ability to change out the nip roll and change the angle of web wrap around the nip roller. The nip roll carriage is driven by a Bellofram Pneumatic 2.5-inch cylinder (6, Figure 3-1), which imparts the nip load for testing. The nip load which is applied is measured by two Omega S-beam load cells (Model CCCB-200) (7, Figure 3-1) which are in a force feed back loop with an e-p transducer (AllenAire Type 2GD4A). The nip load is displayed on the machine through a MAGPOWR Digital Tension read out. The e-p transducer is controlled by a LABVIEW program, which in turn gives the researcher to ability to finely tune the amount of nip load applied through a testing run. The next station is the winding station that is coupled to the Reliance A-C Drive and controlled through the Reliance motor controller. The next station is the Wound-On-Tension load cell.

The Wound-On-Tension roller is mounted to a BLH load cell, Model LTT-100/DXT-15 (10, Figure 3-1). The WOT tension is displayed and the load cell is excited by a BLH Transmitter/Indicator-DTR on the machine. To combat the effect of the changing wound roll diameter on the WOT measurement, two idler rollers are placed on either side of the WOTM. The two idler rollers maintain a constant angle of wrap of 180 degrees. The experimental machine is connected to a personal computer through a National Instruments Data Acquisition Card Model: DAC ATMIO-16E-2. Through the DAC, a LABVIEW program interfaces and controls the nip load and records and displays WOT, WLT, nip load, speed, and time.



1. Unwinding Roll Station with Magnetic Hysteresis Brake
2. Fife Lateral Web Guide
3. Fife Inferred Gate
4. Web Line Tension Load Cell
5. Web Line Speedometer
6. Pneumatic Nip Load Cylinder
7. Nip Force Load Cell
8. Nip Roller
9. Winding Roll Station
10. **Wound On Tension Load Cell**

Figure 3-1: Winding Machine Layout Diagram

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3-2: MATERIAL TESTING

Knowledge of essential material properties is very important to the scope of this investigation. To obtain a consistent sample of newsprint rolls, a set of tests of the material friction and one test run on the winding machine under the same winding parameters were performed. To test the coefficient of friction, web to web, an experimental setup was used that conforms to the ASTM D1894 specification for friction measurement. For each sample, a total of nine runs were performed and an average was obtained from three samples.

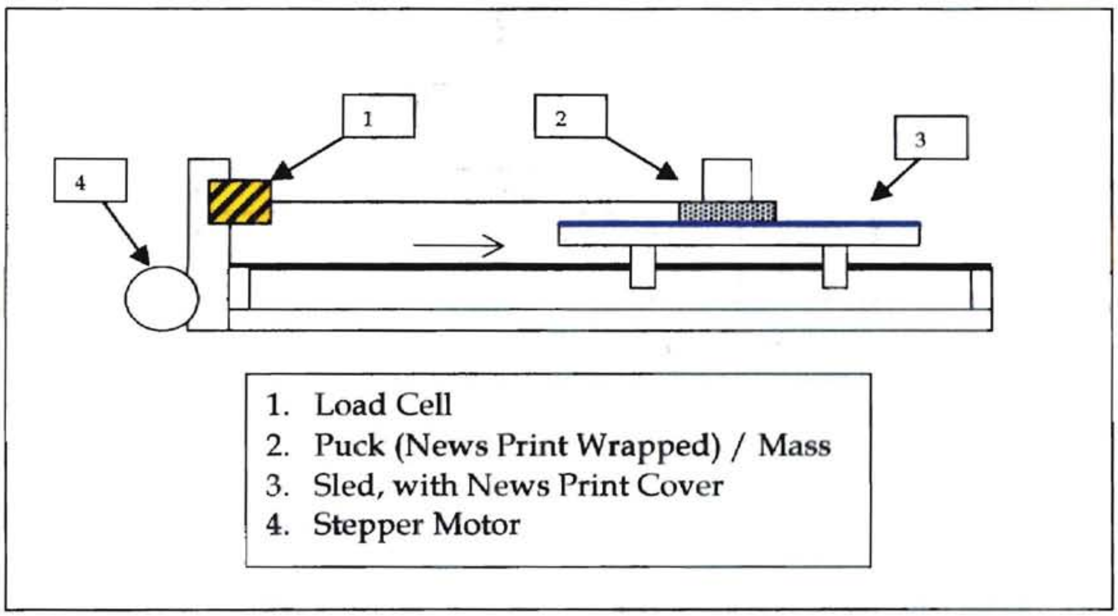

Figure 3-2: Side View/Friction Testing Machine Schematic

The radial or stack modulus (Er) is needed for use with the mathematical winding models to estimate the pressure distribution. To determine the radial modulus of the material, a sample of a stack of the material with the dimensions

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6″ x 6″ x 1″was cut. To test Er an experimental stand was used that employs a Bellofram S30 four-inch diameter pneumatic cylinder to compress the sample set of web between two parallel plates that are four inches in diameter. The test stand is instrumented with an LVDT to precisely measure the amount of compression in the stack as the pneumatic cylinder extends. The experimental stand is controlled through a LABVIEW program, which also records the pressure versus strain data.

		Run1		Ave.
μk	0.26	0.25	0.27	0.26
μs	0.31	0.378	0.38	0.36
		Run2		
μk	0.26	0.25	0.25	0.25
μs	0.34	0.37	0.38	0.36
		Run2		
μk	0.26	0.26	0.27	0.26
μs	0.35	0.41	0.44	0.40

Table3-2: News Print Friction Data

The pressure versus strain characteristics exhibited by this type of web material is nonlinear in nature. As previously stated in chapter two, Pfeiffer's expression, equation (1), is useful for relating pressure and strain in a stack. The determination of the K2 factor exhibits the nonlinear behavior of the web material, which is exhibited in equations [8]. The results are given in Table 3-3.

	Run1	Run2	Run3	Ave.
K1	0.1898	0.1981	0.1870	0.1916
K2	32.7450	32.6464	32.8237	32.7384
(K1K2)	6.2100	6.4700	6.1400	6.2733

Table 3-3: Experimental Er Test Results

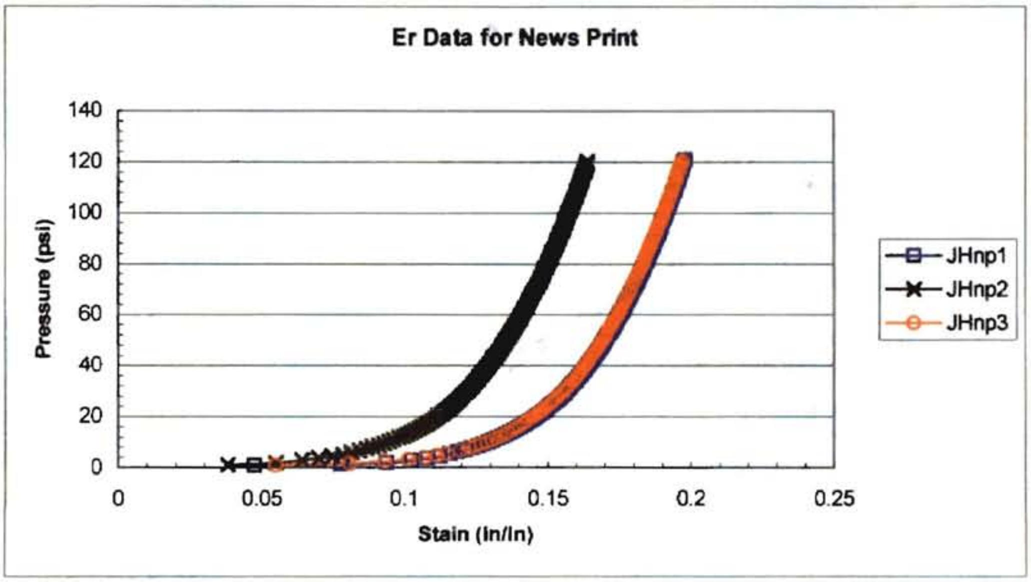

Figure 3-3: Experimental Stress Strain Data for NewsPrint

The in-plane modulus or Et is another material property needed for the calculation of the pressure prediction models. In order to test the in-plane modulus, a fifty-foot piece of new print web was secured to the floor with a piece of tape. On the opposite end, a small metal bracket was attached with similar tape, through this metal bracket a force transducer was attached. An index mark was placed on the web material and on another piece of paper attached to the floor just in front of the metal bracket. A force was applied through the metal

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bracket and then a mark was made on the index paper attached to the floor, to be able to calculate the change in length compared to original length or strain. The web material was run through a range of forces to be able to infer stress. The following graph in Figure 3-4 is of a typical Et testing run. The values in Table 3-4 are the three values and average of each Inplane modulus test.

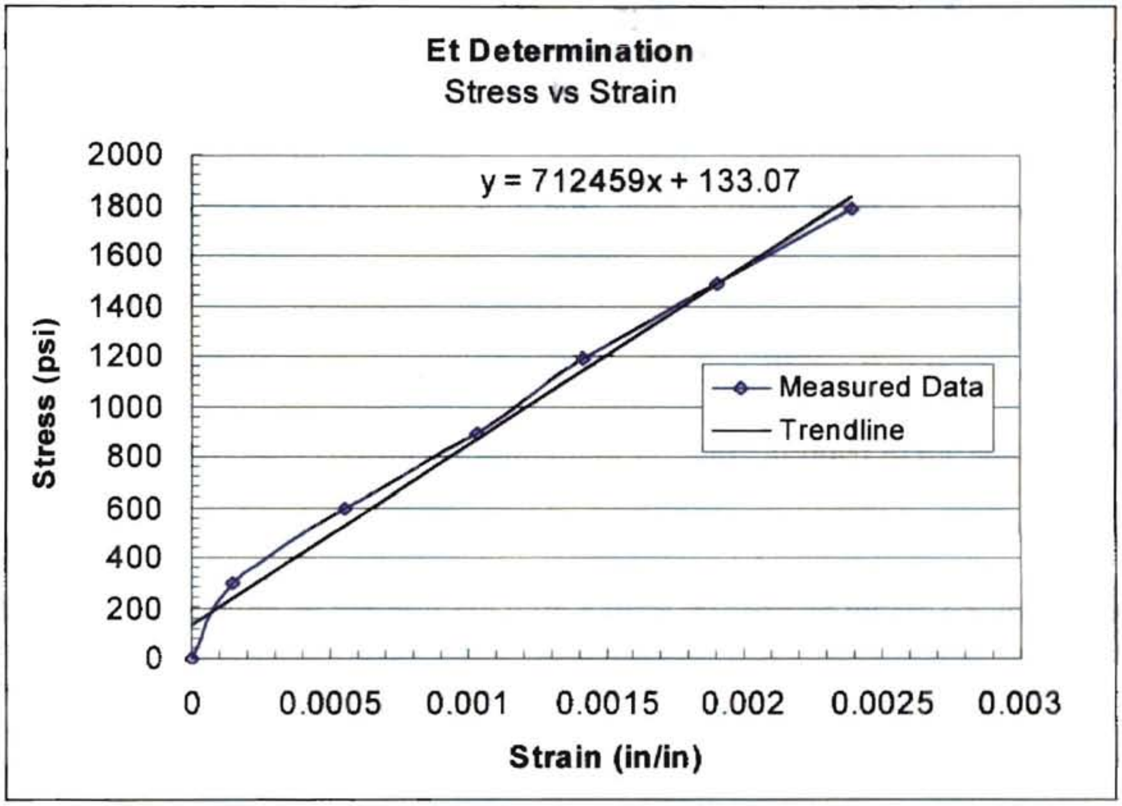

Figure 3-4: Inplane Modulus Calculation Graph

In order to compare the pressure distribution with the WOTM, a means was needed to physically measure the pressure without changing the actual state of pressure in the roll. The easiest and most cost effective way for the WHRC to be able to perform this measurement was though the use of pull-tabs made of steel with a brass envelope, see Figure 2-1. The stainless steel tab is a Precision

Brand Feeler Gauge that is ½" x 10" and 0.001 inches thick. The tab is polished and tempered C1095 High Carbon Spring Steel. The brass envelope used was made from Precision Brand cold rolled half-hard CDA200 with a tensile strength of 51,000 - 67,000 psi.

Test 1	Test 2	Test 3	Ave. (psi)
816,000	712,000	723,000	750333

Table 3-4: Inplane Modulus (Et) Test Values

To be able to properly use pull-tabs, each of them must be calibrated. In order to calibrate the pull-tabs a 6"x 6" x 6" stack of web material was used in the Instron 8502 tensile testing machine. The Instron allows that the researcher to be able to precisely control the amount of pressure applied to the stack of web material. The pull-tabs are inserted in the web stack, a load is applied, and then the researcher pulls on the pull-tab with a force transducer where several pulls are performed at the same pressure. The pull-tab is tested in the aforementioned method through several increasing pressures and from these test a calibration curve can be developed from the graphing of force versus pressure. The researcher can now use the pull-tab during testing and relate the pull forces needed to start movement into a roll pressure at that radial location.

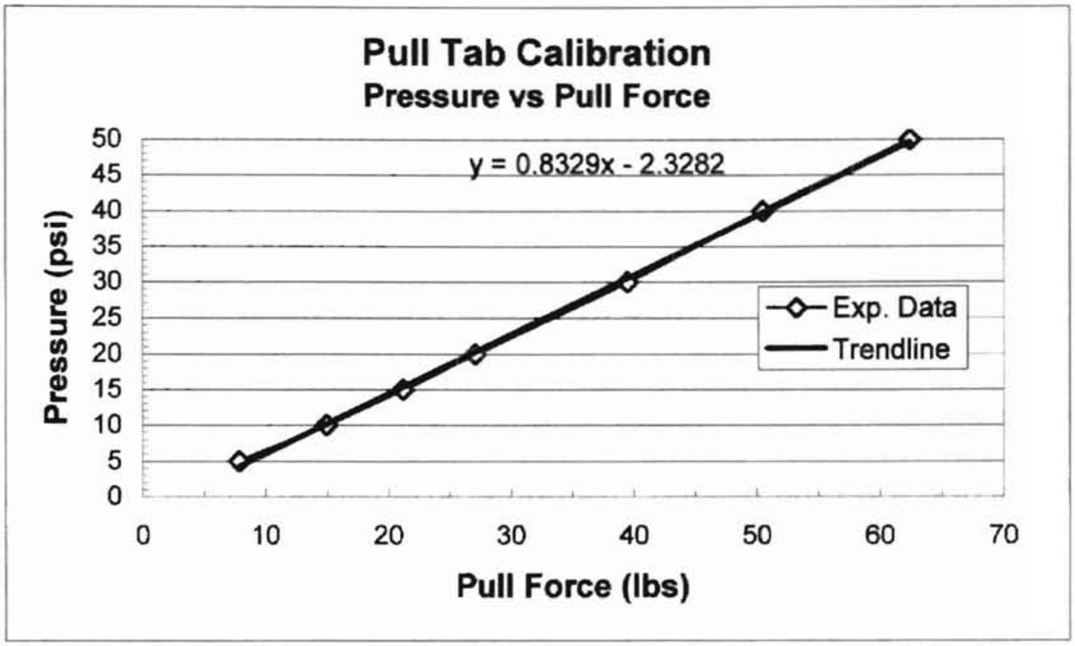

Figure 3-5: Pull-Tab Calibration Graph

CHAPTER IV

EXPERIMENTAL RESULTS AND DISCUSSION

In order to investigate the wound-on-tension measurement method, a two stage testing process needed to be performed. The first process was to test the newsprint material with the wound-on-tension measurement device in the winding path. These tests spanned a range of nip loads while the web line tension was maintained through out for each of the tests. The tests were performed with a 4-inch and 10-inch diameter nip roller at 2.5,5,10,20 and 30 PLI nip loads. In the second stage, the exact same tests as before were performed with the exception that the wound-on-tension measurement was not in the winding path and pull-tabs were inserted through out the pile height of the winding roll. Each winding condition and pull-tab test were performed three times apiece.

The need to understand the behavior that WOT takes on, as Nip Load changes or as Web Line Tension (WLT) changes can be seen in the following graphs. In the graph in Figure 4-1, WLT was held constant and nip load was varied over time. As nip load was decreased, a regular decrease in WOT can be observed [11]. The graph in Figure 4-2 is of WOT and WLT was varied over

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time. From this graph, as the WLT was decreased by three pounds the WOT also decreased by at least three pounds.

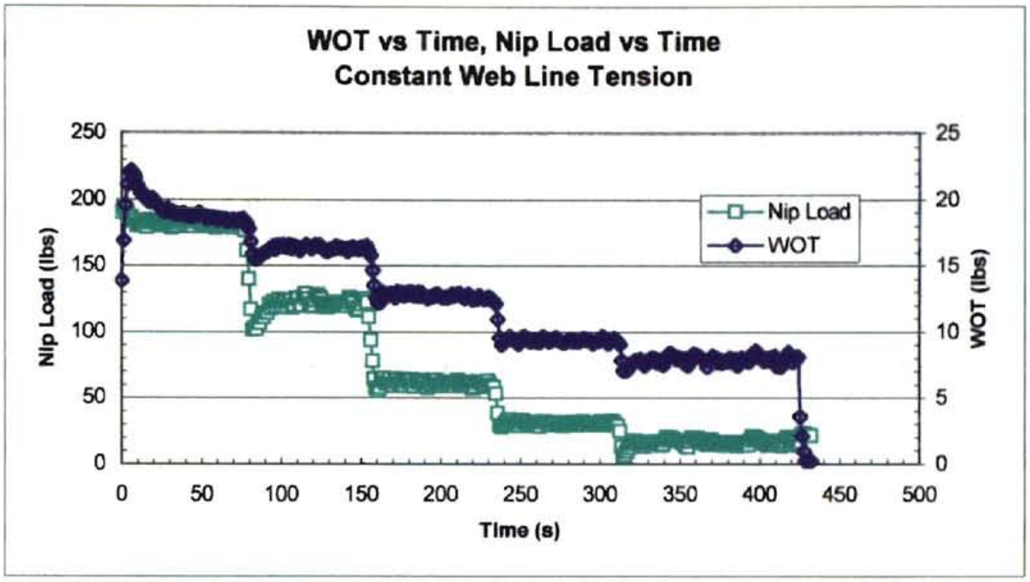

Figure 4-1: Varying Nip Load Effects on WOT

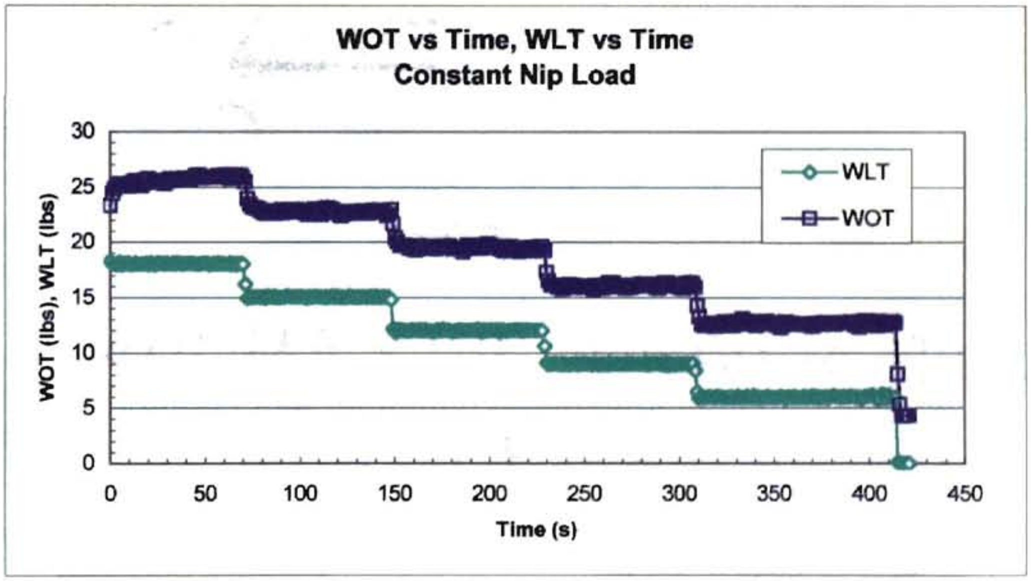

Figure 4-2: Varying WLT on WOT

The above two graphs demonstrate how WOT can be affected by WLT and nip load.

4-1: WOUND-ON-TENSION MEASUREMENT

To perform the initial test, the WOTM device was in the winding path and recorded the amount of tension on the web as it is wound onto the winding roll. This measurement was done by pulling the first layer of the material away from the winding roll and then passing the web over the WOTM device and then the web returns to the winding roll. The picture of the WOTM device and setup can be seen in Figure 4-3. As the winding roll continues to increase in diameter, the amount of web to web area contact changes or continually increases. The Figures 4-4 and 4-5 are of graphs of a typical run with the WOTM device in the winding path. Figure 4-4 is with a 4-inch nip roller and at 6-pounds (1-PLI) of WLT.

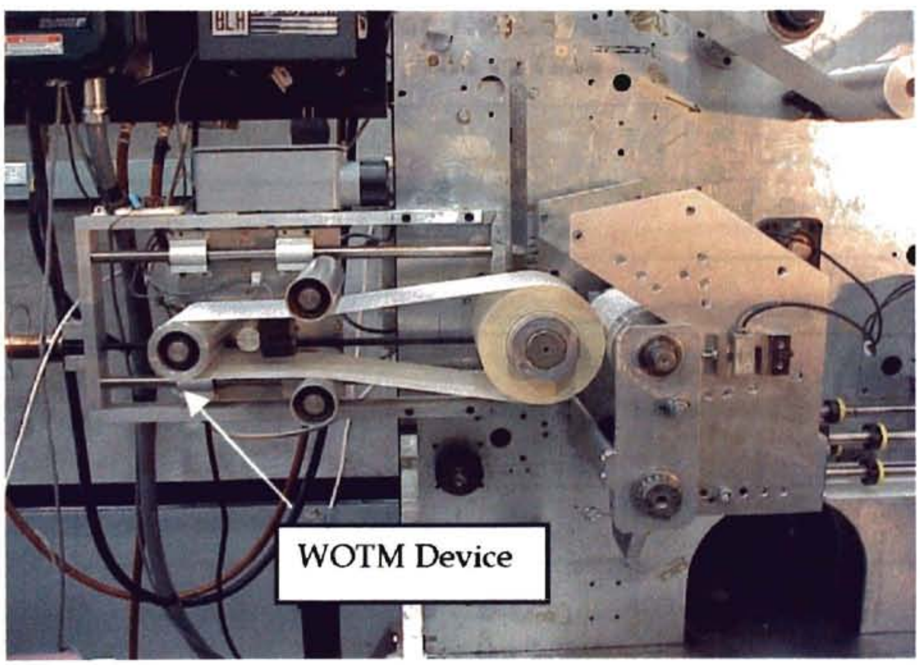

Figure 4-3: WOTM Device and a Half Wound Roll / 4-in Nip

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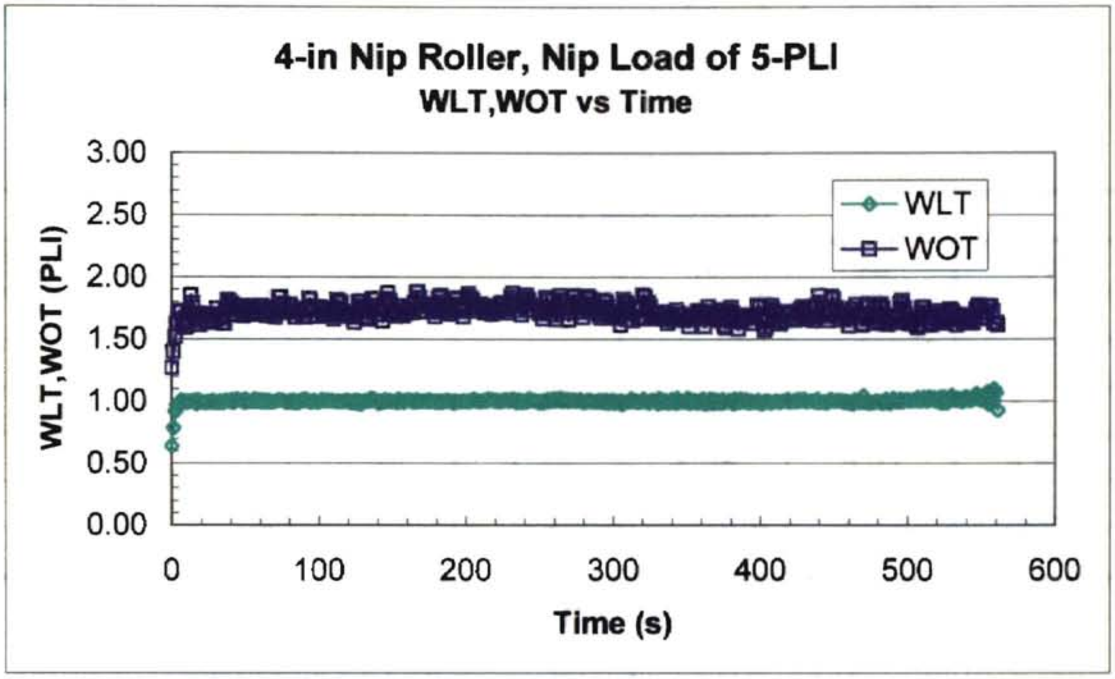

Figure 4-4: Typical WOT Run with 4-inch Nip Roller

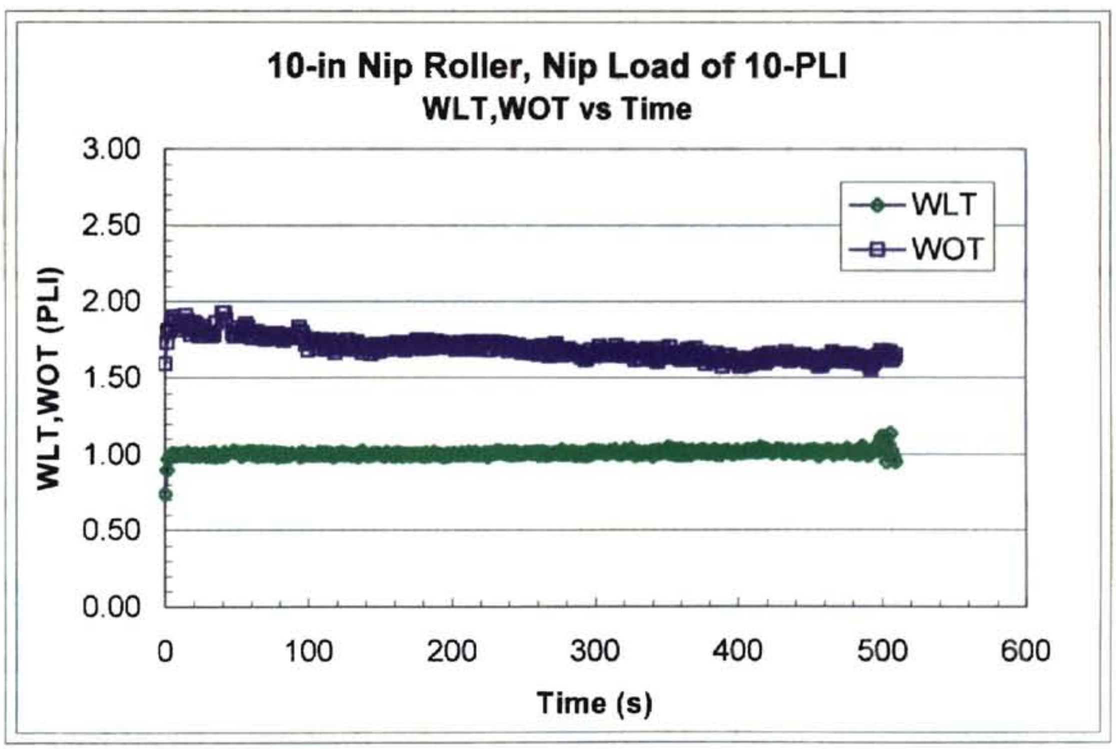

Figure 4-5: Typical WOT Run with a 10-inch Nip Roller

The average results of the testing using a four and ten-inch nip roller are as follows:

4-inch Diameter Nip Roller					
Nip Load (PLI)	**2.5**	**5**	**10**	**20**	**30**
WOT A (PLI)	1.36	1.79	2.50	3.89	5.14
WOT B (PLI)	1.36	1.71	2.38	3.37	4.47
WOT C (PLI)	1.33	1.69	2.27	3.26	3.87
AVE.	1.35	1.73	2.39	3.51	4.49
STDev	0.014	0.040	0.094	0.275	0.521
95% CI	0.02	0.05	0.11	0.31	0.59

Table 4-1: 4-inch Nip Roller Wound-On-Tension

10-inch Diameter Nip Roller					
Nip Load (PLI)	**2.5**	**5**	**10**	**20**	**30**
WOT A (PLI)	1.17	1.34	1.96	2.61	3.64
WOT B (PLI)	1.15	1.36	1.96	2.52	3.49
WOT C (PLI)	1.16	1.34	1.85	2.43	3.22
AVE.	1.16	1.35	1.93	2.52	3.45
STDev	0.0076	0.0115	0.0510	0.0714	0.1751
95% CI	0.009	0.013	0.058	0.081	0.198

Table 4-2: 10-inch Nip Roller Wound-On-Tension

As seen in Tables 4-1 and 4-2, each nip load was tested three times for each nip roller diameter. The average values for these testing runs are used in all calculations and used to develop the graph in Figure 4-6. Thus it was determined that a comparison of the WOT measurement, which had been averaged for all wound roll radius, was reasonable. From previous testing, a degradation of WOT was observed after multiple tests under high nip load conditions. In order to assure integrity between tests an untested or new roll of

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newsprint was used. From Figure 4-6 the graphs of values of WOT for the four and ten inch nip rollers are approaching 1-PLI ,the web line tension, as nip load approaches zero. With the range of tests completed, the next stage is to test using pull-tab measurements instead of the WOTM device.

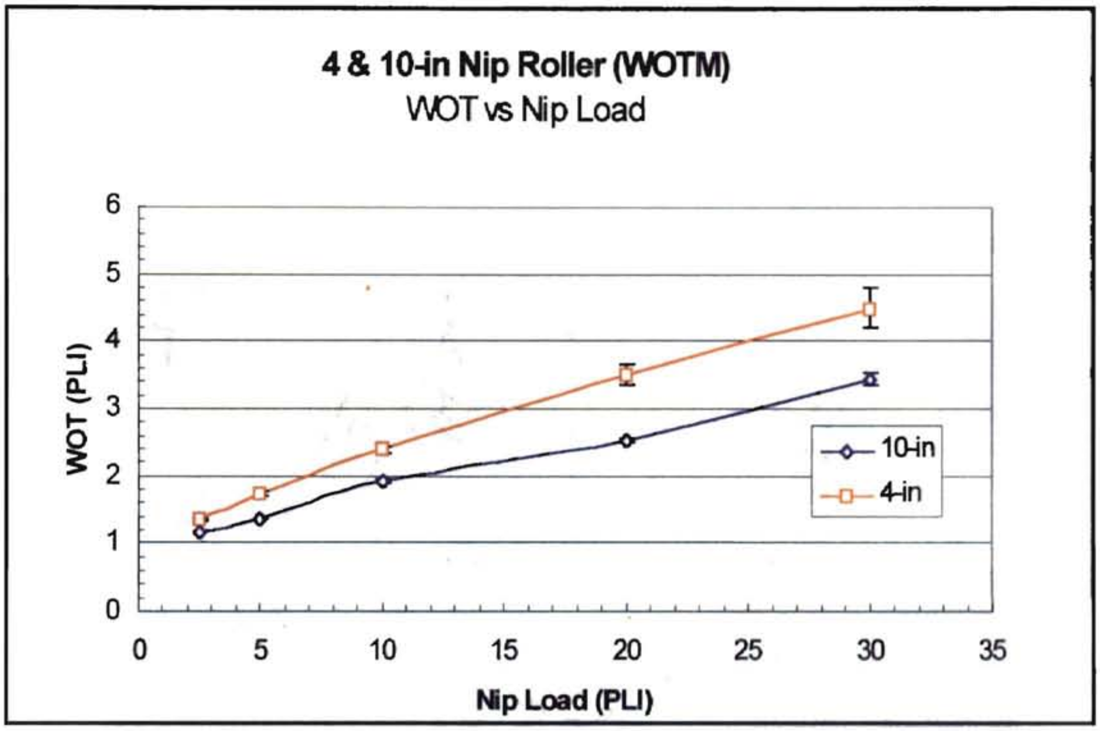

Figure 4-6: Measured WOT for 4 and 10 inch Nip Roller

4-2: PULL-TAB MEASUREMENT

To perform the pull-tab measurements the WOTM device was not included in the winding path. Because the WOTM device is not in the winding path, the area of contact between the outer layer and second layer is three hundred and sixty degrees. As the winding roll increases in diameter this area of contact continues to grow through out the duration of the wind. As stated earlier, pull-tabs are used to measure the radial pressure as a function of radial location. The pull-tabs are inserted into the winding roll as the roll is being wound. In this investigation, the pull-tabs were inserted at every half-inch starting at one half inch from the core and stopping at one half inch from the outside diameter of the roll. Because of the dimensions of the winding machine and the newsprint rolls, a total of six pull tabs were inserted during each test, a total of three pulls were imparted on each pull-tab for one test. The three pull-tab measurements were used to determine the average pressure at that radius.

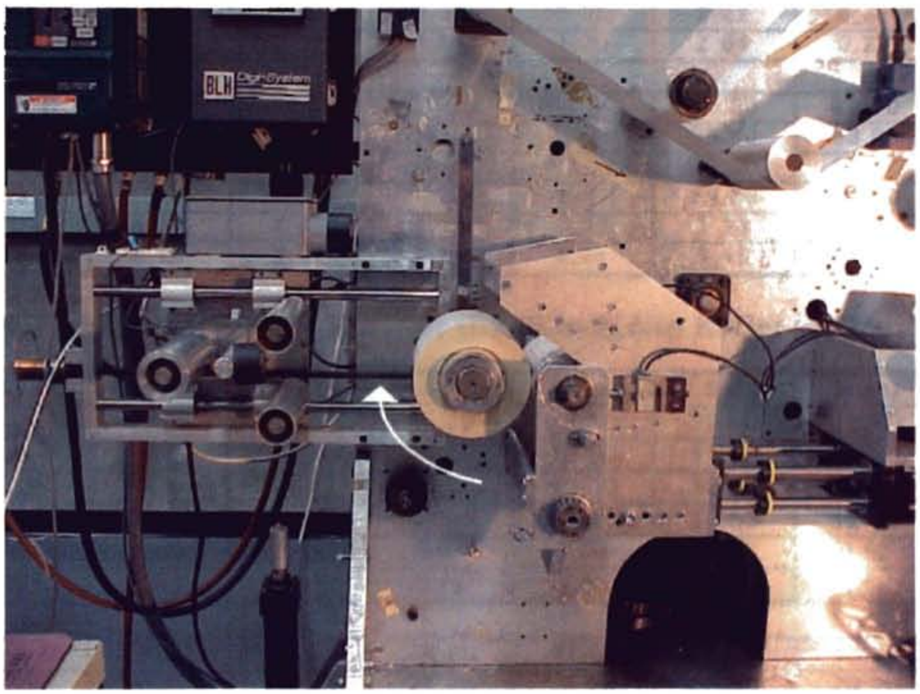

Figure 4-7: Pull-Tab configuration of the winding machine

For the two nip diameters, four and ten inch, a total of three winding conditions were tested and a web line tension of 1-PLI was maintained. The pull-tab tests were performed at 2.5,10, and 30 PLI for the 10-inch nip roller and at 2.5,10, and 20 PLI for the 4-inch nip roller. The 4-inch nip roller was not tested at the 30 PLI case because of the pressures induced at this condition makes it impossible to test with pull-tabs because the tabs would fail. The following two tables are the normalized results from the pull-tab test for each nip diameter.

Pile H.	0.5 (in)	1 (in)	1.5 (in)	2 (in)	2.5 (in)	3 (in)
	12.20	11.70	14.40	14.30	13.00	11.70
Run A	11.70	11.80	9.40	10.10	11.80	11.60
2.5	12.50	13.80	11.90	13.10	11.60	12.10
Averages	12.13	12.43	11.90	12.50	12.13	11.80
STDev	0.33	0.97	2.04	1.77	0.62	0.22
95% CI	0.373	1.09	2.31	2.00	0.70	0.24
Run B	26.30	30.00	25.20	25.90	26.40	25.50
	28.60	24.20	25.60	27.40	26.20	25.70
10	26.00	24.90	23.50	25.30	21.60	25.20
Averages	27.00	26.40	24.80	26.20	24.70	24.80
STDev	1.16	2.58	0.91	0.88	2.22	0.21
95% CI	1.31	2.93	1.03	1.00	2.51	0.23
Run C	69.00	61.20	61.00	64.90	61.50	62.10
	58.00	68.00	66.40	55.40	58.40	63.00
30	62.00	57.20	56.00	59.30	59.50	58.40
Averages	63.20	61.10	61.10	60.00	59.80	61.20
STDev	4.55	4.46	4.25	3.90	1.28	1.99
95% CI	5.14	5.04	4.81	4.41	1.45	2.25

Table 4-3: Pressure Data for the 10-inch Nip Roller (psi)

Pile H.	0.5 (in)	1 (in)	1.5 (in)	2 (in)	2.5 (in)	3 (in)
	11.20	12.40	11.70	12.40	10.90	12.70
Run A	10.10	12.60	11.40	12.50	11.70	12.50
2.5	13.90	12.80	10.80	12.30	12.00	11.50
Averages	11.70	12.60	11.30	12.40	11.53	12.23
STDev	1.60	0.16	0.37	0.08	0.46	0.52
95% CI	1.81	0.18	0.42	0.09	0.53	0.59
Run B	38.20	34.80	33.80	31.40	30.10	33.00
	30.00	29.50	28.60	31.20	31.80	29.20
10	35.70	28.70	32.70	28.80	28.00	29.10
Averages	34.60	31.00	31.70	30.50	30.00	30.40
STDev	3.43	2.71	2.24	1.18	1.55	1.82
95% CI	3.88	3.06	2.53	1.34	1.76	2.05
Run C	49.30	47.40	49.30	49.10	47.90	49.11
	46.30	49.70	49.90	50.28	48.60	49.20
20	52.50	54.70	50.12	53.50	50.80	50.00
Averages	49.37	50.60	49.77	50.96	49.10	49.44
STDev	2.53	3.05	0.35	1.86	1.24	0.40
95% CI	2.86	3.45	0.39	2.10	1.40	0.45

Table 4-4: Pressure Data for the 4-inch Nip Roller (psi)

The values in Tables 4-3 and 4-4 are the results of three individual windings being performed at the same conditions, and each result is the accumulated average of three pulls on one tab. Therefore, each of the averages in the tables are accumulation of three tests under those specific testing conditions. The graphs of the average pressures for the 4-inch nip roller are in Figure 4-8. The graphs of the average pressures for the 10-inch nip roller are in Figure 4-9. The behavior of these graphs shows a plateau region of uniform pressure distribution through the middle of the wind. When using a wound roll model, such as that of Hakiel, which was introduced earlier, it is found that uniform pressure results only in certain circumstances. First of all the ratio of Er/Et must be very high, as in newsprint for these pressures, and second the winding tension must be constant through out the wind. Hakiel's model will be used in an iterative fashion to determine what winding tension or WOT produced these experimental pressures.

The output graphs from Hakiel's model can be seen in Appendix A and in Figures 4-10 and 4-11. The pressures predicted by Hakiel's model were compared to the pressures measured with the pull-tabs. The WOT was iterated until the predicted and measured pressures were in agreement. The model also takes into account a percent error and for the following graphs and all of the graphs in Appendix A, there was much less than one percent error for each inferred WOT calculated.

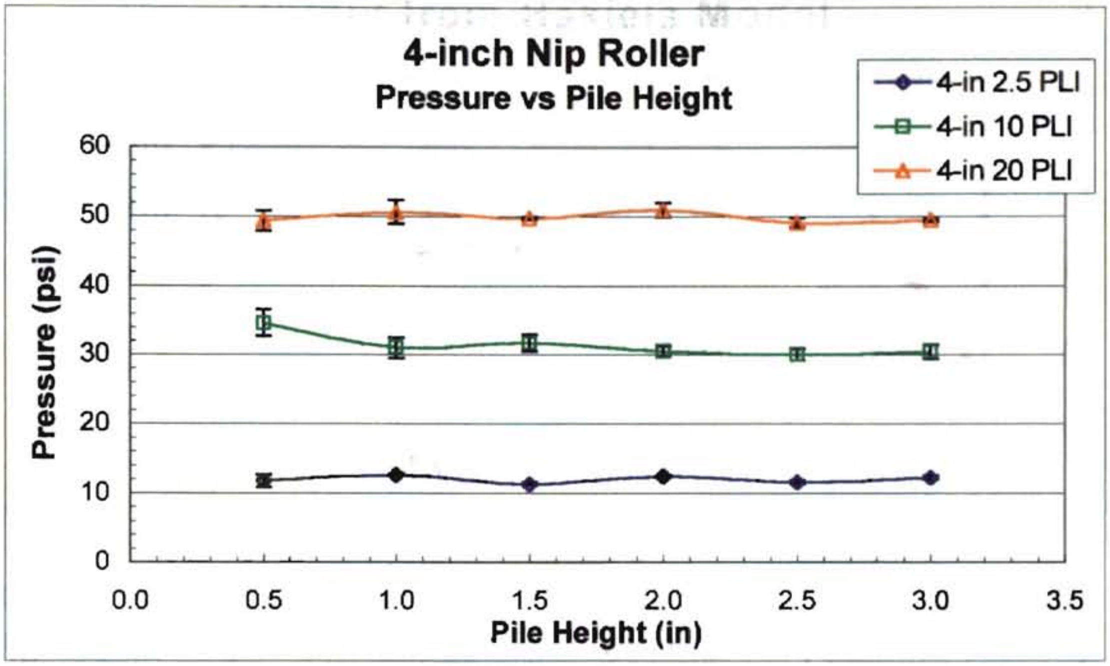

Figure 4-8: 4-inch Nip Roller Pull-Tab Average Data

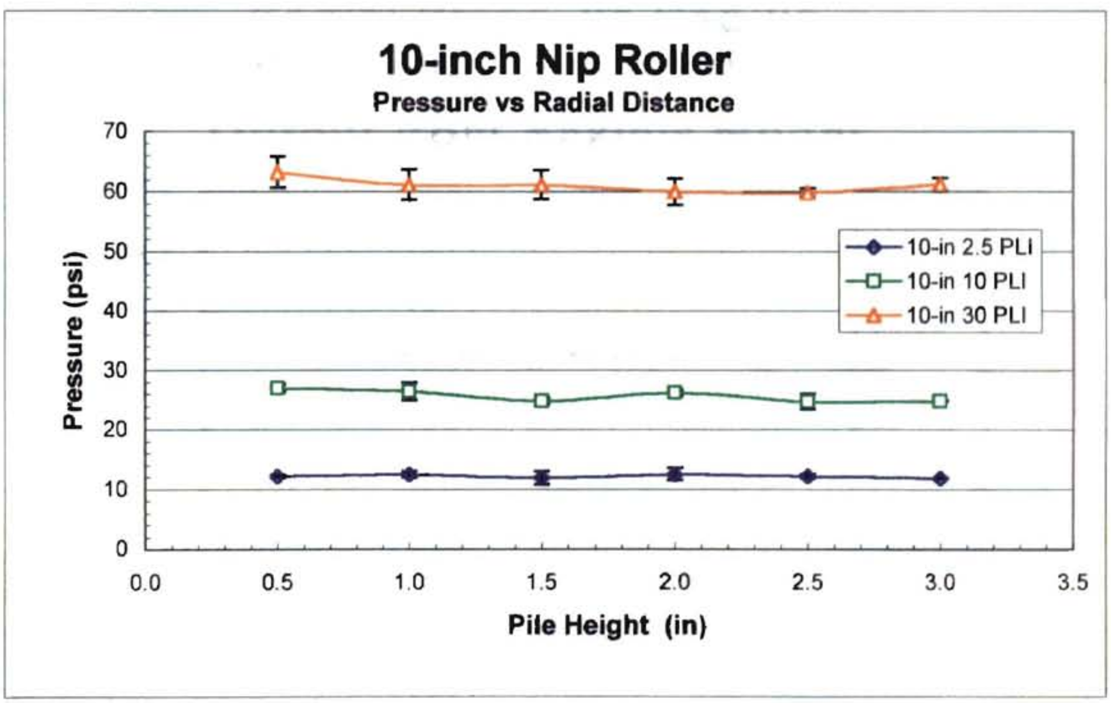

Figure 4-9: 10-inch Nip Roller Pull-Tab Average Data

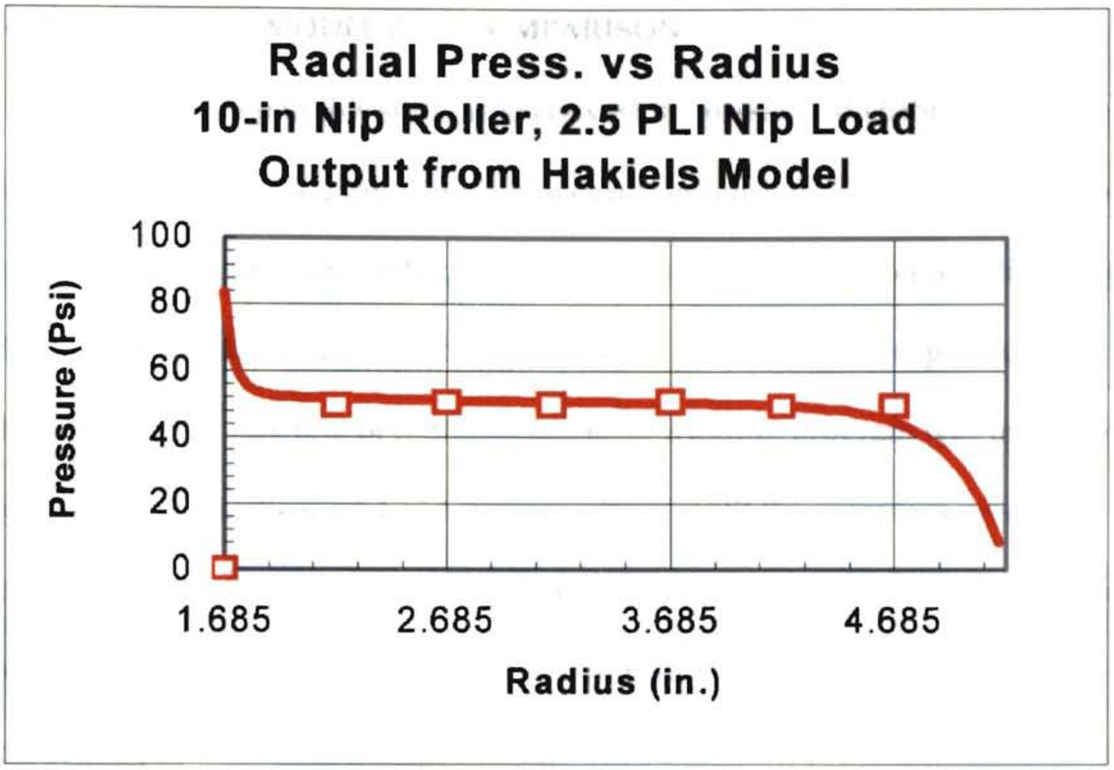

Figure 4-10: Output from Hakiels model with Pull-Tab pressures, 10-in Nip

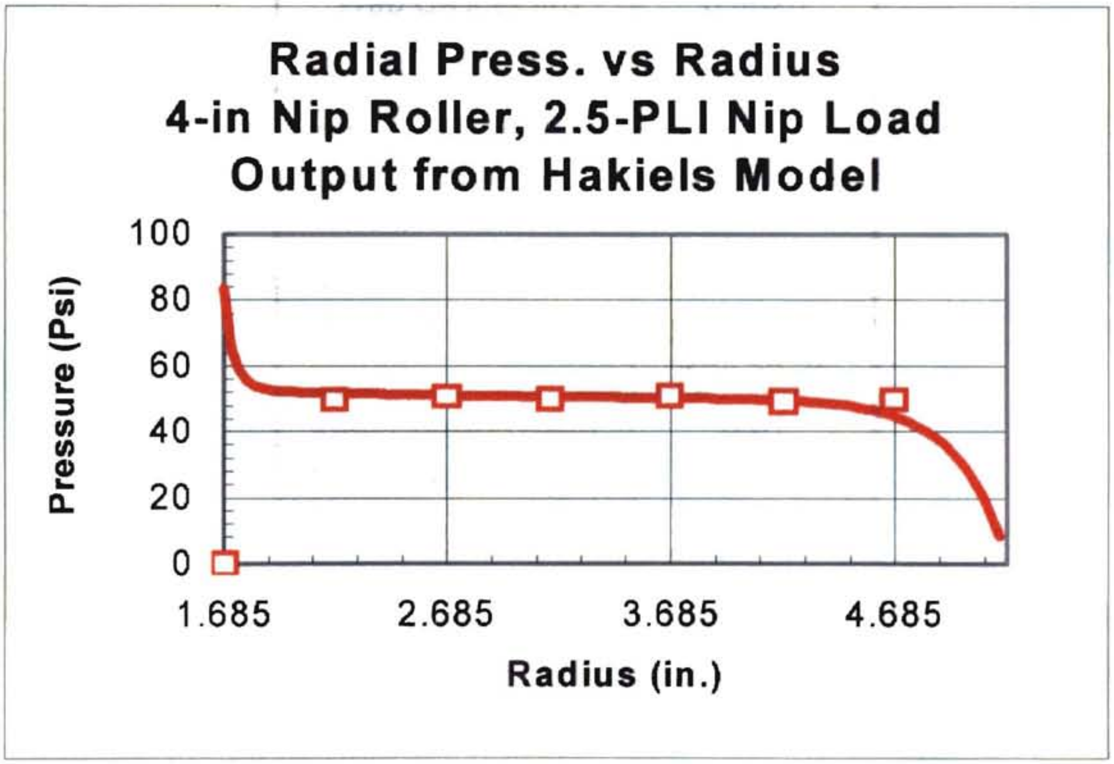

Figure 4-11: Output from Hakiels model with Pull-Tab pressures, 4-in Nip

4-3: WOUND ROLL MODEL AND COMPARISON

The next step in this study is to convert the pressure distributions developed in Section 4-2 into values of wound-on-tension. To infer a wound-on-tension from the pressure distribution data the wound roll model developed by Hakiel [9] was used; Hakiel's wound roll model predicts how the pressure or stress varies as a function of radial distance. A winding program was used that incorporates Hakiel's model and it iterates WOT until the pressures predicted from the model compared to the values obtained from pull-tab testing within a percent error specified by the user. The parameters needed to use the iterative model are shown in Table 4-5.

Web Width (in)	6
Web Caliper (in)	0.0028
Core ID (in)	3
Core OD (in)	3.4
Roll OD (in)	10.5
Web-Web kCOF	0.25
Tang Mod. Et (psi)	750,000
Rad. Mod. Er (psi)	K1= 0.190
	K2= 32.75
Web Poisson Ratio	0.01
Core Mod. Ecm (psi)	30 x 10^6
Core Poisson Ratio	0.33

Table 4-5: Parameters for the Winding Model

After using the winding model for the inferred WOT iterated from the model, a comparison of the WOT measured, from Tables 4-1 and 4-2, and WOT calculated can be made. In Table 4-6, the results from both the Winding runs and the Pull-tab runs can be seen. From the WOT measured and WOT calculated a set of graphs can be seen in Figures 4-10 and 4-11.

4-in	2.5 PLI	10 PLI	20 PLI
WOT Calc.	1.90	3.17	4.00
WOT Meas.	1.35	2.39	3.51
WOTC/WOTM	1.40	1.30	1.20
10-in	**2.5 PLI**	**10 PLI**	**30 PLI**
WOT Calc.	1.90	2.85	4.43
WOT Meas.	1.16	1.93	3.45
WOTC/WOTM	1.60	1.40	1.30

Table 4-6: WOT Measured & WOT Calculated for 4 & 10 in Nip Roller

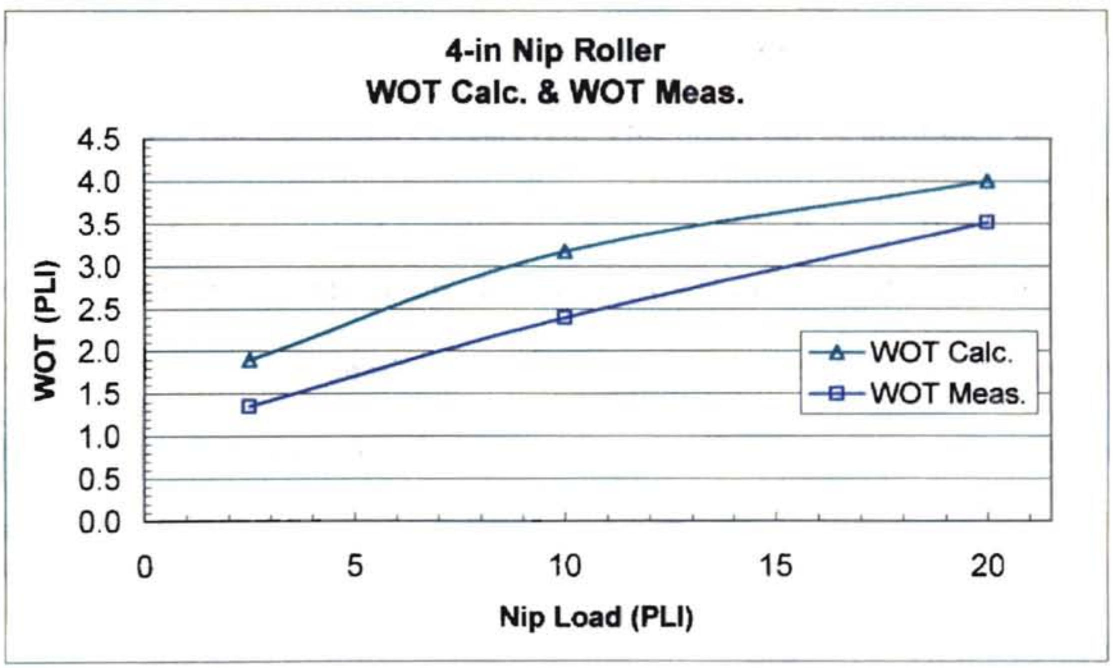

Figure 4-12: 4-in Nip Roller WOT Calculated and WOT Measured

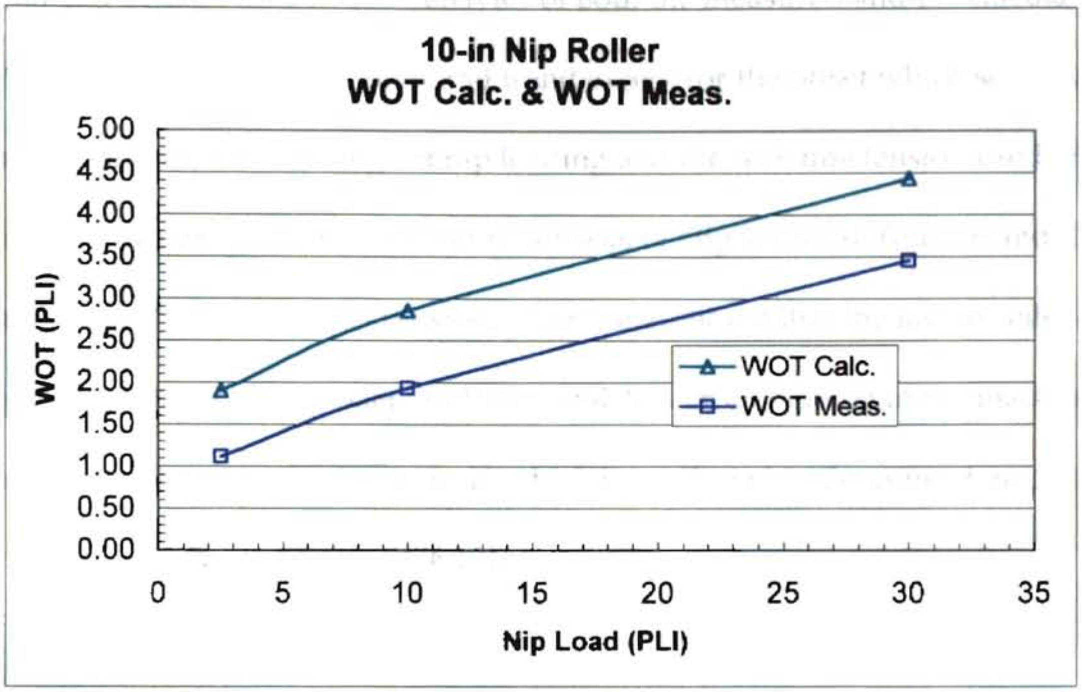

Figure 4-13: 10-in Nip Roller WOT Calculated and WOT Measured

From the graphs in Figures 4-12 and 4-13, an offset in the WOT measured and the WOT calculated can be observed. This offset can be attributed to the pulling away of the first layer of the web material during winding in the WOTM mode of the experimental setup. This difference in the calculated and the measured WOT would imply that the WOTM device definitely interferes with the measurement of the actual amount of tension that is being wound on to the winding roll.

The most important question, now that it appears that the wound-on-tension measurement is an interfering type of experiment, is whether a correction factor can be established. The behavior of both the measured and the calculated WOT has the same basic pattern and trend except for the offset which seems to remain constant for this range of nip loading and the web line tension used. For the center winding scenario, the WOT consists of Nip-Induced-Tension and the magnitude of the Web-Line-Tension. It has been shown that the lay on roller or nip roller induces a component of WOT, which is an elongation in the machine direction of the web, causing a strain which is attributed to the contact mechanics of the nip and the winding roll [6,12].

The tension that can be observed on the web just prior to the nip roller is the same as the WLT, the tension or WOT immediately after the nip roller is observed to be significantly higher. The difference in WOT and WLT tension is a function of the nip load and the diameter of the nip roller. The problem with the WOT measurement method is as the web is pulled away from the winding roll this allows slip to occur between the first and second layer of newsprint or which ever material is being tested. This slippage is the reason that the measured value of the wound-on-tension using the WOTM device is lower than WOT derived from pull-tab measurements. The amount of slippage will decrease as the coefficient of friction and the nip load increase, this means that the WOTM device would more precisely predict the wound-on-tension for a material with higher coefficient of friction.

As stated earlier the nip roller induces an increase in the amount of wound-on-tension that is measured over the web-line-tension. To correct the difference in the measured wound-on-tension and the calculated wound-on-tension an exponential correction factor was used in the form of the band brake or the capstan function. Equation (5) is the form used of the band brake equation to correct the measured values of wound-on-tension.

$$(5) \qquad WOT_{measured} = {WOT_{caculated}}\Big/{\exp(\mu\theta)}$$

In Equation (5) μ is the coefficient of friction and θ is the angle of wrap of the first layer around the winding roll between the nip roll and the tangent point at which the web exits to the WOT measurement device. The angle of wrap around the winding roll varies during the wind starting at 90°and finishing at an angle of 110°. The corrected values for WOT measured for the 4 and 10-inch nip roller can be seen in Table 4-7.

4-in Nip Roller			
	2.5 PLI	**10 PLI**	**20 PLI**
WOT Calc.	1.90	3.17	4.00
WOT Meas.	1.35	2.39	3.51
WOT Corr.	1.91	3.38	4.97
10-in Nip Roller			
	2.5 PLI	**10 PLI**	**30 PLI**
WOT Calc.	1.90	2.85	4.43
WOT Meas.	1.12	1.93	3.45
WOT Corr.	1.73	2.60	4.47

Table 4-7: WOT, Measured, Calculated, and Corrected

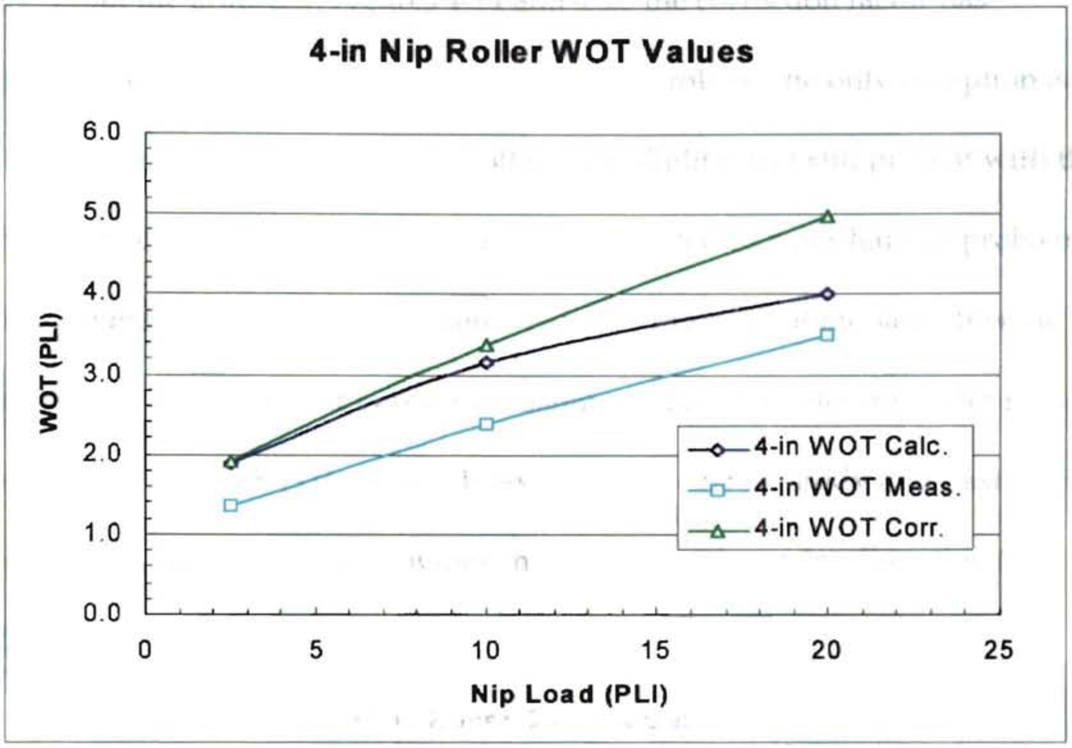

Figure 4-14: 4-in Nip Roller WOT, Measured, Calculated, and Corrected

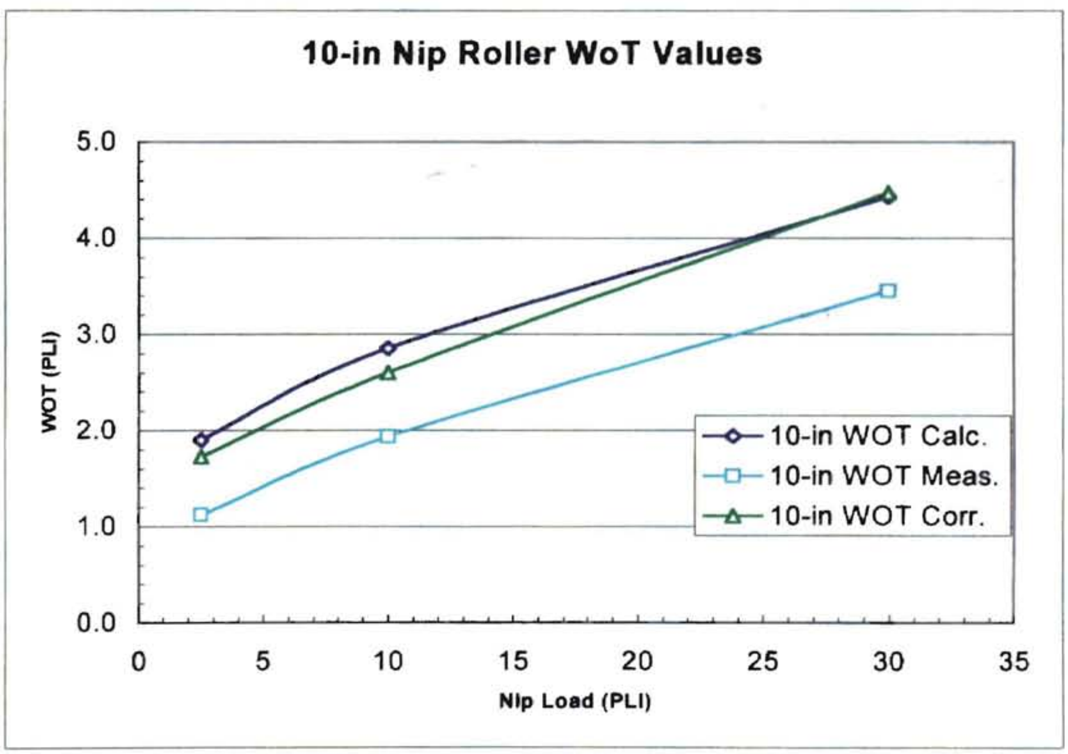

Figure 4-15: 10-in Nip Roller WOT, Measured, Calculated, and Corrected

From the graphs in Figures 4-14 and 4-15 the correction factor has collapsed the offset for both the 10 and 4-inch nip rollers, the only exception is the last data point on the 4-inch nip roller. The slight offset still present with the 20-PLI case of the 4-inch nip roller could be attributed to a mechanical problem with the winding machine experiment. Another example of the same type of correction factor, on similar newsprint, using a 6-inch diameter nip roller is as follows in Figure 4-16, [11]. So combined with the current study and past experimental data it becomes obvious that the correction using Equation (5) is a viable solution.

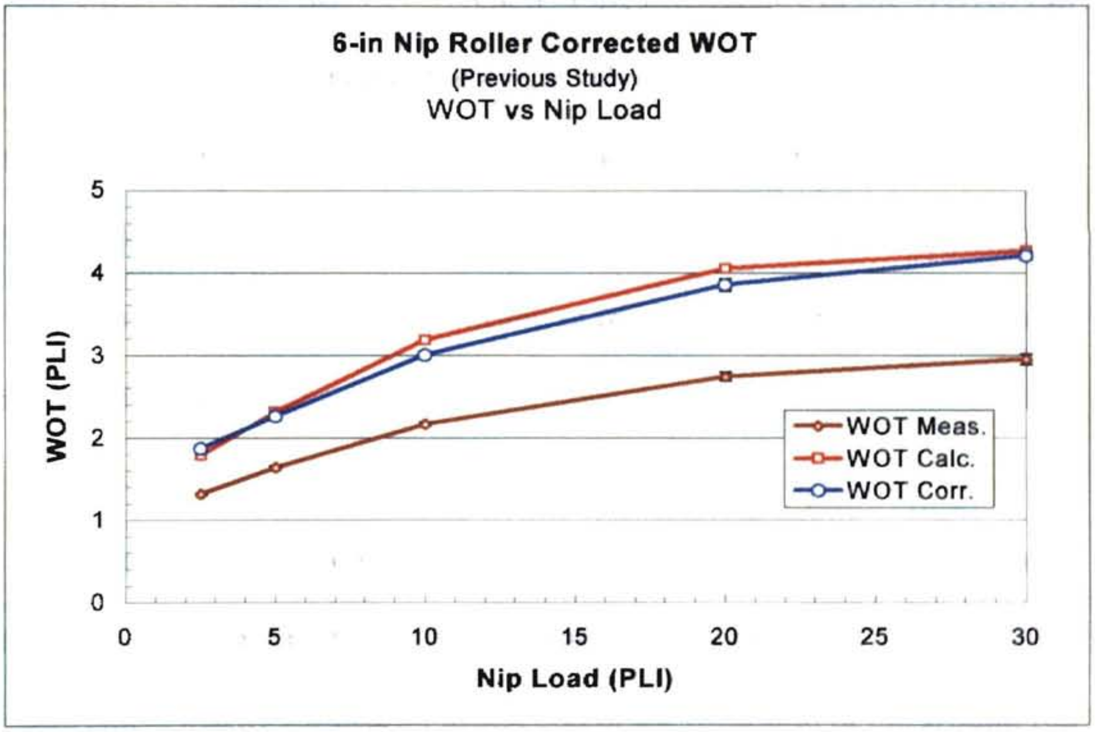

Figure 4-16: 6-in Nip Roller, Corrected WOT, [11]

CHAPTER V

CONCLUSIONS AND FUTURE WORK

5-1: CONCLUSIONS

It can be concluded that the Wound-On-Tension measurement method used for this study is an interfering type of measurement method. In addition, it appears that for some cases a correction of the interference of the WOTM can be done to allow the prediction of the actual value of wound-on-tension. The measurement of the wound-on-tension in the center winding configuration is effected by the amount of slippage between the first and second a layer of the winding roll. The greater the coefficient of friction of the material the less slippage that will occur.

The Wound-On-Tension measurement device can be used as a non-destructive measurement device in industry and in research. This type of measurement allows for precise prediction of the condition of the wound roll with out causing any roll defects or destruction. The correction factor for newsprint could be expanded and generalized to be used with most of the common web handling materials.

5-2: FUTURE WORK

To be able to understand the wound-on-tension measurement method in further detail, testing of varying types of materials through similar testing procedures as this study would lead to a better understanding of the effects of the wound-on-tension measurement device. In addition, testing should be performed on materials with higher and lower kinetic coefficient of friction than that of newsprint. The testing of these different types of material with varying coefficient of friction would allow the researcher to develop a larger encompassing correction for different materials. Also, the testing of materials with similar values for tangential and radial modulus with varying coefficient of friction would allow for further understanding of the effects of the wound-on-tension-measurement device.

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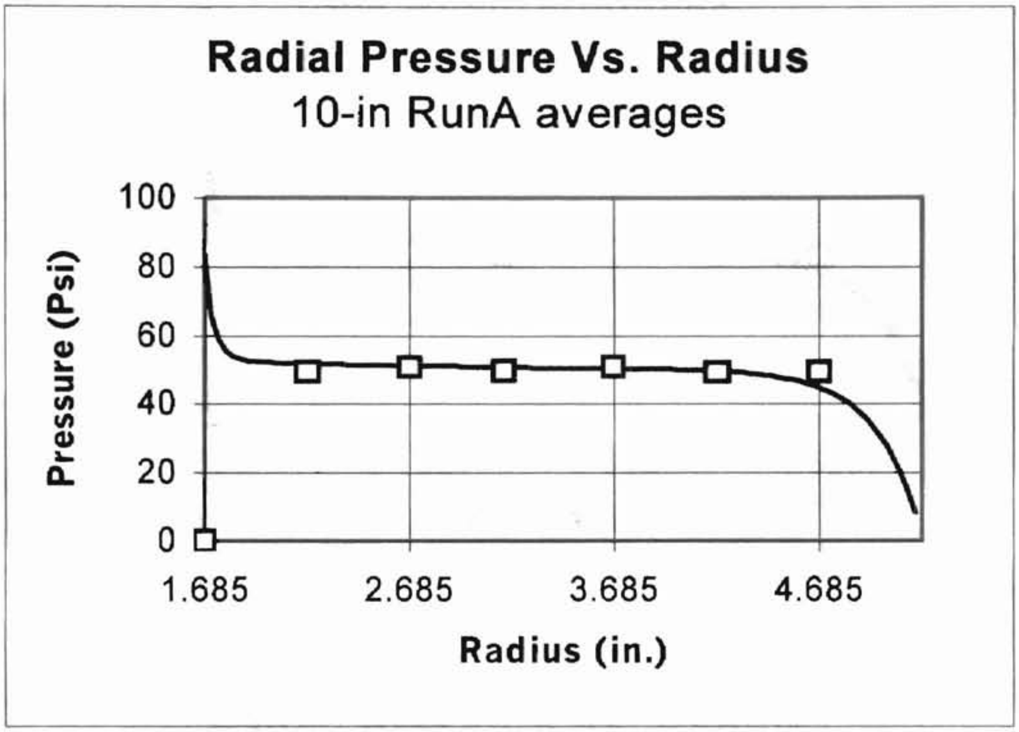
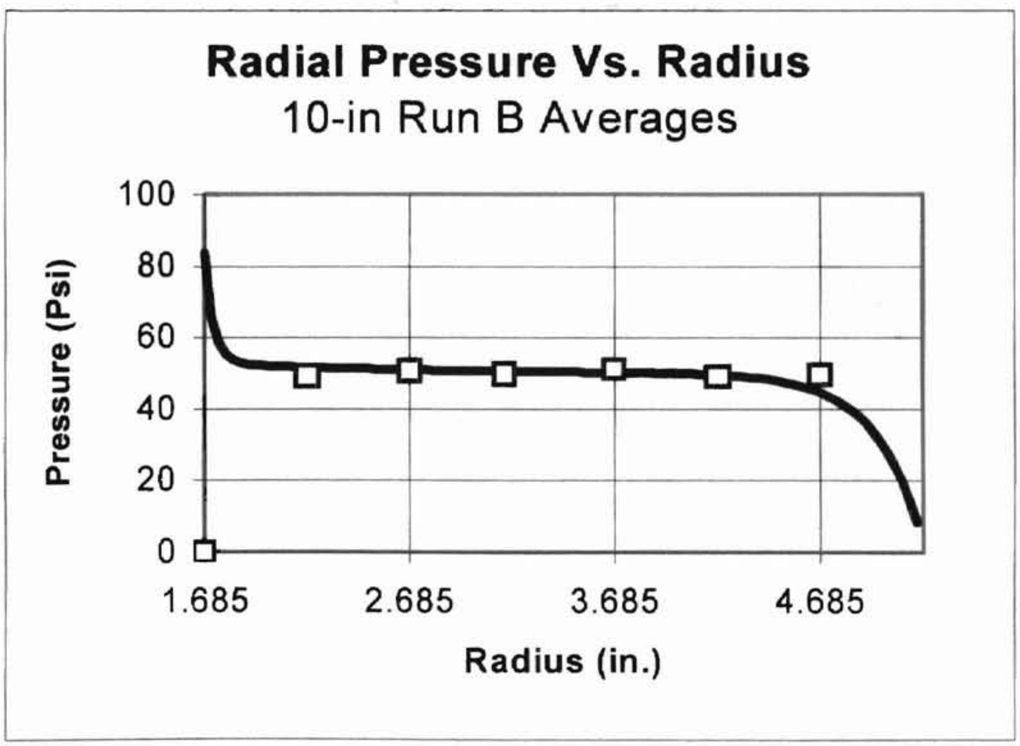
[11] Good, J.K., Hartwig, J.L., Markum, R., "*A Comparison of Center and Surface Winding using The Wound-In-Tension Method*", Procedure of the Fifth International Conference on Web handling, Web Handling Research Center, Oklahoma State University, Stillwater, Oklahoma.

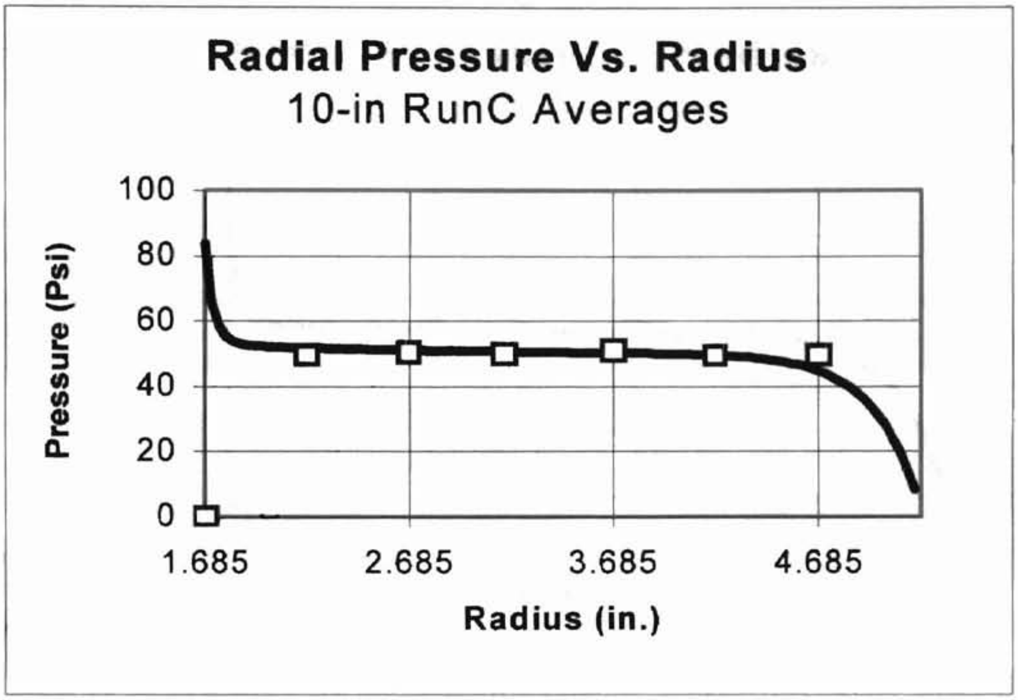
[12] Pfeiffer, J.D., "*Mechanics of Rolling Nip on Paper Webs*", TAPPI, Journal Vol. 51, No. 8, August 1968

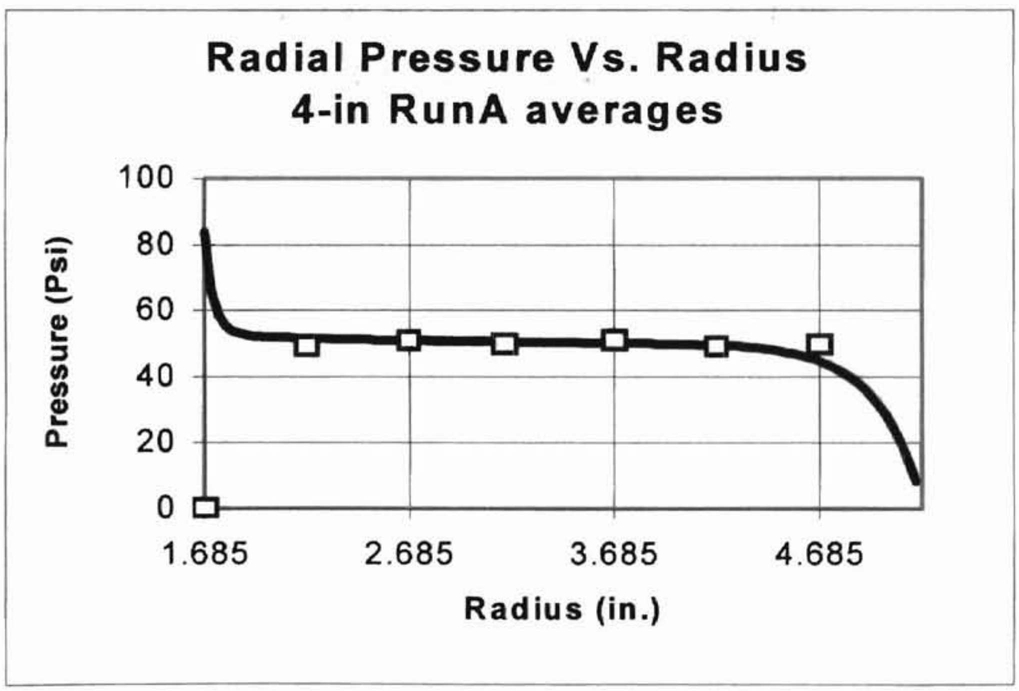
APPENDIX A

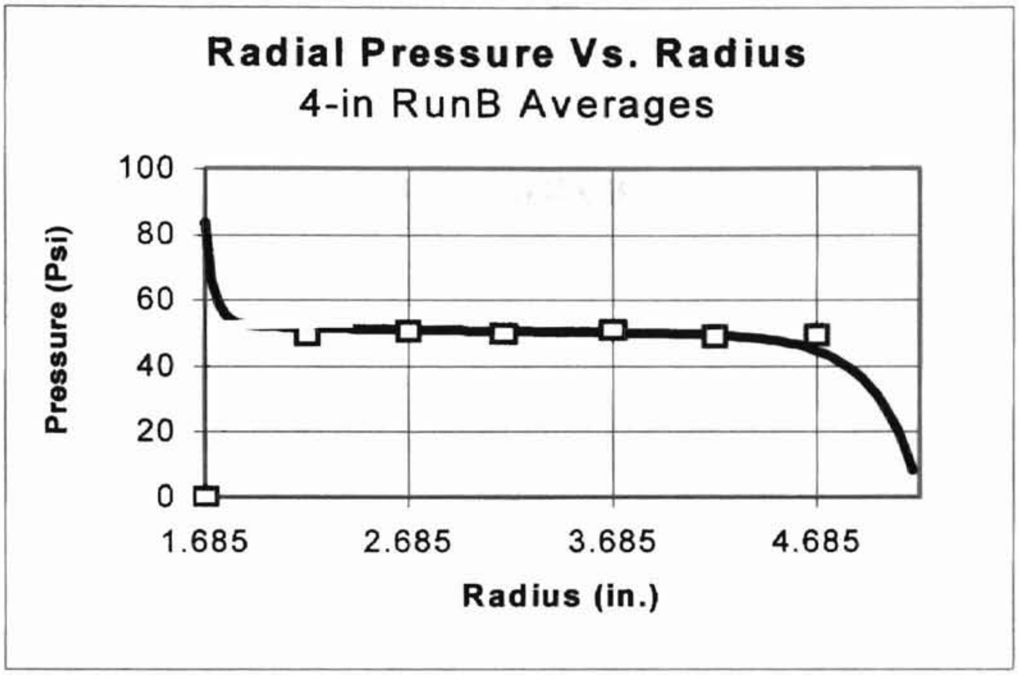
Hakiel's model pressure output comparison graphs.

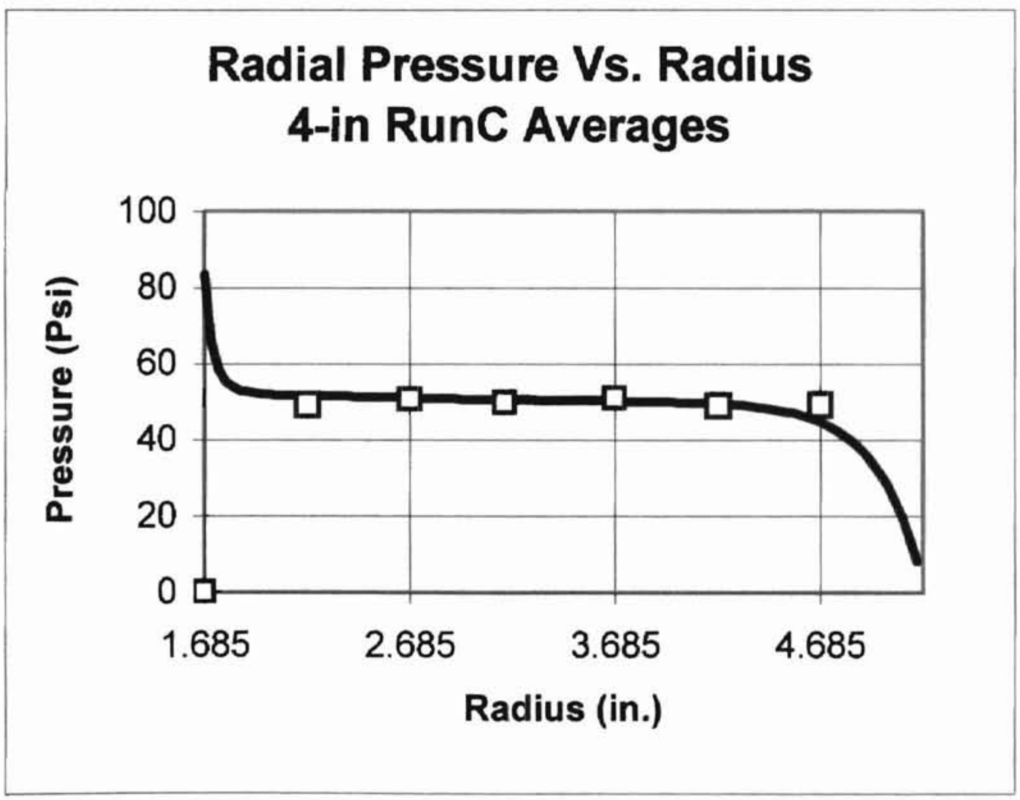





Radial Pressure Vs. Radius
10-in RunC Averages
100
80
60
40
20
0
Pressure (Psi)
1.685
2.685
3.685
4.685
Radius (in.)

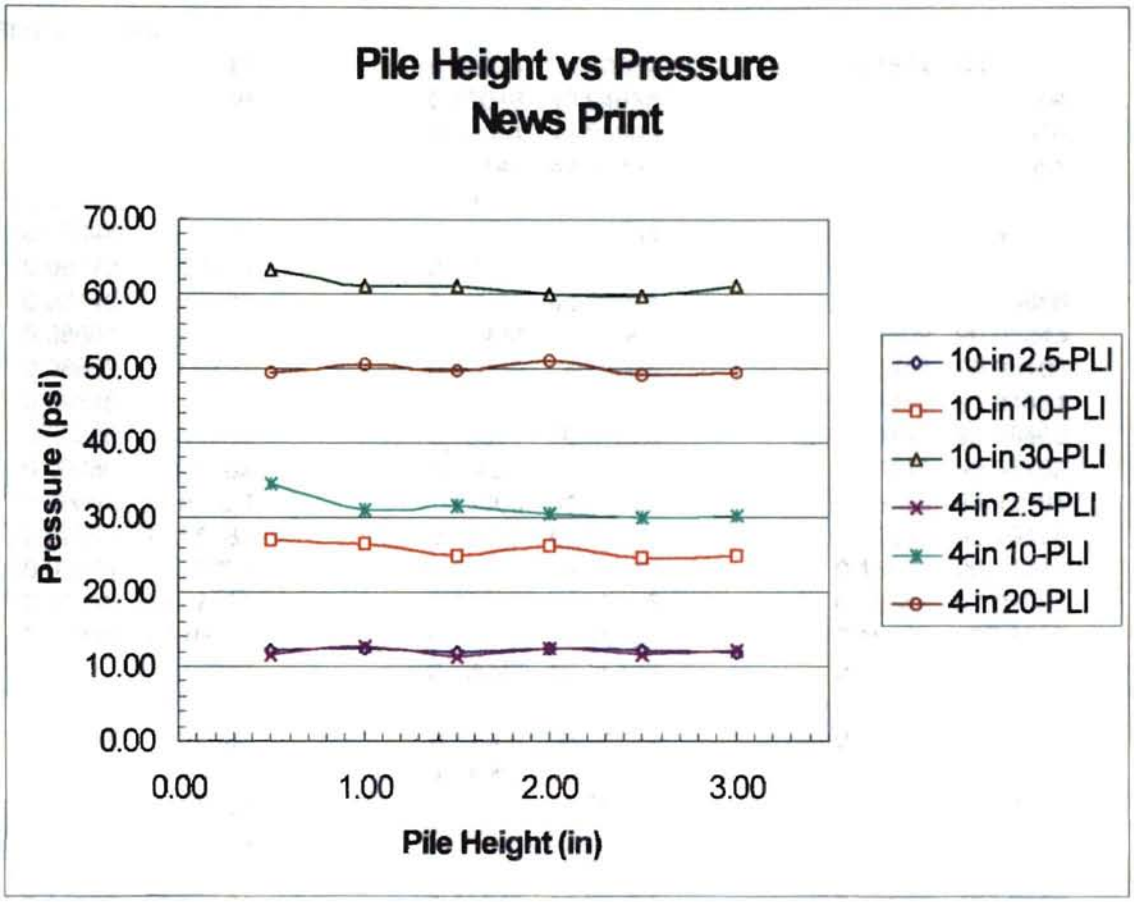

Radial Pressure Vs. Radius
4-in RunA averages
100
80
60
40
20
0
Pressure (Psi)
1.685
2.685
3.685
4.685
Radius (in.)


Radial Pressure Vs. Radius
4-in RunB Averages
Pressure (Psi)
100
80
60
40
20
0
1.685
2.685
3.685
4.685
Radius (in.)


Radial Pressure Vs. Radius
4-in RunC Averages
Pressure (Psi)
100
80
60
40
20
0
1.685
2.685
3.685
4.685
Radius (in.)

APPENDIX B

Pressure graphs for both the 4 and 10-inch nip rollers.



Radial Modulus(Er) Test results: News Print, Test 1

Strain	Pressure
0.0383	1.12142
0.05505	1.82956
0.06435	2.69479
0.07016	3.49477
0.07493	4.31409
0.07844	5.12373
0.08173	5.84879
0.08445	6.57385
0.08691	7.29648
0.08899	8.03121
0.09115	8.73451
0.09306	9.44265
0.09486	10.15562
0.09642	10.84926
0.09807	11.55982
0.09971	12.28729
0.10116	12.97368
0.10246	13.70598
0.10383	14.47938
0.10505	15.23344
0.10632	16.002
0.10763	16.78264
0.10863	17.55603
0.10984	18.33909
0.111	19.09799
0.11202	19.93664
0.11306	20.70761
0.11384	21.50034
0.11485	22.31724
0.11583	23.11238
0.11671	23.94861
0.11748	24.7921
0.1183	25.62591
0.11909	26.45731
0.1199	27.32738
0.12058	28.2192
0.12149	29.0651
0.12219	29.94725
0.12305	30.86565
0.12382	31.78647
0.12442	32.70488
0.12499	33.61604
0.12589	34.51269
0.12623	35.45284
0.12706	36.37125
0.12772	37.28965
0.12841	38.19114

0.12974	40.0352
0.13018	40.94635
0.13084	41.85509
0.13141	42.77833
0.13207	43.68224
0.13261	44.57164
0.13321	45.48279
0.13374	46.38911
0.13428	47.3051
0.13459	48.1945
0.13536	49.11291
0.13571	50.01923
0.13627	50.92313
0.1369	51.81495
0.13725	52.73577
0.13777	53.63243
0.13839	54.5605
0.13873	55.45957
0.13928	56.35139
0.13968	57.23354
0.14036	58.14711
0.14061	59.07518
0.14113	59.96217
0.14154	60.85157
0.14194	61.76756
0.14245	62.66421
0.14286	63.54636
0.14329	64.4406
0.14375	65.31792
0.14406	66.21941
0.14449	67.13298
0.14493	68.00788
0.14528	68.91178
0.14587	69.81085
0.14619	70.70026
0.14668	71.57274
0.14703	72.49114
0.1475	73.36604
0.14772	74.26511
0.14814	75.12552
0.14846	76.01975
0.14883	76.90916
0.14886	77.77681
0.1497	78.69038
0.14997	79.57494
0.15035	80.44984
0.15075	81.32958

0.1514	83.07697
0.15172	83.94704
0.15196	84.82436
0.15252	85.73551
0.15269	86.59107
0.15299	87.47323
0.15352	88.35297
0.1537	89.19886
0.15409	90.08343
0.15441	90.95108
0.15465	91.81631
0.15497	92.66463
0.15545	93.55162
0.15558	94.41685
0.1558	95.29176
0.15621	96.15215
0.15647	97.01981
0.15689	97.8802
0.15716	98.76477
0.15737	99.60825
0.15767	100.488
0.15806	101.346
0.15839	102.2136
0.15866	103.0571
0.15886	103.9441
0.15925	104.7972
0.15942	105.6794
0.1599	106.5543
0.16022	107.4075
0.1603	108.263
0.16068	109.1162
0.16084	109.9935
0.16123	110.8829
0.16167	112.0551
0.16175	113.0605
0.16216	114.2931
0.1628	115.5523
0.16306	116.6157
0.16326	117.5317
0.16365	118.4041
0.16401	119.267
0.16404	120.1249

Radial Modulus(Er) Test results: News Print Test 2

Strain	Pressure
0.0383	1.12142
0.05505	1.82956
0.06435	2.69479
0.07016	3.49477
0.07493	4.31409
0.07844	5.12373
0.08173	5.84879
0.08445	6.57385
0.08691	7.29648
0.08899	8.03121
0.09115	8.73451
0.09306	9.44265
0.09486	10.15562
0.09642	10.84926
0.09807	11.55982
0.09971	12.28729
0.10116	12.97368
0.10246	13.70598
0.10383	14.47938
0.10505	15.23344
0.10632	16.002
0.10763	16.78264
0.10863	17.55603
0.10984	18.33909
0.111	19.09799
0.11202	19.93664
0.11306	20.70761
0.11384	21.50034
0.11485	22.31724
0.11583	23.11238
0.11671	23.94861
0.11748	24.7921
0.1183	25.62591
0.11909	26.45731
0.1199	27.32738
0.12058	28.2192
0.12149	29.0651
0.12219	29.94725
0.12305	30.86565
0.12382	31.78647
0.12442	32.70488
0.12499	33.61604
0.12589	34.51269
0.12623	35.45284
0.12706	36.37125
0.12772	37.28965
0.12841	38.19114
0.12912	39.11921
0.12974	40.0352
0.13018	40.94635
0.13084	41.85509
0.13141	42.77833
0.13207	43.68224
0.13261	44.57164
0.13321	45.48279
0.13374	46.38911
0.13428	47.3051
0.13459	48.1945
0.13536	49.11291
0.13571	50.01923
0.13627	50.92313
0.1369	51.81495
0.13725	52.73577
0.13777	53.63243
0.13839	54.5605
0.13873	55.45957
0.13928	56.35139
0.13968	57.23354
0.14036	58.14711
0.14061	59.07518
0.14113	59.96217
0.14154	60.85157
0.14194	61.76756
0.14245	62.66421
0.14286	63.54636
0.14329	64.4406
0.14375	65.31792
0.14406	66.21941
0.14449	67.13298
0.14493	68.00788
0.14528	68.91178
0.14587	69.81085
0.14619	70.70026
0.14668	71.57274
0.14703	72.49114
0.1475	73.36604
0.14772	74.26511
0.14814	75.12552
0.14846	76.01975
0.14883	76.90916
0.14886	77.77681
0.1497	78.69038
0.14997	79.57494
0.15035	80.44984
0.15075	81.32958
0.15091	82.21173
0.1514	83.07697
0.15172	83.94704
0.15196	84.82436
0.15252	85.73551
0.15269	86.59107
0.15299	87.47323
0.15352	88.35297
0.1537	89.19886
0.15409	90.08343
0.15441	90.95108
0.15465	91.81631
0.15497	92.66463
0.15545	93.55162
0.15558	94.41685
0.1558	95.29176
0.15621	96.15215
0.15647	97.01981
0.15689	97.8802
0.15716	98.76477
0.15737	99.60825
0.15767	100.488
0.15806	101.346
0.15839	102.2136
0.15866	103.0571
0.15886	103.9441
0.15925	104.7972
0.15942	105.6794
0.1599	106.5543
0.16022	107.4075
0.1603	108.263
0.16068	109.1162
0.16084	109.9935
0.16123	110.8829
0.16167	112.0551
0.16175	113.0605
0.16216	114.2931
0.1628	115.5523
0.16306	116.6157
0.16326	117.5317
0.16365	118.4041
0.16401	119.267
0.16404	120.1249

Radial Modulus(Er) Test results: News Print Test 3

Strain	Pressure				
0.05496	0.76614	0.16357	40.42915	0.18381	81.245
0.08081	1.40178	0.16423	41.28713	0.18431	82.42683
0.09351	2.20417	0.16459	42.1427	0.18467	83.33799
0.10154	3.0404	0.16514	43.00552	0.18505	84.1573
0.10731	3.88872	0.16569	43.86592	0.18531	84.99837
0.1116	4.66936	0.16628	44.70698	0.18575	85.82977
0.11518	5.45001	0.16673	45.57705	0.18567	86.62975
0.11956	6.6681	0.1672	46.43745	0.18635	87.46839
0.12292	7.65901	0.16786	47.30268	0.18641	88.30704
0.12496	8.36957	0.16827	48.14375	0.18666	89.09977
0.12683	9.11154	0.16874	48.9969	0.1873	89.94567
0.12878	9.86802	0.16926	49.86455	0.18748	90.76982
0.13067	10.59791	0.16979	50.72737	0.18774	91.57705
0.13209	11.3858	0.17036	51.5636	0.18805	92.3867
0.13353	12.17853	0.17076	52.41191	0.18829	93.2205
0.13509	12.99543	0.17113	53.29407	0.1885	94.03983
0.13636	13.79299	0.17154	54.15688	0.18893	94.86639
0.13782	14.63647	0.17217	55.01487	0.18917	95.66879
0.13908	15.50896	0.17258	55.87285	0.18943	96.48084
0.14044	16.30894	0.17283	56.72358	0.19	97.30741
0.14152	17.14034	0.17335	57.56223	0.19015	98.11948
0.14252	17.95481	0.17367	58.43955	0.19037	98.9412
0.14353	18.77171	0.17431	59.27337	0.19056	99.74844
0.14464	19.59586	0.17469	60.11685	0.19068	100.5557
0.14556	20.41276	0.17508	60.97966	0.19123	101.3701
0.14662	21.15231	0.1755	61.83523	0.1915	102.1895
0.14755	21.92571	0.17575	62.66421	0.1919	103.0064
0.14844	22.6846	0.1762	63.51253	0.19199	103.8063
0.14935	23.47974	0.17677	64.3681	0.19233	104.6136
0.15016	24.27247	0.17708	65.214	0.1926	105.4111
0.1511	25.06278	0.17753	66.05022	0.19278	106.228
0.15177	25.87968	0.17786	66.90337	0.19305	107.0256
0.15262	26.67241	0.17808	67.75894	0.19342	107.8231
0.1535	27.51106	0.17862	68.59759	0.19354	108.6255
0.15413	28.35213	0.17906	69.41691	0.19387	109.4255
0.15495	29.20044	0.1793	70.28939	0.19413	110.2352
0.15581	30.02217	0.17971	71.14496	0.19432	111.0158
0.15655	30.88499	0.17994	71.95943	0.19461	111.8279
0.1572	31.74539	0.18034	72.79083	0.19485	112.623
0.15801	32.60337	0.18078	73.64157	0.19517	113.4303
0.15875	33.46619	0.18123	74.49472	0.19538	114.2085
0.15924	34.32417	0.18145	75.33095	0.1955	114.9915
0.1599	35.22083	0.18183	76.14301	0.19555	115.7867
0.16047	36.07881	0.18211	76.98891	0.1962	116.5939
0.16131	36.95855	0.18246	77.82514	0.19656	117.3818
0.16182	37.83586	0.18289	78.66379	0.1965	118.1576
0.16254	38.69143	0.18335	79.52177	0.19661	118.9383
0.16299	39.55424	0.18358	80.37734	0.19716	119.7189

Radial Modulus(Er) Test results: News Print Test 4

Strain	Pressure				
0.04754	0.70814	0.16333	38.89203	0.18392	79.181
0.07787	1.18909	0.16395	39.75968	0.1842	80.02931
0.09376	1.88756	0.16448	40.58866	0.18454	80.84138
0.10259	2.69479	0.1651	41.46356	0.18495	81.67519
0.10802	3.55761	0.16552	42.29738	0.18532	82.46551
0.1125	4.39626	0.16616	43.16503	0.18548	83.27998
0.11591	5.24216	0.16666	44.02301	0.1858	84.1138
0.11879	6.0373	0.16716	44.87374	0.18611	84.91378
0.12144	6.82036	0.16758	45.72448	0.18644	85.75243
0.1237	7.60584	0.16833	46.57038	0.18683	86.59591
0.12588	8.39132	0.16875	47.41386	0.18717	87.39589
0.12771	9.14538	0.16924	48.26701	0.18738	88.2152
0.12945	9.90427	0.16974	49.11049	0.18754	89.02001
0.13106	10.67766	0.17009	49.95881	0.18786	89.8345
0.13267	11.44622	0.17064	50.84096	0.18817	90.63448
0.1342	12.20753	0.17086	51.64577	0.18854	91.47312
0.13554	12.96401	0.17145	52.50375	0.18878	92.26102
0.13707	13.73499	0.17211	53.34482	0.18912	93.06583
0.13829	14.48905	0.17253	54.19797	0.18944	93.86098
0.13953	15.26244	0.17304	55.05837	0.18972	94.67303
0.14052	16.0455	0.17328	55.8946	0.18985	95.48752
0.14188	16.77297	0.17391	56.73808	0.19008	96.29233
0.14279	17.54637	0.17395	57.5864	0.19047	97.09956
0.14403	18.28834	0.17443	58.42505	0.19081	97.8802
0.14498	19.08349	0.17519	59.2637	0.19103	98.70918
0.14598	19.86171	0.1753	60.09993	0.19126	99.50674
0.14689	20.64236	0.17593	60.92891	0.19165	100.2995
0.14808	21.423	0.17637	61.76756	0.19182	101.1309
0.14887	22.17464	0.17657	62.61104	0.19215	101.9019
0.1499	22.9432	0.17709	63.41827	0.19226	102.7067
0.15048	23.76977	0.17738	64.28592	0.19265	103.5018
0.15135	24.55524	0.17791	65.11491	0.19292	104.2849
0.15233	25.38423	0.17833	65.97047	0.19313	105.0873
0.15317	26.16004	0.17867	66.77528	0.19346	105.8607
0.15401	26.9721	0.17893	67.61635	0.19364	106.6727
0.15472	27.80833	0.17946	68.44775	0.19393	107.4268
0.1557	28.6349	0.17971	69.27914	0.19422	108.2534
0.15631	29.47355	0.18006	70.13229	0.19454	109.0219
0.15698	30.33878	0.1804	70.96611	0.19466	109.8074
0.15763	31.17501	0.18083	71.77576	0.19486	110.5953
0.15828	32.0475	0.18124	72.6144	0.19496	111.3808
0.15895	32.89823	0.18158	73.41922	0.19537	112.1638
0.15967	33.75863	0.18192	74.25062	0.19581	112.9324
0.1602	34.58519	0.18216	75.07476	0.1958	113.7106
0.16085	35.47943	0.18264	75.90858	0.19607	114.4719
0.16158	36.33258	0.18276	76.73273	0.19639	115.2332
0.16212	37.18331	0.1832	77.53754	0.19657	116.0332
0.16283	38.03405	0.18347	78.39069	0.197	116.8138

VITA

Johnny Lee Hartwig

Candidate for the Degree of

Master of Science

Thesis: A STUDY OF THE WOUND-ON-TENSION MEASUREMENT METHOD

Major Field: Mechanical Engineering

Biographical:

Personal Data: Born in Dewey, Oklahoma, on August 17, 1969; son of Jim and Beverly Hartwig.

Education: Graduated from Dewey High School, Dewey, Oklahoma in May 1987; received Bachelor of Science degree in Mechanical Engineering from Oklahoma State University, Stillwater, Oklahoma in December 1998. Completed requirements for the Master of Science degree with a major in Mechanical Engineering at Oklahoma State University in May, 2000.

Experience: Research Assistant, Mechanical and Aerospace Engineering, Oklahoma State University, 1993-97
Graduate Research Assistant, Mechanical and Aerospace Engineering, Oklahoma State University, 1997-99
Mechanical Engineer, Zebco Corporation, 1999-Present

Professional Associations: American Society of Mechanical Engineers, Society of Automotive Engineers